Stellar radio beacons for Galactic astrometry

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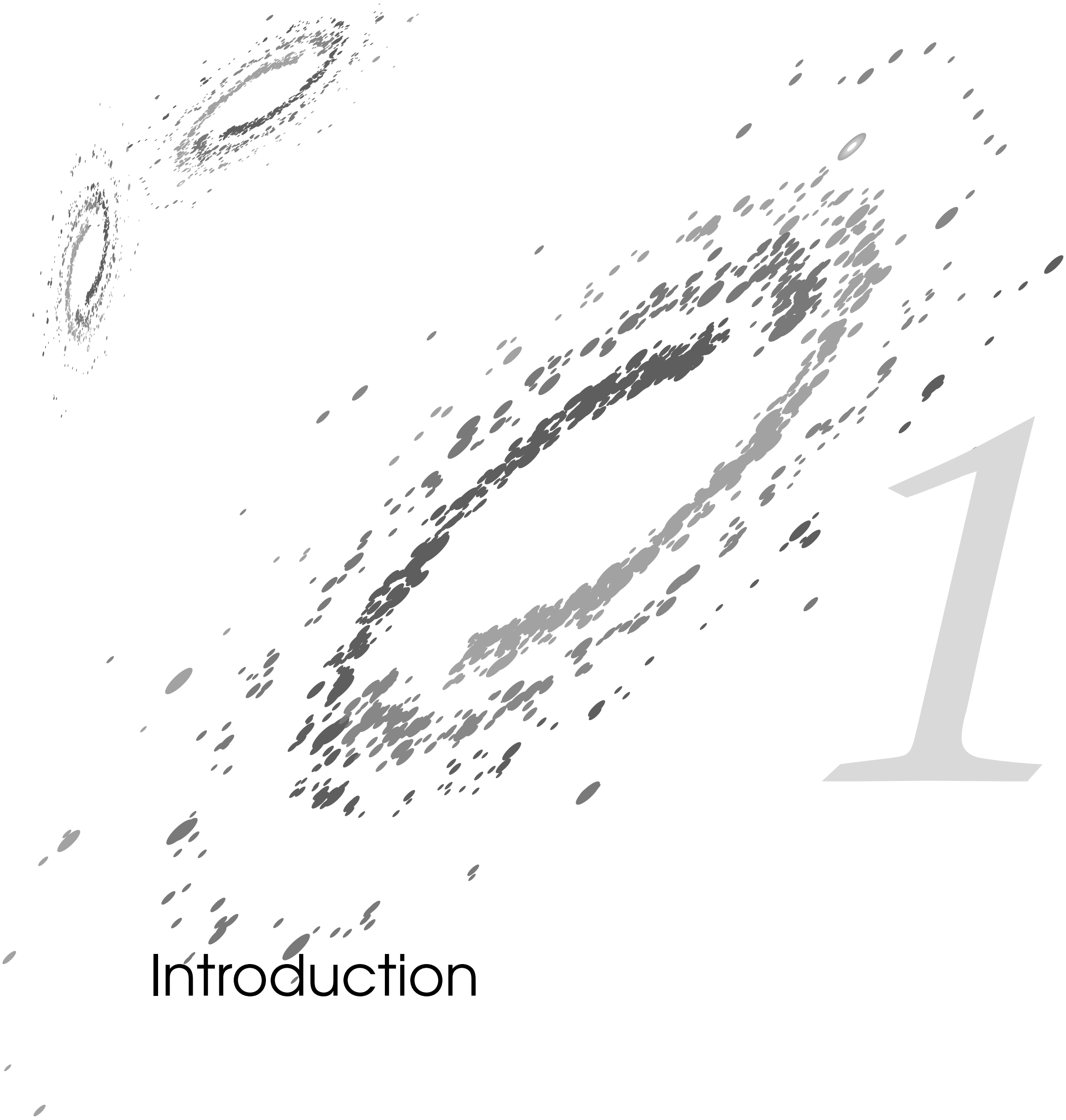

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Introduction

1.1 Historical review of the Milky Way

One hundred years before the publication of this thesis, the “Great Debate” took place at the Smithsonian Museum of Natural History in Washington D.C. At that time, there was a discussion about the actual dimensions and nature of our Galaxy led by Harlow Shapley and Herber Curtis. During the debate, divergent conclusions were drawn from the interpretation of the limited astronomical information available. Shapley explained that the Sun was located in what he defined as an island universe with an approximate size of 90 kpc surrounded by nearby smaller gaseous nebulae. He also suggested that other galaxies (or island universes) might exist but they were too far away, and thus undetectable. In contrast, Curtis explained that the Sun was centrally located in a smaller galaxy ($\lesssim$ 10 kpc size) surrounded by other similar galaxies (<3 Mpc). Curtis argued that these distant galaxies were only visible near the Galactic poles because of the obscuring matter within the Galactic disk. Notably, Shapley and Curtis were equally right and wrong regarding their descriptions of the Milky Way. All in all, the main issue hampering this debate was the lack of reliable distance estimates that could be used to determine which objects were faint nearby or bright faraway sources. During the following years, several methods were used and refined to estimate precise distances in astronomy as we will briefly show. However, as I will highlight throughout this thesis , three specific methods stood out and have been widely used in astronomy to establish the fundamentals of our current understanding of the Galaxy: the trigonometric parallax, Hertzsprung Russel diagram main sequence fitting (spectroscopic parallax) and the period-luminosity relation.

Some insights about the “Great Debate” came at the end of 1902’s. Edwin Hubble (1929), on the one side, identified individual Cepheids in M31 and M33. He then used the period-luminosity relations to estimate distances to these satellite galaxies, i.e., 275 and 263 kpc respectively (Hubble 1926, 1929). During the same decade, Bertil Lindblad and Jan Oort also made some advances. On the one hand, Lindblad proposed a kinematic model of the Milky Way based on measurements of radial velocities and proper motions of individual stars (Lindblad 1927a,b). On the other hand, Oort estimated the location of the center of the Milky Way (at ~6.3 kpc in the direction of the Sagittarius constellation) as well as the solar rotational velocity (Oort 1927). Although by the beginning of the 1930’s some aspects of the Milky Way were already established (size, structure, rotational speed, rational center and relative sizes and distances of close-by galaxies), the Galactic disk remained hidden due to the obscuring clouds of gas and dust. In fact, Robert Trumpler confirmed the presence of obscuring clouds of gas and dust by showing that the diameter of open stellar clusters diminished with distance less rapidly than the apparent brightness of the individual stars contained in the cluster (Trumpler 1930). Moreover, he showed that this matter of gas and dust estimated that the reduction of the apparent brightness of the stars was around 0.7 mag kpc^{-1}, which at some point will entirely block the light at optical wavelengths. Since this obscuration was mainly at shorter wavelengths, it produces a corresponding apparent reddening in the of stars.

In 1951, Walter Baade demonstrated that dark clouds and star-forming regions in the Andromeda galaxy were confined to the visible spiral arms (Baade 1951). Following this idea, Morgan et al. (1953) obtained spectroscopic parallaxes to 27 OB associations, HII regions and K giant stars. The distribution of these objects started suggesting a Galactic spiral structure, particularly three arm segments of three spiral arms close to the Sun. Thereafter, future investigations follow this path by enlarging the samples of young stellar objects and refining the spiral arm fitting (see e.g., Becker & Fenkart 1970).

Close to the beginning of the second half of the XX century, Van De Hulst (1949) proposed that the 21 cm emission (hyperfine emission line of neutral atomic hydrogen) would easily pass through the gas and dust. This conjecture triggered radio observations of Galactic hydrogen clouds (Oort, Kerr and Westerhout). By combining these observations with the kinematic theory proposed by Oort to interpret the radial velocity data coming from a spiral structure, the first accurate image of the structure within the Galactic plane was revealed. Subsequent studies included spectroscopic parallaxes in order to improve the distance accuracy to young stellar clusters that were already presumed to be tracers of spiral structure Humphreys (1976). Finally 1976, Georgelin & Georgelin (1976) combined precise astrometric measurements of HII regions and radial velocities of the spiral stricture obtained at radio wavelengths to generate the first draft of our current understanding of the Galactic spiral model (see Fig. 1.1). Nowadays, although the fundamental Galactic parameter values have been exceedingly refined, our current consensus model of the Galactic structure basically follows the proposal made by Georgelin & Georgelin (1976).

