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B.A., Physics, University of Montana, 2007

DISSERTATION

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Abstract

Recent realizations concerning kinematic measurements of extra-planar layers in nearby galaxies may provide important clues to the origin of such layers and thereby the growth and evolution of galaxy disks. In particular, observations have shown a decrease in rotation speed with height (lags) in the extra-planar layers of multiple galaxies, leading to various models which attempt to understand this gradient in terms of disk-halo flows and accretion of primordial gas. In this thesis we present deep observations and detailed kinematic models of neutral hydrogen (H\textsubscript{i}) in five nearby, edge-on spiral galaxies (NGC 4244, NGC 4565, NGC 4302, NGC 3044 and NGC 4013) observed with the Very Large Array and the Westerbork Synthesis Radio Telescope. These models provide insight concerning both the morphology and kinematics of HI above and within the disk, especially in terms of their lags. Characterization of the magnitude and radial variation of lags aids in determining whether extra-planar HI originates in the plane of the disk (as described in galactic
fountain-type models) or is accreted. In these galaxies we find substantial extra-planar \( \text{H} \text{I} \) is not ubiquitous, while lags appear to be so. Furthermore, the lags we measure are steeper than those produced by purely ballistic effects, indicating that additional physical effects must be at work. In every (with the exception of NGC 4013) galaxy we model, a radial shallowing of the lag is observed, starting at approximately half of \( R_{25} \), and reaching its lowest magnitude near \( R_{25} \). Combining our sample with results from the literature, we see no clear connection between the presence of extra-planar \( \text{H} \text{I} \) and star formation, nor do we see any connection between lag magnitude and star formation. Our findings provide constraints for theoretical scenarios which we will describe.
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Chapter 1

Introduction

1.1 Galaxy Evolution

Provided galactic star formation rates (SFRs) are relatively constant, if there is no source of new material to fuel star formation (SF) in galaxies as they evolve, their gas reservoirs are depleted (Putman et al. 2012 and references therein). Such a scenario would result in little ongoing SF in most galaxies, which is observationally not the case. Alternatively, if fuel from feedback or disk-halo flows were primarily responsible for SF, then newly-formed stars and the interstellar medium (ISM) would have higher metallicities than those observed (e.g. Caimmi 2008, Sommer-Larsen et al. 2003). Accretion of primordial gas from external sources could solve this dilemma. Thus, it is desirable to gauge the ongoing accretion rate for a large sample of galaxies.

Extra-planar layers (defined in § 1.2) act as the interface between the intergalactic medium (IGM) and the main disk of the galaxy. Therefore, any accreted material must go through these layers before it may be used to fuel SF within the disk. Only recently have extra-planar layers been studied in detail, with an even more recent emphasis on their kinematics (e.g. Heald et al. 2007, Oosterloo et al. 2007), in order
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to constrain whether their origins are primarily internal, external, or both.

In this thesis we will explore extra-planar layers (especially neutral hydrogen, i.e. H\textsc{i}) in spiral galaxies in an attempt to understand the origins of extra-planar H\textsc{i} and how it may relate to other extra-planar components, as well as to better constrain the H\textsc{i} accretion rate. This work will help to provide a more complete picture of galaxy evolution as a whole.

1.2 The Diffuse Interstellar Medium and Extra-planar Gas

Prior to addressing the main focus of this thesis, a basic understanding of the Interstellar Medium (ISM) is necessary. The diffuse ISM consists of four basic phases: the cold neutral medium (CNM) with temperatures on the order of 100K, the warm neutral medium (WNM) at approximately 8000 K, the warm ionized medium (WIM) also at 8000 K, and the hot ionized medium (HIM) having a range of $10^6$-$10^7$ K (Kulkarni & Heiles, 1988). The work in this thesis involves the neutral phases, but we refer to the others, especially the WIM in the context of the multiphase extra-planar ISM.

This work focuses on spiral galaxies with an emphasis on gas that is “extra-planar.” After much discussion with members of this sub-field, a common definition has been put forth in Kamphuis et al. 2013 (submitted to MNRAS). By this definition, “extra-planar” gas is gas that exists above the narrowest possible disk having a vertical profile that can be fit with the function $z/z_0$, where $z$ is the distance above the mid-plane, and $z_0$ is the scale height (exponential unless specified). Thus, this term will refer to anything in excess of such a disk, regardless of scale height, kinematics, origin, or additional morphology (e.g. within clumps or filaments vs. a smooth distribution with radius). These definitions prevent us from erroneously re-
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Referring to extra-planar gas as a global “halo,” which could potentially lead to much confusion. For example, halos observed in X-rays extend to greater heights above the mid-plane and have spherical rather than disk-like properties. These are fundamentally different from the thick disks we observe. This change in terminology from “halo” to “extra-planar” is a relatively new development, and at the onset of this work (and at the time that Chapters 2 and 3 were published), “halo” was still considered appropriate (and is still by some). This is mentioned to prevent confusion while addressing the relevant literature.

1.3 Disk-Halo Flows in Spiral Galaxies - Early Models and Observations

Theoretical discussion of the “interstellar galactic corona” in Spitzer (1956) marked the inception of gaseous halo studies. In that paper, Spitzer addressed observational evidence in the form of 1) high latitude/velocity clouds (Münch, 1957), 2) the equilibrium observed in spiral arms - indicating that the gas within is kept in place by external pressure, and 3) radio noise suggestive of an extended corona. Before proceeding, we will give a brief overview of each piece of evidence here.

By observing Ca II and Na I absorption lines in high latitude B and O type stars, Münch (1957) was able to gather evidence for intervening clouds. Spitzer acknowledged that the presence of such clouds indicated that they must exist within a confining medium having a comparable gas pressure to that of the galactic plane. Specifically, it was suggested that a gas with a temperature of \(10^5\) to \(3 \times 10^6\) degrees would suffice to preserve such clouds so far from the plane.

Chandrasekhar & Fermi (1953) describe the outward-driven pressure exerted by magnetic fields associated with spiral arms, as well as kinetic pressure due to the
velocities of the gas within. Should such pressures become too great, as was con- cluded by Spitzer to likely be the case, then gravitational forces would be rendered inadequate to keep the gas within spiral arms intact. Thus, there would need to be an external pressure directed inward to contain the gas within the spiral arms. Gas embedded between spiral arms could provide such pressure.

Baldwin (1954) gathered observational evidence at a wavelength of 3.7 m for a galactic corona having a radius of 10 kpc surrounding M 31. Evidence for an analogous 10-20 kpc corona surrounding the Milky Way was also found by Baldwin (1957). From these observations, Spitzer concluded that a hot corona is likely.

Two decades later, Shapiro & Field (1976) proposed what came to be known as the “galactic fountain” model, which has played a substantial role in our understanding of disk-halo flows. Similar to the motivation of Spitzer (1956), the model itself is driven by a need to cool hot, extra-planar gas resulting from supernova explosions in the scenario that a galaxy is a closed system. Contrary to Spitzer’s work, neither conduction or radiation are determined to be sufficient heat transfer mechanisms, and convection is instead considered: as hot gas rises from the mid-plane, it cools and condenses at heights on the order of 1 kpc. These condensed clouds travel to greater heights before eventually falling back toward the disk.

Later, Norman & Ikeuchi (1989) expanded upon the galactic fountain model, resulting in the “chimney model” in which super-bubbles formed via supernovae explosions of clustered O and B stars expand, and then break in a manner consistent with the Rayleigh-Taylor Instability (Figure 1.1). (The Rayleigh-Taylor Instability dictates that a surface separating fluids of different densities could be stable if no accelerations are present, but breaks when one fluid is driven into the other by an acceleration.) This process creates a chimney-like collimated structure comprised of cool gas, through which hot gas can flow from the mid-plane to great heights.
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The gas subsequently cools and condenses into clouds, which then fall back down to the disk. It is possible that the cycling could also involve gas that remains warm throughout the entire process. This is very similar to the galactic fountain model, but the disk-halo flows are concentrated to small regions rather than a general flow throughout the entire disk. Before the condensed gas falls back towards the mid-plane, due to a decreased gravitational potential with height, it moves to a larger radius as suggested by Bregman (1980). In order to conserve angular momentum, there must also be a decrease in rotational velocity with height. This vertical gradient in rotational velocity is referred to as a lag and is given in units of \( \text{km s}^{-1} \text{kpc}^{-1} \).

Lags have been recently observed in both the Milky Way and external galaxies. They provide valuable insight on the origins and kinematics of extra-planar gas, supplying constraints for models involving disk-halo flows as well as accretion. We will now further discuss evidence for multi-phase extra-planar gas, and for lags, both
in the context of recent observations and simulations, as well as our current work.

1.4 Disk-Halo Flows and Accretion - Contemporary Observations and Models

1.4.1 Observations

Observations of Multiphase Extra-Planar Components

Extra-planar components including hot gas (e.g. Tüllmann et al. 2006b, Hodges-Kluck & Bregman 2013), relativistic particles (e.g. Irwin et al. 1999), dust (e.g. Howk & Savage 1999), warm ionized hydrogen (e.g. Rand 1996; Rossa & Dettmar 2003), and neutral hydrogen (e.g. Swaters et al. 1997, Oosterloo et al. 2007) are seen in multiple galaxies. Here we will briefly discuss each of these, and because of the possible relevance to SNR driven disk-halo flows, how they relate to star formation within galaxies.

When we consider SF within galaxies, it is often useful to instead consider the total infrared luminosity ($L_{TIR}$), or occasionally, the far infrared luminosity ($L_{FIR}$) if $L_{TIR}$ is unavailable. This is because Hα is often used in SFR approximations, and extinction is so high in edge-on galaxies that it is difficult to obtain an accurate value for the SFR. Additionally, given the widely varying sizes of galaxies, we want some measure of SFR per unit area. Thus, we consider $L_{TIR}/D_{25}^2$.

Hot gas having temperatures of $10^6$-$10^7$K (the HIM phase of the ISM) is detected at large heights above the mid-plane [e.g. a scale height of approximately 5 kpc in NGC 891 (Hodges-Kluck & Bregman, 2013)] using X-ray telescopes such as ROSAT, Chandra, and XMM-Newton. As for other external galaxies, Tüllmann et al. (2006b)
conducted a survey with XMM-Newton of nine nearby, highly-inclined galaxies with high far infrared luminosities per unit area ($L_{\text{FIR}}/D_{25}^2$). Their sample selection, focusing on galaxies with high SF, prevented any true assessment of how X-ray halo properties relate to SF, but this was remedied by Anderson et al. (2013). With a larger, varied sample, Anderson et al. (2013) note that in general, early-type (elliptical and S0) galaxies have nearly twice the X-ray luminosity of late-type galaxies and that extended X-ray emission is more likely to be present in the former. The authors state that this difference in X-ray luminosities may be due to the differing morphologies of the galaxies, or the greater average stellar masses and luminosities in early-type galaxies.

With the detection of extra-planar radio continuum emission in the irregular galaxy, NGC 4631, Ekers & Sancisi (1977) began the study of extra-planar cosmic rays in nearby galaxies. A review by van der Kruit (1978) expanded on this to include several other galaxies, and to consider the morphology and strength of galactic magnetic fields (which are traced by cosmic rays) in greater depth. More recently Dahlem et al. (1995) find a connection between the presence of extra-planar radio continuum emission and high SF within galaxies. They also find an abrupt cut-off in radio continuum emission at radii where SF ceases to be prominent. This is consistent with the expectation that supernovae produce these cosmic rays. However, Krause (2011) note that the scale heights of extra-planar radio continuum emission in 5 nearby galaxies do not appear to be related to SF within the disk, in fact, the scale heights are almost constant throughout the sample. This could indicate that other factors, yet to be determined, may be dominant. With this result, it should be noted that not all galaxies in this small sample are edge-on (NGC 253 has a noticeably lower inclination), and one member (NGC 3628) has clearly undergone a minor merger in the recent past. Thus, the trends presented in Kraus (2011) should be considered skeptically. Currently, the Continuum Halos in Nearby Galaxies an EVLA Survey (CHANG-ES) (Irwin et al., 2012) is in the process of increasing the
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number of nearby, edge-on galaxies observed in radio continuum. This will greatly increase our understanding of extra-planar cosmic rays and magnetic fields.

A recent overview of extra-planar dust by Howk (2009) mentions dust clouds seen in absorption that reach heights of approximately 2 kpc in what are generally considered to be “thick disks.” It is thought that these clouds trace a CNM. Observations of nearby, edge-on galaxies with Spitzer (e.g. Burgdorf et al. 2009) and Herschel (e.g. Holwerda et al. 2012) increase our understanding of extra-planar dust. The New HErschel Multi-wavelength Extragalactic Survey of Edge-on Spirals (NHEMESSES) described in Holwerda et al. (2012) targets 12 nearby, edge-on galaxies, in part to measure the thickness of their associated dust layers, and to see if there is any relation to galaxy mass. More relevant to this thesis, they will attempt to detect and characterize extra-planar structures. Additionally, the Herschel Edge-on Galaxy Survey (HEDGES) is also underway. That survey will carry out deeper observations of a smaller sample of galaxies, including NGC 891, NGC 4244, and NGC 4565. We will draw comparisons to these works in later chapters that involve galaxies coinciding with our own analysis.

The WIM is alternatively referred to as Diffuse Ionized Gas (DIG) when considering external galaxies. Rand (1996) found a connection between SF and the presence of extra-planar DIG layers in 15 nearby galaxies, including nine observed in that paper. Rossa & Dettmar (2003) consider 74 nearby galaxies and detect extra-planar DIG layers in 30 galaxies, generally those with higher SFRs, although there are some exceptions.

Probably the most well-known example of extra-planar H\textsc{i} in an external galaxy would be that observed in NGC 891 (e.g. Swaters et al. 1997, Oosterloo et al. 2007). This massive H\textsc{i} layer extends up to 10 kpc above the plane of the disk. This detection played a substantial role in prompting future H\textsc{i} studies of additional external galaxies that will in part be discussed in § 1.5. In addition to NGC 891,
extra-planar H\textsc{i} is seen in several other galaxies, although to a lesser degree (e.g. NGC 5746 by Rand & Benjamin 2008, and NGC 5775 by Lee et al. 2001). One noteworthy galaxy possessing substantial extra-planar H\textsc{i} is UGC 7321, a low surface brightness (LSB) galaxy with low SF (Matthews & Wood, 2003). If one assumes that, as appears to be the case with other extra-planar components, the presence of extra-planar H\textsc{i} is linked to SF, then this is unexpected and requires further consideration.

For all of the extra-planar components described above except H\textsc{i}, there exists a correlation between their presence and SF in the disk, both in localized regions as well as globally. This indicates disk-halo flows akin to those in the aforementioned galactic fountain and chimney models as likely origins. However, such trends have not been reported for H\textsc{i}, and in fact there is evidence that at least some extra-planar H\textsc{i} has an external origin, which we will discuss further in § 1.4.3. Considering the kinematics of multiphase extra-planar layers, such as lags, may shed light on this problem. Lags are measured in extra-planar ionized gas and H\textsc{i} since both components may be observed spectroscopically, and with sufficient spatial resolution. As we will see, lags may help constrain the origin of extra-planar gas, but should also be dependent on the physical processes operation in these environments. We will discuss these lag determinations that have been made prior to this thesis now.

**Observed Lags in Ionized Gas Layers**

Heald et al. (2007) measured lags in three extra-planar Diffuse Ionized Gas (DIG) layers [NGC 5775 (−8 km s\(^{-1}\) kpc\(^{-1}\)), NGC 891 (−17 km s\(^{-1}\) kpc\(^{-1}\)), and NGC 4302 (−35, 23 km s\(^{-1}\) kpc\(^{-1}\); approaching and receding halves respectively)], resulting in a trend of low SF rates (SFR) with steeper lags. If H\textsc{i} and DIG layers share similar kinematics and the Heald et al. (2007) trend holds, then, the same should be expected for H\textsc{i}. Also worth consideration is that the DIG lag in NGC 4302 shows some radial variations, with the lag steepening to nearly −60 km s\(^{-1}\) kpc\(^{-1}\) for radii
greater than 4 kpc on the receding half. Heald et al. (2007) also noted the near constancy of the lag per unit DIG scale height, although the interpretation of that result is unclear.

Measuring and comparing both \textsc{hi} and DIG lags is particularly useful when determining the origins of extra-planar \textsc{hi}. Since DIG layers have been found to correlate with SF in galaxies, if \textsc{hi} layers share the same kinematics, then it is likely that the two extra-planar phases have similar origins. However, if their kinematics differ, their origins may differ as well. Alternatively, there may be additional effects from magnetic tension or pressure gradients (described in § 1.4.2) at work that affect the two phases differently. Thus, regardless of how well the kinematics of the two phases match, there is much to learn from both.

**Observed Lags in \textsc{hi} Layers**

Candidate lagging \textsc{hi} layers have been seen in multiple galaxies [e.g. NGC 2403 (Schaap et al. 2000, Fraternali et al. 2002), NGC 4559 (Barbieri et al., 2005)]. These are moderately-inclined ($i < 85^\circ$), and were dubbed “bearded” galaxies due to the appearance of what is presumed to be lagging extra-planar \textsc{hi} in major axis position-velocity diagrams (Sancisi et al. 2001; Figure 1.2). However, given the projection effects resulting from the inclination of these galaxies, it is difficult to accurately assess the scale height of the \textsc{hi} layers, rendering determining an actual value for the lag impossible. For these reasons, lags will only be discussed for galaxies having an edge-on orientation with respect to the observer.

Lags have been observed in the extra-planar \textsc{hi} layers of several edge-on galaxies including the Milky Way ($-22, -15$ km s$^{-1}$ kpc$^{-1}$; Levine et al. 2008, Marasco & Fraternali 2011), NGC 891 ($-15$ km s$^{-1}$ kpc$^{-1}$; Oosterloo et al. 2007), and UGC 7321 [$-25$ km s$^{-1}$ kpc$^{-1}$ (or shallower); Matthews & Wood 2003]. Along with these,
Figure 1.2 Figure 5 from Barbieri et al. (2005) shows a major axis position-velocity diagram of the moderately-inclined galaxy, NGC 4559. The “beard” emission is most readily seen on the systemic side in the approaching half between velocities of 725 km s$^{-1}$ and 800 km s$^{-1}$. Contours are at 2, 4, 8, 16, 32, 64$\sigma$, with $\sigma = 0.48$ mJy beam$^{-1}$. The white dots show the rotation curve from their models.

there are several more ambiguous cases such as UGC 1281 where a line of sight warp component was favored but a lag could not be ruled out (Kamphuis et al., 2011), and NGC 5775 where several extra-planar extensions are lagging, but there is not an overall global thick disk (Irwin, 1994). Additionally, the lags in both the Milky Way and NGC 891 have been shown to shallow radially (Figure 1.3).

The magnitudes of these observed lags vary from galaxy to galaxy, as do their radial variations. From this small number of measured lags, there are currently no definite trends connecting lag properties to H I scale height, SF, H I or total mass, H I extent, optical radius, or environment. Furthermore, the observations, analysis and modeling differ between galaxies, yielding potentially inconsistent results. Additionally, lags may not start at the midplane, but at greater heights. It is also possible
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Figure 1.3 Figure 15 from Oosterloo et al. 2007 shows the rotation curves in NGC 891 as a function of height above the mid-plane. Note how the differences become less pronounced at large radii, which is consistent with a radially shallow lag.

that they may not be simply linear gradients, although the measured lags to date appear to be consistent with such a scenario. To understand the nature of these lags, we must consider a larger sample, and do so in a consistent fashion. Finally, we must also consider and compare additional components of the ISM.

The above observations involving both H I and DIG layers have inspired multiple theoretical efforts, which we will consider in the next section.

1.4.2 Theoretical Expectations for Lags Involving Internal Processes

We now return to the kinematics of purely ballistic disk-halo flows such as those initially considered in Bregman (1980). The primary motivation for ballistic models, in which hydrodynamic considerations may be omitted, is their simplicity - one may consider only gravitational effects in such cases. Thus, ballistic models are a natural starting-point for determining the underlying physics of lagging extra-planar
While considering ballistic models in an attempt to explain DIG kinematics, Collins et al. (2002) found lags that were shallower than those observed. (Although this comparison is based on subsequent observations. The observational data available at the time, for which the projection effects had yet to be understood, indicated the opposite, thus that paper states otherwise.) Later attempts by Fraternali & Binney (2006) also resulted in lags too shallow to match observations. From these, it may be concluded that it is likely that more than purely ballistic effects are necessary.

Marinacci et al. (2011) suggest an internally generated hot halo rotating more slowly than the main disk of the galaxy, producing a drag force that would lead to a lag. However, in such a scenario involving only internal processes, the difference in rotational velocities between the main disk and the halo would be too little to produce observed lags.

In addition to the overall magnitudes of global lags that have been discussed so far, it is also useful to consider how they vary radially. An entirely geometric expectation, without any consideration of hydrodynamic effects such as extra-planar pressure gradients, drag, or magnetic fields, considers the relationship between the rotational velocity and the gravitational potential: gas with an initial rotational velocity is launched high above the plane of the disk. At the new, increased height, the gas is further from the gravitational center, and must experience a decrease in rotational velocity (lag) to conserve angular momentum. This effect is more pronounced at smaller radii, where a certain height above the disk is a greater fraction of the radial distance from the center, resulting in a larger relative change in the gravitational potential, and thus a steeper lag. This effect may be seen in Figure 3 of Collins et al. (2002). While this simple geometric interpretation likely plays some role in the observed shallowing of lags, additional effects must also be considered. Benjamin (2002) discussed kinematics of multiphase galactic halos, including lags produced by
purely ballistic effects (described above), as well as pressure gradients and magnetic tension. The following is a summary of the ideas expressed in that paper.

Firstly, radial pressure gradients can have substantial effects on lags. This is largely due to the fact that an acceleration caused by a pressure gradient would be inversely proportional to the gas density \[ a_p = \left( \frac{dp}{dR} \right)/\rho, \] where \( a_p \) is the acceleration caused by the pressure gradient, \( \rho \) is the density of the rising gas, \( p \) is the pressure, and \( R \) is the radius. Thus, pressure gradients have a large impact high above the plane of the disk where, provided cycling clouds are not purely ballistic, their densities will be lower. Possible sources of pressure are magnetic fields, cosmic rays, or hot gas. If we consider a barotropic fluid rotating in a gravitational field first, such a scenario will yield approximately cylindrical rotation, meaning that there must be some force counteracting the gravitational potential. Specifically, if there exists a low pressure region near the center of a galaxy, there will be an inwardly directed acceleration that would be additive to the gravitational acceleration. When considered for heights above the disk, this inward acceleration would, to some degree, negate the effects due to conservation of angular momentum described in §1.3. Thus, an outward pressure gradient with an acceleration directed radially inward may cause a shallower global lag. Conversely, a pressure gradient producing a radially outward force may result in a steeper global lag, or even a decrease in rotation velocity. If such pressure gradients, or the behavior of the density of cycling clouds, vary radially themselves, then a radial change in the lag may occur. Given how little is currently known of halo pressure gradients, the degree to which clouds’ densities could vary as they cycle, as well as the potentially substantial impacts even small pressure gradients may have, it is difficult to say to what degree these will alter the characteristics of any given lag.

A more complicated scenario would be if the magnetic fields were curved, the magnetic tension would produce a radially inward acceleration of the form \[ \frac{v^2}{\tau_{\text{cur}}}, \] where
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\(v_A\) is the Alfven speed (defined as \(v_A = \frac{B}{\sqrt{\mu_0 \rho_p}}\) where \(B\) is the magnetic field, \(\mu_0\) is the permeability in a vacuum, and \(\rho_p\) is the density of charged particles in a plasma), and \(r_{cur}\) is the radius of curvature. This acceleration would be proportional to the radius of curvature of the magnetic field at a given point. Benjamin (2002) comments on how this scenario would follow similar principles to those presented in Boulares & Cox (1990) in which the authors hint at a possible vertical component to galactic magnetic fields that could produce pressure gradients. Currently, there is not enough known about magnetic field geometries to say how relevant this effect would be.

Of particular relevance to the work presented in this thesis, Benjamin (2002) notes that determining how lags vary radially will be crucial in distinguishing between models. Clearly, observational evidence must be gathered to determine which models, or combinations of models are correct.

1.4.3 Accretion from External Sources

The simulations and theoretical arguments presented thus far have considered only internal processes. However, observational evidence for accretion exists in both the Milky Way and external galaxies, the effects of which we now consider. We will see that accretion may be relevant to understanding extra-planar gas kinematics.

Observational Evidence for Accretion

The G-Dwarf Problem

Based on metallicity values of the interstellar medium (ISM), and related theoretical predictions, there exists an observed paucity in the number of metal deficient G dwarfs both within the Milky Way (e.g. Caimmi 2008) as well as in external galaxies (e.g. Worthey et al. 1996) that is known as the G-dwarf Problem. In other words, if
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the Milky Way is a closed system, then stars forming heavier metals throughout their lifetimes before eventually replenishing the ISM with these metals at the end of their lives should result in an increasing metallicity in the ISM over time. Alternatively, this could be viewed as stars possessing a range of metallicities, with those having formed earliest having the lowest. However, what is observed is a lack of such stars when considering the current metallicity value of the ISM. This discrepancy could potentially be explained by the steady accretion of gas with metallicities of approximately 0.1 of that found in the Sun, at a rate of approximately $1 M_\odot yr^{-1}$ (Wakker et al., 1999). If such accretion is taking place, lowering the metallicity of the ISM, then it stands to reason that the ISM may not have been at the low values in the past as were initially predicted. Thus, the low-metallicity G-Dwarf stars would no longer be expected. There is also the alternative of “prompt initial enrichment” in which early episodes of SF rapidly raised the metallicity of the disk (e.g. Li et al. 2000).

One could argue that the lifetime of a G-dwarf star is approximately 10 Gyr, so stars formed at early times - when the metallicity of the ISM would likely be at its lowest value, could have evolved off of the main sequence. However, an analogous problem is now seen in both K (Casuso & Beckman, 2004) and M dwarfs (Woolf & West, 2012), both types having average lifetimes longer than the age of the universe.

**High-Velocity Clouds in the Milky Way**

As noted by Wakker & van Woerden (1997, and references therein), high-velocity clouds (HVCs) are observed in the Milky Way. The velocities (in many cases counter-rotating), locations, and low metallicities of these clouds indicate external origins are likely. Much of the work involving such clouds has involved neutral gas, but more recent observations by Shull et al. (2009) and Lehner et al. (2012) consider HVCs in the context of streaming ionized and neutral gas in the Milky Way that involve observations of ionized gas from multiple species. The observations by Lehner
et al. (2012) show that most HVCs are within 5-15 kpc of the Sun and those with the highest velocities are likely associated with the Magellanic Stream, indicating accretion is taking place. Wakker et al. (2008) also measured distances to HVCs as well as IVCs (intermediate-velocity clouds, generally thought to have internal origins), including the Cohen Stream and the Smith Cloud. They found distances to IVCs to be within a few kpc of the Sun, with HVCs 10-15 kpc away, and the furthest at a distance of 30 kpc (although that detection is not confirmed). However, in general (associated with the Magellanic Stream or not), the masses \(10^5-10^6 \, M_\odot\) and filling factor of these HVCs indicate that it is unlikely that a majority of extra-planar material may be attributed to them (Sancisi et al. 2008 and references therein). Figure 1.4 shows a recent depiction of the locations of these clouds.

The accretion rate of HVCs as assessed by Sancisi et al. (2008), is 0.1-0.25\(M_\odot\) \(yr^{-1}\) (including He and ionized gas), which is substantially lower than the estimated SFR within the Milky Way of approximately 1 \(M_\odot\) \(yr^{-1}\). Thus, accretion of HVCs alone could not be sufficient to replenish \(\text{H} \, \text{i}\) in our galaxy to fuel SF. However, Lehner et al. (2012) claim that the ionized gas is likely more important than the neutral component, and the accretion of both could result in a total accretion rate of 0.4-1.4 \(M_\odot\) \(yr^{-1}\).

**Anomalous Features in External Galaxies**

Anomalous clouds analogous to the HVCs seen in the Milky Way are seen in multiple external galaxies including M 31 and M 33 (Westmeier et al., 2005), and NGC 891 (Oosterloo et al., 2007) (Figure 1.5). Some are counter-rotating relative to the disk, indicating they could not have originated from the main galaxy. Additionally, filamentary structures that could potentially be associated with accretion are seen in NGC 891 (Oosterloo et al., 2007) and NGC 5775 (Irwin, 1994).

Anderson et al. (2013) consider 2165 galaxies using stacked images and see ev-
Figure 1.4 Figure 1 from Putman et al. (2012) shows the distribution of H\textsc{i} clouds (marked as plus signs in the case of compact HVCs) and ionized high velocity gas (denoted by circles and diamonds) in the Milky Way.

Evidence for accretion-driven hot gas halos expected in galaxy evolution simulations discussed below. Hodges-Kluck & Bregman (2013) investigate the extended hot halo in NGC 891 and find that some of it is likely due to accretion. They also argue that the substantial extra-planar H\textsc{i} in NGC 891 along with their inferred hot gas cooling rate are inconsistent with a steady state model. Specifically, given that the H\textsc{i} is condensing and falling back toward the disk, the cooling rate of the hot gas is too low to replenish the extra-planar H\textsc{i} quickly enough to remain in equilibrium. Additionally, based on examination of superbubbles in NGC 891, they stress that a galactic fountain could not account for all of the H\textsc{i} halo mass. Somewhat contrary to the H\textsc{i} filament and counter-rotating material described in Oosterloo et al. (2007), Hodges-Kluck & Bregman (2013) put forth that it is unlikely that a sufficient amount of gas could be accreted via filaments (as in “cold mode” accretion), and suggests “hot mode” accretion may play some role. We will address both modes of accretion in detail in the next section.
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Figure 1.5 Figure 4 from (Oosterloo et al., 2007) show channel maps with anomalous gas in NGC 891. The arrows in the top panels show a filament and the arrows in the two central panels point to counter-rotating H\textsc{i} clumps. Contour levels are $-0.4, -0.18, 0.18, 0.4, 1, 2, 4, 10, 20, \text{and} 40 \text{ mJy km s}^{-1}$. The velocities of each channel in km s$^{-1}$ are in the upper-right corner of each panel.

Recent Theoretical Simulations Involving Accretion

Expanding upon the ideas introduced by White & Rees (1978) in which material from a hot halo accretes onto the galactic disk, Kereš et al. (2005) discuss external origins for extra-planar gas. They use smoothed particle hydrodynamics (SPH) simulations to investigate spherically accreted gas that is shock-heated, and then cooled again before condensing and forming stars (hot mode). In addition, they find a substantial fraction of the gas is accreted along filaments and instead radiates at temperatures roughly an order of magnitude lower (cold mode). In both cases, the cool external gas obtains its initial heat energy from gravitational infall. The two modes of ac-
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creartion are each dominant at different redshifts. Cold mode accretion dominates at redshifts greater than 3, in low mass galaxies, and low-density environments, while hot mode accretion dominates in low-redshift environments, high mass systems, and high-density environments. The simulations indicate that environmental effects are quite strong, showing low mass galaxies dominated by hot mode accretion in higher density environments and vice versa.

One shortcoming of the simulations presented in Kereš et al. (2005), due to low spatial resolution, is that they cannot say exactly how cold mode gas enters a galaxy’s disk. They consider three possibilities which, with sufficient resolution, could yield detectable kinematic signatures. (Naturally, improved resolution in SPH simulations would also be of use.) The first scenario involves accreted gas falling within the virial radius, and then being abruptly stopped by a shock near the galactic disk. Alternatively, gas may accrete smoothly onto the galactic disk, with the infall velocity gradually converting to rotational. A third possibility would involve an adiabatic slowing of infalling gas due to pressure gradients, or a series of small shocks. Follow-up simulations with higher resolution were presented in Kereš & Hernquist (2009). Their findings indicate that clouds form within filaments ($T = 10^5$ K) flowing through hot gas ($T = 10^6$ K) high above the disk. These clouds then remain intact as they fall to the disk.

Another shortcoming of these simulations that the authors acknowledge is a lack of Active Galactic Nuclei (AGN) or stellar/supernova feedback that could potentially suppress accretion. The latter would likely only be relevant in the hot mode due to its lower density and high covering factor. Supernova feedback would also be more significant in low mass systems due to lower gravitational potentials regardless of accretion mode. As noted by the authors, inclusion of such feedback could alter their simulations substantially.

The most recent simulations by Nelson et al. (2013) indicate that hot mode
accretion may play a more important role than previously thought, especially in massive galaxies. Their conclusions rely heavily on the code used in simulations, with a higher fraction of accreted gas being hot mode when using more sophisticated code. They too omit feedback from their simulations, but have mentioned it as a key element in future work.

Simulations involving infalling multiphase gas described by Kaufmann et al. (2006) reproduce extra-planar kinematics, in particular the lag, similar to those seen for the \( \text{H} \text{I} \) in NGC 891. Their models consider hot gas condensing into clouds, and then cooling to be partially neutral as it falls toward the disk. To conserve angular momentum, the gas rotates more rapidly as it approaches the mid-plane in a cylindrical fashion as opposed to a spherical inflow. In their simulations, the infall velocities are approximately 10 km s\(^{-1}\) for a galaxy such as M33, while the free-fall velocity for material within that galaxy would be 70 km s\(^{-1}\). From this, they conclude that there must be some drag from the hot corona. Furthermore, a continuous heating source, driving thermal instability is necessary to maintain such a multiphase medium. Otherwise, the temperatures throughout the halo become constant, decreasing instabilities rather than amplifying them. A continuous supply of hot gas via gravitational collapse is found to be sufficient for this purpose. In these simulations, accretion would account for nearly all extra-planar \( \text{H} \text{I} \).

However, not all are in agreement with the assertions presented in Kaufmann et al. (2006). Fraternali & Binney (2008), which expands on simulations presented in (Barnabè et al. 2006, and Fraternali & Binney 2006), investigate accretion of what is assumed to be primordial gas onto NGC 891 and NGC 2403 and how accreted and disk-halo cycled gas might interact via a drag force, which has the effect of enhancing the accretion rate. The accretion rates they find are comparable to the SFRs in those galaxies. Additionally, they estimate that accretion accounts for 10-20% of extra-planar gas, with a majority still attributed to disk-halo flows. In their
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Simulations, cooler, streaming coronal gas (streaming to circumvent lengthy cooling times of hot coronal gas) with low angular momentum is “swept up” by clouds produced in galactic fountain flows. They stress this point, going so far as to say that due to a lack of thermal instabilities in the corona, and to avoid an unphysically large accretion rate to account for the large amounts of extra-planar H\textsc{i} observed in NGC 891, substantial extra-planar H\textsc{i} layers cannot form from cooling coronal gas alone, but must be the result of feedback to some degree.

Further considering disk-halo flows and accretion, Marinacci et al. (2011) build upon ideas explored in Marinacci et al. (2010) to simulate galaxies surrounded by hot coronae rotating 50-200 km s\textsuperscript{-1} slower than the main disk. These models rely on momentum and heat exchanges between the two media as disk clouds in disk-halo flows circulate in the hot corona to reproduce observed kinematics such as lags. During these exchanges, gas is stripped from a cloud by the corona. The stripped gas streams behind the cloud, mixing with the hot coronal gas. This results in relatively efficient cooling of the coronal gas as compared to the lengthy cooling times for such hot gas described in Fraternali & Binney (2008). The trailing, mixed gas condenses into smaller H\textsc{i} clouds, and then falls toward the disk. Marinacci et al. (2011) find that the momentum loss to the corona would contribute approximately \(-7\) km s\textsuperscript{-1} kpc\textsuperscript{-1} to the deceleration of clouds (approximately 50\% of the total \(-15\) km s\textsuperscript{-1} kpc\textsuperscript{-1} lag) produced in a galactic fountain model in the galaxy NGC 891. When combined with ballistic effects, this would help to reconcile the discrepancies between purely ballistic models (e.g. Collins et al. 2002) and observations. These ideas are further explored by Marasco et al. (2013) and illustrated in (Figure 1.6). Marasco et al. (2013) consider observational evidence of absorption by the cooling/mixing gas. They find that 75-95\% of warm absorbers are consistent with their models, in terms of their distribution on the sky, velocities, and column densities.
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Figure 1.6 Figure 1 from Fraternali et al. (2013) illustrating cool gas ejected from the disk and into the lower galactic corona by supernova explosions as described in Marasco et al. (2013). The gas in the wake of the cloud mixes, resulting in cooler coronal gas that will eventually fall onto the disk.

