Chapter 1

Introduction

The Milky Way is the cornerstone of our understanding of galaxies. The structure and kinematics of its gas and stars can be studied in unique detail due to their relative proximity. However, being located well within the Galactic disk and thereby observing the Milky Way in non–linear projection makes it difficult to properly map its large-scale morphology.

One of the interesting findings has been that observations of molecular line emission (CO, HI) and stellar motions show signatures of a Galactic Bar in the inner Galaxy. However, its characteristics such as elongation, thickness and viewing angle are still poorly constrained. One of the main obstacles has been the strong obscuration by interstellar dust toward the inner Galaxy, which makes optical studies of the stellar population in that region almost impossible. The extinction is less severe at near- and mid-infrared wavelengths. To characterise the structure and formation history of the Milky Way, several infrared surveys were conducted during the past decade: ISOGAL, MSX, DENIS, 2MASS. These data contain a wealth of information on the structure of the stellar populations that has yet to be fully analysed. Having entered a golden age for Galactic astronomy, soon even more detailed imaging and spectroscopy will be provided by the Spitzer Space Telescope, while the GAIA satellite will provide unprecedented astrometry.

My thesis research has focused on the structure and stellar population of the inner 4 kpc of the Milky Way. I have analysed data from recent infrared surveys and obtained SiO radio maser line observations of late-type giants to study the star formation history and the gravitational potential of the inner Galaxy. With ages ranging from less than 1 to 15 Gyr, the infrared-luminous late-type giant stars are representative of the bulk of the Galactic stellar population, and hence trace its star formation history. Their spatial abundance variation maps the stellar mass distribution, and thereby probes the Galactic gravitational potential. The reddening of their spectral energy distribution can be used to map the interstellar extinction. Their envelopes often emit strong molecular masers (OH, SiO) that can be detected throughout the Galaxy, and through the precise measurement of the maser line velocity they reveal the stars' line-of-sight velocities. Therefore they are ideal tracers of the Galactic kinematics and gravitational potential.

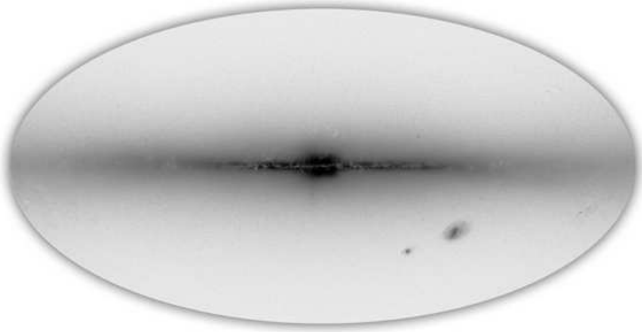

Figure 1.1: *This infrared image taken by the 2MASS satellite shows the plane of our Milky Way Galaxy as a thin disk. Dust obscuration makes the optical appearance of the Milky Way much more patchy.*

1.1 Late-type giants

In this section I shall briefly discuss the life cycle of stars, with emphasis on the red giant and asymptotic giant branch phases.

A low- to intermediate-mass star ($M_* < 8\,M_\odot$) spends 80 to 90 percent of its life on the so called main-sequence phase. This phase ends when a large fraction of the star's hydrogen has been converted to helium. Then the stellar core contracts and heats until hydrogen fusion starts in a shell surrounding the core. This causes the stellar envelope to expand to about 50 to 100 solar diameters, while the surface temperature decreases. Stars in this phase are called red giant branch (RGB) stars.

When the core temperature is high enough, helium nuclei fuse into carbon and oxygen. For stellar masses less than 2.3 solar masses (low mass stars), the core is degenerate and core helium burning begins abruptly in a so called core helium flash. In the Hertzsprung-Russell (HR) diagram this event marks the tip of the red giant branch. For higher mass stars helium burning begins more gradually. The core helium-burning phase lasts between 10 and 25 percent of a star's main-sequence lifetime.