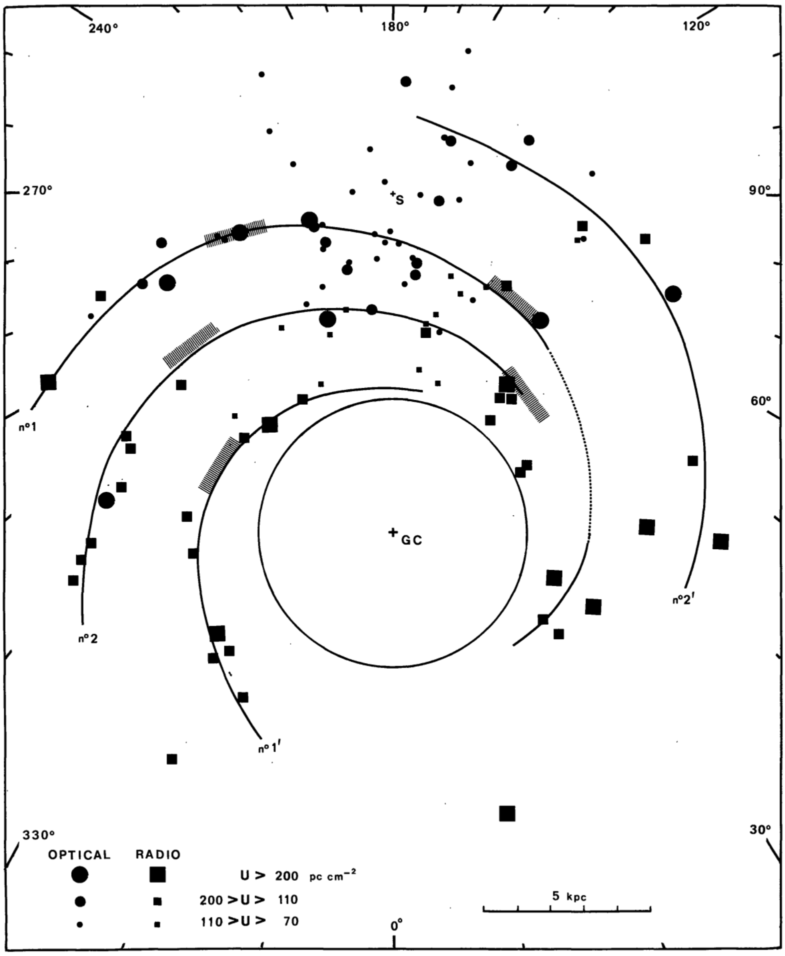

Figure 1.1: *Spiral model of the Milky Way proposed by Georgelin & Georgelin (1976) using excited HII regions in the Galaxy. The positions of the Sun and the Galactic center are marked with an "S" and "GC", respectively.*

1.2 The importance of Galactic plane studies

The Milky Way represents the cornerstone of our understanding of the diversity of galaxies in the universe. The structure and kinematics of the gas and stars in the Milky Way can be studied with unique detail given our privileged position. In fact, we have already identified that our Galaxy has a pronounced spiral structure that includes a prominent central bar, and therefore, it is classified as a as a Hubble type Sb (Vaucouleurs type SB(rs)bc II) galaxy. Furthermore, there are two fundamental Galactic processes directly associated with the spiral structure and the bar: rotation and star formation. These processes are happening mainly in the Galactic plane, where the flat disk slowly rotates as a near liquid, producing spiral arms, which in turn, are constantly being populated with young stars. Gas and dust, enriched by heavy elements released in supernova explosions, are continuously condensing to form stars. All of these Galactic constituents (i.e., stars, dust, gas, etc.) radiate across the entire electromagnetic spectrum, from radio to X-rays. However, being well located within the Galactic disk, and thereby observing the Milky Way from within, making it very difficult to accurately map its large-scale morphology, notably in the inner Galaxy. The importance of a kinematic analysis made in the Galactic plane is that it clarifies the behavior of the Galaxy as a gravitational system, which leads to important conclusions about its mass, evolution and history (including previous mergers). In the following subsections, we describe the major structures of the Galactic plane: the spiral structure and the Galactic bulge.

1.2.1 Spiral Structure

Spiral galaxies have been documented by astrophotographers back to the end of the XIX century, since then, the hypothesis that the Milky Way harbors spiral structure gained attraction. This view was only confirmed until the Galactic spiral structure was resolved using radio observations. To begin, we can consider the Galactic model illustrated by R. Hurt (see background in Fig. 1.3), which is an informed artistic impression constrained by the available data (Churchwell et al. 2009) of the face-on Milky Way. Nowadays, the discussion of the Galaxy's structure is framed in terms of four major spiral arms (or two, see e.g., Drimmel 2000; Xu et al. 2018) and a central bar.

- The elongated central bar is considered to be a prominent feature of spiral galaxies. However, the physical mechanisms that generate this type of structure are still poorly understood. IR surveys revealed that in the Milky Way, we can distinguish two bar substructures. On the one hand, a "narrow" Galactic bar oriented about 45° with respect to the Sun's direction and about 8.7 kpc long. On the other hand, a "boxy" bar oriented about 22° with respect to the direction to the Sun about 6.5 kpc long.

- The Sagittarius-Carina arm seems to begin at the far end of the boxy bar, with a continuous and dense concentration of bright stellar clusters and High Mass Star Forming Regions (HMSFRs) along the arm. This arm extends from quadrant I up to quadrant IV, and it has a width of~250 pc. It is the closest arm with respect to the Sun in the direction of the Galactic center (~1 kpc).

- The Scutum-Crux arm originates at ~ 6kpc in the direction of the Galactic center at the near end of the narrow central bar and it arcs in front of the Galactic center. Additional information from Southern observatories is needed to confirm how this arm extends in the far side of the Milky Way.

- The Norma-Outer arm seems to originate at the near end of the boxy central bar. It circles behind the Galactic center, it curves outward beyond the Perseus arm and it reaches the anti-Galactic center region. Its nearest distance to the Sun is approximately 5.4 kpc, but plausible kinks in this arm have been suggested based on gas and stellar components evidence.

- The Perseus arm is the closest arm to the Sun (or in general with respect to the local arm). It is believed to be one of two dominant spiral arms (along with the Scutum-Crux arm). It originates at the far end of the narrow central bar, and, as the Outer arm, it curves around the Galaxy reaching the anti-Galactic center region.

Finally, I want to highlight that the first tracers used to map the structure of the Galactic plane were massive and very bright optical stars. The location of these stars can be determined by spectroscopic parallax, and since they have very short lifetimes, they are expected to remain close to their place of birth (similar to what it is assumed for masers in HMSFRs, see section 1.3.3). Follow up surveys of young stellar clusters, OB associations and H II regions have been carried out to augment the original observations. Moreover, the observational limitations at optical wavelengths throughout the Galactic plane were overcome by radio observations of neutral hydrogen, and carbon monoxide, which in turn are associated with molecular hydrogen (H_2), a significant characteristic of star-forming regions (see e.g., Xu et al. 2018). The fact that radio wavelengths are not obstructed by interstellar matter is an important element of this thesis as we explain in the following section. It is worth knowing that other methods such as X-ray binary stars distributions, motions of variable stars, synchrotron emission, interstellar extinction, density stars based on infrared and optical surveys are further improving the tracing the spiral structure.

1.2.2 The inner Galaxy: Galactic bulge

The inner Galaxy is now understood to be strongly dominated by a massive bar, based on infrared morphology studies (e.g., Blitz & Spergel 1991; Dwek et al. 1995), the spatial distribution of red clump stars (e.g., Babusiaux & Gilmore 2005), maser stars (Habing et al. 2006) and the dynamics of red giants (Rich et al. 2007; Kunder et al. 2012). Indeed, an N -body model in which the bar forms via dynamical buckling from a preexisting massive disk fits the red giants dataset so well that $< 10\%$ of the bar might be in the form of a classical bulge, a result that is sustained by the clear demonstration of cylindrical rotation, a signature of strongly triaxial or boxy bulges (Howard et al. 2008). Recently, compelling evidence emerged for an additional X-shaped structure (see Fig. 1.2), similar to that seen in a number of extragalactic edge-on boxy bulges (McWilliam & Zoccali 2010; Wegg & Gerhard 2013). It has proven hard to isolate the population responsible for this structure and to study the kinematics (De Propris et al. 2011; Vásquez et al. 2013). However, there is a growing consensus that the X-shaped structure is dominated by the metal rich bar (Ness et al. 2012).

