The Multi-Messenger Astrophysics of the Galactic Centre
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Thousands of Stellar SiO masers in the Galactic center:

The Bulge Asymmetries and Dynamic Evolution (BAaDE) survey

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Abstract. A radio survey of red giant SiO sources in the inner Galaxy and bulge is not hindered by extinction. Accurate stellar velocities (<1 km/s) are obtained with minimal observing time (<1 min) per source. Detecting over 20,000 SiO maser sources yields data comparable to optical surveys with the additional strength of a much more thorough coverage of the highly obscured inner Galaxy. Modeling of such a large sample would reveal dynamical structures and minority populations; the velocity structure can be compared to kinematic structures seen in molecular gas, complex orbit structure in the bar, or stellar streams resulting from recently infallen systems. Our Bulge Asymmetries and Dynamic Evolution (BAaDE) survey yields bright SiO masers suitable for follow-up Galactic orbit and parallax determination using VLBI.

Here we outline our early VLA observations at 43 GHz in the northern bulge and Galactic plane ($0 < l^\circ < 250$), and ALMA observations at 86 GHz in the southern bulge ($250 < l^\circ < 360$). We report a preliminary overall 70% detection rate in our color-selected MSX sources.

Keywords. masers, surveys, Galaxy: bulge, Galaxy: kinematics and dynamics, infrared: stars

1. Introduction

While there is compelling evidence for a bar in the central kiloparsec of the Milky Way, the description of how this bar relates to the thin disk and central nucleus is still incomplete. In part, this is due to the extremely high extinction toward the plane. Current optical and infrared campaigns are not able to pierce through the dust at low Galactic latitudes and, to a great extent, these optical/IR surveys have begun to reach impasses that cannot be easily resolved with increases in their sample size.

The goal of the Bulge Asymmetries and Dynamic Evolution (BAaDE) project is to significantly improve models of stellar dynamics and structure of the Galaxy using the largest ever radio survey of ∼30 000 red giant sources in the Galactic bulge and plane including areas not reachable with optical surveys. The stellar sources are being used as point-mass tracers of the dynamics, where ALMA and VLA observations of the SiO maser lines yield accurate line-of-sight velocities, rotation curves and velocity dispersions. VLBI follow-up could provide 3-D orbital information. Analysis of the data will also provide statistics on the stellar properties, including cross-correlations with catalogs at other (infrared) wavebands, and will reveal peculiar sources for more detailed study.

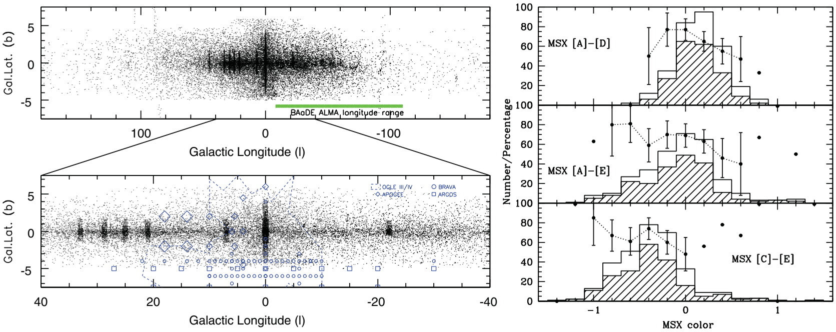

Figure 1. Left: Galactic distribution of color-selected MSX sources. Southern bulge sources are targeted with ALMA at 86 GHz, other sources are observed with the VLA at 43 GHz. The blow-up shows where optical surveys are surveying their sources. Note that the BAaDE sources are sampling the Galactic plane much more effectively, including $b = 0°$. Vertical striping is an artifact of stretching in latitude. Right: Detection rate of 86 GHz SiO masers as function of MSX color. The BAaDE sample is selected using MSX colors showing the highest detection rates.

