Chin. J. Astron. Astrophys. Vol. 1, No. 2, (2001) 144–151
(*http://www.chjaa.org* or *http://chjaa.bao.ac.cn*)

Chinese Journal of
Astronomy and
Astrophysics

Distribution of SiO and OH Maser Stars in the Galactic Plane

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Received 2000 November 30; accepted 2001 January 28

Abstract The observational results of the Nobeyama 45-m SiO maser survey and the Arecibo 305-m OH maser survey are assembled for an analysis of the distribution and kinematics of late-type stars in the Galactic plane. It is found that neither SiO maser stars nor OH maser stars show any concentration to the spiral arms, which imply that they do not belong to the arm population and quite possibly they are low-mass stars in late stage of evolution. A rotational curve is also derived for these objects and a few features which may be real are discussed and compared with those derived from planetary nebulae and AGB stars.

Key words: stars: late-type – maser – Galactic distribution – kinematics

1 INTRODUCTION

Circumstellar SiO and OH masers are popularly detected in oxygen-rich late-type stars. Since the discovery of SiO masers (Snyder & Buhl 1974), more than 600 emissions have been detected in late-type stars. Mira variables, semi-regular variables, symbiotic stars and OH/IR stars are all emitters of SiO maser. Large-scale detections of SiO maser emission started after the IRAS mission by which a large number of late-type stars with circumstellar envelopes were found. Circumstellar OH 1612 MHz maser was first found in near-IR sources (Wilson & Barret 1968) and many more were found in Mira and IRC sources. With the advent of the IRAS PSC catalog, many new OH/IR stars are easily identified by the far-IR radiation from their dusty circumstellar shells so that a number of new OH maser stars are found.

The velocity of SiO and OH maser lines is the indicator of the radial velocity of their emitters. Usually SiO maser lines are multi-peaked and limited to a small range of velocity (usually smaller than 10 km s^{-1}), its center velocity coincides with the stellar radial velocity from comparisons with the optical spectroscopic observation. The difference between the velocity of SiO maser emission and the radial velocity from the Doppler shift of the spectral lines of their optical spectrum is less than a few km s^{-1} (Jewell et al. 1991). This coincidence is explained by the radiative transfer model for SiO maser pumping, according to which the SiO maser emission is amplified mostly in the tangential direction so that the expansion velocity of the

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circumstellar envelope has no effect. OH maser is usually double-peaked and the mean velocity of the two peaks is also the stellar radial velocity. According to the mechanism of OH maser pumping, the two peaks come, one from the receding, and one from the approaching side of the shell and they are shifted one to the blue and one to the red side of the stellar velocity, and their average cancels out the effect of circumstellar expansion. In addition, the SiO and OH maser emission is strong in comparison with thermal emission and much more transparent due to their radiation in the radio rather than in the optical. Therefore, SiO and OH maser stars are excellent probes of the Galactic distribution of late-type stars and useful tools for studying their Galactic kinematics.

2 DATA

As noted above, there have been some observations in SiO and OH maser lines towards late-type stars. But most of these observations are done with small antennas, which have two disadvantages for a systematic study of the Galactic distribution and kinematics of late-type stars. One is the relatively low sensitivity that results in the non-detection of relatively weak maser sources. The other is the heterogeneity of the observing systems, which makes it difficult to treat all the results equally. Therefore, we selected one systematic survey each of SiO and OH masers for our data in order to get a unified scenario of the distribution and kinematics of the late-type stars.

The SiO maser data we adopted is the result obtained by the 45-m telescope at Nobeyama Radio Observatory. The antenna started searching for the SiO $J = 1 - 0$ rotational transition lines at vibrational states $v = 1$ and $v = 2$ from color-selected IRAS PSC objects in 1993. This is a very sensitive system in millimetre wave: a 1 Jy-strong source at the corresponding frequency of 43 GHz, can be detected as a 5 sigma signal with a velocity resolution of about 1 km s^{-1} and a band width of 250 MHz. At the same time, the SiO $J = 1 - 0$, $v = 1$ and $v = 2$ transitions are the most popular emission among all the detected SiO rotational transitions. The joint effect is that more than 400 SiO maser stars at 43 GHz were detected for the first time with the 45-m telescope system.

