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Maser Surveys *Chair: Jessica Chapman*

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SiO Maser Surveys of Nearby Miras and their Kinematics in the Galaxy

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Abstract. I review recent developments of SiO maser observations of miras, and discuss their kinematics in the Galaxy. They are deeply related to problems in other fields, such as the noncircular motion of Galactic spiral arms, streaming motions of stars in the solar neighborhood, and the interface between the interstellar and circumstellar medium revealed by Far-IR imaging of some miras, as well as the bar structure of the Galaxy. Recent automated surveys of variable stars in optical bands have increased the number of red variables enormously. Most of these stars were not observed in the radio before because of their blue colors. We have obtained radial velocities of these long-period variables with SiO masers. The longitude-velocity diagrams have revealed interesting deviations of stellar motions from the circular motion of the Galaxy, some of which show spatial motion similar to that of the Hercules group of stars. Important developments of SiO maser observations have been made for symbiotic stars, one of which showed a nova eruption with concurrent γ ray emission in 2010 (V407 Cyg). SiO masers have been monitored for this star after the nova eruption. I summarize the SiO maser observations of individual stars also.

Keywords. masers, stars: kinematics, stars: late-type, surveys

1. Introduction

Almost 40 years have passed since the discovery of SiO masers in miras (Kaifu *et al.* 1975). So far, we have performed many maser surveys of silicon monoxide at ∼43 GHz (see a summary in Deguchi 2007). We have surveyed approximately 4000 stars and detected half of them. Why do we need to add more? The previous surveys were made mostly for infrared bright, optically faint stars located at relatively distant places in the Galactic disk or bulge. At this time, we are focused more on the nearby blue objects, i.e., optically well observed mira variables, because a lot of new red variables were catalogued recently by automated optical photometric surveys. Therefore, we have made a new survey of nearby mira variables. This subject is related to the Galactic kinematics of stars, streaming motions of stars in the solar neighborhood, and the bar structure of the Milky Way Galaxy, or possibly related to streaming motions of stars in merging dwarf galaxies (Deguchi *et al.* 2007a; Deguchi *et al.* 2010).

The stars we can observe using SiO masers are mostly aged stars, i.e., stars in the Asymptotic-Giant-Branch phase of stellar evolution. Their ages are typically a few Giga years old. Because they rotate in our Galaxy a few tens of times, their motions are perturbed by the gravitational potential of the bulge bar periodically. As a result, their spatial motions deviate from the circular motions of the Galaxy considerably.

SiO masers occur in the rotational transitions of vibrationally excited states of silicon monoxide. The masers require hot gas of more than 1000 K. They are emitted in the very inner circumstellar shell of late-type stars, i.e, at 2–3 stellar radii. They have two strong lines at 42.820 and 43.122 GHz, the $J = 1$–0 $v = 1$ and 2 transitions. The two transitions are observable simultaneously by some radio telescopes, and for many stars, the intensities of these two transitions are approximately equal (see Nakashima & Deguchi 2007). It is nice to observe both transitions and secure detections. In our previous surveys, we took our sample from infrared catalogs, for example, IRAS, MSX, and 2MASS, Spitzer Glimpse etc. (Deguchi *et al.* 2004). However, recently the Automated Optical Sky Surveys have been made and several catalogs were published. One is the NSVS: Northern Sky Variability Survey (Williams *et al.* 2004), and another is the ASAS: All Sky Automated Survey, which was mainly focused on the Southern sky (Pojmanski *et al.* 2012). These two catalogs listed up ~ 50 thousands of variable stars, most of which are new. We have chosen our targets from the long-period variable stars in these catalogs, and have made a survey of them (Deguchi *et al.* 2012). We have also made a small complementary survey based on the AAVSO variable star catalog, which will be published in a future paper.

2. Overview

We surveyed about 580 stars and detected 330 of them in total. Our sample consists of optical miras and semiregulars. The detection rate of semiregulars is very low, i.e., about 10%, so that it is negligible in a discussion. A histogram of the period of the sample (see a similar one in figure 3 of Deguchi *et al.* 2012) indicates that the SiO maser detections peak at the period bin between 300 and 400 days, and that SiO maser emitting miras have slightly longer periods on average than those with no detections. The color-magnitude diagrams show that most of the stars have bluer colors than the usual sample (see a similar one in figure 2 of Deguchi *et al.* 2012). The median value of the color, $H - K$ or logarithmic ratio of IRAS 25 to 12 micron flux density falls at a much bluer part than that of the previous samples.