The stellar population in the inner Galaxy has a scale height of about 0.3 kpc, and a radial velocity dispersion of about 100 km s^{-1}. This population is contains an old, relaxed stellar component (<10 Gyr), where its abundance distribution is broad, with a mean of $[Fe/H] \sim -0.25$ dex (McWilliam & Rich 1994). Given these conditions, most of the stars in the bulge are loss-mass stars that are expected to produce maser emission as the matter that is going in the outflows is the proper environment for the production of OH, H_2O, SiO masers (Habing et al. 2006). Very Long Baseline Interferometry (VLBI) observations of OH, H_2O, SiO masers in the Galactic plane have been used to study the kinematic conditions of the Milky Way. Habing et al. (2006) reported a strong effect in the corotational resonance at 3.3 kpc, a small effect

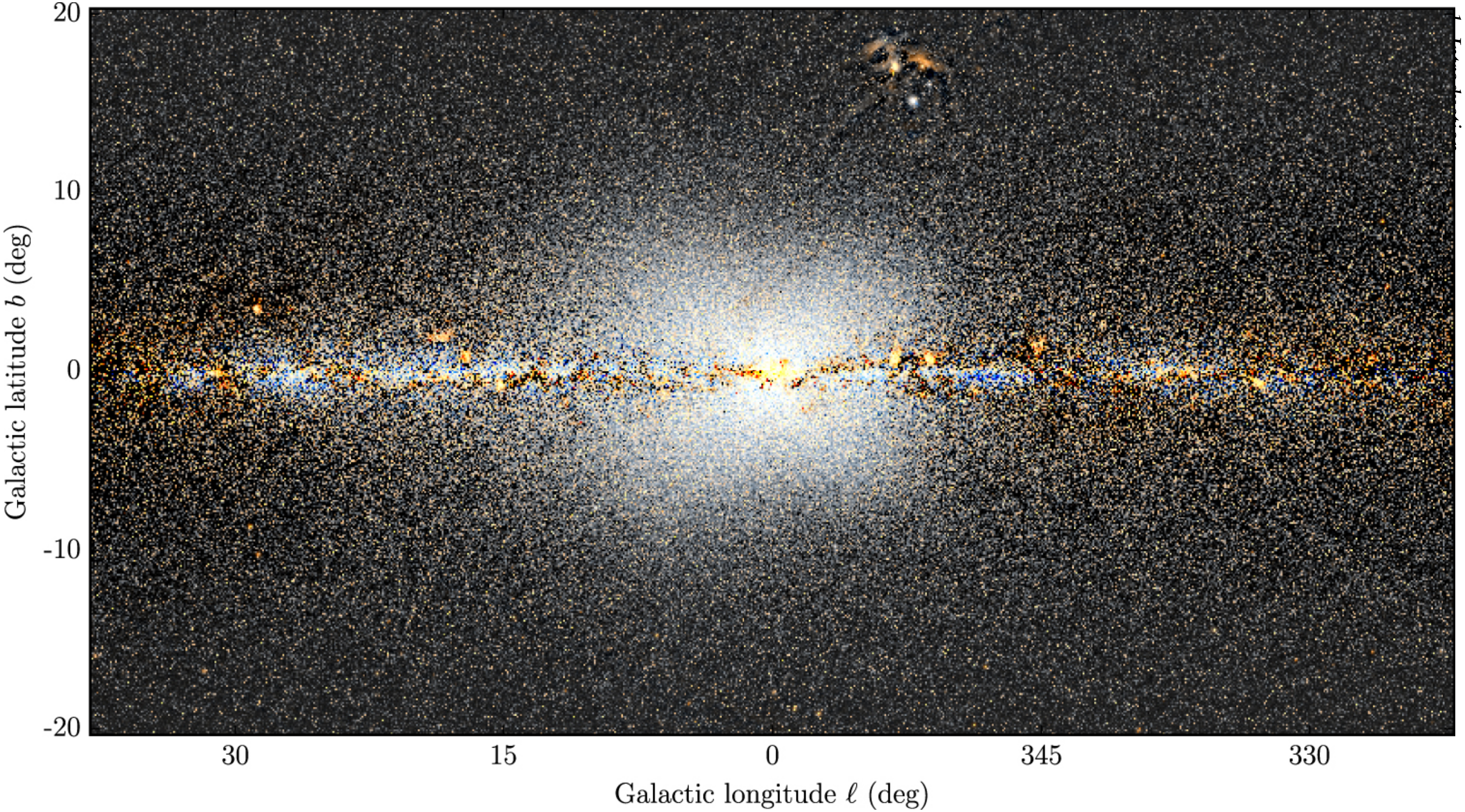

Figure 1.2: *Milky Way view in Galactic coordinates obtained by WISE which reveals an X-shape morphology in the Galactic bulge similar to what it has been seen in other (edge-on) galaxies. Ness & Lang (2016).*

of the Outer Lindblad Resonance at 5kpc and no effect of the Inner Lindblad Resonance at 0.8 kpc; those are important parameters in order to understand the evolution of our galaxy. Finally, the centre of our Galaxy contains a massive black hole. A dense cluster of stars surrounds Sgr A*, and proper motions indicate high velocities of up to 5,000 km s^{-1} (hyper velocities stars) that have been also detected by *Gaia* at high Galactic latitudes. 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). Future VLBI investigations are expected to resolved by the massive black hole in the Galactic center (Event Horizon Telescope).

The understanding of the structures in the Galactic plane previously related (i.e., spiral structure and Galactic bulge) strongly depends on precise astrometric measurements, where recently the *Gaia* mission and radio astrometric measurements have revolutionized our view of the Miky Way.

1.3 Precise astrometric measurements

In general, precise astrometric measurements are fundamental to research in any branch of astronomy. In particular, distance estimates (which are derived from accurate positional measurements) are crucial to establish the physics of astronomical objects. They are not only needed for tracking trajectories but also for estimating quantities such as mass, size, mass-loss and total emission energy of a body. A good fraction of our understanding of stellar, Galactic and extragalactic structures and their evolution over time heavily relies on this factor, yet distance determination still poses a challenging task.

Trigonometric parallax is a powerful and widely used technique to estimate unbiased distances in astronomy (Brunthaler et al. 2005; Reid & Honma 2014; Gaia-Collaboration et al. 2018). Precise parallaxes are obtained by measuring the apparent relative motions of an astrophysical object caused by the change of the position of the observer. The challenge then becomes detecting relative motion in astronomical scales with the required precision to produce physically relevant quantities. The measurement of the apparent relative motions to several stars is used to be made with ground-based observatories at optical wavelengths, but the technique was limited to nearby stars in the solar neighborhood Upgren (1978). Since then, several studies have been developed, as in Monet et al. (1992), showing that modern ground optical based instruments can reach a high accuracy to determine the relative parallax. This technique started to show its greatest potential with the Hipparcos mission and later on with *Gaia*.

1.3.1 Hipparcos mission

It was not until 1989 that high precision in the absolute parallax was reached with the Hipparcos satellite. The Hipparcos mission, a scientific project of the European Space Agency (ESA), was designed to drastically improve the precision in the measurement of positions in the optical band and to provide absolute measurements of proper motion and parallax for a large amount of stars. In 1997, the Hipparcos Catalogue was published containing more than 118.000 stars for which positions, parallaxes, and proper motions were presented with accuracies of 0.8–3 mas(yr^{-1}). With this accuracy, precise distances could be obtained out to $\sim$ 200 pc. Nevertheless, this is only a fraction of the scales covered by the Milky Way, as seen in Figure 1.3 (Perryman et al. 1995).

