*Cosmic Masers: Proper Motion toward the Next-Generation Large Projects*
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# Masers in evolved stars; the Bulge Asymmetries and Dynamical Evolution (BAaDE) Survey

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**Abstract.** The Bulge Asymmetries and Dynamic Evolution (BAaDE) project attempts to improve our knowledge about the structure and dynamics of the inner Milky Way galaxy by sampling tens of thousands of infrared color-selected evolved stars with circumstellar envelopes (CSEs). The SiO masers in these CSEs yield the object's line-of-sight velocity instantly and accurately, and together provide a sample of point-mass particles that are complementary to high-mass star formation masers typically found in the Galactic Disk as well as to optical samples that cannot reach into the Galactic Plane and Bulge due to extremely high visual extinction. This presentation introduces the BAaDE survey and highlights current results.

**Keywords.** Milky Way galaxy, Galaxy structure, Asymptotic Giant Branch stars, masers, circumstellar material

## 1. Introduction

Currently the general picture of the structure and dynamics of the Milky Way galaxy is that it is a spiral galaxy consisting of a disk characterized by a nearly flat rotation curve and a stellar bar embedded in a bulge, rotating like a solid feature. Whereas this simple symmetric model seems sufficient to explain the major building blocks, only the fine details hidden in observations may reveal the origins and perturbations that have shaped the Milky Way as we see it today. Obtaining a more complete view of the stellar populations and stellar kinematics allow to better disentangle the Milky Way's history, which then can be applied to understand galaxy formation elsewhere.

Surveys to determine the shape and composition of the Milky Way have been performed since the development of optical instrumentation some centuries ago. It was only in the early 1900s that a biased view due to the existence of interstellar extinction was revealed, explaining for example the "zone of avoidance". A one-degree wide region with low extinction toward the Galactic Bulge, the so-called *Baade's window*†, has since been recognized as one of several "windows" for its ability to provide the least extinction-affected observational views of Bulge stars in the optical, albeit located several degrees

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† Wilhelm Heinrich Walter ("Walter") Baade, German astronomer, 1893-1960

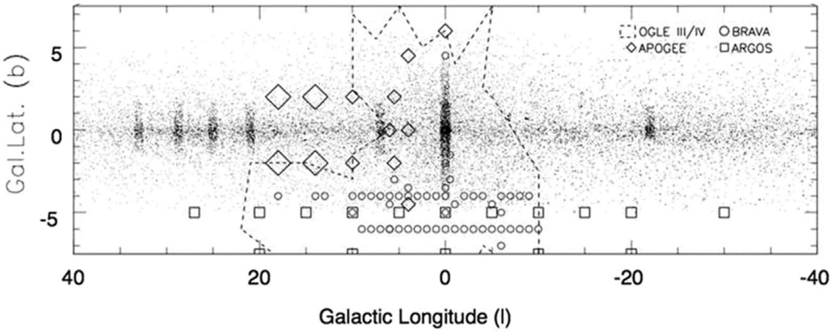

**Figure 1.** The BAaDE sample compared to sky coverage footprints of ground-based optical and NIR surveys toward the Bulge. BAaDE is sampling the inner Galaxy where other surveys are lacking coverage. Note that MSX observed a few regions with higher sensitivity resulting in a higher density of (fainter) targets in some directions, including the Galactic Center.

away $(l = 1.02^\circ, b = -3.92^\circ)$ from the most inner part of the Galaxy. Observations in the near-infrared (NIR) and mid-infrared (MIR) wavebands, where extinction is reduced by an order of magnitude, only recently became feasible with the development of high angular resolution detectors that are able to (mostly) circumvent confusion due to the high stellar density in the Plane and Bulge areas. Nevertheless, these surveys typically either lack the footprint (Figure 1) or kinematic observations to obtain a more complete and homogeneous coverage of the inner Galaxy.