When the core helium is exhausted, the core contracts, the envelope expands and the stellar surface temperature decreases. The star is now powered by hydrogen and helium burning in shells surrounding the core, which consists of carbon and oxygen nuclei with a degenerate distribution of electrons. A star in this phase is called an asymptotic giant branch (AGB) star. This name originates from the fact that in the HR diagram for low mass stars the AGB branch approaches the RGB sequence asymptotically. They can be as large as several hundred solar radii

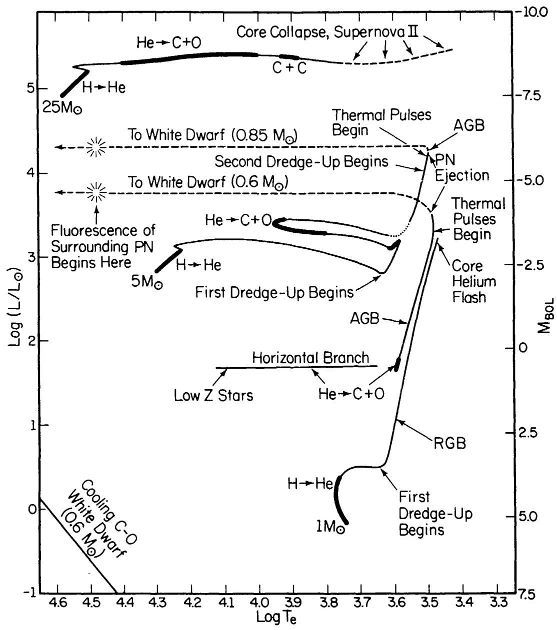

Figure 1.2: *Stellar evolution tracks of 1, 5, and 25 $M_\odot$ stars in the H-R diagram (Iben 1985).*

and have a relatively cool surface temperature of about 3000 K.

At the beginning of the AGB phase, helium shell burning prevails over shell hydrogen burning, so the C-O core grows steadily in mass, approaching the hydrogen shell (E-AGB). When the mass of helium between the core and the hydrogen shell drops below a critical value, the helium shell exhibits oscillations that eventually develop into the first helium shell flash and the thermally pulsating (TP-AGB) phase begins. A dredge-up (the third dredge-up) may take place during this phase, bringing carbon to the surface.

Mass-loss reduces the envelope mass until the residual envelope is ejected in a short superwind phase. The strength of the wind controls the decrease of the stellar mass (as the star climbs the AGB in the HR diagram), which also affects the evolution of its surface composition. Mass-loss may occur also in RGB stars close to the RGB tip, but with much lower intensity than in AGB stars.

The third dredge-up is fundamental to explain the conversion of a fraction of oxygen-rich AGB stars into carbon-rich AGB stars (for which [C/O]> 1) and predicts that the latter form only above a specific minimum luminosity. Carbon stars are virtually absent in the Galactic bulge, whereas they are numerous in the Magellanic Clouds, suggesting that the lower metallicity there provides for a more efficient dredge-up.

AGB stars produce roughly one third of the carbon in the Galaxy, almost the same amount as supernovae and Wolf-Rayet stars. By returning dust and gas to the interstellar medium, RGB and AGB stars pave the way for the formation of future generations of stars and planets.

Due to their low surface temperatures, late-type giants (RGB and AGB) are bright at infrared wavelengths. Facing a high interstellar extinction toward the central regions of the Milky Way that obscures stars at visible wavelengths, red giants are the best targets for studies of the stellar populations, dynamics, and star formation history in the inner Galaxy.

1.1.1 AGB star and variability

An important property of AGB stars with direct applications to Galactic structure studies is their luminosity variability. The radial pulsations of AGB stars are confined to the large convective envelopes and should not be confused with the thermal pulse that originates in the helium burning shell. The latter leads to a longer-term variability.

Variable AGB stars are named in several different ways based on the light curve properties and periods: large amplitude variables (LAV), long period variables (LPV), Mira variables, semiregular (SR) and irregular variables.

By definition, Mira stars show pulsations with large amplitudes at visual wavelengths (more than 2.5 mag) and vary relatively regularly with typical periods of 200 to 600 days. Semiregular variables show smaller amplitudes (less than 2.5 mag) and they have a definite periodicity. Since they are obscured in the visual, this classification cannot be applied to inner Galactic variable AGB stars. Therefore, for inner Galactic variable stars 'LAVs' and 'LPVs' refer to variations in the K-band. Mira stars are usually LAVs with K-band variation amplitudes larger than 0.3 mag.

Another important class of AGB variable stars are OH/IR stars, which are dust-enshrouded infrared variable stars. They are discovered in the infrared and show 1612 MHz OH maser emission. Their periods are typically longer than 600 days and can exceed 1500 days.