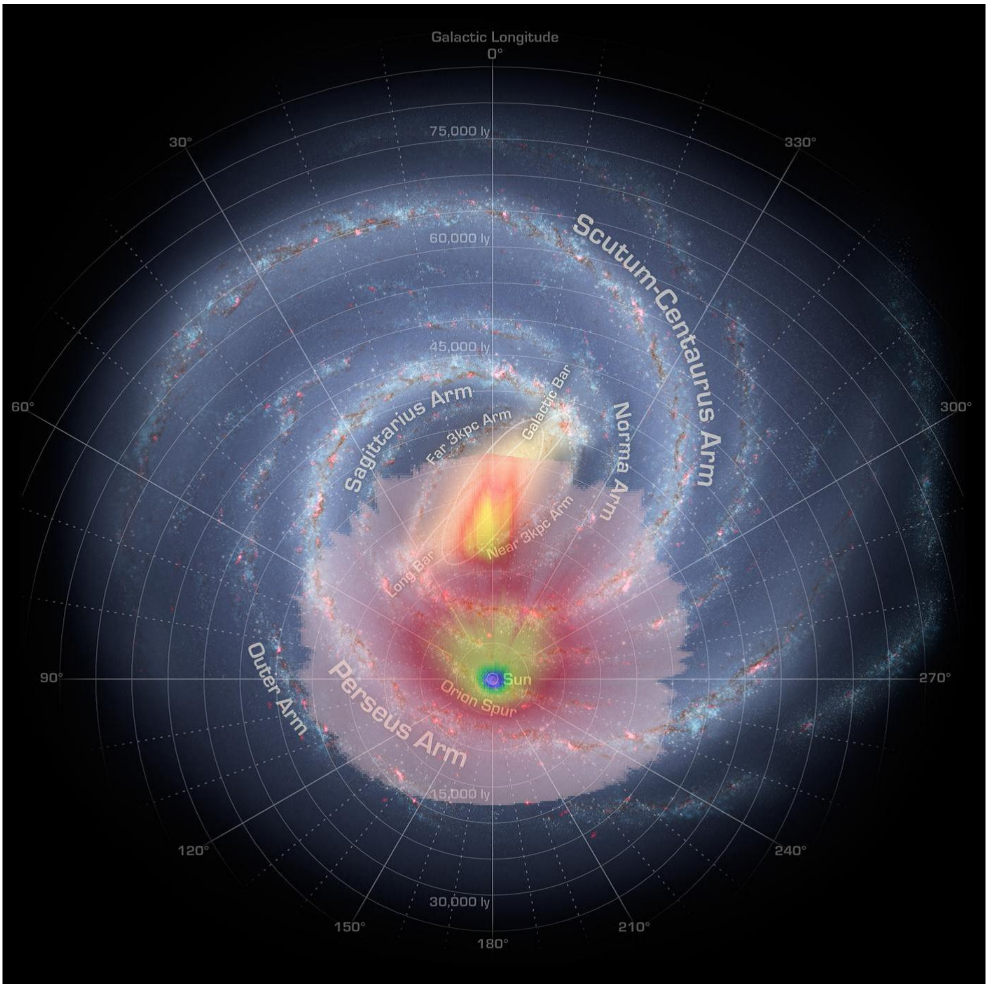

Figure 1.3: *Comparison between the Galactic areas observed by Hipparcos in blue and green, and Gaia as red maps density distributions (X. Luri and CU2/DPAC). In the background, an informed artistic impression of the Milky Way as reference (NASA/JPL-Caltech/R. Hurt).*

1.3.2 *Gaia* revolution

The new era for the astrometry in the optical regime has come with the *Gaia* satellite. *Gaia* is an ongoing mission of the European Space Agency which launched in 2013 (Perryman et al. 1995; Gaia Collaboration et al. 2016b). *Gaia* was designed to precisely measure 3D positions and 3D velocities of a billion of stars. Using this astrometric information, one can determine astrophysical properties of the stellar objects, such as effective temperature and total luminosity, in order to unravel the formation, structure, and dynamics of the Milky Way.

In 2016, the first *Gaia* data release (DR1) provided positions (0.3 mas uncertainty) and photometric data (0.03 mag uncertainty) in the *G*-band for ~1 billion stars. Light curves in the G-band for Cepheids and RR Lyrae were provided. Finally, parallaxes (0.3 mas uncertainty) and proper motions (1 mas yr^{-1} uncertainty) were estimated for ~2 million objects for which Hipparcos data was available from Tycho-2 catalogue (Tycho-*Gaia* Astrometric

Solution, TGAS).

The second *Gaia* data release (DR2) was accessible from 2018. In this data release, precise parallaxes, proper motions, and multiband photometry (G, $G_{\rm BP}$, $G_{\rm RP}$) were estimated for 1.3 billion stars. For different subsets of several (7 to 60) million stars, radial velocities, stellar effective temperature, extinction, reddening, radius and luminosity were published. Finally, and fundamental for this thesis, variability information was provided in the form of variable type classifications and light curves for 0.5 million stars.

1.3.3 Advantages of radio astrometry

Even with the high accuracy data that *Gaia* is providing, at low Galactic latitudes the absorption and scattered behavior of the electromagnetic radiation caused by dense regions of dust and gas complicate precise astrometric measurements. Stellar radio emission from powerful sources is not dramatically affected by the Interstellar Medium (ISM). Together with the low absorption index of the atmosphere at radio frequencies, we have a scenario in which radio astrometry provides complementary data to all the astrometric missions at different wavelengths, particularly in the Galactic plane. However, radio astronomy studies the sky properties between 10 meters (30 MHz) and 1 millimeter (300 GHz)[1], hence in order to reach high angular resolution measurements, single dish observations are insufficient. For instance, one of the largest single dish antennas, the Robert C. Byrd Green Bank Telescope (120 m diameter), can reach angular resolutions up to $\sim 30''$, which is comparable to the human eye at optical frequencies.

In order to reach higher angular resolutions using radio telescopes, radio astronomers use interferometry. By using at least two receivers, we are able to detect the signal from a source that is unresolved with one receiver. The signal will arrive first to one of the receivers and later to the other due to the difference in path that one signal has to cross with respect to the other (see Figure 1.4). The interference of these signals will cause fringes similar to those seen in interferometry experiments at optical wavelengths. If we take several pairs of receivers, each interferometer pair will measure a Fourier component of the entire brightness distribution of the source. In addition to the technology used to create an electronic delay, they also have to use high computational power to make the Fourier transform to recreate radio images from the interferometer data. The astrometric result is an image with the same angular resolution as an instrument of the whole collection. The resolution in this case goes as λ/B, where B is the baseline between the receivers.

The interferometry technique applied by connecting telescopes over long distances is known as VLBI. In general terms, each received signal from each radio telescope must be connected to a central station to correlate the data (see Fig. 1.4). This connection can be made by fiber-optic, coaxial cable or even by recording the measurements on tapes that are, then, transported to a central location where they are correlated.

1.4 Masers as tracers of stellar populations

During the past decade, several VLBI astrometry campaigns have shown their potential to detect radio stellar beacons with $\sim 1\mu$as resolution. In order to obtain 6D phase space information from these radio emitters, they must be not only very bright (high brightness temperature that allows VLBI) but also posses narrow spectral lines (for radial velocity estimates from Doople

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[1] In addition, it also studies wavelengths longer than about 20 centimeters (1.5 GHz), but at this point there are some irregularities in the ionosphere that distort the incoming radio signals via scintillation.

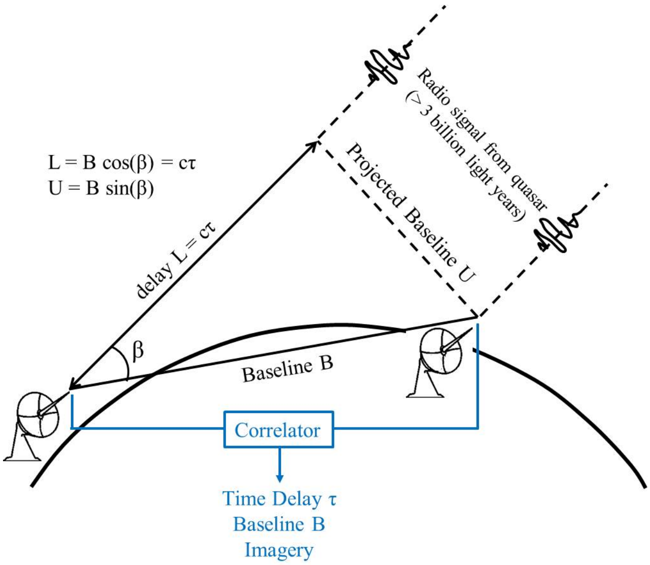

Figure 1.4: *Principle of Radio Interferometry is illustrated here by two antennas which detect a radio sources a different time due to the delay (L). Image provided by Computational Physics INC.*

efect). In the following subsections, we explain starting from the theory how astronomical masers satisfy those conditions, and therefore, are widely use for radio astronomic campaigns to trace the structure of the Galaxy (see Fig. 1.5) and even external galaxies (see Fig. 1.6).