1.4.4 Remaining Questions and Motivation for this Work

There exist several unsolved issues concerning the acquisition of extra-planar gas in nearby galaxies. These are as follows:

1. There exists a clear connection between SF on local and global scales with several extra-planar multiphase components. Is this also true for extra-planar H\textsc{i}?
2. What percentage of extra-planar gas may be attributed to accretion, and how is the gas accreted?
3. A connection is seen between steep DIG lags and low SF in three galaxies. Does this hold for H\textsc{i} lags?
4. Lags are seen to vary radially in a few galaxies. Is this a common feature of lags? If so, why?
5. Is there a connection between lags and SF, total mass, H\textsc{i} mass, or the extent H\textsc{i} above the plane of the disk? Are these purely ballistic effects, or do magnetic tension and pressure gradients play some role?
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Are they affected by accretion? Can radial variations be understood in an accretion scenario?
6. What effects do companion galaxies and environment have on lag characteristics?

These questions are the primary motivation for the work presented in this thesis. The observations and modeling presented in subsequent chapters greatly increase the number of nearby, edge-on spiral galaxies with deep, high-resolution H\textsubscript{i} observations and detailed modeling, in some cases utilizing new instruments, as well as newly-developed and innovative software. In the next section, we address ongoing observational studies used in this thesis that hope to answer these questions.

1.5 Ongoing Observational Studies of Disk-Halo Flows and Accretion

1.5.1 The Westerbork Hydrogen Accretion in LOcal GA laxieS Survey

The Westerbork Hydrogen Accretion in LOcal GA laxieS (HALOGAS) survey (Heald et al., 2011) targets 22 edge-on or moderately inclined spiral galaxies for deep, uniform $10 \times 12$ hour observations using the Westerbork Synthesis Radio Telescope (WSRT). This survey will allow us to establish whether there is any connection between extra-planar H\textsubscript{i} and SF, as well as the degree to which contributions from external origins are relevant. This thesis includes modeling of two of the best-studied edge-on galaxies in the sample: NGC 4244 and NGC 4565.

Aside from the characterization of extra-planar gas, one goal of HALOGAS is to investigate morphological features such as bars and rings as well as their kinematics.
1.5.2 Studies with the Very Large Array

Our work using the VLA is both separate from and complimentary to HALOGAS. A primary reason for our sample selection was to address high SFRs that HALOGAS does not encompass, and also to study the extra-planar HI in NGC 4302, for which a very steep lag has been found in the extra-planar DIG as discussed earlier. NGC 3044 and NGC 4013 have rather high SFRs. The range of SFRs among these galaxies, which combined with the HALOGAS edge-ons, makes them ideal for probing the relation between the presence of extra-planar HI, lag magnitude, and the radial variation of lags with SF on both global and local scales. Additionally, data taken in the B configuration especially will yield higher resolution than the HALOGAS data. This will enable us to better constrain lag properties, particularly close to the plane of the disk.

1.6 Observational Methods

1.6.1 The 21-cm Transition of Neutral Hydrogen

The first radio spectral line predicted by van de Hulst (1945) and discovered by Ewen & Purcell (1951) was the 21-cm transition of neutral hydrogen, which involves the hyperfine splitting of the F=1 and F=0 levels of the ground state ($1^2S_{1/2}$) (Kulkarni & Heiles, 1988). This is a magnetic dipole transition resulting from collisions, with the fraction of such collisions that actually end with a photon being absorbed or emitted relying heavily on the excitation or spin temperature. The CNM and WNM, which are both stable and detectable at 21 cm, until recently, have been considered to have
temperatures of approximately 100 K and 8000 K respectively. Work by Heiles & Troland (2003) indicate a peak temperature of 40 K for the CNM, and have found an unexpectedly large fraction the WNM at temperatures (500-5000 K) corresponding to an unstable state.

The 21 cm transition is ideal for observing galactic morphology and kinematics for multiple reasons, primarily: 1) The 21-cm line is optically thin to column densities of approximately $10^{22}$ cm$^{-2}$ where H i self-absorption takes place (Braun et al. 2009, Figure 13), allowing for observations of gas on the far side of galaxies, including most with edge-on orientations. 2) The extent of the H i disk is substantially greater than that of the optical, allowing for observations and modeling of the outskirts of galaxies. This is extremely useful when constraining features such as warps and flares. Also, H i is unaffected by extinction, unlike optical emission lines from DIG.

1.6.2 Aperture Synthesis

Since resolution is proportional to the wavelength divided by the aperture diameter, long wavelengths require large apertures to gain sufficient resolution. This is especially true for the 21-cm line. Assuming $\theta = \frac{k\lambda}{D}$, $\theta$ is in radians, and $k$ is approximately 1 (Wilson et al., 2009), a resolution of approximately 10" requires an aperture diameter of approximately 5 km. It would be impractical to manufacture a single aperture with a diameter of several kilometers. Thus, we rely on aperture synthesis.

Aperture synthesis employs principles of interferometry to allow multiple small apertures or elements to be combined to create a single, larger aperture with a diameter equivalent to the longest baseline. This can most easily be illustrated by considering a 2-element interferometer as described in Wilson et al. (2009). The response from the combination of the two elements may be found by multiplying
the output from each after compensation for the unequal signal paths (the delay) -
this complex quantity is called the visibility. While the necessary resolution may be
gained with a 2-element interferometer, such an arrangement would be greatly lacking
in sensitivity and spatial frequency coverage. Because of this, additional elements
must be spaced at intermediate distances from the center, creating an array.

When dealing with such arrays, we consider a coordinate system using earth-based
east ($u$) and north ($v$), both generally in units of wavelength and together known as
the $uv$ plane, as well as $\nu$ - the frequency. In this scenario, the $xy$ plane would be
the $uv$ plane projected onto the celestial sphere. Or, alternatively, the $uv$ plane is
the projected baseline plane as seen from the source as it is tracked by the array. To
convert visibilities from the $uv$ plane to intensities in the $xy$ plane, an inverse Fourier
transform is performed. However, since the $uv$ plane is not sampled completely, the
problem is not so simple. One must start with the “dirty beam” (point spread
function; the Fourier transform of the $uv$-plane sampling function), which is used to
create a “dirty image.” A dirty image, which is the convolution of the desired image
with the dirty beam, contains artifacts referred to as “sidelobes,” which result from
the incomplete sampling of the $uv$ plane. To eliminate such artifacts, the image must
be deconvolved, or “cleaned.”

There are several common cleaning algorithms used, the most common based
on the Högbohm algorithm (Högbohm, 1974). That algorithm finds and measures the
peak intensity in the dirty image. A clean component (the dirty beam multiplied
by the peak value and a gain factor) is then subtracted from the dirty image at
the location of the peak. A model containing the subtracted components is created.
The process is repeated until the desired threshold is reached, at which the dirty
image is comprised of noise referred to as the “residuals.” The final clean image is a
combination of the clean components convolved with a “clean beam,” which is a fit
to the central peak of the dirty beam and the residual noise from the dirty image.
The image must finally be divided by the primary beam response.

As one may assume, there are multiple ways to sample the $uv$ plane, each yielding different results. We will now discuss the properties of existing arrays, as well as their advantages and disadvantages. One example would be the WSRT, which is an east-west array. Such an arrangement takes advantage of the Earth’s rotation to increase $uv$ coverage. A drawback of an east-west array is that instead of being circular, the resulting beam will have elongation determined by the inverse of the sine of the Declination of the source (Wilson et al., 2009). Naturally, the effect will be more pronounced for low-Declination sources. Consistent spacing between elements such as that in the WSRT allows for multiple measurements of the same $uv$ components, thereby increasing the accuracy for each, but reduces the total number of $uv$ components measured (Wilson et al., 2009). Contrary to the WSRT, the VLA has uneven (but not random) spacings in a “Y-shape.” The VLA also takes advantage of the Earth’s rotation to increase $uv$ coverage, but is less dependent on it than an east-west array. Additionally, both telescopes are capable of moving individual antennas into different configurations to change the way in which the $uv$ plane is sampled to improve resolution (increase antenna spacings) or to increase sensitivity (decrease antenna spacings). However, their general shapes remain the same. Data from multiple configurations may also be combined.

1.6.3 Observations and Data Reduction

Observations of NGC 4244 and NGC 4565 were done using the WSRT as part of the HALOGAS survey, while observations of NGC 4302, NGC 3044, and NGC 4013 were performed with the VLA in B and C configurations. Details of these observations will be given in the appropriate chapters of this thesis.

To give proper credit for the data presented in this thesis, it is noted that data
for galaxies observed with the VLA (NGC 4302, NGC 3044 and NGC 4013) were reduced by L. Zschaechner and R. Rand (NGC 4302, C array) using standard spectral line methods described below. However, to maintain consistent data reduction methods for the entire HALOGAS sample, data reduction for galaxies observed with the WSRT (NGC 4244 and NGC 4565) was done by Dr. George Heald and Dr. Gianfranco Gentile of the HALOGAS collaboration. Further details concerning those two galaxies may be found in Chapters 2 and 3 respectively. In this section, we will address the data reduction of the first three.

The Astronomical Image Processing System (AIPS) was used to reduce data for NGC 4302, while the Common Astronomy Software Applications package (CASA) was used for NGC 3044. NGC 4013 was first reduced using CASA, but then re-done in AIPS to eliminate side-lobes, as well as to expedite the process.

Data reduction was performed using standard spectral-line methods. Flagging of bad data (primarily caused by Radio Frequency Interference or RFI) was performed upon initial inspection (being careful not to flag channel-dependent RFI prior to Hanning-Smoothing), as well as after smoothing and calibration. Baseline corrections were made when necessary.

Bandpass calibration is performed to solve for frequency-dependent changes in the gain. To determine absolute flux values, a gain calibration is then performed using the gain calibrator, which is selected based on both its brightness and distribution (ideally a point source), which are well-studied for the commonly-used calibrators. The gain calibrator need not be near the target source. Next, a phase calibration is performed using the phase calibrator. The purpose of the phase calibration is to measure atmospheric and instrumental effects. Because of this, the phase calibrator must be within a few degrees of the target source. As is the case with the gain calibrator, bright point sources are desirable. The calibration solutions are then applied to the data.
Chapter 1. Introduction

Once the data are calibrated, the target source is separated from the calibrators, and if multiple observations exist, they are combined. This applies to multiple observations in the same configuration, as well as those using different configurations. At this point, the data are ready for imaging as described in § 1.6.2. However, using only steps to this point often produces images with artifacts and low dynamic range. Thus, self calibration is frequently beneficial.

Self calibration is often necessary because, as described above, gain and phase calibrations are generally done on sources other than the target. Observations of the calibrators are not done synchronously with observations of the target source, resulting in errors from both atmospheric variations (primarily in the phases), as well as electronics. Furthermore, they are at slightly different locations in the sky, introducing additional errors. Self calibration uses the target source to create a model. The complex gains of the model are then found. A new model is then created from the corrected data, and the process is repeated until improvements cease. Only minor corrections were needed for NGC 4302, so self calibration was performed at a late stage by averaging several channels of the line data to obtain a large enough signal to noise ratio to produce good solutions. In contrast, NGC 4013 had particularly prominent side-lobes, so self calibration was performed before continuum subtraction.

Image cubes were created for each galaxy using the tasks IMAGR (AIPS) and CLEAN (CASA) based on the principles described in § 1.6.2. To produce optimal cubes, different weighting schemes were used, including Uniform (higher resolution, reduced side-lobes, higher rms noise), Natural (low resolution, high signal to noise ratio), and Briggs, with the latter-most using a range of “robust” parameters. Since we require both high-resolution and recovery of faint, extended emission, the final cubes used in the modeling process involved robust parameters close to zero. However, lower-resolution cubes were examined for any faint emission that may have
been missed. Additionally, our models were also checked against the lower-resolution cubes for consistency.

1.7 Tilted-Ring Modeling

Understanding the three-dimensional morphology and kinematics of H\(_i\) in galaxies (i.e. a six-dimensional phase space) is essential to understanding the origins of the material within them. Unfortunately, we observe the distribution in only two spatial, and one velocity dimension. Hence, we must make assumptions about symmetry in order to model the full distribution. This is where tilted-ring modeling is especially useful.

Introduced by Rogstad et al. (1974), tilted-ring modeling involves creating an empirical model galaxy comprised of a series of concentric rings for which parameters such as the inclination, position angle, surface brightness, scale height, etc. are specified (Figure 1.7). Traditionally, these models assume axisymmetry, and are thus unable to fit asymmetries and localized structure throughout the galaxy. Because of this, and the large number of free parameters involved, by-eye fits are necessary to some degree. Initially, modeling was performed in the Groningen Image Processing System (GIPSY) using HALOMODGALZ (Heald et al., 2007), a modified version of the task GALMOD (van der Hulst et al., 1992) that allows lags to be modeled. Later models were created in the new, semi-automated Tilted Ring Fitting Code (TiRiFiC) (Józsa et al., 2007). TiRiFiC includes several features that are non-existent in GALMOD, such as \(\chi^2\) minimization to expedite the modeling process, the ability to divide the model galaxy into wedges of azimuth to model asymmetries, and approximations of bars and spiral structure. The addition of these features allows for increased flexibility in the modeling, and the opportunity to fit some distinct features that are impossible to create with tilted rings alone.
Chapter 1. Introduction

Figure 1.7 Figure 14 from Rogstad et al. (1976) illustrates the basic concept of tilted-ring modeling (in this case the galaxy is M 33). Note how warp components both across and along the line of sight are created by changing the tilt of the rings.

For each galaxy, simple models involving a single thin disk are initially created. To these basic models, features such as warps (changing the inclination and position angle), flares (increasing the scale height radially) and thick disks (a second, thicker component added to the thin disk), radial motions, lags, and bars are added when necessary. Care is taken to avoid needlessly increasing the complexity of each model. Fortunately, each of these features has a unique set of signatures in channel maps, major and minor axis position-velocity diagrams, and moment maps, which ensure a unique optimal model. For instance, a warp component along the line of sight causes an apparent thickening of the disk, which mimics a halo when looking at the moment map of a galaxy. However, such a warp also adds a signature indentation in the outer edges of channel maps and the systemic sides of minor axis position-velocity diagrams, which are not characteristic of a halo, and thus the two may be distinguished. Most importantly, we take great care to ensure that any possible lags cannot be explained by any other model component. Such features will be
Chapter 1. Introduction

Figure 1.8 From left to right: channel maps, major axis position-velocity (P-V) diagrams, and minor axis P-V diagrams showing the data for NGC 4565 (top), an early model (middle), and an optimized model (bottom). The early model is a thin disk with a warp component across the line of sight only. The optimized model includes a flare, warp, bar, lag, and radial motions. Arrows indicate the direction in which flux is redistributed during the modeling process (i.e. in going from early models to the optimal model), while rectangles draw attention to regions of substantial improvement. The locations of each panel in velocity or major and minor axis offsets are given in the upper left-hand corner of the top panels. It should be noted that we examine all slices to the resolution limit of the data, but only present representative slices for each galaxy. For a detailed description of the models, please see Zschaechner et al. 2012, especially Figures 3, 10, and 12b.

illustrated throughout this thesis, but Figure 1.8 provides initial examples of the diagrams involved, with simple and then optimized models.

1.7.1 Gauging Uncertainties in Tilted Ring Modeling

A rigorous statistical analysis of the fitting of tilted ring models is generally omitted from the literature (e.g. Barbieri et al. 2005, Oosterloo et al. 2007, Rand & Benjamin 2008). Such studies employ a simple model focusing on the quantification of certain features in observed galactic disks, driven by a specific scientific question. The main goal of this thesis is to constrain the vertical structure of the H I disk, which means giving significant weight to faint emission. If fitting were fully automated, a goodness-of-fit criterion such as a $\chi^2$ (which TiRiFiC provides) could be used to distinguish
Chapter 1. Introduction

models by significantly down-weighting the bright emission that would otherwise
dominate the statistic and render it meaningless for our purposes. In principle, a
reduced $\chi^2$ with such a weighting could also account for the varying number of free
parameters among models. However, it is generally much more efficient to use the
judgment of the modeler and adjust certain parameters manually, but this makes an
accurate accounting of the degrees of freedom in each model difficult.

We therefore rely on fitting by eye to guide our choice of models. A visual
comparison of data and models provides a powerful method for deciding how models
must be altered to fit the data, easily allowing attention to be focused on regions
of interest. One statistic we could examine, regardless of the number of degrees of
freedom, is the rms of the residual cube, down-weighting regions of bright emission.
In fact, when we examine this statistic, we indeed find a significant reduction after
major changes such as the addition of a flare. However, the numerical difference due
to the addition of radial motions, a bar, or a lag is negligible.

The uncertainties we determine for lag values are done by inspection. The lag is
increased or decreased in a given model until the changes are noticeably detrimental
to the fit. Such methods yield an approximately $2\sigma$ level of confidence.
Chapter 2

Observations and Modeling of NGC 4244

2.1 Chapter Overview

We present 21-cm observations and models of the H\textsc{i} kinematics and distribution of NGC 4244, a nearby edge-on Scd galaxy observed as part of the Westerbork Hydrogen Accretion in LOcal GAAlaxyS (HALOGAS) survey. Our models give insight into the H\textsc{i} kinematics and distribution with an emphasis on the potential existence of extra-planar gas as well as a negative gradient in rotational velocity with height above the plane of the disk (a lag). Our models yield strong evidence against a significantly extended halo and instead favor a warp component along the line of sight as an explanation for most of the observed thickening of the disk. Based on these models, we detect a lag of $-9^{\pm 3}_{\pm 2}$ km s$^{-1}$ kpc$^{-1}$ in the approaching half and $-9^{\pm 2}_{\pm 2}$ km s$^{-1}$ kpc$^{-1}$ in the receding half. This lag decreases in magnitude to $-5^{\pm 2}_{\pm 2}$ km s$^{-1}$ kpc$^{-1}$ and $-4^{\pm 2}_{\pm 2}$ km s$^{-1}$ kpc$^{-1}$ near a radius of 10 kpc in the approaching and receding halves respectively. Additionally, we detect several distinct morphological and kinematic
features including a shell that is probably driven by star formation within the disk.

This chapter has been published in the Astrophysical Journal (Zschaechner, L. K., Rand, R. J., Heald, G. H., Gentile, G., Kamphuis, P., 2011, Volume 740, Issue 1, article id. 35, 16). Minor modifications have been made for consistency with later work presented in Chapters 4-6.

2.2 Introduction

Understanding the distribution and kinematics of vertically extended gas in disk galaxies is crucial for comprehending the relevance for the evolution of disk-halo flows (e.g. the galactic fountain model presented by Shapiro & Field 1976 and refined by Bregman 1980; and the chimney model of Norman & Ikeuchi 1989), interactions with the intergalactic medium (IGM) such as cold accretion of primordial gas (Kereš et al. 2005, Sancisi et al. 2008) and interactions with neighboring galaxies. Furthermore, comprehension of the interactions between ISM energization from star formation and accretion, i.e. feedback (e.g. Efstathiou 2000) is also imperative.

Galactic gaseous halos have been been observed in X-rays (e.g. Tüllmann et al. 2006b), radio continuum (e.g. Irwin et al. 1999), dust (e.g. Howk & Savage 1999), ionized hydrogen (e.g. Rossa & Dettmar 2003) as well as neutral hydrogen (H\textsc{i}) (e.g. Swaters et al. 1997, Oosterloo et al. 2007). For the radio continuum (e.g. Dahlem et al. 2006), diffuse ionized gas (DIG) (e.g. Rossa & Dettmar 2003), X-ray (e.g. Tüllmann et al. 2006a), and dust (Howk & Savage, 1999) there is a correlation between the presence of these halo components and star formation in the disk, both locally, in regions throughout the galaxy as well as globally. This favors disk-halo flows akin to those in the aforementioned galactic fountain and chimney models as likely origins.
Despite the likely connection between several halo components and star formation, the prevalence and properties of extra-planar H\textsc{i} in galaxies and any potential connection to star formation is not well understood. While there are many examples of H\textsc{i} shells and holes associated with star formation (e.g. Boomsma et al. 2008), no correlation between the prevalence of widespread H\textsc{i} halos and star formation activity has been established among multiple galaxies as has been done for other halo components. Clearly, this can only be remedied through greatly expanded observations.

Another clue to halo origins lies in their kinematics. Trends concerning extra-planar H\textsc{i}, such as the presence and magnitude of any decreases in rotation speed with height (lags) or correlations with the kinematics of DIG layers are useful in determining its origins. One observational issue is whether H\textsc{i} and DIG halos show the same kinematics, suggesting a common origin. Recent measurements have shown lags in multiple DIG layers (Heald et al., 2007), leading to various models which attempt to understand this gradient in terms of disk-halo flows and accretion of primordial gas.

It has been shown that entirely ballistic models of disk-halo cycling, simulated in Collins et al. (2002) and Fraternali & Binney (2006), are too simple in that they are unable to reproduce the observed kinematics. It is possible the observed motions may partially be due to pressure gradients, magnetic tension (Benjamin, 2002) or external influences and feedback such as those described in Fraternali & Binney (2008). Additionally, “baroclinic” (where gas pressure does not depend on density alone) hydrostatic models considered in Barnabè et al. (2006), have been able to reproduce the observed lag in NGC 891, as has the hydrodynamic simulation of disk formation by Kaufmann et al. (2006). It is likely that halos form and evolve via a combination of disk-halo flows as well as external influences.

Of further interest is the radial variation of lags. Basic geometric arguments
predict a shallowing of the lag with increasing radius as may be seen in Figure 3 of Collins et al. (2002), but this could be complicated, for example, by pressure gradients (Benjamin, 2002). This will be discussed in greater detail in § 2.7.2.

Detailed kinematic modeling of deep observations of H i emission has been done for only a small number of galaxies including NGC 891 (Swaters et al. 1997, Oosterloo et al. 2007), NGC 5746 (Rand & Benjamin, 2008), and NGC 2403 (Fraternali et al. 2002). Through the Westerbork Hydrogen Accretion in LOcal GAaxies (HALOGAS) survey (Heald et al., 2011), which targets 22 edge-on or moderately inclined spiral galaxies for deep 10×12 hour observations using the Westerbork Synthesis Radio Telescope (WSRT), we aim to substantially increase this number in order to ascertain information concerning the origins of neutral extra-planar gas. Through deep observations and kinematic modeling of these galaxies, we will establish whether there is any connection between extra-planar gas and star formation as well as the degree to which contributions from external origins are relevant.

As part of the HALOGAS survey, we present observations and models of NGC 4244, a nearby edge-on Scd galaxy, which exhibits a thickened H i layer upon inspection of the zeroth-moment map (presented here, Figures 2.1, 2.2) as well as in previous work (Olling, 1996). The first goal of the modeling is to determine the cause of the observed thickening, whether it is due to the presence of an H i halo, flare, warp along the line of sight, or any combination of these possibilities. Second, we constrain whether a lag exists. Finally, we will identify local features, such as possible energy injection sites, which will be discussed further in § 2.7.4. This work will aid in establishing trends concerning the presence of halos and lags and any connection between disk-halo interactions and/or accretion. In the case of NGC 4244, which has a low star formation rate (0.12 M⊙ yr⁻¹; Heald et al. 2011), we are especially concerned with the potential existence of a lag. If the trend found by Heald et al. (2007) for DIG layers in galaxies with low star formation rate resulting in steeper
lags holds true for H\textsc{i}, then a steep lag is expected.

2.3 Observations and Data Reduction

Here we provide a brief explanation of the observations and data reduction process. A detailed description, which applies to all of the HALOGAS galaxies including NGC 4244, may be found in Heald et al. (2011).

Observations of NGC 4244 were primarily obtained as part of the ongoing HALOGAS survey. To best observe faint extended emission, the array was used in Maxishort configuration with baselines ranging from 36 m to 2.7 km for 6 × 12 hours. Of the 10 fixed antennas, 9 were used and were spaced at 144 m intervals on a regular grid. Additionally, 4 × 12 hours of archival data (Dahlem et al., 2005), observed in the traditional Westerbork variable configuration are used. The total bandwidth is 10 MHz with 1024 channels and two linear polarizations.

Data reduction was done in Miriad (Sault et al., 1995). The H\textsc{i} data were im-

Figure 2.1 The H\textsc{i} zeroth-moment map overlaid on H\textalpha{} (top) and MIPS 24\textmu{}m (bottom) images. Each image is rotated counter-clockwise by 43°. H\textsc{i} contours begin at 6.4 × 10^{19} \text{cm}^{-2} and increase by factors of 2. The H\textsc{i} beam is shown in the lower left-hand corner in white. The H\textalpha{} image is supplied by Rene Walterbos from Hoopes et al. (1999).
Chapter 2. Observations and Modeling of NGC 4244

Figure 2.2 A zeroth-moment map of NGC 4244 showing the slice locations for the bv plots in Figure 2.6 (solid), as well as the range of the evenly spaced slices in Figure 2.10 (dashed). Boxes a and b correspond to the regions shown in Figures 2.11 and 2.13 respectively. Contours begin at $6.4 \times 10^{19}$ cm$^{-2}$ and increase by factors of 2. The HI beam is shown in the lower left-hand corner in white. An encircled dot and cross denote the approaching and receding halves respectively.

aged with a variety of weighting schemes, creating multiple data cubes. Clark deconvolution (Clark, 1980) was performed using mask regions defined on the basis of unsmoothed versions of the data. Offline Hanning smoothing led to a final velocity resolution of 4.12 km s$^{-1}$. The 1σ rms noise in a single channel of the full resolution cube is 0.22 mJy bm$^{-1}$, or corresponding to a column density of $N_{HI} = 3.5 \times 10^{18}$ cm$^{-2}$.

For the primary modeling, we use a cube with a robust parameter of 0 for intermediate resolution and sensitivity, with a 21″×13.5″ beam, having a position angle of $-0.7^\circ$. Additionally, to maximize sensitivity to faint extended emission we use a Gaussian $uv$ taper corresponding to 30″ resolution in the image plane to create
Chapter 2. Observations and Modeling of NGC 4244

Table 2.1. NGC 4244 Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance (Mpc)</td>
<td>4.4a</td>
<td>Heald et al. (2011)</td>
</tr>
<tr>
<td>Systemic velocity (km s(^{-1}))</td>
<td>244</td>
<td>Olling (1996), This work</td>
</tr>
<tr>
<td>Inclination</td>
<td>88°</td>
<td>This work</td>
</tr>
<tr>
<td>SFR (M(_\odot) yr(^{-1}))</td>
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<td>Heald et al. (2011)</td>
</tr>
<tr>
<td>Morphological Type</td>
<td>Scd</td>
<td>de Vaucouleurs et al. (1991)</td>
</tr>
<tr>
<td>Kinematic Center (\alpha) (J2000.0)</td>
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<td>This work</td>
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<tr>
<td>Kinematic Center (\delta) (J2000.0)</td>
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<td>This work</td>
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<tr>
<td>Optical Radius (kpc)</td>
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<td>Fry et al. (1999)</td>
</tr>
<tr>
<td>Total Atomic Gas Mass (10(^9)M(_\odot))</td>
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<td>This workc</td>
</tr>
<tr>
<td>Total Atomic Gas Mass (10(^9)M(_\odot))</td>
<td>2.2</td>
<td>Olling (1996)d</td>
</tr>
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</table>

a Distance is the median value of distances found on the NED database, excluding those obtained using the Tully-Fisher relation.
b This value is adjusted for the difference in distance of 4.4 Mpc used in this paper and 3.6 Mpc used in Fry et al. (1999).
c Includes neutral He via a multiplying factor of 1.36. The value using single dish data is 2.7\times10\(^9\)M\(_\odot\) (Springob et al. 2005).
d Scaled to our assumed distance.

A second cube. Further smoothing to 60" resolution yielded negligible additional extended emission. Arcseconds are converted into parsecs via multiplying by 21.35 pc arcsecond\(^{-1}\) [obtained by assuming a distance of 4.4 Mpc (Table 2.1)], resulting in a resolution of approximately 450\times290 pc for the full resolution cube.

A summary of observational and data reduction parameters may be found in Table 2.2.
Chapter 2. Observations and Modeling of NGC 4244

Table 2.2. NGC 4244 Observational and Instrumental Parameters

<table>
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<tr>
<th>Parameter</th>
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<td>2009 Nov 15</td>
</tr>
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<td>2009 Nov 27</td>
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<tr>
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<td>2003 Feb 19-20</td>
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<td></td>
<td>2003 Feb 20-21</td>
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<td></td>
<td>2003 Apr 13-14</td>
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<tr>
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<td>12h17m29.901s</td>
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<tr>
<td></td>
<td>37d48m29.00s</td>
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<tr>
<td>Number of channels</td>
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<tr>
<td>Velocity Resolution</td>
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<tr>
<td>Full Resolution Beam Size</td>
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</tr>
<tr>
<td></td>
<td>450×290 pc</td>
</tr>
<tr>
<td>RMS Noise – 1 Channel (21×13.5&quot;)</td>
<td>0.22 mJy bm(^{-1})</td>
</tr>
<tr>
<td>RMS Noise – 1 Channel (30×30&quot;)</td>
<td>0.37 mJy bm(^{-1})</td>
</tr>
</tbody>
</table>

2.4 The Data

The full resolution zeroth-moment map is produced using the Gronigen Image Processing System (GIPSY; van der Hulst et al. 1992 task moments after applying a mask to the full resolution cube based on the 3\(\sigma\) limit of a 90" smoothed cube. This is shown overlaid onto H\(\alpha\) (Hoopes et al., 1999) and 24 \(\mu\)m MIPS (NASA/IPAC Infrared Science Archive) images in Figure 2.1 as well as in grayscale in Figure 2.2. A warp component that is perpendicular to the line of sight is apparent. Also, as will be shown through modeling described in §2.5, the minor axis extent is largely due to a warp component along the line of sight. Minor asymmetries may be noted, such as slight differences in the warped disk in the approaching (northeast) and receding
(southwest) halves as well as more radially extended emission in the receding half. Additional localized asymmetries and irregularities are also present throughout. The 30” map (not shown) displays the same indications of a warp as well as the previously mentioned asymmetries. Even with the increased sensitivity of this map, it does not reveal any substantial faint emission not already seen in the full resolution cube.

We calculate a total $\text{H}_\text{i}$ mass of $2.5 \times 10^9 M\odot$, while the single dish estimate for the total $\text{H}_\text{i}$ mass is $2.7 \times 10^9 M\odot$ (Springob et al. 2005), indicating that these observations recover most of the flux.

Full resolution representative channel maps are provided in Figure 2.3. Note the faint streak-like emission in the lowest contours extending radially outward from the center of the galaxy in the 310 km s$^{-1}$ and 322 km s$^{-1}$ channels. Figure 2.4 shows a position-velocity diagram along the major axis ( lv diagram) with the rotation curve derived through modeling. The previously mentioned asymmetries are also easily seen in the channel maps as well as the lv diagram.

Careful inspection of the data lays the foundation for the modeling process described below.

2.5 Models

To extract information from the data useful in constraining the $\text{H}_\text{i}$ distribution and kinematics, including a possible lag, model data cubes are created using GIPSY. Using the task $\text{galmod}$, a model galaxy is divided into concentric rings where the column density, rotational velocity, scale height, velocity dispersion, inclination and position angle for each are specified. Additionally, we use a version of $\text{galmod}$, modified by one of us (G. H.) to allow a linear gradient in rotational velocity with height. These tasks assume axisymmetry, which is only approximately true for NGC 4244 (best
seen in Figures 2.1 through 2.4). Therefore, the approaching and receding halves are modeled separately, which greatly improves the models for each half but does not completely eliminate issues due to asymmetries as will be demonstrated. These remaining issues however, do not impact our final result concerning the existence and magnitude of a lag.

For initial estimates of the column densities as well as the rotation curve, we used the models of Olling (1996), who found evidence for a flaring gas layer. Given
the improved depth of our data by comparison (with the rms noise for this data being 0.22 mJy bm\(^{-1}\) compared to 1.9 mJy bm\(^{-1}\) for a cube of similar resolution (28.3×10.1\(^{\prime}\)) used by Olling) as well as differences in modeling techniques used, it is possible for the results to differ.

Rough initial estimates for the kinematic center and systemic velocity were found using the zeroth and first moment maps. Estimates for the position angles were determined via inspection of the zeroth-moment map and were immediately refined prior to altering additional parameters. The estimated column densities are refined first by matching both the shape and total flux in the vertical profile (Figure 2.5, made by including emission only within a major-axis distance of 5\(^{\prime}\) from the center to avoid effects such as the warp and tapering of the disk found at larger radii) and zeroth-moment maps of the model with those of the data.

Provided a good fit for previous steps, the rotation curve is then honed primarily through the use of lv diagrams, tracing emission along the edge with the highest velocities (terminal side). These, along with minor axis (bv) position-velocity diagrams, as well as channel maps of models and data must all be examined to fine

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Figure 2.4 Major axis position-velocity diagram. Contours begin at 2\(\sigma\) (0.44 mJy bm\(^{-1}\)) and increase by factors of 2. Asymmetries are once again prevalent in the two halves. The rotation curve for each half is shown with crosses. Arrows near the horizontal axis indicate the approximate starting point of the radial decrease in the lag discussed in § 2.5.2. The warp component across the line of sight creates the appearance that the rotation curve extends beyond the data, but at heights above the midplane, these points are constrained.
Figure 2.5 Log-scale vertical profiles of the data, flaring model and Olling’s 1996 model with a constant inclination for both halves. The other models in this paper are not shown as they match the data closely, to within one line width. Notice how the data are fit with a single exponential and do not display prominent emission in the wings.

As will be demonstrated, the key to this method is to start with the simplest possible model and then add features such as warps and flares - one at a time - to fully understand the individual contribution of each additional degree of complexity. This allows for subtle distinctions between features, which otherwise may be misinterpreted. In the end, an acceptable model is one that fits all of the plots well. The quoted errors indicate visually estimated uncertainties rather than formal 1σ error bars.

It should be noted that new, semi-automated tilted ring fitting software (TiRiFiC)
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(Józsa et al., 2007), which allows for a chi-square fit of models to observed data cubes is now available. Advanced models for NGC 4244 were examined in both TiRiFiC and galmod and each produced comparable results. Given the advanced stage of modeling already completed via galmod, as well as the localized features in NGC 4244, TiRiFiC was not used extensively in this case. However, the advent of TiRiFiC’s automated processes will help to expedite the fitting of the remaining galaxies in the HALOGAS sample.

2.5.1 Features Considered While Modeling

The bv diagrams shown in Figure 2.6 and the channel maps in Figure 2.7 illustrate a number of the features that were noticeably sensitive to the model parameters we endeavor to match. There is a notable “T” shape in the panels closest to the galactic center in the bv plots in Figure 2.6, which morphs into a “V” shape in the outer panels (schematically indicated in certain panels of Figure 2.6). Additionally, the contours on the systemic side are flattened. There is also a substantial lopsidedness best seen at −5.1’ and −6.9’ in Figure 2.6 around the midplane, primarily due to the component of the warp perpendicular to the line of sight, but also partially due to asymmetries.
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Figure 2.6 Minor axis position-velocity diagrams of NGC 4244 and models. Slice locations are those displayed by solid lines in Figure 2.2 and velocity ranges vary from panel to panel. Contours begin at $3\sigma$ (0.66 mJy km s$^{-1}$) and increase by factors of 3. All models include a projection of a warp across the line of sight. The W model is favored and others are shown for illustrative purposes only. The symbols provided in the lower right-hand corners of selected panels indicate quality of fit to the data judged by eye. Crosses indicate a very poor fit, blank a somewhat poor fit, boxes a reasonable one, and asterisks a good fit. The “V” shape and flattened systemic side are emphasized with gray dotted lines, while the “T” shape is shown in black and white lines. (A) displays models with no lags, while (B) shows analogous plots, but with the addition of lags as well as the omission of the 2C model. The magnitudes of lags are $-7$ km s$^{-1}$ kpc$^{-1}$ for both halves of 1CL as well as FL, $-9$ km s$^{-1}$ kpc$^{-1}$ for the WL and WFL models, and $-9$ km s$^{-1}$ kpc$^{-1}$ for the 2CWL model. Due to local asymmetries, the emission extending on the negative minor axis offset near $125$ km s$^{-1}$ in the panel corresponding to 6.9' is not considered while modeling. Additionally, on the receding half, the side with a positive offset is given less weight in the fitting process for the same reason.
The channel maps displayed in Figure 2.7 reiterate the need for a warp perpendicular to the line of sight. Prominent features that were sensitive to model parameters considered during the modeling process include the spacing and angle of the contours at the tips of each plot closest to the center of the galaxy. Also considered is the approximately 45 degree slant along the outermost edges at more extreme velocities and at mostly negative minor axis offsets in the approaching half and positive offsets in the receding half.
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Figure 2.7 Channel maps of NGC 4244 compared with models. Contours begin at $3\sigma (0.66 \text{ mJy beam}^{-1})$ and increase by factors of 3. Velocities are given in the first column in kilometers per second. All models include a projection of a warp perpendicular to the line of sight. Lag models are denoted with an L. (See Figure 2.6 caption for the lag magnitudes.) The pure flare and pure two-component models are not included as they are shown to be poor matches in the bv plots. Finally, the WF model has also been excluded as it is similar to the warp only model. The definition of symbols follows that set forth in the caption of Figure 2.6. The approaching half is shown in (A) while the receding half is shown in (B).
In both Figures 2.6 and 2.7, the visual assessment of the quality of the fit between the models and data is indicated in each panel via symbols explained in the caption of Figure 2.6. The assignment of each symbol heavily relies on the criteria described above.

