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# Stellar SiO masers in the Galaxy: The Bulge Asymmetries and Dynamic Evolution (BAaDE) survey

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**Abstract.** Circumstellar SiO masers can be observed in red giant evolved stars throughout the Galaxy. Since stellar masers are not affected by non-gravitational forces, they serve as point-mass probes of the gravitational potential and form an excellent sample for studies of the Galactic structure and dynamics. Compared to optical studies, the non-obscured masers are in particular valuable when observed close to the highly obscured Galactic Bulge and Plane. Their line-of-sight velocities can easily be obtained with high accuracy, proper motions can be measured and distances can be estimated. Furthermore, when different mass and metallicity effects can be accounted for, such a large sample will highlight asymmetries and evolutionary traces in the sample. In our Bulge Asymmetries and Dynamic Evolution (BAaDE) survey we have searched 20,000 infrared selected evolved stars for 43 GHz SiO masers with the VLA in the northern Bulge and Plane and are in the process of observing another 10,000 stars for 86 GHz SiO masers with ALMA in the southern Bulge. Our instantaneous detection rate in the Bulge is close to 70%, both at 43 and 86 GHz, with occasionally up to 7 simultaneous SiO transitions observed in a single star. Here we will outline the BAaDE survey, its first results and some of the peculiar maser features we have observed. Furthermore we will discuss the prospects for obtaining proper motions and parallaxes for individual maser stars to reconstruct individual stellar orbits.

**Keywords.** Masers, Surveys, Infrared: Stars, Stars: Late-type, Circumstellar Matter, Galaxy: Kinematics and Dynamics

## 1. Introductory Background

The Galactic Bulge formed largely by dynamical evolution, and it provides us with a remarkable laboratory to study the processes that must have taken place in many disk galaxies in the local universe between $z = 1$ and now. The central part of the Galaxy seems strongly dominated by a massive bar, based on analysis of the infrared morphology (e.g., Blitz & Spergel 1991, Dwek *et al.* 1995), spatial distribution of red clump stars (e.g., Stanek *et al.* 1997, Babusiaux & Gilmore 2005), and dynamics of red giants from the Bulge Radial Velocity Assay survey (*BRAVA*, Rich *et al.* 2007, Kunder *et al.* 2012).

Optical surveys of the Bulge are a powerful approach to learn about the populations and dynamics in the less reddened and obscured regions where $|b| > 4°$. To a great extent, however, surveys in the optical or infrared bands have begun to reach impasses that cannot be easily resolved with increases in sample sizes.

Red giant circumstellar maser sources, which can be exploited with the Atacama Large Millimeter/submillimeter Array (ALMA) and the Karl G. Jansky Very Large Array (VLA), offer a bold new approach to address the most pressing problems in the study of the inner Galaxy. Kinematic studies of stellar populations using Galactic masers have

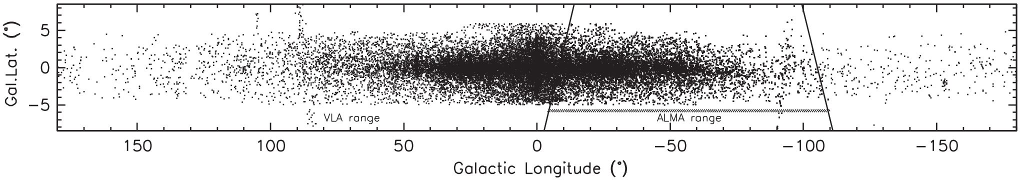

**Figure 1.** Galactic distribution of ∼ 30,000 color selected MSX sources in the BAaDE survey. Sources south of Declination −35° (roughly $-10° < l < -105°$) are observed with ALMA at 86 GHz, the others with the VLA at 43 GHz. With a detection rate of about 70% we expect to derive line-of-sight velocities for nearly 20,000 sources, most of which are in the Galactic Bulge.

been proven prosperous once it was recognized that color selection of IR sources detected by the IRAS satellite was quite predictive in finding stellar OH (1612 MHz) masers in asymptotic giant branch (AGB) stars. The instantaneously obtained stellar line-of-sight velocities could be readily used for kinematic studies. About 3000 OH/IR stars have been studied in the Galaxy, mostly in the Galactic Bulge and Center regions (e.g., Lindqvist *et al.* 1992, Deguchi *et al.* 2002, Debattista *et al.* 2002, Habing 1996).