The OH 1612 MHz maser data are taken from the observation by the 305-m telescope at Arecibo Observatory. Thanks to the large collecting area of this huge antenna, the sensitivity of the Arecibo telescope system at 18 cm is high enough to detect a 25 mJy source at 3 sigma level with a velocity resolution of about 1 km s^{-1}, on the same order as the resolution of the Nobeyama 45-m telescope. A limitation of the system is the small observable sky coverage because it is fixed. The search for OH 1612 MHz maser emission from late-type stars started in 1985 and continued to 1993. About 1400 IRAS PSC sources with $F_{25} > 2$ Jy were observed and the OH 1612 MHz maser emissions were detected from 385 of them.

Our SiO maser data were taken from Izumiura et al. (Izumiura, Deguchi, Nakada et al. 1994; Izumiura, Catchpole, Deguchi et al. 1995; Izumiura, Deguchi, Hashimoto et al. 1995; Izumiura, Deguchi, Fujii et al. 1999; Deguchi, Fujii, Izumiura et al. 2000), and Jiang et al. (Jiang, Deguchi & Yamamura 1996; Jiang, Deguchi & Ramesh 1999). We tried to guarantee the quality of the data by discarding several tentative detections (e.g., in Izumiura, Deguchi, Nakada et al. 1994; Izumiura, Catchpole, Deguchi et al. 1995) in the bulge direction. The velocity in Local Standard of Rest (LSR) is taken to be the average of the center velocities of the $v = 1$ and $v = 2$ lines if both are detected, otherwise the center velocity of the only detected line. The sample consists of 443 SiO maser stars. Our OH maser data come from Eder, Lewis

& Terzian (1988), Lewis, Eder & Terzian (1990), Chengalur, Lewis & Eder (1993) and Lewis (1994). Most of the sources from these papers are normal double-peak OH/IR stars and we took the results of the LSR velocity from these papers. However, there are a few exceptions for which we calculated the LSR velocity in our own way. Several sources have variable OH maser line profiles. A few of them were detected as single peaked one time and as double peaked another time; in such cases we used the center velocity of the double-peak line profile. Some of them were detected twice as double-peaked, with velocities that differed by small amounts (usually less than $1\,\mathrm{km\ s^{-1}}$), which could have been caused by uncertainties in the observation and data reduction. In such cases the average of the LSR velocities of the two observations was taken as the true LSR velocity of the object. Using individual velocities would result in little difference in the velocity determination.

Another type of object is discarded by us, namely, where more than one object is detected within one beam of the antenna so that one IRAS PSC source is associated with two OH maser stars. In principle we can believe that at least one of the two OH maser stars is a true IRAS PSC object, but without higher resolution, we are unable to identify which one is the correct OH maser association. Moreover, usually the two OH maser stars are quite different from each other in their kinematic features, namely, their LSR velocities. So, such sources are excluded. Eventually, 382 OH maser stars are kept in our sample.

In order to study the distribution of these objects in the Galactic plane, their distances must be determined. It is never easy to determine the distance accurately. Under the constraint that only the IRAS PSC photometric data are available to all the sources, we adopt a method based on an estimation of infrared bolometric correction and the assumption of a universal absolute luminosity. The details of the method are described by Jiang et al. (1996). Once the distance to the object is known, the Galactocentric distance can be calculated from simple trigonometry. The circular rotational velocity can also be derived under the assumption that the radial velocity is the projection of stellar circular velocity on the line of sight direction. During the calculation, two fundamental parameters are given the following values: solar distance to Galactic center $R_0 = 8.5\,\mathrm{kpc}$, solar rotational velocity around Galactic center $\Theta = 220\,\mathrm{km\ s^{-1}}$. About the universal absolute luminosity of the objects, a value of $8000\,L_\odot$ is used, which was derived from the distribution of O-rich AGB stars by Jiang & Hu (1993). Because the luminosity in fact varies from source to source, there must be some error induced in the calculated distance to the individual objects. Another factor of uncertainty in calculating the distances is the bolometric correction. This could lead to an uncertainty of about 40% in the final results.

