Why Galaxies Care About AGB Stars: A Continuing Challenge through Cosmic Time
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A Masing BAaDE's Window

Thousands of SiO Masers in Thousands of AGB Stars in the Galaxy

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Abstract. We report on the Bulge Asymmetries and Dynamic Evolution (BAaDE) survey which has observed 19 000 *MSX* color selected red giant stars for SiO maser emission at 43 GHz with the VLA and is in the process of observing 9 000 of these stars with ALMA at 86 GHz in the Southern sky. Our setup covers the main maser transitions, as well as those of isotopologues and selected lines of carbon-bearing species. Observations of this set of lines allow a far-reaching catalog of line-of-sight velocities in the dust-obscured regions where optical surveys cannot reach. Our preliminary detection rate is close to 70%, predicting a wealth of new information on the distribution of metal rich stars, their kinematics as function of location in the Galaxy, as well as the occurrence of lines and line ratios between the different transitions in combination with the spectral energy distribution from about 1 to 100 μm. Similar to the OH/IR stars, a clear kinematic signature between disk and bulge stars can be seen. Furthermore, the SiO $J = 1 \rightarrow 0$ (v=3) line plays a prominent role in the derived maser properties.

Keywords. masers, surveys, stars: late-type, Galaxy: kinematics and dynamics, infrared: stars

1. Introduction

This symposium highlighted many reasons "Why Galaxies Care About AGB stars". The reasons relevant to the "Bulge Asymmetries and Dynamic Evolution (BAaDE)" survey, described here, can be summarized as:

– Asymptotic Giant Branch (AGB) stars are luminous and abundant; they are relatively easy to find and study in large quantities in the (near-)infrared where their spectral energy distributions (SEDs) peak.

– AGB stars are a mix of stellar populations: a range of stellar masses, ages and metallicities, for which detailed modeling provides a wealth of physical information as function of location in the Galaxy.

– AGB stars are variable stars and are oases of simple molecules; it is possible to determine a crude distance (with period-luminosity relations) and bolometric magnitude, and observing the molecular lines (thermal as well as maser lines) reveals the accurate stellar line-of-sight velocity instantly.

– Surveys of AGB stars can be combined with the physical and kinematic properties and outline the dynamics of the individual populations in the Galaxy.

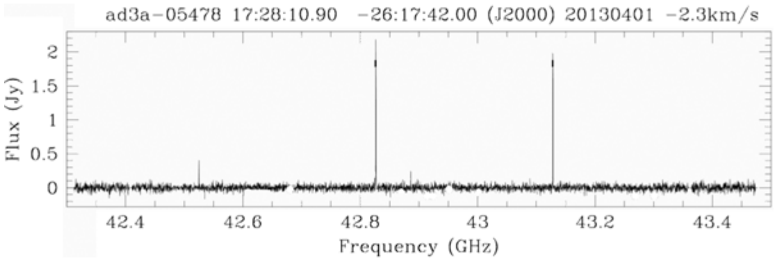

Figure 1. Typical VLA 43 GHz detection of bright SiO isotopologue $J = 1 \rightarrow 0$ maser lines in a source. From left to right: SiO (v=3), SiO (v=2), ^{29}SiO (v=0), and SiO (v=1).

AGB stars are excellent probes of the structure and evolution of the Galaxy!
The BAaDE survey aims to *significantly* improve the models of the dynamics and structure of the inner Galaxy, by probing into the regions of the Galactic Bulge and Galactic plane not reachable with optical surveys. This can be done by using stellar SiO masers as *radio* detected point masses. Similar surveys have been performed earlier, using the less abundant (∼3000) OH masers found in thick-shell AGB stars (i.e., typically the OH/IR stars, e.g., Sevenster *et al.* 2000). However, with the release of the recent space-based (near-)infrared surveys in the Galactic Plane, in particular the Midcourse Space eXperiment (*MSX*) survey (Egan *et al.* 2003), many thousands of candidate thin-shell AGB stars (i.e., typically the Mira-type stars) have become available. With a judicious infrared color selection these stars can be surveyed for the SiO maser with a high detection rate (Sjouwerman *et al.* 2009).