A high chance of SiO maser occurrence associated with objects that may be used as independent dynamical probes can also be achieved by targeting infrared stars. The SiO masers usually reside in thin envelopes with “bluer” colors on the circumstellar envelope sequence (CSE, Sjouwerman *et al.* 2009). The SiO masers may be observed both at J=1–0 transitions at 43 GHz and at J=2–1 transitions at 86 GHz, allowing a complete coverage of the Galactic Plane when combining observations taken with the VLA and ALMA.

Our goal is to produce samples of radio-detected red giants that are comparable to the 10,000 stars of BRAVA, or the 28,000 stars of the Abundances and Radial velocity Galactic Origins Survey (*ARGOS*, Freeman *et al.* 2012). By using SiO masers, which are detectable in red giants spanning a wide range in luminosity and distances, we probe into the highest extinction, most crowded regions of the Milky Way: the Plane and Galactic Center. We have thus begun an observational program (Bulge Asymmetries and Dynamical Evolution, BAaDE) using the VLA and ALMA to undertake a targeted survey that in principle are not reachable with optical surveys.

## 2. Targeted Observations and Results

We selected candidate targets that had good quality infrared fluxes in the Midcourse Space Experiment survey (MSX) Point Source Catalog version 2.3 (Price *et al.* 2001, Egan *et al.* 2003). Furthermore we required that the candidate targets fulfilled the criteria for MSX region *iiia* – the region corresponding to IRAS region IIIa where we expect a high occurrence of SiO masers (Sjouwerman *et al.* 2009).This selection yielded about 30,000 sources (Figure 1). Dec $\geqslant -35°$ sources were observed at 43 GHz with the VLA during 2012-2017 and the lower Declination sources were reserved for ALMA observations at 86 GHz, which have begun in 2015. A comparison in detection statistics and detection bias between using the two surveys is found elsewhere in this volume (Stroh *et al.* 2018).

Due to the lack of calibrators, we are using a novel self-calibration scheme to use the brightest masers to detect the weaker ones. This method works very well because we can use that the typical detection rate, using our infrared color-selection scheme, is well over 50% for both VLA and ALMA observations, even though we spend less than a minute of observing time per source (Figures 2 and 3). It is promising to show, in Figure 4, that our survey already surpasses the detail obtained with OH/IR stars (see e.g., Habing 1996).