3 DISTRIBUTION IN THE GALACTIC PLANE

Shown in Fig. 1 are all the SiO and OH maser stars in Galactic coordinates. Most of the SiO maser objects are confined close to the Galactic plane, with $|b| < 15°$. There is a concentration towards the Galactic center, i.e., $|l| < 15°$ and $|b| < 10°$. The other sources are distributed from about 30° to 240° in Galactic longitude. The lack of sources from $l = 240°$ to $l = 330°$ is due to the limitation of the location of the Nobeyama 45-m telescope whose geographical latitude is 35°. The absence of SiO maser stars at the very center is entirely artificial: no objects were selected for observation in order to avoid potential confusion of sources in this crowded region. The confinement to the Galactic plane can also be attributed to selection effect, since most of the observations were targeted on IRAS PSC sources in the Galactic plane. The concentration to the Galactic center direction is, however, very likely to be real, i.e., the SiO maser stars are more abundant in the direction of the Galactic center than in the anti-center direction. Jiang et al. (1997) explained this phenomenon by a decreasing number ratio of O-rich stars to C-rich stars along the Galactocentric distance.

Most OH maser stars appear in a strip, which is the major Galactic longitude range accessible from the Arecibo fixed antenna. Nevertheless, the density of OH maser stars is much higher inside the Galactic plane than outside. Besides the reason that the late-type stars are more densely located in the Galactic plane, another reason could be that the high-latitude sources are halo objects of lower-mass and have smaller mass-loss rate which may be not enough to stimulate OH maser. Like the SiO maser stars, the OH maser stars are more concentrated to the inner disk than to the outer disk. Lewis (1994) attributed this difference to the UV intensity changes in the two directions since the existence of circumstellar OH molecule depends on the disruption of water molecules by interstellar UV radiation. Jiang et al. (1997) thought this might be caused by the same reason which brought about the SiO maser concentration to the Galactic center, i.e., a decreasing number ratio of O-rich stars to C-rich stars along the Galactocentric distance.

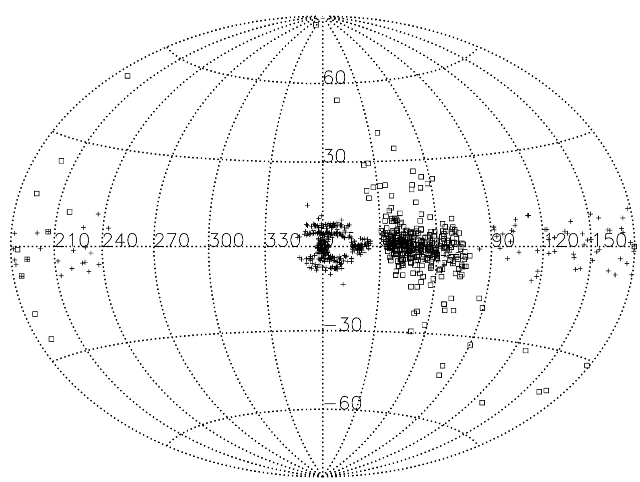

Fig. 1 Distribution of the Nobeyama SiO maser and the Arecibo OH maser stars in the Galaxy. Crosses denote the SiO maser stars and squares the OH maser stars.

An important feature of the Galactic structure is its spiral arms. In Fig. 2 (a), the SiO and OH maser stars with distances less than 15° from the central plane are projected onto the Galactic plane. The spiral arms determined from the locations of HII regions by Georgelin & Georgelin (1976) are also shown by solid lines, where the pitch angle of the spirals is taken as 12°. The clustering around the Sun at $[-8.5, 0.0]$ is apparent from the location of both SiO and OH maser stars. This can be understood by their smaller distance and hence their being more easily detected. There is no significant clustering in the spiral arms, not even in the two arms close to the sun. The SiO maser stars are more or less evenly distributed in the arms and in the inter-arm regions. The area that SiO maser stars span is quite large. The furthest is almost 20 kpc from the Sun and many are about 10 kpc distant from the Galactic center. The spiral feature should be present if the SiO maser stars belonged to the arm population. Therefore based on the distribution of the SiO maser stars, they are not arm population objects. The OH maser stars do not cover as large an area as the SiO maser stars due to the restriction of the Arecibo fixed antenna. But neither do they show evidence of concentration to the Sagittarius-Carina arm which is accessible from Arecibo. Their only feature is the concentration to the conic beam formed by the Arecibo scan. For a clearer look at the nearby situation, the region around the Sun is amplified in Fig. 2 (b). In addition, the Orion-Cygnus arm just outside the Sun is shown by a short-dash line. The distance effect has little variation within this range on detection limitation of the observational system, while no enhancement of distribution of SiO or OH maser stars is found to any of the Perseus, Orion-Cygnus and Sagittarius-Carina arms.