A major step forward towards identifying objects suitable for studies of the inner Bulge used the newly derived predictive properties of MIR color-color diagrams. In particular, specific colors derived from the Infrared Astronomical Satellite (IRAS) identify relatively thick circumstellar envelopes (CSEs) conducive to sustain 1612 MHz ground-state hydroxyl (OH) masers (van der Veen & Habing (1988)). The maser radiation, in the radio wavebands, is not affected by interstellar extinction and is luminous enough to be detected at great distances, covering the entire Milky Way. Once the spectrum is observed to show a typical double-peaked profile, the stellar line-of-sight velocity is known. Several surveys combined have revealed about 4000 stellar OH masers, with about two thirds in the inner Galaxy. The resulting kinematics have been studied and used in modeling of the dynamics of the Galaxy. Even though the OH masers are found in the optically obscured regions in the Plane and Bulge, indeed also in the very center of the Galaxy, their collective number is insufficient to perform a detailed analysis of Galactic structure and asymmetries. Adding the known sample of another couple of thousand stellar silicon-monoxide (SiO) masers, mostly found by Japanese research groups, only expands the data partially as many OH and SiO masers share the same stellar host.

To significantly improve the situation, a new bold approach must be employed. Large-scale optical and NIR ground-based surveys like 2MASS, APOGEE, BRAVA and OGLE, whether or not primarily with the goal of obtaining data for the purpose of studying Galactic dynamics, have yielded incredible amounts of useful data. However, these surveys still carry the aforementioned biases with incomplete coverage and therefore do not reach all the way into the Plane and Bulge. On the other hand, recent sensitive and high angular resolution space-based multi-band NIR and MIR surveys (MSX, GLIMPSE, WISE, etc.) have enabled selecting large samples, less affected by interstellar extinction and closer to the zero-latitude Plane and Galactic Center, based on color and color-magnitude properties of specific types of objects.

### 1.1. *The Bulge Asymmetries and Dynamic Evolution project*

To reach all the way into the mid-Plane, the above mentioned NIR and MIR surveys have enabled us to select objects with specific properties probing deep into the Galactic Plane and Bulge. For example, the MIR-bright low-to-intermediate mass (0.8-8 $M_\odot$) long-period variable Miras occupy a certain region in the MIR color-color space. These stars on the Asymptotic Giant Branch (AGB) have substantial yet relatively thin CSEs, the ones that are likely to harbor SiO masers. Specifically, we drew our target sample from the Midcourse Space Experiment (MSX) point source catalog as it covers the entire Plane and provides colors that promise a high SiO maser detection rate (Sjouwerman *et al.* (2009)). The total sample consists of about 28 000 objects of which two-thirds, north of Declination −35°, can be observed with the Karl G. Jansky Very Large array (VLA) and the remaining southern sources with the Atacama Large Millimeter/submillimeter Array (ALMA). These radio interferometers are sufficiently sensitive to obtain a meaningful observation in a very short time interval, such that observing thousands of sources does not impose a major impact on telescope resources. Requiring a minimal spectral resolution to recognize maser lines and requesting a detection limit realistically needed for follow-up Very Long Baseline Interferometry (VLBI) campaigns, less than a minute observing time per target source is needed.

Unfortunately, the VLA and ALMA are not identical instruments. The VLA receivers are capable of observing up to a frequency of 50 GHz, whereas ALMA at that time did not have observing capabilities below a frequency of 80 GHz. Fortunately, on the other hand, the SiO molecule has rotational transitions that can be observed with the VLA around 43 GHz (J=1-0) as well as with ALMA around 86 GHz (J=2-1). Furthermore, it appears that observations for individual objects in the J=1-0 transitions are interchangeable for observations in the J=2-1 transitions (and vice-versa) when used for dynamical modeling purposes (Stroh *et al.* (2018)). This ensures that an SiO maser survey, combining the VLA and ALMA results to analyze the northern and southern parts of the Milky Way, should at most only suffer from minimal observational bias in the data taken between the two different instruments. That is, if there is bias, it would be in the uncorrected (for line-of-sight dependent interstellar extinction) infrared color selection and limiting magnitude of the MSX point source catalog.