The bluer color of the star indicates that the circumstellar envelope is optically thin in the infrared bands and they are stars with very low mass-loss rates. However, we detected SiO masers at a detection rate similar to those in the previous surveys. Does this mean that the SiO maser intensity of this sample is stronger than that of the previous red

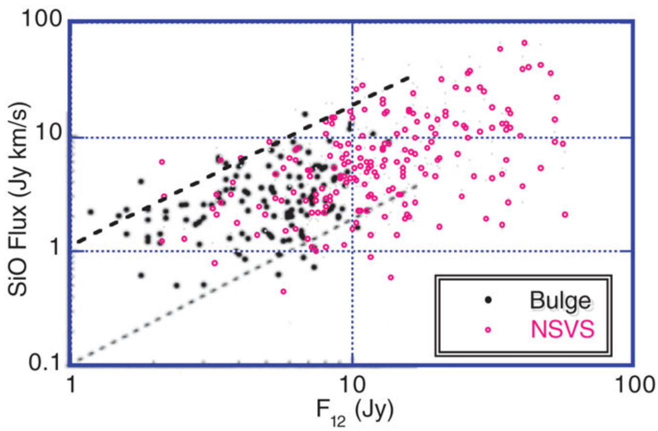

Figure 1. IRAS 12 μm intensity versus SiO maser integrated intensity ($J = 1$–0 $v = 2$). The red filled circles indicates the current sample of nearby miras, while black dots indicate SiO maser sources in the Galactic bulge taken from Jiang *et al.* (1995). See a similar plot in Jewell *et al.* (1991).

samples? No, it is not. In Figure 1, we plotted maser intensity against IRAS 12 micron flux density, and compared the present sample with the bulge stars. It indicates that the upper boundary of the SiO maser intensity is proportional to the IRAS 12 micron flux density (with an inclination of approximately unity). This means that the intrinsic SiO maser intensity does not vary between the present optical mira sample and the bulge IRAS sample, if normalized by IRAS 12 micron flux density.

3. Kinematics of SiO maser sources

Figure 2 shows the longitude-velocity diagram of the current sample of optical miras. Filled circles are disk miras at low Galactic latitudes and unfilled are miras at high-latitudes. Note that these stars are bright optical miras, which are relatively close, i.e., at a distance within about 3 kpc from the Sun. Distances were well estimated using the Period-Luminosity relation for this sample of miras with a period shorter than 400 d (Whitelock *et al.* 2008) and for periods longer than 400 d (Ita & Matsunaga 2011). Several groups of stars in this diagram show characteristic deviations from circular rotation, which are indicated by green ellipses. One group at a Galactic longitude of about 30° shows a radial velocity of −50 km s^{-1}, which deviates by 100 km s^{-1} from Galactic circular rotation. The other group is located at a longitude range between 90° to 140° at a radial velocity of −60 km s^{-1}, and the third group is located at V_{lsr} = 60 km s^{-1} at a longitude of about 30°. The two broken curves in Figure 2 are the expected velocities for known moving groups: the Hercules moving group and the Arcturus moving group. The Arcturus moving group is considered to be a remnant of a hypothetical dwarf galaxy merged into our galaxy in the past.

The same diagram, if overlaid on the CO J = 1–0 map (Dame *et al.* 2001), contrasts the difference between the distribution and the spiral arms (see Figure 6 of Deguchi *et al.*

