Spring 4-16-2018

Infrared Properties of Stars in the Bulge Asymmetries and Dynamical Evolution Survey

Eddie Hilburn
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INFRARED PROPERTIES OF STARS IN THE BULGE ASYMMETRIES AND DYNAMICAL EVOLUTION SURVEY

by

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BACHELOR OF SCIENCE, PHYSICS

THESIS
Submitted in Partial Fulfillment of the Requirements for the Degree of

Master of Science
Physics

The University of New Mexico
Albuquerque, New Mexico

May, 2018

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ACKNOWLEDGEMENTS

I owe a great many thanks to a great many people. Most of all to my wife Jessica for all of the times when I have disappeared into the office for hours on end. I look forward to all the additional time we’ll be able to spend together. Your boundless love and support mean the world to me.

I would also like to thank the many Air Force leaders who have allowed me the flexibility to pursue my academic goals. To CMSgt. (ret.) Leroy Ainsworth, Col. Monti Knode, Col. Heather Anderson and the many others who have supported me along this path – thank you.

This would certainly have been a much more difficult road without the incredible support of my advisor, Dr. Ylva Pihlstrom. From the countless rewrites to the panicked eleventh-hour emails when simulation results were in question, she has provided a model of wisdom and patience which I can only hope to emulate in my own life.

Finally, none of this would be possible without the support of my family. The love and support of my parents and siblings have provided the foundation from which I am able to reach for all of my dreams. Thank you for always being there for me.

Eddie Hilburn
INFRARED PROPERTIES OF STARS IN THE BULGE ASYMMETRIES AND DYNAMICAL EVOLUTION SURVEY

by

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B.S., Physics, University of Texas at San Antonio, 2015
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ABSTRACT

The Bulge Asymmetries and Dynamical Evolution (BAaDE) survey is an SiO maser survey of 28,062 infrared-selected evolved stars primarily in the Galactic plane. By cross-matching the BAaDE target sources with nine different infrared catalogs, we have constructed a catalog with wavelength coverage from 0.71 to 80 μm. Using this catalog, we fit the data for each source to a model spectral energy distribution (SED) generated with the radiation transport program DUSTY in order to obtain characteristics such as bolometric flux, source effective temperature, and the optical depth of the circumstellar envelope.

The overall goal of the BAaDE survey is to extract a gravitational potential in order to model Galactic dynamics, by providing line-of-sight velocities and positions for each source. The results would be greatly enhanced if, in addition to the positions and velocities, we could also provide a distance estimate. We explore a new method of estimating distances to the BAaDE sources by creating a series of template SEDs, differentiated by infrared color in the region of the spectrum covered by the Midcourse Space Experiment (MSX; 8.28 – 21.34 μm). We calibrate the first of these template SEDs using similarly colored Red Giant stars with known parallax-distances, and obtain an empirical relation between the bolometric flux and distance of sources with similarly shaped SED.
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1. Introduction

The Milky Way presents at once the highest resolution and most obscured environment for the study of galactic evolution. Our location within the Galaxy enables extensive stellar catalogs to be built, including measurements of stellar velocities and even distance estimates in some cases. In addition, the distribution of these and other stellar properties as a function of Galactic longitude can be acquired. Our position within the Galaxy, however, prevents face-on observations, making exact maps of stellar properties across the Galaxy difficult. In particular, attempts to observe the central bulge region have been difficult due to obscuration, and remain so in most parts of the electromagnetic spectrum, with visible extinctions of up to 28 magnitudes toward the Galactic Center (Yusef-Zadeh & Wardle 1992). For this reason, observations into the Galactic bulge are largely restricted to infrared and longer wavelengths, which suffer less extinction from intervening dust.
The past few decades have seen a number of investigations of the structures of the Galactic bulge region. Images from the COBE telescope in 1990 (Fig. 1.1) show a peanut-shaped bulge toward the Galactic center (Hauser et al. 1990). Using 2.4μm data from balloon observations by Matsumoto et al. (1982), Blitz and Spergel (1991) showed direct evidence that this bulge contains a stellar bar, as had previously been implied by gas dynamics (Peters 1975; Sanders & Huntley 1976; Liszt & Burton 1980; Mulder & Liem 1986). The data analyzed by Blitz and Spergel not only suggested a bar-like structure, but also offered constraints on the geometry. For example, the data showed evidence of triaxiality of the bar, that the side of the bar nearest to us is rotated toward positive Galactic longitude, and that there likely is a tilt with respect to the $b = 0°$ plane. Using an IRAS selected sample of late-type stars in the bulge region, Whitelock and Catchpole (1992) presented derived distances based on period-luminosity relations, revealing a prolate spheroid shaped bar inclined to the line of sight by $\sim 45°$. They further considered an X-shaped distribution as a combination of two triaxial ellipsoids to address the peanut shape seen in COBE images, but the sample size was too small to conclude whether this was a viable model or not. Using data from the Diffuse Infrared Background Experiment (DIRBE) on the COBE spacecraft, Weiland et al. (1994) analyzed the brightness contours of the bulge region and found support for most of the findings of Blitz and Spergel (1991). Specifically, evidence was found for a triaxial bar with its near end at positive longitudes, although a tilt relative to the plane was not necessary to fit the data. Additionally, Weiland et al. found that the bulge is better described as a
“box” than a “peanut”, as the lobes seen in earlier COBE images were flattened out. A scale height of $2^\circ \pm 0^\circ.2$ of the bulge was reported.

Later observations and subsequent analysis of the data has not reached consensus regarding the exact geometrical parameters of the bar structure in the bulge. Vanhollebeke et al. (2009) provides a listing of a sample of the bar geometrical parameters estimated from a variety of observational methods at that point in time. The estimated values in some cases vary by as much 75%, illustrating the uncertainties of the measured values of the shape, brightness distribution, age and population of the bulge and any associated bar. More recent bulge surveys such as ARGOS (Ness et al. 2012), GIBS (Zoccali et al. 2014) and APOGEE (Nidever et al. 2012) are pushing closer to the plane and bulge, yet they are still fundamentally limited by extinction, and also to some extent by confusion. To a great extent, optical and infrared surveys have reached a limit that cannot be surpassed simply by increased sample size away from $b = 0^\circ$.

These findings and many others have contributed to our current understanding of the environment of the Galactic bulge region, but also highlight how much we still do not know. The studies discussed above reflect only a few of the numerous approaches used to study this intractable region of space. Yet despite the difficulty, our proximity alone makes the Galactic bulge a remarkable laboratory in which to study in detail the processes occurring in spiral galaxies in general. To this end, the Bulge Asymmetries and Dynamical Evolution (BAaDE) survey is currently underway and seeks to significantly improve our understanding of the dynamics, structure and range of stellar ages in the bulge and inner Galaxy populations. In this chapter we describe the BAaDE survey (Sect.
1.1), the typical characteristics of the stars constituting the BAaDE sample (Sect. 1.2), and give a brief overview of the infrared data discussed in this thesis (Sect 1.3).

1.1 The Bulge Asymmetries and Dynamical Evolution (BAaDE) Survey

The BAaDE survey is a targeted search for SiO maser emission in 28,062 infrared (IR) color selected red giant stars, most of which are likely to be on the Asymptotic Giant Branch (AGB). Through a judicious color selection (Sect. 1.1.1), a high probability that our sources have properties conducive for SiO maser emission is ensured, and based on our preliminary bulge detection rate we expect the final catalog to consist of ~20,000 SiO emitting infrared stars. The maser emission is observed using the Very Large Array (VLA) in central New Mexico for the sources which can be observed in the Northern Hemisphere and using the Atacama Large Millimeter Array (ALMA) in Chile for sources visible only in the Southern Hemisphere. The SiO molecule has maser transitions at both 43 GHz and 86 GHz, and by observing these radio emission lines in the plane of the Galaxy, we are able to bypass the problem of extinction almost entirely, providing a vast library of point-mass tracers of the Galactic gravitational potential. These observations provide line of sight velocities accurate to ~1 km/s, so that we then have a set of correlated positions and velocities. Along with their individual stellar properties, this data can be used to better constrain modeling aimed at understanding the dynamics and evolution of our Galaxy as well as the AGB phase of stellar evolution.
1.1.1 Source Selection

The masers being studied in the BAaDE project arise in the circumstellar envelope (CSE) surrounding an ageing star. To pre-select for sources with envelopes likely to harbor SiO maser emission, the target stars were selected based on their

![Figure 1.2: Comparison of IRAS (top-right) and MSX two-color diagrams for selection of oxygen-rich AGB stars with differing CSE properties. Stars selected for the BAaDE project are from region IIIa/iia. (Reproduced with permission from Sjouwerman et al. 2009, Fig. 8)](image)
Table 1.1: MSX color selection criteria for inclusion in the BAaDE project. Sources with this classification are expected to contain SiO maser emission (Sjouwerman et al. 2009).

\[
\begin{align*}
\text{MSX iiia: } & -0.6 \leq [A] - [D] < +0.4 \\
& -0.7 \leq [A] - [E] < +0.4 \\
& -0.75 \leq [C] - [E] < +0.1
\end{align*}
\]

infrared colors, following the selection method first reported by van der Veen and Habing (1988) using colors from the IRAS catalog. This work contains an “evolutionary track” in the [12]-[25]/[25]-[60] two-color diagram for AGB stars, where the diagram was divided into regions corresponding to different evolutionary stages along a mass-loss continuum (Top right panel of Fig. 1.2), from Mira variables at the lower left (IIIa region) to OH/IR stars and Planetary Nebulae in the upper right of the diagram. Stars which are expected to exhibit SiO maser emission fall along the early part of the track, including Mira variables with an evolved, oxygen-rich CSE, in the region labelled IIIa.

Thus, by selecting sources based on IRAS colors, a sample of oxygen-rich sources can be constructed. However, one of the difficulties with using IRAS for selecting SiO maser candidates in the plane and bulge region is that IRAS suffers from significant confusion due to the low angular resolution of its instrument and the high stellar density in the region.

To solve the issue of confusion, more recent infrared surveys with improved angular resolution can be used. Sjouwerman et al. (2009) have conducted a study comparing the IRAS color selection criteria to the colors available from the Midcourse Space Experiment (MSX) point source catalog (PSC). With a smaller beam, the confusion
problem is considerably less in the MSX survey, although there is likely some confusion even with MSX within the central degree of the Galaxy. Moreover, the MSX mission focused primarily on observations of the Galactic plane at latitudes $|b| < 6^\circ$, as well as parts of the sky that were not covered by IRAS. For these reasons, color selection from this catalog is ideal for the goals of the BAaDE survey. The bands used for the MSX mission (8.28, 12.13, 14.65 and 21.34 $\mu$m for bands A, C, D and E respectively; B bands excluded for reasons explained in Sect. 2.1) do not extend to the longest wavelength (60$\mu$m) of the van der Veen and Habing IRAS color-color diagram, hence the vertical depth of the IRAS diagram is not converted into corresponding MSX color-color diagrams, which effectively means that a set of carbon-rich sources may be included in our sample. Despite this, associations are well established along the horizontal [12]-[25] mass-loss progression, and criteria are given for mapping MSX-derived colors to IRAS two-color diagram regions I-V. The criteria for MSX region iii which were used to select the sources for the BAaDE project are given in Table 1.1. Applying these color criteria to the full MSX PSC, we have selected 28,062 SiO maser candidates with good MSX infrared photometry, primarily in the Galactic plane and bulge regions (Fig. 1.3).

Figure 1.3: The Galactic distribution of the 28,062 BAaDE sources. Sources are primarily within $|b| < 6^\circ$, and concentrated in the Galactic bulge region.
1.2 Source Characteristics

The stars selected for the BAaDE project are evolved red giant stars, most of which likely lie on the Asymptotic Giant Branch (AGB) of the Hertzsprung-Russell (HR) Diagram (Fig. 1.4). Largely based on the review by Habing (1996 and references therein), I here give a general description of these stars.

