Positional Offsets Between SiO Masers in Evolved Stars and their Cross-Matched Counterparts

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ABSTRACT

Observations of dust-enshrouded evolved stars selected from infrared catalogs requiring high positional accuracy, like infrared spectroscopy or long baseline radio interferometric observations, often require preparational observational steps determining a position with an accuracy much better than 1″. Using phase-referencing observations with the Very Large Array at its highest resolution, we have compared the positions of SiO 43 GHz masers in evolved stars, assumed to originate in their infrared detected circumstellar shells, with the positions listed in the MSX, WISE, 2MASS, and Gaia catalogs. Starting from an MSX position it is, in general, simple to match 2MASS and WISE counterparts. However, in order to obtain a Gaia match to the MSX source it is required to use a 2-step approach due to the large number of nearby candidates and low initial positional accuracy of the MSX data. We show that the closest comparable position to the SiO maser in our limited sample never is the MSX position. When a plausible source with a characteristic signature of an evolved star with a circumstellar shell can be found in the area, the best indicator of the maser position is provided by the Gaia position, with the 2MASS position being second-best. Typical positional offsets from all catalogs to the SiO masers are reported.

Keywords: catalogs – infrared: stars – masers – radio lines:stars – stars:AGB – surveys

1. INTRODUCTION

The Bulge Asymmetries and Dynamical Evolution (BAaDE) project is surveying more than 28,000 color-selected red giant stars in the Galactic plane for SiO maser emission (L.O. Sjouwerman et al., in prep.). With an instantaneous detection rate well over 50%, a unique sample of dynamical tracers in the plane is being constructed. At the frequencies of the SiO maser (43 GHz and 86 GHz) visual extinction is not a hinder, and extremely accurate line-of-sight stellar velocities (≲ 2 km s⁻¹) are determined at the locations of the stars (Habing et al. 1996, and references therein). The number of sources will be large enough to trace complex kinematic structures and minority populations. The velocity structure of these tracers will be compared with the kinematic structures seen in molecular gas and other objects near the Galactic Center, and thereby highlight kinematically coherent stellar systems, complex orbit structure in the bar, or stellar streams resulting from recently infallen systems. Investigations of the bar and bulge dynamics have begun using a subset of this new kinematic information in the inner Galaxy region (Trapp et al. 2018).

The BAaDE survey also identifies sufficiently luminous SiO masers suitable for follow-up parallax and proper motion determination using very long baseline interferometry (VLBI). With VLBI, it may be possible to investigate in detail orbits of stars constituting the stellar bar. Spectroscopic infrared (IR) data of the targets will also be taken to investigate metallicity effects.
across the bar and bulge region. Such follow-up studies require positional accuracies of the targets of the order of 0′′1 or less. As the general BAaDE observing strategy using the NSF’s Karl G. Jansky Very Large Array (VLA) in the C and D configurations with resolutions of 1-2″ utilizes the masers themselves for phase corrections (L.O. Sjouwerman et al., in prep.), the known positional accuracy is not improved beyond that of the initial Midspace Experiment (MSX) positions (1-2″; Egan et al. 2003). To improve the SiO maser target positions, proper VLA A-array phase-referencing observations could be performed instead, pushing the accuracy down below 0′′01, e.g. as shown here. However, doing such observations is impractical for several reasons. First, there are very few suitable VLA 43 GHz calibrators in the plane, severely limiting the number of sources that could be observed in this fashion. Second, phase-referencing is time consuming, and re-observing the detected sample in this mode would in principle mean tripling our original time request at the telescope. Alternatively, we investigate whether cross-matching the parent MSX positions with other general all-sky IR and optical catalogs, like the Two-Micron All Sky Survey (2MASS; Skrutskie et al. 2006), the Wide-field Infrared Survey Explorer (WISE; Wright et al. 2010), and the Gaia Data Release 2 (DR2; Gaia Collaboration et al. 2016, 2018) with typical claimed absolute positional accuracies ≲ 0′′1, can be used to improve the positional information. If so, the intermediate phase-referencing observations with the VLA in extended configurations may not be required to obtain sufficiently accurate positions for follow-up studies.