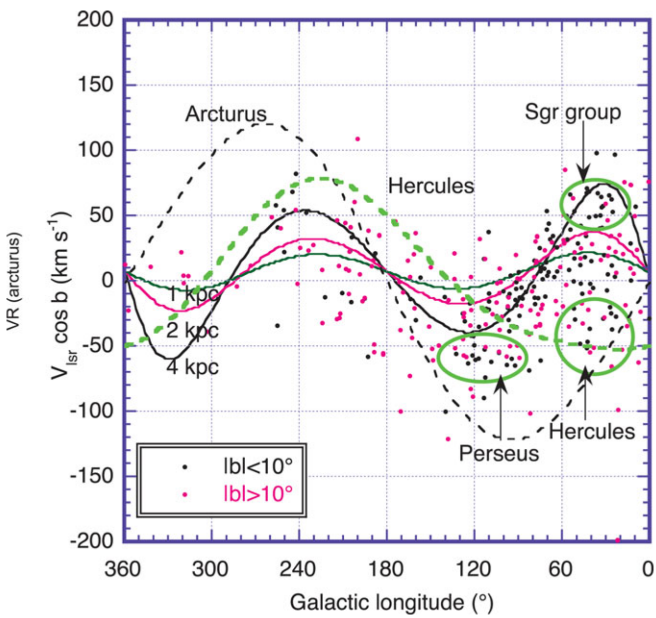

Figure 2. Longitude-velocity diagram of nearby miras with SiO masers. Thick curves indicate the expected radial velocities of stars at distances of 1, 2, and 4 kpc from the Sun for a circular orbit with a flat rotation curve of 220 km s^{-1} and a Sun-Galactic center distance of 8 kpc. The green ellipses indicate the groups of stars deviant from circular rotation.

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Table 1. Distance statistics for Perseus and Sgr deviant groups of stars

Group (number)	Quantity	D_k (kpc)	D^*_{Lc} (kpc)
Perseus	average	5.27	2.19
(18)	standard dev.	1.04	1.26
	probability†	—	$< 10^{-4}$
Sgr	average	3.46	2.65
(17)	standard dev.	0.62	1.22
	probability†	—	0.02

Notes:
*: luminosity distances calculated from the period–luminosity relations given by Whitelock *et al.* (2008) and Ita & Matsunaga (2011) for the periods below and above 400d, respectively.
†: a probability of the Student's t-test for the averages of two sets of D_k and D_{Lc} being generated by the same distribution function.

2012). The first group, that deviates about 100 km s^{-1} from circular rotation is called here the Hercules group, because this velocity is explained by the known moving group called the Hercules moving group originally discovered by Olin Eggen, or later a more extended one for blue short-period miras by Feast & Whitelock (2000). The second group is called the Perseus group, because the distribution of these stars in the l–v diagram fall on the Perseus spiral arm feature of CO emission. It has been well known that the Perseus spiral arm has a 30 km s^{-1} inward motion from the circular rotation of the Galaxy (Xu *et al.* 2006; Reid *et al.* 2009; Asaki *et al.* 2010). We calculated the distances of these stars using the period-luminosity relation and obtained an average distance of about 1.9 kpc. So that it is consistent with the Perseus spiral arm. Another deviant group is called the Sgr group, which deviates from the circular rotation by about 30 km s^{-1}. The average luminosity distance is about 2.7 kpc, while the kinematic distance is 3.5 kpc. The difference is statistically significant with a 98 percent confidence level as shown in Table 1. Therefore, the Sgr group is also explained by the noncircular motion.

The largest velocity deviation from circular motion is the Hercules group of stars. It is explained by the resonance effect at the outer Lindblad resonance. The bar gravitational potential moves at the bar-pattern speed, which is considered to be approximately 55 km s^{-1} kpc^{-1}, while the speed of the Sun is about a half of the bar pattern speed. Therefore, the bar potential minimum passes the Sun every 0.2 Gyr or so (twice if the bar is symmetric). If we take a rotational coordinate which is moving with the average circular motion of the Galaxy, the star slightly deviated from the circular rotation exhibits epicyclic motion in an ellipsoidal orbit in the rotational coordinate frame. The outer Lindblad resonance occurs at the radius of 7 to 8 kpc, which makes the major axis of the ellipse toward the Sun (see Appendix 3 of Deguchi *et al.* 2010). Therefore, we observe a large negative radial velocity at a Galactic longitude of about 30 degrees. This occurs for all of the stars as far as the stars with ages more than the rotational period of the bar, say about 0.2 Gyr. It has been known that a few percent of stars in the solar neighborhood belong to this moving group (Famaey *et al.* 2005). This is like the winter Olympic game, called "half pipe" Here a player is a star, and the half pipe is the bar potential. In the case of the Galaxy, the gravitational potential is rotating with a pattern speed, so that the pipe must be rotating. At the radius of the Sun, the bar gravitational potential is represented by a very shallow dip. The player can have a large outward motion if it is resonant with the rotation of the bar. This is a simple explanation for the Hercules group. However, for the other two groups, the stars are in a spiral arm, and they have longer periods, and they are much younger compared with the time scale of the bar-pattern rotational period. So that gas friction and magnetic field make the