Recent observations from the MACHO, EROS and OGLE surveys initiated a discussion on the pulsation modes of long period variables and on the period-luminosity relations. Such period-luminosity relations are important for Galactic structure studies as they yield estimates for a star's distance. The new data reveals four parallel period-luminosity sequences (A-D). However, the classical period-luminosity relation discovered by Feast et al. (1989), which is based on visual observations of Mira stars, still holds and coincides with the C sequence. Large amplitude variables with a single periodicity, like probably most of our SiO targets, populate this sequence.

1.1.2 Circumstellar maser emission

MASER stands for Microwave Amplification by Stimulated Emission of Radiation. In 1964 Charles Townes, Nicolay Gennadiyevich Basov and Aleksandr Mikhailovich Prochorov received the Nobel Prize for their discovery of the maser phenomenon. Now, forty years later, we know of thousands of astronomical masers, "radio radiation detected in some lines of certain astronomical molecules, attributed to the natural occurrence of the maser phenomenon" (Elitzur).

Maser radiation is caused by a population inversion in the energy levels of atoms or molecules. The non-equilibrium inversion is caused by different pumping mechanisms, in astronomical objects usually infrared radiation and collisions.

An observed line can be identified as a maser line on the basis of its unusually narrow line-width, or when line ratios indicate deviations from thermal equilibrium.

Various molecules can show maser emission. Astronomical masers are found around late-type stars (circumstellar masers), and in the cores of dense molecular clouds (interstellar masers). A comprehensive review of astronomical masers was given by Elitzur (1992) and Reid & Moran (1988). In this thesis we study circumstellar maser emission.

The circumstellar envelopes of oxygen-rich late-type stars can exhibit maser emission from SiO, H_2O, and OH molecules (Habing 1996). Masers occur in distinct regions at various distances from the central star. SiO masers at 43 and 86 GHz originate from near the stellar photosphere, within the dust formation zone (Reid & Menten 1997). Water masers originate further out, at distances of up to 10^{15} cm from the central star, while OH masers are found in the cooler outer regions of the stellar envelope, about ten times further out.

The presence or absence of particular maser lines in a circumstellar envelope appears to depend on the opacity at 9.7μm: a higher mass-loss rate leads to a more opaque dust shell, which shields molecules better against photodissociation by interstellar UV radiation.

SiO masers arise from rotational transitions in excited vibrational states. These levels can be highly populated only near the star where the excitation rates are high. SiO maser emission has been detected in different transitions towards oxygen-rich AGB stars (i.e. Mira variables, semi-regular variables, OH/IR stars) and supergiants. The relative intensity of different SiO maser lines varies among different sources, indicating that the SiO maser pumping mechanism depends on the mass-loss rate. Maser pumping is dominantly radiative, as suggested by the observed correlation between the maser intensity and the stellar infrared luminosity. However, collisional pumping cannot be ruled out. A maser line can show the stellar line of sight velocity with an accuracy of a few km s^{-1}.

H_2O (22 GHz) and OH (1612 MHz, 1667 MHz and 1665 MHz) masers originate from transitions in the ground vibrational state. H_2O maser spectra are irregular and variable. Therefore they are not useful for an accurate determination of stellar line of sight velocities. The 1612 MHz OH maser line is pumped by radiation from the circumstellar dust, which excites the 35 μm OH line and has a typical double-peaked profile. The stellar velocity lies between the two peaks and the distance between the two peaks yields a measure of the expansion velocity of the circumstellar envelope.

Lewis (1989) analysed colours of and masers from IRAS stars, suggesting a chronological sequence of increasing mass-loss rate: from SiO, via H_2O to OH masers. This sequence links AGB stars via the Mira and OH/IR stages with Planetary Nebulae. However, parameters other than mass-loss, such as stellar abundance, probably also play an important role (Habing 1996).

