Astrophysical Masers and their Environments
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SiO maser survey of evolved stars in the Galaxy: various environments of maser sources

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Abstract. Using the SiO J = 1–0 v = 1 and v = 2 lines near 43 GHz, we have detected about 2000 of 3600 sources observed with the Nobeyama 45-m radio telescope. The sources were chosen from IRAS/MSX/2MASS catalogs using color-selection criteria to pick up mass-losing oxygen-rich AGB stars and some post-AGB objects. A number of interesting sources were also found: supergiants in a massive star cluster, a nova with light echo (V838 Mon), AGB stars in globular clusters, and AGB candidates associated with dwarf galaxies. With the exception of the stars in the massive open star cluster, these 'unusual' objects are associated with metal poor environments where mass losing oxygen-rich AGB stars are unexpected. It is inferred that these objects were created by stellar merging which can occur in dense star clusters.

Keywords. Masers, SiO, Evolved stars, Mergers

1. Introduction

SiO maser sources are useful probes of Galactic structure and stellar evolution. Using the Nobeyama 45-m telescope, we have so far observed about 3600 objects and have obtained about 2000 detections of the SiO $J = 1$–0 $v = 1$ or $v = 2$ lines at 43.122 and 42.821 GHz respectively. For a summary of disk objects, see Deguchi *et al.* (2004b). Figure 1 shows a sky distribution of the observed and detected objects in Galactic coordinates. A large concentration of detected sources can be seen at the center, which is the Galactic bulge, while a feature extended to the left is the Galactic disk ($l \lesssim 0°$). The almost vacant part on the right ($-270° \gtrsim l \gtrsim 0°$) is the region of southern sky that we cannot access from Nobeyama. However, we added a few sources observed using SEST and Mopra telescopes (Deguchi *et al.* 1990, 2001), so this is not totally empty. Our surveys are mostly targeted surveys based on infrared catalogs, namely the IRAS catalog. However, the IRAS catalog is not complete in the Galactic center region. An unbiased ('blind') survey of the inner bar region of the Galactic bulge (Fujii *et al.* 2006) was made recently based on the MSX and 2MASS catalog of infrared sources (Egan *et al.* 2003), resulting in ~ 160 detections. Another unbiased survey of the Galactic center area of $24' \times 24'$ was made in 2001–2003, resulting in ~ 200 SiO detections (Deguchi *et al.* 2004a). Our surveys in the Galactic center and disk are summarized in Table 1. The survey depths and color selection criteria are not uniform among these surveys. From our experience, we have found that about 1/3 of SiO detections have corresponding OH 1612 MHz objects while the other 2/3 of SiO sources have no OH detections (Deguchi *et al.* 2004a; Sevenster

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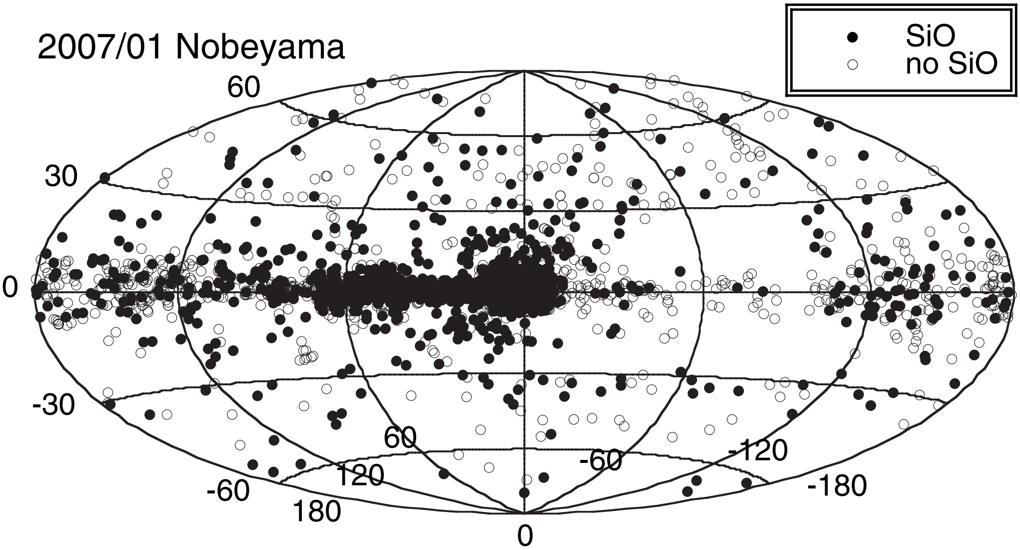

Figure 1. Distribution of observed objects in the Galactic coordinates in the Hammer-Aitoff projection. The filled and open circles indicate SiO detections and non-detections.