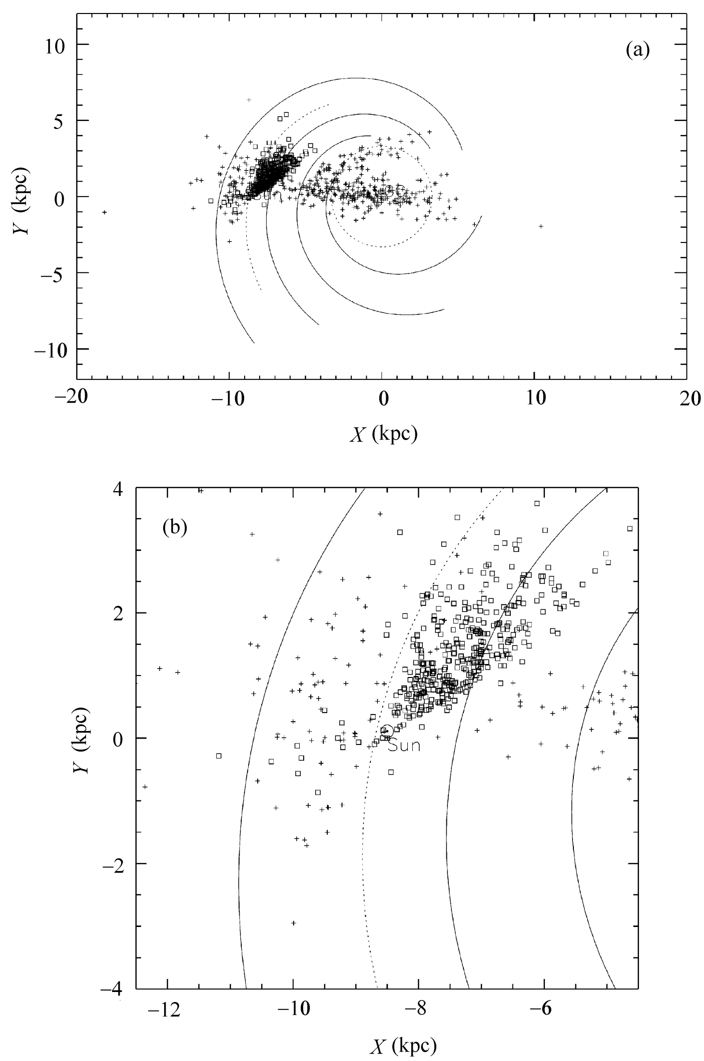

Fig. 2 (a) Distribution in the Galactic plane. Crosses denote the SiO maser stars and squares denote the OH maser stars. Overlaid is the spiral arms by solid line derived from the distribution of HI molecular clouds by Georgelin & Georgelin (1976). The coordinate origin is at the Galactic center and the Sun is at $[-8.5, 0.0]$. The Orion-Cygnus arm and the circle with radius 3.3 kpc from the center are plotted over by dot lines. (b) Nearby part of Fig. 2 (a) amplified. The Orion-Cygnus arm is added by a dot line.

Therefore in spite of the fact that the observation is far from being complete in the Galactic plane, the distribution of SiO and OH maser stars detected up to now do not show any enhancement in the spiral arms, rather, they appear to be uniformly distributed in and out of the arms.