1.4.1 Maser theory in Astronomy

Astronomical microwave amplification by stimulated emission of radiation (maser) has been detected for more than half century (see e.g. Litvak 1969). Maser emission can occurs and can be detected if a number of conditions are full filled: (1) there must be a sufficient abundance of molecules, (2) the gas must be out of thermal equilibrium and a population inversion must occur so that higher energy states of the atoms (or molecules) are over-populated, (3) a seed photon with the right frequency must be available and (4) a long amplification path must be present (see for example, Elitzur 1992). In order to explain the maser emission, consider a two level system (a ground state with energy E_0 and its first excited state E_1) with an energy difference between the levels of $E_{10} > 0$ and number densities of n_0 and n_1 respectively. In addition, a background radiation with a specific energy density u_ν at frequencies near $\nu = E_{10}/h$ (h is Planck's constant) is assumed to be present. It is possible to write the rate of change of n_1 as:

$$\frac{dn_1}{dt} = n_0 n_c k_{01} + n_0 \bar{n}_\gamma \frac{g_1}{g_0} A_{10} - n_1 n_c k_{10} - n_1 A_{10} - n_1 \bar{n}_\gamma A_{10}, \tag{1.1}$$

where n_c is the density of collisional species, k_{01} and k_{10} are the collisional rate coefficients, A_{01} and A_{10} are the Einstein coefficients, $\bar{n}_\gamma = c^3 u_\nu / 8\pi h \nu^3$ defined as the dimensionless photon occupation number, and g_1 and g_0 are the statistical weight of the two levels. In equation 1.1, the terms on the right correspond to the following processes: collisional excitation,

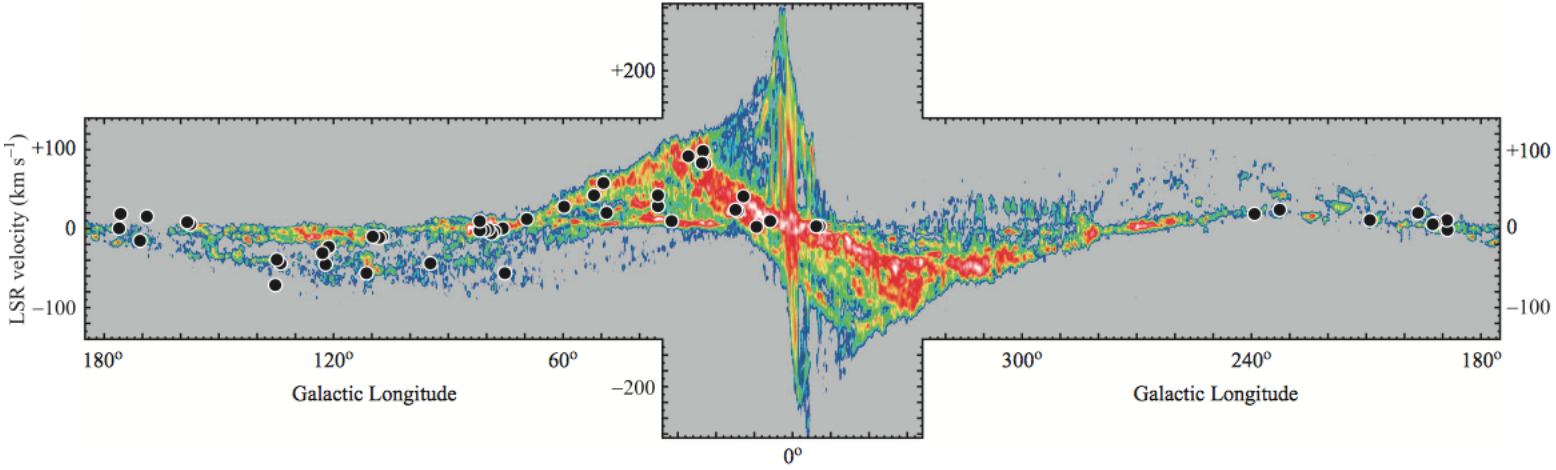

Figure 1.5: *Location of 52 maser sources for which accurate astrometric data is available, superposed on the longitude-velocity diagram of CO (Honma et al. 2012).*

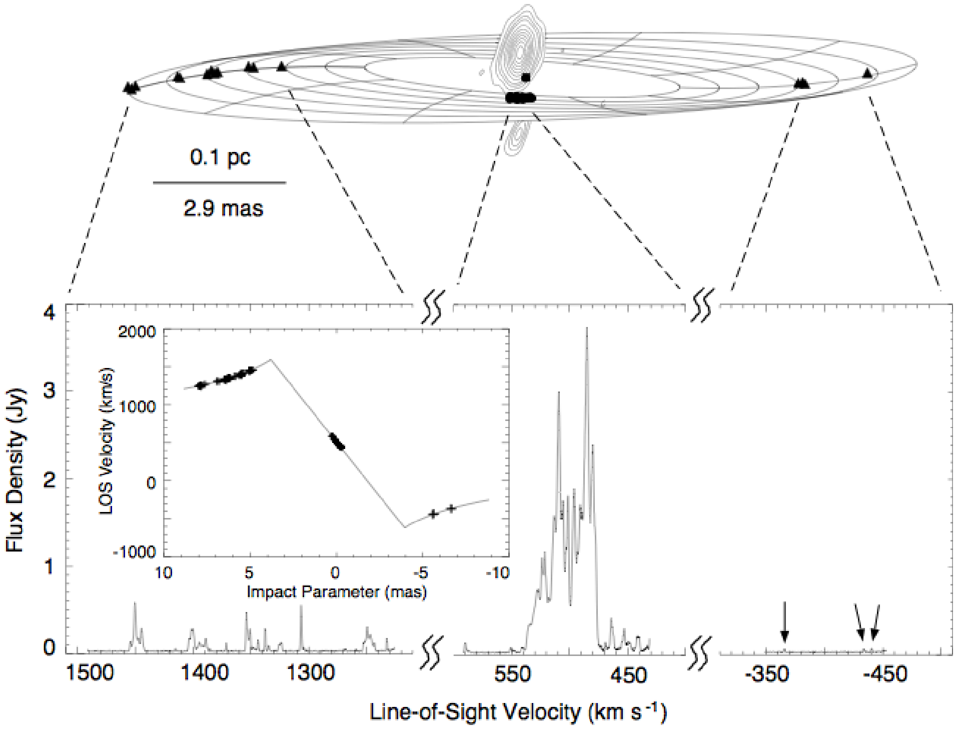

Figure 1.6: *The upper panel shows the best-fitting warped disk model for the galaxy NGC4258 overplotted on actual maser positions as measured by the VLBA. The total power spectrum is displayed in the lower panel (Herrnstein et al. 1999).*

radiative excitation, collisional deexcitation, spontaneous emission and stimulated emission, respectively. Positive terms correspond to populating processes and negative to depopulating processes. Under specific conditions, a process may act to "pump" the excited state by radiative excitation or collisional excitation to a higher level that then decays back to level (1). If this process is faster than the depopulating processes, the populations may satisfy the following relation $n_1 > g_1 n_0 / g_0$.

Therefore, the excitation temperature $T_{\mathrm{exc},10} = E_{10}/k \ln\left(\frac{n_0 g_1}{n_1 g_0}\right)$ (k denotes the Boltzmann constant), is negative and, it can be shown, that stimulated emission is stronger than radiative de-excitation. As an additional consequence of population inversion, the absorption coefficient ($k_\nu \propto (1 - n_1 g_0 / n_0 g_1)$) and the optical depth ($\tau_\nu = \int k_\nu dS$; S=surface) are also negative. Finally, The antenna temperature T_A, which is a measured quantity in radio astronomy, is proportional to the emission I_ν and it can be written as:

$$T_A = T_A(0) e^{-\tau_\nu} + \frac{h\nu/k}{e^{\frac{h\nu}{kT_{\mathrm{exc}}}}}(1 - e^{-\tau_\nu}). \tag{1.2}$$

Given that $\tau_\nu < 0$, then $e^{-\tau_\nu} > 1$ indicating that there is an amplification of the emission rather than attenuation. This exponential amplification of the seed radiation, caused by the population inversion (created by collisional or radiative processes), can reach a critical value resulting in a "saturated" maser. In this maser, the amplification is linear with respect to the path length rather than exponential and because of the total gain depends on the path length, the maser radiation is even more beamed (Elitzur 1992; Pandian 2007). All in all, the emission can reach beamed high brightness temperatures that allow using masers as optimal targets for high-resolution VLBI observations.