Table 1. Recent SiO maser surveys in the Galactic center and disk

name	area	survey mode	detections	paper
N. Gal. Cap	$b > 30°$	targeted	24	Ita *et al.* (2001)
G.C.	$7' \times 13'$	unbiased	9	Miyazaki *et al.* (2001)
G.C.	$200'' \times 100''$	unbiased	15	Deguchi *et al.* (2002)
disk	$40 < l < 70°$	targeted	134	Nakashima *et al.* (2003)
LAV G.C.	$24' \times 24'$	targeted	196	Deguchi *et al.* (2004a)
Inner disk	$-10 < l < 40°$	targeted	254	Deguchi *et al.* (2004b)
Inner bar	$7° \times 2°$	targeted	163	Fujii *et al.* (2006)
Off-plane	$\|b\| > 3°$	targeted	119	Deguchi *et al.* (2007a)

et al. 1997). This is the main reason that we do extensive SiO maser surveys in various parts of the Galaxy.

2. Observations and color selection criteria of objects

The 45-m millimeter-wave telescope at Nobeyama operates at frequencies between 22 and 115 GHz. The beam size of the telescope is about $40''$ at 43 GHz. We use a HEMT receiver at 43 GHz with a bandwidth of 2 GHz, and system temperature of about 200 K. We can observe simultaneously four lines of SiO $J = 1$–0 from $v = 0$ to $v = 3$, and the ground rotational line of ^{29}SiO. However, for distant objects, we usually detect only the two strongest lines in the first and second vibrationally excited lines. Therefore, this paper discuss only the SiO $J = 1$–0 $v = 1$ and $v = 2$ lines. Our recent observations are summarized in Table 1.

2.1. *Color selection criteria from MSX catalog and 2MASS*

Van der Veen & Habing (1988) classified IRAS point sources by the IRAS two-color diagram; mass-losing AGB stars fall into type IIIa and IIIb regions, and post-AGB stars fall into type VIb for which SiO masers are unlikely. After 2000, we shifted to using the

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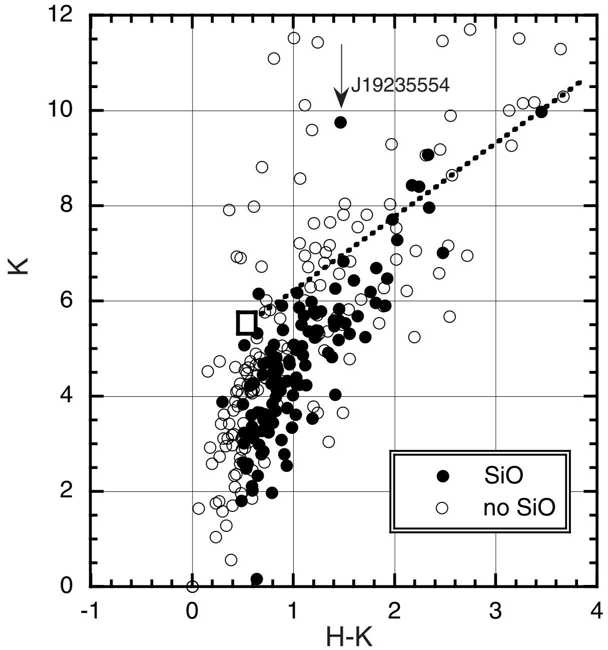

Figure 2. Plot of 2MASS $H-K$ against K for an off-Galactic-plane sample Deguchi *et al.* (2007). Filled and unfilled circles indicate SiO detections and no detections. The square indicates M5III without reddening at a distance of 8 kpc. Interstellar and circumstellar extinctions move the position of the star along the dotted line.