Some quantities are kept constant throughout all of the models for the entire process. These are the systemic velocity (244 km s\(^{-1}\)), kinematic center (12h17m29.90s, 37d48m29.00s) and the run of the position angle derived from the component of the warp perpendicular to the line of sight, column density profile, rotation curve (both shown in Figure 2.8) and velocity dispersion (12 km s\(^{-1}\) decreasing to 10 km s\(^{-1}\) at a radius of 7.7' or 10 kpc).
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Figure 2.8 Shown are parameters used for the models. The rotation curves, column densities and position angles presented are consistent for all models. The inclinations are those used for the warp and two-component models.

2.5.2 Individual Models

Several possible models are considered. Some are eliminated quickly upon inspection of the vertical profile or zeroth-moment map, while others require substantially more effort to discern between them. Vertical distributions are exponentials in all models. Exponential scale heights vary among models and are listed in Table 2.3. All of the models, unless otherwise noted, match the zeroth-moment map and vertical profile reasonably well, as will be graphically shown in Figure 2.9 and in the following discussion.

One-component Model

The simplest model involves a single disk with a slight warp perpendicular to the line of sight [deviating by 4-5° from the inner disk (Figure 2.8) and beginning
Table 2.3. NGC 4244 Model Exponential Scale Heights Rounded to the Nearest 25 pc.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>scale height $-1C$ (pc)</td>
<td>600</td>
</tr>
<tr>
<td>scale height $-F$ (pc)</td>
<td>$550 \to 1100^a$</td>
</tr>
<tr>
<td>scale height $-W$ (pc)</td>
<td>$550, 575^b$</td>
</tr>
<tr>
<td>scale height $-WF$ (pc)</td>
<td>$550 \to 1100^a$</td>
</tr>
<tr>
<td>scale height $-2C$ (pc)</td>
<td>$525, 1050^c$</td>
</tr>
<tr>
<td>scale height $-2CW$ (pc)</td>
<td>$425, 850^c$</td>
</tr>
</tbody>
</table>

$^a$the first value applies to radii within the optical radius. Beyond this radius, the scale height linearly increases until the final value (twice the initial) is reached.

$^b$Values for the approaching and receding halves respectively.

$^c$Values for the thin and thick components respectively. These are consistent for both halves.

at a radius of 12 kpc. For such a model, all other quantities aside from column densities and rotational velocities are held constant with radius. The inclination is found to be 88° for the best fit to the vertical profile. For the final model, the scale height is about 600 pc. This simple model (referred to as “1C” in figures) cannot be immediately eliminated based on the fit to the vertical profile and zeroth-moment map (Figure 2.9). However, one may note that in the bv plots in Figure 2.6, the one-component model lacks sufficient flux on the systemic relative to the terminal side in each panel. As can be seen in the channel maps in Figure 2.7, shown most prominently in the plots closest to the systemic velocity and noted with an arrow, the edge of the diagram away from the center of the galaxy comes to a definitive point at a positive minor axis offset on the approaching half, and a negative offset
Figure 2.9 Zeroth-moment maps of the data and models. The model plots are comprised of both the approaching (positive offset) and receding (negative) separately modeled halves. Contours begin at $6.4 \times 10^{19} \text{cm}^{-2}$ and increase by factors of 2.

on the receding, which is not seen in the data. No other combination of inclination and scale height improves this this.

**Warp Along the Line of Sight**

Adding a projection of the warp along the line of sight (referred to as “W” in figures), by gradually decreasing the inclination in the outermost rings (shown in Figure 2.8), matches the observed “T” shape from the data in the central bv diagrams in Fig-
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Figure 2.6 significantly better than the 1C model. This is the result of bringing flux from outer rings with lower projected velocity into higher latitude regions. If the inclination decreases too quickly, the “T” shape becomes excessive.

In contrast to the one-component model, the channel maps in Figure 2.7 show the flux is pushed upward and at high z pushed away from the center in the major axis direction, in panels with velocities close to the systemic velocity in the warp model, which matches the data more closely. However, if too much of a warp is present in the model, then analogous to the “T” shape verging on becoming too “Y”-shaped in the bv diagrams, there will be an indentation on this edge. This is not seen in the data.

The best fit LOS warp component deviates by 8 degrees from the inner disk and as in the PA warp, starts at a radius of 12 kpc (Figure 2.8).

Flaring Model

Upon initial inspection of the zeroth-moment maps, it may be noted that the edges in the outer radii taper significantly in minor axis extent. Because of this, a substantial flare can be ruled out immediately as it would cause the zeroth-moment map to become too boxy and fail to fit this aspect of the data. However, this is not to say for certain that a modest flare may not be present. For this reason, a representative flaring model (referred to as “F” in figures) is created by starting with the one-component model and increasing the scale height outward radially. This increase begins at the optical radius (10.4 kpc; Table 2.1) and increases linearly, approximately doubling by a radius of 15 kpc. Comparison of zeroth-moment maps from the data (Figure 2.9) and model indicates that a modest flare yields a slight improvement compared to the one-component model. Unlike the warp model, the modest flare does not eliminate the rounding on the systemic side of the bv plots.
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(Figure 2.6) or the thinning on the outer edges of the channel maps seen in the one-component model. A more extreme and less physical flare (abruptly doubling the scale height at the optical radius and then holding it constant at larger radii) helps to reduce these problems in the bv plots and channel maps, but once again, causes the zeroth-moment map to become boxy and an obvious mismatch to the data (not shown).

The pure flare model clearly does not match the data in the bv plots. However, adding the same modest flare to the warp model (referred to as “WF” in figures) does not appear to have a substantial effect; in fact, it is almost identical to the warp model as shown in the zeroth-moment map in Figure 2.9 as well as the bv plots in Figure 2.6. This indicates that such a flare could be present in NGC 4244, but that the component of the warp along the line of sight is dominant and effectively hides most of its contribution. Since we are unable to determine whether or not the flare exists due to the minimal contribution it would have compared to the warp, and for the sake of clarity, it is omitted from further models.

Two-component Model

H I halos have been observed in several galaxies, with NGC 891 among the most notable (Oosterloo et al., 2007). One of the primary goals of HALOGAS is to determine the frequency of occurrence and origins of such halos. We therefore examine the possibility of such a halo in NGC 4244.

The addition of a halo to the model is made via combining a second, thicker exponential component to the first, keeping the inclination of both at 88° (referred to as “2C” in figures). Upon inspection of the vertical profile and zeroth-moment map, there is no immediate motivation for a second component, as reasonable fits can be made with less complicated models. For both halves of NGC 4244, multiple
ratios of scale height and flux in each component were tested in attempts to match the vertical profile, but none was successful. In fact, when considering only the vertical profile, a two-component model cannot be made to match the data, as during the modeling process, the components tend to converge to a single scale height, resulting in a one-component model.

However, since the existence of a halo is of primary concern, we have made substantial attempts to optimize this model. Since the vertical profile and zeroth-moment map provide no useful constraints for the relative scale heights of the two-components or for the percentage of flux contained within the halo, we use illustrative fixed values, with the scale height of the extended component twice that of the thin component, and with 25 percent of the flux residing in the extended component. These values are chosen because they represent a reasonable scenario compared to other galaxies with halos (Oosterloo et al., 2007).

Through optimization of this two-component model, it is found that a reasonable fit to the data is impossible without including a warp component along the line of sight. A halo will only add to the complexity of the model and if a warped model without a halo is sufficient (or in this case, slightly better), then the simpler model should be used. Thus, we reject the two-component model with or without such a warp. We do however, retain a two-component model with a warp component along the line of sight ("2CW") in figures throughout this paper for illustrative purposes only.

**Improvement With the Addition of a Lag**

At this point, prior to the addition of a lag, we place our confidence in the single component LOS warp model. However, as may be seen in Figures 2.6 and 2.7, the optimized models with no lag do not exactly match the data. Adding a lag at this
stage will best illustrate its contribution to the models. We continue to include the 
one-component model, the flaring model with a warp component along the line of 
sight, as well as the two-component model with a warp component along the line of 
sight for illustrative purposes as well as to demonstrate the reliability of the result 
concerning the lag.

The columns in Figure 2.6 denoted with “L’s” in the titles show the models as 
before, but with optimal lags for each model. Upon inspection of these plots, it 
becomes evident that the addition of a lag is an almost universal improvement. By 
adding a lag, flux in the models is drawn to the systemic side, thus duplicating 
the aforementioned “T” and “V” shapes in the data. Furthermore, the edge of the 
 systemic side becomes flatter in almost all of the panels as in the data, whereas in 
the no lag models, only the models including a line of sight warp component appear 
relatively flat. Additionally, the channel maps are improved. They narrow in the z 
direction at velocities further from systemic, more closely matching the data.

The warped model with the addition of a lag of $-9^{\pm 3}_{2}$ km s$^{-1}$ kpc$^{-1}$ and $-9^{\pm 2}$ km s$^{-1}$ kpc$^{-1}$ in the approaching and receding haves respectively is a reasonable 
fit. Error bars are estimated via visual inspection of the range of lags which could 
potentially match the data and under the (inexact) assumption that the models 
have no additional uncertainties (e. g. uncertainty in column density or rotational 
velocity), as making such estimates would be unwieldy.

For the two-component warp model, a lagging halo is simulated by adding a lag in 
only the thick component. The addition of the lag substantially improves the model 
for the receding half with a lag as steep as $-9$ km s$^{-1}$ kpc$^{-1}$, but fails to adequately 
duplicate the “V” shape in Figure 2.6 in the approaching half. Even with a lag of as 
steep as $-28$ km s$^{-1}$ kpc$^{-1}$ this shape cannot be duplicated. Given this difficulty, a 
lag of $-9$ km s$^{-1}$ kpc$^{-1}$ is used in the final model to optimize the fit for the overall 
shape of the data.
The improvement due to the lag is present in all models. This attests to the robustness of the lag in that, regardless of the optimal morphological model, there are features which cannot be re-created without it. Once again, the one-component warp model with the addition of a lag appears to be the best match to the data.

The Radial Variation of the Lag

Upon establishing the existence of a lag, it must be characterized by not only the magnitude of the gradient in the z direction but also its radial variation. Using the one-component warped model, bv diagrams further from the center of the galaxy than those shown in Figure 2.6 are examined in Figure 2.10 using a 30×30″ cube, with the range of slice locations corresponding to the dashed lines in Figure 2.2. The data, at these large radii, are best fit with a shallowing lag, decreasing in magnitude to $-5\pm2\,\text{km\,s}^{-1}\,\text{kpc}^{-1}$ and $-4\pm2\,\text{km\,s}^{-1}\,\text{kpc}^{-1}$ near a radius of 8′ (10 kpc) in the approaching and receding halves respectively. This is most easily seen on the terminal side of each panel: the data contours become more rounded, whereas the model with a constant lag retains too much of a “V” shape, with data contours extending further on the terminal side than those of the model. However, on the negative offset side of the receding half, the shallowing of the lag may be even more substantial. This is best seen in panels corresponding to -8.2′ and -9′. Uncertainties are still quantified based on the positive offset side, and $-4\,\text{km\,s}^{-1}\,\text{kpc}^{-1}$ is only given as an upper limit for the side with negative offset. There is no strong indication of any radial variation at radii smaller than approximately 6′ (7.5 kpc). It should be noted that the S/N of the data is considerably diminished at and beyond a radius of 10′ and determining the lag this far from the center approaches the limits of our modeling capabilities. The error estimates are once again by eye. These estimates are made by examining how much the lag may be increased or decreased before becoming detrimental to the model, and have a roughly 2-σ confidence level.
Figure 2.10 by diagrams showing the warp model with no lag (left-most column), a best estimate for a constant lag (center), and a best estimate for a radially varying lag (right). The cube represented here has a resolution of 30". Contours begin at 3σ (1.1 mJy bm^{-1}) and increase by factors of 3. Data contours are black and model contours are superimposed in white. The lags in km s^{-1} kpc^{-1} for each panel of the varied warp model are given, while the lag for the constant warp model is given in the top panel only. The offset of the slices from the center in arcminutes is given in the left-most panels and correspond to the dashed lines in Figure 2.2. The quality of fit of individual panels to the data is indicated by the convention initiated in Figure 2.6. Boxes are placed to show the more subtle differences between panels. Differences which are more readily apparent to the eye are not explicitly marked in this way. The primary issues to note are the slope of the model contours compared with those of the data on the terminal side as well as any shift up or down between them. Also considered is the matching of the model and data contours on the high-z edges on the systemic side. The approaching half is shown in (A) while the receding half is shown in (B).
2.6 Distinct Features

Aside from the global characterization of H I kinematics and distribution, it is a goal of HALOGAS to characterize localized features which may be accretion events or indications of disk-halo cycling. Furthermore, there exist prominent features in the data we wish to demonstrate are not global in the sense that our models do not attempt to reproduce them. Perhaps the most significant is a shell-like feature located in the western quadrant of the approaching half. An arcing feature is seen in a zeroth-moment map made by including channels ranging from 149 km s$^{-1}$ to
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Figure 2.11 A zeroth moment map of the shell-like feature on the approaching half centered at 12h17m42s, 37d53m9s and described in the text (top) and plotted over the Hα image (bottom) with the H\textsc{i} beam displayed in the upper right-hand corner of the top plot. The H\textsc{i} contours start at 4.7×10^{18} cm^{-2} and increase by factors of \sqrt{2}. The velocity range included is 162-174 km s^{-1}. The box in the lower panel outlines the star forming region described throughout the text.

175 km s^{-1}, extending from roughly 3.6’ to 5.1’ along the major axis (Figure 2.11). Corresponding extended emission is also observed as line splitting in the bv plots (Figure 2.12), which will be discussed in §2.7.4.

An additional noteworthy feature is observed in the receding half (Figure 2.13), roughly 4.3’ to 6.8’ radially from the center, and present in channels corresponding to 281-302 km s^{-1}. This feature displays an elongated path curving away from the major axis in the H\textsc{i} contours, starting from the midplane and extending beyond 1.5’ above the midplane. Furthermore, it appears that there may be a hole or vent in
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Figure 2.12 bv plots at the location of the shell-like feature displayed in Figure 2.11. The dashed lines in the center panel show line splitting at the center of the presumed shell, while the left and right panels correspond to the approximate locations of the shell walls. Contours begin at $0.56 \text{ mJy km s}^{-1}$ and increase by factors of $\sqrt{18}$.

the H I at this location, which may correlate with Hα features (Figure 2.14). Details of this feature will be discussed in § 2.7.4.

A narrow, pronged, faint streak may be seen from 302 km s$^{-1}$ to 355 km s$^{-1}$ in the channel maps of the receding half (Figure 2.3). Beyond 355 km s$^{-1}$ it becomes difficult to discern the streak from the regular emission of the galaxy which can be modeled. However, by comparing the H I along the mid-plane in these channels for each half, it is seen that the receding half extends only slightly further than the approaching. Thus, it is possible that, rather than there existing a streak of additional H I, there may instead be a dearth of H I at moderately high z in these channels. This feature will not be discussed further as we have no clear explanation.

Several small-scale shell-like features are also seen in both halves of NGC 4244, but are not shown or discussed further as they do not have substantial effects on the modeling and appear to have no immediate connection to features in the plane of the disk.
2.7 Discussion

2.7.1 The Warp in NGC 4244

Our models show that a warp starting around a radius of 12 kpc exists in NGC 4244. This warp is not only seen in the zeroth-moment map, forming a classic shallow integral shape, but also along the line of sight through our more in-depth modeling. These two-components of a warp, while representing tilts around axes off-set by 90° from each other, are similar in amplitude (8° and 4-5°) and starting point (Figure 2.8). Considering both contributions, the angle included by the spin vector of the inner, flat disk and the spin vector at the outermost radius, 17.5 kpc,
for which we can reliably determine inclination and position angle (i.e. the warp amplitude) is 9-9.5°. The starting point, being near the optical radius is consistent with the first two rules of commonly observed warp behavior (Briggs, 1990). This agreement between two independently modeled quantities as well as the consistency with past observations attests to the reliability of the models.

### 2.7.2 Impact on Lag Trends

In addition to the presence of extra-planar gas, trends concerning its properties such as the existence and magnitude of lags are of use in determining its origins. Although we do not detect a vertically extended H\textsc{i} halo in NGC 4244, we do detect a lag in a thickened H\textsc{i} layer having a scale height of approximately 550-575 pc. This indicates that substantial extra-planar gas need not be present in order for a lag to be observed, as is potentially seen in UGC 1281 (Kamphuis et al. 2011), although for that galaxy, a more substantial line of sight warp component is favored in place of a lag.

Any correlations with DIG layers and their kinematics are also critical. Results from Fraternali et al. (2004) show agreement between the kinematics of the H\textsc{i} and DIG layers off the plane in NGC 2403, providing an early indication that they may be connected. Heald et al. (2007) discovered a trend [albeit for only 3 galaxies: NGC 891 (−17.5 km s\(^{-1}\) kpc\(^{-1}\)), NGC 4302 (−30 km s\(^{-1}\) kpc\(^{-1}\)) and NGC 5775 (−8 km s\(^{-1}\) kpc\(^{-1}\))] of a shallower lag with increasing star formation activity for extraplanar DIG. At this time, H\(\alpha\) data for NGC 4244 is being analyzed by additional HALOGAS members to determine the DIG kinematics and results are forthcoming (Wu et al. 2011, \textit{in prep}). Although we cannot say for sure, the low star formation rate of 0.12 M\(_\odot\) yr\(^{-1}\) in NGC 4244, which is substantially lower than those in the galaxies previously listed, indicates that if a lag in the DIG exists, then it should be steep.
compared to the trending galaxies. However, the lag in H\textsubscript{i} in NGC 4244 is shallower than the DIG lags for NGC 4302 and NGC 891 and slightly steeper than that found in NGC 5775. Given this, either the trend of low star formation with steeper DIG lags will be broken if the H\textsubscript{i} and DIG lags match, or the magnitudes will differ, possibly indicating different origins.

Heald et al. (2007) also found that, although the lags differed substantially in the three DIG layers studied, they are in better agreement with each other when expressed in terms of km s\textsuperscript{−1} per DIG scale height with an average value of \(-20\) km s\textsuperscript{−1} per scale height. If one considers the NGC 4244 lags in such terms, the H\textsubscript{i} lag found in NGC 4244 is dissimilar to those found in the DIG layers of previously modeled galaxies. Assuming the warp model, with scale heights of 550 pc and 575 pc in the approaching and receding halves respectively, the lag is roughly \(-5\) km s\textsuperscript{−1} per scale height.

However, it is useful to note that possibly differing magnitudes in the H\textsubscript{i} and DIG lags do not necessarily mean that they do in fact have different origins. The H\textsubscript{i} and DIG have substantially different distributions, with the H\textsubscript{i} having significantly greater radial extent as may be seen in Figure 2.1. Since the magnitude of a lag from an internal source is somewhat dependent on where the gas is initially launched, at least in ballistic models (Collins et al. 2002, Fraternali & Binney 2006), it is safe to say that different radial density profiles, as are commonly seen in H\textsubscript{i} and DIG layers, can potentially result in differences in the lags.

We now compare the magnitude of the lags in NGC 4244 with lags found in the H\textsubscript{i} halos of other galaxies. Gradients in H\textsubscript{i} layers have been modeled for NGC 891 \([-15\) km s\textsuperscript{−1} kpc\textsuperscript{−1} (Oosterloo et al., 2007)], UGC 7321 \([-25\) km s\textsuperscript{−1} kpc\textsuperscript{−1} (Matthews & Wood, 2003)] and the Milky Way \([-22\) km s\textsuperscript{−1} kpc\textsuperscript{−1} (Levine et al., 2008), \(-15\) km s\textsuperscript{−1} kpc\textsuperscript{−1} (Marasco & Fraternali 2010)]. The lag measured for NGC 4244 is substantially shallower than these. The star formation rate in NGC 4244 of
0.12 M\(_\odot\) yr\(^{-1}\) is substantially lower than that of NGC 891 [3.8 M\(_\odot\) yr\(^{-1}\) (Oosterloo et al., 2007)] and the Milky Way [0.68-1.45 M\(_\odot\) yr\(^{-1}\) (Robitaille & Whitney, 2010)], but comparable to UGC 7321 [0.15 M\(_\odot\) yr\(^{-1}\) (Heald et al., 2011)]. Given the small number of galaxies mentioned above and the lack of any pattern concerning star formation rate and the magnitude of a lag in extraplanar H\(_I\), it is still too early to establish a significant trend.

**The Relation Between the Lag and Star Formation Within NGC 4244**

Although the lag in the H\(_I\) layer of NGC 4244 does not fit the trend with star formation rate seen by Heald et al. (2007) for DIG layers, we can ask whether such a trend is apparent *within* NGC 4244: the lag is comparable on the two sides of the galaxy, but is this also true of the star formation rate? If the Heald et al. (2007) trend continues, then a large contrast in star formation rate would be unexpected.

We consider the star formation in each half separately by using H\(_\alpha\) (Hoopes et al., 1999) and 24 \(\mu\)m MIPS data (NASA/IPAC Infrared Science Archive). Using these, we apply the method described in Kennicutt et al. (2009) to correct for extinction. We estimate the uncorrected H\(_\alpha\) flux in each half by measuring the percentage of the total H\(_\alpha\) flux in each and then using the total H\(_\alpha\) luminosity for NGC 4244 found in Kennicutt et al. (2008) of 10\(^{40}\) erg s\(^{-1}\). Accounting for the slight difference in distances used, these estimates are 5.4 \times 10^{39} and 4.4 \times 10^{39} erg s\(^{-1}\) in the approaching and receding halves respectively. (This ordering will remain consistent throughout this section.) Assuming a monochromatic flux \(L = \lambda L_\lambda\) for the 24, 70 and 160 \(\mu\)m data, the total infrared (TIR) fluxes are found to be 1.1 \times 10^{42} and 1.0 \times 10^{42} erg s\(^{-1}\). By assuming a Salpeter IMF and then applying a conversion between line fluxes and star formation rates supplied by Kennicutt et al. (2007), the star formation rate for each half may be determined:

\[
SFR_{M_\odot\ yr^{-1}} = 9 \times 10^{-42} [L_{H\alpha} + a L_{TIR}] \text{(erg s}^{-1})
\]  

\[2.1\]
(where $a = 0.0024$). These are found to be $0.064$ and $0.054 \, M_\odot \, yr^{-1}$. The star formation rate in the approaching half is approximately 15% higher than that in the receding half. However, the uncertainties in both the lag magnitude and the local star formation rates do not allow for an unambiguous conclusion regarding the trends seen by Heald et al. (2007), but there is no indication of deviation from it.

### The Radial Variation of the Lag

Now we consider the radially outward decrease in the magnitude of the lag, which has yet to be fully explained. This decrease begins just within the optical radius (near 7' or 9 kpc) and continues until just past the start of the warp. Thus, it may be concluded that this is an effect independent of the warp. By comparing the span of this radial variation in lag with the distribution of star formation as traced in Hα and 24 μm emission (Figure 2.1), The onset of the decreasing lag magnitude coincides with a sharp decline in star formation, again going against the tentative trend for extraplanar DIG rotation found by Heald et al. (2007). However, it is premature to assume that star formation is the only process affecting the magnitude of the lag and other factors may be the cause. Simple geometric arguments predict a shallowing of the lag at large radii. The most basic interpretation of the geometry, without any consideration of gas dynamical effects, considers the relationship between the rotational velocity and the gravitational potential: gas rotating at high $z$ is further from the gravitational center than the gas at the same radius in the midplane, resulting in a slower rotational velocity. This effect is most noticeable at smaller radii, where a certain height above the disk is a larger fraction of the radial distance from the center, resulting in a larger relative change in the gravitational potential, and thus a steeper lag.

Additionally, a radial pressure gradient could affect the lag and its radial variation. According to Benjamin (2002), a radial pressure gradient directed inward may
cause a steepening of the lag. In contrast, an outward pressure gradient may result in a shallowing of the lag or even an increase in rotation velocity. Such gradients could also vary with radius. Given the uncertainty in the pressure gradients in question, as well as the potentially substantial impacts even small pressure gradients may have, it is difficult to say to what degree these will alter the magnitude of any given lag.

Observationally, a radially varying lag is also seen in NGC 891 (Oosterloo et al., 2007), where the gradient in the inner regions is $-43 \text{ km s}^{-1} \text{ kpc}^{-1}$ and decreases to $-14 \text{ km s}^{-1} \text{ kpc}^{-1}$ in outer radii. This shallowing of $2.5 \text{ km s}^{-1} \text{ kpc}^{-2}$ is comparable to what the models indicate for NGC 4244, although the uncertainties (as judged by eye) make this a difficult comparison. Furthermore, the shallowing of the lag in NGC 891 was seen closer to the center in both Hα (Kamphuis et al., 2007) and H I. Thus, the origins of the shallowing of the lags in NGC 4244 and NGC 891 may be different.

Also displaying radial variation in the lag is the DIG in one quadrant of NGC 4302 (Heald et al., 2007), but the trend found in that galaxy was opposite from what we detect in the H I in NGC 4244. NGC 4302 displayed a substantial steepening of the lag, going from approximately $-23 \text{ km s}^{-1} \text{ kpc}^{-1}$ to almost $-60 \text{ km s}^{-1} \text{ kpc}^{-1}$ at radii outward of 4.25 kpc.

Ultimately, a larger sample of galaxies where this phenomenon is observed and modeled will greatly aid in determining its cause and nature.

2.7.3 Impact on H I Halo Trends

There is substantial evidence against the existence of an extended H I halo in NGC 4244, most notably the failure of the addition of a second vertical component by itself or accompanied by a warp along the line of sight to improve the fit of the vertical profile (Figure 2.5), and that the appearance of Figure 2.1 does not differ
Chapter 2. Observations and Modeling of NGC 4244

substantially from the 10× shallower Olling data. Furthermore, a second component added to the warp model yields no overall improvement to the bv plots or channel maps and adds an unnecessary degree of complexity. The significance of the lack of an H i halo has yet to be determined. Having such a small number of galaxies observed to this depth and modeled using these methods makes it impossible to extract any reliable trends. This will be remedied in the near future via the HALOGAS survey and EVLA observations involving some HALOGAS team members. For now, we can only compare the results for NGC 4244 with those of previously modeled galaxies.

Extended neutral halos have been detected in several galaxies listed below. The full resolution 1σ rms noise per channel for each external galaxy is given in mJy bm\(^{-1}\). An extended neutral halo is seen in the Milky Way (Levine et al., 2008), with a scale height of 1.6 kpc (Marasco & Fraternali 2011) NGC 891 (Swaters et al. 1997; 0.09 mJy bm\(^{-1}\), 23.4×16" resolution), with a scale height of 1.25-2.5 kpc (Oosterloo et al., 2007), NGC 4559 with a maximum scale height of 4 kpc (Barbieri et al. 2005; 0.52 mJy bm\(^{-1}\), 12.2×24.5" resolution), as well as UGC 7321 (Matthews & Wood, 2003) with a FWHM of 3.3 kpc; 0.36-0.40 mJy bm\(^{-1}\), 16.2×15.7" resolution Uson & Matthews 2003). These are all substantially greater than our estimated scale height for NGC 4244 of 565 pc, although that is only for a thickened disk, rather than a disk-halo combination as seen in those galaxies listed above. NGC 4559 and UGC 7321 are discussed below.

NGC 4559 has a star formation rate; 0.69 M\(_{\odot}\) yr\(^{-1}\) (Heald et al., 2011), approximately 5 times that of NGC 4244. Roughly 10% of the total H i mass is contained in its halo (Barbieri et al., 2005). If H i halos are due to star formation, then this would be consistent with NGC 4244 having a smaller halo, or as found in this work, none at all.

UGC 7321 is also a galaxy with low star formation, with a rate of 0.15 M\(_{\odot}\) yr\(^{-1}\). This rate of star formation is comparable to that of NGC 4244, and yet a
H\textsubscript{I} halo is detected in UGC 7321, but not NGC 4244. At first glance, the two galaxies appear quite similar. Both display thickened disks with warps in H\textsubscript{I}, and by comparing with results for UGC 7321 in O’Brien et al. (2010), their rotation curves indicate similar masses, and thus similar gravitational potentials. Finally, neither has close companion galaxies. In spite of these similarities, extended wing structures are seen in the vertical profiles shown in Figures 2 and 5 of Matthews & Wood (2003), which are absent in analogous plots of NGC 4244 (not shown), drawing a clear and fundamental distinction between the morphologies of the two. The presence of a halo in UGC 7321, a galaxy with a comparable star formation rate to that of NGC 4244, indicates that H\textsubscript{I} halos are not necessarily due solely to star formation.

### 2.7.4 Analysis of Distinct features

It is not the primary intent of this paper to perform an exhaustive study of small-scale features. NGC 4244 is nearly devoid of prominent, energetic H\textsubscript{I} shells as well as expanding features akin to those seen in more actively star forming galaxies. However, a small number of notable features are detected (§5) and will be discussed.

**The Shell-Like Feature**

Firstly, we consider the shell-like feature in the approaching half. This feature is above and slightly offset radially from a region of star formation (Figure 2.11), which extends between 3.5’ and 4.6’ along the major axis in the H\textalpha and 24 \textmu m data. The feature’s proximity to a region of star formation as well as the lack of nearby external features indicate an internal origin. To estimate the energy required to produce it, the number density must first be found. For the calculations below we assume this feature is indeed a shell created by multiple supernovae in the disk. Following the
approach taken by Rand & van der Hulst (1993), we measure the peak flux in the limbs of the presumed shell to acquire a column density. To obtain the number density, we then consider the path length along the line of sight ($l$) to be:

$$2\sqrt{d^2 + 2d r}$$  \hspace{1cm} (2.2)

Where $d$ is the shell wall thickness and $r$ is the inner radius of the shell. Since the shell walls are not well resolved, we set $d$ equal to the beam resolution parallel to the disk of about 17”. From this, a value of 1280 pc is obtained for $l$, which yields a number density of $0.15 \, \text{cm}^{-3}$.

Now using Figure 2.12, an estimate for the expansion velocity ($V_{exp}$) is 25 km s$^{-1}$. Together with the estimate for the shell’s radius in parsecs ($R_{\text{shell}} = 750$ pc) and assuming a constant expansion, its age is approximately $2.9 \times 10^7$ years.

We now calculate the energy required to produce such a shell from Chevalier (1974) where $n_0$ is the H\textsc{i} number density in cm$^{-3}$, $R_{\text{shell}}$ is the radius of the shell in parsecs, and $V_{exp}$ is in km s$^{-1}$ as described above:

$$E_E = 5.3 \times 10^{43} n_0^{1.12} R_{\text{shell}}^{3.12} V_{exp}^{1.4} \, \text{erg}$$  \hspace{1cm} (2.3)

Given these estimates, we find that a single burst of energy of roughly $5.4 \times 10^{53}$ ergs or the equivalent of 540 supernovae would be required to produce this shell. (assuming an energy of $10^{51}$ ergs per supernova) If the shell instead formed from a continuous supply of energy as described in McCray & Kafatos (1987):

$$E_C = 1.16 \times 10^{41} n_0 R_{\text{shell}}^5 t_7^{-3} \, \text{erg}$$  \hspace{1cm} (2.4)

where $t_7$ is the age in units of $10^7$ years, this would only require $1.7 \times 10^{53}$ ergs or 170 supernovae.

Now considering the H$\alpha$ luminosity of this region we again use the total H$\alpha$ luminosity for NGC 4244 found in Hoopes et al. (1999). The fraction of the total
Ho emission originating from this region is approximately 4%. Thus, its luminosity, uncorrected for extinction is found to be $4.0 \times 10^{38} \text{ erg s}^{-1}$.

To correct for extinction, we examine the 24 $\mu$m data. Summing the flux over the same region as for the H$\alpha$ data and once again assuming a monochromatic flux, the 24 $\mu$m luminosity is approximately $4.8 \times 10^{39} \text{ erg s}^{-1}$.

Using the method described in Kennicutt et al. (2007), we determine the star formation rate, this time with $a = 0.038$ and replacing $L_{\text{TIR}}$ with the 24 $\mu$m luminosity to account for localized regions.

The star formation rate for this region is found to be $0.0046 \, M_\odot \text{yr}^{-1}$, which would account for 3.8% of the ongoing star formation in NGC 4244. However, Kennicutt et al. 2007 caution that this conversion is intended for entire galaxies rather than localized regions, which limits its physical meaning.

Using this star formation rate (assuming it is constant) as well as the estimated age for the shell, a calculation akin to that presented in McKee & Williams (1997) yields an estimated 650-700 supernovae to have gone off in the region, rendering supernovae a very plausible source.

**Curved Feature**

Attending now to the curved feature in the receding half shown in Figure 2.13, we examine its potential connection to star formation. It is likely that there is some correlation between this feature and the underlying star forming region seen in the both H$\alpha$ and 24 $\mu$m data. The best resolved emission is seen in the H$\alpha$ data, which shows a curious extension of emission from possibly blown out gas (Figure 2.13 bottom panel, highlighted in boxes) which to some extent fills in the gap defined by the H I contours, indicating that the H I gas may have been forced outward in that
Chapter 2. Observations and Modeling of NGC 4244

Figure 2.14 An $\text{H}_\text{i}$ channel map at $298\,\text{km\,s}^{-1}$. $3\sigma$ and $7\sigma$ $\text{H}_\alpha$ contours are overlaid on an $\text{H}_\text{i}$ grayscale to show the outline of the faint $\text{H}_\alpha$ emission. Notice the gap in the $\text{H}_\text{i}$ near the location of the potential $\text{H}_\alpha$ outflow also shown in Figure 2.13.

direction. This structure does not appear in the $24\mu\text{m}$ data (not shown). When examining individual channel maps, it can be noted most prominently at $294\,\text{km\,s}^{-1}$ and $298\,\text{km\,s}^{-1}$, a gap in the $\text{H}_\text{i}$ forms, once again suggesting a channeling of the gas away from the midplane and into higher $z$ in this area (Figure 2.14). This hole in the $\text{H}_\text{i}$ emission may be analogous to those seen in other galaxies such as NGC 4559 (Barbieri et al., 2005). However, it is possible that the features are coincidental.

2.7.5 Comparison to Previous NGC 4244 Models

Our results concerning NGC 4244, using direct visual comparisons between models and data, represent an improvement over those obtained using the methods found in Olling (1996). Firstly, the warp resulting from models presented in this paper is more pronounced than that previously indicated. Furthermore, the inclination in central parts of the galaxy is higher ($88^\circ$ as opposed to $84.5^\circ$). The vertical profiles
Chapter 2. Observations and Modeling of NGC 4244

in Figure 2.5 show a comparison between the models. It should be noted that in this case, the lower inclination in the Olling model does not create the expected rounding near the top of the vertical profile and there is a lack of H I in the wings. However, this is because the H I distribution near the center of the Olling model is much higher than in the models presented here. This is also seen in bv diagrams of the Olling model (not shown). Additionally, there is no need for a flaring layer in the current models in order to fit the data, although one may be present. These discrepancies cannot be accounted for by improved observations alone and appear to result from differences in technique (i.e. by eye vs. more numerical where numerical techniques are more susceptible to complications due to asymmetries as well as distinct and localized features in the data). Specifically, Olling (1996) attempts to deproject the galaxy by considering the combined effects of velocity dispersion, rotational velocity, and surface brightness to determine the azimuthal extent of the emitting region corresponding to channel surface density distributions (CSDDs, where one axis is the major axis, and the other is the axis along the line of sight). Once these parameters are constrained, the inclination and scale height are estimated at a number of radii (12 in the case of NGC 4244). The inclination and scale height are varied simultaneously to minimize the difference between the observed and modeled widths, with each point weighted by the square of the inverse of its uncertainty. Such a method is prone to the same difficulties due to projection effects as are experienced in by eye fits. Additionally, few points are used to determine these quantities using this method, whereas by eye methods utilize much more of the data.