Only stars with a main-sequence mass less than about $6 \, M_\odot$ (hereafter, “low mass”) become AGB stars. More massive stars end their life as supernovae, while AGB stars result in the formation of planetary nebulae. Comparisons of supernova and planetary nebula formation rates indicate that 95-98% of all stars at the end of their life become supernovae, while the remaining stars become planetary nebulae.

![HR Diagram](chart.png)

Figure 1.4: An HR Diagram highlighting the evolutionary path of low mass stars, below approximately $6 \, M_\odot$. The low temperatures and large sizes give these stars the common moniker: Red Giants.
life in our Galaxy are low mass stars. As described in Sect. 1.1, the evolutionary track identified in the IRAS color-color diagram by van der Veen and Habing is a mass-loss progression. As a low mass star enters the AGB phase, its core consists primarily of carbon and oxygen. A thin shell of helium separates the core from an extensive “mantle” of hydrogen. The nuclear burning fueling the stellar luminosity is primarily due to hydrogen fusion at the boundary of the helium shell, increasing the mass of the helium layer. At regular intervals, as the mass of the helium shell reaches a critical point, helium will ignite and burn into carbon and oxygen. This helium ignition results in a rapid increase in the luminosity of the star, and once this period of helium burning ends, a subsequent decrease in luminosity, and efficiently causes dredge-up of material to the outer layers. The regular variability observed in Miras arises in the shell of hydrogen surrounding the helium layer, which has to change its temperature and pressure in order to retain stability against gravity. The period and amplitude of this variability increase as an AGB star ages. Another characteristic feature of AGB stars is mass loss. During the AGB phase, stars shed mass at rates between $10^{-7}$ and $10^{-4} M_\odot/yr$, with rates increasing as the star ages. According to the model developed by Goldreich and Scoville (1976), this mass loss is a spherically symmetric outflow of gas. Stellar matter is ejected at a velocity on the order of 10 km/s for up to $\sim 10^5$ years, and when it reaches a point far enough from the central star to cool, part of it condenses into particles of dust. This dust and the remaining gas constitute a circumstellar envelope (CSE) that is accelerated outward from the star via radiation pressure. The dust particles reemit stellar light in the infrared, reddening the appearance of the star.
As the CSE builds up over time, the observed emission of the star is progressively reddened. Vassiliadis and Wood (1993) found that these two features are correlated: the mass loss rate is tied to the thermal pulsation period. This implies that the thermal pulse is a significant contributor to the mass loss in AGB stars.

Thermally pulsing AGB stars can be further categorized based on the characteristics of their variability. As stated previously, both the amplitude and period of variability are expected to increase with the mass loss rate and time. Semiregular variables (SR) are classified based on amplitude variations in the visual band of $\Delta V < 2.5^m$. Periods for SRs are longer than 50 days, with a peak between 125 and 175 days. Mira variables are classified by $\Delta V \geq 2.5^m$, and period $P > 100$ days, peaked near 275 days. OH/IR stars continue this progression, but most have not been detected at visual wavelengths. Instead, they are classified by $\Delta m_{bol}$ between 1 and $2^m$. Similarly, OH/IR stars have much longer periods, between 500 and 3000 days. Habing (1996) argues that stars with $P > 100$ days and $\Delta m_{bol} > 0.7^m$ (referred to as Large Amplitude Long-Period Variables, LALPVs) can be considered one class of object based on smoothly joining periods, an increase in luminosity with period, similar light curves (adjusted for periodic variation) and similar Galactic distribution in the thin disk.

As discussed in Sect. 1.1, the BAaDE survey has selected a narrow part of this distribution of variable stars. Based on the MSX Region iiia defined by Sjouwerman et al., we have selected for stars with CSEs. This selection is chosen to maximize SiO maser detection in stars with relatively thin CSEs. Most LALPVs exhibit maser activity of one or more types. The possibility that all Miras contain SiO masers was first suggested by
Cahn (1977), and this has been supported by numerous studies (Hall et al. 1990; Jewell et al. 1991). In 1989, Lewis proposed a chronology for the formation of well-known masers. From this sequence, SiO masers are the first to arise in LALPVs, and persist for much of the remaining life of the star. This is supported by Jewell et al. (1991), which indicates SiO to be the most prevalent type of maser.

1.3 IR Catalog

For each of the BAaDE targets, we have compiled IR data from nine separate catalogs and twenty-four wavelength bands. The spectral coverage ranges from the near-IR DENIS I-band at 0.71 μm to Herschel far-IR data at 80 μm. The process for compiling this data set is detailed in Chapter 2.

From the IR data, we were able to construct spectral energy diagrams (SEDs). Because our target sources are Miras surrounded by a CSE, these SEDs are expected to differ significantly from a blackbody distribution due to absorption and reemission in the IR by the intervening dust. In order to analyze the constructed SEDs, we have used the radiative transfer modeling program DUSTY (Ivezic, Nenkova & Elitzur, 1999) to create model SEDs based on varying certain properties of the central star and the CSE. By fitting the observed SEDs to the models, we can determine properties such as the bolometric flux and effective stellar temperature, and the relative thickness and opacity of the CSE. The process for creating both the observed and model SEDs, and the fitting procedure used is detailed in Chapter 3.
In Chapter 4 we examine two approaches by which we attempt to estimate distances to the sources in our sample. The first makes use of relationships between IR color, period and luminosity, and we show that the errors associated with each successive relationship render the distance estimate unreliable. The second approach we develop here, using the shape of the SEDs of sources with known distances to calibrate a relationship between the bolometric flux obtained via model SED fitting and a distance to sources with similarly shaped SEDs.

In Chapter 5, I will discuss efforts regarding extinction corrections for our sources. While IR and longer wavelengths are less affected by interstellar extinction than optical wavelengths, the density of the Galactic bulge region does result in some level of extinction. This extinction varies significantly over even closely spaced regions of the sky, and increases with distance. Determining the appropriate correction to apply for our sources has proven to be a challenge, but one that can’t ultimately be ignored.

Although beyond the scope of this thesis, the IR data collected will be used for other purposes in conjunction with our SiO maser survey, for example:

- Correlation of SiO detection/non-detection rates to the IR colors and magnitudes
- Construction of a detailed SiO luminosity function, once distances are known
- Constraining SiO maser excitation conditions, for example with line ratios

Also in Chapter 5, I will explore in a preliminary fashion how these operations could be performed and the potential findings associated with each.
2. IR Catalog Building

The BAaDE IR database is compiled from observations by nine different infrared missions. It includes twenty-four wavelength bands from MSX, 2MASS, DENIS, WISE, GLIMPSE, ISOGAL, MIPSGAL, AKARI and Herschel PACS catalogs (for an overview of the spatial coverage see Fig. 2.1; for wavelength coverage see Fig. 2.2). The final number of uniquely identified cross-matches from each band is listed in Table 2.1. The catalogs are available in the NASA/IPAC Infrared Science Archive (IRSA, http://irsa.ipac.caltech.edu), with the exception of ISOGAL, available in the CDS portal (http://vizier.u-strasbg.fr/viz-bin/VizieR-2). Each catalog contains specific information and flags associated with the given mission and its instruments. Although the details vary between the catalogs, our cross-matching follows a typical strategy. Based on the original BAaDE catalog MSX positions, a positional cross-match is performed. After applying quality flags, if more than one source is detected within the search radius, the source that is redder is assumed to be a more likely match. For each catalog, the method of applying the flags is described in Sect. 2.3 and filtering between multiple candidate matches is described in Sect. 2.4.

2.1 Establishing Search Radius

The MSX PSC includes 6 spectral bands, but only 4 were included in the BAaDE IR database: MSX A (8.28 μm), MSX C (12.13 μm), MSX D (14.65 μm) and MSX E (21.34 μm).
μm). The quality of the B1 and B2 bands was deemed too low so they were excluded.

Quality flags, $Q$, for the observations in the MSX PSC were reported using the signal-to-noise ratio (SNR) as a proxy (Egan et al. 2003). The threshold for inclusion in the MSX PSC was a single band quality flag of $Q \geq 3$, which corresponds to a reliability of 95%, but allowed for other bands detected for that source to be lower quality. All band measurements with quality flags $Q < 2$ (reliability of 80%) were excluded from the final BAaDE IR database. Applying this quality filter excluded a significant number of individual MSX band detections: 1, 308, 14, and 14,928 in bands A, C, D and E respectively.

The stars for the BAaDE project were chosen using IR colors from the MSX mission (Sect. 1.1.1). The accuracy of positions reported in the MSX PSC is thus a primary determinant.

![Figure 2.1: The Galactic distribution of the sources included in the BAaDE IR database. The latitude displayed for each catalog is $|b| < 6^\circ$.](image)
<table>
<thead>
<tr>
<th>IR Catalog Selection</th>
<th>Central Wavelength (μm)</th>
<th>Final Unique Cross-matches</th>
</tr>
</thead>
<tbody>
<tr>
<td>MSX All</td>
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<td>28,062</td>
</tr>
<tr>
<td>MSX A</td>
<td>8.28</td>
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<tr>
<td>MSX C</td>
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<td>27,754</td>
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<td>MSX D</td>
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<td>2MASS All</td>
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<td>Herschel PACS70</td>
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</table>

Table 2.1: Summary of catalogs included in the BAaDE IR database. The final cross-matches listed for each catalog are the result of photometry filtering and selection from multiple matches in a given source search radius. The numbers listed here are the number of final cross-matches included in the BAaDE IR database.
when establishing the search radius in other catalogs. The uncertainty in position depends on the quality of the detection, and has been quantified for detections in the MSX A band (8.28 \( \mu \text{m} \)) specifically, with uncertainties ranging from 0.80” to 2.21” \( (Q_A = 4 \text{ and } 2 \text{ respectively}) \). The measured positional accuracy was established by cross-referencing MSX sources to the Tycho-2 catalog (Høg et al. 2000) with a quoted standard deviation in the offset positions of 60 mas. The full distribution of the offsets between the MSX and Tycho-2 positions is given in the MSX PSC Version 2.3 Explanatory Guide (Egan et al. 2003, Fig. 9 and 10), and shows most offsets falling within a 5” radius of the source, establishing the search radius used in the BAaDE cross-matching procedure. While the MSX PSC suggests there may be a few sources with positional offsets larger than 5” from the MSX position, this number is small and is dominated by sources with \( Q_A \leq 2 \). Increasing the search radius beyond 5” results in a higher risk of false cross-matches in the most crowded regions found in the inner Galaxy.

2.2 IR Coverage Overview for the BAaDE Sample

Evolved stars have circumstellar envelopes that are both bright as well as red, allowing for a comprehensive BAaDE IR database to be constructed based on the nine included catalogs. However, the IR surveys were different in scope including both sensitivity as well as sky coverage. To give a good overall understanding of our BAaDE IR database, in this section we outline the wavelength coverage and sky coverage of the different surveys, starting with a brief description of each survey.
The Midcourse Space Experiment (MSX) was a 2-year, satellite based IR survey which focused on increasing IR coverage of the sky that was either missed by IRAS and COBE, or was confused due to high source density, including the Galactic plane. It used a 35cm clear aperture telescope, and made observations in 6 spectral bands from 4.29-21.34 µm. Out of these, 4 were used for astronomical observations: MSX A, C, D and E (8.28, 12.13, 14.65 and 21.34 µm).

The 2MASS mission is an all-sky survey using two 1.3m ground-based telescopes, one in each hemisphere resulting in 99.998% sky coverage. The 2MASS observations include data in 3 near-IR bands: J, H and Ks (1.24, 1.66 and 2.16µm). The detection limits for 2MASS range from a faintness limit of magnitude 15.8 in the J-band to a saturation limit of magnitude 4 in the K-band.