We here report on a limited study using the VLA in a regular phase-referencing observing scheme to determine the positions of a set of masers to <0′′01 accuracy. The resulting positions of the masers are compared to matched MSX, WISE, 2MASS and Gaia positions, in order to obtain a limited empirical determination of the positional agreement between the IR/optical and radio data. While some other catalogs with claimed accurate astrometry exist, they were not included in our study due to their more limited sky coverage.

2. DATA COLLECTION

2.1. Source Selection

Phase-referenced observations at the VLA were used to achieve accurate positions of the SiO maser. The accuracy of the derived positions depends in part on the goodness of the calibrated phases, requiring a bright calibrator source with good positional accuracy, located near the target field. The VLA calibrator J1755−2232 is positioned in the inner Galactic plane and has a listed brightness of 0.32 Jy/beam in the VLA calibrator manual along with an absolute positional accuracy quoted between 0′′002−0′′01, and was therefore chosen to be the phase-referencing calibrator. Within a distance of 0′6 of J1755−2232, 33 previously BAaDE detected SiO maser stars were observed in this experiment. The initial field centers used for observing these targets were the MSX positions included in Table 1.

2.2. VLA Observations and Data Reduction

The sources were observed in June 2015\(^1\) under project code 15A-497 with the VLA in the A-array configuration, yielding an angular resolution of about 50-100 milli-arcsecond (mas). The Doppler-shifted frequencies of both the \(^{28}\text{SiO}(1−0)\) \(v = 2\) and \(v = 1\) lines were covered by our setup (600 km s\(^{-1}\) total velocity bandwidth). A phase-referencing cycle time of 50 seconds was used, with 20 seconds on the calibrator bracketing each target source, which in turn was observed for 30 seconds. Each target was observed twice, resulting in a typical 1.7 km s\(^{-1}\) (250 kHz) channel r.m.s. noise of 13 mJy/beam, agreeing with the estimated theoretical r.m.s. noise for observations at low elevations and 1 minute on-source integration.

The data were calibrated using the AIPS package, and a deconvolved map of each maser was constructed using the CLEAN algorithm with a robust weighting of zero. The resulting synthesized beam sizes were almost identical, 0′′1.128×0′′.045 at a position angle of 30°. Of the 33 targets 26 were detected. Because SiO masers are variable throughout the stellar cycle with a period of a few hundred days, this is a likely reason for the seven non-detections. For the detections, a two-dimensional Gaussian fit was performed to determine the peak flux position of the emission, listed as the VLA positions in Table 1, determined from the channel with peak emission of the \(v = 1\) or \(v = 2\) lines. On average the signal-to-noise ratio (S/N) of the detection in one channel was 25, leading to 1-\(\sigma\) uncertainties in the reported SiO positions of about 1.0 mas in \(x\) and 2.8 mas in \(y\) using the relation \(\Delta \theta_i = (0.54 \theta_i)/(S/N)NR\), where \(\theta_i\) is the full-width at half maximum of the synthesized beam in the \(i\)-direction (Reid et al. 1988). Given the beam position angle, the resulting errors in Right Ascension (R.A.) and declination (decl.) are approximately 0.8 and 2.4 mas. Spectra of these sources, along with the line properties, will be published as part of the main BAaDE project; see L.O. Sjouwerman et al. (in prep.).

2.3. MSX, WISE and 2MASS Data

\(^1\) This date, 2015.5, coincides with the epoch of Gaia DR2.
The BAaDE sources were originally selected from the MSX Point Source Catalog version 2.3 (Egan et al. 2003), based on their IR color in order to optimize for the detection of SiO masers (Sjouwerman et al. 2009). The MSX mission was designed to collect IR photometry along the full Galactic plane, and in regions not covered by IRAS. For regions toward the Galactic center in particular, where IRAS was heavily confused due to the high source density, MSX significantly improved existing IR catalogs. MSX has a beam of 18′′3, with astronomically useful bands observed at 8.3, 12.1, 14.7 and 21.3 μm (bands A, C, D, and E, respectively). The MSX positional information is dominated by information from band A as it is the most sensitive band along with having the shortest wavelength. The MSX astrometric accuracy depends on the detection quality (Egan et al. 2003), and the sources selected for the BAaDE sample used quality photometry flags $Q_X \geq 3$ (i.e., 3 and 4) where $Q_X$ indicates the quality in band $X$, translating into a positional accuracy between 0″80–1″7.