2.8 Summary and Conclusions

We present tilted ring models based on deep 21-cm observations of NGC 4244. In these observations, we note a thickened H I disk, with thinning at outer radii and
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evidence for a warp. We also note asymmetries in the approaching and receding halves as well as localized features. The models tested, in order of approximate increasing complexity, include a single disk with constant inclination, a single disk with a warp component along the line of sight, a single flaring disk, a thin and thick disk, and combinations of these.

From these models, we conclude that the disk of NGC 4244 is substantially warped both perpendicular to as well as along the line of sight. We do not detect an extended H I halo, but with a scale height of 0.6 kpc, the disk is quite thick. If H I halos are due to disk-halo flows, then given the low star formation rate in NGC 4244 compared to other galaxies with H I halos, the lack of a halo is unsurprising. However, it is still too early to establish a trend, which will hopefully become apparent when additional cases are considered.

In spite of not detecting an extended halo, we do detect a vertical lag in rotation speed of $-9^{+3}_{-2}$ km s$^{-1}$ kpc$^{-1}$ and $-9 \pm 2$ km s$^{-1}$ kpc$^{-1}$ in the approaching and receding halves respectively. The magnitude of this lag decreases outward with radius to $-5 \pm 1$ km s$^{-1}$ kpc$^{-1}$ (approaching) and $-4 \pm 2$ km s$^{-1}$ kpc$^{-1}$ (receding) near 10 kpc, although subtle changes are within the error estimates. Beyond 13 kpc, the S/N ratio no longer allows for a reliable lag estimate, so we cannot discern whether the lag vanishes entirely at some point.

This is potentially the first instance where models favor a lag in H I in a galaxy where an H I halo does not exist. There may be a lag in UGC 1281 (Kamphuis et al. 2011), in which a halo is also absent, but in that case the lag cannot be distinguished from a warp component along the line of sight without deeper observations. Given fluctuations in the position angle seen in the zeroth and first moment maps, it is possible that the warp in NGC 4244 begins closer to the center than in the models presented, which may indeed lessen or eliminate the need for a lag. However, such a scenario is unlikely as these fluctuations may instead be due to localized features, a
bar or spiral arms, which would be more in-line with current understanding of warps (Briggs 1990, van der Kruit & Freeman 2011).

Modeling aside, we observe two substantial localized features which may correlate with star formation: a shell-like feature and an unexplained curved structure originating in the midplane and possibly connected with a feature extending up to a height of 1.5 kpc. A third distinct feature, a faint H I streak is anomalous. Finally, no additional substantial energetic features are detected, although numerous small-scale shell-like features are seen, but not displayed.

We hope to use information gathered from our models of NGC 4244 in addition to information from the rest of the HALOGAS galaxies to further the development of trends concerning H I kinematics, warps, extra-planar gas and any connections with disk-halo interactions, as well as accretion.

2.9 Acknowledgments

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Chapter 2. Observations and Modeling of NGC 4244

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Chapter 3

Observations and Modeling of NGC 4565

3.1 Chapter Overview

We present 21-cm observations and models of the neutral hydrogen in NGC 4565, a nearby, edge-on spiral galaxy, as part of the Westerbork Hydrogen Accretion in LOcal GAlexieS (HALOGAS) survey. These models provide insight concerning both the morphology and kinematics of HI above, as well as within, the disk. NGC 4565 exhibits a distinctly warped and asymmetric disk with a flaring layer. Our modeling provides no evidence for a massive, extended HI halo. We see evidence for a bar and associated radial motions. Additionally, there are indications of radial motions within the disk, possibly associated with a ring of higher density. We see a substantial decrease in rotational velocity with height above the plane of the disk (a lag) of $-40^{+5}_{-20}$ km s$^{-1}$ kpc$^{-1}$ and $-30^{+5}_{-30}$ km s$^{-1}$ kpc$^{-1}$ in the approaching and receding halves, respectively. This lag is only seen within the inner $\sim4.75'$ (14.9 kpc) on the approaching half and $\sim4.25'$ (13.4 kpc) on the receding, making this a radially shal-
lowing lag, which is now seen in the H\textsc{i} layers of several galaxies. When comparing results for NGC 4565 and those for other galaxies, there are tentative indications of high star formation rate per unit area being associated with the presence of a halo. Finally, H\textsc{i} is found in two companion galaxies, one of which is clearly interacting with NGC 4565.

This chapter has been published in the Astrophysical Journal (Zschaechner, L. K., Rand, R. J., Heald, G. H., Gentile, G., Józsa, G., 2012, Volume 760, Issue 1, article id. 37, 17). Minor modifications have been made for consistency with later work presented in Chapters 4-6.

3.2 Introduction

Understanding the origins and evolution of extra-planar gas is key to interpreting how spiral galaxies are affected by their environments. Whether galaxies exist in dense clusters or groups, or are relatively isolated, extra-planar gas is the bridge between galaxy disks and the intergalactic medium (IGM). Is this gas ejected from the plane of the disk, driven by star formation as described in the galactic fountain (Shapiro & Field 1976, Bregman 1980) and chimney (Norman & Ikeuchi, 1989) models? Does some of it result from accretion from external sources (e.g. Kereš & Hernquist 2009) such as companion galaxies or the IGM itself? If so, how would these internal and external components interact with each other? To answer these questions, a thorough study of extra-planar gas morphology and kinematics in a large number of galaxies is necessary.

Extra-planar components including hot gas (e.g. Tüllmann et al. 2006b), relativistic particles (e.g. Irwin et al. 1999), dust (e.g. Howk & Savage 1999), ionized hydrogen (e.g. Rand 1996; Rossa & Dettmar 2003) as well as neutral hydrogen (H\textsc{i}) (e.g. Swaters et al. 1997, Oosterloo et al. 2007) have been observed. For all except
Chapter 3. Observations and Modeling of NGC 4565

H I there is a correlation between their presence and star formation in the disk, both in localized regions as well as globally. This indicates disk-halo flows akin to those in the aforementioned galactic fountain and chimney models as likely origins. However, such trends have not been reported for H I, and in fact there is evidence that at least some extra-planar H I has an external origin in the Milky Way (Wakker & van Woerden, 1997) and nearby galaxies (Sancisi et al., 2008). This is an issue that motivates this work.

In addition to probing the origins of different halo components through their morphology, we may also gain information through understanding their kinematics. In galactic fountain-type models, gas is launched from the plane of the disk and moves to larger radii. In order to conserve angular momentum, there must be a decrease in rotational velocity with height. This vertical gradient in rotational velocity is referred to as a lag. However, other physical processes may affect the magnitude of such a lag (see below); hence, measurement of lags should help to constrain the physics of extra-planar components, and may shed light on important elements of galaxy evolution.

Heald et al. (2007) measured lags in three extra-planar Diffuse Ionized Gas (DIG) layers, resulting in a trend of low star formation rates (SFR) with steeper lags. If H I and DIG layers share similar kinematics and the Heald et al. (2007) trend holds, then, the same should be expected for H I.

Simple dynamical models of disk-halo cycling, where only ballistic effects are considered (Collins et al. 2002, Fraternali & Binney 2006), have produced lags significantly shallower than those observed. These discrepancies between models and observations indicate that additional factors must be considered. Firstly, internal complications such as those produced by extra-planar pressure gradients or magnetic tension (Benjamin, 2002) have yet to be examined thoroughly, but could potentially explain these discrepancies without resorting to external factors.
Explanations involving infalling gas such as interaction of disk-halo cycled gas with a possible hot, low angular momentum, low metallicity halo predicted by cosmological simulations (Marinacci et al., 2011) and the hydrodynamic simulation of disk formation in Kaufmann et al. (2006) have successfully reproduced the observed lag in NGC 891.

However, while much attention has been focused on results for NGC 891, observed lags differ among the three galaxies considered in Heald et al. (2007) and one would like to understand the physical cause of such variations. More relevant here, extensive modeling of extra-planar H I kinematics has until recently been carried out for only a small number of edge-on galaxies, using observations with a range of resolutions and sensitivities. These include NGC 891 (Oosterloo et al., 2007), where DIG and H I lags agree, pointing to similar origins for both components, and other galaxies summarized in § 3.7.4. Furthermore, the trend of steeper lags with lower SFRs found by Heald et al. (2007) needs to be further tested, while variation of lags within extra-planar gas layers, such as radial gradients, may also constrain their origin. With the aforementioned evidence for an external source for at least some extra-planar H I, it is imperative to understand how kinematic information may constrain these two possible origins of extra-planar gas.

The Westerbork Hydrogen Accretion in LOcal GAlaxies (HALOGAS) survey (Heald et al., 2011), which targets 22 edge-on or moderately inclined spiral galaxies for deep, uniform 10×12 hour observations using the Westerbork Synthesis Radio Telescope (WSRT), will greatly increase this number. This survey will also allow us to establish whether there is any connection between extra-planar H I and star formation, as well as the degree to which contributions from external origins are relevant. A primary goal of HALOGAS is to estimate the rate of H I accretion in spiral galaxies.

Aside from the characterization of extra-planar gas, one goal of HALOGAS is to
investigate morphological features such as bars and rings as well as their kinematics. These features will be discussed throughout this paper.

### 3.2.1 NGC 4565

NGC 4565 is classified as a SAb galaxy (de Vaucouleurs et al., 1991) with a SFR of $0.67 \, \text{M}_\odot \, \text{yr}^{-1}$ calculated in Heald et al. (2012) using total infrared (TIR) flux measurements. This places it near the low star-forming end of the HALOGAS sample. However, based on its rotation curve, it is among the most massive, which would presumably hinder gas being ejected to large heights above the disk. This combination gives it substantial importance in determining overall trends involving extra-planar H\textsc{i} and star formation.

At a distance of 10.8 Mpc (Heald et al., 2011), NGC 4565 is relatively nearby, and among the best studied edge-on spirals. It has been observed in optical continuum (e.g. Kormendy & Barentine 2010), H\textalpha (Rand et al., 1992), radio continuum (Kodilkar et al., 2008), CO line emission (Neininger et al., 1996), and X-rays (Vogler et al., 1996).

In the optical, NGC 4565 is seen to have a box-shaped bulge indicating a bar (Kormendy & Barentine, 2010). Additionally, Neininger et al. (1996) found radial motions in CO emission along the minor axis, which they suggested could be due to a bar or a spiral density wave. We see evidence for the bar in H\textsc{i} as will be discussed in § 3.4.

Kodilkar et al. (2008) detect a radio continuum halo extending up to 3 kpc. In contrast, Rand et al. (1992) found that NGC 4565 was lacking a smooth DIG halo, which is consistent with its low star formation rate.

Unexpectedly, substantial X-ray emission, generally not seen in galaxies with-
Chapter 3. Observations and Modeling of NGC 4565

Table 3.1. NGC 4565 Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Reference</th>
</tr>
</thead>
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<tr>
<td>Distance (Mpc)</td>
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<td>Heald et al. (2011)</td>
</tr>
<tr>
<td>Systemic velocity (km s&lt;sup&gt;-1&lt;/sup&gt;)</td>
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<td>This work</td>
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<td>Inclination</td>
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<td>SFR (M&lt;sub&gt;☉&lt;/sub&gt; yr&lt;sup&gt;-1&lt;/sup&gt;)</td>
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</tr>
<tr>
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</tr>
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<td>D&lt;sub&gt;25&lt;/sub&gt; (kpc)</td>
<td>16.2</td>
<td>de Vaucouleurs et al. (1991)</td>
</tr>
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<td>Total Atomic Gas Mass (10&lt;sup&gt;9&lt;/sup&gt;M&lt;sub&gt;☉&lt;/sub&gt;)</td>
<td>9.9&lt;sup&gt;c&lt;/sup&gt;</td>
<td>This work</td>
</tr>
</tbody>
</table>

<sup>a</sup>Distance is the median value of distances found on the NED database, excluding those obtained using the Tully-Fisher relation.

<sup>b</sup>The A classification indicating no bar is likely erroneous based on Neininger et al. 1996, Kormendy & Barentine 2010, and this work.

<sup>c</sup>Includes neutral He via a multiplying factor of 1.36. The value using single dish data is 10.2×10<sup>9</sup>M<sub>☉</sub> (Springob et al. 2005)

out enhanced star formation activity, was detected both within and above the disk (Vogler et al., 1996). The nature of this X-ray emission is still unknown.

Finally, H<sub>I</sub> observations of NGC 4565 were previously performed using the Very Large Array (VLA), but detailed models were not created from those data (Rupen, 1991). However, a comprehensive description was provided in that paper, mentioning several features we now see in greater detail, and with a higher level of confidence. Additional WSRT data were taken (Dahlem et al., 2005), which were further interpreted in van der Hulst & Sancisi (2005). These WSRT data are supplemented with the HALOGAS data to produce the final dataset presented here. 3.1 summarizes parameters for NGC 4565.
3.3 Observations and Data Reduction

Here we provide a brief explanation of the observations and data reduction process. A detailed description, which applies to all of the HALOGAS galaxies, may be found in Heald et al. (2011).

NGC 4565 was observed using the Westerbork Synthesis Radio Telescope (WSRT) by Dahlem et al. (2005) as well as through the HALOGAS survey. The archival observations were done in the Traditional WSRT configuration, using four distinct spacings between the fixed and movable antennas, starting at 36 m and incremented by 18 m. Observations obtained as part of HALOGAS were in the Maxi-short configuration with baselines ranging from 36 m to 2.7 km in order to maximize sensitivity to faint, extended emission. Of the 10 fixed antennas, 9 were used and spaced at 144 m intervals on a regular grid. The total bandwidth is 10 MHz with 1024 channels and two linear polarizations. The total observing time is $10 \times 12$ hours, and observing dates are listed in Table 3.2.

Data reduction was performed in Miriad (Sault et al., 1995). Images were created with a variety of weighting schemes, creating multiple data cubes. Clark deconvolution (Clark, 1980) was performed using mask regions defined on the basis of unsmoothed versions of the image cube. Offline Hanning smoothing led to a final velocity resolution of 4.12 km s$^{-1}$ in a single channel. The 1$\sigma$ rms noise in a single channel of the full resolution cube is 0.31 mJy bm$^{-1}$, corresponding to a column density of $N_{HI} = 5.1 \times 10^{18}$ cm$^{-2}$.

To optimize our resolution, we use a cube with a robust parameter of $-2$. The beam for this cube is $24.27 \times 11.45''$; $1'' = 52.4$ pc ($1270 \times 600$ pc) with a position angle of $-0.47^\circ$. By using this cube, we sacrifice some sensitivity to faint extended emission. However, we later examine and apply the same models to a second cube where a Gaussian $uv$ taper yielding $44 \times 34''$ resolution is used. Primary beam cor-
Table 3.2. NGC 4565 Observational and Instrumental Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
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<td>2009 Mar 10-11</td>
</tr>
<tr>
<td></td>
<td>2009 Mar 11-12</td>
</tr>
<tr>
<td></td>
<td>2009 Mar 15-16</td>
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<td>2009 Apr 12-13</td>
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<tr>
<td></td>
<td>2009 Apr 24</td>
</tr>
<tr>
<td></td>
<td>2009 Apr 27-28</td>
</tr>
<tr>
<td>Observation Dates – Dahlem</td>
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</tr>
<tr>
<td></td>
<td>2003 Apr 14-15</td>
</tr>
<tr>
<td></td>
<td>2003 May 14-15</td>
</tr>
<tr>
<td></td>
<td>2003 May 19-20</td>
</tr>
<tr>
<td>Pointing Center</td>
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</tr>
<tr>
<td></td>
<td>25d 59m 13.50s</td>
</tr>
<tr>
<td>Number of channels</td>
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</tr>
<tr>
<td>Velocity Resolution</td>
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</tr>
<tr>
<td>Full Resolution Beam Size</td>
<td>24.27(\times)11.5&quot;</td>
</tr>
<tr>
<td></td>
<td>1270(\times)600 pc</td>
</tr>
<tr>
<td>RMS Noise – 1 Channel (24.27(\times)11.5&quot;)</td>
<td>0.31 mJy beam(^{-1})</td>
</tr>
<tr>
<td>RMS Noise – 1 Channel (44(\times)34&quot;)</td>
<td>0.24 mJy beam(^{-1})</td>
</tr>
</tbody>
</table>

...rection has been applied to both cubes using the Miriad task `linmos`. In the case of moment maps, which are created using methods described in Serra et al. (2012), this is done in the last step.

3.4 The Data

Upon initial inspection of the zeroth moment map (Figure 3.1), H\textsc{i} emission can consistently (i.e. along most of the disk) be seen up to heights of 1.5-1.75' in the full-resolution and smoothed cubes respectively. As will be shown in § 3.5, this does
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Figure 3.1 The H\textsc{i} zeroth-moment map displaying the full-resolution (black contours and grayscale) and smoothed 44" × 34" (gray contour) cubes. Full resolution contours begin at 3.0 × 10^{19} \text{cm}^{-2} and increase by factors of 2. The smoothed contour is at a level of 1.1 × 10^{19} \text{cm}^{-2}. Both beams are shown in the lower left-hand corner. Two companion galaxies may be seen, NGC 4562 in the southwest corner and IC 3571 north of the center. Note the strong, asymmetric warp across the line of sight as well as the connection between NGC 4565 and IC 3571. Diagonal lines parallel to the minor axis indicate slice locations shown in Figure 3.3.

not mean that an extended H\textsc{i} halo is necessary to fit the data. Also evident in the zeroth moment map is an asymmetric warp component across the line of sight. This warp is most prevalent in the receding (NW) half of the galaxy, where the disk tilts upward and then flattens at large radii. In the faint emission, a connection is seen between NGC 4565 and the companion in the northeast quadrant (IC 3571), which was also noted by van der Hulst & Sancisi (2005). This interaction may contribute to the asymmetry of the warp.

We calculate a total H\textsc{i} mass of 9.9 \times 10^{9} M_{\odot}, while the single dish estimate for the total H\textsc{i} mass is 10.2 \times 10^{9} M_{\odot} (Springob et al. 2005), indicating that these observations recover most of the flux.
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The warp across the line of sight is also clear in the channel maps shown in Figure 3.2. Also seen more clearly in the channel maps is a substantial asymmetry in the distribution of gas in the approaching and receding halves.

There exist two nearby companions within the field of view: IC 3571 near the northeast quadrant of the galaxy with a velocity range of 1225-1299 km s\(^{-1}\) and NGC 4562 in the southwest with a velocity range of 1266-1427 km s\(^{-1}\).
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Figure 3.2 Representative channel maps of the data with a resolution of 24.3"×11.5". Contours begin at 2σ (0.61 mJy bm⁻¹) and increase by factors of 2. The −2σ contour is also shown with dashed lines. The velocities in km s⁻¹ are given in each panel and the velocity spacing is approximately 7 resolution elements. Note the slanted outer edges present in both halves, which correspond to the projection of the warp perpendicular to the line of sight as well as the asymmetric gas distribution in each half. The beam is shown in the bottom left panel.
Figure 3.3 Position-velocity diagrams parallel to the minor axis showing the data, one-component (1C) model, and various flaring (F) models. The Fi model is the flare model with disk inflow at small to moderate radii beyond the bar, and the Fio model is the flare model with both inflow in the inner parts of the disk and outflow in at large radii. The second to last column shows the Fio model with a global lag of \(-10 \text{ km s}^{-1} \text{ kpc}^{-1}\), while the final column shows the Fio model with an optimized radially varying lag. Details for models involving radial motions are described in §3.5.1 and details of the lag models are described in §3.5.1. All models shown here include a bar with an orientation 30° from the line of sight and a radial motion of \(-20 \text{ km s}^{-1}\). Contours are as in Figure 3.2. Slice locations are given in the first column and can be seen in Figure 3.1. Arrows indicate the direction emission is moved due to the addition of radial motions. The approaching half is SE while the positive minor axis offset is NE as seen in Figure 3.1.
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There is a large velocity spread seen in minor axis position-velocity (bv) diagrams near the center of the galaxy [Figure 3.3 (column 1, row 5)]. As we will show in § 3.5.1, this velocity spread is kinematic evidence for a bar with an orientation that is at least partially along the line of sight with radial motions.

There also exist indications of radial motions not associated with the bar. These are best seen as a slanting of the data contours on the systemic side in most panels of Figure 3.3. The direction of the slant at minor axis offsets < 40" is different from that at minor axis offsets 40" - 80". Our modeling will show that this indicates a sign change in the direction of radial motions at larger radii rather than with height above the plane.

Crucial to certain aspects of the modeling, such as radial motions, is the distinction between the near and far side of NGC 4565. Fortunately, from the orientation of the dust lane seen in the 2MASS Large Galaxy Atlas (Jarrett et al., 2003), we can infer that the side northeast from the plane of the disk is nearer than the southwestern side. This side corresponds to the positive side along the minor axis in the figures.

Modeling of the features listed above will be discussed further in the next section.

Finally, from our continuum data we simply present a vertical profile in Figure 3.4. The detectable extent is comparable to that found by Kodilkar et al. (2008).

3.5 The Models

Models were created using the tilted ring fitting software (TiRiFiC) (Józsa et al., 2007)\(^1\), which allows for a \(\chi^2\) minimization fit. Aside from its fitting capabilities, this software employs methods similar to the Groningen Image Processing System

\(^1\)http://www.astron.nl/~jozsa/tirific/

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Figure 3.4 The vertical profile of the H\textsc{i} continuum at 30" resolution corresponding to major axis values between $-4'$ and $+4'$. The FWHM is approximately 1.2' or 3.8 kpc.

(GIPSY) (van der Hulst et al., 1992) task \textit{galmod}. For each ring, parameters such as the central position, systemic velocity, inclination, position angle, surface brightness, rotational velocity, radial velocity, velocity dispersion and scale height may be specified.

Contrary to models created using \textit{galmod}, those created using \textit{TiRiFiC} need not be axisymmetric. \textit{TiRiFiC} allows the user to divide the model galaxy into wedges of azimuth in order to model asymmetries throughout the disk without requiring the creation of multiple models. Additionally, \textit{TiRiFiC} allows for a gradient in the rotational velocity with height. \textit{TiRiFiC} can also superimpose gaussian components onto the disk, which can be used to resemble bars and spiral structure in the model. Naturally, as is the case for tilted ring models in general, these are greatly oversimplified and should only be used as tools to approximate the morphology of these features and not to fully explain their kinematics.

Although a majority of the modeling of NGC 4565 was done in \textit{TiRiFiC}, the
Figure 3.5 The vertical profile of the data, one-component (1C), and flaring (F) models corresponding to major axis values between $-4'$ and $+4'$. Especially note the fit of each model near the peak of the profile as well as near the wings.

An initial estimate for the systemic velocity was taken from Rupen (1991). The rotation curves were determined via inspection of the terminal side of major axis position-velocity (lv) diagrams, akin to the envelope tracing method (Sancisi & Allen 1979, Sofue & Rubin 2001). Surface brightness estimates were determined using the GIPSY task \texttt{radial}. The run of the position angle was initially estimated by eye and inclinations close to $90^\circ$ were considered. Initial estimates for the exponential scale height were determined solely by a fit to the vertical profile (Figure 3.5). All of these parameters were later refined both by comparing observed and modeled position-velocity diagrams, channel maps, zeroth-moment maps and vertical profiles.

\texttt{TiRiFiC}'s automated fitting capabilities were used when appropriate. However,
at the level of detailed analysis of lopsided and asymmetric disks, which may be described by including non-standard parameterizations, this possibility is useful only to a certain degree. Nevertheless, if provided with reasonable initial constraints, TiRiFiC may expedite the fitting process. The degree to which additional refinement by eye is necessary depends greatly on any distinct features present in the region of fitting.

### 3.5.1 Individual Models

Several basic models are initially considered. These include a simple one-component (i.e. single disk with a constant exponential scale height and no warp or flare), flare, a substantial warp component along the line of sight, and a model with a second, thickened disk simulating an extended global halo. The one-component and flare models are labeled as 1C and F in figures.

Upon examination of the zeroth moment map (Figure 3.1) as well as the vertical profile (Figure 3.5), the latter two models (not shown) may be eliminated quickly due to a lack of thickening of the gas layer at small to intermediate radii that is a feature of these models as well as poor fits to position-velocity diagrams and channel maps. The observed vertical profile is almost entirely devoid of wing structure, making it difficult to fit while maintaining the correct curvature and width near the center with such models. A substantial warp component along the line of sight places flux high above the midplane on the systemic side of the bv diagrams as is seen in the data. However, it also creates indentations along the major axis at large radii in channel maps as well as on the systemic side of bv diagrams. These are not seen in the data. As for a halo model, adding a second thicker component not only increases the width of bv diagrams on the systemic side, but also increases the width closer to the terminal side. Again, this is not seen in the data. For these reasons, only the
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1C and F models are considered further and described below.

Although multiple types of models are considered, some parameters remain fixed. These include the central position (12h 36m 20.63s, 25d 59m 16.8s), systemic velocity (1220 km s$^{-1}$), velocity dispersion (10 km s$^{-1}$), the run of the position angle and inclination, the surface brightness profile, and the rotation curve. All models include a bar and a small-scale feature that are discussed in § 3.5.1 and 3.5.1.

Due to asymmetries, the disk is divided into two halves along the minor axis, and each half independently modeled in what follows.

One Component Model

A model consisting of a single component with an exponential scale height of 470 pc was created. This model is a reasonable approximation to the data, but with deficiencies. The first of these may be seen in the vertical profile (Figure 3.5) where the 1C model is too flat near the top compared to the data. If the scale height is decreased to match the data near the center, then the model becomes too narrow in the wings. No other combination of scale height and inclination improves the fit. In the bv diagrams shown in Figure 3.3, the 1C model is too thick at terminal and intermediate velocities when compared to the data. Furthermore, an excess of emission in the 1C model can be seen at major axis offsets within ±5’ of the center offsets of the lv diagrams corresponding to −16” and −32” in Figure 3.6 and b. Finally, in Figure 3.7, one may note that, while the minor axis thickness is well matched at velocities close to systemic, the 1C model is too thick at small and intermediate major axis offsets. As will be shown, these issues are all remedied by allowing the scale height to vary in the form of a flare.
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Flaring Model

Instead of using a single exponential scale height throughout the disk, if we allow the disk to flare [scale height = 4\" (200 pc) near the center, increasing to scale height = 12\" (600 pc) in outer radii], the issues mentioned above are all but eliminated, as may be seen in the third columns of Figures 3.6 and b. Other variations in the scale height were tested, but this was found to be the best fit to the data. Figure 3.8 shows the radial variation of scale height used in our flaring models. Note that the scale height increases in steps rather than a straight line. A smoothed version would produce nearly identical results, but arbitrarily smoothing the scale height distribution could imply that the models are better constrained than they are in reality. Thus, we include the steps as they are a better representation of the modeling process and limitations. Nevertheless, the scale height is seen to rise in a nearly linear fashion.

Although some improvements with the flare model are seen in lv diagrams where the excess emission in the 1C model is not seen, the most convincing evidence for improvement is also seen in bv diagrams and channel maps (Figures 3.3 and 3.7). In Figure 3.3, one may note a widening on the systemic relative to the terminal side of the data best seen in panels within ±3\', which is significantly better matched by adding a flare. Additionally, in Figure 3.7 it is seen that there is a thickening at large major axis offsets in the channel maps that is best reproduced via the addition of the flare (e.g. the panel corresponding to 1381 km s$^{-1}$).

Key parameters for the models described above, with the 1C and F models differing only in scale height behavior, are shown in Figure 3.8.

Up to this point, we have discussed modeling only global features found throughout the disk. Now we will discuss the modeling of more localized features such as a bar and adding further refinements such as radial motions. Given that Figures 3.3 through 5 provide the most detailed representation of the models, these figures all
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include the features that will be described below. Abbreviated representations of the models excluding them will be shown in order to show their effects.

Including a Bar

As mentioned in § 3.2.1 and 3.4 there are indications of a bar in NGC 4565, which we will show can also explain the large velocity spread in panels near the center in Figures 3.3 and 3.10. The effects of adding a bar are most clearly seen in the latter Figure, which shows no-bar and bar models side-by-side. We model this bar by adding a series of 1D gaussian emission components starting at the center and moving outward radially along some azimuthal direction in the disk. The dispersion of the gaussian component is specified along the azimuthal angle and is 15” in our models. The amplitude is also specified. Additionally, parameters which are specified in rings as described above may also be set, notably the azimuthal position and radial velocity. It should be noted that these parameters allow for an approximation of a bar, and do not account for more complex streaming motions or morphology. Figure 3.9 shows how this bar appears in a face-on view of our best model.

We examine several orientations with respect to the line of sight, keeping in mind that Kormendy & Barentine (2010) assume a line of sight (i.e. end-on) orientation due to the boxy bulge seen in the optical, while Athanassoula (2005) states that such boxy bulges are indicative of components across the line of sight (i.e. side-on), but possibly only as little as 10° from the end-on view. From the clear indications of radial motions described below, we can be certain that the bar is at least partially end-on, although it is difficult to gauge how much. We explore this in our models.

First we examine a line of sight or end-on orientation and assume that the half-length of the bar roughly extends to 1.25' (4 kpc), or just within a ring of higher density in the disk (Figure 3.8). A linearly increasing rotation curve is used, which
matches the rest of the disk at radii larger than 45". (Note: aside from the bar, no H\textsubscript{i} is included in the main disk interior to this radius.) Adding a bar in this way allows for some spread in the velocity range (Figure 3.10, column 3), while remaining in a narrow range along the minor axis. However, the full velocity spread seen in the data is not achieved. Such a model is improved by adding radial motions of $\pm 20$ km s\textsuperscript{-1} (Figure 3.10, column 4). Due to projection effects and limited spatial resolution, we cannot discern whether this is inflow or outflow.

For $\pm 30^\circ$ and $\pm 45^\circ$ offsets from the line of sight (positive corresponds to the near side of the bar being in the NW quadrant), we achieve a somewhat improved fit with radial motions of $\pm 40$ km s\textsuperscript{-1}. Finally, increasing the offset to $\pm 60^\circ$ from the line of sight requires increasing the radial motions to $\pm 60$ km s\textsuperscript{-1}. These results ignore any additional radial motions in the disk beyond the bar, which are shown to be necessary in § 3.5.1. These motions in the disk render constraining the orientation and radial motions of the bar even more difficult.

The length of the bar and the dispersion of the gaussian distortions remain constant in all cases. For the figures in this paper we display a $-30^\circ$ offset bar with a radial motion of $-20$ km s\textsuperscript{-1}. It should be noted that $+30^\circ$ paired with $+20$ km s\textsuperscript{-1} produces the same results. The disk radial motions decrease the amplitude of the optimal bar radial motion, hence we choose $-20$ km s\textsuperscript{-1} for the latter instead of $-40$ km s\textsuperscript{-1} as mentioned above.

**Additional Morphological Modifications**

In the approaching half, a clump of brighter emission is seen between $-20$ and $-50^\circ$ above the plane of the disk, centered at a velocity of 1075 km s\textsuperscript{-1} (Figure 3.3, panel corresponding to 5\textquotesingle). This is not to be confused with the slant due to radial motions mentioned in § 3.4, and described in § 3.5.1. To sufficiently achieve both of these
elements, an arc centered at $-55^\circ$ from the line of sight in azimuth within the disk, and spanning $45^\circ$, is added to the far quadrant of the approaching half in all models (Figure 3.9). This is likely an azimuthal continuation of the larger radial extent of the receding half relative to the approaching half, or possibly spiral structure, rather than a unique feature. The modeling of such features as spiral structure will be explored in future HALOGAS papers.

Radial Motions in the Disk

There are several indications of radial motions beyond the bar. This is most readily seen in Figure 3.3 as well as in Figure 3.10. Note first the slope of the highest contours on the systemic side of the approaching half, particularly evident in the panels corresponding to 0' and 1'. This is appropriately reversed for the receding half. These are indicative of radial inflow at small to intermediate radii. This is modeled by introducing an inflow starting with an extreme value of $-50 \pm 5$ km s$^{-1}$ at 1.75' (5.5 kpc) and quickly decreasing with radius before becoming undetectable beyond 2.75' (8.6 kpc). This inflow is symmetric in both halves and is very likely associated with the ring of higher density. The model in the fourth column of Figure 3.3 (Fi) includes all of these motions. Arrows in Figure 3.3 indicate the significant but often subtle effects of adding such inflow. The directions of the arrows correspond to the direction in which emission is displaced due to radial motions. Additional isolated regions of inflow are seen in each half, but these are not symmetric and are likely associated with spiral structure. It should be noted that a more modest inflow of 10-15 km s$^{-1}$ spread over a larger radial range could not reproduce what is seen in the data.

In addition to the indications of radial inflow in the inner parts of the galaxy, indications of outflow are seen at large radii. This is best seen as the overall negative slope on the systemic side, opposite in direction from that produced by the inflow,
±40-80″ off the plane of the disk in panels between -5' to +5' (once again indicated by arrows). This is modeled by allowing a radial outflow of 10 km s\(^{-1}\) beginning at 6.75″ (21.2 kpc), and extending outward to the edge of the disk in each half [Figure 3.3, column 5 (Fio)].

The distribution of radial motions in the models may be seen in Figure 3.11.

It is difficult to tell with certainty if the observed radial motions are due to streaming along spiral arms or another source. However, the substantial inflow located within and just outside the ring of higher density indicates that the inflow in this region may be true axisymmetric inflow or associated with the bar rather than spiral arms.

The Addition of a Lag

As previously discussed in § 3.5.1 and seen in the bv diagrams in Figure 3.3, the data are relatively thin near the terminal side compared to the systemic. This is somewhat remedied by the addition of a flare (§ 3.5.1), but improvements may still be made through adding changes in rotational velocity with height above the disk. This causes observed velocities of emission at high z to be displaced towards the systemic side in the bv diagrams, resulting in a thinning in the width near the terminal side and a thickening on the systemic side. This is best seen in the bv diagrams closer to the center, shown in Figures 3.12 and b where the contours on the terminal side become more rounded to better match the data with the addition of a lag. This is also evident at the terminal edge of lv diagrams, where emission is displaced to lower velocities. It should be noted that these effects are subtle but cannot be reproduced by changing the flare parameters. If a lag is present in the data, then we should see some or all of these features, provided there is sufficient resolution. However, given how thin and far away the disk is, our resolution is lacking, so our error bars are
large. We find an optimal lag peaking at $-40^{+5}_{-20}$ km s$^{-1}$ kpc$^{-1}$ between 1.25' and 4.75' (3.9 and 14.9 kpc) in the approaching half, and $-30^{+5}_{-30}$ km s$^{-1}$ kpc$^{-1}$ between 1.25' and 4.25' (3.9 and 13.4 kpc) in the receding half. These quickly decrease in magnitude within the specified range in both halves, as shown in Figure 3.14. This lag distribution is again represented in Figure 3.15 as an azimuthal velocity that rises more steeply at high z.
Figure 3.6 Position-velocity diagrams of the approaching (A) and receding halves (B) parallel to the major axis showing the data, one-component (1C), and flaring (F) models. The final two columns (Fio and Fio + Lag) display the flare model with radial motions and then with the optimal lag described in § 3.5.1 and 3.5.1. All models shown here include a bar with an orientation 30° from the line of sight and a radial motion of $-20$ km s$^{-1}$. Contours are as in Figure 3.2. The heights above the plane of the disk are given in the first column. Note that the lag is difficult to detect in these diagrams, primarily due to its being only within the inner 3-4'. More convincing evidence is shown in Figure 3.14. Perhaps the most noticeable discrepancy is the spread of the emission in the data compared to the model in panels corresponding to $-48^\circ$. This can be attributed to a slight asymmetry in the flare.
Figure 3.7 Channel maps showing the data, one-component (1C) model, and various flaring (F) models. The final two columns (Fio and Fio + Lag) display the flare model with radial motions and then with the optimal lag described in § 3.5.1 and 3.5.1. Only subtle differences are seen with the addition of a lag, all within 3-4' from the center, most notably in the bottom row. More convincing evidence is shown in Figure 3.14. All models shown here include a bar with an orientation 30° from the line of sight and a radial motion of −20 km s$^{-1}$. Contours are as in Figure 3.2. Velocities are given in each panel of the first column.
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Figure 3.8 Key parameters used in the optimal models, with the 1C and F models differing only in scale height. These are rotational velocity ($v_{rot}$), column density ($C_{dens}$), position angle (PA), inclination, and for the F model, scale height (SH). Inclination is shown using thickened lines. Note that the receding half extends further than the approaching half, which drops to zero in column density at approximately 30 kpc. Values for other parameters beyond this point are excluded in that half.