The Deep Near-Infrared Survey of the Southern Sky (DENIS) catalog provides a high-sensitivity data set of the Galactic center south of declination +2°. The survey ran from 1995-2000 and used the 1m telescope at the European Southern Observatory in Chile. The DENIS dataset provides the bluest part of the BAaDE IR database with the optical I-band centered at 0.82µm, and has two overlapping bands with 2MASS (J and K, 1.228 and 2.145 µm respectively), potentially providing variability information for the BAaDE sources.
• WISE is a NASA project to survey the full sky in the mid-infrared spectral region. It utilized a 40cm aperture space telescope, and observed in four spectral bands: 3.4, 4.6, 12 and 22\(\mu\)m (W1-W4 respectively). There were three separate phases of the WISE mission, depending on the available coolant quantity. The Cryogenic Survey (All-Sky) operated for ~7 months and surveyed the full sky in all 4 bands, the 3-Band Cryo Phase picked up for an additional 50 days with reduced 12\(\mu\)m sensitivity, covering an additional 30% of the sky. The final Post-Cryo Phase operated for just over 4 months, observing an additional 70% of the sky with increased sensitivity in the 3.4 and 4.6\(\mu\)m bands.

• The AKARI All-Sky Survey was an 18-month satellite mission observing 96% of the sky in the mid- and far-infrared. We have included data from the Infrared Camera (IRC) point source catalog at effective wavelengths of 9 and 18 \(\mu\)m. We assessed the Far-Infrared Surveyor (FIS) bright source catalog for inclusion in the BAaDE database in order to provide additional data points in the far-IR, but there were ultimately too few catalog matches to be useful. Using the same 5” search radius from the MSX positions yielded 701 candidate matches. The minimum distance required between sources in the FIS detection algorithm is 48”, which limits the catalog’s usefulness in the region of this study. An upcoming release of a faint source catalog in the same bands will warrant additional consideration.
The GLIMPSE data included in the BAaDE IR database comes from 3 different GLIMPSE missions over 5 different observing epochs (GLIMPSE I, GLIMPSE II, and GLIMPSE 3D). Each of the GLIMPSE missions included observed a different portion of the Galactic Mid-plane. The GLIMPSE I data from 2007 includes observations from $\ell=10-65^\circ$ and $295-350^\circ$, and $b=\pm1^\circ$. The GLIMPSE II data spans two epochs. The observing range was $\ell=\pm10^\circ$ and $b=\pm1, \pm1.5, \text{ or } \pm2^\circ$ depending on the longitude. Likewise, GLIMPSE 3D spans two epochs, and extends the observing latitudes to $b=\pm3$ or $\pm4.2^\circ$ in the Galactic center. The GLIMPSE mission uses the IRAC instrument on the Spitzer Space Telescope, with observing bands at 3.6, 4.5, 5.8 and 8$\mu$m.

The ISOGAL mission surveyed approximately 16 square degrees, primarily focused on the Galactic center region. It used the ISOCAM instrument on the Infrared Space Observatory, a satellite telescope operated by the European Space Agency, with filters at 7 and 15 $\mu$m. Because of the high source density sky region it was intended to study, care was taken to limit photometric error below 0.2 mag. Observations were limited to low brightness sources, identified by IRAS flux measurements $F_{12} < 6$ Jy, in order to avoid saturation. The limiting magnitudes range between 7.0 and 10.1 depending on the density of the source region and the wavelength.
The MIPSGAL mission utilized the MIPS instrument on the Spitzer Space Telescope and observed the inner Galactic plane, from $-62^\circ < \ell < +63^\circ$. The MIPS instrument contains detectors centered at 24, 70 and 160$\mu$m, but problems with the 70 and 160$\mu$m data warrant their exclusion from the high quality catalog. The MIPSGAL 24$\mu$m data are not susceptible to any image saturation, as the analog-to-digital converter for the instrument saturates well before the detector.

The Herschel PACS instrument is part of the Herschel Space Observatory (HSO), and contains three detectors at 70, 100 and 160$\mu$m. It operated for nearly 4 years, and was used to collect data on specific targets and fields as opposed to a sky survey. The spatial coverage is therefore less complete than for some of the other catalogs included in the BAaDE IR database, covering about 4.5% of the sky. We assessed each of the bands included in the PACS PSC for inclusion in the BAaDE database, but only the 70$\mu$m catalog contained a substantial number of matches ($>1000$) with our sources.

The overall spectral coverage and magnitude range of the data included in the BAaDE IR database can be seen in Fig. 2.2. The magnitude ranges shown are not necessarily indicative of the sensitivity or saturation limits of the respective catalog. Rather, they are the 1-sigma range about the mean of each band for the sources included in the final BAaDE IR database.
Figure 2.2: IR coverage of the BAaDE IR database spans 0.71 – 80 μm and 18.2 magnitudes (1-sigma range).
2.3 Photometry Filtering

After the initial cross-matching based on position, we filtered each catalog to remove data of poor quality. Examples of insufficient quality include saturated sources, or sources for which a good position could not be determined due to poor signal-to-noise ratio, etc., the details of which depend on the specific catalog (see details below). For most catalogs, this resulted in a number of instances in which a candidate match was excluded due to poor data quality. The only exceptions to this are the two surveys which utilized the Spitzer Space Telescope: GLIMPSE and MIPSGAL. The photometric requirements required for inclusion in their respective catalogs were high enough that no additional filtering was required. Table 2.2 gives a listing of filters applied to each included catalog, and summarizes the number of detections in each band which were affected.

2.3.1 Two Micron All Sky Survey (2MASS)

The 2MASS PSC contains flags which denote the quality level of the observations. The two flags used here are the photometric quality flag (ph_flag) and the read flag (rd_flag). The photometric quality flag gives an overall quality value for each band calculated using the uncertainty, signal-to-noise ratio and similar metrics. The values ‘\(X\)’ and ‘\(U\)’ specified in Table 2.2 correspond to the inability to extract a valid brightness estimate for a detection and an upper limit on magnitude respectively. Further, ‘\(U\)’ could mean that either the source was not detected in the specific band, or that the
<table>
<thead>
<tr>
<th>Catalog</th>
<th>Initial Candidates</th>
<th>Flag</th>
<th>Value for Exclusion</th>
<th>Observations Excluded</th>
</tr>
</thead>
<tbody>
<tr>
<td>DENIS</td>
<td>I: 18,968 J: 25,413 K: 25,848</td>
<td>#flg</td>
<td>$≠ '0000'$</td>
<td>I: 15,588 J: 14,048 K: 16,873</td>
</tr>
<tr>
<td>AKARI</td>
<td>_09: 21,652 _18: 21,669</td>
<td>EXTENDED## FQUAL##</td>
<td>$≠ 0$ $≠ 3$</td>
<td>_09: 203 _18: 100</td>
</tr>
<tr>
<td>ISOGAL</td>
<td>_07: 966 _15: 1,159</td>
<td>mag# qual#</td>
<td>‘88.88’ or ‘99.99’ $&lt; 3$</td>
<td>_07: 11 _15: 17</td>
</tr>
<tr>
<td>HERSCHEL</td>
<td>PACS70: 6,457</td>
<td>flag_elong flag_edge flag_blend</td>
<td>$≠ 0$ $≠ 0$ $≠ 0$</td>
<td>PACS70: 48</td>
</tr>
<tr>
<td>GLIMPSE</td>
<td></td>
<td></td>
<td></td>
<td>No flags applied.</td>
</tr>
<tr>
<td>MIPS GAL</td>
<td></td>
<td></td>
<td></td>
<td>No flags applied.</td>
</tr>
</tbody>
</table>

Table 2.2: Photometric filtering applied to source catalogs before including data into the BAaDE IR database. For a description of the flag values, see the section detailing the specific catalog in the text.

detection was not resolved in a consistent manner with the other bands. The read flag indicates the method used to calculate the magnitudes and uncertainties of each observation. The 2MASS instrument collects exposures at 51ms and 1.3s. The
combination of which exposure is used for a given detection and the algorithm used to fit this detection is encoded in this flag. The values ‘0’ and ‘6’ listed in Table 2.2 correspond to no detection in a given band and inconsistent resolution across all bands respectively.

2.3.2 DENIS

The DENIS catalog contains several quality related fields, and we made use of two of them. The ‘flg’ field associated with each band is a hexadecimal value which indicates various problems with a detection or source such as signal artifacts, saturation, etc. A value of ‘0000’ indicates there are no problems with the source or image, and this is the value we required for inclusion in the BAaDE IR database. The ‘qual’ field is a rating from 0-100 (poor to perfect) giving a general quality level of the detection in each band. An empirical threshold value of 80 was required for database inclusion. This threshold was to some degree an arbitrary choice, but extensive source checks during photometry filtering and cross-matching support the choice. The difference between using ‘qual’ = 80 vs 100 was 501 detections from an original set of 30,147. After photometry flags were applied, the data set still contained magnitudes brighter than the saturation limits of the DENIS detectors: 9.8, 7.5 and 6 for I, J and K respectively. All detections above this level were filtered. During the source cross-matching process, additional sources were found to be saturated even though the reported magnitudes were below the saturation thresholds. An example is shown in Fig. 2.3. To address this, we further
filtered all DENIS cross-matches which had 2MASS detections brighter than J=6.5 or K=6 mag. The thresholds were relaxed from the DENIS saturation limits to account for the fact that a large fraction of the sources we are observing are variable. This filtered 21 cross-matches from the final product.

2.3.3 WISE

The ALLWISE catalog combines observations made in all three phases of the WISE operation. The combined datasets increase the photometric and astrometric accuracy of the catalog, and fill in lower coverage regions of the All-Sky Survey. The increased sensitivity in W1 and W2 results in most candidate sources being above the saturation limits of these detectors. Fig. 2.4 shows a distribution of the photometric uncertainties for the WISE cross-matches from the ALLWISE and WISE All-Sky catalogs. By replacing the W1 and W2 detections from the ALLWISE catalog with those from the WISE All-Sky
Figure 2.4: Comparison of WISE photometric uncertainties for the W1 and W2 bands in the ALLWISE and WISE All-Sky catalogs. This comparison is only for the sources included in the BAaDE IR catalog, and does not accurately reflect distribution throughout the WISE catalogs.

catalog, we significantly increase the reliability of the measurements we include from these bands. Doing so also reduces the overall number of final cross-matches in these bands.

The photometry related flags which we applied to the WISE catalog candidate matches include a flag for extended objects (\textit{ext\_flg}), a flag for confusion and contamination (\textit{cc\_flg}), and a flag for overall photometric quality (\textit{ph\_qual}). The extended object flag applies to the entire source, while the other flags were applied to individual bands. Applying these band-by-band flags resulted in the filtering of 7 additional candidate matches due to no remaining detections. Since the WISE catalog includes both point sources and extended objects, we took care to filter any objects flagged as extended.
The flag for confusion and contamination is a 4-character string with information about diffraction spikes, image persistence, halos from a nearby bright source and optical ghosts. These are designated with capital letters (‘D’, ‘P’, etc) if the artifact is confirmed, lower case if they are suspected, or ‘0’ if there are no problems with the source or image extraction. For the BAaDE IR database, we filtered all candidate matches with a confirmed artifact flag. The photometric quality flag is derived from the SNR for detection in each band. The WISE catalog required at least one band to have a detection with SNR > 5. For inclusion in the BAaDE IR database, we required each band to have SNR ≥ 3.

2.3.4 AKARI

For the AKARI data, we filtered for extended sources and for valid flux. The values are given by flags ‘EXTENDED##’ and ‘FQUAL##’ respectively, where ‘##’ designates the band to which the flag applies. Both of these are binary flags, leaving no ambiguity in their interpretation. After applying them to the AKARI data, 165 candidate matches were filtered because they no longer contained detections in any band.