MSX and 2MASS catalogs. The MSX color criteria are similar to the IRAS selection criteria [$-0.4 < log(F_E/F_C) < 0.4$, where F_C and F_E are MSX 12 and 21 μm flux densities, respectively]. In addition, we check the 2MASS images and find a near-infrared counterpart for the selected MSX source and require the counterpart to have a color index $H-K > 0.8$. Figure 2 shows the diagram of the NIR color index $H-K$ against K magnitude. A typical M5 giant at a distance of 8 kpc occupies the position indicated by the square, and both interstellar and circumstellar reddening move the position of the M5 star along the line with inclination of about 1.5. Therefore, if we correct the interstellar and circumstellar extinction by a formula, $m_K = K-[A_K/E(H-K)]\times(H-K-[H-K]_0)$ (Nishiyama *et al.* 2006; $[A_K/E(H-K)] \sim 1.5$ and $[H-K]_0 \sim 0.5$), we can use the corrected K magnitude (m_K) as a distance measure (Fujii *et al.* 2006). If an object is located lower than this line corresponding to a constant distance, it is a nearby foreground object; if it is located higher than that line, it is very distant object or non-AGB star, probably a young stellar object. In this way we can select oxygen-rich mass-losing AGB stars quite effectively. With these selection criteria, we get an average SiO detection rate of about 60 %.

3. Various environments of maser sources

Here we will describe individually interesting sources in various environments in the Galaxy, that were found in the SiO surveys.

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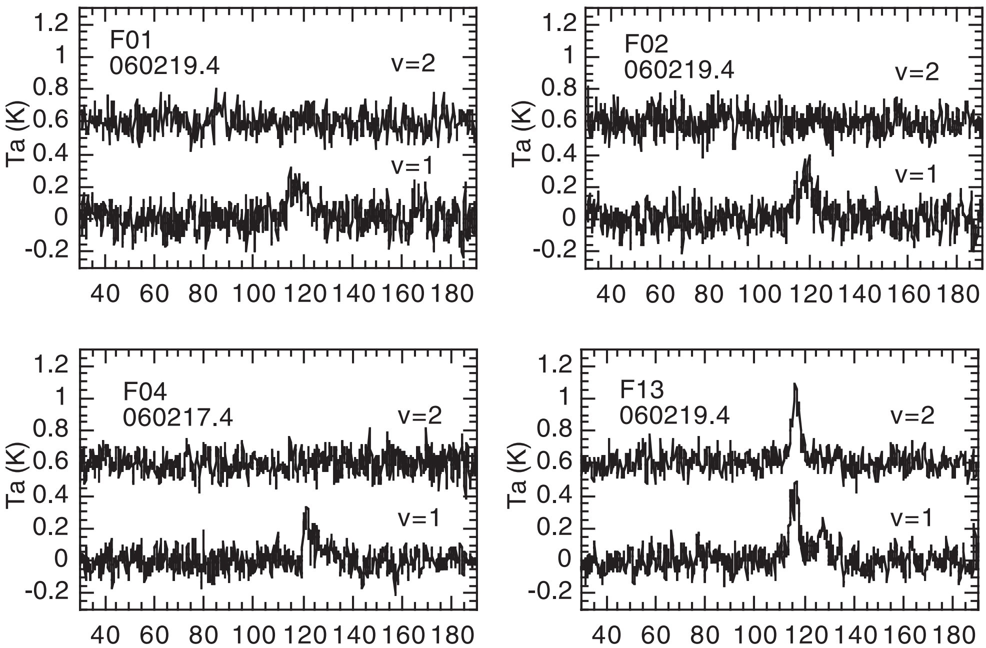

Figure 3. SiO $J = 1\text{–}0$ $v = 1$ and 2 spectra toward M supergiants in the Scutum young massive star cluster.