Figure 3.9 A face-on view of the optimal model as seen from a viewer located in the SW quadrant. Note the extent of each half, the bar at the center with a half-length of 1.25', the ring of higher density at approximately 1.7', as well as the additional arc added to the far side of the approaching half. The black dot indicates the original orientation of the observer. Contours begin at $7.7 \times 10^{15}$ cm$^{-2}$ and increase by factors of 2. Grid units are in pixels and 1 pixel = 4".
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Figure 3.10 Minor axis position-velocity diagrams showing models with no bar, a bar oriented 30° from the line of sight, the same bar with an inflow of $-40$ km s$^{-1}$, and the same bar with an inflow of $-20$ km s$^{-1}$ as well as additional radial motions that are not associated with the bar. These additional radial motions are described in § 3.5.1. Note the large spread in velocities in each panel related to the bar itself, as well as the slanting of the contours at 1175-1250 km s$^{-1}$, indicative of additional radial motions. Contours are as in Figure 3.2. Dashed lines indicate the major axis and systemic velocity.
Figure 3.11 Radial motions in each half, excluding those associated with the bar. Negative values indicate inflows. Due to limited resolution, and complications from the bar, no radial motions are constrained for radii less than 45" (2.4 kpc). The sharp dip coincides with the ring of higher density, while the shallower dips are likely associated with spiral structure.
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Figure 3.12 Position-velocity diagrams parallel to the minor axis showing the data, flaring (Fio), and several models constraining different lags, the parameters of which are given in Figure 3.14. The optimal lag is included in the Fio + Lag model, while FLmin and FLmax are models with the lower and upper limits. The final column shows a global lag of $-10 \text{ km s}^{-1}\text{ kpc}^{-1}$ that fits the data well near the center, but as can be seen in Figure 3.3 does not match the data at large radii. Contours are as in Figure 3.2 and slice locations are given in the first column. Rectangles indicate regions where effects of the lag are most noticeable, and the panels containing them are magnified in Figure 3.13.

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Figure 3.13 Magnified panels corresponding to those with rectangles in Figure 3.12. Note the rounding and slope of the contours near the terminal side in each panel.

For completeness we also include a model with a constant global lag throughout the galaxy in the sixth column of Figure 3.3. Such a lag overestimates the rounding on the terminal side in panels corresponding to ±5' and ±7', emphasizing the need for radial variation in the lag.

Figure 3.14 The optimal, maximum and minimum lag distributions in each half. Due to limited spatial resolution, no lag is constrained for radii less than 45'' (2.4 kpc).
3.5.2 On the Uniqueness of the Models

A rigorous statistical analysis of the fitting of tilted ring models is generally omitted from the literature (e.g. Barbieri et al. 2005, Oosterloo et al. 2007, Rand & Benjamin 2008). Such studies employ a simple model focusing on the quantification of certain features in observed galactic disks, driven by a specific scientific question. In our case the main aim is to constrain the vertical structure of the H\textsc{i} disk, which means giving significant weight to faint emission. If fitting were fully automated, a goodness-of-fit criterion such as a $\chi^2$ (which TiRiFiC provides) could be used to distinguish models by significantly downweighting the bright emission that would otherwise dominate the statistic and render it meaningless for our purposes. In prin-
ciple, a reduced $\chi^2$ with such a weighting could also account for the varying number of free parameters among models. However, it is generally much more efficient to use the judgment of the modeler and adjust certain parameters manually. But this makes an accurate accounting of the degrees of freedom in each model difficult. For instance, the radial scale height dependence (Figure 3.8), shows eight values and eight inflections, indicating sixteen values were varied. However, for this and other parameters, finer variations may have been considered and discarded as providing insignificant improvement. Likewise, initially most parameters for the approaching and receding models are the same, and then some parameters varied as needed, but some deviations between halves may have been tested and discarded to keep the models simple. If so, the number of parameters allowed to vary was larger than the final model would suggest.

We therefore rely on fitting by eye to guide our choice of models. A visual comparison of data and models provides a powerful method for deciding how models must be altered to fit the data, easily allowing attention to be focused on regions of interest. One statistic we could examine, regardless of the number of degrees of freedom, is the rms of the residual cube, downweighting regions of bright emission. In fact, when we examine this statistic, using only emission above $3\sigma$, we indeed find a significant 7% reduction for models which include a flare (all models beginning with “F”) rather than a constant scale height (1C). However, among the flaring models, the numerical difference due to the addition of radial motions, a bar, or a lag is negligible. Nevertheless, improvement is clearly seen in Figures 3.3, 3.10, 3.13 respectively. In spite of such limitations, we address the need for such features here.

Firstly, the additional arc in the receding half (§ 3.5.1), which is included in all models presented in this paper, can be justified rather simply. There are clear indications that a feature of higher flux density exists in this region, but only in one quadrant of the disk (Figure 3.3, panel corresponding to 5’). The feature could be
reproduced with an overall change in position angle, allowing flux to be redistributed at high z, but as this feature is seen only in a select region of the disk, such a change would worsen the fit in other parts of the disk. Additionally, a change in position angle for only this region would be unphysical and was seen to be a less desirable match during the modeling process (not shown).

The addition of radial motions duplicates slants, slopes, and curves in the data (Figure 3.3) that are otherwise not reproducible. One could argue for changes in the position angle near the center to reproduce these slants, but through modeling, we see that such a change would not fit the data as well. Furthermore, warping near the center, as well as both the positive and negative changes in position angle required to reproduce the correct slanting would be uncharacteristic of warping typically seen in other galaxies (Briggs, 1990).

It is clear that a bar exists in NGC 4565, both from previous works at other wavelengths (Kormendy & Barentine 2010, Neininger et al. 1996), as well as our models. Substantial improvement can be seen in Figure 3.10, although due to projection effects, the uniqueness of this bar is difficult to constrain. Thus we provide generous uncertainties for the quantities involved (§ 3.5.1).

Finally, the lag is best constrained using faint emission, high above the plane of the disk. For this reason, improvements due to a lag do not exhibit substantial changes in the rms of the residuals. Nonetheless, subtle improvements are seen in Figure 3.6 and b, as well as Figure 3.12 and b. The characteristics of the lag may initially be interpreted as H I that appears (at least in projection) above the plane of the disk that is rotating more slowly than H I in the midplane. The issue of projection effects could hinder the uniqueness of our models if such effects are not considered carefully. However, signatures in both bv diagrams and channel maps described at the beginning of § 3.5.1 allow us to successfully rule out inclination effects in this case. From this we may conclude that the observed effects are extremely likely due
Chapter 3. Observations and Modeling of NGC 4565

to a lag. A range of possible values for this lag is given in Figure 3.14.

3.6 The Companion Galaxies

While NGC 4562 is not our primary target, some information may be extracted from a basic model. We assume a distance of 12.5 Mpc based on values obtained from the NASA/IPAC Extragalactic Database (NED). The total H\textsc{i} mass for this galaxy (including a factor of 1.36 to correct for He) is $3.5 \times 10^8 M_\odot$. Our models include flux extending out to a radius of 2.75' (10 kpc). This small angular size limits our modeling capabilities in this case. The scale height is found to be about 7” (400 pc). The galaxy is slightly inclined at 82°. There are no indications of a strong warp component along the line of sight, although there exists a slight warp component across it. The rotation curve is relatively flat, and peaks at 65 km s$^{-1}$.

No model is created for IC 3571. However, assuming approximately the same distance as NGC 4565, its H\textsc{i} mass is found to be $5.6 \times 10^7 M_\odot$ and the extent of its largest axis is approximately 1.8’ (5.8 kpc).

3.7 Discussion

3.7.1 The Warp in NGC 4565 and Interactions With Companions

The warp in NGC 4565 is highly asymmetric, not only extending further and reaching higher values in position angle on the receding half, but also flattening at large radii on that side as well (Figure 3.8). There was a hint of this flattening in a few channels as noted by Rupen (1991), most prominent in the channel corresponding to $v_{hel} =
1459 km s$^{-1}$. Here we see it from $v_{hel} = 1440$ to 1473 km s$^{-1}$. A similar flattening is also seen in NGC 5907 (Sancisi, 1983).

Additionally, there is a slight rise in inclination for radii larger than 8.75’ (27.5 kpc), causing the galaxy to become more edge-on. This is only seen in radii beyond the extent of the emission in the approaching half, thus it is only seen in the receding half.

It is difficult to determine the exact cause of the asymmetries in the warp, but it is possible that the companion galaxies play some role. NGC 4565 is clearly interacting with IC 3571, as can be seen in Figure 3.1 by the bridge of material between them. Additionally, material closer to the plane of the disk appears to be displaced above the plane, toward IC 3571 (Figure 3.1). Given the location of IC 3571, it may contribute to the asymmetry in the component of the warp across the line of sight. This was also noted by van der Hulst & Sancisi (2005).

Emission likely tied to IC 3571 as part of the bridge between the two galaxies could not be reproduced in models, which is unsurprising. The velocity range associated with this emission is reasonably close to that of the main disk of NGC 4565 (Figure 3.16), and is likely only a disturbance of gas within the disk as opposed to accretion from IC 3571.

### 3.7.2 The Flaring Gas Layer

The exponential scale height in NGC 4565 begins to increase in both halves from an initial 4” (200 pc) near a radius of 3 arcminutes (9.4 kpc), eventually reaching a value of 12” (600 pc) at a radius of 7 arcminutes (22.8 kpc). This is just within the optical radius (8.1’ or 25.5 kpc).

Flares are seen in other galaxies, including M 31 (Brinks & Burton, 1984) and
Chapter 3. Observations and Modeling of NGC 4565

Figure 3.16 Position-velocity diagrams along the minor axis showing the bridge between NGC 4565 and IC 3571 in the smoothed (44” × 34”) cube. Contours begin at 2σ (0.48 mJy bm⁻¹) and increase by factors of 2. A −2σ contour is shown as dotted lines. Major axis offsets are given at the top of each panel.

the Milky Way (Kalberla et al. 2007 and references therein). However, there exist galaxies for which extensive H I modeling has been done that do not show flaring gas layers, including NGC 5746 (Rand & Benjamin, 2008) and NGC 4559 (Barbieri et al., 2005), indicating that flares are common although not ubiquitous.

3.7.3 Halo Trends

Our models yield no evidence for a massive, extended H I halo in NGC 4565. This is shown by the vertical profile in Figure 3.5 where there are no indications of a second, extended component that exists globally throughout the data. Furthermore, a second component is not seen to improve position-velocity diagrams or channel maps (not shown).

We return to the issue discussed in § 3.2.1 of whether there is any connection between H I halos and disk star formation activity. It is difficult to extract any concrete trends regarding H I halos with such a small number of galaxies having been observed to this depth and subsequently modeled in detail. The situation is in
Chapter 3. Observations and Modeling of NGC 4565

Table 3.3. Extra-Planar Properties of Edge-on Galaxies (As of NGC 4565)

<table>
<thead>
<tr>
<th>Galaxy</th>
<th>H(<em>I) mass (10^9 M</em>\odot)</th>
<th>(L_{TIR}/D_{25}^2) (10^{10}) ergs(^{-1}) kpc(^2)</th>
<th>1C, H, a</th>
<th>Thickest Component</th>
<th>H(_I) Lag (km\ s^{-1}) kpc(^{-1})</th>
<th>Ref.*</th>
</tr>
</thead>
<tbody>
<tr>
<td>UGC 1281</td>
<td>2.75 b</td>
<td>n/a c</td>
<td>F</td>
<td>0.18  0.31</td>
<td>n/a</td>
<td>1, 2</td>
</tr>
<tr>
<td>UGC 7321</td>
<td>1.1</td>
<td>0.35 H, F</td>
<td>2.2 d</td>
<td>(\leq</td>
<td>\ -25</td>
<td>)</td>
</tr>
<tr>
<td>NGC 4244</td>
<td>2.5</td>
<td>0.53 1C</td>
<td>0.56</td>
<td>n/a</td>
<td>3, 5, 8, 9</td>
<td></td>
</tr>
<tr>
<td>NGC 5746</td>
<td>10</td>
<td>1.16 1C</td>
<td>0.4</td>
<td>n/a</td>
<td>3, 4, 10, 11</td>
<td></td>
</tr>
<tr>
<td>NGC 5775</td>
<td>9.9</td>
<td>1.45 F</td>
<td>0.2  0.6</td>
<td>n/a</td>
<td>3, 9, 11, 12</td>
<td></td>
</tr>
<tr>
<td>Milky Way</td>
<td>8</td>
<td>3.0 H, F</td>
<td>1.6</td>
<td>(-22,-15)</td>
<td>11, 13, 14</td>
<td></td>
</tr>
<tr>
<td>NGC 3044</td>
<td>3.0</td>
<td>6.62 H</td>
<td>0.42 d</td>
<td>n/a</td>
<td>3, 4, 14, 15</td>
<td></td>
</tr>
<tr>
<td>NGC 891</td>
<td>4.1</td>
<td>8.71 H, F</td>
<td>1.25  2.5</td>
<td>(-15)</td>
<td>3, 8, 12, 16</td>
<td></td>
</tr>
<tr>
<td>NGC 5775</td>
<td>9.1</td>
<td>25.6 1C + features</td>
<td>1</td>
<td>n/a</td>
<td>3, 4, 14, 17</td>
<td></td>
</tr>
</tbody>
</table>

*1-component (1C), halo (H), flare (F), or a combination of these.

b(Private communication) P. Kamphuis.

cAppropriate \(L_{TIR}\) is not available for this galaxy. However, based on H\(_\alpha\), its star formation rate is 0.0084 \(M_\odot\) yr\(^{-1}\) (van Zee, 2001), rendering it among the lowest of the galaxies presented here based on calculated rates for the rest.

dGaussian as opposed to exponential layer. In the case of NGC 891, see Oosterloo et al. 2007 for details on the distribution used to fit the halo component.


The process of being remedied via the HALOGAS survey and Expanded Very Large Array (EVLA) observations involving some HALOGAS team members. In Table 3.3 we compare properties including total H\(_I\) mass, total infrared luminosity per unit area, scale heights, and lags of NGC 4565 with those of previously modeled edge-on galaxies.

The total infrared luminosity per unit area for each galaxy is calculated in this work unless otherwise stated. These calculations are done based on equations found in Dale et al. (2009), and involve the optical area (de Vaucouleurs et al. 1991 in most
Chapter 3. Observations and Modeling of NGC 4565

cases; additional references are provided in the table). Spitzer MIPS data are used if available for a given galaxy, otherwise IRAS data are used.

Immediately apparent is the pattern of higher infrared luminosity per unit area (i.e. star formation rate per unit area) and the presence of extra-planar H\textsc{i} in the form of a halo. The obvious exception is UGC 7321. NGC 5775 could be considered an exception, since a global H\textsc{i} halo is absent. However, in that case, prominent extra-planar features including extensions and arcs are present.

Still, we must emphasize that this result is based on only a few galaxies and modeling methods differ amongst them. Further analysis of the HALOGAS sample, in which individual galaxies are modeled in a fashion consistent from galaxy to galaxy, will provide a stronger test of this trend.

3.7.4 The Lag in NGC 4565 and Other Galaxies

We do not detect substantial extra-planar H\textsc{i} in the form of a global halo, which indicates that there is no strong disk-halo cycling in NGC 4565. However, the H\textsc{i} has some vertical velocity dispersion and experiences a lag when it rises above the plane of the disk. The lag we detect is within the innermost 4.75’ (14.9 kpc) and 4.25’ (13.4 kpc) in the approaching and receding halves, respectively. As is the case for UGC 1281 (Kamphuis et al., 2011) and NGC 4244 (Zschaechner et al., 2011), this indicates that substantial extra-planar gas need not be present in order for a lag to be observed. (Although for UGC 1281, a larger line of sight warp component is favored over a lag, yet a lag cannot be ruled out.)

The H\textsc{i} lag detected in NGC 4565 is very steep. This would be consistent with the Heald et al. (2007) trend in which DIG lags are seen to steepen with decreasing SFR, provided that H\textsc{i} and DIG lags share a common origin. Although the DIG lag in NGC 4565 is unknown, modeling of the DIG within the HALOGAS project is
A radially varying lag is seen in NGC 4565, which we will now discuss. The onset of this shallowing is at 2.75’ (8.6 kpc) in the approaching half and 2.25’ (7 kpc) in the receding. Given the large uncertainty associated with the lag in general, it is difficult to constrain the manner in which it shallows, although outside of 4.75’ (14.9 kpc) in the approaching half, and 4.25’ (13.4 kpc) in the receding half, it appears to be zero.

An entirely geometric interpretation of the shallowing of a lag at large radii, without any consideration of effects such as extra-planar pressure gradients, drag, or magnetic fields, considers the relationship between the rotational velocity and the gravitational potential: gas rotating high above the plane of the disk is further from the gravitational center than the gas at the same radius in the midplane, resulting in a slower rotational velocity. This effect is more pronounced at smaller radii, where a certain height above the disk is comparable to the radial distance from the center, resulting in a larger relative change in the gravitational potential, and thus a steeper lag. This effect may be seen in Figure 3 of Collins et al. (2002) and may in part be why a lag is only seen in the inner third of the disk in NGC 4565. However, it should again be noted that such purely ballistic models have under-predicted observed lag magnitudes (Fraternali & Binney 2006, Heald et al. 2007), indicating that additional factors must be considered.

This radial variation could also be affected by an extra-planar pressure gradient if the cycling gas does not orbit purely ballistically and is subject to hydrodynamic influences. According to Benjamin (2002), a pressure gradient directed radially inward may cause a steeper global lag. An outward pressure gradient may result in a shallower global lag, or even an increase in rotation velocity. If such pressure gradients vary radially themselves, then a radial change in the lag may occur. Given how little is currently known of halo pressure gradients, as well as the potentially
substantial impacts even small pressure gradients may have, it is difficult to say to what degree these will alter the characteristics of any given lag.

In HI, radially shallowing lags are also seen in NGC 4244 (Zschaechner et al., 2011) and NGC 891 (Oosterloo et al., 2007), and the Milky Way Marasco & Fraternali (2011). In NGC 4244 the lag decreases from $-9 \text{ km s}^{-1} \text{kpc}^{-1}$ to $-5 \text{ km s}^{-1} \text{kpc}^{-1}$ and $-4 \text{ km s}^{-1} \text{kpc}^{-1}$ in the approaching and receding halves respectively. This would correspond to a shallowing of 2-2.5 km s$^{-1}$ kpc$^{-2}$ (although, as stated in that paper, and is the case for NGC 4565, the uncertainties in the radial variation are large). In NGC 891, the gradient in the inner regions is $-43 \text{ km s}^{-1} \text{kpc}^{-1}$ and decreases to $-14 \text{ km s}^{-1} \text{kpc}^{-1}$ in outer radii, corresponding to a shallowing of 2.5 km s$^{-1}$ kpc$^{-2}$. In the Milky way, the lag starts with a magnitude of approximately $-45 \text{ km s}^{-1} \text{kpc}^{-1}$ and reaches a value of $-15 \text{ km s}^{-1} \text{kpc}^{-1}$ near 4.5 kpc, resulting in a more rapid shallowing of 6.7 km s$^{-1}$ kpc$^{-2}$. The lag in NGC 4565 also decreases rapidly with radius. Considering the onset of the shallowing of the lag in each half and their respective lag magnitudes (Figure 3.14), this corresponds to a shallowing of 6.4 km s$^{-1}$ kpc$^{-2}$ and 4.8 km s$^{-1}$ kpc$^{-2}$ in each half for our optimal models. Judging by the minimum and maximum lag models, the shallowing could be between 6.4 and 38 km s$^{-1}$ kpc$^{-2}$ in the approaching half (although the latter value is very unlikely as it would imply that a very rapid drop of $-60 \text{ km s}^{-1} \text{kpc}^{-1}$ occurs in a very narrow annulus of 1.6 kpc, which does not seem physically realistic) and between 4 and 7.6 km s$^{-1}$ kpc$^{-2}$ in the receding. Thus, the lag in NGC 4565 appears to shallow more rapidly than in NGC 4244 and NGC 891, but at a similar rate to that of the Milky Way.

In NGC 4244, the onset of the shallowing of the lag is seen just within the optical radius, whereas the shallowing of the lag in NGC 891 is closer to its center. In the Milky Way, the lag begins to shallow immediately at the center, and reaches a constant value near 4.5 kpc. In NGC 4565, the shallowing of the lag begins at
approximately 2.5′ (7.9 kpc), which is less than half the optical radius of 8.1′ (25.5 kpc). The lag then reaches a constant value of zero near 5′ (15.7 kpc). Thus, there does not yet appear to be a characteristic radius at which the lags begin to shallow, or where the lags reach constant values.

In addition to these edge-on examples, NGC 4559, a moderately inclined galaxy also shows evidence for a radially decreasing lag (Barbieri et al., 2005). Although a true velocity gradient in height above the plane of the disk cannot be measured in this case, Barbieri et al. (2005) find a decrease in the rotational velocity of the thick halo component compared to the thin disk of roughly $-60$ km s$^{-1}$ near the center of the galaxy, and $-20$ km s$^{-1}$ at large radii. As long as the vertical extent of the lagging halo does not fall in a similar way, this drop would indicate a true radially decreasing lag. However, because of its inclination, NGC 4559 does not yield an unambiguous case of a radially varying lag.

This small sample shows evidence for discrepancies in the nature of the radial variations in lags in each galaxy, including differences in the radius of the onset of shallowing and the rate of shallowing. Although three edge-on external galaxies as well as the Milky Way clearly show a shallowing lag with increasing radius, a larger sample must be studied in order to extract reliable trends.

### 3.7.5 The Bar in NGC 4565

We find kinematic evidence for radial motions, which we associate with a bar. Given the inclination of NGC 4565, we only observe a rather limited 2-D projection; not nearly enough to determine its length and thickness using only spatial information, so we must rely on its kinematics. However, observations at other wavelengths are considered in order to help constrain morphological properties. In the optical, the bar is seen as a boxy bulge (Kormendy & Barentine, 2010). Additionally, a ring may
be seen in higher resolution 24μm MIPS (NASA/IPAC Infrared Science Archive) data (Figure 3.17), as well as CO and 1.2 mm continuum emission (Neininger et al. 1996, Yim et al. 2013 in prep). The radius of the ring (1’ to 1.7’ in the 24μ data, and peaking from 1’ to 1.5’ with an outer radius of 3’ in the CO data) is consistent with the ring of higher density seen in H I, and is thus consistent with the length of the bar we have modeled.

Parameters related to the bar are difficult to constrain, thus we will only state what may be reliably extracted from these data. We can say that the bar exists with a half length of approximately 1.25’ (4 kpc). According to Neininger et al. (1996) the bar’s orientation is between 0° and ±45° from end-on. Due to limited resolution and projection effects, we cannot improve upon this. In fact, by adjusting the rotation curve along the bar and radial motions within the disk, these data allow for an even
There appear to be radial motions up to $\pm 60$ km s$^{-1}$ within the bar. For these radial motions we cannot discern between inflow and outflow, largely because we cannot determine the sign of the orientation due to projection effects, although within the length of the bar, a net inflow is expected (e.g. Athanassoula 1992). Furthermore, even without changing the sign of the orientation, changing the direction of radial motions produces too little of an effect at most orientations to determine which is correct. This may be further complicated by radial motions that vary in magnitude along the bar, of which there is some indication in that further from the center there appears to be less need for such motions, but this is complicated by projection effects and is not enough to make meaningful constraints. These properties are extremely interconnected, and our spatial resolution limited, hence the large ranges presented here. Fortunately, as may be seen in Figure 3.10, the effects from radial motions outside the bar far outweigh any contributions from the bar itself. Thus, we must stress that the conclusions we draw from our final models that are not directly about the bar are unaffected by the bar itself.

### 3.7.6 Radial Motions in the Disk

Observations of purely axisymmetric inflows, not associated with motions along a bar or spiral structure, have been ambiguous (Wong et al. 2004 and references therein). Our work does not break this ambiguity, but rather provides additional constraints.

We see clear indications of a net inflow beginning around the ring of higher density (1.75’ or 5.5 kpc), and extending out to 2.75’ (8.6 kpc). The extreme value of this inflow is $-50\pm5$ km s$^{-1}$. Unlike the issues related to constraining the bar, the signatures for this inflow are clear and appear to be unique. There are additional regions in which the models are improved by inflow, but these are almost certainly
due to spiral arms. Since this inflow is associated with the ring, it could be associated with the bar potential. Finally, there exists evidence for a net outflow of 10 km s$^{-1}$ beginning near a radius of 6.75’ (21.2 kpc) and extending outward in both halves.

The observed effects of the outflow are primarily seen above the plane of the disk at a height of 40 to 80” (2-4 kpc). A range of inclinations corresponding to a warp component along the line of sight were tested, but none could replicate the asymmetric slant in the data. Furthermore, if the apparent offset from the plane of the disk were due to projection effects alone, then these would correspond to radii between 50 and 70 kpc, placing them well outside the disk. Therefore, these motions likely do exist above the plane of the disk, rather than being due to such effects. It is also possible that any outflow could be caused by material being pulled outward due to tidal interactions.

Both NGC 4559 (Barbieri et al., 2005) and NGC 2403 (Schaap et al. 2000, Fraternali et al. 2002) have shown similar indications of radial inflows, estimated between 10 and 20 km s$^{-1}$. In each case, the authors note that the inflow is high above the plane of the disk. As mentioned above, our data and models indicate that most of the outflow in NGC 4565 is in the thicker, flaring layer. The inflow however, is close to the plane of the disk and is significantly higher than these values.

### 3.8 Summary and Conclusions

Through our models we determine the following:

1. In NGC 4565 we see a flaring layer, but no massive, extended extra-planar H I layer throughout the galaxy. There are two companion galaxies, one of which is clearly interacting with NGC 4565 via a bridge of extra-planar material.

2. We detect a lag peaking in magnitude at $-40^{+5}_{-20}$ km s$^{-1}$ between 1.25 and...
Chapter 3. Observations and Modeling of NGC 4565

4.75’ (3.9 and 14.9 kpc) on the approaching half, and \(-30^{+5}_{-30}\) km s\(^{-1}\) between 1.25 and 4.25’ (3.9 and 13.4 kpc) on the receding half. Both lags quickly decrease with radius and are zero at radii larger than the upper end of the specified range.

3. A bar was previously known to exist within NGC 4565 for which we model a half-length of 1.25’ (4 kpc). Our models indicate radial motions along this bar of 20 to 45 km s\(^{-1}\). A ring of relatively high density is seen near the end of the bar.

4. Our models indicate a radial inflow beyond the bar that may be associated with the ring of higher density. This inflow starts at a radius of 1.75’ (5.5 kpc) with a value of \(-50^{\pm}5\) km s\(^{-1}\) and decreases with radius before becoming undetectable outside of 2.75’ (8.6 kpc). A net outflow of 10 km s\(^{-1}\) may be present at large radii, most prominently seen 2-3 kpc above the plane of the disk. The origin of this outflow is unclear.

At this time, we are still limited to a small number of galaxies for which deep observations exist and detailed models have been made. Even fewer of these, such as NGC 4565, are edge-on. However, in edge-ons, a trend is now seen suggesting some connection between the presence of substantial extra-planar H\(_I\) and star formation rate per unit area within a given galaxy. Additionally, we now see radially shallowing lags in three edge-on galaxies, and possibly one that is moderately inclined. Further work with the full HALOGAS sample will either dismiss or strengthen these early results.

3.9 Acknowledgments

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Chapter 4

Observations and Modeling of
NGC 3044

4.1 Chapter Overview

We present observations and kinematic models of the neutral hydrogen (H\textsubscript{i}) in NGC 3044, a nearby, edge-on spiral galaxy. We model the galaxy as a single, somewhat thickened disk with an inclination of 85°. We detect substantial amounts of extra-planar H\textsubscript{i}, which we do not model as it appears to be associated with distinct/localized filaments, shells, and possibly accreted material, rather than being of a global nature. The kinematics near the center of NGC 3044 are greatly disturbed, complicating the models at small radii. However, we clearly detect a lag of $-33^{+6}_{-11}$ km s\textsuperscript{-1} kpc\textsuperscript{-1} in the approaching half, and $-33\pm6$ km s\textsuperscript{-1} kpc\textsuperscript{-1} in the receding half starting at the midplane. The lag shallows radially, reaching a value of zero at approximately R\textsubscript{25}. The large-scale kinematic asymmetry of the approaching and receding halves suggests a recent disturbance to the disk.
Chapter 4. Observations and Modeling of NGC 3044

4.2 Introduction

NGC 3044 has a relatively high SFR, rendering it an essential addition to our sample. By examining Figure 4.1, note how the disk appears to be asymmetric and disturbed, possibly through a recent interaction or merger. However, NGC 3044 has no nearby companions, making its peculiar morphology somewhat of a mystery. We will consider this possibility further in § 4.6.3 while including our own work in this context. Basic observed parameters of NGC 3044 are given in Table 4.1.

DIG observations of NGC 3044 (among other galaxies) are presented by Collins et al. (2000). They note the asymmetric nature of the galaxy, as well as extra-planar DIG extending to roughly 1 kpc above the mid-plane.

Rand et al. (2011) used Spitzer observations to study extra-planar Polycyclic
Aromatic Hydrocarbons (PAHs, molecules up to 20 angstroms in diameter) and gas-phase line ratios in NGC 3044, but the results were ambiguous. Specifically, other galaxies in that paper (NGC 891 and NGC 5775) showed higher $[\text{Ne,III}]/[\text{Ne,II}]$ in extra-planar layers than in the main disk. No such trend could be determined for NGC 3044.

Tüllmann et al. (2006b) included NGC 3044 among their sample of nearby, edge-on galaxies when performing X-ray observations of gaseous halos with XMM-Newton. These observations yield a soft X-ray halo extending to approximately 3 kpc above the mid-plane on average. The authors conclude that this halo is spatially coincident with the extra-planar DIG. Thus, DIG and X-rays suggest disk-halo cycling at some level.

Lee & Irwin (1997) previously observed and modeled NGC 3044 using the VLA in C configuration, and we will compare our work to their findings in § 4.6. We also utilize the VLA to make deeper observations with higher resolution. We will discuss these observations in detail in the next section.

### 4.3 Observations & Data Reduction

Observations of NGC 3044 were obtained with the VLA in both the B and C configurations. The 8 kHz bandwidth was divided into 256 channels, yielding a velocity resolution of 31.25 kHz per channel (6.6 km s$^{-1}$ - increased to 6.7 km s$^{-1}$ during data reduction in order to properly combine all tracks).

Data reduction was performed in CASA using standard spectral line methods. Self-calibration was performed after combining all tracks, but before continuum subtraction. This yielded a substantial reduction in sidelobes, as well as improved detection of faint, extended emission. A variety of \textit{uv} weighting schemes were tried,
Chapter 4. Observations and Modeling of NGC 3044

Table 4.1. NGC 3044 Parameters

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\(^a\)Distance is the median value of distances found on the NED database, excluding those obtained using the Tully-Fisher relation in order to be consistent with HALO-GAS.

\(^b\)Adjusted from 0.71 to account for different distances used.

\(^c\)Includes neutral He via a multiplying factor of 1.36. Value obtained using single dish data would be 5.1\times10^9M\(_\odot\) (Springob et al., 2005).

in the end Briggs weighting with a robust parameter of 3 was used for our final, full resolution cube. The rms noise of our full resolution (12.27×11.4") cube used for most of the modeling is 0.28 mJy bm\(^{-1}\). A second cube was created using the same parameters, but with an outer \(uv\) taper of 7 k\(\lambda\), yielding a final resolution of 22.52×21.4". Primary beam correction was applied to all cubes using the CASA task IMMATH. In the case of moment maps, which are created using methods (see below) described in Serra et al. (2012), primary beam correction is done in the last step.

The zeroth-moment maps (Figure 4.2) are created using a Python script provided by Dr. Paolo Serra of the HALOGAS collaboration (Serra et al., 2012). This script sums over velocity in a mask created by including points with values higher than 4\(\sigma\) in either the original cube, or smoothed cubes (in both space and velocity) created using
Chapter 4. Observations and Modeling of NGC 3044

Table 4.2. NGC 3044 Observational and Instrumental Parameters

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<td>0.32 mJy bm$^{-1}$</td>
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a series of filters of differing resolutions that are specified by the user. Furthermore, the script also smooths in velocity as well as in spatial directions.

4.4 The Data

NGC 3044 was previously observed in H$_{\text{I}}$ by Lee & Irwin (1997) in C configuration only. Our data taken with the B configuration provide improved spatial resolution, while our C configuration data maintain the same level of sensitivity, but more sensitive for the same channel width. Additionally, the full-resolution cube presented in
Chapter 4. Observations and Modeling of NGC 3044

Figure 4.2 A zeroth-moment map of NGC 3044. The full resolution cube is represented in black, while an outline of the smoothed cube is in gray. Contour levels for the full resolution cube begin at $2.4 \times 10^{20} \text{ cm}^{-2}$ and increase by factors of $\sqrt{2}$. The gray contour is at $9.2 \times 10^{19} \text{ cm}^{-2}$. Black lines represent the slice locations of bv diagrams in Figure 4.7, and gray lines represent slice locations in Figure 4.8. The beams are shown in the lower left-hand corner (white is full resolution, black is the smoothed cube). Note the apparent thickness of the H I layer, including extra-planar features. Also note the asymmetry in H I about the dynamical center (the middle slice is taken at the kinematic center).

this work has a velocity resolution three times finer than does the cube presented in Lee & Irwin (1997). Most of the noteworthy features we see upon inspection are also identified in their paper - it is later in the modeling stages where our data provide additional constraints. Thus, we will only briefly mention the most prominent features, and refer the reader to Lee & Irwin (1997) for greater detail when appropriate, especially in the case of H I shells, since that was a prime focus of their work.

Immediately evident from the zeroth-moment map is the apparent thickness of the H I disk, as well as the substantial lop-sidedness. Prior to modeling, it is impossible to say whether this thickness is due to extra-planar gas, flaring or inclination effects. This lop-sidedness is also seen in the bv diagrams displayed in Figure 4.3, which
Figure 4.3 An $iv$ diagram along the major axis. Note the flatness of the terminal side of the receding half, and the slant on the approaching half that brings velocities at small to moderate radii closer to the systemic relative to the receding side at the same offsets. Also note the slight difference in spacing between the contours on the terminal sides of each half, indicating that the approaching half has a higher velocity dispersion. Contours begin at $2\sigma$ (0.56 mJy bm$^{-1}$, or $3.0 \times 10^{19}$ cm$^{-2}$) and increase by factors of two.

Also shows the differing kinematics of the two sides. Also noteworthy are several features also seen by Lee & Irwin (1997), the most striking being the extra-planar extension in the NW quadrant of the galaxy, which corresponds to “F10” in their work. There also exists a prominent gap in the highest contours in the midplane diagonally beneath this feature.

Upon initial inspection of Figure 4.2, it can be seen that the kinematic and large scale morphological centers differ by approximately 0.4’ (2.2 kpc) (the central slice is taken at the kinematic center we determine later). There are indications in the outer parts of the disk that there may be a warp component across the line of sight, although modeling is required to say for sure. The overall clumpiness of the data indicate probable contributions from spiral structure. These properties may also be seen in the channel maps of Figure 4.4.

The mass we determine from our observations is close to that using single-dish observations (Springob et al., 2005), thus we recover most flux (see Table 4.1).
Figure 4.4 Channel maps of NGC 3044 in a rotated frame with the origin at the kinematic center show the substantial asymmetries within the galaxy. Note the extra-planar emission at positive $z$ in panels corresponding to 1106-1205 km s$^{-1}$. Velocities are given for each panel. Central channels are shown in Figure 4.6. Contours are presented as in Figure 4.3.
Chapter 4. Observations and Modeling of NGC 3044

We will now consider a more in-depth analysis of the data through tilted-ring modeling. Most modeling was performed using the full-resolution cube, but models were compared with the smoothed cube for consistency.

