Cosmic Masers: Proper Motion toward the Next-Generation Large Projects
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SiO maser line ratios in the BAaDE Survey

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Abstract. Multi-transition SiO maser emission has been detected in over 10 thousand evolved stars across the plane of the Milky Way by the Bulge Asymmetries and Dynamical Evolution (BAaDE) survey. In addition to the large source catalog of the survey, the frequency coverage is also unprecedented: the J=1–0 (43 GHz) data cover seven separate transitions of SiO, and the J=2–1 (86 GHz) data cover ten SiO transitions. In contrast, most other SiO maser data only probe the SiO v=1 and v=2 at 43 GHz and/or the v=1 at 86 GHz. Our extended range allows for the derivation of SiO line ratios for a huge population of evolved stars, including those derived from rare transitions associated with ^{29}SiO and ^{30}SiO isotopologues. We examine how these ratios are affected by the specific combinations of transitions that are detected in a single source. Furthermore, we present a class of 'isotopologue dominated' sources where the ^{29}SiO transitions are the brightest in the 43 GHz spectrum. Finally, using Optical Gravitational Lensing Experiment (OGLE) light curves of our maser stars, changes in line ratios as a function of stellar phase are discussed.

Keywords. SiO masers, asymptotic giant branch stars, stellar variability, circumstellar envelopes

1. Introduction

Prior to observations conducted for the Bulge Asymmetries and Dynamical Evolution (BAaDE) survey about 4,000 stars hosting SiO masers had been identified in the literature, whereas the BAaDE SiO maser survey has so far identified over 9,800 Galactic SiO masers with the VLA, and over 5,000 with ALMA (see Sjouwerman's contribution to these proceedings). Therefore, the BAaDE sample is the largest and most uniform database of SiO masers, making it the most comprehensive set of observations with which to compare SiO maser modeling. Here we present line ratios and relationships between line properties and stellar phase for ∼9,800 BAaDE masers from the VLA portion of the survey. These results can be used to constrain models to study pumping mechanisms, and to tie observed line ratios to properties in the circumstellar envelope (CSE). With an unprecedented number of detected masers sources, many of which lie deep in the Galactic bulge, a major goal of the BAaDE survey is to establish these masers as sign-posts signaling CSE conditions in stars throughout the Galaxy. Radio observations are unique in their ability to probe these sources in the Galactic plane and bulge. For results on the ALMA portion of the survey see Stroh *et al.* (2019); for results of the thermal SiO v=0 transition see Dike *et al.* (2021).

The VLA portion of the BAaDE survey utilizes a spectral setup covering seven separate SiO transitions, six of which are maser transitions. The seventh, the SiO v=0, can be

Table 1. BAaDE detections for individual transitions.

J=1−0 transition	Frequency (GHz)	Number of detections	Percent (entire sample)	Percent (O-rich AGBs)
SiO v=0	43.424	118	0.6%	1.5%
SiO v=1	43.122	9297	51.2%	62.1%
^{29}SiO v=0	42.880	1461	8.0%	15.1%
SiO v=2	42.820	9177	50.5%	61.1%
^{29}SiO v=1	42.584	19	0.1%	0.2%
SiO v=3	42.519	2034	11.2%	17.1%
^{30}SiO v=0	42.373	223	1.2%	2.6%

either a maser or a thermal transition. Table 1 shows the detection rates of each of these transitions in both the full sample and in a slightly smaller sample which has been filtered for C-rich asymptotic giant branch (AGB) stars and other potential contaminating sources.

2. Ratio results

We calculate average line ratios for all pairs of transitions detected in the survey as well as for pairs of lines when a third line is present in the same spectrum; the presence of a third line often shifts the average line ratios, sometimes drastically. These shifts may indicate a change in CSE conditions or the presence of a line overlap, leading to deviations in the level populations associated with the masers. Results regarding a few specific ratios follow.

2.1. *Primary lines (^{28}SiO v=1 and v=2)*

The ^{28}SiO v=1 and v=2 lines are nearly always detected as a pair. Out of 9,727 detected sources 8,660 sources show both lines (89%), 583 are detected in v=1 without v=2, and 462 in v=2 without v=1 in our sample. These primary lines are almost always the brightest in a given source, and as such are nearly always present when any additional lines are detected. One notable exception is when the ^{29}SiO v=0 emission is the brightest (or only) emission in a source (see Lewis *et al.* 2020).

When both lines are detected in a typical O-rich AGB source they have similar flux densities, with the v=2 line measuring typically 93% of the v=1 flux density. The v=1 line being slightly brighter than the v=2 is consistent with other populations of Mira variables (Alcolea, Bujarrabal, & Gomez-Gonzalez 1990; Nyman *et al.* 1993).