2.3.5 ISOGAL

The ISOGAL explanatory supplement lists magnitudes of 88.88 and 99.99 as non-detections. These values were filtered before incorporating the data into the BAaDE IR database, and any candidate matches for which both bands resulted in non-detection
were excluded entirely. In addition to this, we used the quality flag for each band given in the catalog to filter detections with ‘qual’ < 3, excluding a total of 14 matches when this resulted in no valid detection in either band.

### 2.3.6 HERSCHEL

For the Herschel PACS catalog, we applied three filters for image quality. These filters used the flags reported in the catalog for elongated or blended source detections ('flag_elong' and 'flag_blend'), as well as sources for which the detection lies along the edge of the scan ('flag_edge'). In total, applying these flags excluded 48 cross-matches.

### 2.4 Cases with Multiple Candidate Matches

At this point we have formed a list of all candidate cross-matches, and removed unreliable data products from our candidate sets. By searching within a 5” radius of the original MSX positions, we inevitably encountered cases for which multiple matches were reported for a given position. Using the 2MASS detections as an example, there were 3,297 cases with 2 candidate matches and 537 cases with 3 or more candidate matches. Perhaps the most accurate method of selecting the correct cross-matched candidate would be a manual comparison between each catalog and the MSX PSC detection. This is obviously not practical considering the size of the BAaDE survey, but in each case this is the last step in the process. While we were able to effectively apply many scripted filtering criteria, there always remained a number of matches for which
manual selection was the only reliable method. Cross-matching statistics for each catalog are given in Table 2.3.

### 2.4.1 Two Micron All Sky Survey (2MASS)

The 2MASS catalog is perhaps the most important cross-match for the project, as it provides a more accurate position of the SiO masers than the MSX PSC. The positions reported in the 2MASS catalog are therefore currently incorporated by the BAaDE team in the data reduction pipelines for both the VLA and ALMA. With nearly 30,000 targets, it would require an unreasonable amount of time to phase-calibrate individually each VLA and ALMA target to measure accurate positions. However, a VLA phase-referencing test was done for a subset of our sources, and the resulting SiO maser positions were compared to the reported positions in the MSX, 2MASS, GLIMPSE and other catalogs.

<table>
<thead>
<tr>
<th>Catalog</th>
<th>Initial Matches</th>
<th>Initial 1-to-1 Matches</th>
<th>Final Matches</th>
</tr>
</thead>
<tbody>
<tr>
<td>2MASS</td>
<td>31512</td>
<td>23243</td>
<td>27050</td>
</tr>
<tr>
<td>DENIS</td>
<td>30147</td>
<td>11885</td>
<td>10162</td>
</tr>
<tr>
<td>WISE</td>
<td>25508</td>
<td>11428</td>
<td>8925</td>
</tr>
<tr>
<td>GLIMPSE1</td>
<td>5688</td>
<td>4955</td>
<td></td>
</tr>
<tr>
<td>GLIMPSE2a</td>
<td>3375</td>
<td>2481</td>
<td></td>
</tr>
<tr>
<td>GLIMPSE2b</td>
<td>3531</td>
<td>2638</td>
<td>9759</td>
</tr>
<tr>
<td>GLIMPSE3a</td>
<td>1195</td>
<td>974</td>
<td></td>
</tr>
<tr>
<td>GLIMPSE3b</td>
<td>1198</td>
<td>1003</td>
<td></td>
</tr>
<tr>
<td>ISOGAL</td>
<td>1265</td>
<td>1263</td>
<td>1250</td>
</tr>
<tr>
<td>MIPSGAL</td>
<td>12883</td>
<td>12867</td>
<td>12875</td>
</tr>
<tr>
<td>AKARI</td>
<td>24989</td>
<td>24985</td>
<td>24821</td>
</tr>
<tr>
<td>HERSCHEL</td>
<td>6457</td>
<td>6457</td>
<td>6409</td>
</tr>
</tbody>
</table>

Table 2.3: Cross-matching statistics for catalogs included in the BAaDE IR database.
This confirmed that the positions reported in 2MASS were within 0.2” of the SiO maser positions observed with the VLA. Additionally, since our sources are red giant AGB stars, the spectral range covered by the bands in 2MASS spans the area over which the SED is likely to peak, giving critical information about the effective temperature of a given source. Finally, the $K_s$ band (2.17 $\mu$m) is frequently used as the base from which extinction is calculated for the rest of the spectrum (at least in the IR; see Sect. 5.3), so having an extensive set of observations in this band will be crucial as we refine our SEDs within the Galactic plane.

Of the 27,050 eventual unique matches to the BAaDE source list, only 23,243 were initially matched one-to-one, leaving 3,807 BAaDE targets with multiple matches to resolve. Due to the size of the data set, it was impractical to perform a manual selection, thus we devised filtering criteria which could be applied to reduce the duplicates to a manageable number. When devising these criteria, we applied the following assumptions (based on our original BAaDE sample selection criteria), the BAaDE sources are most likely to be: a) red, and b) bright. The results of the filters described below are summarized in Table 2.4. Following each filter application, we manually examined a subset of the remaining cases with multiple matches, in order to devise a further filtering method. In 67% of the cases, the filters described below select the candidate source with the closest distance to the original MSX position.

After photometry flags were applied, we calculated colors for each candidate match, and used those as the first filtering criteria. Comparisons were made only between the same color within a multiply-matched set, and color precedence was applied in the
following order: $J - K$, $J - H$ and $H - K$. In each comparison, the source with the 
reddest color value was accepted to the BAaDE IR database.

Not every set contained detections in bands which allowed color comparisons. In the 
cases where colors could not be directly calculated, we considered whether the 
candidate was detected or not in the J-, H- and K-bands. In particular, if a candidate 
source was only detected in the J-band, it was rejected. This was in line with our 
reasoning that our sources are bright and red, and thus should have been easily 
detected in the H- or K-band if detected in the J-band. In some cases this filtered one or 
more candidates from the set without reducing the overall set to a single match, thus 
the number reported in Table 2.4 does not reflect the full impact of this filter. If every 
candidate match in the set was detected in the J-band only, we selected the candidate 
with the highest signal-to-noise ratio. In order to apply the SNR filter, we required a 
minimum SNR of 15, and required the SNR of the higher SNR candidate to be at least 
120% of the SNR of the candidate to which it is compared. This was done to control for 
minute differences between detections which may not be meaningful.

After applying the ‘Color’ and ‘J-only’ filters, there were 1,104 BAaDE targets remaining 
with multiple matches. We next applied a filter to select the brightest candidate in the 
K- or the H-band within a set. In order to apply this filter, all candidates in a set must be 
detected in a common band, and we required a minimum difference in magnitude of 
0.20. If the difference in magnitude was less than this threshold, we selected the 
candidate with reported coordinates which were closest to the search coordinates.
We applied one final filter before resorting to manual resolution. In many cases, the candidates in a set displayed a trend between the bands which were detected: one candidate was detected in the K-band only while the other candidate was detected in the J- and H-bands only. According to the 2MASS documentation, this is a result of a failure in the band-merging process. When we were able to identify these cases, we combined the detections and took the position from the candidate detected in the K-band. This merging occurred in 65 of the cases caught by this filter; in the other cases, we accepted the candidate with the K-band detection and rejected the remainder of the set.

<table>
<thead>
<tr>
<th></th>
<th>Cases Reduced to Single Match</th>
</tr>
</thead>
<tbody>
<tr>
<td>Color</td>
<td>1564</td>
</tr>
<tr>
<td>J-only</td>
<td>1139</td>
</tr>
<tr>
<td>Brightness</td>
<td>816</td>
</tr>
<tr>
<td>K-only</td>
<td>151</td>
</tr>
<tr>
<td>Manual</td>
<td>137</td>
</tr>
</tbody>
</table>

Table 2.4: Summary of 2MASS cross-match filtering results

2.4.1.1 Cross-Match Confirmation – Coordinate Shift

Because of the ad-hoc nature of the filters applied to resolve multiply-matched sources in the search region, it is expected that there are cases where the incorrect match was selected. As a check to see to what extent this may have occurred, we created an alternate set of search coordinates by shifting the original search coordinates. The
Figure 2.5: 2MASS source selection comparison between BAaDE selected sources and randomly selected sources in the same area of the sky. Sources were treated in the same manner with regard to photometry. The 2MASS sources cross-matched to our IR-selected BAaDE sources are clearly distinct from a randomly selected sample of stars in the same region of the sky.

coordinates were randomly shifted by $\pm 72"$ in both RA and Dec (total shift of 101.8").

From these new coordinates, they were randomly shifted again within a box of side length 18". The total offset is then between 89" and 115" from the original coordinates. Searching the 2MASS catalog within 5" of the new coordinates returned 17,967 sources compared to 31,152 for the original coordinates. After eliminating all of the candidate sources with multiple matches and applying the same photometric flags, we compared the colors and magnitudes of the two samples. Fig. 2.5 shows the BAaDE
and the shifted sample of matches in a color-magnitude and color-color diagram. While there is some overlap between the two samples, the BAaDE sample, which is pre-selected to be red and bright sources, is clearly offset from a randomly selected sample. This demonstrates that, although certainly not 100% accurate, our filtering methods to select the candidate cross-match most likely to be a red giant work for the bulk of the sources.

### 2.4.1.2 Cross-Match Confirmation – Mass-loss Rate

A number of studies have used $K_s - [12]$ and $K_s - [15]$ colors to classify the shell thickness (Olivier et al. 2001; Messineo et al. 2004). Olivier et al. report the following relationship for oxygen-rich stars:

$$\log \dot{M} = \frac{-21.34}{(K - [12] + 3.00)} - 2.40$$

Using the 2MASS K-band and MSX C-band (12.13 μm), we obtain a mean mass loss rate for the BAaDE sample of $\dot{M} = 2.14 \times 10^{-6} \, M_\odot/yr$. Figure 2.6 shows the distribution of mass loss rates for our sources. This distribution is in accord with the accepted rates of $10^{-4} - 10^{-7} \, M_\odot/yr$ for AGB stars with a CSE, and we take this as further confirmation of both the overall target selection of the BAaDE project and the quality of our cross-match between the MSX and 2MASS catalogs.
Figure 2.6: Mass-loss rates for the BAaDE targets derived using the relationship given in Olivier et al., 2001. Rates are consistent with AGB stars with a CSE, and serve as further confirmation of BAaDE target selection and 2MASS cross-match.

2.4.2 DENIS

The DENIS catalog proved to be the most difficult to match with our MSX-selected sources. The biggest reason for this is that the catalog lists each detection as an independent event, and does not attempt to merge detections of the same object as a single reported source. The impact this has is that multiple matches within the 5” radius of the reported MSX position may in fact be the same source, and care is required in the way this is handled. The detections listed in the DENIS catalog are identified by the ‘denisid’ field, which is composed primarily of the sexagesimal equatorial position. The catalog also lists the date the observation was made (‘obsjd’), and we made use of these
fields to identify the number of independent sources. If a source is listed with different observation dates, the mean of the magnitudes was used for the BAaDE IR database.

We recorded a flag for these sources, as they may be useful in constraining the variability of our sources in future work. If the listings were observed on the same date, we simply kept the first observation listed in that set.

The final filter applied before manual matching was a check for 2MASS proximity. The spatial resolution of these two surveys was the highest in our dataset, so that reported positions could be compared with greater confidence. In order to resolve the multiple matches in a given set, we required the candidate to be within 1” of the 2MASS position, with no other candidate sources within 2”. After applying this filter, we manually matched the final 163 sources.