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motion of spiral arms slightly different. We need a more sophisticated explanation for the other two groups of stars.

A 3D N-body numerical simulation of the stars in a barred spiral galaxy has been made by a number of people (e.g., see Baba *et al.* 2009; Monari, *et al.* 2011). Large deviations from circular motion can be found on the UV plane in this simulation, as well as where further minor groups of stars are.

4. Implications

The kinematics of nearby miras are directly related with the proper motion measurements by VLBI astrometry. Systematic observations have been made by the Japanese VLBI system, called VERA (Kobayashi *et al.* 2008). This telescope measures angular separations between a maser source and a continuum reference source with two-beam receivers and obtains the parallaxes and proper motions of maser sources. One example is the case of VY Canis Majoris observed by Choi *et al.* (2008). With this telescope, the accurate parallax and proper motions have been obtained for about 20 miras, and more will come in the near future (Honma 2012). Though current progress is limited to the very bright objects only, they will reveal some spatial motions of SiO maser sources, and will give precise complete 3D spatial motions of these stars in the Galaxy, as well as the motion of the maser clouds in the spiral arms.

Another related issue comes from the field of infrared astronomy. Recently infrared satellites, Spitzer and Akari, took far-infrared images of some miras, which have a large-angular-size circumstellar envelope. I mention here only an example of R Cas, which is one of the strong SiO maser sources (Cotton *et al.* 2004). In the far infrared images between 60 and 160 microns, this star exhibts an extended far-IR emission of the size of about a few arcminutes (Ueta *et al.* 2010). In their FIR images, the stellar position does not fall at the center of the emission, but slightly shifted to the East. In fact, some stars show a clear bow-shock. This occurs due to the motion of the star relative to interstellar medium. From a number of these observations, we can obtain the stellar motions in the interstellar medium (Ueta *et al.* 2011). We can also obtain the proper motions of the central star from VLBI measurements. Therefore, we get the proper motion of the interstellar medium in the Galaxy.

I have to mention a recent development made by the Korea Yonsei 21m telescope. Cho *et al.* (2010) made an interesting survey of symbiotic stars using the 43 GHz SiO maser lines. They can observe 43 GHz SiO and 22 GHz H_2O masers simultaneously. The symbiotic star is a spectroscopic binary. If the counterpart is a mira, it has an extended envelope and the secondary is often a white dwarf showing high temperature characteristics. They found SiO masers in 27 stars in 47 surveyed stars. The SiO masers usually show a central peak in the spectrum, and double peaks are relatively rare. However, in the case of the symbiotic stars, SiO maser spectra often seem to show double peaks. This is likely due to gas flow in a binary system.

5. Individual objects

5.1. *V407 Cyg*

I would like to talk about individual objects, especially about the V407 Cygni, which is a SiO maser source, but made a nova eruption in 2010 March. This is the first SiO maser source which is observed to be a classic nova, and this is also the first nova ever detected in γ rays. The optical light curve indicates that it is a typical classical nova; a rapid rise

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and gradual decline in the light curve. A very interesting aspect of this nova is that the H_α line showed a very wide width for the first one week (Munari *et al.*2011). The half width was initially up to 3000 km s^{-1}, and gradually decreased down to several 100 km s^{-1} by three weeks after the eruption. The Fermi-LAT (Large Area Telescope) detected γ ray toward this object concurrently (Abdo *et al.* 2010).