2. Maser stars

A small fraction of stars in the Galaxy (i.e., mass-losing AGB and RGB stars) emit strong maser lines that are unobscured and observable over most of the entire extent of the Galaxy (Habing 1996, A&ARev. 7, 97). Being a “small fraction”, these sources typically are not confused, and even if so, the velocity of the line emission allows one to distinguish between objects in the same field. Furthermore, the maser line emission brings a great advantage over optical and infrared observations by instantaneously yielding the line-of-sight velocity of the star to an accuracy of $\sim$1 km s^{-1}, allowing (one-dimensional) kinematic and dynamical studies upon detection. Radio interferometers like the VLA and ALMA provide sub-arcsecond accurate positions where needed, and follow-up Very Long Baseline Interferometry (VLBI) observations can provide proper motions and distances.

Rewarding studies of Galactic structure using OH/IR stars were performed during 1985-2000, once it was determined that color selection of sources detected by the IRAS satellite were quite predictive in finding stellar OH (1612 MHz) masers (e.g., Olnon *et al.* 1984, ApJL 278, L41). Since that time about 3000 OH/IR stars have been studied in the outer Galaxy as well as in the bulge and Galactic center regions. In the bulge and Galactic center (where IRAS was heavily confused) stellar density and interstellar extinction severely hinder similar studies at infrared and optical wave bands. OH/IR samples strongly support the presence of a Galactic “bar” and show a strong asymmetry in the sample’s kinematics, in particular for $23° < l < 33°$ (e.g., Sevenster 1999, MNRAS 310, 629). However, the sample of OH masers is too small to allow a meticulous kinematic Galactic structure analysis of, for example, the Scutum and Sagittarius-Carina arms, or to determine whether gaseous features such as the 3-kpc and 135-km s^{-1} arms are dynamically young. More dramatically, it was shown by Vauterin & Dejonghe (1998, ApJ 500, 233) that simply distinguishing between an axi-symmetric versus a tri-axial bulge distribution requires a sample of the order of one thousand maser stars. Finer detail requires much larger and denser samples, i.e., more stellar velocities per unit of space to measure the phase-space density and feed into the dynamical modeling.

3. The BAaDE project

Such denser sampling *by a factor of $\sim$30-40* can be obtained by using stars with SiO masers (Fig. 1; Sjouwerman *et al.* 2009). The SiO maser not only occurs in the high-mass

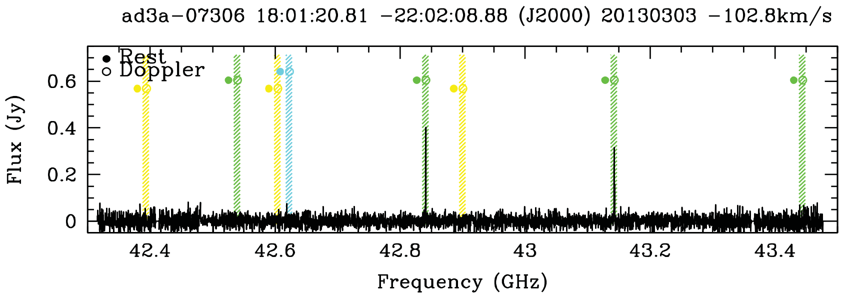

Figure 2. Typical VLA 43 GHz spectrum showing the SiO J=1–0 (v=2) and (v=1) masers. Occasionally only one of these masers or HC_5N (for C-rich stars, at 42.6 GHz) is detected. In extreme cases up to 7 SiO lines (of which three lines are from Si isotopes) show up in the shaded regions.

loss phase, but also in the populous RGB stars (0.5–5 $M_\odot$) that have lower mass-loss rates (few 10^{-6} $M_\odot$/yr). The SiO masers lie closer to the star and are not influenced by the external environment as are the OH masers (i.e. where the conditions needed to form OH masers can be disrupted). Also, observing the lower mass stars increases the potential number of point masses since lower mass (i.e. RGB) stars are more numerous. The stars must have a high enough metallicity to form SiO, which implies they need to have formed from already reprocessed material in their birthplaces. This fact allows these stars to be tracers of the chemical enrichment of the Galaxy as a function of Galactic radius. Also, the OH and SiO masering stars may not trace exactly the same age and dynamical population — or they could be completely dynamically distinct classes of objects. Current samples of maser stars are too small to address such fundamental questions, and the VLA and ALMA are essential to complete the surveys sampling well into the plane.

