Relation of SiO maser emission to IR radiation in evolved stars based on the MSX observation

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ABSTRACT

Based on the space MSX observation in bands A(8\,\mu m), C(12\,\mu m), D(15\,\mu m) and E(21\,\mu m), and the ground SiO maser observation of evolved stars by the Nobeyama 45-m telescope in the v=1 and v=2 J=1-0 transitions, the relation between SiO maser emission and mid-IR continuum radiation is analyzed. The relation between SiO maser emission and the IR radiation in the MSX bands A, C, D and E is all clearly correlated. The SiO maser emission can be explained by a radiative pumping mechanism according to its correlation with infrared radiation in the MSX band A.

Subject headings: infrared: stars — masers — stars: late-type

1. Introduction

The relation between SiO maser emission and IR radiation was predicted by the radiative pumping model for the SiO maser by Deguchi & Iguchi (1976) in which SiO maser is pumped by the $\Delta v = 1$ vibrational transition at 8\,\mu m. Bujarrabal & Rieu (1981) analyzed a radiative pumping model in which the SiO molecules are located in the inner circumstellar envelope and proposed that the inversion is achieved by a direct population transfer from the $v-1$ state via the absorption of stellar 8\,\mu m photons. This is followed by an optically thick radiative decay back to $v-1$. Their calculation predict that the SiO maser peak intensity be smaller than the 8\,\mu m flux.

Bujarrabal & Rieu (1981) were also the first to look at whether there exists a relation between the SiO maser emission and stellar IR radiation. Their analysis of data from about 20 objects showed that the observations satisfy the requirement to pump SiO maser radiatively, i.e. they lie below the line $S_{\text{peak(SiO)}} \leq S(8 \mu m)$ (Bujarrabal & Rieu 1981). Bujarrabal
et al. (1987) assembled observational data of more evolved stars and analyzed the relation between SiO maser emission and radiation in some mid-infrared bands and found a good correlation exists between them. However, analysis of the integrated intensity of the bulge SiO maser sources resulted in large scattering between the SiO maser integrated intensity and the infrared fluxes at the IRAS bands 12, 25 and 60µm (Jiang et al. 1995).

The progress in infrared space astronomy and SiO maser surveys makes it possible now to revisit the relation between SiO maser and mid-infrared emission. The Midcourse Space Experiment (MSX) mission surveyed the entire Galactic plane within |b| ≤ 4.5° in five infrared bands B, A, C, D, and E, at 4, 8, 12, 15 and 21µm respectively (Price et al. 2001). In addition to its 30 times better spatial resolution than IRAS, the most sensitive band A of MSX is centered at 8µm where the proposed infrared radiation pumps the SiO J=1-0 maser. Furthermore, large scale searches for SiO maser emission from evolved stars in different parts of the Galactic plane have been carried out in the J=1-0 rotational transition at the first and second vibrationally excited states by the Nobeyama 45-m telescope (Ita et al. 2001). This effort detected a large number of faint SiO maser objects with F_{12} \sim 1Jy (where F_{\lambda} means the flux intensity in Jy at band \lambda and \lambda refers to the IRAS band 12µm, 25µm, MSX band A, B, C, D, E).

2. Data

All the SiO maser data in present study are based on the observation by using the Nobeyama 45-m telescope. The combination of a large antenna and sensitive detector at 43GHz in this system made it feasible to detect an SiO maser emission of the J=1-0 rotational transition as weak as 0.2 K. Since 1992 (Nakada et al. 1993), this system has been used to observe thousand of the IRAS PSC sources that are candidates for evolved stars defined by their IRAS colors, and has detected about 500 new SiO maser objects during the surveys of the bulge (Izumiura et al. 1994, 1995a,b), the inner disk (Izumiura et al. 1999; Deguchi et al. 2000a,b), the outer disk (Jiang et al. 1996, 1999), and the northern pole (Ita et al. 2001).

