Stellar radio beacons for Galactic astrometry

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English Summary

One hundred years ago, we still had a very basic knowledge of our Galaxy, the Milky Way. It was unclear whether the stars in the sky were part of a group, and therefore there could other groups of stars in the universe, or the stars were widely spread in the universe. That is why a debate was organized between two renowned American astronomers at the time who proposed different hypotheses based on the available observations. On the one hand, Harlow Shapley proposed that we live in an island universe and that other island universes have not been detected because they were so far away. On the other hand, Heber Curtis proposed that we live in a small galaxy, and that other galaxies cannot be observed because of the dust present in our Galaxy that absorbs the light coming from other galaxies. By looking back, one finds that the basis of this discord was the lack of accurate measurement of the distances to other stars. By not having a reliable distribution of the stars around the Sun, it was impossible to determine which objects in the sky are part of our Galaxy or those that seem well beyond.

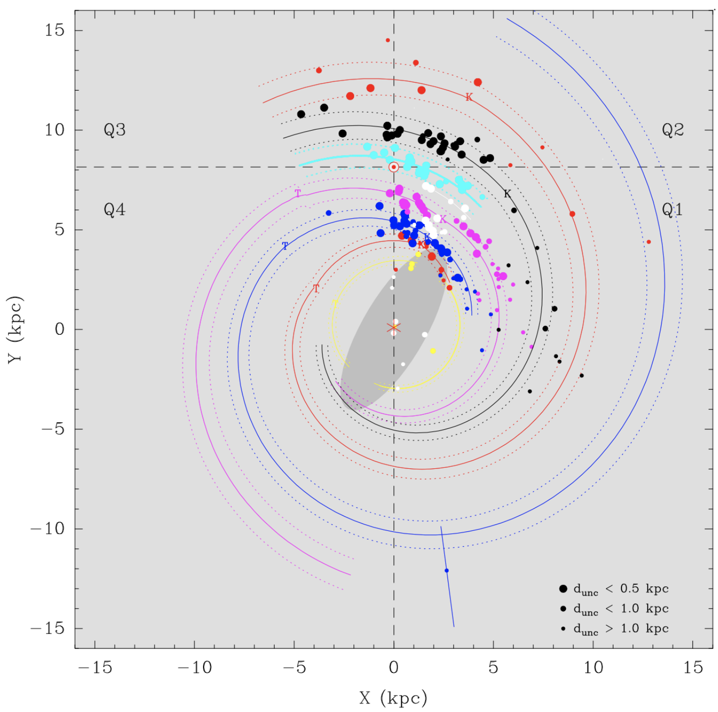

Figure B1: *Plane view of the Milky Way showing the positions of the high-mass star-forming regions measured by the BeSSeL survey and the inferred positions of the spiral arms (Reid et al. 2019), where the distance uncertainty is expressed as the marker size. In this view, the Sun is located at (0,8.15) kpc from the center and the Galaxy rotates in the clockwise direction.*

Over time, new technologies came into use, that allowed astronomers to establish more accurate distances and stellar motions finding that the island universes, or galaxies, are extra-

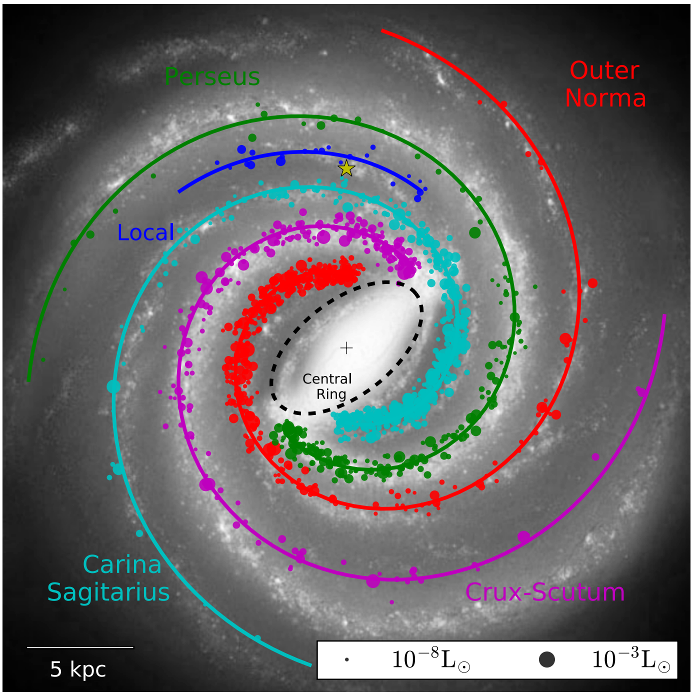

Figure B2: *Simulated distribution of High Mass Star-Forming regions overlaid on an artist impression of the Milky Way (R. Hurt: NASA/JPLCaltech/SSC). The size of the points represents the luminosity for each source.*

galactic objects that are moving with respect to us. In addition, it was found that our Galaxy has a specific shape where the stars are found in a rotating disk that exhibits several morphological pecularities such as prominent spiral arms and a central bar (Fig. B1 and B2).

During the time of this thesis, the *Gaia* space mission provided accurate position and velocity measurements for more than a billion stars in the Milky Way. However, the data provided by *Gaia* is limited by the large amount of dust that absorbs and scatter the light at optical wavelengths, particularly forward the Galactic plane. In contrast, radio waves are not affected by the dust and therefore, can easily penetrate the Galactic plane providing complementary data (Fig. B3). Recent campaigns in the radio wavelength regime (see for example BeSSeL [8] and BAaDE [9]) have measured accurate positions and motions of bright stellar sources (known as masers [10]) in the Galactic plane using a technique called Very Long Baseline Interferometry (VLBI). In this technique, a stellar object is detected by several radio antennas spread at long distances, even at different continents. The signals detected are combined generating a detailed image of the object. By studying the positions and velocity of the stars in the Galatic plane using VLBI, large Galactic structures have been detected (Fig. B1 and B2).