BAaDE is surveying 28 000 *MSX* color-selected red giant stars with the Karl G. Jansky Very Large Array (VLA) north of Declination −35, and the Atacama Large Millimeter/submillimeter Array (ALMA) in the south for the range in Galactic Longitude that the VLA cannot observe ($-110 < l° < -5$). Each individual detection provides a line-of-sight velocity for a given stellar position. Furthermore, for each source a comprehensive set of (near-)infrared photometry is compiled, in an attempt to characterize the central star and its surrounding circumstellar envelope (CSE) through modeling of the individual SEDs. Ultimately, it is the intent to obtain proper motion and parallax measurements from a subset of the sources with Very Long Baseline Interferometry (VLBI), to characterize the type of stellar orbits found in the inner Galaxy (Van Langevelde *et al.*, IAU Symp. 348).

The BAaDE survey is complementary to the optical *Gaia* survey that is obscured in the Bulge and plane (Gaia Collaboration *et al.* 2016). As BAaDE focuses on the inner Bulge area and and evolved stellar population, it is also complementary to the radio BeSSeL survey that uses methanol masers in star forming regions to model the spiral structure in the Galactic Plane (Brunthaler *et al.* 2011).

2. Results

During 2013 to 2017 ∼19 000 sources were observed with the VLA covering four SiO $J = 1 \rightarrow 0$ transitions and three isotopologue lines at 43 GHz (Fig. 1). The preliminary detection rate, after analyzing about half of the data, is close to 70 % for both the VLA and ALMA data when we include the occasional detection of a line from a carbon-bearing species (i.e., from HC_5N and/or HC_7N) in the carbon-rich stars. Of the ∼9 000 sources planned to be observed with ALMA covering three SiO $J = 2 \rightarrow 1$ transitions and one isotopologue line at 86 GHz and the CS line at 98 GHz, about 2 000 have been observed and analyzed in Cycles 2, 3 and 5. The results below are based on preliminary data sets.

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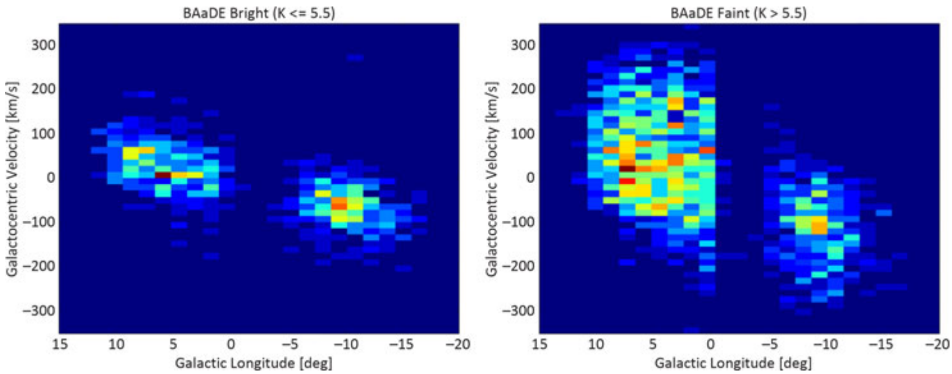

Figure 2. Longitude-velocity histogram plots of the first VLA ($0 < l^\circ < 10$) and ALMA ($l^\circ \approx -10$) observations. After splitting in a bright (left, K-magnitude = 5.5 or brighter) and a faint (right, $K > 5.5$) sample, the bright sample shows a tighter galactic rotation on either side of the Galactic Center ($l = 0$) than the more dispersed fainter sample. [Trapp *et al.* (2018)]

2.1. *Survey Sanity Checks*

A major bias in the BAaDE survey is that approximately 2/3 of the sample is observed in the 43 GHz $J = 1 \rightarrow 0$ transitions with the VLA and 1/3 in the 86 GHz $J = 2 \rightarrow 1$ transitions with ALMA. The assumption is that the detectability in either set of transitions is similar, and thus that a similar sensitivity in either set will sample a similar volume of the Galaxy. To check this assumption, we therefore used the Australia Telescope Compact Array (ATCA) to observe a (bright) subsample quasi-simultaneously at 43 and 86 GHz. The conclusions drawn by Stroh *et al.* (2018) are that the assumption in general holds, but it does depend on whether the 43 GHz $J = 1 \rightarrow 0$ (v=3) transition is detected or not.