<table>
<thead>
<tr>
<th>DENIS Duplicate Filter</th>
<th>Cases Reduced to Single Match</th>
</tr>
</thead>
<tbody>
<tr>
<td>DENIS ID</td>
<td>5604</td>
</tr>
<tr>
<td>2MASS proximity</td>
<td>1864</td>
</tr>
<tr>
<td>Manual</td>
<td>163</td>
</tr>
</tbody>
</table>

| Table 2.5: Summary of DENIS cross-match filtering results |

### 2.4.3 GLIMPSE

Matching sources from the GLIMPSE catalogs was made much easier due to prior matching between these catalogs and the 2MASS catalog. The GLIMPSE catalogs contain a 2MASS identifier field (`tmass_designation`), which we used to cross-match with the 2MASS sources already identified in the BAaDE IR database. A candidate match
was only rejected entirely if no determination could be made during the 2MASS portion of the cross-matching process. Some candidate sources in each catalog were not matched to the 2MASS catalog, but the number in each was small enough that we performed the matching manually to the BAaDE source. The five GLIMPSE catalogs were combined into a single listing in the BAaDE IR database. If a candidate source was matched in more than one of the catalogs, the mean magnitude was calculated between them, and the position reported in the most recent GLIMPSE catalog was used.

<table>
<thead>
<tr>
<th>GLIMPSE Duplicate Filter</th>
<th>Number of Candidates Rejected</th>
</tr>
</thead>
<tbody>
<tr>
<td>2MASS match</td>
<td>GLIMPSE I: 7</td>
</tr>
<tr>
<td></td>
<td>GLIMPSE II: 13</td>
</tr>
<tr>
<td></td>
<td>GLIMPSE 3D: 2</td>
</tr>
<tr>
<td>Manual</td>
<td>GLIMPSE I: 5</td>
</tr>
<tr>
<td></td>
<td>GLIMPSE II: 13</td>
</tr>
<tr>
<td></td>
<td>GLIMPSE 3D: 2</td>
</tr>
</tbody>
</table>

Table 2.6: Summary of GLIMPSE cross-match filtering results

2.4.4 Others

For all other catalogs, the number of multiple matches was low enough that manual cross-matching was a feasible solution. The number of candidate matches in each catalog is given in Table 2.7.

<table>
<thead>
<tr>
<th>Catalog</th>
<th>Manual Cross-matches</th>
</tr>
</thead>
<tbody>
<tr>
<td>AKARI</td>
<td>2</td>
</tr>
<tr>
<td>ISOGAL</td>
<td>1</td>
</tr>
<tr>
<td>MIPSGAL</td>
<td>8</td>
</tr>
<tr>
<td>HERSCHEL</td>
<td>0 (all results were one-to-one)</td>
</tr>
</tbody>
</table>

Table 2.7: Summary of catalogs with low numbers of multiple matches
3. DUSTY Modeling

After building the BAaDE IR database described in Chapter 2, spectral energy distributions (SEDs) were created for each source. The shapes of the SEDs clearly deviate from a black body function, thus requiring more detail than a simple fitting algorithm with a black body curve for a given temperature can provide. The circumstellar envelope surrounding AGB stars affects the light we observe in a non-linear fashion. To calculate a hypothetical emerging SED, we used the radiative transfer modeling program DUSTY (Ivezic, Nenkova & Elitzur 1999) to generate models based on selected stellar and CSE parameters. In this chapter, we will describe the process we used to generate the models. We will describe the inputs to (Sect. 3.1) and outputs from (Sect. 3.2) DUSTY, along with the effects each selected parameter has on the models. Finally, we describe the procedure used to fit the model SEDs to the data (Sect. 3.3).

3.1 Input Parameters

The parameters used in creating the DUSTY models include both stellar and CSE properties. Table 3.1 lists the parameters and the range of values that were used in this study. The DUSTY program provides different options for the type of radiation source, including spherical or planar geometry, up to 10 blackbodies of different luminosities, or various broken power law energy distributions. For our modeling, we used a single blackbody and varied the effective temperature. The options for CSE properties include
specifications of the size and distribution of dust grains, the chemical composition fractions, the density distribution and thickness of the CSE as a fraction of the shell inner radius and the optical depth at a specified wavelength. The density distribution and chemical composition of the CSE were held fixed in all of our models. The density distribution of the CSE is considered sufficiently similar for all AGB stars, and DUSTY gives options for broken power law, exponential decay, numerically specified and radiatively driven distributions. The radiatively driven wind distribution option uses the full hydrodynamic equations, and is the most appropriate for the AGB stars included in the BAaDE project, hence this distribution was chosen and held fixed for all models. For the dust composition, we assume that the primary dust component is some form of silicate, as the IR color selection of our sources is intended to select stars with primarily oxygen-rich CSEs. The DUSTY program contains data for several common dust grain types, including both warm and cold silicates. The outputs of both were compared using one of our sources as a framework, with little difference between the two. Since the CSEs around our objects are thinner and closer to the star than, for instance, the CSE

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value Range</th>
<th>Number of Steps</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effective Temperature</td>
<td>2200-3500 K</td>
<td>14</td>
</tr>
<tr>
<td>CSE Boundary Temperature</td>
<td>500-1500 K</td>
<td>11</td>
</tr>
<tr>
<td>CSE Thickness (r/r₁)</td>
<td>30-300</td>
<td>10</td>
</tr>
<tr>
<td>Opacity (8.3 µm)</td>
<td>0.002-3.00</td>
<td>68</td>
</tr>
<tr>
<td>Scale</td>
<td>( \frac{Obs}{Mdl} \times 10^{±2} )</td>
<td>21</td>
</tr>
<tr>
<td>Total models:</td>
<td></td>
<td>2,199,120</td>
</tr>
</tbody>
</table>

Table 3.1: The free parameters used when creating the BAaDE DUSTY model library. The “Scale” parameter is implemented in MATLAB code (see text); the other parameters are inputs to the DUSTY program.
surrounding an OH/IR star, we chose to use the warm silicate data as 100% of the dust contribution in our CSEs. The input parameters which were varied in our models are the effective temperature of the star, the temperature at the inner boundary of the CSE, and the thickness of the CSE as a ratio of the inner and outer radius (see Table 3.1).

3.2 DUSTY Outputs

For each set of input parameters a total of 64 models with different opacities were generated. DUSTY outputs several files with various information, including a detailed spectrum for each model. This spectrum is output as a fraction of the total bolometric flux

\[ f(\lambda) = \frac{\lambda F_\lambda}{\int F_\lambda d\lambda} \] (3.1)

By formatting our SEDs to use \( \lambda F_\lambda \) as the dependent variable, we can incorporate a scaling factor in our fitting algorithm which effectively gives a bolometric flux measurement for the source. For each source, a baseline scale is calculated by taking a ratio of the observed SED value to the modeled DUSTY SED value at a specified wavelength, \( \frac{\lambda F_{\lambda, \text{obs}}}{f(\lambda)} \), and multiplying the DUSTY model SED by this value. To calculate a range of scales to use in the fitting process, this value is then multiplied by a step factor, \( 10^{(scl - 11)/5} \), where scl runs from 1-21. This gives 21 different scale values stepped by multiples from \( 10^{-2} \) to \( 10^2 \). The best fit scale for each source is then the
equivalent of the bolometric flux for that source.

3.3 Data Fitting

The model fitting for the sources in the BAaDE IR database was done by calculating a $\chi^2$ goodness-of-fit value for each model comparison. For each data point present in a given source, the observed value was compared to a model value and the error calculated and summed via the following equation:

$$\log_{10} \chi^2 = \frac{\sum \left( \log_{10} \frac{\text{Obs}}{\text{Md}} \right)^2}{N}$$

(3.2)

Because each source is detected in a different number and distribution of bands, the sum of errors is divided by the actual number of comparisons, $N$. This ensures an accurate comparison between the $\chi^2$ goodness-of-fit calculated for each source in our sample. After calculating a $\chi^2$ value for each model, the model which gave the smallest value is taken as the best fit. With over 2 million fits calculated for each source, there are many which will be statistically equivalent in their goodness-of-fit value. In order to account for this distribution of equally valid fits, we then calculate the mean of the best 100 models. These mean parameters are what we report here, and the basis of the remainder of our analysis. Figure 3.1 is an example of the fitting performed for one of our sources. An excerpt of the code for these operations written in MATLAB is given at the end of this chapter.
Figure 3.1: Sample SED for one of the BAaDE sources. The model SED curve is an average of the best 100 fits to the data shown in blue.

One limitation regarding our DUSTY implementation is worth mentioning here. DUSTY allows for the input of up to 999 wavelength grid points to be modeled. The grid used in creating our DUSTY model library contains 118 wavelengths from \(0.01 - 3.6 \times 10^4\) \(\mu m\). While we ensured the central wavelengths of each of the bands included in the BAaDE database were included in this grid, a more rigorous approach would be to take into account the spectral response function of each filter. It’s difficult to say how much this modification would alter our results, but for strict accuracy it may be necessary to modify this in future implementations.
\( \chi^2 \) Matlab Code Excerpt

\% XSpec gives the DUSTY wavelength index used to compare to BAaDE
\% wavelength, in order of inclusion in BAaDE IR database.

XSpec=[50,77,84,92,19,23,29,24,26,30,34,39,74,94,36,38,42,48,46,83,96,53,89,110];

scale=cell(1,21);

for imgs=1:length(BAaDE.Sources)

    X2=zeros(numel(scale),numel(BAaDEmodels),size(BAaDEmodels{1},2));

    for mdl=1:numel(BAaDEmodels)

        for tauscan=1:size(BAaDEmodels{mdl},2)

            % Finding a non-nan value to scale.
            if ~isnan(BAaDE.SED(imgs,2))
                DUSTY=BAaDEmodels{mdl}(XSpec(2),tauscan);
                SED=BAaDE.SED(imgs,2);
                base_scl=(SED./DUSTY);
            elseif ~isnan(BAaDE.SED(imgs,3))
                DUSTY=BAaDEmodels{mdl}(XSpec(3),tauscan);
                SED=BAaDE.SED(imgs,3);
                base_scl=(SED./DUSTY);
            elseif ~isnan(BAaDE.SED(imgs,1))
                DUSTY=BAaDEmodels{mdl}(XSpec(1),tauscan);
                SED=BAaDE.SED(imgs,1);
                base_scl=(SED./DUSTY);
            end

            for scl=1:length(scale)
                count=0;
                scale{scl}=BAaDEmodels{mdl}*base_scl*power(10,(scl-11)/5);

                for k=1:length(XSpec)
                    if ~isnan(BAaDE.SED(imgs,k)) && ~isnan(BAaDEmodels{mdl}(XSpec(k),tauscan))
                        X2(scl,mdl,tauscan)=X2(scl,mdl,tauscan)+((power(BAaDE.SED(imgs,k) - (scale{scl}(XSpec(k),tauscan)),2),/(scale{scl}(XSpec(k),tauscan))));
                        count=count+1;
                    end
                end
                X2(scl,mdl,tauscan).=X2(scl,mdl,tauscan)./count;
            end
        end
    end

[least_scl,least_mdl,least_tau]=ind2sub(size(X2),find(X2==min(X2(:))));
for j=1:100

    min_X2_index=find(X2==min(X2,[],'omitnan'));
    min_X2(j)=X2(min_X2_index(1));
    [least_scl(j),least_mdl,least_tau(j)]=ind2sub(size(X2),min_X2_index(1));
    X2(min_X2_index(1))=nan;

    if ~isnan(BAADE.SED(imgs,2))
        DUSTY=BAADEmodels{least_mdl}(XSpec(2),least_tau(j));
        SED=BAADE.SED(imgs,2);
        least_base(j)=(SED./DUSTY);
    elseif ~isnan(BAADE.SED(imgs,3))
        DUSTY=BAADEmodels{least_mdl}(XSpec(3),least_tau(j));
        SED=BAADE.SED(imgs,3);
        least_base(j)=(SED./DUSTY);
    elseif ~isnan(BAADE.SED(imgs,1))
        DUSTY=BAADEmodels{least_mdl}(XSpec(1),least_tau(j));
        SED=BAADE.SED(imgs,1);
        least_base(j)=(SED./DUSTY);
    end

    temp_mdls(:,j)=BAADEmodels{least_mdl}(:,least_tau(j));
    least_fbol(j)=least_base(j)*power(10,(least_scl(j)-11)/5);
    least_Te(j)=BAADEtemp_eff(least_mdl);
    least_T1(j)=BAADEtemp_cse(least_mdl);
    least_cse(j)=BAADEshell(least_mdl);

    if least_tau(j) < 6
        temp_tau(j)=least_tau(j)*.002;
    elseif least_tau(j) < 10
        temp_tau(j)=.01+(least_tau(j)-5)*.01;
    else
        temp_tau(j)=.05+(least_tau(j)-9)*.05;
    end