3.1. *Scutum young massive star cluster*

The young open star clusters often contain several M-supergiants. Measuring equivalent widths of the CO first-overtone bands at 2.3 μm, Figer *et al.* (2006) identified 14 M-supergiants in the open cluster called # 122 in Bica's infrared cluster catalog (Bica *et al.* 2003). Assuming the Saltpeter's initial mass function, they found that, if the total mass of the cluster is about 3×10^4 $M_\odot$ and the age approximately 10^7 years, such a young massive star cluster can contain as many as 14 M-supergiants. Some of these supergiants are IRAS or MSX objects. So we observed all of these M-supergiants with our telescope, and in addition a few more objects nearby. We detected SiO masers in five of these, but one, we call X18, turned out to be non-member from its radial velocity (Nakashima & Deguchi 2006). The radial velocities of the other four objects are about $120\,\mathrm{km\,s^{-1}}$ (see Fig. 2). We also detected the 22.235 GHz water maser line in one object.

What can we obtain from these observations? First, the radial velocity of the star cluster is $118.1 \pm 2.8\,\mathrm{km\,s^{-1}}$. Previously one OH 1612 MHz maser was detected at $102\,\mathrm{km\,s^{-1}}$ (Blommaert *et al.* 1994), but this was emission from a single OH peak so that the true radial velocity of the star was uncertain. The radial velocity we obtained gives the kinematic distance of 6.5 kpc, suggesting that this cluster is located at a tip of the Scutum-Crux spiral arm beyond the bulge bar. Second, we calculated the velocity dispersion from this limited data. Assuming an intrinsic velocity dispersion of $2\,\mathrm{km\,s^{-1}}$ in the SiO measurements, the true velocity dispersion of this cluster is inferred to be $2 - 2.5\,\mathrm{km\,s^{-1}}$ (Jiang *et al.* 1996). From this dispersion and a radius of 1 arc minute of the cluster size, we obtain a virial mass of about 10^4 $M_\odot$ for the cluster showing that it has a large mass. SiO observation are clearly useful for obtaining the physical parameters of massive stars in star clusters.

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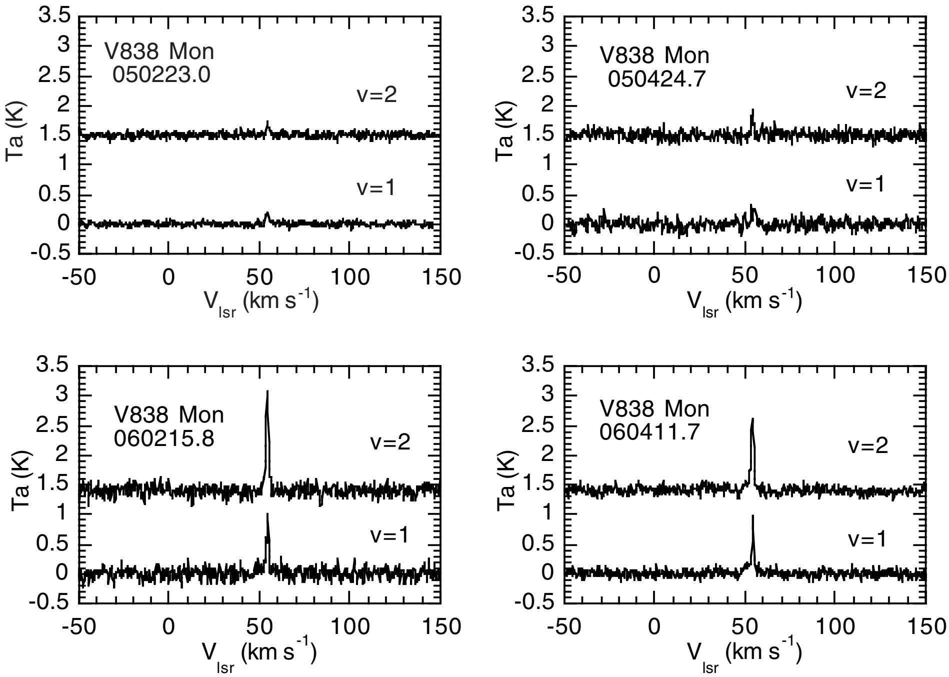

Figure 4. Intensity variation of the SiO $J = 1$–0 $v = 1$ and 2 toward V838 Mon. Dates of observations are 2005 Feb. 22, 2005 April 24, 2006 Feb. 15, and 2006 April 11.