Based on the MSX positions and their accuracy, for each MSX position with a maser detected, a search radius of 5″ was used to search the NASA/IPAC Infrared Science Archive (IRSA) for cross-matches in the WISE and 2MASS surveys, with the results listed in Table 1.

The WISE survey scanned the sky at 3.6, 4.6, 12 and 22 μm (bands W1, W2, W3, and W4, respectively) with angular resolutions of 6″1, 6″4, 6″5 and 12″0. Initially, the WISE All-Sky catalog positions were referenced with respect to the 2MASS catalog, giving accuracies of ≈0″15, but the more recent AllWISE catalog has since improved upon the accuracy to <0″1 by also implementing proper motion for reference objects. Within the search radius only single cross-matches were found.

| R.A. (h:m:s) | decl. ("') | R.A. (m:s) | decl. ("') | R.A. (m:s) | decl. ("') | R.A. (m:s) | decl. ("') |
|-------------|------------|------------|------------|------------|------------|------------|------------|
| 17:57:45.7491 | -22:40:37.634 | 57:45.74 | 40:37.9 | 57:45.748 | 40:37.60 | 57:45.747 | 40:37.62 |
| 17:56:35.1030 | -23:38:16.087 | 56:35.09 | 38:16.1 | 56:35.118 | 38:15.92 | 56:35.110 | 38:15.91 |
| 17:57:16.8026 | -23:37:19.622 | 57:16.78 | 37:21.0 | 57:16.802 | 37:19.47 | 57:16.810 | 37:19.56 |
| 17:57:37.2920 | -23:37:07.215 | 57:37.73 | 37:08.0 | 57:37.738 | 37:07.15 | 57:37.730 | 37:07.27 |
| 17:52:32.9523 | -23:32:21.200 | 52:32.93 | 32:22.3 | 52:32.955 | 32:21.18 | 52:32.961 | 32:21.03 |
| 17:52:32.1456 | -23:30:19.551 | 52:32.09 | 30:20.5 | 52:32.139 | 30:19.49 | 52:32.147 | 30:19.58 |
| 17:55:19.7673 | -22:28:49.418 | 55:19.82 | 28:49.1 | 55:19.757 | 28:49.44 | 55:19.773 | 28:49.43 |
| 17:53:17.0344 | -22:26:02.737 | 53:17.06 | 26:02.4 | 53:17.034 | 26:02.61 | 53:17.040 | 26:02.70 |
| 17:57:33.5178 | -22:24:26.355 | 57:33.50 | 24:28.1 | 57:33.543 | 24:26.07 | 57:33.522 | 24:26.19 |
| 17:54:53.7339 | -22:23:30.810 | 54:53.76 | 23:30.4 | 54:53.750 | 22:31.00 | 54:53.740 | 22:30.60 |
| 17:53:29.5411 | -22:21:46.851 | 53:29.59 | 21:47.2 | 53:29.538 | 21:46.82 | 53:29.542 | 21:46.77 |
| 17:56:48.5306 | -22:17:41.335 | 56:48.50 | 17:42.4 | 56:48.552 | 17:41.29 | 56:48.542 | 17:41.35 |

Two candidate matches were found within the 5″ search radius. The selected cross-match is the reddest, brightest and also the closest candidate.
with reported WISE positional accuracies of on average 0\'035 and 0\'036 in R.A. and decl.

The 2MASS project observed the full sky with a resolution of 2\arcsec, using the 1.24, 1.66 and 2.16\,\mu m (J, H, and K\textsubscript{s}) bands (Skrutskie et al. 2006). Cross-matches to all of our SiO maser detected MSX sources were found in the 2MASS Point Source Catalog, with three fields showing two possible cross-matches within the search radius (marked in Table 1). Given the anticipation of our targets being dust-enshrouded evolved stars, most likely asymptotic giant branch (AGB) stars, the source which was reddest and brightest was selected, which in all three cases also corresponded to the closest match in position. The quoted accuracies for all 2MASS positions are 0\'06 in both R.A. and decl.