    BAADE.Ch(imgs)=power(10,mean(min_X2,'omitnan'));
    BAADE.Fbol(imgs)=mean(least_fbol,'omitnan');
    BAADE.Opacity(imgs)=mean(temp_tau,'omitnan');
    BAADE.Shell(imgs)=mean(least_cse,'omitnan');
    BAADE.TempEff(imgs)=mean(least_Te,'omitnan');
    BAADE.TempCSE(imgs)=mean(least_T1,'omitnan');
    BAADE.Model(:,imgs)=mean(temp_mdls,2,'omitnan');
end
4. Distance Estimates

With the main BAaDE survey, the overall goal is to extract a gravitational potential to model Galactic dynamics. The outcomes would be greatly enhanced if, in addition to the positions and velocities, we could also provide a distance estimate. Distances based on the kinematics are difficult to derive since the kinematics in the inner Galaxy are not well modeled (indeed, this is an expected outcome of the BAaDE project). Specific targets can be selected for follow-up Very Long Baseline Interferometry (VLBI) studies to determine accurate parallax distances and absolute proper motions, although this is time-consuming and can only be done for a subset of the targets. The Gaia satellite operates at optical wavelengths and will likely be able to measure proper motions for brighter giants in the outer bulge ($|b| > 8^\circ$), but severe crowding/reddening closer to the plane will almost certainly limit Gaia’s contribution in the plane. There will therefore probably be some overlap between our survey and that of Gaia in the outer bulge, and a subset of our SiO masers will likely have Gaia astrometry, hence we anticipate some mutual reinforcement between the data sets. To derive distance estimates to the bulk of our sample, however, we will in this chapter investigate whether ‘statistical’ distance estimates can be made. Two methodologies are explored: a) estimating the distances by using the SED derived fluxes and applying a period-luminosity estimate (Sect. 4.2), and b) estimating the distances by matching an SED shape to an SED template with a known distance (Sect. 4.3). The distances obtained from Gaia for example, can be used to calibrate these SED templates. With either of
these methods, there are likely to be large error bars associated with the luminosity estimate obtained. For the dynamical studies, however, it is already a success if a distance in front or behind the Galactic center can be determined, i.e., if a distinction can be made between a co-rotating or counter-rotating orbit.

4.1 Deriving Luminosities from Known Distances

By combining a bolometric flux with a measured distance, a luminosity estimate can be inferred for individual sources. Utilizing the radiative transfer modeling program DUSTY, we have obtained estimates of the bolometric fluxes for the sources in the BAaDE survey (Chap. 3). In order to test the results obtained from DUSTY, we have compiled a set of 10 well-studied Red Giant stars for which parallax measurements have been made, and thus accurate distance estimates exist for these 10 sources. As 8 of these sources are not situated in the Galactic plane, they are not included in our BAaDE catalog. We therefore gathered infrared data for each of these from the same catalogs used in the BAaDE IR database (Chap. 2), and performed a fit to a modeled SED in the same manner as the BAaDE sample (Chap. 3). 2MASS J-, H-, and K-band magnitudes were obtained for all of these targets, while the remaining longer wavelength IR bands were more sparsely sampled with 4-7 points per source, as several IR missions used for BAaDE were limited to the plane. However, a 2MASS dominated SED is sufficient to provide a reasonable model SED fit, and allow us to estimate the bolometric flux.

<table>
<thead>
<tr>
<th>Name</th>
<th>IR Data Points</th>
<th>$f_{bol}$ (erg/s/cm$^2$)</th>
<th>Distance (kpc)</th>
<th>$L/L_\odot$</th>
</tr>
</thead>
<tbody>
<tr>
<td>VX Sgr</td>
<td>6</td>
<td>$5.016 \times 10^{-6}$</td>
<td>1.57$^a$</td>
<td>$3.854 \times 10^5$</td>
</tr>
<tr>
<td>VY Cma</td>
<td>5</td>
<td>$2.403 \times 10^{-6}$</td>
<td>1.14$^b$</td>
<td>$9.735 \times 10^4$</td>
</tr>
<tr>
<td>IRAS 18282-0959</td>
<td>4</td>
<td>$2.837 \times 10^{-8}$</td>
<td>3.61$^c$</td>
<td>$1.153 \times 10^4$</td>
</tr>
<tr>
<td>R Cas</td>
<td>4</td>
<td>$5.805 \times 10^{-6}$</td>
<td>0.176$^d$</td>
<td>$5.605 \times 10^3$</td>
</tr>
<tr>
<td>RR Aql</td>
<td>6</td>
<td>$7.419 \times 10^{-7}$</td>
<td>0.633$^e$</td>
<td>$9.267 \times 10^3$</td>
</tr>
<tr>
<td>S CrB</td>
<td>6</td>
<td>$2.089 \times 10^{-6}$</td>
<td>0.418$^f$</td>
<td>$1.138 \times 10^4$</td>
</tr>
<tr>
<td>U Her</td>
<td>4</td>
<td>$2.834 \times 10^{-6}$</td>
<td>0.266$^g$</td>
<td>$6.251 \times 10^3$</td>
</tr>
<tr>
<td>S Crt</td>
<td>6</td>
<td>$8.730 \times 10^{-7}$</td>
<td>0.441$^h$</td>
<td>$5.293 \times 10^3$</td>
</tr>
<tr>
<td>T Lep</td>
<td>6</td>
<td>$2.019 \times 10^{-6}$</td>
<td>0.327$^i$</td>
<td>$6.730 \times 10^3$</td>
</tr>
<tr>
<td>UX Cyg</td>
<td>7</td>
<td>$4.640 \times 10^{-7}$</td>
<td>1.85$^j$</td>
<td>$4.950 \times 10^4$</td>
</tr>
</tbody>
</table>

Combining the bolometric flux estimates from the modeled SED and the distances given by the parallax measurements, we have calculated a luminosity estimate for each of these sources. Table 4.1 lists the number of IR data points used for the model, the modeled bolometric fluxes, the parallax distances, and the resulting luminosities.

Several of the sources in this limited sample are well known, e.g. VX Sgr. VX Sgr and VY CMa have been classified as a Red Super Giants (RSGs), hence not Mira variables. Estimates of their bolometric luminosities of $3.43 \times 10^5$ and $2.95 \times 10^5 \, L_\odot$ respectively were made by Mauron and Josselin (2011). Overall, RSGs are expected to have luminosities largely falling in the range of $2 \times 10^4 - 6 \times 10^5 \, L_\odot$, thus our SED estimates for these two objects agree well with theoretical expectations and the estimates by Mauron & Josselin (2011). Studies of AGB stars provide a wide range of
peak luminosities from $7,700 \, L_\odot$ - $20,000 \, L_\odot$ (Blommaert et al. 2006; Ojha et al. 2007). Using this peak luminosity range as a guide, and excluding the two RSG stars, our luminosity estimates are all in good agreement with expected values, and we conclude that we are able to obtain a good estimate of the bolometric flux from the modeled SEDs.

4.2 Estimating Distances Using a Period-Luminosity Relationship

Many studies have examined the relationship between the period (P) and luminosity (L) of Mira stars. For example, it was shown by Feast et al. (1989) that oxygen-rich Miras in particular show a good P-L relation with very little scatter ($\sigma = 0.13$ mag) in $K$. While we do not have period data for most of the BAaDE sample, Matsunaga et al. (2009) used a sample of Mira stars to measure the P-L relationships, and shows a relation between the $K_s - [8]$ color and the period, as well the $K_s - [8]$ color and the variability amplitude, $\Delta K_s$.

As our BAaDE sources have data for both MSX A (8.28 $\mu$m) and 2MASS K (2.16 $\mu$m) bands, we thus can estimate the periods from Matsunaga’s P-L relation. As a mathematical relation was not quoted in their paper, we obtained the full catalog of Matsunaga et al. from the CDS portal (Vizier), and cross-matched their positions with the cited Ramirez et al. (2008) catalog from which Matsunaga et al. observed their $K_s - [8]$ relations. Our purpose was to recreate the plots shown in Matsunaga et al. and obtain a function for the relations. Matsunaga et al. cited a 0.5” tolerance when cross-
Figure 4.1: Period-Color relationship reported by Matsunaga et al. (2009). Their paper did not list a mathematical relation, so the plot has been recreated here and fit quadratically (Eqn 4.1). In order to make use of the relation, we restrict the comparison with the BAADE sample to the same region about the Galactic Center and to $K - [8] > 3.8$, the region of the plot with the clearest adherence to the fit.

matching, from which they identified 1,233 counterparts. Using the same tolerance, we obtained 1,228 uniquely identified cross-matches between the catalogs, which should yield reasonable agreement between our data sets. From this set of cross-matches, we isolated 280 sources (compared to 282 cited) with good $K$-band and period data from Matsunaga et al. and good 8 $\mu$m data from Ramirez et al. Using this data, we calculated a quadratic fit between the $K_{\text{mean}} - [8]$ color and the period given in Matsunaga et al. and calculated a quadratic fit to the data:

$$\log_{10} P = a(K - [8])^2 + b(K - [8]) + c$$  \hspace{1cm} (4.1)
\[ a = -7.829 \times 10^{-3} \]
\[ b = 0.1596 \]
\[ c = 2.043 \]

The data and fit are shown in Fig. 4.1. For \( K - [8] < \sim 3.8 \), the fit becomes unreliable, but for higher values the fit is reasonably good.

The Matsunaga et al. analysis is based on a region close to the Galactic Center, and likely suffers from significant extinction. The \( K - [8] \) colors used to obtain the period relation have not been corrected for extinction, and this likely leads to some error in the calculated period. In order to minimize the introduction of further errors, we restrict

![Figure 4.2](image.png)

**Figure 4.2**: Comparison of \( K - [8] \) colors between the Matsunaga et al. data set and the BAADE Galactic Center sample. Both data sets have been zero-magnitude corrected. The slight differences in color distribution are likely due to variability of the sources, the difference in \( K \)-band reporting methods (mean vs single epoch observation), and different filters used for [8]-band observations [GLIMPSE [8] vs MSX A (8.28 \( \mu \)m)].
$K - [8] > 3.8$. This equates to 318 sources from the full BAaDE IR catalog, hereafter the Galactic Center sample. Figure 4.2 gives a comparison of the color distribution between the Matsunaga et al. sources and the BAaDE Galactic Center sample.

Using equation 4.1, we calculate a period for the Galactic Center sample. Further, we use this calculated period to obtain an estimate for the luminosity, $K_s$, of these sources via the relation given by Matsunaga et al.

$$M_{K_s} = -3.555(\log P - 2.3) - 6.883 \quad (4.2)$$

Together with the $K$-band flux obtained from the 2MASS data in our sample, we have derived estimates for distances to the sources in the BAaDE Mira population (Fig. 4.3).
It should be noted here that each relation utilized in this analysis introduces errors to the final distance determination. For the Galactic Center sample, the mean $K - [8]$ observation uncertainty is 0.21 magnitude. This error propagates through each step of this process, each of which contains its own uncertainty. Compounding these errors are the variability of the sources and the high extinction toward for the Galactic center. The unrealistic distances shown in Fig. 4.3 serve to illustrate the difficulty in performing distance estimates, especially in the Galactic plane. If we extend the relations derived from the $K - [8]$ colors to the full BAaDE sample, the results obtained are even more wildly unrealistic, with derived distances up to 637 kpc. Obtaining an extinction corrected relation between the period and color could provide a way forward. This would then necessitate correcting the extinction of any source for which we desired a period, luminosity or distance. Even if this correction were perfect, however, the compounding of uncertainties is still likely to lead to unusable estimates.