1.2 The Milky Way galaxy

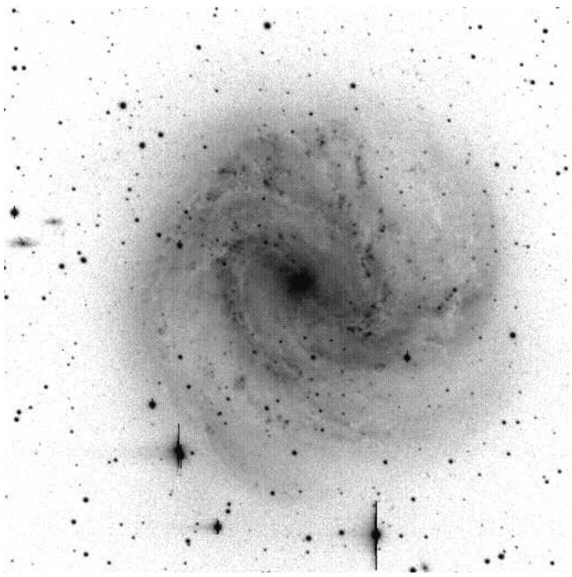

Figure 1.3: *The Southern Pinwheel galaxy, M83, was classified as intermediate between normal and barred spiral galaxies by G. de Vaucouleurs. It has both a pronounced disk component exhibiting a spiral structure, and a prominent nuclear region, which is part of a notable bulge/halo component. The Milky Way might look similar to M83.*

Our home Galaxy, the Milky Way, is a large disk galaxy. It is likely to be of Hubble type SBbc, with its main components being the bulge, the disk, and the halo.

The Milky Way today is the result of star formation, gas flow, and mergers integrated over time. The different Galactic components were not formed by independent events, and their formation history is largely unknown. The possible connection between the star formation history and the formation of Galactic structures is equally unknown.

Halo
The halo is composed of a dark matter and a stellar halo. The dark halo is of yet unknown nature and dominates the total Galactic mass, as suggested by dynamical studies of satellite galaxies. The stellar halo, a roughly spherical distribution of stars whose chemical composition, kinematics, and evolutionary history are quite different from stars in the disk, contains the most metal-poor and possibly some of the oldest stars in the Galaxy. It retains important information on the Galactic accretion history. The recent discovery of stellar streams in the halo (e.g. Helmi et al. 1999; Ibata et al. 1994) supports the hierarchical clustering and merging scenario of galaxy formation.

Disk
The disk is usually divided into two components, the thin and thick disks. The thick disk (Gilmore & Reid 1983) is older that 10 Gyr. Its metallicity ranges from -1.7 to -0.5 [Fe/H], it has a scale height of 0.7-1.5 kpc, a scale length of 2-3.5 kpc and a vertical velocity dispersion of 40 km s^{-1}. The thin disk has a scale-height of about 250 pc and contains stars of all ages. The thick disk was probably formed from the thin disk during a merger event that heated the disk (Gilmore et al. 2002).

Bulge
There is some confusion in the use of the term "bulge". In the literature it is often used to indicate everything in the inner few kiloparsec of the Galaxy, i.e., the bar and the nuclear disk. Wyse et al. (1997) prefer to define a "bulge" as a "centrally concentrated stellar distribution with an amorphous, smooth appearance. This excludes gas, dust and recent star formation by definition, ascribing all such phenomena in the central parts of the Galaxy to the central disk, not to the bulge with which it cohabits."

The "bulge" is dominated by an old stellar component (10 Gyr). Its abundance distribution is broad, with a mean of [Fe/H]~ -0.25 dex (McWilliam & Rich 1994). It has a scale height of about 0.4 kpc, and a radial velocity dispersion of about 100 km s^{-1}.

There is growing evidence of a non-axisymmetric mass distribution in the inner Galaxy. This is found from the near-infrared light distribution, source counts, gas and stellar kinematics, and microlensing studies. However, it is not clear yet whether a distinction should be made between the triaxial Galactic bulge and the bar in the disk – a bar is defined as a thin, elongated structure in the plane.

In face-on galaxies, it is not unusual to observe both a central bulge and a bar (i.e. NGC1433). In general, bars may be populated by both old and young stars. In addition, barred galaxies often show a ring around the bar. From studies of edge-on galaxies there is indication that peanut-shaped or box-shaped (rather than spheroidal) bulges may be associated with bars. The Milky Way provides the closest example of a box-shaped bulge, and therefore it is a unique laboratory to investigate the structure and kinematics of a boxy bulge and its relation with the disk. A bar and a triaxial bulge could both be present, distinct, and coexisting.

The existence of a distinct disk-like dense molecular cloud complex in the central few hundred pc of our Galaxy, the Central Molecular Zone (CMZ), was established in the early 1970s. Observations of ongoing star formation and the presence of ionizing stars suggest that this is a component different from the bulge. In the longitude-velocity diagram (Fig. 1.4) it generates a remarkable feature called the 180 pc-Nuclear Ring. It can be understood as a gaseous shock region at the transition between the innermost non intersecting X1 orbits and the retrograde X2 orbits (Binney et al. 1991). The total mass of the CMZ (including the central stellar cluster) amounts to $(1.4 \pm 0.6)10^9 M_\odot$, of which 99% is stellar mass, and 1% gaseous mass. Its stellar luminosity amounts to $(2.5 \pm 1)10^9 L_\odot$, 5% of the total luminosity of the Galactic disk and bulge taken together (Launhardt et al. 2002).