2.4. Gaia Data

The Gaia mission is conducting a full sky survey at 0.7\,\mu m (G-band). Although the spectral energy distribution (SED) from dust-enshrouded stars has its peak in the (near-)IR, the specific selection for stars with thinner shell envelopes in the BAaDE survey (i.e., Miras instead of OH/IR stars) allows on occasion for optical emission being detected, for example, by Gaia. Whereas we do not anticipate many Gaia counterpart matches in the most obscured regions in the Galactic plane and for the thicker shell objects in the entire BAaDE sample, the sensitive Gaia data is expected to yield some counterpart matches that can be studied here along with the IR catalogs.

The Gaia DR2 provides high quality astrometric data (Gaia Collaboration et al. 2018; Lindegren et al. 2018), which was used to search for cross-matches to our SiO maser sample. The Gaia data, however, had to be treated differently than the IR data, as searching within 5 arcseconds of the MSX positions provides up to 8 matches for individual MSX sources. Given the uncertainty in the MSX positions, a smaller search radius could not be applied without the risk of missing the correct cross-match. To ensure the correct candidate was selected, color and brightness criteria were applied, similar to what was done for the 2MASS multiple candidates (Sect. 2.3). Gaia DR2 contains photometry for the full G band covering 0.33-1.05\,\mu m, and for some sources also the photometry and associated color measured with the integrated G\textsubscript{BP} and G\textsubscript{RP} bands at 0.33-0.68\,\mu m and 0.63-1.05\,\mu m, respectively (Evans et al. 2018). As the targeted objects typically are large-amplitude variable stars, another characteristic that could be used in ensuring a proper cross-match is a variability indication. Only one candidate counterpart with this information was found in the Gaia data for our sample, and thus we ignored this characteristic further in our matching scheme\textsuperscript{2}. In addition, the positional offsets between the Gaia-selected candidates and the VLA SiO masers, as well as the offsets between the Gaia candidates and the previously cross-matched 2MASS positions were considered to aid in the Gaia cross-matching procedure:

- For the set of 26 masers, one source had no Gaia candidate cross-match at all, possibly due to optical extinction. Note that this region around the calibrator is at G006.63+1.38, a region for which not much extinction is expected, which may explain the large fraction of optical counterparts. The remaining 25 sources had a combined number of 78 candidate cross-matches in the Gaia DR2 catalog within a 5\arcsec radius of the MSX position. The Gaia G band magnitude was collected for all 78 candidates, as was the G\textsubscript{BP}−G\textsubscript{RP} color, which existed for 47 candidates.

- A cross-match was determined to be the most likely match if the G\textsubscript{BP}−G\textsubscript{RP} color (if existing) was the reddest amongst the candidates, and if the positional offset to the SiO maser was the smallest and < 0\farcs5. For 14 of the 25 sources with Gaia data, such cross-matches existed. It turns out that for all these 14 sources, also the Gaia-2MASS offset was consistently the smallest and < 0\farcs5.

- Subsequently, returning to the original 78 candidates and selecting on Gaia-2MASS offsets only, the same 14 candidates with Gaia colors were selected along with 11 additional cross-matches for those lacking color information\textsuperscript{3}.

Figure 1 presents a color-magnitude diagram showing the distribution of the 47 candidate cross-matches within 5\arcsec (crosses) on top of a set of 5,758 randomly selected Gaia sources in the neighborhood of our targets, illustrating the spread of the colors of the candidates. We note that, assuming an M\textsubscript{bol} ≈ −6 for the brightest AGB stars, a Gaia magnitude fainter (larger) than 12 for this sample (Fig. 1) also indicates that our counterparts are more distant than 4 kpc. We therefore may ignore any Gaia parallax (i.e., π < 0.25 mas) and proper motion\textsuperscript{4} corrections here. The 14 circles denote

\textsuperscript{2} For calculating a measure of variability other than using the Gaia DR2 variability flag, see e.g. Quiroga-Nuñez et al. (2018); Belokurov et al. (2017). This is beyond the scope of this paper.

\textsuperscript{3} This implies that a 2-step matching scheme, following the sequence MSX→2MASS→Gaia, is the best approach also when no accurate phase-referenced SiO maser positions are available as is the case for the majority of the BAaDE sample.