3.2. *V838 Mon*

The second example is V838 Monocerotis. This nova appeared in January 2002 and a light echo was observed a month and a half later. A movie showing the expansion of the light echoes was created from HST images by Bond *et al.* 2003. In this picture we can see a red central star. In fact, spectroscopic observations revealed that the central star left after the nova eruption was an M supergiant (Munari *et al.* 2002). We detected SiO masers in this star three years after the eruption (Deguchi *et al.* 2005), in February 2005. The SiO maser intensities became stronger by 50% two months later. A half year later, we found that SiO maser intensity was about five times stronger (see Fig. 3). However, we could not detect any other transitions of SiO, including the 86 GHz transition apart from the $J = 1$–0 $v = 1$ and 2 lines. Monitoring observations of SiO emission from this star have been made by Mark Claussen using VLA and VLBA. Soker & Tylenda (2003) proposed that the central star, an M-supergiant, was created by a merging binary with 7 and 0.5 $M_{\odot}$ main-sequence objects. This star turned out to be in a star cluster, because the surrounding blue stars are all B stars located nearly at the same distance of 6–7 kpc (Afsar & Bond 2007). Such an environment probably helps binary merging to occur easily (Lombardi *et al.* 2003). Such binary merging can create AGB-like stars (similar to a pre-main sequence star going down along the Hayashi track; Tylenda & Soker 2006). A very rough estimation of the birth rate and life time of this kind of phenomena indicates that a few percent of OH/IR stars originated from binary merging (Deguchi *et al.* 2005).

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3.3. *SiO maser sources in globular clusters*

The third example is a globular cluster. Low-mass stars usually evolve into carbon-rich stars in the AGB phase (Iben 1981). Therefore, SiO masers were not expected to occur in old globular clusters. In fact, globular clusters are generally not associated with IRAS sources. One day, Noriyuki Matsunaga, a student of University of Tokyo, came to my place and wished to search for SiO masers in Miras in globular clusters. One of the candidates is in the famous bulge cluster Terzan 5. which is an MSX source with a flux density of a few Jy at 12 μm. We detected SiO masers in this star as well as three objects in other globular clusters (Matsunaga *et al.* 2005). The observed radial velocities coincide with optically measured average radial velocities of these globular clusters to within about 30 km s^{-1}. We found that the optical radial velocities of these globular clusters are quite inaccurate, because the average radial velocities of these clusters are determined by observing only a few cluster-member stars. A big question is how are oxygen-rich AGB stars created in such old clusters? They are similarly bright objects to the disk or bulge AGB stars in terms of K-magnitude and IRAS flux densities. Therefore, their masses can be more than 1 $M_\odot$, which should not be found in these old globulars. One explanation is a binary merger hypothesis. In globular clusters, there are a number of blue stragglers which are luminous and are considered to have masses of more than 1 $M_\odot$ (Piotto *et al.* 2004). These stars have been created by binary merging due to three-body encounters in globulars. After a while, they can evolve into AGB stars, or as in V838 Mon, merging can directly make M-giants.

3.4. *SiO maser sources in dwarf galaxies or their tidal tails*

We spent a considerable time searching for very distant SiO maser sources. So far the most distant SiO maser source ever detected is an OH/IR star in the Large Magellanic cloud (van Loon *et al.* 1996). One of the most nearby galaxies accessible from Northern hemisphere is the Sgr dwarf elliptical galaxy (Ibata *et al.* 1994), also called SagDEG. The distance to this galaxy is about 24 kpc from the Sun. Another one is the Canis Majoris dwarf galaxy (Martin *et al.* 2005), or it is sometimes called Monoceros over-density (Martin *et al.* 2004a). The center of SagDEG is located south of the Galactic bulge. The orbital plane of this galaxy is almost perpendicular to the Galactic plane (Ibata *et al.* 2001b), and a number of globular clusters, tidal debris, M-giants and carbon stars (Ibata *et al.* 2001ab), have been observed along the tidal stream (Majewski *et al.* 2003, 2004). We used the 45-m telescope to search for SiO masers in candidate stars along the tidal tails. Because of its distance, the candidate stars are expected to be quite faint in the near- and middle-infrared. A problem is that there are many contaminating foreground objects. Radial velocities can be used to judge the association with these dwarf galaxies. Figure 5 shows SiO maser spectra of our probable candidates for associations with SagDEG and CMa dwarf. The radial velocity of 110 km s^{-1} in the right-panel spectrum fits well with the optically measured average velocity of M giants of CMa dwarf (Martin *et al.* 2005). Also this is a faint object with the IRAS 12 micron flux density of 2 Jy and 2MASS K magnitude of 6.2. A luminosity distance of about 7 kpc coincides well with the estimated distance of CMa dwarf. The left panel shows the SagDEG candidate. This is a very faint object of 1 Jy at 12 μm, and has an estimated luminosity distance (from 2MASS $K = 9.7$) of about 20 kpc from the Sun, far beyond the Galactic bulge. The radial velocity of this object is slightly different with the velocity of SagDEG. However, SagDEG has several tidal streams with different velocities, so that, we think that it is associated with one of SagDEG tidal streams. A question here is why such oxygen-rich AGB stars are associated with these dwarf galaxies of old population. One explanation is that it is a binary merger product.