By selecting MIR sources and observing them in the radio regime, the traditional optically selected small-area Baade's window may symbolically be re-defined as *BAaDE's* window; a new view of the Milky Way that is unrestricted in extent and shares the same low-to-no interstellar extinction requirement to study stars in the Galactic Plane and Bulge.

The Bulge Asymmetries and Dynamic Evolution (BAaDE) project aims to significantly improve models of the structure and dynamics of the inner Galaxy. The goal is to probe into regions not reachable with optical and NIR sampling of the Galactic Bulge and Plane by performing an SiO maser survey in evolved AGB stars. These CSE masers reveal the stellar line-of-sight kinematics and can be used as point-mass particles in dynamical modeling representing the older stellar populations. The survey will be complementary to many other surveys, either because of very limited overlap (e.g., sampling different types of objects) or by providing additional information (e.g., providing velocities). The project also includes novel studies to obtain relatively accurate stellar distances in order to derive general stellar properties like bolometric and maser luminosities. The BAaDE survey, by itself or in combination with approximate distances, will yield a wealth of data allowing many different studies and statistical analysis on AGB stars, CSEs and SiO maser modeling and occurrence. For the latter see the contribution by Lewis *et al.* in these proceedings. In the remainder, we will showcase our data and highlight some of the early results published elsewhere.

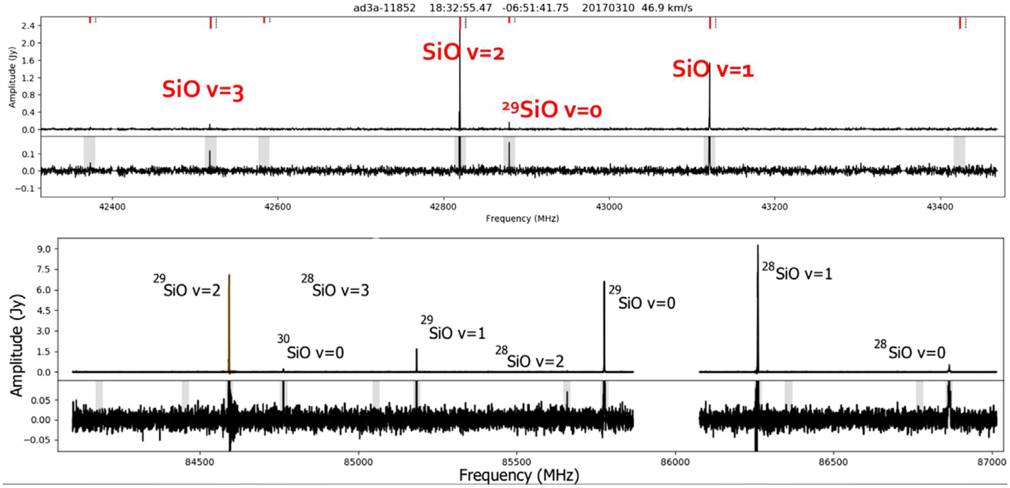

**Figure 2.** Typical spectra for the BAaDE survey detections. Up to seven transitions can be detected using the VLA (top) for sources north of Declination $-35^{\rm d}$ and up to eleven using ALMA (bottom) for the more southern sources.

## 2. Observations

The VLA observations started in 2013 and finished in 2017 (using Semesters 13A through 17A) whereas the ALMA observations took place from 2015 through 2022 (during Cycles 2-8) and included about 19 000 versus 9 000 targeted observations at 43 GHz versus 86 GHz. It should be noted that ALMA was still adding new antennas to the array during our campaign, resulting in reduced time on source in the later years. The spectral resolutions used were about 2 and 1 km/s, respectively, and both survey observations achieved an RMS channel noise of about 15 mJy/beam. All maser detections were assumed to be point-like using the baseline lengths involved, which drastically simplified our data calibration procedures; specifically we used self-calibration on the bright masers (Sjouwerman et al. in preparation).