Classical novae are a thermonuclear run-away, which occurs on the surface of a white dwarf in a binary system. The donor star in this case is a mira-type variable. The separation between the two stars is enough large to compose a detached binary. The shock which has started from the surface of the white dwarf expands first to the radius of about 1 AU and makes an optically thick hot envelope around white dwarf, when the optical light curve becomes maximum. It gradually interacts with the cool envelope of the AGB star, when X-rays are emitted. It took about 20 days in the case of V407 Cyg. The γ-ray emission appeared in the first 1 week or so, and died out quickly. The X-ray emission comes later. It has been known that the donor is a mira of a period of 745 days with SiO masers. It is interesting to know how the SiO maser emitting regions of the donor star are influenced by the nova outburst. If we assume the shock speed is 1000 km s^{-1}, it crosses a distance of 10 AU in 2 weeks. It is a good time scale for measuring the variation of SiO maser intensities in this star.

In fact, three months before the nova eruption, this object was observed with the Yonsei 21m telescope (Cho *et al.* 2010). The spectra exhibited clear emission in the SiO $J = 1$–0 $v = 1$ and 2 lines and the H_2O 6_{16}–5_{23} line. Later, we recognized that this is the source in which we detected SiO masers 6 years ago (Deguchi *et al.* 2005a). A week after the eruption, we luckily had observation time at the Nobeyama 45m telescope. We detected SiO maser emission in the $J = 1$–0 $v = 2$ line, but not in the $v = 1$ line. Since then, we continued to observe the time variation of SiO masers. The spectral variation of the $v = 2$ emission in the first two months is shown in figure 2 of Deguchi *et al.* (2011). Initially the profile exhibited the emission at the red-shifted side only. It continued for

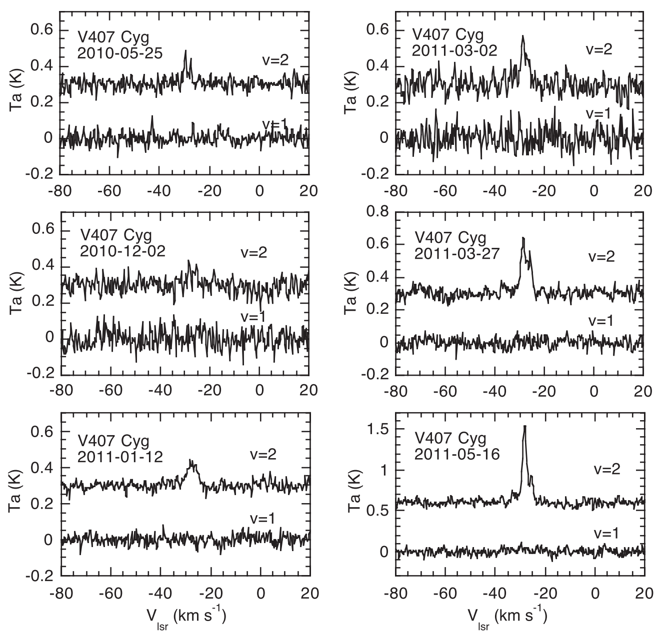

Figure 3. Spectral variations of SiO masers from V407 Cyg two months after the 2010 nova outburst. The SiO $J = 1$–0 $v = 1$ emission has never been detected after the nova outburst.

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the first one week and the intensity decreased very much. Then, it disappeared 20 days after the nova eruption (Nelson *et al.* 2012). I thought the emission would never come back for a year or so. Contrary to my expectation, new emission appeared at the lower velocity a month later.

How do we interpret this result? We consider the geometry of the binary as shown in Figure 3 of Deguchi *et al.* (2011). The SiO masers are usually emitted at about 2–3 stellar radii from the red giant. The nova shock is decelerated due to its ploughing of the circumstellar material of the mira and is going down gradually. Initially the material released by the explosion was estimated to be about 10^{-6} $M_\odot$ and the shock speed is about 3000 km s^{-1} (Abt *et al.* 2010; Orlando & Drake 2012). In 12 days, it reaches a distance of about 20 AU from the white dwarf. In such a case, most of the SiO masers near the mira vanish except in the shadow of the mira. Therefore, it emits a receding (red-shifted) part of SiO masers. After 3 weeks, all the SiO maser terminates because soft X-ray emission penetrated into the whole envelope, and quenched SiO masers. We can explain the disappearance of SiO masers very well with this model, except one fact that the lower velocity SiO maser appeared a month later.