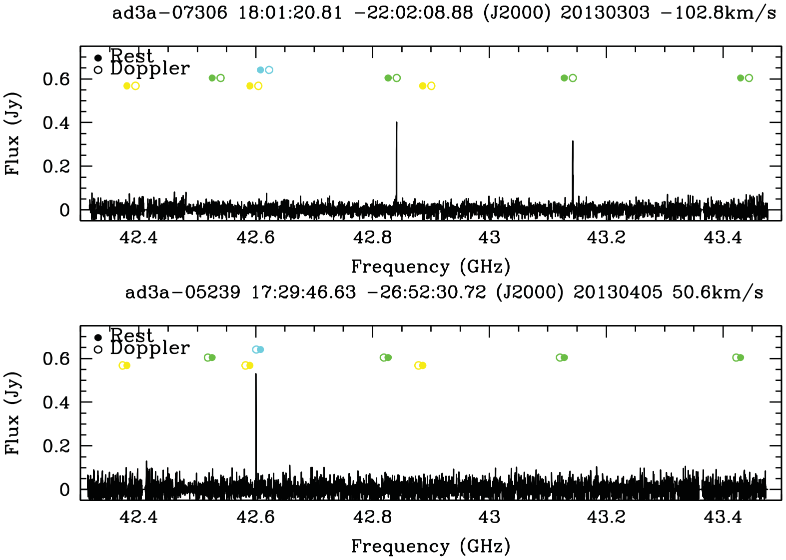

**Figure 2.** Vector-averaged VLA spectra, ranging from about 42300 to 43500 MHz, labeled with the source name, the position (J2000), the observing date (UT) and the derived LSR velocity. To guide the eye, the filled circles show all potential SiO transitions (plus a carbon line) at $V_{LSR}=0$ and the open circles are those lines shifted to the derived $V_{LSR}$. Top: a typical VLA detection with two J=1-0 $^{28}$SiO maser lines, from left to right (v=2) and (v=1). Bottom: an example of a carbon line detection ($HC_5N$) instead of an SiO maser. Carbon detections also yield a velocity for dynamical purposes and in addition allow for a sub-study toward carbon-rich sources.

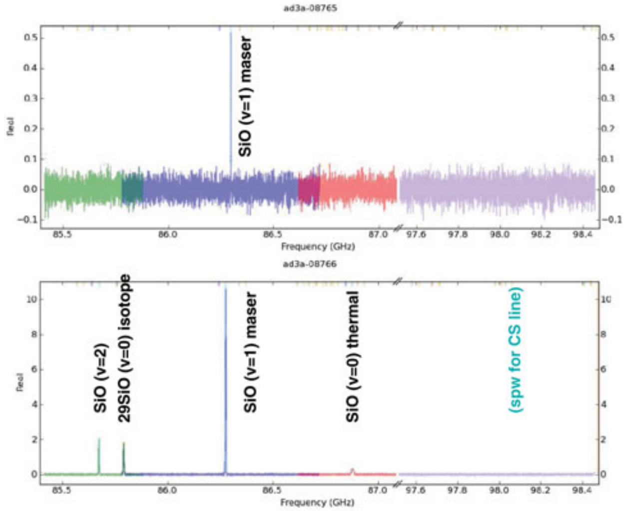

**Figure 3.** Vector-averaged ALMA spectra, using 3 overlapping spectral windows ranging from 85400 to 87100 MHz where SiO transitions are expected, combined in the same panel with an additional spectral window from about 97550 to 98450 MHz for potential lines of carbon bearing molecules (i.e., CS). Top: a typical ALMA detection with a single J=2-1 (v=1) $^{28}$SiO maser line. Bottom: an example of a multi-line detection with all possible SiO transitions detected.

We are currently compiling our list of detections and selecting candidate sources for VLBI follow-up observations. The extended list of new line-of-sight velocities, in combination with the prospect of deriving proper motions for a subset of sources located right

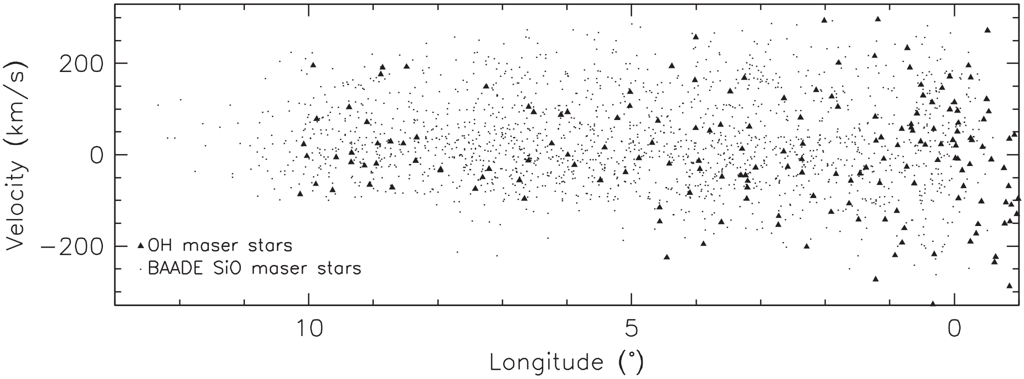

**Figure 4.** Preliminary longitude-velocity diagram of a subset of masers in the Galactic Bulge and Plane ($|b| \ll 5°$) showing the increased information density obtained with SiO masers in the BAaDE survey (small dots) compared to the known population of OH masers (filled triangles).

in the Galactic Plane and in the Galactic Bulge and Center will contribute significantly to the modeling of Galactic dynamics and the understanding of Galactic evolution.

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