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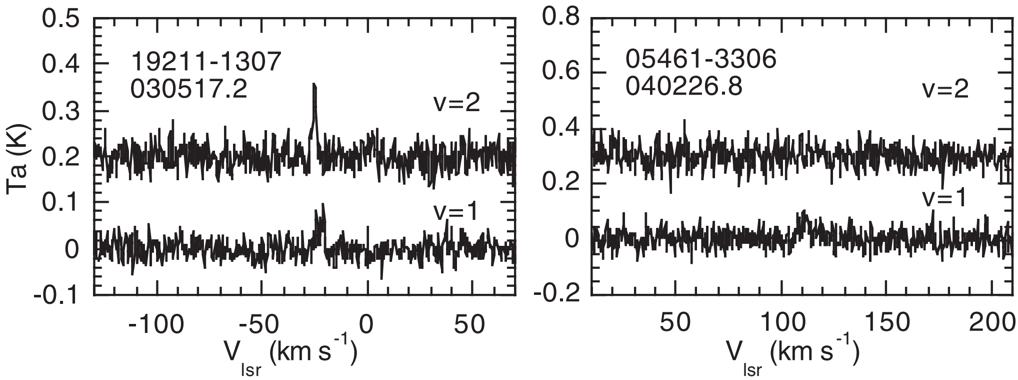

Figure 5. SiO $J = 1$–0 $v = 1$ and 2 spectra toward candidates associated with dwarf galaxies.

4. Conclusions

SiO masers turned out to be a powerful probe of Galactic structure as well as a probe of stellar evolution. V838 Monocerotis, which emits SiO masers, is an example of stellar mergers. SiO maser phenomena can be a tool to investigate massive open star clusters and globular clusters and the tidal tails of dwarf galaxies. The SiO maser surveys demonstrate that SiO maser sources can exist in metal-rich environments in the Galaxy as well as in the metal-poor environments of old populations such as globular clusters. For such old populations, they are possibly binary merger products or their progeny.

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Discussion

Goss: Pulsers have been found in Terzan 5. Do these pulsers influence the SiO maser sources?

Deguchi: More than 20 pulsers were found in this globular cluster. Among them, several millisecond pulsers were found and they are known as close-binary systems. Close binaries are considered easily merged in a dense stellar system. Stellar merging can make blue strugglers, which finally evolved into mass-losing oxygen-rich AGB stars with masers.

Rodriguez: The radial velocity of the extra object ($V_{lsr} = 84\,\mathrm{km\,s^{-1}}$) is not far from the average velocity of the Scutum star cluster. Is it still not a member of the cluster ?

Deguchi: No, a separation of $40\,\mathrm{km\,s^{-1}}$ is too large for this object to be a member of the cluster. The velocity dispersion of the cluster is just a few $\mathrm{km\,s^{-1}}$. It is just a foreground object.

Menten: Concerning V838 Mon, were any other molecules detected?

Deguchi: No, part from two vibrationally excited SiO J = 1-0 transitions, nothing has been detected towards this star. Mark Claussen has been monitoring the SiO maser intensities of these transitions. It is a pity that he could not come to this conference.

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