For a survey this large, multiple observing proposals in different proposal cycles or semesters are the norm. The effects of proposing for cumulative observations are — at least in the case of the BAaDE SiO maser survey — that 1) publications based on preliminary analysis on part of the data appear before the final data set is in hand, that 2) different observing priorities between the allocations resulted in some strategy and data quality trade-offs and that 3) acquired knowledge based on the preliminary data may alter the original observing strategy and target list, potentially affecting homogeneity. That is, whereas the VLA survey was completed mostly homogeneously covering up to seven SiO (isotopologue) transitions for ∼19000 objects, the VLA and early ALMA data allowed to recognize contaminating sources (carbon-rich evolved stars, young stellar objects) using infrared colors and removing them from our ALMA target list. This opened up to reassign correlator resources originally intended to identify these sources and reallocate that bandwidth to cover additional potential SiO (isotopologue) transitions. The 6000 ALMA targets observed after 2018 therefore cover eleven transitions compared to ∼1400 observations covering only the four above ∼85.5 GHz. It should also be noted that the BAaDE science 'data' consists of spectra (Figure 2); it has never been the intention to create images nor image cubes other than for checking purposes, which is somewhat different from the regularly adopted ALMA "image science" philosophy.

## 3. Results

As at this time all observations have just been completed, the final data reduction and combination of the data sets will be reported on elsewhere. From the early data, however, several results have been obtained and are summarized here.

Pihlström *et al.* (2018) have investigated the positional agreement of the input catalog, the MSX PSC 2.3, with phase-referencing VLA A-array configuration maser positions. In addition, the maser positions were matched with possible WISE, 2MASS, and Gaia counterparts. The Gaia positions, due to optical extinction and after careful matching procedure only reliably available for a small subset of the sources, typically agree with the radio maser position to within $0.01''$ (10 mas). The more readily available 2MASS counterparts, generally used for the data reduction, match well within $0.2''$. The WISE and MSX positions are less accurate and typically deviate around a quarter and one arcsecond from the radio position, respectively.

Additionally, as so far is the case in all the BAaDE reobservations of known detections (i.e., in the below), the re-detection rate is around 80%. This is shockingly similar to the instantaneous detection rate in genuine Mira-type AGB stars in the BAaDE survey, which suggests the speculation that SiO masers are present in all these sources with a "maser-on" time of 80% of the stellar pulsation cycle.

Stroh *et al.* (2018) resolved the potential detection rate bias in the SiO 43 GHz (J=1-0) versus the 86 GHz (J=2-1) transitions in (near) simultaneous observations of bright — likely nearby — SiO masers. At least 75% of the 43 GHz detections were also detected at 86 GHz, with a fraction of the non-detections attributed to bad weather conditions. This supports the suggestion of Sjouwerman *et al.* (2004) that 43 GHz and 86 GHz SiO masers typically co-exist (simultaneously) in the same source, with the same line-of-sight velocity of the maser. They find that, in terms of detectability for the BAaDE survey, the 86 GHz masers are on average a factor 1.36 fainter than the 43 GHz masers. Interestingly the ratio is influenced by the presence of the 43 GHz $v=3$ transition: it reaches unity when the line is present and a factor two when not. Their work likely also demonstrates the validity the radiative pumping model that includes a water-overlap transition (Desmurs *et al.* (2014)). Finally, given the limited average difference and large spread in J=1-0 to J=2-1 maser line ratios, detecting the 86 GHz maser on the remote side of the Galaxy should not be much harder than detecting the 43 GHz maser, justifying BAaDE's pragmatic application of observational constraints on the southern and northern hemisphere to probe the entire Milky Way galaxy.