This thesis demonstrates how robust astrometric measurements can be done in the radio regime for young massive stars throughout the Galaxy. Such results are compared with simulations for Galactic areas which have not been observed to determine the limits of this

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

[9] http://www.phys.unm.edu/ baade/

[10] Which are naturally generated in different stellar environments and follows the same physical principle as lasers but in the radio regime.

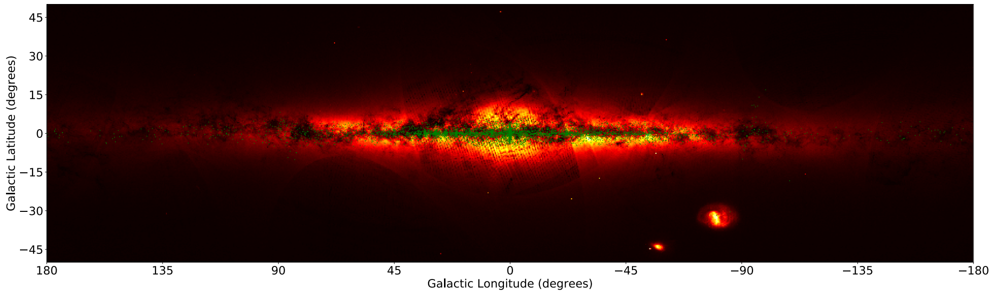

Figure B3: *The Galactic distribution of the radio stellar targets used in the BAaDE project without a Gaia counterpart (green points) overplotted on the first sky map projection produced by Gaia. This sample accurately correlates with highly obscured regions in the optical regime. Credit: ESA/Gaia/DPAC.*

technique. In addition, the matching between the optical and the radio data are established for evolved stars around the Sun, which are used to characterize the stellar population in the Galactic plane using additional information at infrared wavelengths. Finally, a study of a particular binary system was carried out that demonstrates how much stellar information can be obtained by having accurate astrometric measurements from different epochs and at different frequencies.

The goal of this thesis is to demonstrate how accurate astrometric measurements of radio stellar beacons can be used to obtain crucial information of particular stellar properties of different stellar systems, as well as to deduce major Galactic structures and parameters. To do that, we made use of astrometric and photometric observations at different wavelengths, advanced Monte Carlo simulations, and theoretical modeling. This thesis aims at answering these four questions:

- **Chapter 2:** How can VLBI astrometric measurements of High Mass Star-Forming Regions be used to trace spiral arm structures?
- **Chapter 3:** How accurate can we estimate the structural parameters of the Milky Way if we have observations with limited sensitivity and a fixed location of the telescopes?
- **Chapter 4:** How can cross-matches of astrometric data at different wavelengths be used to study old stellar populations in the Solar neighborhood?
- **Chapter 5:** How can astrometric measurements be used to discover and study variable stellar radio emission from a binary stellar system?

In the following paragraphs, I describe the content of each scientific chapter of this thesis by illustrating how they answer the questions related above.

In Chapter 2, an investigation is presented on one High Star-Forming Region located in the Outer spiral arm of the Milky Way: Sharpless 269 (S 269). Using 16 observations with the Very Large Baseline Array (VLBA) in the United States, accurate measurements of the distance and proper motions of the water masers in S269 were made. The astrometric results obtained confirm a flat Galactic rotation curve at large distances from the center of the Milky Way. Using the obtained distance together with a Galactic simulation and observations of other young massive stars in the Outer region, it was possible to prove the existence of a kink in the Outer arm. In addition, three sources were found in the *Gaia* catalog that are likely members of the same stellar association given their proper motion, parallax and evolutionary stage (very massive young stars).

In Chapter 3, the population of young massive stars in the Milky Way has been simulated, generating many samples, and comparing them with observed samples from the BeSSeL survey. It was verified that the structural parameters of the Milky Way obtained by BeSSeL are not biased by the sample selection used. In fact, the published error estimates appear to be conservative for most parameters. We show that future BeSSeL data and future observations using masers from the southern region of Milky Way will improve the estimates of the structural parameters of the Milky Way and reduce their mutual correlation.

In Chapter 4, the targets of the BAaDE project have been studied with data from several surveys optical, infrared and radio. By cross-matching these surveys, we have characterized the BAaDE target sample around the Sun (2,060 stars), which mainly consists of evolved stars. The absolute bolometric magnitudes (stellar emission in the spectrum) were compared to samples of evolved stars from the literature finding that our selection is contaminated with low luminous objects, likely Young Stellar Objects. Nevertheless, we found that the properties of stars, for which there are SiO masers detected, are consistent with oxygen-rich Mira stars with periods between 250 and 750 days.

In Chapter 5, we have serendipitously rediscovered the radio emission of the binary system Ross 867-8 when we were inspecting the astrometry of archival data of the Giant Metrewave Radio Telescope in India. In this binary system, both dwarf stars share similar characteristics such as spectral type, astrometric parameters, age and emission in infrared, optical and X-rays. In addition, after reviewing the archival data of several radio observatories, we confirm that although both stars were likely coeval, only Ross 867 is very bright at radio wavelengths, while Ross 868 remains undetected. As they have a large orbital separation, this binary star system provides a laboratory to examine and restrict the stellar properties linked to radio activity in dwarf stars. Finally, it was speculated that the difference observed in radio activity between the stars could be due to differences in magnetic field topologies or that Ross 867 has an intrinsically different dynamo.