4.3 Estimating Distances Using SED templates

The P-L method for obtaining distance estimates (as described above), has far too many sources of error to give a useful estimate for an individual source. One of the strengths of the size of the BAaDE IR database is the ability to take a statistical approach to problems such as distance estimation. By far the greatest number of detections in our database are in the MSX A-, C- and D-bands (8.28, 12.13 and 14.65 $\mu$m). This mid-IR regime is less affected by extinction than, for example, the 2MASS wavelengths, and is likely dominated by the CSE rather than the foreground. Using the MSX bands
Figure 4.4: Galactic distribution of the “BAaDE sample” (as defined in Sect. 4.3). These sources are those for which we have the most confidence in our cross-matching and model fitting procedures. Comparing this distribution to the full BAaDE data set (Fig. 1.3) reveals no obvious bias.

(including the E-band when available), our basic methodology is to classify the SEDs into bins of different shapes, and create a template SED for each shape bin. If the template can be calibrated to a given distance by using sources of known distances, comparing an SED to the template could provide a distance measurement. While such a statistical approach is still likely to contain large error bars, it will allow distances to be inferred for a large part of our sample.

Before beginning the distance analysis, we select a subset of the full BAaDE data set. This selection is intended to target the sources in which we have the most confidence of a) correct cross-matching and b) quality of fit to the modeled SED. We make this selection based on a $\chi^2$ threshold, $\chi^2 < 1.015$, from the SED fitting process. Additionally, we require the sources in this data set to be detected in a minimum of 8 separate IR bands. This selection corresponds to 68% of the full BAaDE data set, and the Galactic distribution is shown in Fig. 4.4. For the remainder of this chapter, unless otherwise specified, we refer to this subset as the “BAaDE sub-sample”.

Again for this method, we have neglected extinction corrections for now. For the sources in the BAaDE sub-sample, we calculated the slope of the MSX bands and binned
these into 10 bins of increasingly red color (Fig. 4.5). For each of these bins, we calculated a template SED. First, all sources in a given bin were scaled to the mean value of the MSX A-band. After scaling, the mean value for each band was calculated. This "mean SED" was then fit to a model SED via the same method described in Chap. 3.
The goal then is to calibrate this mean SED to a distance based on sources with known distances which have a similar SED shape.

In the process of building the template SEDs, our models have undergone three different iterations. The most recent version has the most expansive range and density of fitting parameters, but does have its own set of shortcomings which will be addressed in the next iteration. The primary limitation that we can see is that the models so far do not probe into sufficiently low optical depth values. Here we describe the differences between the fits provided by each version of DUSTY models, and illustrate how we intend to use them to estimate distances to our sources.

4.3.1 SED Templates - Version 1

From Fig. 4.5, a by-eye analysis reveals the different shape of each bin. To calibrate derived distances, we compare these template SEDs to sources with known distances. Taking the set of sources from Table 4.1, we calculate a slope for the MSX wavelengths and assign each to a bin. For most of the template sources, there was no MSX data available, and we have inferred values for the MSX bands based on the DUSTY modeled SED. Figure 4.6 shows a plot of the mean BAaDE SED for Bin 1, along with the sources form Table 4.1 whose calculated MSX slopes place them in this bin.

This version of models was intended as a proof-of-concept, and the parameter space (see Chap. 3 for discussion of model parameters) was only sparsely probed. At wavelengths greater than ∼1 μm, we observe a promising correlation between our
Figure 4.6: Model SEDs for sources with known distances in Bin 1, using the first version of our DUSTY-generated models. Also included is the model SED for the calculated mean of the BAaDE sources in this bin. Using the sources with known distance, a template SED can be created for this bin to which a given source can be compared to estimate a distance.

modeled flux and the distance to the sources with known parallax. In order to obtain a higher fidelity set of parameters, we proceeded with expanding the model library.

4.3.2 SED Templates - Version 2

Version 2 of our DUSTY-generated model library greatly expanded the parameter values to which we were able to fit our sources. The values and step sizes are very similar to that given in Table 3.1. The only difference between them is the range of opacities.

When generating this set of models, we made a change to the wavelength at which the opacity is evaluated, from 9.7 µm in version 1 to 8.3 µm in version 2, to better coincide with one of our primary observation bands. When this change was made, the opacity...
range was not shifted to coincide with the expected lower values of at this wavelength.

This resulted in the bluest sources in our sample (those in Bin 1) fitting poorly due to the inability to probe adequately low values of opacity. Nonetheless, we show the progression of Bin 1 with these updated models in Fig. 4.7. The overall trend is still present and encouraging, though the fit to the data (not shown) is relatively poor in comparison to the previous version.

4.3.3 SED Templates - Version 3

In our most recent version of the model library, we have extended the range of opacities at which we evaluate our SEDs. The parameters of these models are otherwise the same as those used in version 2, and are represented in Table 3.1. At the
time of this writing, we have not completed the fitting procedure for the full BAADE data set. We have, however, completed the fitting for the sources for which we have parallax-derived distances and the mean SED for each bin. The mean SEDs in Fig. 4.8 were generated using this version of the model library. Again, we plot Bin 1 for analysis.

In version 3, we again observe the relationship between the model-derived bolometric flux and parallax-derived distance. For two of these sources, it is likely that we are still not probing to low enough opacity values, and another iteration will be necessary to continue to even more optically thin models. Because we have limited IR data on each of these sources (Table 4.1), it is imperative that we obtain the best possible fit in order to properly calibrate our distance estimation method. Even so, with only 4 sources by which to calibrate, our estimates will be very rough. Indeed, this limitation is even more pronounced in our other bins, which contain no more than one source of known

Figure 4.8: Same as Fig. 4.6, using most recent version of models.
distance. Additional overlapping sources between the BAaDE project and measurements from e.g. Gaia and VLBI will be vital to our calibration.

Using this latest set of models, we next attempt to calibrate a relationship between the bolometric flux of a source and a distance. Using Bin 1 (Fig. 4.8) as an example, we plot the distance against the inverse-square-root of the bolometric flux for the four sources with known distances in this bin (Fig. 4.9). We then calculate a linear fit to these points, and obtain a formula relating the two variables:

$$D = (2.9 \times 10^{-4}) f_{bol}^{-1/2} + 0.14$$  \hspace{1cm} (4.3)

where $f_{bol}$ is the bolometric flux expressed in units of erg/s/cm$^2$, and $D$ is the distance to the source in kpc.

Figure 4.9: Distance as a function of bolometric for the 4 sources in Bin 1 with known distance. Using these sources, we calculate a linear fit in order to calibrate the relationship between distance and flux for this bin. Equation for the fit is given as Eqn. 4.3.
Using this formula, and the Galactic Center distance of 8.7 kpc (Vanhollebeke, Groenewegen, & Girardi 2009), we obtain a bolometric flux for our Bin 1 template (Fig. 4.10):

\[ f_{bol} = 1.148 \times 10^{-9} \text{ erg/s/cm}^2 \]

The distribution of distances obtained for sources in Bin 1 is shown in Fig. 4.11, and plotted as a function of Galactic longitude in Fig. 4.12. Overall, these distances appear to be realistic estimates. The increased distance obtained toward the Galactic Center is most likely the result of extinction. These findings can be improved by applying an extinction correction to each source. While correcting the extinction is beyond the scope of this work, we discuss the beginning steps by which it might be accomplished in

![Figure 4.10: Template SED for Bin 1 (dotted line) calibrated to the Galactic Center distance of 8.7 kpc. Sources with known distance shown for comparison. By plotting source SEDs with similar shape, we can estimate a distance based on their relation to the Template SED.](image-url)
Sect. 5.3. Part of this process will involve distinguishing between disk and bulge sources, and this will help to constrain the accuracy of the distance estimation method we have developed here.

Figure 4.11: Distances for the full set of BAaDE sources in Bin 1 (bluest) of our SED shape bins. These distances were calculated using Eqn. 4.3. The outliers with $D > 15 \text{kpc}$ are poor catalog cross-matches with consequently poor model fits (e.g., Fig. 5.1).

Figure 4.12: Distances vs Galactic longitude for the same sources in Fig. 4.11. Distance increases toward the Galactic Center are likely the most affected by extinction.
5. Ongoing and future work

In this chapter, we briefly discuss the continuation of the research using the BAaDE IR data. Sections 5.1 and 5.2 describe improvements which can be made to the IR catalog data and SED modeling library to provide higher fidelity to our source and CSE characterization. In section 5.3 we discuss our limited attempts to this point to correct for foreground extinction. Additionally, we describe a means by which extinction correction might be performed in a specific region toward the Galactic bulge using research by Gonzalez et al. (2012), Trapp et al. (2018) and an extinction curve for the IR spectrum covered by the BAaDE IR catalog compiled from sources given in Table 5.1. Section 5.4 briefly describes applications correlating the IR data and SiO maser characteristics.

5.1 IR Catalog Improvements

Chapter 2 described in detail the procedures we used to create the BAaDE IR Catalog. While we have taken great care to ensure the quality of the detections and the accuracy of the cross-matching between the included IR catalogs, errors will inevitably be found and corrected. Using the $\chi^2$ value generated via our fitting algorithm, it is a simple but tedious matter to evaluate the worst fits by eye for quality and accuracy. That is, some sources have poor $\chi^2$ values reported for all models, which indicates there may be data points included that greatly deviate from the expected SED shapes. In some cases, the variability of our sources between the observing epochs in different catalogs will
Figure 5.1: Example of a poor SED fit due to misidentification during IR catalog cross-matching. In this case, the GLIMPSE data is inconsistent with the other catalogs. Examining fits with consistently poor $\chi^2$ values following fitting will enable identification of these types of errors and improve the BAaDE IR catalog.

degrade the fits, but in other cases visual inspections make it obvious that source misidentifications were made in one or more of the IR catalogs. Figure 5.1 gives an example of such a case.

5.2 SED Model Parameter and Fitting Improvements

As discussed in Chap. 3, we have constructed a library of model SEDs using the DUSTY radiative transfer program. We have probed the parameter space of the target sources and CSEs across a range of expected values (Table 3.1), but the density of the modeled
parameter space can be increased to provide additional detail and accuracy to the model parameters given from the SED fitting. In particular, creating models with different CSE chemical composition may provide better fits for those sources which can be identified as carbon-rich, and may help in that identification. Additionally, the density of steps at the lower end of the range of optical depths included in our models can be increased significantly. Our most recent fitting run has shown that most of our sources have optical depths at 8.3 $\mu$m of less than 0.5, with a mean of 0.386. This is expected due to our thin shell criteria, and supports the validity of our models.

Finally, apart from increasing the density of the model parameter space, improvements can be made by incorporating the instrument spectral response functions to our fitting algorithm, rather than fitting to the central isophotal wavelength.

![Extinction curve compiled for the BAaDE IR wavelengths, normalized to $A_K$. Estimated values and sources are given in Table 5.1.](image)

Figure 5.2: Extinction curve compiled for the BAaDE IR wavelengths, normalized to $A_K$. Estimated values and sources are given in Table 5.1.
5.3 Extinction Corrections

The analysis in this work does not contain any correction for foreground extinction or bolometric corrections along the lines of sight to our targets. The IR wavelengths used in our analysis are less affected by extinction than e.g. visible wavelengths. For the deeper targets in our survey, however, even the relatively low extinction in the IR will make a difference in the shape of the SED and our ability to constrain the parameters of the source and CSE, and consequently, distance to the source.