The SiO maser data in this study is compiled from Izumiura et al. (1994, 1995a,b, 1999); Deguchi et al. (2000a); Jiang et al. (1996, 1999), which mostly consists of sources in the Galactic plane. These studies achieved approximately the same detection limit, with sensitivity of about 0.15 K at a 5σ level that varies slightly depending on the system condition, weather etc. To guarantee the quality of the data, tentative detections listed in these papers were rejected and the final sample of SiO maser stars consists of 443 objects. Maser emission at both v=1 and v=2 J=1-0 transitions were detected in 421 of these stars while there are 11 stars in which the SiO maser emission is detected at only the v=1 J=1-0 transition and
another 11 stars at only ν=2 J=1-0 transition. The antenna efficiency is taken to be 50%, which results in a conversion factor \( \sim 3.6 Jy/K \) from antenna temperature to SiO maser flux intensity.

The infrared data are taken from the initial MSX Infrared Point Source (Version 1.2) Catalog (Egan et al. 1999). This catalog provides photometric measurements in five infrared spectral bands to many SiO maser stars, in particular most of the maser stars in the Galactic plane. It was released in 1999 and is available through IPAC at http://www.ipac.caltech.edu/ipac/msx/msx.html. This catalog contains infrared observations on more than 300,000 sources, and lists the flux density at the MSX bands with the quality index, variability index etc. The MSX PSC1.2 appears to be complete above 0.2 Jy and about 50% complete at a flux of about 0.17 Jy, in the most sensitive band A in the inner Galactic plane (Egan et al. 1999). Details on the MSX survey are referred to Egan et al. (1999).

The SiO maser stars are cross-associated with the MSX PSC1.2 sources by position coincidence. The position of SiO maser stars is adopted from IRAS PSC since the HPBW of the 45-m telescope at 43GHz is about 40", much bigger than a typical IRAS PSC error ellipse of about 10×20" in radius. The position of the MSX PSC1.2 is more accurate than the IRAS PSC. The MSX position uncertainty is on the order of 2.0" in both the in-scan and cross-scan directions and the typical rms position error cited in the MSX PSC1.2 is about 2-4". The radius to search for the MSX counterparts of the SiO maser stars is set to be 30" and the same for all the SiO maser stars for simplicity.

Within the search radius of 30", 310 of the 443 SiO maser stars are cross-associated and 133 are not cross-associated with the MSX PSC sources. The distribution of these two groups of objects in the Galaxy depends strongly on the Galactic latitude. The associated stars are located at \(|b| < 6^\circ\). The non-associated stars mostly are located at \(|b| > 4.5^\circ\), i.e. 131 of the 133 non-associated stars have \(|b| > 4.5^\circ\) and only 2 objects with \(|b| < 4.5^\circ\) where the MSX survey fully covered (see Fig.1). The two non-associations with \(|b| < 4.5^\circ\) are actually bright with the flux density at IRAS 12\(\mu\)m band larger than 4 Jy and their IRAS PSC position should be relatively accurate. In order to know whether they were detected by MSX, a further check of the co-added MSX images was made and showed that they were actually detected by MSX clearly in all the A, C, D and E bands but missed in the catalog. Among the 310 associated SiO maser stars, 4 objects are found to have 2 counterparts each within the search radius. The counterpart whose flux intensity in the MSX C band is close to that at the IRAS 12\(\mu\)m is regarded to be the right one because these two bands are quite analogous. The other 306 stars have unique counterpart within this search radius. There are five SiO maser stars whose photometric results in band C are unavailable in the MSX PSC catalog possibly because of the faintness since their F\(_{12} < 3.0 \text{Jy}\). The co-added MSX
images neither show clear evidence of detection. The photometric results in the MSX band A which is the key band for this study are available in the MSX PSC1.2 catalog for all the associated objects except IRAS 03469+5833. Since the counterpart of IRAS 03469+5833 is bright in the MSX C band with $F_C = 5.5$ Jy close to its IRAS 12$\mu$m intensity $F_{12} = 7.3$Jy which also proves the right association, the detection in band A is expected. Indeed, the object is clearly detected in the MSX image in band A. The missing of bright sources in the MSX PSC V1.2 may be ascribed to the incompleteness of the catalog. Further discussion is confined to the objects that are actually in the MSX PSC1.2.