Trapp *et al.* (2018) performed an early kinematic analysis using the pilot VLA and ALMA data. They showed that there is a clean division into two separate kinematic populations: a "cold", low dispersion ($\sigma \sim$50 km/s) foreground (and background!) Galactic Disk component consisting of the younger and more massive AGB stars and a "hot", high dispersion ($\sigma \sim$100 km/s) component reminiscent of older and lower mass AGB stars that would be typically found in the Galactic Bulge or Bar (Figure 3). Interestingly the higher dispersion stars, apart from deviating more from circular motions that can be expected from the low dispersion disk stars, also show signs of cylindrical rotation at the higher latitudes, as predicted by bar models (Shen *et al.* (2010)). That is, based on the pilot BAaDE SiO maser data, the inner Galaxy shows evidence of a (tri-axial) bar and is not completely described by an elliptical shape and kinematics of an ensemble of fully independent orbits.

Stroh *et al.* (2019) have published the early 86 GHz ALMA data, about 1400 sources observed for four SiO transitions and the CS-line. The latter was included to distinguish non-detections in oxygen-rich sources from carbon-rich sources. In particular, when imaged the carbon-rich (evolved) AGB stars would clearly show a point-like source whereas the more extended structures could be identified with young stellar objects

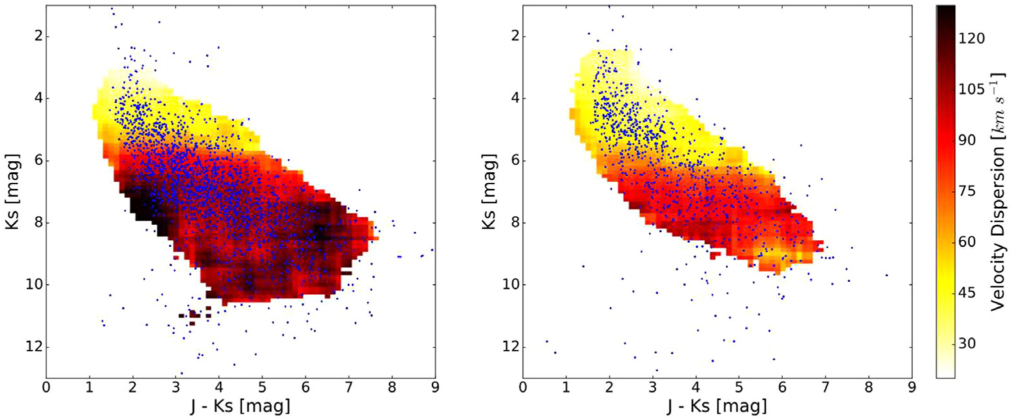

**Figure 3.** The BAaDE pilot data reveals the separation of the Disk and Bulge populations, where the start of the distinction using the far-side ALMA apparent $K_s$-magnitude (∼6.5 mag) is fainter than the near-side VLA apparent $K_s$-magnitude (∼5.5 mag). See Trapp *et al.* (2018).