The spiral arms are well delineated by young stars and their associated HII regions as well as by molecular clouds. The distributions of Cepheid variables, open clusters and HII regions close to the Sun are clearly enhanced along the three nearby arms based on optical observations. Radio observations in HI and CO molecule lines further delineate the other two arms — Scutum-Crux and Norma arms — close to the Galactic center by giant molecular clouds. But the SiO and OH maser stars are not gathering in the arms. The reason could be that they are so old as to have moved away from their birthplaces in the arms. Being late-type stars does not necessarily make them old. If only they are not massive stars, their age may be old enough to bring them away from the spiral arms. The non-enhancement in the arms may imply that these SiO and OH maser stars are low-mass stars in the late-stage of evolution. As indicated by the existence of large circumstellar shell, the SiO and OH maser stars have experienced strong mass loss and they are good candidates for AGB stars. Fundamentally AGB stars are classified into two types – low-mass and intermediate-mass stars. If it is true that the SiO and OH maser stars are not arm population, they may belong to low-mass, rather than intermediate-mass AGB stars. Of course, this conclusion is based on the assumption that intermediate-mass stars tend to be arm population more than low-mass stars do.

4 ROTATION CURVE OF THE DISK

To study the rotation curve of the Galactic disk, we picked out the sources with $|b| < 15°$ and $0 < V_{\rm rot} < 400\,{\rm km\ s^{-1}}$. The restriction on the Galactic latitude is obvious to exclude the halo objects from their apparent position. The second condition on rotational velocity tried to avoid the high velocity objects that may belong to the halo and the objects whose non-circular motion is so large as to induce considerable error in calculating the rotational velocity. In addition, the objects with $|l| < 15°$ or $|l - 180| < 15°$ are excluded for the similar reason that small deviation from circular motion can introduce large error of the rotational velocity during the calculating process. Indeed many sources in such area have negative values of rotational velocity that are physically not applicable.

The rotational velocities of the objects look very scattered as shown in Fig. 3 (a). The scale of scatter could be as large as $\sim 150\,{\rm km\ s^{-1}}$. The uncertainty of rotational velocity comes mainly from two aspects. One is the error in determining the distance as described in Section 2. The other is the deviation of the object from circular motion. Because these maser sources are not massive stars, they are more influenced by collisions with other objects when moving in the Galaxy and their orbits can thus be non-circular when compared to massive stars or large molecular clouds. The uncertainty in measuring stellar LSR velocity is negligible in comparison with the above two factors. Just from Fig. 3 (a), it is difficult to see any tendency in the rotation curve. In order to bring out any general trend, the data are binned at an interval of 0.4 kpc and the results are displayed in Fig. 3 (b) for both SiO (crosses) and OH (squares) maser stars. Within the distance scale commonly covered by the SiO and OH maser samples, i.e., 5.5 kpc $< R < 11$ kpc, the tendency is consistent. The rotation curve rises from about $R = 5.5$ kpc to $R = 8.0$ kpc and then falls slightly to $R = 12$ kpc. Within 2.0 kpc $< R <$ 5.5 kpc, only SiO maser stars are detected and the rotational velocity keeps constant except for a peak around

$R = 5\,\mathrm{kpc}$. Beyond $R = 12\,\mathrm{kpc}$, there are still a few SiO maser stars but they may not represent the general tendency of the rotation curve significantly due to their small number. Combination of these two groups of data basically reflects the same tendency of the rotation curve, as shown by the filled circles in Fig. 3 (c).