1.4.2 VLBI maser projects

Maser emission is associated with both the early and late stages in the life of a star. Galactic maser emission has been detected in the cores of dense molecular clouds that are regions of active star formation (so-called interstellar masers), and also around late-type stars, in which case the masers are referred to as circumstellar. Maser radiation probes small-scale structures in these sources and is now used to measure distances by (1) kinematic means (the equivalent of the classic moving cluster method), and (2) trigonometric parallax Reid et al. (2019). In the following subsections, two major maser projects that are the basis of this thesis are described. Each project is observing different maser species in the Galactic plane, unraveling different stellar populations in the spiral arms and the inner Galaxy. Additionally, although individual radio continuum studies have shown their potential to enlighten the physical processes behind radio stellar emission, VLBI stellar observations could provide additional resolution and sensitivity to detect planetary systems at radio frequencies (Katarzyński et al. 2016).

Finally, it is worth mentioning that although this thesis focuses on maser emission in the Milky Way, extragalactic maser emission has also been detected and studied. These extragalactic detections have been used to study nearby galaxies (Brunthaler et al. 2005) as well as cosmological parameters. In fact, the Megamaser Cosmology Project (MCP) is trying to improve the Hubble Constant value (to a prediction of 3%) by measuring the distance to 10 galaxies in the Hubble flow using VLBI data.

Bar and Spiral Structure Legacy Survey

The Bar and Spiral Structure Legacy (BeSSeL[2]) is a VLBA Key Science project aiming to study the spiral structure and kinematics of the Milky Way (Reid et al. 2009a, 2014). This survey uses VLBI arrays to detect water (22 GHz) and methanol (6.7 & 12.2 GHz) maser emission directly associated with young massive stars and HII regions. The spatial and kinematic distributions of these objects seem to trace the Galactic spiral structure. For more than ten years, the BeSSeL survey has refined data processing techniques to reach comparable parallax uncertainties with respect to *Gaia* in regions where optical measurements are limited by extinction.

The stellar targets are observed at different epochs over a period of a year to estimate accurate positions, distances, proper motions and radial velocities (from the maser lines via the Doppler effect) of these HMSRFs. The motion of water (in the outflow) and methanol masers (in the disk) are averaged to estimate the motion and position of the massive central object (see Fig 1.7). Given this 6D phase-space information, the position for each spiral arm is estimated as well as the fundamental parameters of the Galaxy such as the distance to the Galactic center (R_0), the circular rotation speed of the Sun (Θ_0), the rotation curve and the 3D peculiar motion of the Sun ($U_\odot$,$V_\odot$,$W_\odot$).

Currently, the BeSSeL survey has published precise astrometric data for more than 150 sources. This has allowed us to locate several spiral arms (see Fig 1.8). In their most recent publication, Reid et al. (2019) determined a distance to the Galactic center of $R_0 = 8.15 \pm 0.15$ kpc, solar rotation speed $\Theta_0 = 236 \pm 7$ km s^{-1}), and a flat rotation curve (-0.2 km s^{-1} kpc^{-1}).

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[2] http://bessel.vlbi-astrometry.org/

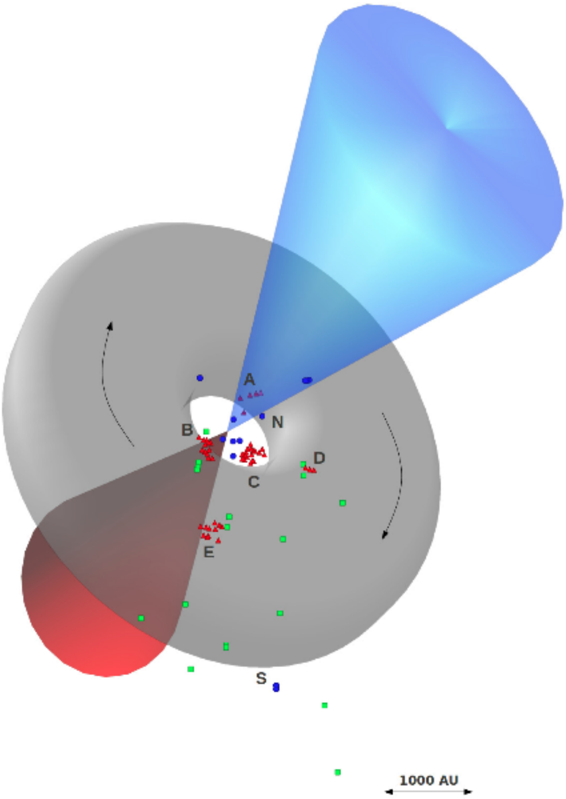

Figure 1.7: *Three-dimensional sketch of a massive star-forming region (NGC 7538-IRS 1). The two cones are the red- and blue-shifted part of the large-scale molecular bipolar outflow. The triangles, circles, and boxes represent the* CH_3OH*,* H_2O *and OH masers detected, respectively (Surcis et al. 2011).*

The BeSSeL survey continues with additional VLBI observations of masers associated with HMSFRs, improving constraints on the size and morphology of the Milky Way, as well as refining its fundamental parameters, and structure.

Bulge Asymmetries and Dynamical Evolution Project

To a great extent, surveys in the optical/IR bands have begun to reach impasses that cannot be easily resolved with increases in sample sizes. Red giant maser sources, as can be exploited with ALMA, VLA, and the VLBI arrays, offer a bold new approach to address the most pressing problems in the study of the bulge/bar. Evolved AGB stars that harbor several maser species (see Fig 1.9), particularly SiO maser emission are part of an older, dynamically relaxed population in the inner Galaxy. The dynamics of such evolved stars still carry the signature of past star-formation and merger events (Pasetto et al. 2016). In this context, the Bulge Asymmetries and Dynamical Evolution (BAaDE[3]) collaboration has made considerable progress by constructing a sample of ~30,000 stellar targets of SiO masers candidates in the Galactic plane and comparable to the 20,000 stellar counterparts in optical surveys (Sjouwerman et al.

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[3] `http://www.phys.unm.edu/~baade/`

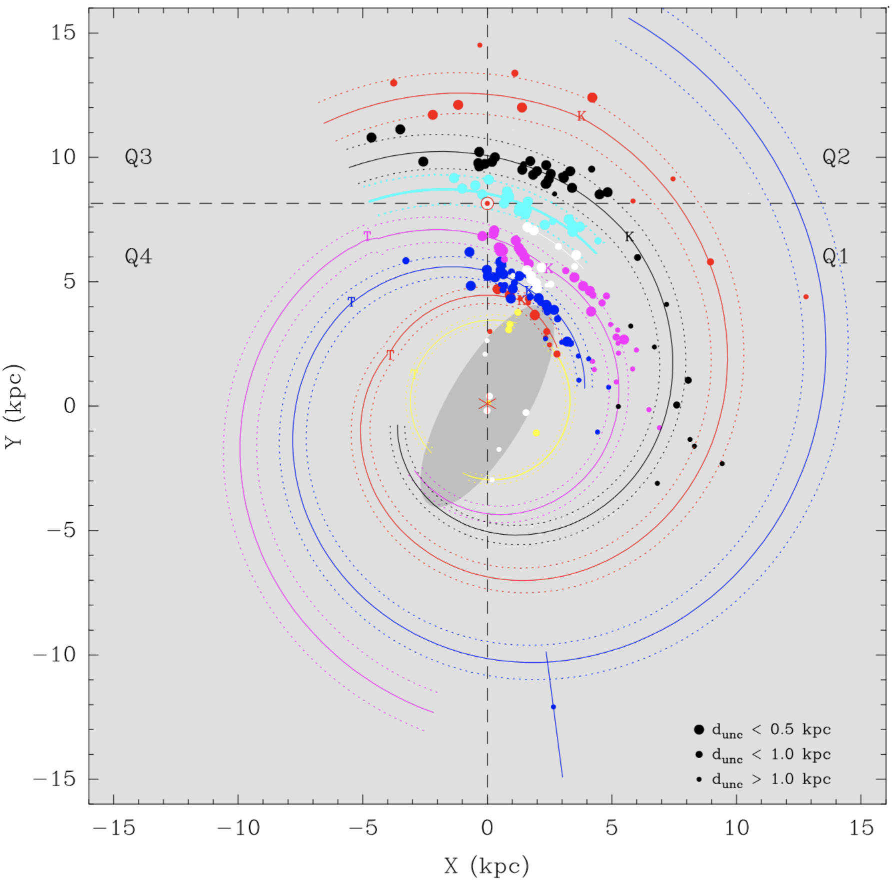

Figure 1.8: *Plan view of the Milky Way from the north Galactic pole showing (1) the positions of the high-mass star-forming regions measured by the BeSSeL survey and (2) the inferred positions of the spiral arms (Reid et al. 2019). For these star-forming regions precise trigonometric parallaxes were measured using different maser species. In this view, the Sun is located at (0,8.15) kpc and the Galaxy rotates in clockwise direction.*