2.2. *SiO v=3*

The ^{28}SiO v=3 line is also a maser line but is considerably fainter than the v=1 or 2 lines and is detected in 2,034 sources (11%). As compared to the v=1 line, the v=3 line is about 6 times dimmer. Sources that show the SiO v=1, 2, and 3 lines generally have $log(\frac{F(^{28}SiOv=2)}{F(^{28}SiOv=1)})$ values that are higher than sources that only show the SiO v=1 and the v=2. The fit to the distribution of all sources with v=1 and v=2 lines yields an average value of $log(\frac{F(^{28}SiOv=2)}{F(^{28}SiOv=1)}) = -0.034$ and width of 0.22, while the fit to the distribution of sources also containing the v=3 line gives an average of $log(\frac{F(^{28}SiOv=2)}{F(^{28}SiOv=1)}) = 0.010$ and a width of 0.17.

As it has been shown that the SiO v=1 transition is relatively brighter than the SiO v=2 in Mira variables, and the SiO v=2 is brighter in OH/IR stars, these line ratio trends may indicate that the SiO v=3 may be more common in thicker shells (like those of OH/IR stars).The idea that the SiO v=3 line is formed in denser environments is also

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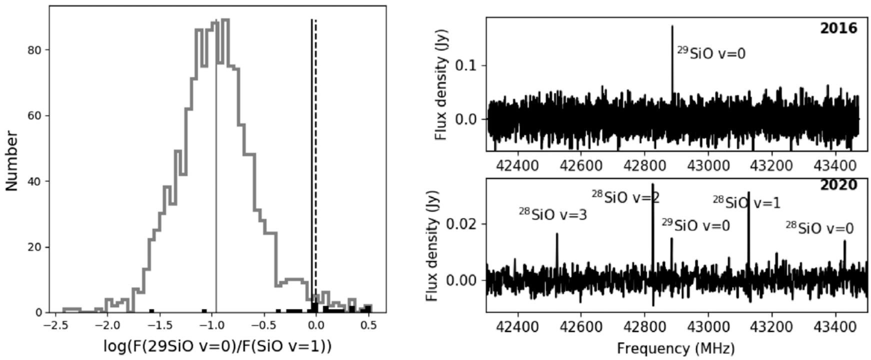

Figure 1. Left: Line ratios between SiO v=1 and ^{29}SiO v=0, showing that this ratio is typically around 10:1. Black histogram bins mark where the ^{29}SiO v=0 line is also detected, demonstrating that the line ratios typical of these detections have much higher ^{29}SiO v=0 flux than average. Right: Two spectra of the same source taken four years apart demonstrating that 43 GHz isotopologue dominated spectra can drastically change ratios to more typical behavior.

supported by the modeling of Desmurs *et al.* (2014), and by observations of its increased detection rate at stellar maximum as will be discussed in Section 3.

2.3. ^{29}*SiO v=0*

The ^{29}SiO v=0 line is a maser line and is detected in 1,475 sources (8%). This line has likely been detected in fewer than 100 sources outside of the BAaDE survey; it is reported as detected in 30 sources by the online maser resource maserdb (Sobolev *et al.* 2019). As compared to the v=1 line it is about 10 times dimmer, but shows a wide spread of ratios and is occasionally brighter than the primary lines.

We find an average of $log(\frac{F(^{28}SiOv=2)}{F(^{28}SiOv=1)}) = -0.067$ and a width of 0.19 when the ^{29}SiO v=0 is present. Therefore, unlike the SiO v=3 line, the ^{29}SiO v=0 line is preferentially found in sources where the $log(\frac{F(^{28}SiOv=2)}{F(^{28}SiOv=1)})$ value is slightly lower than average.

Although ^{29}SiO v=0 and SiO v=3 masers show preferences for sources with different $log(\frac{F(^{28}SiOv=2}{F(^{28}SiOv=1)})$ ratios (^{29}SiO v=0 preferentially occurs when this value is low, while SiO v=3 preferentially occurs when it is high), this tendency is marginal. There is considerable overlap in the primary line ratios which harbor each of these secondary transitions. There are 538 instances of ^{29}SiO v=0, and SiO v=1, 2, 3 all being detected in a single source. In fact, this is the most commonly detected combination of four separate transitions in one source.