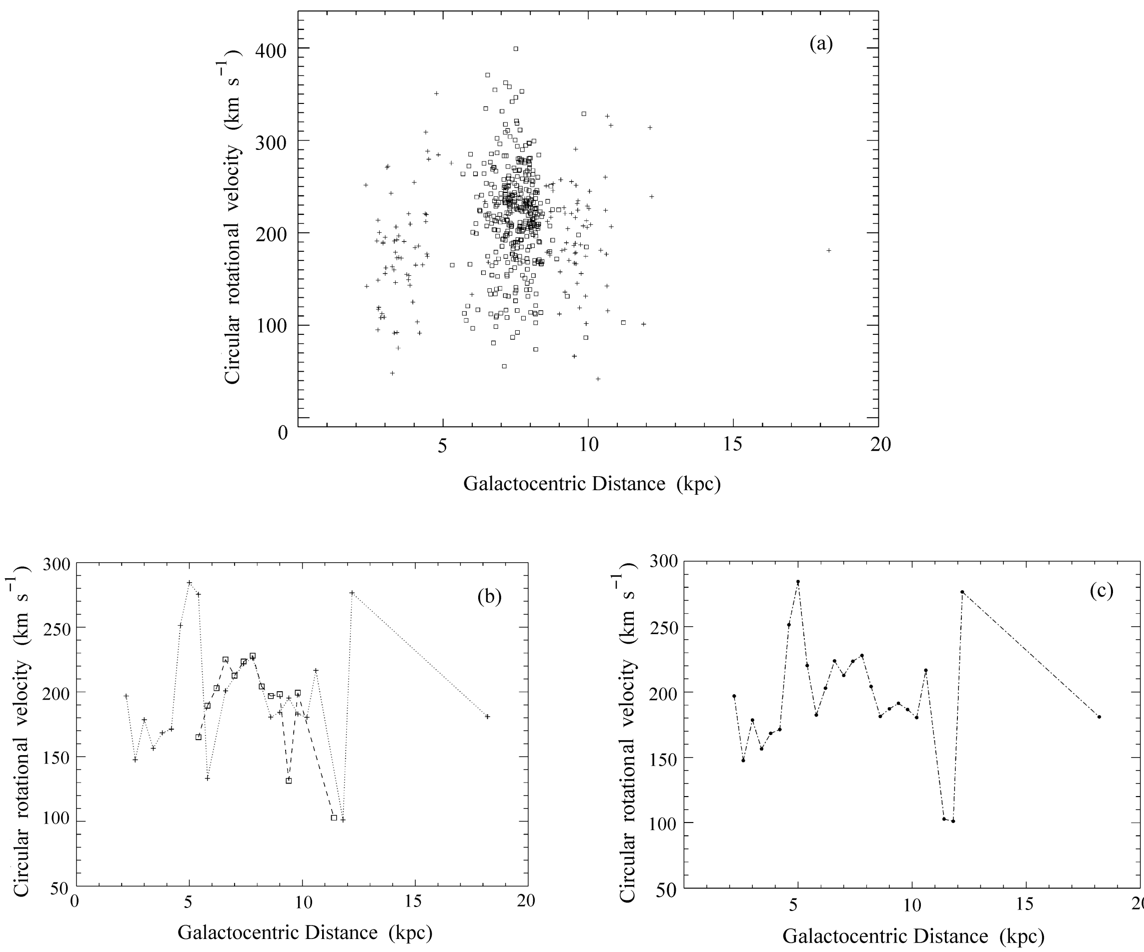

Fig. 3 Circular rotation velocity of objects inside the Galactic plane along the Galactocentric distance. (a) All the sources in the Galactic plane with $0 < V_{\mathrm{rot}} < 400\,\mathrm{km\,s^{-1}}$. Crosses—SiO maser stars; squares—OH maser stars. (b) Rotation curve obtained after the data in (a) are binned into 0.4 kpc bins, separately for the SiO and OH maser stars. (c) Same as (b) but all the SiO and OH maser data are binned together.

The rotation curve determined from planetary nebulae and AGB stars by Amaral et al. (1996) presents a broad maximum around $R = 7.0\,\mathrm{kpc}$, a sharp minimum at 9.0 kpc, and an enhancement around 10.5 kpc. The broad peak in Fig. 3(c) around $R = 7\,\mathrm{kpc}$ and the valley at about 9 kpc corresponds to their first two features, and the point at about 10.5 kpc corresponds to Amaral's enhancement. In general, our results are consistent with Amaral et al. (1996) in the common coverage of Galactocentric distance. This consistency can be understood because the objects in the two samples belong to the same type, i.e., late-type stars with circumstellar envelope; even planetary nebulae are descendants of AGB stars. The consistency suggests that the features exhibited by these two sorts of objects are real in spite of the uncertainty in calculating the distance and rotational velocity. But there is some difference between the two sets of data as well. The peak feature around 5 kpc in Fig. 3(c) is not seen in Amaral et al. (1996)'s data, which is, however, seen in the rotation curve from molecular observation of interstellar gas by Clemens (1985). Because the number of objects in this distance bin is not few, we believe this feature is real. On the other hand, the points beyond 12 kpc are not reliable because the sources with such distances are too few to be of statistical significance. Therefore, the rotation curve of the SiO and OH maser stars is not simple, but fluctuates at a few points, which may imply a complicated distribution of matter in the Galaxy.

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