The cross-associated sample consists of 310 stars, from which 288 are detected with SiO maser emission at both the $v=1$ and $v=2$ $J=1-0$ transitions, 11 detected at only $v=1$ $J=1-0$ transition and 11 at only $v=2$ $J=1-0$ transition, and from which 309 stars are measured in the MSX A band, 305 measured in the MSX C band. There are 298 $v=1$ $J=1-0$ SiO maser stars with association in the MSX A band and 298 $v=2$ $J=1-0$ SiO maser stars with association in the MSX A band.

Most of the sources are variables by comparing their flux intensity in the MSX C band $F_C$ with that at the IRAS 12$\mu$m $F_{12}$. Though the MSX C band is not identical to the IRAS 12$\mu$m band, it is designed to be a narrower analog of the IRAS 12$\mu$m filter and its effective wavelength is just 12.13$\mu$m (Price et al. 2001). Based on the MSX photometric accuracy, the flux differences greater than 10% is indicative of variability rather than photometric error (Cohen et al. 2000). The relative differences of $F_C$ to $F_{12}$ mostly are greater than 10% (Fig. 2), which means the differences between the MSX and IRAS observations are intrinsically from the objects. Further supports to the sources being variable come from the independent redundant observations by MSX and IRAS to some of the objects. Jiang et al. (1995) checked the IRAS variability indexes of the SiO maser stars in the Galactic bulge by then and found about two-thirds with the indexes greater than 90. In the MSX PSC1.2 catalog, 167 of the 310 associated stars have the variability indexes being 1 in at least one band which means the variation over $3\sigma$ (Egan et al. 1999). Most, if not all, the sources are variables. The upper limit of $(F_C - F_{12})/F_{12}$ is about 1.5 and this further implies that the amplitude of variation at this band is not very large. The property of variation is consistent with the SiO maser stars being mostly variable late-type stars (Jiang et al. 1995).

### 3. Relation to infrared radiation

First of all, the relation of SiO maser peak intensity to the infrared radiation in the MSX A band is discussed. Shown in Fig. 3 are the 298 SiO maser stars that are detected the emission at the $v=1$ $J=1-0$ transition and the radiation in the MSX A band. The
SiO maser intensity ranges from about 0.1Jy to 100Jy, covering four orders of magnitude. The linear correlation coefficient between \( F_{\text{SiO1}} \) (where \( F_{\text{SiO1(2)}} \) means the SiO maser peak intensity at the \( v=1 \) (2) \( J=1-0 \) transition) and \( F_A \) is 0.44, which means they are clearly correlated from the statistical point of view. A linear fitting relation is drawn by the so-called ordinary least square (OLS) regression bisector method (Isobe & Feigelson 1990), \[ \log F_{\text{SiO1}} = -0.63(\pm 0.04) + 0.94(\pm 0.05) \times \log F_A. \] The SiO maser peak intensity increases proportionally to the infrared radiation. In addition, the SiO maser intensity is systematically smaller than the infrared radiation at 8\( \mu \)m, as can also be seen from Fig.3 where the equal line is solid, above the fitting dash line. Bujarrabal & Rieu (1981) calculated the requirement for radiative pumping to work is \( F_{\text{SiO}} \leq F_{8\mu}. \) The relation between the SiO maser intensity and the MSX A band flux supports the radiative pumping model to explain the maser occurrence of the SiO \( v=1 \) \( J=1-0 \) transition. Although there are several sources above the equal line in Fig.3, the reason is possibly the variability of the sources because the MSX observation didn’t take place at the same phase of the variation as the SiO maser observation. The variation of the objects and the different phases of the SiO maser and MSX observations can also explain the scattering of sources around the linear fitting line.