4.5 The Models

The position angle of the main disk of NGC 3044 was determined by eye to be 113° (Figure 4.2), and the initial inclination was assumed to be 90° (refined to a final value of $85^{\pm 0.5}_{\pm 1}$. Initial estimates for the rotation curve were based on work presented in Lee & Irwin (1997). These quantities were later adjusted by eye starting with examination of lv-diagrams, followed by channel maps. The surface brightness distribution was originally obtained using the GIPSY task RADIAL. The H I scale height was determined by examining the vertical profile and zeroth-moment maps (Figures 4.5 and 4.2). The initial velocity dispersion is 20 km s$^{-1}$ throughout the disk of the approaching half, and 20 km s$^{-1}$ at the center of the receding half, but decreasing to 10 km s$^{-1}$ by a radius of 1.3’. The higher velocity dispersion in the approaching half is related to the somewhat large spread of velocities most readily seen in lv diagrams (Figure 4.3). Finer adjustments to these parameters were made iteratively throughout the modeling process.

Due to asymmetries throughout the galaxy, we model the two halves separately. The systemic velocity was somewhat difficult to determine, in part because the kinematic and morphological centers are in different locations, which Lee & Irwin (1997) also noted. However, with TiRiFiC, we now have considerably more flexibility to model complicated kinematics and morphology. In our first approach, we set the systemic velocity to 1280 km s$^{-1}$, a value for which the rotation curves in each half are within reasonable agreement (within 5-10 km s$^{-1}$ scatter of each other). Our
reasoning for this is that, for an undisturbed galaxy, it is more physically plausible that the two rotation curves are comparable to each other. However, this approach fails to fit central channels (Figure 4.6), and would require additional components (such as arcs or a bar, which were also attempted with varying degrees of success, a bar being the worst fit) to match the kinematics near the center. Thus, to fit central channels, the systemic velocity is decreased to 1260 km s\(^{-1}\) (Figure 4.6; even this choice still leads to some mismatches with the data, but was found to be the best value), which in turn causes a large discrepancy in the rotation curves of the two halves. A different systemic velocity could be used for outer rings, which would bring the rotation curves into better agreement, but for simplicity, we choose to allow only a single systemic velocity for all radii in our models. Thus, this appears to be a true
Chapter 4. Observations and Modeling of NGC 3044

Figure 4.6 Central channel maps showing the data, the final model in the center (VSYS = 1260 km s\(^{-1}\)), and a model with a systemic velocity of 1280 km s\(^{-1}\). The major axis offset is with respect to the kinematic center chosen for our models. Neither model is a perfect fit as the central regions of NGC 3044 are abnormally complicated. However, the 1260 km s\(^{-1}\) is a better fit, although the differences are subtle. Note how the shape of all data channels at velocities of 1269 km s\(^{-1}\) and higher appear as though they should be a part of the receding half, indicating that the systemic velocity must be lower than 1282 km s\(^{-1}\). This velocity range was chosen as it provides the clearest examples showing that a systemic velocity of 1280 km s\(^{-1}\) (or higher) would indeed be a poor fit to the data. Regions with noticeably poor fits in the 1280 km s\(^{-1}\) model are marked with boxes.

difference in the kinematics. Fortunately, a shift in the systemic velocity (provided the rotation curves are properly adjusted as well) primarily affects the central regions, so this has a minimal effect on final models. More importantly, in large part because we do not rely on central regions for measuring lags, a shift in systemic velocity has no impact on lag values acquired through modeling.
4.5.1 Individual Models

We now address individual models created in our analysis and their defining characteristics.

The best fit achieved with a one-component model uses an exponential scale height of 7" (635 pc). As can be readily seen in Figure 4.5, there is extra-planar emission that such a model fails to fit. Because of this emission, a two-component model with the thin disk having a scale height of 4" (360 pc), and the thick disk having a scale height of 8" (730 pc) is tested and found to be a comparable fit to the data, but does not fit the extra-planar emission either. Other combinations of scale heights were also investigated, but none of these could improve upon the fit. Also in the bv diagrams of Figure 4.7, there is little improvement through the addition of a second component. Thus, there is no compelling reason for a second component, especially given the increase in the number of free parameters, so it is omitted from further analysis.

We make several more attempts to model the off-set emission on the positive side of the vertical profile, which can also be seen toward the positive side in bv-diagrams between 1100 and 1250 km s\(^{-1}\). This emission is not only off-set in height above the mid-plane, but also shows somewhat peculiar kinematics (Figure 4.7, panels -1.6’ through 0.9’). We attempt to model this asymmetry by adding a warp, variations in velocity dispersion, radial motions, as well as a vertically off-set component, but are unsuccessful in characterizing the emission in its entirety. The off-set component improves models to some degree, but we choose to omit it here because the emission in question appears to be comprised of multiple distinct features (e.g. shells), none of which is suitable for tilted-ring modeling. Furthermore, by omitting this component, the distinction between these extra-planar features and the main galaxy is clearer in later discussions. Furthermore, this component did not affect the lag values.
Figure 4.7  BV diagrams showing the data, 1C, 2C, 1C + constant lag, 1C + optimal lag, and final models. There is little improvement between the 1C and 2C models. Note in the fourth column the improved fit of the curvature on the terminal sides through addition of a lag, but that a constant lag is too steep at large radii on both halves. The curvature is matched by allowing the lag to shallow radially (column 5). Finally, the addition of radial motions fit the slants on the systemic sides (column 6). Contours are presented as in Figure 4.3.
Figure 4.8  $Bv$ diagrams of the approaching (A) and receding half (B). Note the improvement of the fit due to the radial shallowing of the lag. Adding arcs to the model allows for an improved fit to the higher contours, but has no noticeable effect on the lag (column 4). Finally, as may be seen in the final column, the slants on the systemic sides are brought into closer agreement with the data through the addition of radial motions. Contours are presented as in Figure 4.3.
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Minor Axis Offset (arcsec)
Chapter 4. Observations and Modeling of NGC 3044

Figure 4.9 Representative channel maps of the approaching (A) and receding (B) halves. The models presented here are the 1C, 1C with an optimal lag, and then our final 1C optimal lag model with arcs and radial motions. Note the narrowing of the channel maps toward the center due to the lag. The addition of radial motions replicates some of the slant seen in the data. Also note the previously mentioned extra-planar emission at 1376 km s$^{-1}$ and 1416 km s$^{-1}$, which we do not model. Contours are presented as in Figure 4.3.
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Figure 4.10 The parameters used in the models of NGC 3044 including rotational velocities, column densities, scale height, inclination and position angle. Note the discrepancies in the rotation curves of the two halves. The bold line in the bottom-right panel represents the inclination in both halves.

For the sake of completeness, we remark on the possibility of a warp component along the line of sight (or a decrease in overall inclination), which could also increase the apparent width of the disk, and even mimic a lag. Fortunately, line of sight warp components show signature midplane indentations on the systemic sides of bv-diagrams, as well as in the outer regions of channel maps, that are not seen in the data. This effect can already be seen to some degree in the one and two component models in panels corresponding to 0.9' in Figure 4.7, and decreasing the inclination worsens it.

Adding a Lag to the Models

Of the galaxies presented in this thesis, NGC 3044 shows the clearest and most immediate signs of a lag. By examining the final three columns of Figure 4.7, especially
Figure 4.11 The optimal lag distributions along with the range of uncertainties for lag values. The uncertainties are quite high near the center, where projection effects, as well as the complicated nature of the central regions of NGC 3044 render precise modeling difficult. The lag distributions in each half are quite similar, and go to zero near $R_{25}$ (2.5' or 13.6 kpc). Note how the minimum and optimal lags are the same for certain radii on the approaching half.

at $\pm 0.9'$ and $\pm 1.6'$, one can see that the once rectangular (as in the distribution of flux is concentrated near the terminal and systemic sides even at large minor axis offsets) model bv-diagrams are now more of a smooth “V”-shape, in significantly better agreement with the data.

First we consider an overall, global lag optimally found to be $-33^{+6}_{-11}$ km s$^{-1}$ kpc$^{-1}$ in the approaching half, and $-33 \pm 6$ km s$^{-1}$ kpc$^{-1}$ in the receding. While this global lag does improve the fit to the data, it is clear from Figure 4.7 that the lag is too steep at large radii. By allowing the lag to shallow with radius, we see an improvement to the fit in the outer regions of the galaxy (column 5 of Figure 4.7, column 3 of Figure 4.8). As may be seen by examining the more rounded curvature on the terminal side of the bv diagrams at large radii, the model with a radially varying lag is a reasonable representation of the data. We show the radial variations of the lag and its uncertainties (those quoted above are only near the center, with the uncertainties decreasing with radius) in Figure 4.11 and rotation curves in the disk and at $z=20''$ in Figure 4.12.
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Figure 4.12 The rotation curves at the midplane, as well as at \( z=20'' \) (1.8 kpc).

Modeling Radial Motions and Distinct Features

In our final models, we add radial motions, as well as three distinct arcs to improve the fit. We find that these features do not noticeably affect the lag values.

We see slants along the systemic side in the bv-diagrams (primarily those within 1.8’) akin to those seen in NGC 4565. These are modeled with radial motions of 15 km s\(^{-1}\) for the entire approaching half, and \(-15\) km s\(^{-1}\) within 100” (9.1 kpc) on the receding half. Also on the receding half, the sign of the radial motions change and decrease in magnitude to 10 km s\(^{-1}\) at a radius of 2’ (11.6 kpc). These variations are seen in Figure 4.13. The signature in the data of such a sign change is a change in the slants of the bv diagrams between 0’ and 0.9’, primarily on the systemic sides. It should be made clear that due to projection effects, the true sign of these motions cannot be determined (i.e. inflow vs. outflow) in absolute certainty. However, the dusty extension below the plane of the disk on the approaching half in Figure 4.1 indicates that the SW side (positive in bv diagrams) is the near side, and we quote
the radial motions under this assumption. The opposing signs of the radial motions near the center on each half is mildly intriguing as they suggest a systematic shift in velocities with respect to the center as opposed to global radial inflow or outflow.

The clumpiness of the data along the mid-plane indicates that, as to be expected, spiral structure is likely present. Furthermore, during the modeling process, it became clear that some of these features cannot be modeled by entire rings, and instead require the addition of arcs extending over only parts of the disk to properly fit the data. We add such arcs sparingly to avoid unnecessarily increasing the complexity of the models. Thus, not every clump is modeled, but can still be reasonably assumed to be due to spiral structure, or possibly merger activity. Note that, due to projection effects, we do not claim these are unique representations of these features, but rather approximations that allow us to more closely match the data, and to show that they have little effect on our derived lag values. We briefly describe the arcs included in our models below.
In Figure 4.8, one may note that there is more flux present near the systemic side in the central panels (0.9'-1.8') in the data compared to the models, especially at positive minor axis off-sets. This property cannot be replicated by increasing the surface brightness of entire rings, as doing so would oversaturate the systemic sides at large radii (not shown). Thus, one arc, centered at an azimuth in the disk of 120° (the approaching half is centered at 0° for reference), having an initial azimuthal width of 40° while decreasing radially to 20°, is added between 2.6' and 3.4' (14.5 and 18.1 kpc) radius. The rotational velocity of this arc begins at 200 km s$^{-1}$ for smaller radii, and increases radially to 245 km s$^{-1}$. The inclination and position angles of this arc are 85° and 118°, respectively. The surface brightness distribution assigned to this arc approximately doubles the total surface brightness in this region. The scale height of this feature, as well as the two arcs described below, is 7" (630 pc). A face-on view of the final model including the features described here may be seen in Figure 4.14.

By examining Figure 4.8, it can be seen that in the data, there is more emission in the higher contours of panels corresponding to 1.6' and 1.8'. To improve the fit (however slightly), a second arc extends from 1.6'-1.8' (8.8-10.2 kpc) radius, and is centered at an azimuth of 30° with an azimuthal width of 90°. Radial motions of 15 km s$^{-1}$ are added, as well as a lag of −22 km s$^{-1}$ kpc$^{-1}$. Again, this feature approximately doubles the surface brightness of this region. The rotational velocity begins at 115 km s$^{-1}$ for smaller radii and increases radially to 125 km s$^{-1}$. The inclination and position angles of this arc are 85° and 113°.

Finally, in panels from 0.9'-2.1' of Figure 4.8, there is an excess of emission on the systemic side in the upper, left-hand corner of the data. To duplicate this emission in the models, a final arc centered at an azimuth of 30°, with a width of 180° is also included. The radial extent is from 2.4’ to 3.4’ (12.9-18.1 kpc). The rotational velocity of this arc is 165 km s$^{-1}$, while the inclination and position angles...
Figure 4.14 A face-on view of the final model for NGC 3044 including all distinct features. The black dot is the orientation of the observer. “F1” denotes the first arc described in this section, while “F2” denotes the second. Note that the third feature is too faint to be seen in this map.

of this arc are 85° and 113°. This arc is fainter than the previous two, only adding approximately 20% more flux to the total for this region.

The Final Models and Their Uncertainties

The final models include a single component with a scale height of $7 \pm 0.5"$ (635 ± 45 pc), a systemic velocity of $1260 \pm 5$ km s$^{-1}$, a radially shallowing lag with a maximum value of $-33 \pm 6$ km s$^{-1}$ kpc$^{-1}$ in the approaching half, and $-33 \pm 11$ km s$^{-1}$ kpc$^{-1}$ in the receding, three additional arcs, and radial motions described in the previous section. The uncertainties in the rotation curves are approximately 5 km s$^{-1}$ for individual rings. While we have attempted to quantify as many uncertainties as possible, the somewhat subjective nature of tilted-ring modeling makes absolute error estimates impossible. However, we examine the residuals and the sums of their squares of the 1C, 1CL, 1CLV, and our final model, and find a substantial decrease
between early and final models. The percent decrease in the sum of the square of
the residuals is 6.4% between the 1C and 1CL models, 15.2% between the 1C and
1CLV models, and 37.7% between the 1C and final models. This steady decrease
demonstrates improvement between each successive model. The residuals for selected
models are shown in Figure 4.15.
Figure 4.15 Residuals of the models shown in Figure 4.7. White represents an excess of emission in the models, and black represents a paucity. Contours are presented as in Figure 4.3, but also with equivalent negative contours.
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Figure 4.16 Major axis position-velocity (lv) diagrams showing the data, one component (1C), and optimal models. Although radial motions and additional features are included in the final model, almost all of the improvements seen here are due to the addition of a radially varying lag. Contours are presented as in Figure 4.3.
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4.6 Discussion

4.6.1 The Lag in NGC 3044

The lag in NGC 3044 is relatively steep compared to other galaxies such as NGC 4244 and NGC 891. The lag starts close to the midplane and shallows radially. In the approaching half, the shallowing begins near a radius of 1' (5.4 kpc), while shallowing begins near 1.4' (7.6 kpc) in the receding. Both of these are well within $R_{25}$ (2.5' or 13.6 kpc). However, the lag appears to drop to zero near 2.4' (13.1 kpc) and 2.6' (14.1 kpc) in the approaching and receding halves, respectively. Both of these values are close to $R_{25}$, so there may indeed be some connection, the possibility of which we will explore in greater depth in Chapter 6.

4.6.2 A Comparison to Previous Work

As mentioned previously, Lee & Irwin (1997) observed and modeled the H I in NGC 3044. A primary focus of their paper was localized and distinct extra-planar features, which we consider only briefly. Additionally, they do not consider vertical gradients in rotation speed, which is the core of our work. As for the models themselves, the inclinations found by both groups agree (85°). Adjusting for the difference in distances used, the exponential scale height they determine (490 pc) is somewhat narrower than ours (635 pc). After converting the Lee & Irwin (1997) kinematic center to J2000.0 coordinates, we find a difference in right ascension of 0.6s, and a difference in declination of 8.6", or approximately 12" (1.1 kpc) total between our models. Perhaps the greatest difference in the models is the systemic velocity. They find a systemic velocity of 1287 km s$^{-1}$, while we find 1260 km s$^{-1}$. Furthermore, the rotation curve modeled by Lee & Irwin (1997) is approximately symmetric, while ours differs by approximately 30 km s$^{-1}$ between the two halves. However, if we
change the systemic velocity to 1280 km s\(^{-1}\) in our models, the rotation curves become symmetric. We choose our final systemic velocity by matching the central channels (Figure 4.6), and then changing the rotation curve to accommodate. Also useful when constraining the systemic velocity is the asymmetry in the two halves seen via visual inspection of lv diagrams (Figure 4.16), which clearly indicates that the rotation curves and/or the surface brightness distributions in the two halves must differ greatly. Fortunately, although we are confident in the value determined using our models, the absolute value of the systemic velocity has no impact on lag values.

4.6.3 The Possibility of a Minor Merger

The complicated kinematic and morphological nature of NGC 3044 suggests that it may have undergone a minor merger. Merger activity could also account for the relatively high star formation rate in NGC 3044. However, it is also possible that internal processes, such as those in connection with the massive shells found within NGC 3044, could cause some large-scale irregularities. Lee & Irwin (1997) also make note of the possibility of a merger, but state that the most recently a merger could have taken place would have been 10\(^8\) years ago.

As previously stated, the central regions of NGC 3044 are quite disturbed and asymmetric. We find that the kinematics cannot be modeled by the introduction of a bar (as can only be approximated using TiRiFiC, See Chapter 1), radial motions, or an increase in velocity dispersion. There are hints of anomalous gas near the center and in extra-planar regions.
4.6.4 Summary & Conclusions

NGC 3044 is a somewhat lop-sided galaxy with indications of having undergone a minor merger at some point. Aside from this possibility, NGC 3044 is a relatively isolated galaxy. There are several distinct features within NGC 3044, some of which are extra-planar.

Through modeling, NGC 3044 is found to be comprised of a single, thick disk with a scale height of $7''$ (635 pc). This disk has an inclination of $85^\circ$, and is somewhat warped across the line of sight. The rotation curves on the two halves of the galaxy are either asymmetric by roughly $20$ km s$^{-1}$, or else the inner and outer regions of the galaxy have differing systemic velocities. We detect a relatively steep lag of $-33^{\pm6}_{-11}$ km s$^{-1}$ kpc$^{-1}$ on the approaching side and $-33\pm6$ km s$^{-1}$ kpc$^{-1}$ on the receding side that shallows with radius, vanishing near $R_{25}$. Our models include radial motions that may indicate a systematic shift in velocities near the center, possibly related to the asymmetries in the rotation curves or varying systemic velocities described above.

For the moment we will refrain from discussing overall trends until Chapter 6 when our entire sample, as well as galaxies already considered in the literature, may be included.
Chapter 5

Observations and Modeling of NGC 4013

5.1 Chapter Summary

NGC 4013 is a distinctly warped galaxy with a high SFR. Through deep H\textsc{i} observations and modeling we determine that the H\textsc{i} disk is very thin (central scale height of 3" or 210 pc), but flaring. We detect a lag of −28±7 km s\textsuperscript{−1} kpc\textsuperscript{−1} starting at a radius of 1.9' (8.0 kpc) and 1.4' (5.8 kpc) in the approaching and receding halves, respectively. The lack of extra-planar H\textsc{i} is somewhat intriguing given the high SFR, as well as other extra-planar components that are detected in this galaxy.

5.2 Introduction

NGC 4013 is nearby, edge-on spiral galaxy with a relatively high SFR. It is a member of the NGC 4151 group containing 16 galaxies, but is itself rather isolated (Giuricin
et al., 2000). Arguably, its most noteworthy feature is its substantial warp originally seen in HI by Bottema et al. (1987). Here we present detailed HI observations and tilted-ring models of this galaxy. A brief summary of NGC 4013’s observational properties is provided in Table 5.1. Before presenting our work, we will review some of the key findings throughout the literature concerning NGC 4013.

Rand (1996) presents an analysis of the DIG in nine nearby, edge-on spiral galaxies, including NGC 4013. In that work, four extra-planar filaments are found to extend 2.5 kpc from the disk. These filaments could be related to outflows fueled by SN activity near the center. The extra-planar DIG is not nearly as prominent as in NGC 891 or NGC 5775, which have higher SFRs. The DIG is observed again, along with extra-planar dust through extinction, by Rueff et al. (2013), whose findings for the DIG are consistent with those presented in Rand (1996). They also find extra-planar dust up to approximately 2 kpc above the disk. The dust is highly structured and filamentary - far more so than the DIG. They conclude that direct evidence for a connection between the extra-planar DIG and extra-planar dust is lacking, suggesting the gas associated with the dust is either atomic or molecular.

Verstappen et al. (2013) observe the dust in seven nearby, edge-on spiral galaxies using Herschel. According to their analysis, NGC 4013 is the only galaxy within their sample to display substantial extra-planar dust.

All of these results suggest disk-halo cycling at a level above those of galaxies such as NGC 4244 and NGC 4565, but lower than that of NGC 891.

García-Burillo et al. (1999) present CO observations of NGC 4013, emphasizing its box-shaped bulge that is likely due to a bar. They note extra-planar extensions showing some connection to the extra-planar DIG described by Rand (1996). Additionally, they find a 130 km s$^{-1}$ spread in velocities near the center, which they note has no corresponding HI feature.
Chapter 5. Observations and Modeling of NGC 4013

Table 5.1. NGC 4013 Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Reference</th>
</tr>
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<tbody>
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<td>Distance (Mpc)</td>
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<td>Nasa Extragalactic Database</td>
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<td>Systemic velocity (km s(^{-1}))</td>
<td>835</td>
<td>This work</td>
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<tr>
<td>Inclination</td>
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<td>SFR (M(_{\odot}) yr(^{-1}))</td>
<td>1.28(^b)</td>
<td>Rueff et al. (2013)</td>
</tr>
<tr>
<td>Morphological Type</td>
<td>SBc</td>
<td>Tully et al. (1988)</td>
</tr>
<tr>
<td>Kinematic Center (\alpha) (J2000.0)</td>
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<td>This work</td>
</tr>
<tr>
<td>Kinematic Center (\delta) (J2000.0)</td>
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<td>This work</td>
</tr>
<tr>
<td>(D_{25}) (kpc)</td>
<td>22.3</td>
<td>de Vaucouleurs et al. (1991)</td>
</tr>
<tr>
<td>Total Atomic Gas Mass (10(^9)M(_{\odot}))</td>
<td>2.1(^c)</td>
<td>This work</td>
</tr>
</tbody>
</table>

\(^a\)Distance is the median value of distances found on the NED database, excluding those obtained using the Tully-Fisher relation to be consistent with HALOGAS.

\(^b\)Adjusted for differing assumed distances. Based on IRAS L\(_{FIR}\).

\(^c\)Includes neutral He via a multiplying factor of 1.36. Value obtained using single dish data is 2.4\times10\(^9\)M\(_{\odot}\) (Springob et al., 2005).

Martínez-Delgado et al. (2009) discovered a tidal stellar stream extending 3 kpc above the plane of the disk in NGC 4013, possibly indicating a minor merger has taken place approximately 3 Gyr ago. Such a scenario was previously unexpected, as NGC 4013 appears to be relatively isolated and undisturbed.

Perhaps most relevant to the work presented here, H\(_I\) observations and modeling were presented in Bottema (1995). Those observations were done using the WSRT, achieving a spatial resolution of 19" \times 13", velocity resolution of 33.3 km s\(^{-1}\), and a single channel rms noise of 0.3 mJy bm\(^{-1}\). As will be shown in the next section, our data improve upon these numbers. We will also make a comparison between our models and those presented in Bottema (1995) in § 5.8.
5.3 Observations & Data Reduction

Observations of NGC 4013 were completed with the VLA in B and C configurations. Data reduction was performed in AIPS using standard spectral line methods. Self-calibration (four iterations) was performed after combining all tracks, but before continuum subtraction, and led to substantial improvement. Although the velocity resolution of these data is 6.7 km s\(^{-1}\), due to incomplete (not all of the awarded time was observed) observations, we average three channels to obtain our desired rms noise level for the full resolution cube. A variety of weighting schemes were used to make cubes, with the final, full resolution cube using Briggs weighting and a robust parameter of 2. The low resolution cube uses a robust parameter of 2 with an outer uv taper of 7 kilo-lambda. Observation dates and cube parameters are given in Table 5.2. The primary beam correction was performed in AIPS.

5.4 The Data

Immediately clear from the zeroth-moment map (Figure 5.1) is the prominent, nearly symmetric warp in NGC 4013. Hints of a line of sight warp component, flare, or possibly a thickened H\(\text{I}\) layer may also be seen. One may also note the thin disk as well. The zeroth-moment maps were created using methods described in Chapter 3.

Channel maps centered around the systemic velocity (Figure 5.2) again show the prominent warp in NGC 4013. Evidence for a line of sight warp component may be seen by the splitting in channels corresponding to 736 km s\(^{-1}\) and 756 km s\(^{-1}\). It is clear that the disk is very thin near the center.

The total mass we derive from our observations is close to that derived from single-dish data (Springob et al., 2005), which implies that there is no substantial
Chapter 5. Observations and Modeling of NGC 4013

Figure 5.1 A zeroth-moment map of NGC 4013. The full resolution cube is represented in black, while an outline of the smoothed cube is in gray. Contour levels for the full resolution cube begin at $2.6 \times 10^{20}$ cm$^{-2}$ and increase by factors of two. The gray contour is at $9.5 \times 10^{19}$ cm$^{-2}$. Black lines represent the slice locations of bv diagrams in Figure 5.5, and white lines represent slice locations in Figure 5.6. The beams are shown in the lower left-hand corner (white is full resolution, black is the smoothed cube). Note the prominent warp. Also note the apparent thickness of the warped regions, possibly due to a flare, thick disk, or a warp component along the line of sight.

flux missing.

We now consider tilted-ring models created from these data.
## Chapter 5. Observations and Modeling of NGC 4013

### Table 5.2. NGC 4013 Observational and Instrumental Parameters

<table>
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<tr>
<th>Parameter</th>
<th>Value</th>
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</thead>
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<tr>
<td>Observation Dates – C Configuration</td>
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<tr>
<td></td>
<td>2010 Nov 20</td>
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<tr>
<td></td>
<td>2010 Nov 28</td>
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<tr>
<td>B Configuration</td>
<td>2011 Mar 21-23</td>
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<tr>
<td></td>
<td>2011 Apr 02</td>
</tr>
<tr>
<td></td>
<td>2011 Apr 22</td>
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<td>2011 May 02</td>
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<td></td>
<td>2011 May 04</td>
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<tr>
<td></td>
<td>2011 May 09</td>
</tr>
<tr>
<td>Total Time in C Configuration (hours)</td>
<td>9(^a)</td>
</tr>
<tr>
<td>Total Time in B Configuration (hours)</td>
<td>9.5(^b)</td>
</tr>
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<td>Pointing Center</td>
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</tr>
<tr>
<td></td>
<td>43d 56m 48.00s</td>
</tr>
<tr>
<td>Number of channels</td>
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</tr>
<tr>
<td>Velocity Resolution</td>
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</tr>
<tr>
<td>Primary Cube Beam Size</td>
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</tr>
<tr>
<td></td>
<td>900(\times)700 pc</td>
</tr>
<tr>
<td>Primary Cube PA</td>
<td>4.92(^d)</td>
</tr>
<tr>
<td>Secondary Cube Beam Size</td>
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<td></td>
<td>1700(\times)1400 pc</td>
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<td>Secondary Cube PA</td>
<td>84.37(^e)</td>
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<td>RMS Noise – 1 20.1 km s(^{-1}) Channel (12.27(\times)11.14(^\prime))</td>
<td>0.18 mJy bm(^{-1})</td>
</tr>
<tr>
<td>RMS Noise – 1 20.1 km s(^{-1}) Channel (23.4(\times)19.7(^\prime))</td>
<td>0.23 mJy bm(^{-1})</td>
</tr>
</tbody>
</table>

\(^a\)Although nine total hours were observed, approximately three of these hours had substantial RFI and were flagged heavily.

\(^b\)Approximately two hours of these data were omitted due to poor quality, resulting in 7.5 hours used in the final cubes.

\(^c\)Averaged to 20.1 km s\(^{-1}\) for modeling in order to improve SNR.
Figure 5.2. Channel maps of NGC 4013 show the substantial warp. Velocities are given for each panel. Contours begin at $2\sigma$ (0.36 mJy km$^{-1}$, or $6.4 \times 10^{19}$ cm$^{-2}$) and increase by factors of two.
Chapter 5. Observations and Modeling of NGC 4013

5.5 The Models

As is generally the case, due to asymmetries, we have modeled the approaching and receding halves of NGC 4013 separately. Initial estimates for the inclination and position angle were made by eye. The initial rotation curve was estimated based on the terminal side of the lv diagrams. The initial surface brightness distribution was set by examining the flux distribution along the midplane. All models presented here share the same surface brightness distribution, velocity dispersion (15 km s$^{-1}$), systemic velocity (835 km s$^{-1}$), central position (11h 58m 31.6s, 43° 56' 52.2''), central inclination (90°), position angle distribution, and rotation curve. The parameters not given here are shown in Figure 5.3.
Chapter 5. Observations and Modeling of NGC 4013

Figure 5.4 Vertical profiles of the data, one-component (1C), line of sight warp (W), warp with a flare (WF), and warp, flare with radial motions (WFR) summed over a range of ±60" (4.3 kpc) from the center in order to avoid as much of the warped regions as possible. Additionally, we present the WF/WFR model with a central scale height of 4" as opposed to 3" in order to illustrate the subtle difference between the two since such differences are pushing the limits of the resolution of the data.

5.5.1 Individual Models

We now address individual models and their defining characteristics, starting with a simple one-component model with a warp component across the line of sight (1C in figures).

As stated previously, it is clear that there exists a warp component in NGC 4013 that lies across the line of sight. Thus, we model it with a single disk having an exponential scale height optimally found to be 7" (500 pc). To this model we add a PA warp for which parameters are given in Figure 5.3. This model fails to match the vertical profile [summed over ±60" (4.3 kpc) from the center in order to avoid the warped outer regions as much as possible (Figure 5.4)], overestimating its width, yet cannot reproduce the spread near the systemic side of bv diagrams (Figures 5.5, and 5.6) or the thickness of channel maps at large radii in the warped regions of the galaxy (Figure 5.7). The splitting of most of the bv diagrams near the systemic side is indicative of a warp component along the line of sight, which we now address.
Figure 5.5 Bv diagrams showing all of the models presented in this paper. Note the clearly poor fit of the 1C model, especially on the systemic side of each panel and near the center. The W model is an improvement, but still lacks the proper distribution near the systemic sides that is achieved through the addition of a flare. The differences between the WF and WFR models are subtle, but can be seen by the curvature at high z in the central panel, as well as the slants on the systemic sides of the others. Contours are as in Figure 5.2.
Figure 5.6 The same as Figure 5.5, but with the approaching (A), and receding (B) shown separately, and in greater detail. We also include the final WFRL model here. Note the improved match in the curvature on the terminal sides of panels corresponding to $\pm 2.0' \, \text{and} \, \pm 2.3'$ that is due to the lag in this model.
Chapter 5. Observations and Modeling of NGC 4013

Figure 5.7 Representative channel maps showing the approaching (A) and receding (B) halves of NGC 4013. Note the splitting in the panel corresponding to 736 km s\(^{-1}\) and how this is achieved by adding a warp component along the line of sight. Also note the differing lengths of the two tails due to the splitting, and how this is achieved by adding radial motions to the models. There is a clear improvement due to the addition of a lag, best seen in the warped region corresponding to 656 km s\(^{-1}\), 975 km s\(^{-1}\), and 1015 km s\(^{-1}\). Contours are as in Figure 5.2.
Chapter 5. Observations and Modeling of NGC 4013

We add a line of sight warp component ("W" model in figures, inclination parameters given in Figure 5.3) that begins near the radial onset of the other warp component, but is roughly half the magnitude. The scale height of the layer is reduced to 5" (350 pc) to accommodate for the effects of the warp in this model. One can see clear improvements to the bv diagrams and channel maps, but can also see that the emission near the systemic side is not entirely matched in the former, nor are the outer edges of the latter. The warp also improves the fit to the vertical profile, although a closer match can still be made. In the channel maps, the data show an increasing minor axis thickness with radius, especially in the unwarped component, which is not present in this model. This suggests a flare.

Adding a flare to the model ("WF" in figures) by increasing the scale height with radius allows for a better fit to the vertical profile (parameters shown in Figure 5.3). Additionally, the scale height of the approaching half decreases slightly for radii larger than 3.1' (13.2 kpc). The emission on the systemic sides of bv diagrams is now spread out more, and the aforementioned thickening in the channel maps is well reproduced. One issue to note is that to fit this model, the central scale height is reduced to 3" (210 pc), pushing the limits of our ability to constrain this parameter given our resolution. However, we do see a slight distinction between a scale height of 3" and 4", mainly near the peak, shown in Figure 5.4.

Finally, adding radial motions to the model brings it into a near perfect match with the data. In the approaching half, we introduce 15 km s$^{-1}$ radial motions starting at a radius of 3.4' (14.3 kpc). These velocities linearly increase to 30 km s$^{-1}$ by 4.1' (17.4 kpc). The most striking evidence for these radial motions may be seen in the channel maps corresponding to 736 km s$^{-1}$ and 896 km s$^{-1}$ in Figure 5.7. Note the uneven length of the "tails" in the data at 736 km s$^{-1}$ and how this can be achieved through the addition of radial motions.

In the bv diagrams, there are also indications of radial motions in the receding
half in panels close to the center (Figure 5.6, panel corresponding to $-0.3'$), but these are extremely dependent on the surface brightness distribution at large radii, thus they cannot be constrained meaningfully and are added merely to show the effects they would produce. Judging by the slant on the systemic side of bv diagrams, primarily in the panel corresponding to $-0.3'$, at large and small major axis offsets, it is possible that there are radial motions near the center of the receding half having an opposite sign with respect to those in the outer regions of the approaching half. All of these radial motions are included in the WFR model. It is useful to note that, due to projection effects, we cannot determine the absolute sign of these motions in terms of whether they are inflow or outflow.

For the sake of completeness, a second, thicker disk is briefly considered, but as one may have already assumed, this yields no improvement to the models and is quickly dismissed. For instance, the thickening in the minor axis direction evident in the channel maps as discussed above is naturally well matched by a flare. A thick disk would not reproduce such behavior and add unnecessary complexity to the models.

5.6 The Addition of a Lag

Improvements are seen via the addition of a lag of $-28 \pm 7 \text{ km s}^{-1} \text{kpc}^{-1}$ starting at a radius of $1.9'$ (8.0 kpc) and $1.4'$ (5.8 kpc) in the approaching and receding halves, respectively. The subtle improvements are best seen in panels corresponding to the terminal sides of $\pm 2.0'$-$2.3'$ in the final column of Figure 5.6. (Recall that there is a flaring layer in NGC 4013, so there is more H I present at high $z$ at large radii, making it easier to detect a lag.) Unfortunately, we cannot constrain a radial variation in the lag for this galaxy since it occurs primarily throughout the warp, which could potentially make the lag values unreliable for large radii. However, we can see the
lag extends at this value to at least 2.3', which is just within $R_{25}$.

As for the central regions of NGC 4013, due to a lack of spatial resolution relative to the thickness of the disk, we cannot use the bv diagrams to meaningfully constrain the lag in those regions. (These diagrams are generally our initial approach to gauging lag uncertainties, although channel maps and lv diagrams are checked as well.) If we were to attempt to do so, we would set a limit of $-100$ km s$^{-1}$ kpc$^{-1}$ by comparing various lag models with the data. However, such an extreme value renders an obviously poor fit to channel maps, especially in channels far from the systemic (not shown). Specifically, even small lags remove nearly all the flux from these channels. One could argue that an adjustment to the rotation curve could be made to replace the flux in these channels, but we ultimately avoid such adjustments so as not to obtain a false positive for a lag. (This issue is rather unique to NGC 4013 because of the substantial warp oriented both along and across the line of sight, and the projection effects it produces.) From these channel maps, we set a limit of $-4$ km s$^{-1}$ kpc$^{-1}$ on the lag for radii within 1.9' (8.0 kpc) of the center in the approaching half and 1.4' (5.8 kpc) in the receding half.

For completeness, we show lv diagrams of the 1C and final models in Figure 5.8.
Figure 5.8 Lx diagrams showing the data, one component, and final models. The most substantial changes are near the systemic and at high z. Contours are as in Figure 5.2
The rotation curves on each half nearly match each other, and the average uncertainty in individual rings is approximately 5 km s\(^{-1}\). The runs of the position angle and inclination are both extremely sensitive to small changes of a degree or two in a single ring. The scale height distribution should be considered somewhat skeptically as it approaches the limits of our ability to constrain this parameter given the resolution of the data near the center. Still, a slight change can be seen in the vertical profile when the scale height near the center is changed from 3" to 4" (Figure 5.4). It is also clear that there is a flaring layer in NGC 4013.