2015). Indeed, optical surveys of the bulge are a powerful approach to learn about the populations and dynamics in the less reddened and obscured regions $|b| > 4°$. By using SiO masers, which are detectable in red giants spanning a wide range in luminosity, the BAaDE project has the possibility of densely sampling the highest extinction, most crowded regions of the Milky Way: the plane and the Galactic center.

The sample of 30,000 evolved stars are being observed at the frequencies of the SiO maser (43 GHz and 86 GHz) using the VLA and ALMA for which extremely accurate line-of-sight stellar velocities ($\sim$1 km s^{-1}), flux densities and positions are determined. This number of sources is large enough to trace complex structures and minority populations that are partially obscured by extinction in optical campaigns. The velocity structure of these tracers is to be compared with the kinematic structures seen in molecular gas near the Galactic center, and thereby highlight kinematically coherent stellar systems, complex orbit structure in the bar, or stellar streams resulting from recently infallen systems. Preliminary statistics of the flux

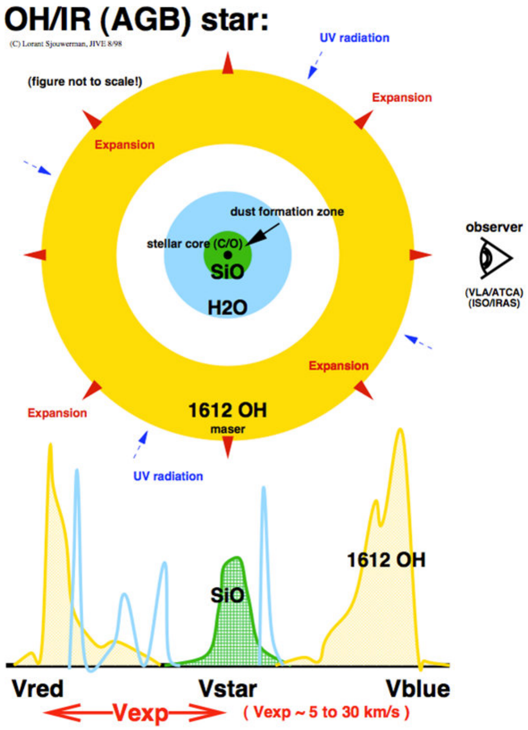

Figure 1.9: *Schematic view of the an evolved star and the different regions where specific molecules are been formed. Excepted maser emission lines from those molecules (affected by Doppler effect in the line of sight) are expected to be detected as it shown in the lower panel. Image courtesy: Lorant Sjouwerman (NRAO).*

density distribution and analysis of the population of SiO stars through IR association already shows exciting results in which very old and younger AGB stars in the inner Galaxy (see Fig. 1.10) show different kinematics (Stroh et al. 2018; Trapp et al. 2018). Finally, modeling of the bar and bulge dynamics will be done using the new kinematic information in the inner Galaxy region. The BAaDE project also identifies sufficiently luminous SiO masers suitable for follow-up orbit and parallax determination using VLBI. The specific aim of BAaDE is to eventually determine in detail orbits of stars supporting the stellar bar.

1.5 This thesis

In this thesis, I researched stellar radio emitters and their counterparts at different wavelengths throughout the Galactic plane. In each investigation, the astrometry was refined to provide insights about the stellar population in different environments. Moreover, these stellar populations were used (1) to trace different Galactic structures, and for some cases, (2) to further investigate particular astrophysical objects. Chapter 2 and 3 are investigations made in the context of the BeSSeL survey for which we used HMSFRs to trace the spiral structure, as well as the fundamental parameters of the Milky Way. In both investigations, high fidelity VLBI

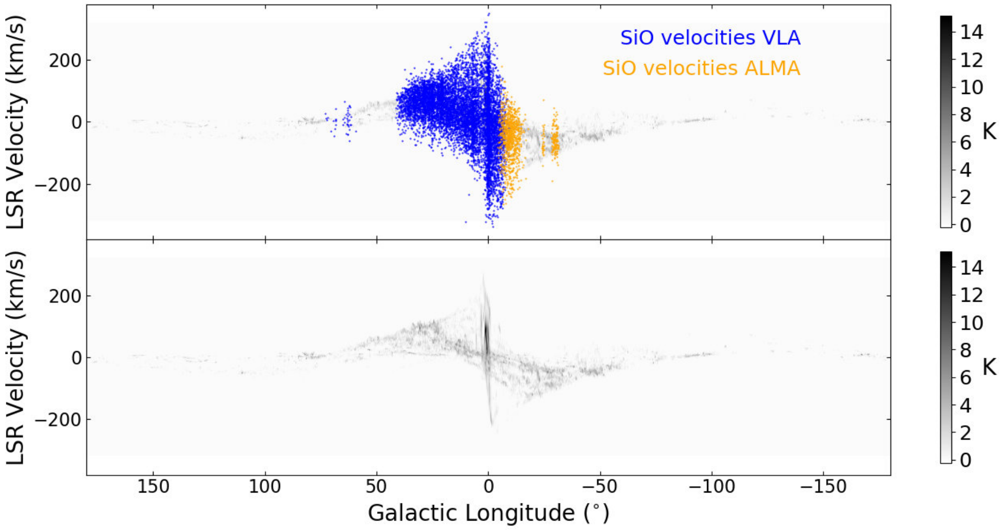

Figure 1.10: *Velocity with respect to the Local Standard of Rest (LSR) as a function of the Galactic longitude for the SiO masers detected by the BAaDE project with the VLA and ALMA. The figure also shows the CO emission (J = 1–0) in grayscale (Dame et al. 2001).*

observations were used to refine the astrometry of the stellar beacons analyzed. In chapter 4, we used another type of maser bearing stellar population, i.e., evolved stars. Although these stars are part of more relaxed population mainly found in the bulge, we focus on the solar neighborhood (<2kpc), where we can estimate precise distances by cross-matching and refining data from IR and optical surveys. This research was made in the context of BAaDE project, using a preliminary data release. Finally in chapter 5, we present an interesting result that showed up when we were inspecting the astrometry of low frequency archival radio data from the Giant Metrewave Radio Telescope (GMRT). The abrupt change in position and flux of one source triggered a whole investigation into the nature of flare emission from a binary system composed of two similar dwarfs with very different behavior at radio frequencies. In the following paragraphs, I expand each investigation in more detail.

In Chapter 2, we present a maser astrometry analysis of the star-forming region S269, an HII region with strong water maser emission that has been monitored for more than 20 years. Based on new, high fidelity multi-epoch observations using the VLBA at 22 GHz (part of the BeSSeL survey), we estimate the 6D phase-space information for this source, resolving the distance disagreement previously found in VERA data. We compare the new distance of S269 (4.15 kpc) with the *Gaia* astrometry of young, early-type stars that would be likely members of the same stellar association finding three candidates. The location of S269, at a distance of 4.15 kpc roughly in the direction of the Galactic anti-center, makes the astrometry of this source very significant for the model of the spiral structure of our Galaxy and its rotation curve. We have found that the new astrometry of S269 is still in agreement with a flat rotation curve. Its 3D position, together with the positions of a number of other BeSSeL targets indicate a more complex structure of the Outer arm than previously inferred. Three scenario's are presented, of which we favor the one that has a kink in the Outer arm, dividing the arm in two segments (at $l = 140^{\circ}$) with different pitch angles.