2.4. ^{29}*SiO v=1*

The ^{29}SiO v=1 transition has only been reported in four sources prior to the BAaDE survey (Cho & Ukita 1995; Rizzo *et al.* 2021), and is additionally the SiO transition with the lowest detection-rate in the VLA portion of the survey. We find 19 detections (0.1%) of this transition, none of which have been reported before.

This transition is mostly detected in sources where the ^{29}SiO v=0 and/or ^{30}SiO v=0 line is relatively bright compared to the primary lines, and is the only secondary line that does not show the trend of being detected more often in sources with other bright lines. It is on average 55% as bright as the ^{29}SiO v=0, and 35% as bright as the SiO v=1. This line is detected in 1.2% of sources that also show the ^{29}SiO v=0 line and 2.7% of sources that also show the ^{30}SiO v=0, which is a considerable increase over the general 0.1%

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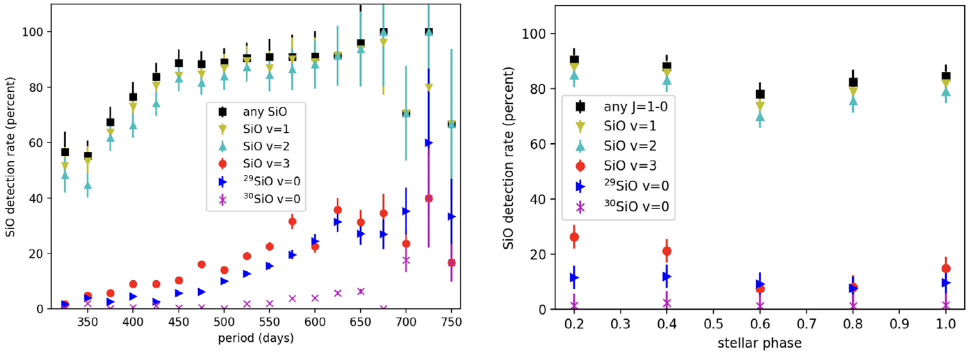

Figure 2. Left: Detection rates of the five most common SiO transitions covered by the BAaDE survey as a function of stellar period. Right: Detection rates of the five most common SiO transitions covered by the BAaDE survey as a function of stellar phase.

detection rate of this line. Sources with the ^{29}SiO v=1 line are also detected in the ^{29}SiO v=0 and ^{30}SiO v=0 lines in 94.7% and 31.6% of sources respectively. This 31.6% may be artificially low and affected by sensitivity as the ^{30}SiO v=0 is roughly half as bright as the ^{29}SiO v=0. In short, a detection of this line marks sources with high relative flux densities and especially high detection rates of the ^{29}SiO v=0 and ^{30}SiO v=0 lines.

2.4.1. Isotopologue dominated spectra

^{29}SiO v=1 detections occur in a small sample of sources where the isotopologue transitions are bright compared to the primary lines (Fig. 1), creating a stark contrast in the average ratios of $log(\frac{F(^{29}SiOv=0)}{F(^{28}SiOv=1)})$ and $log(\frac{F(^{30}SiOv=0)}{F(^{28}SiOv=1)})$ when ^{29}SiO v=1 is present as compared to when it is not. These observational results show that certain sources, perhaps only at certain stellar phases, display isotopologue-dominated spectra where line ratios are very atypical between the ^{28}SiO and other species. These sources were shown to have variable line ratios in (Lewis *et al.* 2020; see Fig. 1). The cause of 43 GHz isotopologue dominated spectra is unknown but is likely related to the maser pumping. Both high $log(\frac{F(^{29}SiOv=0)}{F(^{28}SiOv=1)})$ values and detections of the ^{29}SiO v=1 transition can be used to identify these sources.

3. Line ratios as a function of period and pulsation phase

By cross-matching BAaDE sources with Mira variable sources from OGLE we can also explore these line ratios as functions of period and phase. OGLE has observed 2785 of the BAaDE sources, 2342 of which were detected during the BAaDE survey. The detection rates of all seven SiO transitions are strong functions of stellar period as seen in Fig. 2. The detection rates for the primary lines rise as a function of period up to about 450 days before they flatten out, while the detection rates of the secondary lines continue to rise through 600 days and beyond. The physical explanation for this dependence is the subject of ongoing work.

As OGLE is a long-term monitoring survey with time-coverage overlapping the single-epoch BAaDE observations, we can often reliably check the I-band stellar phase of these cross-matched sources at the time of our maser observations. All detection rates also show a dependence on stellar phase, with maser detection rate being highest near infrared maximum and lowest near minimum (see Fig. 2). The SiO v=3 line shows the strongest dependence on phase, which fits the picture that this line forms in high densities.

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