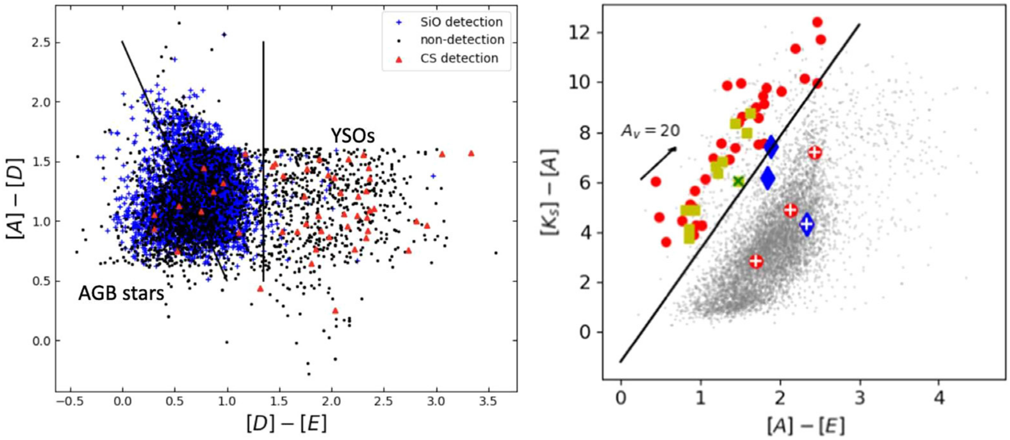

**Figure 4.** Left: MSX colors alone can distinguish between evolved and young stellar objects. Right: To further distinguish between carbon-rich and oxygen-rich evolved stars, the combined 2MASS/MSX [$K_s$]−[A] color is required. See Lewis *et al.* (2020a) and Lewis *et al.* (2020b).

(YSOs) in their embedding molecular clouds, or alternatively planetary nebulae (PNe) or compact HII regions. From this, and the associated line-of-sight velocity information of the detections, they were able to decontaminate the sample and refine the genuine oxygen-rich AGB stars that were the objects of interest using MIR colors, specifically MSX [D]−[E]. This was crucial to understand part of the non-detections, also in the 43 GHz VLA data (see Lewis (2021)), and allowed to remove unlikely SiO maser detections in the remaining ALMA observations; the VLA observations had completed by that time and were refined to oxygen-rich AGB stars afterwards.

Lewis *et al.* (2020a) have expanded the MSX-only color criteria of Stroh *et al.* (2019) with 2MASS $K_s$ data to distinguish sources that are questionable genuine oxygen-rich AGB stars (Figure 4). Where the MSX [D]−[E] color (or [D]−[18], where [18] is taken from AKARI) typically separates the evolved from the young, pre-main sequence stars, the combination of MSX and 2MASS photometry is necessary to distinguish among the evolved stars: the carbon-rich versus the oxygen-rich. This ensures that the BAaDE survey data can be properly assigned to the correct type of object and that any analysis

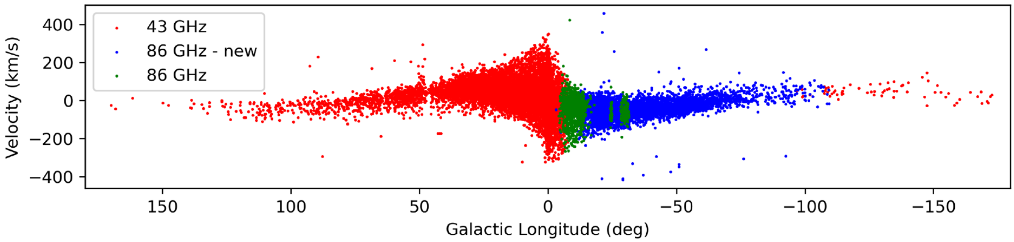

**Figure 5.** The BAaDE survey has recently been completed by including the line-of-sight velocities of the southern ALMA part ($-15^\circ < l < -100^\circ$) providing a full coverage of SiO maser velocities in AGB stars over Galactic longitude.

is not hampered by contamination. The availability of a large sample observed over the entire Galactic Plane also yielded insight in the relative distribution: carbon-rich AGB stars seem to be spread relatively uniformly over the inner Galaxy when compared to the much more peaked distribution of oxygen-rich stars, centered on the Galactic Center.

Lewis *et al.* (2020b) confirmed the separation in Lewis *et al.* (2020a) and resolved a final ambiguity: that of bright single-line detections near 42.9 GHz. This frequency is near a carbon transition (of $HC_3N$) as well as the (oxygen) ($v=0$) transition of the $^{29}$SiO isotopologue. Detecting the latter transition without detecting any other SiO maser, as well as detecting the $HC_3N$ line as a narrow (few km/s), perhaps maser feature were both considered unlikely. Nevertheless, with reobserving these single-line objects Lewis *et al.* (2020b) have shown that these detections should be attributed to the $^{29}$SiO isotopologue, and that it is indeed possible that an isotopologue line can be (much) brighter, or even the only line detected in oxygen-rich AGB stars. Furthermore, this behavior can be reversed, with the typical, traditional 42.8 and 43.1 GHz $^{28}$SiO masers dominating the spectrum within a few years. This should fuel the development of new maser pumping models, which would need to explain this observed behavior.