In order to obtain proper SEDs for each source, it is important to identify the actual cross-matched source in the diverse (near-)infrared catalogs. As described by Pihlström *et al.* (2018), using the position of the parent *MSX* catalog directly makes it less reliable to securely find the photometry in other catalogs, compared to using the counterpart position from the 2MASS (Skrutskie *et al.* 2006), WISE (Wright *et al.* 2010) and *Gaia* DR2 (Gaia Collaboration *et al.* 2018). For follow-up work where the most accurate positions are needed, such as VLBI, the most useful initial astrometric positions are provided by 2MASS, or *Gaia* when available (i.e., if the source is not obscured in the optical).

With no effort to exclude C-rich CSEs (that would not necessarily be expected to emit in the SiO line), these sources may still contribute to the line-of-sight velocities of the entire sample by the detection of transitions of C-bearing molecules captured by the instrumental setup. Overall, a few percent of our detections are of C-rich sources and Lewis *et al.* (in prep.) are in the process of characterizing this sample.

2.2. *First Results on Galactic Dynamics*

Based on the first ∼2 700 SiO maser detections, Trapp *et al.* (2018) have analyzed the kinematics of the sample, which include a substantial number of line-of-sight velocities in high extinction regions within ±1° of the Galactic plane. They confirm that our radio-detected sample is consistent with Mira variables and mass-losing AGB stars, as anticipated using the *MSX* color selection. In Figs 2 and 3 they clearly distinguish two kinematic populations: a kinematic "cold" (small velocity dispersion) population proposed to be in the foreground Disk, and a kinematic "hot" (large velocity dispersion) candidate Bulge/Bar population. Only the kinematically hot giants include the reddest stars. Adopting 8.3 kpc to the Galactic center, and correcting for foreground

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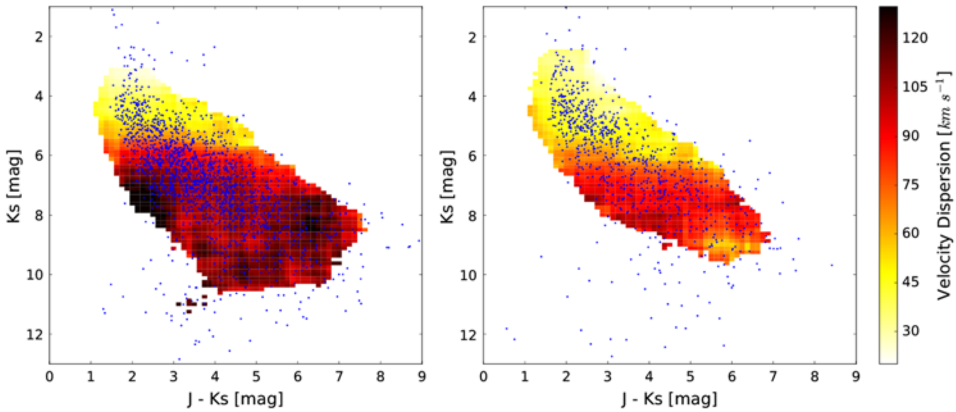

Figure 3. Color-magnitude dispersion diagrams of the VLA (left) and ALMA (right) samples. The clear transition from light to darker regions ($K > 5.5$ and $K > 6$, respectively) indicate a larger dispersion and probably is a signature of stars belonging to the Disk (bright and tight rotation) transitioning to stars making up the Bulge (fainter and dispersed). [Trapp *et al.* (2018)]

extinction, they find that most of the sources have $M_{\rm bol} \approx -5$, consistent with luminous intermediate-age AGB stars.

3. Conclusion

The BAaDE survey is well under way and promises excellent, new data for studying the dynamics and evolution of the Galactic Bulge by combining line-of-sight velocities measured from SiO maser emission in red giant stars with the infrared properties of their circumstellar environment.

Acknowledgements

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