<table>
<thead>
<tr>
<th>Catalog Band</th>
<th>$A_\lambda/A_{ KS}$</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>MSX – all bands</td>
<td>A – 0.55</td>
<td>Gao et al. 2009; Rosenthal et al. 2000</td>
</tr>
<tr>
<td></td>
<td>C – 0.38</td>
<td></td>
</tr>
<tr>
<td></td>
<td>D – 0.40</td>
<td></td>
</tr>
<tr>
<td></td>
<td>E – 0.32</td>
<td></td>
</tr>
<tr>
<td>2MASS – all bands</td>
<td>J – 2.70</td>
<td>Chen et al. 2013</td>
</tr>
<tr>
<td></td>
<td>H – 1.63</td>
<td></td>
</tr>
<tr>
<td></td>
<td>K – 1.00</td>
<td></td>
</tr>
<tr>
<td>DENIS – all bands</td>
<td>I – 4.00</td>
<td>Chen et al. 2013</td>
</tr>
<tr>
<td></td>
<td>J – 1.63</td>
<td></td>
</tr>
<tr>
<td></td>
<td>K – 1.00</td>
<td></td>
</tr>
<tr>
<td>WISE – W1/W2</td>
<td>W1 – 0.55</td>
<td>Chen et al. 2013</td>
</tr>
<tr>
<td></td>
<td>W2 – 0.37</td>
<td></td>
</tr>
<tr>
<td></td>
<td>W4 – 0.31</td>
<td></td>
</tr>
<tr>
<td>GLIMPSE – all bands</td>
<td>1 – 0.53</td>
<td>Chen et al. 2013</td>
</tr>
<tr>
<td></td>
<td>2 – 0.40</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3 – 0.32</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4 – 0.42</td>
<td></td>
</tr>
<tr>
<td>ISOAGAL – all bands</td>
<td>07 – 0.47</td>
<td>Jiang et al. 2006</td>
</tr>
<tr>
<td></td>
<td>15 – 0.40</td>
<td></td>
</tr>
<tr>
<td>MIPSGAL</td>
<td>24 – 0.28</td>
<td>Rosenthal et al. 2000</td>
</tr>
<tr>
<td>AKARI – 9 μm</td>
<td>9 – 0.72</td>
<td>Lutz 1999</td>
</tr>
<tr>
<td>AKARI – 18 μm</td>
<td>18 – 0.39</td>
<td>Gao et al. 2009</td>
</tr>
<tr>
<td>Herschel</td>
<td>n/a</td>
<td>n/a</td>
</tr>
</tbody>
</table>

Table 5.1: Extinction coefficients compiled for the BAaDE IR wavelengths, corresponding to the curve shown in Fig. 5.2. The coefficients are estimates based on information from the given references.
While none of our data have been de-reddened, we have begun to explore methods by which this may be accomplished. Much of the work done to create extinction maps in the Galactic plane define extinction coefficients in terms of extinction in the $K$-band, e.g. $A_\lambda/A_{KS}$. We have created an extinction curve normalized to $A_{KS}$ (Fig. 5.2) for the range of wavelengths covered by the BAaDE IR catalog using coefficients compiled from several sources covering different parts of the IR spectrum, given in Table 5.1. In some cases, the exact band contained in the BAaDE catalog or a function which allowed an exact calculation were used, but in most cases the values were extrapolated from a nearby band or read from a curve displayed as a figure in the given reference.

The extinction curve presented in Fig. 5.2 will likely require some additional calibration. However, two major tasks remain to effectively correct for extinction in our sources: calculating the $K$-band extinction for each source, and distinguishing between disk and bulge sources in our sample. Gonzalez et al. (2012) have created $A_{KS}$ extinction maps in the Galactic bulge region ($-10° < l < +10.2°; -10° < b < +5°$), and provided a searchable web tool (BEAM calculator, http://mill.astro.puc.cl/BEAM/calculator.php) which we have used to collect $A_{KS}$ data for our sources in this region. Using a previous iteration of our DUSTY models, we attempted to perform correction and fitting for a sample of these sources, with varying degrees of success. One problem was that too much extinction was applied to some sources, severely distorting typical SED shapes. It is likely that separating the disk and bulge sources will improve this analysis. In particular, Trapp et al. (2018) has shown that it may be possible to distinguish between the BAaDE disk and bulge kinematical populations by a simple $K$-band magnitude cut,
which could help separate mostly nearby and less extinction affected stars from those further away.

Combining these tools in the bulge region will likely improve the detail with which we are able constrain the modeled parameters of the source and CSE. For sources outside the region covered by the BEAM calculator, we will need to determine other methods for calculating the $K$-band extinction.

5.4 SiO Maser Transitions and IR Correlations

Stepping away from the goal of deriving distances, the BAaDE data set will enable an unprecedentedly detailed statistical study of the red giant CSE properties via correlation of IR and SiO maser properties. The molecular abundances and line strengths in the CSEs provide information about both the stellar and circumstellar chemistry, which will affect both stellar evolution as well as, in the longer term, the chemical evolution of a galaxy.

The presence or absence of specific transitions inform us about the metallicity and the CSE gas chemistry in a given star. Studies of smaller samples of SiO maser stars have been performed previously, finding some evidence of the maser luminosity being correlated with mass-loss rate, and perhaps with properties like $K$-band luminosity (Chibueze et al. 2016; Langer & Watson 1984). Confirming and establishing details of such, and similar, correlations provide insight into the formation and pumping of the SiO
maser lines.

5.4.1 SiO maser detection rate

The SiO maser detection rate in all detected lines as a function of MSX color will be considered, which may correlate with the thickness of the CSE as well as mass-loss rate. For example, Gonzalez-Delgado et al. (2003) reports on a trend where the SiO thermal \((v = 0)\) line abundance decreases as a function of mass-loss rate using approximately 50 Mira variables with SiO maser emission. Given a distance estimate, mass-loss rates can be extracted from our SED model fitting (Chap. 3), thus with our survey we will increase the previously studied sample sizes from a few 10s of stars to thousands.

Previous observational results have shown a consistent trend in which the detection rate of both OH masers in OH/IR star, and SiO masers in AGB stars, decreases with Galactocentric distance (e.g., Blommaert et al. 1993; Jiang et al. 1999). We can confirm and strengthen (and likely refine as a function of stellar type) this inferred metallicity gradient by determining the SiO maser detection rate as a function of longitude and latitude, combined with the detection rate as a function of MSX color. With this information we can address questions such as how much gas is processed as a function of Galactic distance during the evolution of the Galaxy.

We further expect that carbon-rich stars will not be found in the central parts of the Galaxy (e.g., Noguchi, Aoki, & Kawanomoto 2004). Similarly, the rate of non-detections may also correlate with IR color, as they may be either carbon-rich or perhaps oxygen-
rich with specific properties of the CSE not favorable for forming SiO masers.

5.4.2 SiO maser luminosity function

A well-defined SiO maser luminosity function would provide information for statistical constraints on the red giant stellar maser population, including metallicity gradient effects, and thereby give new insight into the bulge’s star formation history. Applying the distances inferred by the method developed in Chap. 4, we may be able to construct a SiO luminosity function which will greatly improve on previous studies of smaller samples (e.g., Izumiura et al. 1995).

5.4.3 SiO maser excitation conditions

Modeling of the SiO maser emission has, over the years, used both collisional and radiative pumping schemes to understand the nature of the SiO maser formation. Our target selection is focused on red giants with optically thin CSEs, favorable for finding maser emission. In these CSEs, the 8 μm silicate feature should appear in emission (see, for example, the models plotted in Fig. 4.5). We will correlate the presence of SiO masers in different transitions (and their intensities) with the 8 μm fluxes as observed in the MSX A band (6.8 – 10.8 μm), and WISE band 3 (7.5 – 16.5 μm). Such a trend has been hinted at before but is not yet conclusive (Messineo et al. 2002; Jiang et al. 2002). While the maser dependency on stellar pulsations could be supporting collisional
pumping, a tight correlation with infrared magnitudes at 8 μm (which are also variable due to the stellar pulsation) and the SiO maser intensity may strongly support an IR-dominated pumping scheme. In fact, Australia Compact Telescope Array (ATCA) data of a subset of the BAaDE SiO maser sources is strongly supporting a radiatively dominated scenario, due to the distribution of the line ratios between different SiO transitions (Stroh et al. 2018).

6. Conclusion

In this thesis, we have sought to determine a means of estimating distances to a sample of IR-selected AGB stars, primarily oxygen-rich Miras. The means for doing so required extensive cross-matching between the BAaDE SiO maser targets and multiple IR catalogs. We have constructed a database of IR information for each of the BAaDE targets from the MSX, 2MASS, DENIS, WISE, GLIMPSE, ISOGAL, MIPSGAL, AKARI and Herchel PACS catalogs. The steps taken to perform this cross-matching can be found in Chapter 2, as well as analysis to ascertain the quality of the matching.

Using the BAaDE IR database, we then constructed SEDs for each source and fit these to modeled SEDs generated using the radiative transfer program DUSTY. Fitting to these models gives us estimates of the source effective temperature and bolometric flux. Additionally, they give estimates of CSE properties such as relative shell thickness, dust condensation temperature and optical depth. While we have only made use of the bolometric flux in our distance estimation work, characterizing these additional
properties will be useful in future analysis of the BAaDE targets, especially once the SiO maser survey has been completed. The procedures and meta-analysis for these findings are described in Chapter 3.

We have developed a method by which we can estimate a distance to the BAaDE sources, and likely to other Mira stars. Binning by the slope of the SED at the MSX wavelengths, we have used sources with known parallax distances to calibrate a relationship within a bin between the bolometric flux for a given source and a distance to that source. We have demonstrated this for one bin in which we have multiple sources with known parallax distances by which to calibrate, and the method can be refined and extended to other bins by additional astrometry from, for example, sources which overlap with Gaia or VLBI missions. The work in this thesis does not address interstellar extinction corrections, but this will also play a part in refining these distance estimates. Chapter 4 contains the details and analysis of our distance estimation procedure.

In Chapter 5, we have identified several improvements which can be made to our IR catalog and SED modeling and fitting procedures. The modeling and fitting results are identified as a means to identify sources within the catalog which have been misidentified during one or more catalog cross-matches. One of the biggest improvements to the fidelity of our results will likely come from applying corrections for line of sight foreground extinction. We have outlined how this task might be undertaken for sources which lie toward the Galactic bulge, using a combination of the work of Trapp et al. (2018) and Gonzalez (2012).
Finally, we have briefly discussed applications correlating the IR data and SiO maser characteristics for the BAaDE sources. Most of these are dependent on the distance estimation procedures we have begun to develop here.
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This research has made use of the NASA/IPAC Infrared Science Archive, which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

This publication makes use of data products from the Wide-field Infrared Survey Explorer, which is a joint project of the University of California, Los Angeles, and the Jet Propulsion Laboratory/California Institute of Technology, and NEOWISE, which is a project of the Jet Propulsion Laboratory/California Institute of Technology. WISE and NEOWISE are funded by the National Aeronautics and Space Administration.

Herschel is an ESA space observatory with science instruments provided by European-led Principal Investigator consortia and with important participation from NASA.

This work is based [in part] on observations made with the Spitzer Space Telescope, which is operated by the Jet Propulsion Laboratory, California Institute of Technology under a contract with NASA.

This publication makes use of data products from the Two Micron All Sky Survey, which is a joint project of the University of Massachusetts and the Infrared Processing and Analysis Center/California Institute of Technology, funded by the National Aeronautics and Space Administration and the National Science Foundation.

This research is based on observations with AKARI, a JAXA project with the participation of ESA.

This research makes use of MATLAB Release 2017a/b, The MathWorks, Inc., Natick, Massachusetts, United States.