We monitored the SiO maser emission since then. In Figure 3, I show the SiO maser spectra one year after. The $v = 2$ emission became stronger now. It probably means that the region of the SiO $v = 2$ emission is replenished by the gas from the inner part, and the maser intensity recovered after one year. However, we have not yet detected any $v = 1$ emission, nor H_2O masers at 22.2 GHz so far. It indicates that the $v = 1$ emission region and H_2O emission region are located at a much outer side of the envelope than the $v = 2$ emission. Therefore, it takes more time to refresh with unaffected gas from inside to reach the $v = 1$ masing region. We recognized that the radial velocity of $v = 2$ emission is gradually increasing with time. This is likely a gas motion due to pulsation of the mira, or equatorial flow of the gas around the binary.

We also tried to detect CO emission from the star. When we pointed at the star, we found broad CO emission, which looked like an inverse-parabolic line shape from the expanding envelope. However, the radial velocity is shifted by about 5 km s^{-1} from the stellar velocity. Therefore we mapped the CO emission using the 40″ grid, 5 point

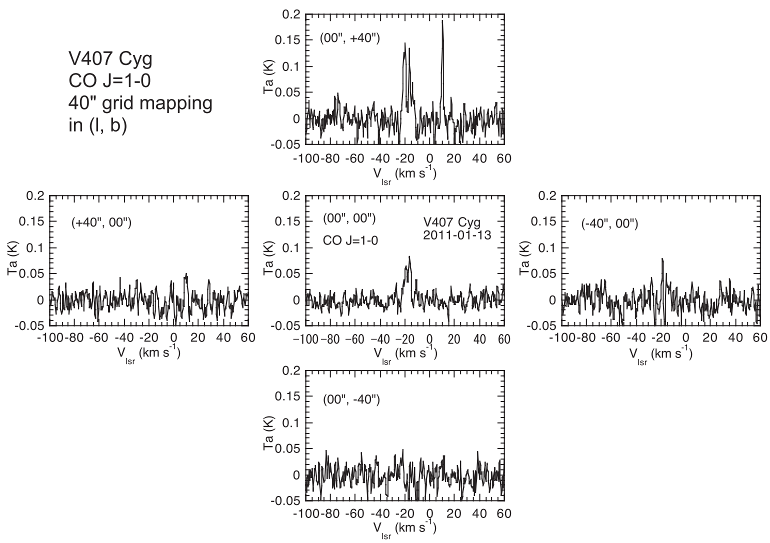

Figure 4. Spectra of the CO $J = 1$–0 line obtained with 40″ grid mapping toward V407 Cyg.

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mapping mode. The results are shown in Figure 4. We found that the strongest emission comes from 40″ north of the star. It indicates that this CO emission is an interstellar component toward this direction. Another sharp interstellar component was also seen at 40″ north. So far, we have not yet found any CO emission from this star.

5.2. *R Aqr*

The most famous, brightest symbiotic star is R Aqr. The circumstellar maser of this star has been well-investigated (see, e.g., Cotton *et al.* 2006). A 7mm radio continuum mapping of this star simultaneously with the SiO maser line was made with the VLA (Hollis *et al.* 1997). The overlaid map showed that the radio continuum comes from a secondary (probable white dwarf) 55 mas apart. Kamohara *et al.*(2010) measured the trigonometric parallax and proper motions of this star with VERA using a phase reference source. The white dwarf is likely receding from us. The proper motion is about 45 mas yr^{-1} to the south east, and the distance is 210 pc, which indicates a spatial motion of about 50 km s^{-1} in the direction away from the Galactic plane. These values obtained with VLBI astrometry coincide well with the past measurements by Hipparcos. It is likely that geometry of the white dwarf and SiO maser star is revealed in these observations. This should provide some hint on the geometry of V407 Cyg previously noted, or symbiotic stars in general.