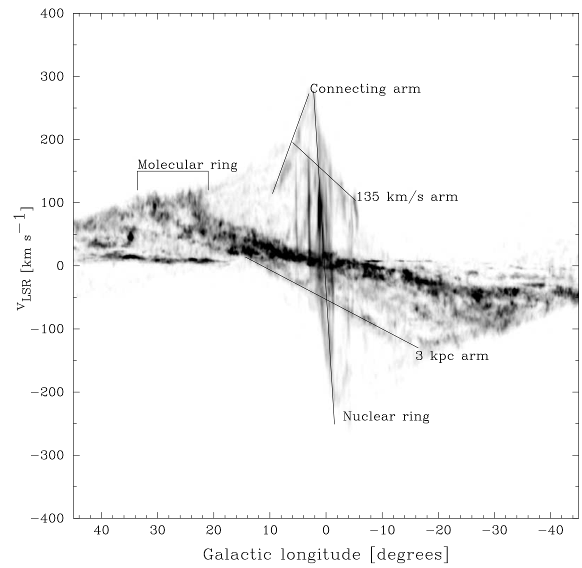

Figure 1.4: *CO (l, v) diagram from Dame et al. (2001). Gas features are labelled as in Fig. 1 of Fux (1999).*

The centre of our Galaxy contains a massive black hole. The advent of adaptive optics has permitted high spatial resolution imaging studies of the Galactic centre. A dense cluster of stars surrounds Sgr A, and proper motions of these stars were recently obtained, showing them to have high velocities of up to 5000 $\mathrm{km\,s^{-1}}$. Thereby the mass of the central black hole has been estimated to be $(3.3 \pm 0.7) \times 10^6$ $M_\odot$ (e.g. Ghez et al. 2000; Schödel et al. 2003). Massive star formation is still going on in the central parsec of the Galaxy.

1.2.1 Stellar line of sight velocity surveys and the importance of maser surveys

Though the AGB phase is very short ($\sim 10^6$ yr) and therefore AGB stars are rare among stars, they are representative of all low and intermediate mass stars, i.e. of the bulk of the Galactic population. They are evolved stars and therefore dynamically relaxed and their kinematics traces the global Galactic gravitational potential. Thermally pulsing AGB stars are surrounded by a dense envelope of dust and molecular gas. They are bright at infrared wavelengths and can be detected even throughout highly obscured regions. Furthermore, the OH and SiO maser emission from their envelopes can be detected throughout the Galaxy, providing stellar line-of-sight velocities to within a few km s^{-1}. AGB stars thus permit a study of the Galactic kinematics, structure and mass-distribution.

This is especially useful in the inner regions of the Galaxy where the identification of other tracers like Planetary Nebulae is extremely difficult. Observations of Hα and [OIII] emission lines which easily reveal velocities of Planetary Nebulae are hampered by high interstellar extinction. A dynamical study of planetary nebulae ($-5°< b < -10°$) was performed by Beaulieu et al. (2000), who found that the spatial distribution of planetary nebulae agrees very well with the COBE light distribution. However, no conclusive results were found comparing the stellar kinematics properties with models of a barred Galaxy. The poor statistics was the main problem.

Performing radio maser surveys is the most efficient way to obtain line of sight velocities in the inner Galaxy. Two extensive blind surveys have been made at 1612 MHz searching for OH/IR stars in the Galactic plane ($|l| < 45°$, $|b| < 4°$), one in the South using the ATCA, and another in the North using the VLA (Sevenster et al. 1997a,b, 2001), yielding a sample of 766 compact OH-masing sources.

Searches at 43 or 86 GHz for SiO maser emission are also successful. SiO maser lines have the advantage to be found more frequently than 1612 MHz OH maser and the disadvantage that they can only be searched in targeted surveys, since the cost of an unbiased search is too high. Several 43 GHz SiO maser surveys of IRAS point sources have been conducted by Japanese groups using the Nobeyama telescope (e.g. Deguchi et al. 2000a,b; Izumiura et al. 1999). However, those surveys are not complete at low latitudes, since there IRAS suffers from confusion.