Dike *et al.* (2021) have paid specific attention to the 43 GHz J=1-0 ground-vibrational state emission. This transition, when detected, is both seen as a wide feature as well as a narrow feature in the individual spectra. The wider features are attributed to thermal emission and used to measure SiO outflow velocities which typically range within 15-30 km/s and are similar to the OH and CO outflow velocities. The narrow profiles are attributed to maser emission in this transition and, for composite thermal/maser profiles, removed when fitting the outflow velocities. It should be noted that the thermal lines typically are seen in the more-nearby sources, suggestive of a sensitivity limited result.

## 4. Summary

The preliminary analysis of the BAaDE survey data has already yielded a wealth of new information, both on the individual sources as well as the distribution and kinematics of the different population components in the Milky Way galaxy. Whereas there are many more topics to address, we think that we understand the potential limitations and possible confusion in the data and are well positioned to study the Bulge Asymmetries and Dynamical Evolution of the Galaxy. This is even more true now that we have completed the results of the final ALMA observations and have a complete coverage of the Galactic Bulge (Figure 5).

## 5. Next Challenges

One of the next moves is to include the BAaDE survey results in realistic Galactic dynamics models. These models will be helped by additional information such as source distances and proper motion measurements. Whereas the latter is probably logistically not feasible for the entire sample, we are investigating an approach that may be successful for a reasonable number of sources. Either way, obtaining proper motions will require an investment of several years.

Measuring distances to a large number of objects may also be unrealistic. That is, the Gaia mission has measured the (geometric) parallax distances to only a fraction of (optically visible) BAaDE targets. However, we have our reservations about blindly assigning these distances to our sources, partly because we challenge the optical counterparts, partly because the stellar photosphere is the size of the anticipated parallax. Geometric parallaxes measured using VLBI techniques on the maser emission in principle is possible, but again unrealistic for a large sample. We are therefore exploring methods using existing infrared photometry (from e.g., MSX, 2MASS, etc.) and existing pulsation cycle period measurements (from e.g., OGLE, VVV, ZTF, etc.); see also the contribution of Bhattacharya *et al.* elsewhere in these proceedings. We are in the early experimental phase of these methods and expect to be reporting on them at a future occasion.

## References

Desmurs, J.-F., Bujarrabal, V., Lindqvist, M., *et al.* 2014, *A&A*, 565, 127
Dike, V., Morris, M. R., Rich, R. M., *et al.* 2021, *AJ*, 161, 111
Lewis, M. O. 2021, *PhD Thesis*, University of New Mexico, USA
Lewis, M. O., Pihlström, Y. M., Sjouwerman, L. O., *et al.* 2020, *ApJ*, 892, 52
Lewis, M. O., Pihlström, Y. M., Sjouwerman, L. O., *et al.* 2020, *ApJ*, 901, 98
Pihlström, Y. M., Sjouwerman, L. O., Claussen, M. J, *et al.* 2018, *ApJ*, 868, 72
Shen, J., Rich, R. M., Kormendy, J., *et al.* 2010, *ApJL*, 720, 72
Sjouwerman, L. O., Messineo, M. & Habing, H. J. 2004, *PASJ*, 56, 45
Sjouwerman, L. O., Capen, S. M. & Claussen, M. J 2009, *ApJ*, 705, 1554
Stroh, M. C., Pihlström, Y. M., Sjouwerman, L. O., *et al.* 2018, *ApJ*, 862, 153
Stroh, M. C., Pihlström, Y. M., Sjouwerman, L. O., *et al.* 2019, *ApJS*, 244, 25
Trapp, A. C., Rich, R. M., Morris, M. R., *et al.* 2018, *ApJ*, 861, 75
van der Veen, W. E. C. J., & Habing, H. J. 1988, *A&A*, 194, 125