\textsuperscript{4} See first footnote.
VLA measured SiO maser positions in evolved stars

5.0
2.5
0.0
2.0
1.5
1.0
0.5
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
Number
Absolute offset from VLA position (arcsec)

Figure 1. A Gaia color-magnitude diagram, with 5,758 randomly selected sources in the neighborhood of the calibrator and target SiO masers plotted as light gray dots. All the 47 Gaia candidate matches for which Gaia colors were available are marked by crosses, showing the spread in the diagram of all candidates. After applying an angular distance offset and a color criterion, the 14 circles denote the selected cross-matches. This illustrates that the applied selection methodology primarily chooses redder and brighter stars, consistent with our targets being mainly redder dust-enshrouded (AGB) stars.

Figure 2. Measured absolute offsets in arcseconds between the VLA SiO maser positions and the MSX, 2MASS, WISE, and Gaia positions. The closest positional match is provided by Gaia if available, and by 2MASS otherwise.

The position used was (J2000) R.A. 17$^h$55$^m$26.284535$^s$, decl. −22°32′10.61573″, which is 22 mas from the VLA catalog position. As a result, the positional errors of the calibrator combined with the VLA-derived errors are governed by the 0.8 and 2.4 mas VLA maser errors in R.A. and decl., respectively. This is much smaller than the typical quoted absolute values of 1.7, 0.035 and 0.060 errors, respectively, for the MSX, WISE and 2MASS catalogs, and of the same order as the error for the Gaia catalog; the Gaia positional accuracy is thus directly comparable to that of the derived VLA maser positions.

3. RESULTS

The attainable accuracy of the derived maser positions depends on the size of the synthesized beam and the signal-to-noise ratio of the detection, but the absolute positional accuracy of the phase-referencing calibrator also has to be considered. The VLA calibrator manual classifies the position of J1755−2232 to be between 0′.002−0′.01 accurate. Conservatively assuming the larger value, an error of 10 mas would be dominating the error of the derived maser positions. By shifting the calibrator data during the calibration procedure, we instead used the position obtained from the Radio Fundamental Catalog (RFC$^5$), providing sub-mas accuracies of 0.16 mas and 0.28 mas in R.A. and decl., respectively.

3.1. Total and systematic offsets

To determine how close the IR/optical catalog positions are to the VLA SiO maser position, offsets were calculated between the VLA and MSX, 2MASS, WISE, and Gaia matches respectively. Figure 2 plots the offset distribution, showing that the MSX positions can always be improved using any of the other catalogs considered here. Furthermore, positions are best matched using Gaia positions when available, next followed by 2MASS. This is further illustrated in the scatter plot of the positions as a function of R.A. and decl., where the Gaia and 2MASS positions are tightly clustered around the VLA maser positions (Fig. 3). The mean offsets between the SiO masers and MSX, WISE, 2MASS and Gaia catalogs are 0′.89, 0′.26, 0′.12 and 0′.01, respectively.

Along with Fig. 3, Fig. 4 separates the spread in the positional offsets into R.A., and decl. components, in order to consider any systematic offsets for any of the
surveys. There is a weak trend of the 2MASS data preferentially reporting a more northern declination than the SiO masers, and conversely, that the MSX data reports a more Southern declination.

4. DISCUSSION

The data confirm that Gaia positions are superior in pinpointing the stellar SiO maser emission if it can be matched. This is not surprising, given that the SiO masers arise close to the central star, at the inside of the larger circumstellar envelope (CSE) where dust and other molecules are residing. SiO masers are further known to be ubiquitous in AGB stars with thin CSEs, allowing for the central star to still be detectable in the optical. If a Gaia match is not obtainable, for example for more optically obscured or thicker shell objects, 2MASS will provide a very good option for improving the positional accuracy compared to any of the other IR catalogs. We here discuss reasons for why the WISE positions appear to be less accurate in tracing the masers (4.1) and how the detection rates in the BAaDE SiO maser survey are improved using 2MASS positions (4.2).