In Chapter 3, I present a model that can be used to test with what confidence one can estimate the fundamental Galactic parameters from maser observations from the BeSSeL survey (water and methanol masers astrometry from star-forming regions). We simulate the BeSSeL database, which consists of astrometric information of masers associated with Galactic young massive stars. The model was compared with blind observational surveys (MMB and Arecibo surveys) in order to refine the simulations, but also to determine the luminosity function of methanol masers. We test different mock samples to investigate possible quantitative biases in the Galactic parameters. The results show that the Galactic parameters can be established robustly and with high accuracy using only sources in the Northern hemisphere (where most of the radio telescopes are located). However, we also quantitatively prove that data from future Southern observatories will reduce the uncertainties and inter-correlations between some Galactic parameters, besides tracing the spiral arms and —notably— the bar.

In Chapter 4, we cross-match the entire BAaDE sample (~30,000 AGB stars) with 2MASS, and *Gaia* for a subsample of BAaDE targets. We show that IR counterparts can be easily identified, while *Gaia* matching is more restricted given extinction at optical wavelengths in the Galactic plane. These multi-wavelength cross-matches compile samples of approximately 2,000 evolved stars around the Sun with precise positional information as well as radio detections of SiO maser emission (radial velocities and flux densities) for a subsample. Variability information from *Gaia* was also used to test period-luminosity relation for a population of faint AGB stars around the Sun and compared with the results obtained in the Magellanic Clouds. All these observables are being used to characterize the stellar population of evolved stars within 2 kpc around the Sun, which was found to be predominately Long Period Variables, optically detectable Miras and carbon stars. The characterization of this stellar population was made in terms of luminosity, variability and dynamics.

Finally, in chapter 5 we present low frequency archival images from the GMRT that were observed to investigated a distant cluster of galaxies. However, the data also show a flare Galactic source that coincides with the position of Ross 867 in optical surveys. This star is part of a binary system with Ross 868, where both dwarfs have been categorized as flaring stars. More interestingly, the stars share several stellar features, however, after reviewing archival data from several radio observatories from 1984 up to 2017, only Ross 867 has been detected in radio frequencies. Given that the binary system has a large orbital separation, we conclude that the detection of radio emission from only one component of the binary points to either significantly different magnetic field topologies or dynamo mechanisms between the two stars. Finally, we emphasize that Ross 867-8 provides a coeval laboratory for future investigations in order to constrain the stellar properties linked to the radio flare emission detected in M dwarfs. We expect that in the future, VLBI observations of Ross 867 and similar stars can be used to link the optical and radio reference frames (Lindegren 2019).

1.6 Outlook

In this thesis, I have shown how astrometric measurements of stellar radio beacons, together with information at other wavelengths, can be used to study different components of the Milky Way, particularly spiral arms, stellar populations, dynamics of stellar groups and specific individual sources in the Galactic plane. In this area, the radio astrometry can provide more accurate results than in any other band. However, it is through the synergy between different spectral bands that a deeper understanding of stellar and Galactic processes can be reached.

This thesis has demonstrated show how masers coming from different stellar populations (young massive and evolved mass losing stars) offer a unique opportunity to sample the dynamical structure of the Galaxy (Habing et al. 2006; Reid & Honma 2014). On the one hand, water and methanol masers are associated with very young stars, still tied to the dissipative gas component of the Galaxy; astrometry of these provides clues on the rotation curve of the Galaxy and the location of the spiral arms (Reid et al. 2014; Quiroga-Nuñez et al. 2017). On the other hand, evolved AGB stars, such as Mira variables producing SiO and OH masers are part of an older, dynamically relaxed population. By matching these findings with surveys at other bands, we are starting to characterize the evolutionary status of the evolved stellar population in the Galactic plane. This would constrain the dynamics of the Galaxy, notably the existence of a bar associated with the inner bulge (Blitz & Spergel 1991; Rich et al. 2007). Moreover, it can be anticipated that the dynamics of such evolved stars still carry the signature of past star-formation and merging events (Pasetto et al. 2016). Finally, VLBI with future southern radio arrays (as SKA) will allow us to do many more sources with substantial better accuracy, because of the improved sensitivity and better calibration options, particularly at 6.7 GHz (methanol maser emission). Below, I add some future work in the field that I am expecting to complete in the following years.

Gaia-VLBI

Gaia detectors are known to become saturated for bright sources, and hence, inaccurate distance estimates are expected for bright stars. VLBI astrometry can offer an independent and supporting technique that validates *Gaia* observations for very bright stars in the Galactic plane, but also to the rotation of the reference frame and parallax zero point Lindegren (2019). Based on the BeSSeL survey, we can establish an accurate and scalable method for inverse phase-referencing using SiO masers in order to propose VLBA follow-up for several BAaDE targets and, therefore, obtain 6D phase-space information. A VLBA pilot project targeting four Mira variables with confirmed *Gaia* counterparts was recently observed aiming to determine extremely accurate line-of-sight stellar velocities and precise positions.

Besides this fundamental comparison of *Gaia* astrometry with VLBI, we are particularly interested in aligning the OH maser and optical photosphere with greater accuracy. Using the EVN baselines at 18cm, we can reach a resolution of around 10 mas and possibly submas astrometric accuracy using the latest advances in radio astrometry (Dorson and Rioja, Orosz). It has been already argued that the alignment was consistent with a model in which the brightest, most blue-shifted spot originates from the front of the shell, exactly on the line of sight to the star‘(van Langevelde et al. 2019). This is predicted to happen if the radio emission from the stellar surface provides the seed photons for the maser amplification. New *Gaia* data and VLBI measurements would allow us to test this alignment with improved accuracy.

Next step BeSSeL

Future radio observatories (such as the ngVLA, SKA2-Mid, African VLBI Network) as well as ongoing projects as the “BeSSeL Survey South” (currently under development in Australia at the University of Tasmania) will complete the mapping and then generate a better 3D positional distribution of masers in our Galaxy. This will allow us (1) to understand better the kinematics of the galaxy and (2) to determine the fundamental Galactic parameter values with even higher accuracy, which is crucial to calibrate Galactic and extragalactic measurements. In support of this, Galactic simulations complement the observations by demonstrating their robustness and potential. Moreover, simulated distributions of the sources on the sky provide a framework for the observational conditions required for future radio astrometric campaigns.

For the BeSSeL survey, I have recently started a campaign to cross-matching VLBI astrometric measurements of HMSFRs in the closest arms with IR catalogs and *Gaia*. We are attempting to accurately describe the spiral arms position as well as quantify the physical parameters of the stellar populations present in these structures.

Next step in BAaDE

We are expecting that the distribution of BAaDE targets in 6D phase-space can be measured to constrain the dynamics of the inner Galaxy. Notably, we have a chance to resolve the populations associated with the Galactic bar Rich et al. (2007), and the X-shaped structure Vásquez et al. (2013). However, astrometric measurements of evolved stars using SiO masers present several complications such as unstable structure close to the stellar surface, and lack of calibrators at X and Q bands which are crucial for phase-referencing (Min et al. 2014). In most cases, the SiO masers are bright enough to allow for reverse phase-referencing, but even so, having nearby calibrators is critical at high frequency where coherence times are short. For this, recent EVN and VLBA proposals have made progress detecting potential calibrators which are key for making progress with VLBI astrometry of these inner Galaxy targets. Moreover, a new VLBA proposal for Mira variables with SiO maser emission located out of the Galactic plane was ranked with the highest priority, and it was observed in 2019. Progress will lead to a new VLBA astrometric proposal to obtain parallax and proper motions for a BAaDE subsample with confirmed *Gaia* counterparts.

I will expand my simulations of maser distributions in the Milky Way to include the inner Galaxy. For this, various key processes that have yet to be modeled must be implemented, such as maximum likelihood estimators for evolved stars in the presence of the Galactic bar in order to make full use of *Gaia* DR3 data. Additionally, I aim to model the source population in order to optimize future astrometric observations using VLBI arrays. Not only will I predict the accuracy that can be reached, but also, the uncertainties in stellar parameters that are expected for a wide range of instrumental conditions. Finally, it is exciting that new wide-band systems will be able to observe the (non-thermal emission) associated with active stars. The μJy sky could be full of targets for which high accuracy astrometry is possible, even to the level that we can detect planets.