A similar relation holds for the SiO maser peak intensity at the \( v=2 \) \( J=1-0 \) transition (Fig.4). The linear correlation coefficient between the maser intensity at this \( v=2 \) line \( F_{\text{SiO2}} \) and \( F_A \) is 0.62, which again means a clearly correlated relation. The OLS bisector linear regression method draws \[ \log F_{\text{SiO2}} = -0.59(\pm 0.03) + 0.93(\pm 0.04) \times \log F_A. \]

In order to see if the relation remains the same in the disk and in the bulge, the sources with \(|l|<15^\circ\) which are supposed to be in the bulge are denoted by small dots and the sources with \(|l|>15^\circ\) which are supposed be in the disk are denoted by open circles in Fig.3. No apparent difference is found in the relation of the maser intensity to the infrared flux intensity in the MSX A band between these two groups of sources.

The relation of SiO maser intensity to the infrared radiation in other MSX bands are examined except in the MSX band B. The MSX survey had lower sensitivity in band B around 4\( \mu \)m (Egan et al. 1999) which led to the failure of detection to most of the SiO maser stars in this band. In bands C, D and E, the relations between the SiO maser emission and infrared radiation are all clearly correlated without exception. The correlation coefficients of the SiO maser peak intensity at the \( v=1 \) \( J=1-0 \) transition with the radiation intensity in the MSX C, D and E bands are 0.44, 0.41 and 0.33 respectively, and the corresponding coefficients at the \( v=2 \) line are 0.66, 0.64 and 0.56. All these correlation coefficients indicate tight correlation from the statistical point of view. The fact that the SiO maser intensity is correlated with the radiation in any of the middle infrared MSX bands can be expected if the radiation at these bands all comes from the stellar continuum radiation other than line emission. It seems no
significant difference between the relation to the intensity in the MSX A band and in other bands C, D, E. This may mean that there is no necessity for the radiation through $\Delta \nu = 1$ transition at 8$\mu$m to be the pumping source of the maser emission. As noted by Bujarrabal et al. (1987), the general correlation of the SiO maser intensity with the mid-infrared radiation may indicate the SiO maser is related to the amount of circumstellar matter in the evolved stars. Another phenomenon in the relations is that the v=2 J=1-0 maser intensity generally exhibits tighter correlation with smaller scattering with the infrared radiation than the v=1 maser intensity and no model ever predicted so. Whether this difference is true requires further investigations such as simultaneous maser and infrared observations.

4. Summary

Based on new database in the mid-infrared provided by the MSX space survey, the relations between the SiO maser peak intensity and mid-infrared radiation in four MSX bands are analyzed. It is found that the SiO maser intensity is correlated with mid-infrared radiation, which confirms the conclusions from previous studies. The result is consistent with the radiative pumping model for the SiO maser emission in evolved stars.

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Fig. 1.— Distribution along the Galactic latitude of the SiO stars with (full line) and without (dash line) MSX association.
Fig. 2.— Relative difference of flux intensity in the MSX C band to the IRAS 12\(\mu\)m band.
Fig. 3.— Relation of the v=1 J=1-0 SiO maser peak intensity with the MSX A band flux is highly correlated. Dash line shows the linear fitting result between log $F_{\text{SiO1}}$ and log $F_A$ by ordinary least-squares (OLS) bisector method and the solid line borders the equal line. The objects with $|l| < 15^\circ$ and $|l| > 15^\circ$ are separated by signs small dot and open circle respectively.
Fig. 4.— Relation of the v=2 J=1-0 SiO maser peak intensity with the MSX A band flux is correlated as well as the v=1 J=1-0 maser. Convention of symbols is the same as in Fig.3.