Up to day more than 1000 maser stars are known in the inner Galaxy. A kinematical analysis of Sevenster's sample of OH/IR stars (Debattista et al. 2002; Sevenster 1999b) shows clear signs of a barred potential. However, the number of line of sight velocities is still too small to allow us an unambiguous determination of the parameters of the bar. Furthermore, although most of the Galactic mass is in stars, a stellar longitude-velocity, $(l-v)$, diagram alone is not sufficient to constrain a model of Galactic dynamics, mainly due to the dispersion velocity of stars, which smooths the various features.

Improved statistics together with additional information on the distance distribution of masing stars will notably improve the understanding of the Galactic $(l-v)$ diagram. Low latitude stars are of particular importance since their motion may contain a signature of in-plane Galactic components, e.g. the nuclear ring, and they may show better the effect of a thin bar. New targeted maser surveys in the Galactic plane are now possible using ISOGAL and MSX sources, it is this simple idea from which the work presented in this thesis originates.

1.3 Outline of this thesis

To increase the number of measured line of sight velocities in the inner Galaxy ($30^\circ < l < -30^\circ$, mostly at $|b| < 1^\circ$), we began a survey of 86 GHz ($v = 1, J = 2 \rightarrow 1$) SiO maser emission. In **Chapter 2** we present the survey that was conducted with the IRAM 30-m telescope. Stars were selected from the ISOGAL and MSX catalogues to have colours of Mira-like stars. SiO maser emission was detected in 271 sources (a detection rate of 61%), doubling the number of maser derived line-of-sight velocities toward the inner Galaxy. I observed and detected the first line on August 26th, 2000: it was an unforgettable moment of joy!

The collection of near- and mid-infrared measurements of SiO targets allow us to study their energy distribution and determine their luminosity and mass-loss. **Chapter 3** describes a compilation of DENIS, 2MASS, ISOGAL, MSX and IRAS 1–25μm photometry of the 441 late-type stars which we searched for 86 GHz SiO maser emission. The comparison between DENIS and 2MASS J and $K_{\rm S}$ magnitudes shows that most of the sources are variable stars. MSX colours and the IRAS $[12] - [25]$ colour are consistent with those of Mira type stars with a dust silicate feature at 9.7 μm in emission, indicating only a moderate mass-loss rate.

Towards the inner Galaxy the visual extinction can exceed 30 magnitudes, and even at infrared wavelengths the extinction is significant. In **Chapter 4** we carry out the analysis of 2MASS colour magnitude diagrams of several fields in the plane at longitudes l between 0 and 30° in order to obtain extinction estimates for all SiO targets. With this analysis we are also able to put new constraints on the near-infrared extinction power-law.

The luminosity of our SiO targets is derived in **Chapter 5** and compared to that of a sample of OH/IR stars. We computed stellar bolometric magnitudes by direct integration under the observed energy distribution. Assuming a distance of 8 kpc for all stars within 5° from the Galactic centre we find the luminosity distribution to peak at $M_{\rm bol} = -5$ mag, which coincides with the peak shown by OH/IR stars in the Galactic centre. We found that the main difference between SiO targets and OH/IR stars is mass loss, which is higher in OH/IR stars. This fact offers several advantages. In contrast to OH/IR stars, SiO target stars are readily detectable in the near-infrared and therefore ideal for follow-up studies to better characterise the central star.

Considerations on the kinematics of SiO targets and future work plans are reported in **Chapter6**.

Finally in the last Chapter (**Chapter 7**) I briefly describe the ISOGAL survey, which is a 7 and 15 μm survey of $\sim$16 deg^2 towards selected fields along the

Galactic plane, mostly toward the Galactic centre. In collaboration with A. Omont (P.I.) and the ISOGAL team, I worked on the finalisation of the ISOGAL point source catalogue (Omont et al. 2003; Schuller et al. 2003). In this Chapter, I emphasise the importance of having several recent infrared surveys, such as DENIS, 2MASS, ISOGAL and MSX, in a common effort to unveil the overall structure of the Milky Way and in particular of its central and most obscured regions. These surveys require a huge amount of technical work which is of primary importance to obtain a reliable point source catalogue that can be used to perform such studies.

It is thanks to these new catalogues that the SiO maser project, i.e. the present thesis, could be performed.

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