By summing the square of the residuals for each model, we may quantify the improvement due to each feature. Adding a line of sight warp component (W) decreases the sum of the square of the residuals by 37.1% as compared to the 1C model. Adding a warp and a flare (WF) yields a decrease of 41.7%, while adding radial motions (WFR) gives a decrease of 42.5%. The final WFRL model yields a total decrease of 39.7%. This decrease is less than the WF and WFR models, indicating that the addition of a lag may be detrimental to some aspects of the model, although we see overall improvements by inspection. The characteristic signature of a lag is clear from the outer bv diagrams, and cannot be reproduced in the models in any other way. One reason for this discrepancy is the prominent warp prevents us from constraining the shallowing of the lag, which may indeed decrease in magnitude at large radii. Selected residuals are shown in Figure 5.9.
5.8 Discussion & Conclusions

In NGC 4013 we find warp components both across and along the line of sight. The characteristics of the warp are unusually well-constrained by the data, largely due to the overall strength and orientation of the warp, as well as the thinness of the main disk. These aspects of NGC 4013 greatly reduce projection effects, and greatly increase confidence in the uniqueness of the models.

The $^{1}$H layer is rather thin with a central scale height having an upper limit of 3” (210 pc), but flares up to 15” (1 kpc) at large radii. The rotation curve peaks at 190 km s$^{-1}$, indicating a large dynamical mass. Radial motions are also seen in NGC 4013, although only on the approaching side with any certainty. The origins of these radial motions are unknown, but could simply be due to spiral structure. We see no evidence for substantial amounts of extra-planar H$^{1}$, but do see evidence for a lag of $−28±7$ km s$^{-1}$ kpc$^{-1}$ at large radii at which there exists a flaring layer. The apparent minor axis thickness of the main disk is due largely to a line of sight warp, but also to a flaring layer.

The lack of extra-planar H$^{1}$ is somewhat unexpected given the high SFR in NGC 4013 as well as the extra-planar DIG and dust. However, one may consider the relatively large dynamical mass of the galaxy as a possible explanation, although such a scenario would be inconsistent with the presence of other extra-planar components. We will explore this possibility further in Chapter 6 when we discuss overall trends among our sample galaxies, as well as those throughout the literature.

5.8.1 A Comparison to Previous Work

Bottema (1995) presents lower resolution observations and tilted-ring models (Bottema, 1996) of NGC 4013. Remarking on the potential H$^{1}$ clouds seen in that work
slightly beyond and near the highest point in the warp on the approaching half, we see no evidence for either, and conclude (as Bottema (1995) suggested) that they are likely artifacts in those data. The models presented in Bottema (1996) and those presented here agree remarkably well. Given the relative simplicity of NGC 4013 in comparison with galaxies such as NGC 4302 and NGC 3044, this agreement should be unsurprising, as there is considerably less room for error.

We briefly note that we do not attempt to combine our data with those of Boomsma (1995) because more recent, deeper observations have been obtained with the WSRT, which we will discuss further in Chapter 7.

As is also noted by Bottema (1995), there are no indications of a bar in $\text{H}_1$, although one appears to be present in CO and at optical wavelengths (García-Burillo et al., 1999). The location of the bar they describe coincides with the central region of lower column densities before the initial peak in $\text{H}_1$ (Figure 5.3).

We see no connections between our $\text{H}_1$ observations and the high-density dust clouds observed by (Rueff et al., 2013). When considering the column densities re-distributed to match the size of our beam, the resulting column density of approximately $1.6 \times 10^{18}$ is below our detection threshold.

### 5.8.2 Summary and Conclusions

We model a single, strongly warped and somewhat flared disk in NGC 4013. Our higher resolution observations and models are consistent with the findings of Bottema (1995, 1996).

We detect no substantial extra-planar $\text{H}_1$ in NGC 4013. This is somewhat surprising given the high SFR and other extra-planar components [e.g. dust (Rueff et al., 2013); DIG (Rand, 1996)] observed in NGC 4013. Ignoring the other extra-planar
components, one might consider that the lack of extra-planar H\textsc{i} may be related to its relatively large dynamical mass, but such a scenario would be inconsistent with the observed high-z dust and DIG. In the flaring layer, we detect a constant lag of $-28\pm7$ km s$^{-1}$ kpc$^{-1}$ (beginning at approximately the same radius as the flare itself). We will explore the lack of extra-planar H\textsc{i} and the lag further in Chapter 7.
Figure 5.9 Residuals of the models presented in Figure 5.6. Contours are as in Figure 5.2, but with corresponding negative contours. Excesses in flux in the models are shown in white, and black corresponds to a paucity.
Chapter 5. Observations and Modeling of NGC 4013

![Diagram showing data and models for NGC 4013 with various parameters and offsets.]
Chapter 6

Observations and Modeling of NGC 4302

6.1 Chapter Overview

We present deep H\textsuperscript{i} observations and models of NGC 4302, a nearby edge-on spiral galaxy in the Virgo Cluster. The kinematics and morphology of NGC 4302 are greatly disturbed, likely by the cluster environment, as well as interactions with its companion, NGC 4298. We model the galaxy as a thin disk having a scale height of 4” (300 pc), and a second, thicker disk (scale height 25” or 1.8 kpc) with an H\textsuperscript{i} hole near the center. We detect lagging extra-planar gas, although its characteristics are difficult to constrain. One unique property of the lag in NGC 4302 when compared to other galaxies within our sample and throughout the literature is that there are indications that its lag may begin 600-1800 pc above the midplane. This starting point, as well as the lag’s irregularity, suggest that NGC 4302’s lag may be greatly influenced by external sources such as the cluster environment or its companion. However, the lag exists in all four quadrants of the galaxy, indicating that it is a
real, global feature. We briefly compare our derived lag values with those found for
the DIG lag in NGC 4302.

6.2 Introduction

NGC 4302 is a nearby, edge-on spiral galaxy that is also a member of the Virgo Clus-
ter. It has a nearby companion (NGC 4298), and is likely undergoing ram pressure
stripping due to the cluster environment Chung et al. (2007). Basic properties of
NGC 4302 are given in Table 6.1.

Chung et al. (2009b) present CO observations of several Virgo cluster galaxies,
including NGC 4302. They note that there are two peaks in the central CO distrib-
ution of NGC 4302 with a trough in the center. NGC 4302 is the only galaxy in
their sample to display such morphology - the rest are single-peaked near the center,
or lacking in strong CO emission in their central regions.

The extra-planar DIG is compared to the extra-planar dust distribution via ex-
tinction within NGC 4302 by Rueff et al. (2013). They find no connection between
the two on local scales, although both extend to approximately 2 kpc above the
midplane. The DIG shows a smooth morphology, while the dust is found primarily
in filamentary and small structures.

Heald et al. (2007) observe and model the extra-planar DIG morphology and
kinematics in NGC 4302. In that work, kinematics in the western half of the galaxy
were more easily constrained although the kinematics of the east side did not signif-
ically differ, thus a global DIG lag exists. They find a lag of $-35 \text{ km s}^{-1} \text{ kpc}^{-1}$ in
the NW quadrant, and $-23 \text{ km s}^{-1} \text{ kpc}^{-1}$, steepening to $-60 \text{ km s}^{-1} \text{ kpc}^{-1}$ near a
radius of 4.25 kpc in the SW quadrant (assuming a distance of 16.8 Mpc). A radially
steepening lag has not been seen in any other galaxy, making NGC 4302 an unusual
Chapter 6. Observations and Modeling of NGC 4302

Table 6.1. NGC 4302 Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance (Mpc)</td>
<td>15.1(^a)</td>
<td>Nasa Extragalactic Database</td>
</tr>
<tr>
<td>Systemic velocity (km s(^{-1}))</td>
<td>1150</td>
<td>This work</td>
</tr>
<tr>
<td>Inclination</td>
<td>90(^\circ)</td>
<td>This work</td>
</tr>
<tr>
<td>SFR (M(_\odot) yr(^{-1}))</td>
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<td>Rueff et al. (2013)</td>
</tr>
<tr>
<td>Morphological Type</td>
<td>Sc</td>
<td>Tully et al. (1988)</td>
</tr>
<tr>
<td>Kinematic Center (\alpha) (J2000.0)</td>
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<td>This work</td>
</tr>
<tr>
<td>Kinematic Center (\delta) (J2000.0)</td>
<td>14d 35m 50.1s</td>
<td>This work</td>
</tr>
<tr>
<td>(D_{25}) (kpc)</td>
<td>24.4</td>
<td>de Vaucouleurs et al. (1991)</td>
</tr>
<tr>
<td>Total Atomic Gas Mass (10(^9)M(_\odot))</td>
<td>2.9(^b)</td>
<td>This work</td>
</tr>
</tbody>
</table>

\(^a\)Distance is the median value of distances found on the NED database, excluding those obtained using the Tully-Fisher relation in order to be consistent with HALOGAS.

\(^b\)Includes neutral He via a multiplying factor of 1.36. Giovanelli et al. (2007) obtain a value of 2.2 assuming the same distance, and after a correction for He.

\(\text{H} I\) observations were carried out by Chung et al. (2007) as part of a larger survey of the Virgo Cluster using the VLA in C configuration, although modeling was not done as part of that work. We combine these observations with higher resolution B configuration observations in order to investigate the kinematics of the extra-planar \(\text{H} I\).

6.3 Observations and Data Reduction

Observations were performed using the VLA in both B and C configurations, with the latter being archival, originally presented in Chung et al. (2009a). Observational parameters are listed in Table 6.2.
Table 6.2. NGC 4302 Observational and Instrumental Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tr>
<td>Observation Dates — C Configuration</td>
<td>10-11 July 2005</td>
</tr>
<tr>
<td>B Configuration</td>
<td>22 Apr 2009</td>
</tr>
<tr>
<td></td>
<td>24-25 Apr 2009</td>
</tr>
<tr>
<td>Total On-Source Time in C Configuration (hours)</td>
<td>8</td>
</tr>
<tr>
<td>Total On-Source Time in B Configuration (hours)</td>
<td>24</td>
</tr>
<tr>
<td>Pointing Center</td>
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</tr>
<tr>
<td></td>
<td>14d 36m 7.0s</td>
</tr>
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<td>Number of channels</td>
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<tr>
<td>Velocity Resolution</td>
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</tr>
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<td>Primary Cube Beam Size</td>
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</tr>
<tr>
<td>Primary Cube PA</td>
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</tr>
<tr>
<td>Secondary Cube Beam Size</td>
<td>24.2×22.8” (1.8×1.7 kpc)</td>
</tr>
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<td>Secondary Cube PA</td>
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</tr>
<tr>
<td>RMS Noise — 1 Channel (24.2×22.8”)</td>
<td>0.41 mJy bm$^{-1}$</td>
</tr>
</tbody>
</table>

Data reduction was performed in AIPS using standard spectral line methods. Self calibration was performed after continuum subtraction on averaged channels in order to obtain a sufficient SNR, which yielded moderate improvement. The full resolution cube was also created in AIPS, but the smoothed cube was created in CASA (using AIPS calibrated data). A variety of weighting schemes were used in the imaging process. The final, full resolution cube was created using Briggs weighting with a robust parameter of three. The smoothed cube was created also using Briggs weighting with a robust parameter of two, and an outer $uv$ taper of 7 kilolambda. Primary beam correction was performed in GIPSY using the task PBCORR.
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Figure 6.1 A zeroth-moment map of NGC 4302 and its companion, NGC 4298. Contour levels for the full resolution cube begin at $1.4 \times 10^{19} \text{ cm}^{-2}$ and increase by factors of 2. The gray contour represents the smoothed cube and is $1.4 \times 10^{19} \text{ cm}^{-2}$. Black lines represent the slice locations of bv diagrams in Figure 6.5, and white lines represent slice locations in Figure 6.6. Note the H\textsc{i} tail, likely due to ram pressure stripping in NGC 4302. Also note the emission in NGC 4298 that appears to be pulled in a similar direction, which would also be characteristic of ram pressure stripping. The beam is shown in the lower left-hand corner.

6.4 The Data

Figure 6.1 shows a zeroth-moment map of NGC 4302 and its companion, NGC 4298. Note the tail on the northern half, which has been attributed to ram pressure stripping (Chung et al., 2007). There are indications that the two galaxies are interacting, but it is uncertain if the apparent bridge between the two is real. NGC 4298 shows asymmetries in a similar direction as the ram pressure stripped gas in NGC 4302, which may indicate ram pressure stripping in NGC 4298 as well.
Figure 6.2 displays all of the channels from the full resolution cube that contain emission. Note how closely the systemic velocities of both galaxies match (channels corresponding to 1132-1152 km s$^{-1}$). Also note again the tail on the N (approaching) half. This apparent bridge is continuous in velocity, increasing the likelihood that it is a real feature.

The H$\text{I}$ mass we calculate from our data is higher than that calculated by Giovanelli et al. (2007) using single dish data by approximately $7\times10^8 M_\odot$. We currently have no explanation for this discrepancy, but have checked the total flux obtained in our cube and find it to still be consistent with our value. Furthermore, we calculate the mass using the same script as was used for the other galaxies presented in this thesis, which have all agreed with literature values.
Figure 6.2 Channel maps of NGC 4302 and NGC 4298. Velocities are given for each panel. Note the ram pressure stripping in the approaching half of NGC 4302, as well as the closely matching systemic velocities of the two galaxies. Contours begin at $2\sigma$ (0.3 mJy bm$^{-1}$, or $7.2 \times 10^{19}$ cm$^{-2}$) and increase by factors of two. Although it is not clear in the figure, the channel corresponding to 965 km s$^{-1}$ is the lowest velocity channel with emission.
Figure 6.3 shows zoomed-in and rotated channel maps of NGC 4302 only. The galaxy is clearly asymmetric, with the ram pressure stripped gas evident on the approaching half, and various extra-planar clumps and extensions (e.g. the extension on the positive minor axis side in channels with velocities of 1256-1299 km s\(^{-1}\)). There is some unusual “spiking” near the outer edges of channels between 1049 km s\(^{-1}\) and 1132 km s\(^{-1}\) (not seen in the figures presented here, but evident at low levels). This spiking may be an artifact from the data reduction, but may also be related to the ram pressure stripping. There are also indications of fluctuations in the position angle that are not characteristic of a warp (e.g. comparing the 1215 km s\(^{-1}\) to 1319 km s\(^{-1}\) channels, they show minor axis offsets in opposite directions from -1' to -3' rather than a general change in one direction), indicating an unusual degree of complexity in this galaxy. Of course, such fluctuations are not necessarily due to changes in the orientation of the disk as a whole, but may be due to localized features, similar to the corrugations seen in \(\text{HI}\) in other galaxies likely associated with global gravitational instabilities (e.g. Matthews & Uson 2008), or possibly associated with SF activity. Detailed modeling is required in order to properly explore these possibilities.
Figure 6.3 Channel maps of NGC 4302 in a rotated frame with the origin at the kinematic center show the substantial asymmetries within the galaxy, largely involving ram pressure stripping on the approaching half. Velocities are given for each panel. Contours begin at $3\sigma$ (0.3 mK km s$^{-1}$, or $7.2 \times 10^{19}$ cm$^{-2}$) and increase by factors of two.
As mentioned in § 6.4, NGC 4302 is an abnormally complicated galaxy, which results in increased difficulty and uncertainties when creating tilted-ring models. We attempt to minimize the addition of distinct features to our models.

Due to asymmetries in NGC 4302, we model the two halves separately. The rotation curve is initially estimated using the values for the DIG presented in Heald et al. (2007). The surface brightness distribution is obtained using the GIPSY task RADIAL. The central PA and inclination are assumed to be 180° and 90° respectively. The velocity dispersion is modeled to be 30 km s\(^{-1}\). All of these quantities are adjusted throughout the modeling process. Systemic velocities between 1130 km s\(^{-1}\) and 1180 km s\(^{-1}\) are tested at early stages, with a value of 1150 km s\(^{-1}\) used for most of the modeling. (Although, based on channel maps shown in Figure 6.3, one may argue that a lower systemic velocity would be a better fit in central regions. However, decreasing the systemic velocity would increase the discrepancy in the rotation curves in each half. Thus, it may be that the inner and outer regions of NGC 4302 may have differing systemic velocities.) The central position used in the models is 12h 21m 42.3s, 14d 35m 50.1s.

### 6.5.1 Individual Models

We first attempt a single component (1C) model. For such a model, we find an optimal scale height of 7.5" (540 pc). As may be seen in the vertical profile shown in Figure 6.4, the bv diagrams in Figures 6.5, 6.6, and the channel maps in Figure 6.7, not all the data can be fit by a single component alone. Specifically, the 1C model is too thick to match the data in the vertical profile, but if the scale height is decreased, the peak will rise too high above that of the data. Additionally, the 1C model is too thick near the terminal sides of bv diagrams, especially near the center. Again, in
channel maps, the 1C model is too thick near the center. Thus, we add a second, thicker component with a H\textsubscript{i} hole near the center to the models.

A range of scale heights are explored, as well as different fractions of mass included in each component. The final model consists of a thin disk having a scale height of 4" (300 pc), and a thick disk with a scale height of 25" (1.8 kpc). However, the thick disk does not begin until a radius of 1.75’ or 7.7 kpc (beyond this radius the two components share the same surface brightness distributions), effectively creating a high-z H\textsubscript{i} hole near the center. This hole is necessary to fit the vertical profile, bv diagrams (Figure 6.5), and channel maps (Figure 6.7) close to the center. While we do not show models having high-z H\textsubscript{i} near the center, one can imagine its inclusion would cause a thickening of the corresponding terminal sides of bv diagrams and central regions of channel maps not seen in the data. Such a scenario may be remedied.

Figure 6.4 Vertical profiles of the data, one-component (1C), and two-component (2C) summed over \pm 40" (2.9 kpc) from the center. Note the substantial improvement gained by decreasing the height of the thin disk, and then adding a second, thicker layer with an H\textsubscript{i} hole near the center.
to some degree by adding a steep lag to the models, but attempts to do so resulted in extremely poor fits to the systemic sides of bv diagrams, and to the outer edges of channel maps (not to mention the poor fit to the vertical profile that eliminates such a model at an even earlier stage).
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Figure 6.5 Bv diagrams showing the data, 1C, 2C, 2CL, and 2CLV models. Notice the overall poor fit for the 1C model, especially the superfluous thickness near the center, largely on the terminal side. The 2C model shows substantial improvement, in part due to the H\textsubscript{i} hole near the center, but also due to the increased spread in z, especially at large major axis offsets, especially on the systemic sides. The 2CL and 2CLV models are the same for the approaching half, but differ slightly for the receding half. The lag models are discussed further in § 6.5.2. Contours are presented as in Figure 6.2.
Figure 6.6 Same as Figure 6.5, but showing the approaching and receding halves, but with more finely sampled slices. Contours are presented as in Figure 6.2.
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Figure 6.7 Channel maps showing the approaching (A) and receding halves (B) of NGC 4302. We model the ram pressure stripping in the approaching half (described in § 6.5.1). Note the excess thickness near the center of the 1C model in both halves that is remedied by the 2C model (with a thinner main disk, and second, thicker component with a central H I hole). The improvements due to the lag are minimal, especially in the approaching half, and are best seen in bv diagrams. Velocities are given in each panel. Contours are presented as in Figure 6.2.

Additionally, one could argue for a single, flaring layer instead of two components. However, attempts to model a flare resulted in abrupt increases in the scale height rather than the gradual flares seen in other galaxies such as NGC 4565, indicating a fundamental difference between what is seen in NGC 4302 and a flare.

We now consider a warp component along the line of sight as a means of thickening the disk. However, such a scenario would not be consistent with the data. Specifically, we do not see the characteristic indentations on the systemic sides of bv diagrams (Figure 6.5), and the outer regions of channel maps (Figure 6.7) that generally indicate a decrease in inclination (see Chapter 2 as these indentations are seen in NGC 4244).

Thus, we settle on a two component (2C) model with a high-z H I hole near
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the center. Note even this model does not reproduce the wings at large offsets in Figure 6.4 due to distinct features and faint, asymmetric emission seen near the edges of the galaxy (Figure 6.1). The parameters for the final model are shown in Figure 6.8.
Figure 6.8 Parameters of the models for NGC 4302. Note the difference in the rotation curves near the center. Also note the fluctuations of the PA on the receding half. These fluctuations are not associated with any warping in NGC 4302, but are likely related to the distinct features described in § 6.5.1. The inclination is given in bold. The scale height of the thick disk is given in bold, with the receding half starting closer to the center, eventually being covered by the solid line of the approaching half in the diagram. The surface brightness is given for the thin disk, but is the same as the thick disk (aside from the H\textsubscript{i} hole, which ends at a radius of approximately 5 kpc).
Figure 6.9  $Lv$ diagrams showing the data, 1C, and 2CLV models. Most improvements are due to the addition of a second, thicker component. Note the improved fit to the panels at high $z$. Contours are presented as in Figure 6.2.
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Distinct Features Included in the Models

While there is much anomalous gas in NGC 4302, we attempt to model only three distinct features. Additionally, although not really “features” per se, we add fluctuations to the PA on the receding half, and fluctuations in the velocity dispersion on both halves. Unlike in other galaxies presented in this thesis, these features affect lag values. With their inclusion, we can say something, however minor, about the kinematics of this gas while making no claims about its origins. We can also illustrate to some degree the ways in which they impact lag values. Although they are added to the models at the same stage, we cannot claim how closely or even whether they are associated with each other. We do not assign physical meaning to these features other than those explicitly given in the model parameters - our primary goal is to assess how they impact lag determinations. They are included in all models unless otherwise specified.

Immediately clear from channel maps (Figure 6.3) is the ram pressure stripped gas on the approaching (N) half. While ram pressure stripping by nature is not modeled well by concentric rings, we attempt to approximate its morphology and kinematics through a wedge (i.e. a feature with limited radial and azimuthal extent in the disk). This wedge begins at a radius of approximately 1’ (4.0 kpc) on the approaching half, and extends to 6.4’ (28.2 kpc). The azimuthal width of each arc is 80°, and each is azimuthally centered on the approaching half. The total velocity dispersion, including that of the main disk, is 30 km s⁻¹, and the inclination is 90°. The corresponding surface brightness distribution, PA distribution, rotation curve, and scale height are given in Figure 6.10. Discussion of the validity of the assumptions used in our models regarding this gas is provided in § 6.6.2.

There exists a disturbed region in the receding half of NGC 4302 from a radius of 0.35’ (1.5 kpc) to 2.6’ (11.2 kpc). In order to better fit this region, we add two
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Figure 6.10 The model parameters for the ram pressure stripped gas. Note the large radius to which the stripped gas extends, as well as the overlap with the main disk. The apparent rotational velocities of the ram pressure stripped gas in the region in which the stripped gas overlaps with the main disk are slower than those of the main disk in our models. However, due to the combined effects of the two model components, and likely peculiar motions in the stripped gas, these velocities should not be interpreted as true rotational velocities.

One may first note a protrusion in the SW quadrant of the galaxy (Feature 1, Figure 6.11, lower-right boxed region). This feature extends from velocities 1173 km s\(^{-1}\) to 1298 km s\(^{-1}\). A seemingly un-related protrusion can also be seen in the NE quadrant of the receding half in this velocity range (upper-left boxed region). At first we attempt to model these features separately, but then note the slant of extra-planar emission in bv diagrams from 0.4' to 1.9'. This slant is best seen at 1.3' Figure 6.6 where an excess of extra-planar emission can be seen on both the positive and negative minor axis off-sets, with the emission on the negative side being closer to the terminal velocities, and the emission on the positive side closer to the systemic. It should also be noted that the extra-planar emission on the negative side is primarily seen from 0.4'-0.7', and then transitions to both sides from 1.0' to 1.3'. The 1.6'
and 1.9' panels show extra-planar emission primarily on the positive side. Judging by this behavior, it appears as though the two protrusions could in fact be related. Thus, we model them as a single, gaussian distortion (imagine an elongated, curved series of gaussians with the gaussian profile along the short axis of the feature) with a systemic velocity of 1250 km s$^{-1}$, a rotational velocity of 20 km s$^{-1}$, and centered at 12h 21m 44.9s and 14d 35m 42s. This systemic velocity was chosen based on the velocity at which the emission appears to be centered (between the two protrusions). We do not mean to suggest that this feature is rotating around a different kinematic center than is the disk, but chose these parameters as a convenient way to model the feature. The amplitude of the gaussians fluctuate along the curve. The curved feature itself is tilted with respect to the plane of the sky (slanting from the box in the upper left-hand corner, down to the box in the lower right-hand corner in Figure 6.11). The curved feature intersects the disk, and has a substantial line of sight component.

A second feature is added to the models after it is seen that channels in Figure 6.5.1 between 1000 km s$^{-1}$ and 1090 km s$^{-1}$ in the model are missing flux relative to the data at intermediate and large radii. Increasing the surface brightness for entire rings, or changing the velocities, does not remedy this issue without compromising the fit for other channels or different radii. Thus, we add a wedge centered at an azimuthal angle of 135°, the arcs that it consists of having widths of 80°, to increase the flux in this region only. The total velocity dispersion of this feature (including that associated with the main disk) is 30 km s$^{-1}$. Additional properties of this wedge are given in Figure 6.12. This feature is denoted as “Feature 2” in figures and throughout the text. Potential origins of both Feature 1 and Feature 2 will be discussed in § 6.6.2.
Figure 6.11 Channel maps showing the data, and models with and without “Feature 1.” Boxes highlight the regions in which improvement is seen through the addition of this feature. It should be noted that the fit is imperfect, but the feature improves the match between the model and data. Velocities are given above each column. Contours are presented as in Figure 6.2.

Fluctuations in PA were added at small and moderate radii on the receding half in combination with the features mentioned above to smooth the transition between the main disk and the anomalous gas. It should be noted that although adjustments to the position angle are typically associated with a warp component across the line of sight, these local fluctuations should not be considered directly related to any warping of the galaxy.

The velocity dispersion of 30 km s\(^{-1}\) increases to 40 km s\(^{-1}\) in the thick component at a radius of 35” (2.5 kpc). On the receding half (still thick component), there is a further increase to 50 km s\(^{-1}\) at a radius of 1.9’ (8.4 kpc). In the thin component, the velocity dispersion decreases to 10 km s\(^{-1}\) at a radius of 35” (2.5 kpc), but as is
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Maps Showing “Feature 2” in NGC 4302. Channel maps showing the data, and models with and without “Feature 2.” Boxes indicate regions of improvement through the addition of this feature. Velocities are given above each column. Contours are presented as in Figure 6.2.

Figure 6.12 The parameters used to model Feature 2 that are not held constant or do not vary in a linear fashion. Recall that Feature 2 is modeled with a wedge instead of gaussian distortions as was the case for Feature 1. Thus, Feature 2 is spread over a larger region than Feature 1.
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does the case for the thick component, the velocity dispersion increases by 10 km s\(^{-1}\) at a radius of 1.9' (8.4 kpc).

6.5.2 The Addition of a Lag

Judging by bv diagrams and channel maps (Figures 6.5, 6.6, and Figure 6.7), the two component model is still not an ideal fit to the data. Emission in the data is effectively displaced toward the systemic side with increasing minor axis off-set in the data in bv diagrams relative to the 2C model, where there is a surplus of emission near the terminal side (best seen beyond major axis offsets of ±1.6’). To remedy these issues, we now add a lag to the models.

At first, the flattening of the lowest contours in the data on the terminal side of bv diagrams in Figure 6.6 prompts us to model a lag starting well above the midplane. In the approaching half, the lag starts 18’’\(^{+2}_{-8}\) (1.3 kpc) above the midplane, and has a constant value of \(-21^{+7}_{-21}\) km s\(^{-1}\) kpc\(^{-1}\) in our optimal models. A variety of lag values, starting heights, and radial variations are also tested, but none match the data as well. It should be noted that, while the lag is constant, the effects from the lag are minimal at large radii because the lag starts so high above the midplane. The lag on the receding half starts 8’’\(^{+1}_{-4}\) (600 pc) above the midplane, at a radius of 1.25’ (5.5 kpc), with a peak value of \(-41^{+13}_{-29}\) km s\(^{-1}\) kpc\(^{-1}\). The lag shallows radially as seen in Figure 6.13. The resulting rotation curves at high z from these lags are shown in Figure 6.14. However, recall that the uncertainties in the lag values are unusually large for this galaxy, which would transfer to the rotation curves at high z.

It should be noted that the radii at which the lags begin are dictated by when the lag begins to produce some effect, not because a lag within those radii is detrimental.
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Figure 6.13 The lag values and their uncertainties for each half. Recall that the lag starts at \(z=18''\) in the approaching half, and \(z=8''\) in the receding half. This should be unsurprising given the extra-planar H\textsc{i} hole near the center that extends to just beyond the radius at which lag effects are noticeable. A model illustrating this ambiguity is shown in Figure 6.15 and Figure 6.15. Also, if the lags were to begin at the midplane, then the optimal model would have a lag of \(-7^{+3}_{-7}\) km s\(^{-1}\) kpc\(^{-1}\) on the approaching half, and \(-27^{+21}_{-55}\) km s\(^{-1}\) kpc\(^{-1}\) on the receding half.

Figure 6.14 The rotation curves at the midplane and at \(z=20''\). Recall that the lags do not start until \(z=18''\) in the approaching half, and \(z=8''\) in the receding half. The approaching half is labeled as “a,” and the receding half is labeled as “r.”
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These shallower lags should be expected when they begin at lower heights as the gas at high z is rotating at similar velocities in each model. Such models are shown in Figure 6.15. Figure 6.16 shows the lag values and their uncertainties for this model, and Figure 6.17 shows the resulting rotation curves at high z for shallower lags beginning at the midplane.

Given the tumultuous nature of NGC 4302, a lag is difficult to constrain. Qualitatively, it is reasonably clear by the emission in bv diagrams that is displaced toward the systemic at high-z (Figures 6.5, 6.6) that gas at high-z is rotating at a slower rate than gas at the midplane. Additionally, as in other galaxies, judging by the more rounded as opposed to v-shaped terminal sides of bv diagrams at large radii (Figure 6.6, −1.9′ and ±2.2′), the lag does appear to shallow with radius. However, the extra-planar kinematics in general are likely impacted by ram pressure stripping and interactions with the companion galaxy. The additional features described in § 6.5.1 impact the lag values in our models, resulting in a compromised ability to determine reliable values for NGC 4302 as compared to other galaxies. Again, it is at least qualitatively clear that the extra-planar gas in NGC 4302 is lagging, and that the lag likely shallows with radius.

6.5.3 A Brief Summary of the Properties of NGC 4298

We model the companion galaxy, NGC 4298. The position angle, inclination, and kinematic center are estimated by eye, and initially refined by tilted ring fitting using the GIPSY task ROTCUR. Also using ROTCUR, we estimate the systemic velocity (1140 km s$^{-1}$) and rotation curve. We use ELLINT to estimate the surface brightness distribution. These quantities are later refined in TiRiFiC. The final value of the position angle is 313°. The inclination is 70°, and the kinematic center is 12h 21m 32.6s, 14° 36′ 22.7″. The rotation curve peaks at 110 km s$^{-1}$ and holds constant
before decreasing at a radius of $1.4'\ (6.2\ \text{kpc})$. The total H\textsc{i} mass we estimate is $1.5 \times 10^9\ M_\odot$, approximately half that of NGC 4302. A rough estimate for the dynamical mass of NGC 4298 based on the kinematics we model is $1.5 \times 10^{10}\ M_\odot$, while NGC 4302 is $1.0 \times 10^{11}\ M_\odot$. Of course, these dynamical masses are lower limits, even more so for a moderately inclined galaxy for which we cannot detect a given distribution of H\textsc{i} to as large a radius.
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Figure 6.15 Bv diagrams showing the data, 2C model, 2CLV (2CL in the case of the approaching half since they are the same) model, a two component model with a lag starting at the center of the galaxy (R=0), but at the same height as the 2CL and 2CLV models, and a two component model with a lag starting at the midplane, but at the same radius as the 2CL and 2CLV models (Z=0). Figure (A) shows the approaching half, and Figure (B) the receding half. The differences in each lag model are subtle. Firstly, note how the R=0 models are nearly indistinguishable from the 2CL and 2CLV models. This is because the lag has little or no effect at small radii, largely because of the high-z H\textsc{i} hole. The Z=0 model on the approaching half is clearly a poorer fit to the data than our optimal model as the panels from −1.6′−2.2′ are too pointed on the terminal side. The differences on the receding half are even more subtle in panels corresponding to 1.6′−2.2′, again showing that the terminal side is too narrow. Contours are presented as in Figure 6.2.
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Figure 6.16 The lag values and their uncertainties for the models with lags beginning at the midplane.

Figure 6.17 The rotation curves at the midplane and at z=20” for the models having lags that start at the midplane. Note the similarities in the resulting rotation curves to those of the models having steeper lags starting higher from the midplane.
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6.6 Discussion

6.6.1 The Final Models and Their Uncertainties

We will now consider a comparison of the sum of the square of the residuals for each model. There is a 17.8% decrease between the 1C and 2C models. There are slightly larger decreases of 18.1% and 18.3% for the 2CL and 2CLV (final) models. The 2CLV model with a lag starting at the midplane decreases this value (with respect to the 1C model) by 16.3%. The overall trend is for sum of the square of the residuals to decrease with each improved model, but by far the largest change is from adding a second component. All of these models include the extra features described in § 6.5.1.

Now we consider the sum of the square of the residuals in the context of the additional features added to the models. The percent decrease when adding the ram pressure stripped gas to the 2CLV model with a lag starting at high z (other features are still included) is 15.6%. Adding Feature 1 results in a decrease of 3.3%, and adding Feature 2 results in a decrease of 10.0%. These numbers indicate that the ram pressure stripped gas and Feature 2 improve the models substantially, while effects from Feature 1 are minimal. However, it should be noted that the improvement from any one of these features yields a greater decrease than the addition and/or refinement of the lag. Thus, since these features affect large regions in which the lag is determined, the lag values should be treated with caution. However, based on the bv diagrams in panels major axis off-set 1.6’ and 2.2’ in Figure 6.15, and to a lesser degree, the improvement in the residuals, we slightly favor the model with a lag starting above the midplane. Select residuals are shown in Figure 6.18.
6.6.2 The Interpretation of Additional Features in the Models

We model ram pressure stripping using azimuthal arcs in one half of the galaxy. Clearly this method can only be used to approximate the kinematics and morphology of the ram pressure stripped gas. An immediate issue with our assumptions is that the ram pressure stripping likely affects more than one half of the galaxy. The arcs in our models create a wedge centered on the approaching half of the galaxy. Such an assumption is unphysical as the gas would likely be stripped across the entire extent of the galaxy, which the wedge does not encompass.

It is unlikely that the ram pressure stripped gas would retain the same systemic velocity as the rest of the galaxy. We do not incorporate this aspect into our models as a separate systemic velocity for the ram pressure stripped gas could not be reliably constrained. We obtain a rough approximation of the rotation curve (although not all the motion may be due to rotation, the gas may be stripped toward or away from the observer as well) of the stripped gas that is significantly slower than the main disk where they overlap (although such values should not be relied upon too heavily, as the overlapping kinematics of ram pressure stripping and main disk are difficult to constrain). Outside the region of overlap, the rotation curve of the stripped gas is approximately 20 km s\(^{-1}\) slower than the peak rotational velocity of the disk.

Features 1 and 2 could be related to merger activity, ram pressure stripping, spiral structure, disk-halo flows, or a combination of these phenomena. The location and velocities of Feature 1 in relation to the companion galaxy indicate that it may be due to an interaction between the two galaxies. The channels in which the companion is closest to NGC 4302 spatially are associated with the approaching half of the
Chapter 6. Observations and Modeling of NGC 4302

galaxy (channels having velocities of 1069-1152 km s\(^{-1}\)). Thus, the slower rotational velocities of this feature may indicate accretion of material from the companion or tidal interactions. It is also somewhat plausible that Feature 1 could be due to disk-halo flows. In contrast, Feature 2 is less likely to be due to disk-halo flows or merger activity, but more likely to be due to spiral structure. It is difficult to even speculate on the degree to which ram pressure stripping could affect either feature.