4.1. WISE versus 2MASS positions

It is clear that the 2MASS positions are more accurate than WISE in predicting the SiO maser positions, despite the better quoted positional accuracy of WISE. There are several possible causes for this; first, WISE data has an intrinsically worse resolution (wider point spread function). By inspecting the fields around the targets in the IRSA database, we noted that some of the 2MASS targets have multiple possible matches, which likely are confused in the WISE data. Secondly, the turnover of the SED for these sources tend to occur around 1-2 μm, with the WISE bands at longer wavelengths being sensitive for emission from the CSE. Like for Gaia, the shorter 2MASS wavelengths are more likely to directly probe the central star, which will then better pinpoint the stellar position no matter how far the CSE extends or how asymmetric the CSE is. The SiO masers are known to occur within a couple to a few stellar radii (Diamond et al. 1994; Perrin et al. 2015), inside the main circumstellar shell and close to the dust condensation radius, beyond which the SiO becomes locked up in dust grains. The WISE data will be more dominated by the full extent of the CSE, and despite a quasi-spherical mass loss assumed during the AGB phase, the larger size overall will likely make it more difficult to exactly measure the position of the central star. We assume that this effect is worse for MSX, which operated at even longer wavelengths than WISE.

4.2. Improved detection rate in the BAaDE survey

As this program intended to improve initial positions from the MSX catalog and to assert what positions to use for VLBI, applying Gaia or 2MASS positions to our VLA survey should improve our maser detection rate. For the 28,000 star BAaDE survey, we rely on an assumed high detection rate initially and then utilize the detected masers to perform self-calibration, applying the resulting phase corrections to nearby targets lacking detections (L.O. Sjouwerman et al., in prep.). The self-calibration procedure prevents improved positional information to be derived, as is usually obtained in the more commonly applied phase-referencing
scheme. This strategy has the clear advantage that it removes hundreds of calibration hours using the sparse high-frequency weather needed for our survey, and still provides velocities along with positions. However, in regions of the sky where the source density is lower our calibration scheme is less effective, and every detection is crucial for the calibration of neighboring targets. Especially for weaker masers, a positional error of 1′′−2′′ could result in the maser not being detected in our pipeline which considers emission to be at the phase center (read MSX position), thereby reducing the effectiveness of our calibration strategy. Exchanging the MSX positions with Gaia or 2MASS positions in the self-calibration scheme should improve our detection rate and thus the efficiency of the survey overall.

While approximately 30% of our BAaDE sample may be expected to be detected in the Gaia DR2 catalog (a full cross-match is currently under way), 96% have cross-matches in the 2MASS survey. Hence we focused on using the 2MASS cross-matches in the VLA campaign. While the Gaia positions would be preferable for VLBI 43 GHz observing, the BAaDE survey is performed in C- and D-configuration at the VLA. With a resulting synthesized beamwidth of 0′′.5−1′′.5, 2MASS positions are sufficiently accurate and there should be little difference in the detection rate using Gaia instead of 2MASS positions. We consequently tested our VLA BAaDE pipeline on a random typical observing run by shifting the sources from the originally observed MSX positions to their corresponding 2MASS positions, and then re-running the pipeline. While the original data reduction reported 208 detections, using the 2MASS positions the number increased to 347, thus a 40% increase in the detection rate (see Fig. 5). All of the originally detected sources were detected with the 2MASS positions, thus the introduced shifts did not shift any sources outside the beam.

5. CONCLUSIONS

By comparing stellar SiO maser positions derived from VLA phase-referencing observations to those listed by the MSX, WISE, 2MASS and Gaia catalogs, we have found that it is always preferred to replace the MSX positions with positions from other catalogs and that Gaia positions most closely match those of the SiO masers (typically within ∼0′′.01). For follow-up work, or new work done by pre-selecting targets using IR colors, the results can be significantly improved by performing cross-matching to either the 2MASS or the Gaia (matched to the 2MASS counterpart) catalogs and using their positional information. The mean offsets between the SiO masers and MSX, WISE, 2MASS and Gaia catalogs are 0′′.89, 0′′.26, 0′′.12 and 0′′.01, respectively. The SiO maser emitting stars considered contain thin CSEs. For objects with thicker shells, and for other work in optically obscured regions, using 2MASS positions should be sufficient. For follow-up VLBI work, additional matching to Gaia positions is clearly pre-
ferred.

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Facilities: VLA, IRSA, WISE, MSX, 2MASS, Gaia

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