Although our *main goal* is to obtain a much-improved characterization of the dynamics and structure of the Galaxy, this homogeneous statistical sample can also be used to address important outstanding questions about the stars themselves:

- What is the relation between the maximum (variable) stellar luminosity and the star's main-sequence mass (both these quantities can be discerned from infrared data) ?
- What is the relation between OH and SiO mass-loss rate, stellar luminosity, metallicity and shell expansion velocity ?
- What is the relation between maser occurrence, different SiO maser lines and mass-loss rate ?
- How do all these properties depend on location in the Galaxy ?

These are just four examples of questions about the stars and their evolution that have only been partly answered by the quest to obtain a better understanding of post-main sequence evolution. These questions can only be addressed with an excellent, homogeneous, statistical sample.

4. Data

The observing strategy is very important for the scientific yield per hour of observation. Both with the VLA at 43 GHz and ALMA at 86 GHz we find that our detection rate is about 70% for 48 targets per hour of observing. With this high instantaneous detection rate, we can expect roughly every other source to be self-calibrated and circumvent the necessity of expensive calibration overhead in a direction where generally calibrators are lacking.

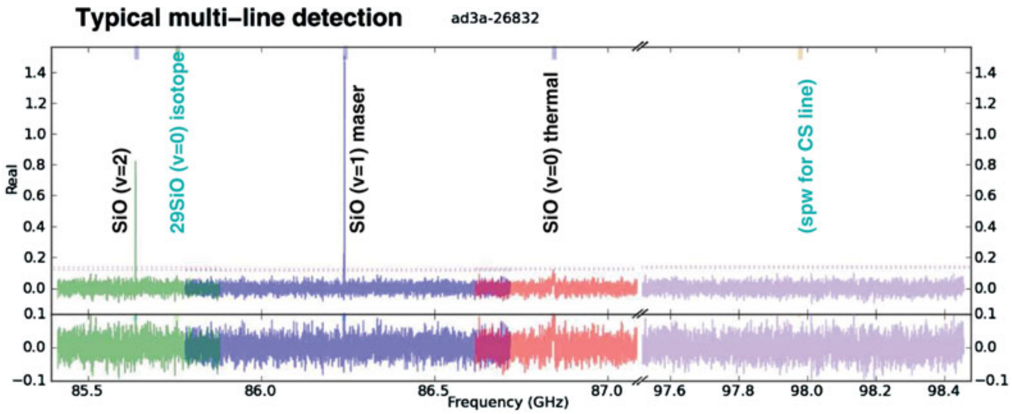

Figure 3. Typical multi-line ALMA 86 GHz spectrum showing the SiO J=2–1 (v=2) and (v=1) masers and (v=0) thermal line (left to right). Occasionally the CS line is detected at 98 GHz instead of SiO which yields a velocity for C-rich stars. The fixed-scale lower panel more prominently shows the noise and weaker emission of the auto-scaled upper panel.

The current status is that we have observed about 11,000 sources with the VLA during 2013-2016 (245h). We have partially covered the Galactic bulge and are detecting SiO masing sources at a high rate with our MSX color selection scheme and completed the survey in the Galactic plane at longitudes outside those containing the bulge. A typical 43 GHz VLA working spectrum is shown in Fig. 2. The ALMA observations of about 1400 sources were taken in 2015 and 2016 (30h) for which we show a typical multi-line detection in Fig. 3.

The VLBI proper motion follow-up studies rely on the availability of good calibrators at 43 and 86 GHz. We are currently in the process of creating a list of calibrators that meet the requirements for accurate astrometry.

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