6.6.3 The Lag in NGC 4302

From our models, we can say that there is some chance the lag in NGC 4302 starts at some point above the midplane. We do not see such behavior in the other galaxies included in our sample, which makes this characteristic somewhat intriguing. One possible explanation is that the lag in NGC 4302 is greatly affected by external processes such as tidal interactions, stripping from the cluster environment, or accretion. External processes could also explain the irregularity and abnormal radial variability (i.e. not shallowing smoothly) of this lag with respect to the lags seen in other galaxies. However, it should be stressed that the lag is seen in all quadrants, and these effects would not produce such symmetric kinematics throughout the entire disk. Thus, disk-halo flows are still a likely origin of the lag itself.

Among the foremost reasons for the difficulty in constraining the lag is the possible interaction between NGC 4302 and its companion. While it is difficult to confirm the presence of a bridge between the two, there are slight indications that one may be present (Figure 6.1). Furthermore, their small spatial separation in their projected region of closest approach (\(\leq 0.5'\) or 2.2 kpc) and shared velocity range (the systemic velocity of the companion also appears to be 1150 km s\(^{-1}\) upon inspection) increase the likelihood of the companion having some bearing on the kinematics of NGC 4302. The region encompassing Feature 1 may indeed be strongly affected by an
interaction, and possibly accretion from the companion galaxy. The velocities of both Feature 1 and Feature 2 are peculiar, with those of Feature 2 clearly slower than that of the main disk of NGC 4302.

In spite of the issues mentioned above, the lag in the receding half does shallow and reach its lowest value just within the optical radius. While we must be very cautious when considering trends among galaxies involving NGC 4302, this behavior is also seen in other galaxies in our sample (e.g. NGC 4244), and will be discussed further in Chapter 7.

6.6.4 A Comparison to Previous Work

Heald et al. (2007) found a DIG lag of $-35 \text{ km s}^{-1} \text{kpc}^{-1}$ in the NW quadrant, and $-23 \text{ km s}^{-1} \text{kpc}^{-1}$, *steepening* to $-60 \text{ km s}^{-1} \text{kpc}^{-1}$ near a radius of 4.25 kpc in the SW quadrant (These values would be $-39 \text{ km s}^{-1} \text{kpc}^{-1}$, $-25 \text{ km s}^{-1} \text{kpc}^{-1}$, $-65 \text{ km s}^{-1} \text{kpc}^{-1}$, and 3.8 kpc using our assumed distance).

The lag of $-21^{+7}_{-21} \text{ km s}^{-1} \text{kpc}^{-1}$ that we detect in the approaching half is significantly shallower than the DIG lag of $-39 \text{ km s}^{-1} \text{kpc}^{-1}$ if one assumes a distance of 15.1 Mpc. Furthermore, the H$\text{I}$ lag may begin above the plane of the disk, adding to the discrepancy in the two values at a given $z$. Some of the difference may possibly be attributed to ram pressure stripping, which, if all else is equal, would have a greater effect on the DIG kinematics than those of the H$\text{I}$ simply because DIG typically has lower density than neutral gas. However, much of the DIG is concentrated near the center of NGC 4302, which would render it more gravitationally bound than H$\text{I}$ at larger radii, and thus, is less affected by ram pressure stripping.

While the lag we detect in the receding half does not appear to steepen radially, it becomes detectable at a radius of approximately 5 kpc, reasonably close to the radius at which the DIG lag steepens. We avoid drawing conclusions from this, but
only remark on the (moderately) coinciding locations.

We also compare our observations to those of Rueff et al. (2013) in which 11, high column density \(2 \times 10^{20} \text{ cm}^{-2}\), approximately 1.5” diameter), extra-planar dust clouds are found in NGC 4302 via their extinction. Such clouds themselves are well beyond the limits of our resolution, but we attempt to find connections between their locations, and the locations of distinct, extra-planar H\textsc{i} features. We find only vague hints at possible connections for a few of the clouds, which are likely coincidental as the majority of the clouds show no discernable connection to extra-planar H\textsc{i}. However, it should be noted that if we smooth the column densities of these clouds to the size of our beam, the column densities for most would decrease to approximately \(4.5 \times 10^{18} \text{ cm}^{-2}\) for the total hydrogen (H\textsc{i} + H\textsubscript{2}), which would be below our detection threshold. However, we do note that the gas column densities of the dust features are lower limits due to the uncertain dust-star geometry.

### 6.7 Summary and Conclusions

We present deep H\textsc{i} observations and detailed models of NGC 4302. We find the best fit model to consist of a thin disk with a scale height of 4” (300 pc), and a second, thicker disk with a scale height of 25” (1.8 kpc) that begins at a radius of 1.75’ (7.7 kpc). To this model we add a component to model the ram pressure stripped gas, as well as two additional features of somewhat ambiguous origin, one possibly due to spiral structure, while the other may be related to either tidal interactions, accretion from NGC 4298, or disk-halo flows.

We model a lag in NGC 4302 that starts 18” (1.3 kpc) and 8” (600 pc) above the midplane in the approaching and receding halves, respectively. (Although, as previously stated, it is possible that these lags start at the midplane.) In the approaching half, the lag starts 18”\(\pm\frac{8}{2}\) (1.3 kpc) above the midplane, and has a constant value of
Chapter 6. Observations and Modeling of NGC 4302

$-21^{+7}_{-21}$ km s$^{-1}$ kpc$^{-1}$ in our optimal models (although we only give these a slight preference). The lag on the receding half starts $8'' \pm 4$ (600 pc) above the midplane, at a radius of $1.25'$ (5.5 kpc), with a peak value of $-41^{+13}_{-29}$ km s$^{-1}$ kpc$^{-1}$. While the characteristics of these lags are difficult to constrain given the complicated nature of this galaxy, that they do not start at the midplane indicates that they may be largely governed by external influences. However, the lag in the receding half reaches its shallowest point just within the optical radius - a characteristic that is seen in other galaxies as well, and may indicate internal origins.

We will discuss how NGC 4302 relates to current extra-planar H I and lag trends in Chapter 7.
Figure 6.18 Residuals of the models presented in Figure 6.5. White indicates an excess of flux in the models, while black indicates a paucity. Contours are presented as in Figure 6.2, but with the addition of equivalent negative contours.
Chapter 7

Discussion and Future Work

7.1 Chapter Overview

We explore trends involving the extra-planar H I of galaxies within our sample, as well as throughout the literature. We attempt to draw connections between the presence and morphology of extra-planar H I and lag properties with SF and environment. We explore possible relations between lag magnitude and SFR such as those originally set forth by Heald et al. (2007) for DIG lags. We detect lags in every galaxy within our sample, a majority of them shallowing with radius. We see no real connection between scale height and an approximation of SFR per unit area ($L_{TIR}/D_{25}^2$). We also see no correlation if the scale height is multiplied by the peak rotational velocity and then compared with $L_{TIR}/D_{25}^2$, but a larger sample is needed. We consider these results in the context of current theoretical simulations, and then discuss possibilities for future related work.
7.2 A Brief Summary of the Galaxies Presented in this Thesis

With a peak rotational velocity of 95 km s$^{-1}$, NGC 4244 has the lowest dynamical mass of the galaxies presented in this thesis. The SFR of NGC 4244 is quite low, with a value of 0.12 $M_\odot$. We model this galaxy as a single, warped thick disk having a scale height of 560 pc and a central inclination of 88°. The lag in NGC 4244 is $-9^{+3}_{-2}$ km s$^{-1}$ kpc$^{-1}$ in the approaching half and $-9^{+2}_{-1}$ km s$^{-1}$ kpc$^{-1}$ in the receding half. This lag decreases in magnitude to $-5^{+2}_{-1}$ km s$^{-1}$ kpc$^{-1}$ and $-4^{+2}_{-1}$ km s$^{-1}$ kpc$^{-1}$ near a radius of 10 kpc in the approaching and receding halves, respectively. NGC 4244 is relatively isolated, and appears to be non-interacting, but is a part of the NGC 4736 group (Giuricin et al., 2000).

The peak rotational velocity of NGC 4565 is 250 km s$^{-1}$, giving it the largest dynamical mass of the galaxies presented in this thesis, as well as the entire HALO-GAS sample. Our models are comprised of a warped and asymmetric disk with a flaring layer having a central inclination of 87.5°, and a central scale height of 210 pc. In NGC 4565 we see a lag of $-40^{+5}_{-20}$ km s$^{-1}$ kpc$^{-1}$ and $-30^{+5}_{-30}$ km s$^{-1}$ kpc$^{-1}$ in the approaching and receding halves, respectively. This lag is only seen within the inner $\sim$14.9 kpc on the approaching half and $\sim$13.4 kpc on the receding, as it cannot be constrained at larger radii. NGC 4565 has two nearby companions, and is clearly interacting with one, located near the warped region on the NW side, although whether there exists a clear bridge between the two is uncertain. It is part of the NGC 4565 group, which has seven members (Giuricin et al., 2000).

NGC 3044 is modeled as a single, thick disk having a scale height of 635 pc. The inclination of this galaxy is determined to be 85°. The rotation curve peaks at 160 km s$^{-1}$, placing it near the middle of our sample in terms of dynamical mass. We detect a lag of $-33 \pm 6$ km s$^{-1}$ kpc$^{-1}$ starting at the midplane, which shallows radially,
reaching a value of zero at approximately $R_{25}$. NGC 3044 is generally thought to be an isolated galaxy, but its lop-sided morphology and peculiar kinematics indicate that it may have undergone a minor merger at some point. NGC 3044 is not listed in a group by Giuricin et al. (2000).

NGC 4013 is modeled with a single, warped, flaring disk, with a central scale height of 210 pc. There is no evidence for substantial extra-planar H\textsc{i} in this galaxy, even in smoothed cubes. The peak rotation of NGC 4013 is found to be 190 km s$^{-1}$, indicating a relatively large dynamical mass. We detect a lag of $-28\pm7$ km s$^{-1}$ kpc$^{-1}$ starting at a radius of 8.0 kpc and 5.8 kpc in the approaching and receding halves, respectively. The onset of this lag is at approximately the same radius at which the galaxy starts flaring. In contrast to the other galaxies presented in this thesis, the lag in NGC 4013 does not appear to shallow with radius. Furthermore, the measured lag in this galaxy is rather steep given that it exists at large radii. NGC 4013 is somewhat isolated, but a member of the NGC 4151 group. Based on deep optical observations of stellar streams, there are strong indications that NGC 4013 has undergone a minor merger with a dwarf galaxy. It is part of the NGC 4151 group, which has 16 members (Giuricin et al., 2000).

NGC 4302 is found to have a thin disk of H\textsc{i} with a scale height of 300 pc, and a second, thicker disk with a scale height of 1.8 kpc. The second disk begins at a radius of 7.7 kpc. The peak rotational velocity is 190 km s$^{-1}$, indicating a dynamical mass comparable to that of NGC 4013. Within NGC 4302, there is clear evidence for ram pressure stripping, as well as indications of interactions with the cluster environment or its companion galaxy. In the approaching half, the lag starts 1.3 kpc above the midplane, and has a constant value of $-21^{+21}_{-7}$ km s$^{-1}$ kpc$^{-1}$ in our optimal models (although by only a slight preference). The lag on the receding half starts 8" (600 pc) above the midplane, at a radius of 5.5 kpc, with a peak value of $-41^{+29}_{-13}$ km s$^{-1}$ kpc$^{-1}$. Due to its complicated nature, lag values for NGC 4302 are considered to

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Chapter 7. Discussion and Future Work

be less reliable than those of other galaxies presented in this thesis. NGC 4302 is a member of the Virgo Cluster, and has a single nearby companion.

7.3 The Relation Between Star Formation and the Presence of Extra-planar H I

As described in Chapter 1, other extra-planar phases have been shown to be related to SFR on both global and localized scales. However, no such relation has been established for extra-planar H I. Morphological evidence, which we will discuss in this section, as well as kinematic evidence (discussed in § 7.5) can be used to determine its origins, which could be due to disk-halo flows, accretion from external sources, or a combination of the two.

Given the varying sizes of the galaxies involved, it is best to draw trends from total infrared luminosity per unit area ($L_{TIR}/D_{25}^2$), which is effectively a measure of SFR per unit area, than by global SFRs. By doing so, we can better gauge the ability of each galaxy to drive a disk-halo flow. We choose the infrared luminosity over Hα as a SFR tracer because Hα is unreliable in edge-on galaxies due to large amounts of extinction. In Table 7.1 we compare properties of the galaxies presented in this thesis, including total H I mass, $L_{TIR}/D_{25}^2$, scale heights, dynamical masses, and lags of NGC 4565 with those of previously modeled edge-on galaxies presented throughout the literature. The total infrared luminosity per unit area for each galaxy is calculated in this work unless otherwise stated. These calculations are done based on equations found in Dale et al. (2009), and involve the optical area (de Vaucouleurs et al. 1991 in most cases; additional references are provided in the table). Spitzer MIPS data are used if available for a given galaxy, otherwise IRAS data are used.
Table 7.1. Disk and Extra-planar Properties of Edge-on Galaxies

<table>
<thead>
<tr>
<th>Galaxy</th>
<th>H\textsc{i} mass $10^9 M_\odot$</th>
<th>$L_{TIR}/D_{25}^2$ $10^{40}$ erg s$^{-1}$ kpc$^2$</th>
<th>1C, 2C, $^a$</th>
<th>Thick Comp.</th>
<th>H\textsc{i} Lag$^b$ km s$^{-1}$ kpc$^{-1}$</th>
<th>Mass$^c$ $10^{10} M_\odot$</th>
<th>Ref.$^*$</th>
</tr>
</thead>
<tbody>
<tr>
<td>UGC 1281</td>
<td>2.75 $^d$</td>
<td>n/a</td>
<td>F</td>
<td>0.18−0.31</td>
<td>n/a</td>
<td>0.6</td>
<td>1, 2</td>
</tr>
<tr>
<td>NGC 5023</td>
<td>6.1</td>
<td>0.31</td>
<td>1C</td>
<td>0.34</td>
<td>−14.9</td>
<td>1.4</td>
<td>3-5</td>
</tr>
<tr>
<td>UGC 7321</td>
<td>1.1</td>
<td>0.35</td>
<td>2C, F</td>
<td>2.2 $^f$</td>
<td>≤</td>
<td>− 25</td>
<td></td>
</tr>
<tr>
<td>UGC 2082</td>
<td>2.5</td>
<td>0.50</td>
<td>1C</td>
<td>0.45</td>
<td>n/a</td>
<td>5.6</td>
<td>3, 4</td>
</tr>
<tr>
<td>NGC 4244$^g$</td>
<td>2.5</td>
<td>0.53</td>
<td>1C</td>
<td>0.56</td>
<td>−9</td>
<td>3.2</td>
<td>4, 5, 9, 10</td>
</tr>
<tr>
<td>NGC 5746</td>
<td>10</td>
<td>1.16</td>
<td>1C</td>
<td>0.4</td>
<td>n/a</td>
<td>62</td>
<td>4-5, 11, 12</td>
</tr>
<tr>
<td>NGC 4565$^g$</td>
<td>9.9</td>
<td>1.45</td>
<td>F</td>
<td>0.2 −0.6</td>
<td>−30, −40</td>
<td>38</td>
<td>4, 10, 12, 13</td>
</tr>
<tr>
<td>Milky Way</td>
<td>8</td>
<td>3.0</td>
<td>2C, F</td>
<td>1.6</td>
<td>−22,−15</td>
<td>20</td>
<td>12, 14, 15</td>
</tr>
<tr>
<td>NGC 4302$^g$</td>
<td>3.0</td>
<td>4.6</td>
<td>2C</td>
<td>0.3−1.8</td>
<td>−20.5, −41</td>
<td>10</td>
<td>4</td>
</tr>
<tr>
<td>NGC 3044$^g$</td>
<td>3.0</td>
<td>6.62</td>
<td>1C</td>
<td>0.64</td>
<td>−33</td>
<td>6.4</td>
<td>4, 5, 15</td>
</tr>
<tr>
<td>NGC 4013$^g$</td>
<td>2.1</td>
<td>7.0</td>
<td>F</td>
<td>0.2−1.0</td>
<td>−28</td>
<td>21</td>
<td>4</td>
</tr>
<tr>
<td>NGC 891</td>
<td>4.1</td>
<td>8.71</td>
<td>2C, F</td>
<td>1.25−2.5</td>
<td>−15</td>
<td>14</td>
<td>4, 9, 13, 16</td>
</tr>
<tr>
<td>NGC 5775</td>
<td>9.1</td>
<td>25.6</td>
<td>1C + features</td>
<td>1</td>
<td>n/a</td>
<td>15</td>
<td>4, 5, 15, 17</td>
</tr>
</tbody>
</table>

$^a$1-component (1C), 2-component (2C), flare (F), or a combination of these. All of the galaxies presented here appear to be warped to some degree.

$^b$Peak lag values in region before shallowing. If two values, then there are different values for each half of the galaxy.

$^c$Dynamical mass calculated using the rotational velocity at the largest detected H\textsc{i} radius ($M = \frac{v^2 R}{G}$). These dynamical masses are lower limit based on the outermost measured H\textsc{i} rotation speed.

$^d$(Private communication) P. Kamphuis.

$^e$Appropriate $L_{TIR}$ is not available for this galaxy. However, based on H\textsc{a}, its star formation rate is 0.0084 M$_\odot$ yr$^{-1}$ (van Zee, 2001), rendering it among the lowest of the galaxies presented here based on calculated rates for the rest, but could be severely underestimated due to extinction.

$^f$Gaussian as opposed to exponential layer. In the case of NGC 891, see Oosterloo et al. (2007) for details on the distribution used to fit the halo component.

$^g$Galaxies presented in this thesis.

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Figure 7.1 The average scale height of the thickest \( \text{H} \text{i} \) layer in each galaxy listed in Table 7.1 plotted against \( L_{\text{TIR}}/D_{25}^2 \). NGC 5775 is the outlier with a \( L_{\text{TIR}}/D_{25}^2 \) of 25.6. Even omitting this point yields no conclusive trends. UGC 7321 is represented by the high point at 2.2 kpc. If this point were omitted as well, then there may be a very slight increase in scale height with an increase in \( L_{\text{TIR}}/D_{25}^2 \).

We first consider the thickness of the \( \text{H} \text{i} \) layers. The thickness is difficult to define given that some galaxies require a single exponential layer, while others require two. Also, some have flares or warps. Furthermore, some galaxies may have smaller scale heights than those presented here due to resolution limitations. It is also possible that a thinner disk could be concealed within those presented here. To be as consistent as possible, we consider the scale height of the thickest modeled layer in the central regions, not affected by warps or flares, and where star formation is
typically concentrated. As is illustrated in Figures 7.1 and 7.2, we see no quantifiable trends linking extra-planar \( \text{H} \text{\textsc{i}} \) thickness with SFR \( (L_{\text{TIR}}/D_{25}^2) \). There were early indications based on Oosterloo et al. (2007) and Zschaechner et al. (2011, 2012) that the presence of extra-planar \( \text{H} \text{\textsc{i}} \) may correlate with SFR within galaxies in a qualitative sense, but the lack of extra-planar \( \text{H} \text{\textsc{i}} \) in NGC 4013 with its high SFR, and the presence of substantial extra-planar \( \text{H} \text{\textsc{i}} \) in the low SFR galaxy, UGC 7321 (Matthews & Wood, 2003) indicate that a simple relation between the two is likely non-existent.

It may be that galaxies with large dynamical masses such as NGC 4565 and NGC 4013 are less likely to have large amounts of extra-planar \( \text{H} \text{\textsc{i}} \) due to stronger gravitational potentials, especially near their centers. Given that both NGC 4565 and NGC 4013 have greatly differing SFR, but similar morphologies (i.e. thin central...
Figure 7.3  The central scale height of the thickest H\textsc{i} layer in each galaxy listed in Table 7.1 times the peak rotational velocity plotted against $L_{\text{TIR}}/D_{25}^2$. NGC 5775 is again the outlier. Again, there is no convincing trend. If NGC 5775 is included, the Pearson Correlation Coefficient is 0.07. If NGC 5775 is omitted, then the Pearson Correlation Coefficient is still only a value of 0.09.

regions and flaring at large radii), it may be that mass as well as SFR is significant when it comes to determining the amount or presence of extra-planar H\textsc{i}. In contrast, NGC 4302 also has a rather large dynamical mass, but has substantial amounts of extra-planar H\textsc{i}. We explore the role dynamical mass might play in Figures 7.3 and 7.4 in which the average scale height of the thickest H\textsc{i} layer in each galaxy listed in Table 7.1 times the peak rotational velocity is plotted against $L_{\text{TIR}}/D_{25}$. The justification for comparing these quantities is the dependence of the scale height on the ratio of the velocity at which material is launched from the disk and the rotational velocity in the ballistic disk-halo cycling considered in the models of Collins et al. (2002). There are only hints of a correlation, but nothing convincing. The Pearson Correlation Coefficient is 0.09 if NGC 5775 is omitted. There is some justification for excluding NGC 5775 from trends as it has a small scale height, but prominent shells and filaments reaching to large heights above the midplane, rendering it difficult to treat in this analysis.
Chapter 7. Discussion and Future Work

Figure 7.4. The same as Figure 7.3, but with $L_{TR}/D_{25}^2$ on a logarithmic scale. Again, no correlation is seen.

7.4 General Properties of Observed H I Lags

Among the galaxies presented in this thesis, we observe lags in every galaxy. With the possible exception of NGC 4302 all of these lags begin at the midplane. (Although the lag in NGC 4013 starts at what is considered to be a height of zero for the warped part of the disk, the warp itself rises above the midplane.) Additionally, the lags of NGC 4244, NGC 4565, and NGC 3044 decrease in magnitude with radius, shallowing between approximately 0.5 and 1.0 times $R_{25}$ (Figure 7.5). The lag in the receding half of NGC 4302 shows similar behavior, but should be considered with less weight than the others. The lag in NGC 4013 does not appear to shallow with radius, but such a shallowing would be difficult to constrain within such a prominent warp.
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Figure 7.5 The radial variations of the optimal lags modeled for NGC 4244, NGC 4565, NGC 3044, NGC 4302, and NGC 5023 (Kamphuis et al. 2013, accepted for publication in MNRAS). The radial distance in each galaxy is normalized to $R_{25}$. Note how all of the lags reach their shallowest values near $R_{25}$. The lag on the approaching half of NGC 4302 is omitted since it is constant, as is the lag for NGC 4013. The lag in NGC 891 is also seen to shallow with radius, reaching its minimum value near 10 kpc ($R_{25}$ is approximately 16.8 kpc) but is not shown here.

7.5 Connections Between HI Lags and Star Formation

Heald et al. (2007) remarked on a possible connection in which low global SFR resulted in steeper DIG lags. Additionally, in that work it was suggested that lag magnitude per scale height might be a constant value among galaxies. However, that work involved only three galaxies: NGC 891, NGC 5775, and NGC 4302, rendering trends difficult to constrain at that time. Of the galaxies presented in this thesis, only NGC 4302 has a measured and modeled DIG lag. However, the analysis of a larger sample of DIG lags in galaxies is currently underway by another HALOGAS team member and results are pending (e.g. Wu et al. 2013).

For this analysis, we consider lags interior to the radius where they begin to shallow. These are the values listed in Table 7.1. As can be seen by examination in Table 7.1, there appears to be no such connection between HI lag magnitude and $L_{TIR}/D_{25}^2$ within a given galaxy. In fact, the shallowest lag we measure is in NGC...
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Figure 7.6 The peak lag magnitude in each galaxy listed in Table 7.1 multiplied by the peak rotational velocity plotted against $L_{TIR}/D_{25}^2$. We see no correlation between these quantities.

4244, the galaxy having the lowest $L_{TIR}/D_{25}^2$ among our sample. In contrast, NGC 3044 has a much steeper lag, and a much higher $L_{TIR}/D_{25}^2$. Thus, the $\text{H}_i$ lags clearly do not follow the Heald et al. (2007) trend. It should be noted that our findings do not indicate the opposite of the Heald et al. (2007) trend, but rather a scattering of lags and SFRs, with no discernible pattern. This lack of a correlation is also seen when considering lag magnitudes per scale height. We consider a further possible relation involving the peak rotational velocity to eliminate some of the gravitational influence (Figure 7.6), but again find no correlation.
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7.6 Connections Between H I Lags and Environment

Among the galaxies presented in this thesis, the one with the strongest indications for environmental factors affecting the lag is NGC 4302. The lag in that galaxy may begin high above the midplane, and displays irregular behavior uncharacteristic of more isolated galaxies. Its presence in all four quadrants indicates that it is truly a global feature in spite of being influenced by external sources.

NGC 4302, NGC 3044, NGC 4565, and NGC 4013 are the galaxies within our sample that have the steepest lags. These are also the galaxies in this thesis showing the strongest evidence for interactions or merger activity. In contrast, NGC 4244 is an isolated galaxy, and has an extremely shallow lag compared to the others. Such a difference in the magnitudes of the lags we observe in each galaxy may indicate that external influences contribute to the lag magnitudes. However, when including other galaxies from the literature, the Milky Way has a moderate lag of $-15/−22$ km s$^{-1}$ kpc$^{-1}$ but is clearly interacting with the Magellanic Clouds (this is not to say that there is any evidence that the Magellanic Stream is directly influencing the lag value). Additionally, NGC 891 also has a relatively shallow lag of $-15$ km s$^{-1}$ kpc$^{-1}$, but is a member of the NGC 1023 Group (Trentham & Tully, 2009). Thus, the degree to which external influences affect lag magnitudes cannot be constrained at this time. It could be that such disturbances could steepen or lessen lag magnitudes depending on the kinematics of a given galaxy and its interaction.

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7.7 Implications for Theoretical Scenarios

The magnitudes of the lags we measure are clearly steeper than those produced by ballistic models such as those presented in Collins et al. (2002). However, such a scenario was already expected as purely ballistic models have already been known to underestimate lags. One possible reason for this discrepancy is angular momentum lost from material ejected high above the plane of the disk in disk-halo flows to a slow-rotating, hot halo encompassing a galaxy.

Assuming the models of Marinacci et al. (2011) in which hot coronal gas is mixed with galactic fountain flows, cools, and then is accreted onto the disk are correct, then the radial shallowing of the observed H\textsc{i} lags in most of the galaxies presented in this thesis indicates that a majority of this accretion must take place within a certain radius near $R_{25}$. This possibility would go against some accretion scenarios, where such gas is expected to accrete onto outer disks to produce warps (e.g. Jiang & Binney 1999, Shen & Sellwood 2006). However, it may be that the accretion considered in those papers may not be associated with accretion that would produce lags in the inner regions of galaxies. It should be noted that we do not consider the radial variation in NGC 4013, the galaxy in our sample with the most substantial warp. The reason for the omission of NGC 4013 when considering radially shallowing lags is the warp itself, as ballistic effects would differ greatly from those associated with a relatively flat disk.

Additionally, with the possible exception of NGC 4302, the lags we measure all start close to the midplane. The primary implication of the lags starting at a low $z$ is that it is unlikely that they are purely accretion driven, and disk-halo flows are more likely responsible. Such a scenario could be consistent with Marinacci et al. (2011) and Marasco et al. (2013) in which accretion of coronal material is driven by its mixing with gas ejected by supernova explosions, although lags close to the plane...
are not explicitly mentioned in those works.

However, the lags Marinacci et al. (2011) simulate are approximately $-15 \text{ km s}^{-1} \text{kpc}^{-1}$. These values match the lags in NGC 891 and the Milky Way, but the lags we measure in NGC 4565, NGC 3044, and NGC 4013 are steeper by a factor of two. This variation, as well as substantially differing morphologies of the latter three galaxies, despite similar lag magnitudes, indicate that there may not be a simple extension of these simulations, and that additional physics may be required to properly fit the extra-planar kinematics in a variety of galaxies.

Marinacci et al. (2011) note that a hot corona rotating 200 km s$^{-1}$ more slowly than the main disk would contribute roughly $-7 \text{ km s}^{-1} \text{kpc}^{-1}$ to the H$\text{I}$ lag in a galaxy such as the Milky Way, while one rotating 75 km s$^{-1}$ slower would only contribute $-3 \text{ km s}^{-1} \text{kpc}^{-1}$ to the lag. If we assume, as Marinacci et al. (2011) suggest, that supernova feedback (i.e. a ballistic disk-halo flow) can account for approximately half of the H$\text{I}$ lag magnitude (a rough assumption that they do not claim or deny will apply to all galaxies), then if the relation is linear, a hot corona would need to rotate 400 km s$^{-1}$ slower than the main disk in NGC 4565, NGC 3044, or NGC 4013 in order to achieve a contribution of $-15 \text{ km s}^{-1} \text{kpc}^{-1}$ (approximately half of their total observed lag values). Given the rotational velocities of these three galaxies, the hot corona would need to be rotating counter to the main disk of the galaxy at great speeds in all three cases. Clearly, such a scenario is extremely unlikely if steady accretion is occurring. This problem may be mitigated if additional factors are also at play that might steepen lags such as higher coronal densities, more efficient drag, or larger clouds.

It should also be noted that NGC 4565 is clearly undergoing an interaction with at least one of its companions. Also, NGC 3044 has indications that it has undergone a minor merger, although there is no conclusive evidence. There also exist stellar streams in NGC 4013 (discussed in Chapter 4) that have been attributed to a minor
merger with a dwarf galaxy. One might suggest that interactions or mergers somehow contribute to lag magnitudes. However, the lags in all of those galaxies are global and fairly axisymmetric. Such behavior would be unlikely if the lags were a byproduct of interactions or mergers. One may instead consider more general environmental factors such as the abundance of gas surrounding each galaxy. Perhaps in some group environments there is more primordial material to accrete, which could potentially contribute to the lags. Such a possibility would be supported by the abnormally shallow lag measured in NGC 4244, which is an isolated galaxy. It is far too early to draw anything conclusive concerning the observed lags and their environments. We simply remark on the possibility that environmental factors may play some role in producing lags.

Additionally, the mode of accretion may have different effects on extra-planar kinematics. Kereš et al. (2005) state that hot mode accretion is dominant in groups and clusters, while cold mode is dominant in lower density regions and at high redshift (although we are only currently concerned with low redshift in this thesis). It is not difficult to imagine that a lag produced through accretion through filamentary structures may differ that produced through the process described in Marinacci et al. (2011) involving a spherical hot corona surrounding the entire galaxy.

The radial shallowing of the lags we observe is consistent with expectations based on conservation of angular momentum (although it is almost certain that there must be more physical processes involved in addition to gravitational effects). However, disk-halo flows modeled Bregman (1980) predicted the opposite trend, in which lags would steepen with radius. Our results indicate that such a scenario would be incorrect. Recall the ideas put forth by Benjamin (2002) in which extra-planar pressure gradients could modify lags. Such considerations could be used to constrain the overall lag magnitudes as well as their radial variations. Currently there are few observational constraints for such pressure gradients. However the pressure due to
magnetic fields and cosmic rays may be greater than the pressure exerted by hot gas at large heights above the midplane (Irwin et al., 2012).

### 7.8 Future Work

There exist eight hours of archival data for NGC 3044 in C-configuration with the VLA (Lee & Irwin 1997). We have omitted these data from this thesis due to their lower velocity resolution, but will add them to our observations prior to final publication. The purpose of including these additional data are to detect additional faint emission. We will also check these data for consistency with our models.

Deep, 12×17 hours WSRT observations of NGC 4013 have been performed by our collaborators. We intend to combine our observations with these prior to final publication, working closely with other individuals involved.

While much of the HALOGAS sample has already been modeled, results for a few more edge-on galaxies are pending. Additionally, distinct features attributed to either disk-halo flows or accretion events must be cataloged for the entire sample, with one goal being to estimate the current neutral accretion rate onto galaxies. DIG observations and models have yet to be made for some of these galaxies, although models are pending for some such as NGC 4565 and NGC 4244 (Wu et al., 2013). Not only do the DIG layers need to be considered for the sample, but other multiphase (extra-planar and main disk) components as well in order to draw any connections to the H I.

Additional higher-resolution observations of the HALOGAS sample may be desirable to constrain lags close to the midplane. Final analysis of the complete HALOGAS sample, as well as theoretical simulations will help to decide whether such observations are warranted.
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In this work we have considered $L_{TIR}/D_{25}^2$ as a method of gauging SFR per unit area. A more accurate quantity to consider would be $L_{TIR}$ divided by the infrared diameter squared, as both would be infrared. Ideally, Spitzer 24μm or WISE data would be used for this as it has the highest resolution of the infrared data. Such a change could potentially affect correlations.

Although a substantial improvement from GALMOD, TiRiFiC still has some limitations. Firstly, it relies on a $\chi^2$ minimization for automated fitting, which is suboptimal considering that much of the emission used to constrain lags is faint. Alternative numerical methods may be a possibility, but may not be time-efficient given the relatively small number of galaxies that still must be modeled. Alternatively, it may be fruitful to simulate galaxies with features such as warps, flares, etc., and allow multiple individuals to model them independently to see if the same results are obtained for each. Finally, TiRiFiC is still undergoing developments in which there may be additional improvements to methods for fitting distinct features such as bars and spiral structure.

Theoretical scenarios are somewhat reliant on the existence of hot halos surrounding galaxies. There have been some detections such as that presented by Dai et al. (2012) in which X-ray emission is detected 80 kpc from the center of the rapidly rotating galaxy, UGC 12591. Additionally, the work presented by Anderson et al. (2013) used stacked images of a large sample of galaxies to detect X-ray halos, but deeper observations are necessary for detections in individual galaxies.

The New HERschel Multi-wavelength Extragalactic Survey of Edge-on Spirals (NHEMESES) described in Holwerda et al. (2012) targets 12 nearby, edge-on, low surface brightness galaxies, in part to measure the thickness of their associated dust layers, and to see if there is any relation to galaxy mass. Another Herschel project in its early stages is HERschel Observations of Edge-on Spirals (HEROES) (Verstappen et al., 2013). Both projects will also attempt to detect and characterize extra-planar
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structures, for which a comparison may be drawn to the extra-planar H I in each
galaxy. Finally the Herschel Edge-on Galaxy Survey (HEDGES) will carry out deeper
observations of a smaller sample of galaxies, including NGC 891, NGC 4244, and
NGC 4565, which have been discussed in this thesis.

7.8.1 The Anomalous H I Thick Disk of the Low Surface
Brightness Galaxy UGC 7321

Results from this thesis indicate that extra-planar H I layers are not ubiquitous,
especially in galaxies with low SF. However, a substantial extra-planar H I layer is
seen in UGC 7321 (Matthews & Wood, 2003), a low surface brightness (LSB) galaxy
with a low SFR. This defies expected trends and demands investigation.

UGC 7321 is currently the best known candidate for an accretion-driven extra-
planar H I. However, its H I kinematics are poorly constrained in that only an
upper limit has been set on the lag magnitude. Thus we must assess any gradients in
rotational velocity with height, anomalous radial motions, or counter-rotating clouds.
All could be signs of primordial accretion and vital to understanding extra-planar
H I origins and evolution.

We have observed UGC 7321 for 21 hours with the VLA during B configuration,
and 7 hours in C configuration. These observations will be combined with 16 hours
of archival C-array data. This galaxy will supplement both this thesis, as well as the
HALOGAS sample.

7.8.2 Additional Radio Surveys of Nearby, Edge-on Galaxies

The ongoing Continuum HAlos in Nearby Galaxies (CHANG-ES) survey (Irwin et al.,
2012) involves deep, multi-configuration, 6 and 20 cm radio continuum (cosmic ray)
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observations of 35 nearby, edge-on galaxies. Galaxies presented in this thesis that are also part of the CHANG-ES sample are NGC 4244, NGC 4565, NGC 3044, and NGC 4302. The extra-planar radio continuum observations can be compared with H\textsc{i} observations to see if there may be any connection between the two. Additionally, through considering Faraday rotation (a method of constraining the line of sight magnetic field strength and order) as well as synchrotron polarization (an across the line of sight interpretation), these data could be used to investigate the magnetic fields that could potentially cause pressure gradients. It is thought that cosmic rays and magnetic fields may be the dominant sources of extra-planar pressure, while in the midplane they play a comparable role to the pressure exerted by hot gas (Irwin et al., 2012). Understanding the pressure due to magnetic fields at varying heights is useful in understanding disk-halo physics, as such gradients could affect both lag magnitudes, as well as their radial variations, as discussed in Benjamin (2002).

Although still in a developmental stage, the Meerkat H\textsc{i} Observations of Nearby Galactic Objects: Observing Southern Emitters (MHONGOOSE) survey will be similar to HALOGAS, but for the southern hemisphere (de Blok 2011). Their sample will include 30 nearby galaxies of varying inclinations that will be observed for 30 hours each.

Additionally, the Square Kilometer Array (SKA) will map H\textsc{i} in and around galaxies to unprecedented sensitivities.
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