5.3. *V838 Mon*

We have also to pay attention to the totally different idea of stellar evolution of red giants, which has been proposed recently for some peculiar stars. The R CrB-type stars are supergiants with hydrogen-deficient carbon-rich atmospheres. Recently they have been considered to be a product of two merged white dwarfs (Tisserand 2011). We have previously known another living example of a merged star, V838 Mon, a famous star with a light echo. One model merging two main-sequence stars with 5–10 $M_\odot$ and 0.1–0.5 $M_\odot$ can create this supergiant (Soker & Tylenda 2003; Tylenda & Soker 2006). We detected the SiO masers of this star in 2005, five years after its nova eruption (Deguchi *et al.* 2005b). Nearby CO emission, which is somewhat related to but is not from the circumstellar envelope of the star, has been mapped (Kamiński *et al.* 2011).

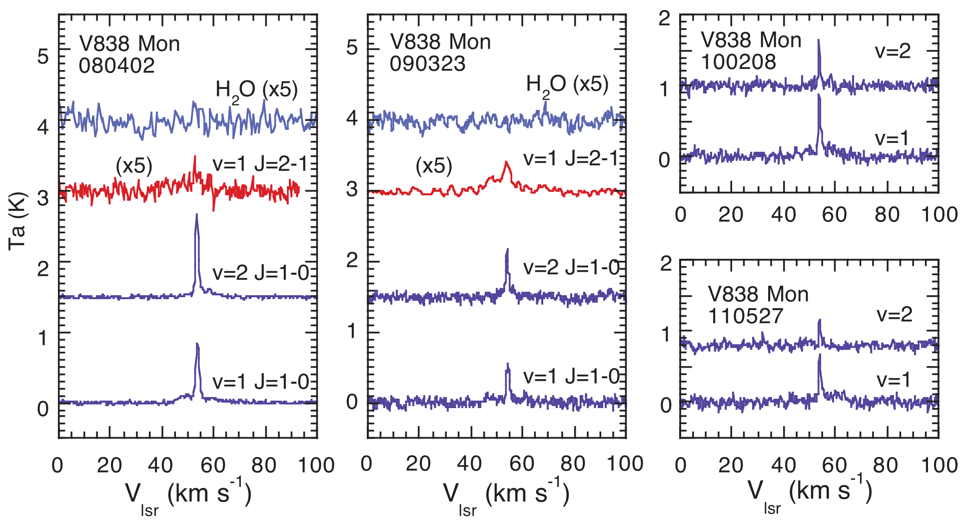

Figure 5. Spectral variations of SiO maser emission from V838 Mon after 2008. The date of observations is shown on the upper left under the star name in *yymmdd* format.

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Since then we have monitored this star every year (Deguchi *et al.* 2007b). Furthermore, we tried to detect the H_2O maser and SiO maser lines at 22 and 86 GHz. In 2009, we finally detected clear emission of the SiO $J = 2$–1 $v = 1$ line at 86.2 GHz (Fig. 5). Therefore the $J = 2$–1 $v = 1$ emission has formed recently in this star. For this star, a sudden mass loss started after the merging event when the supergiant was created. Therefore, our late detection of the $J = 2$–1 $v = 1$ line indicates that the maser emitting region of the $J = 2$–1 emission is much on the outer side of the $J = 1$–0 emission region. We also found that the intensity of the $J = 1$–0 $v = 2$ is decreasing gradually. How long does it take for the disappearance of these lines? This is an interesting problem, if the stellar merging can create OH/IR or SiO maser stars without an AGB phase of stellar evolution. If this time scale is long enough, say, more than 100 years, about 0.1 percent of the observed SiO maser stars can be made in the merging process (see the discussion given in Deguchi *et al.* 2005b). So that to measure how long it continues is an important issue.

6. Conclusion

In the last 10 years a number of unusual phenomena have been observed in AGB and post-AGB stars using maser lines. Most of which are more or less related to binary phenomena. “Water Fountains” may also be included in this category. A nice example of binary nature is the case of IRAS 18286−0959. The H_2O maser proper motion map of this star shows clear double jets, and the axes of both jets seem to show precession on a time scale of $\sim$ 10 years (Yung *et al.* 2011). This is certainly a binary phenomenon. We are not very sure whether the jet is created in an accretion disk around the compact star, or in the atmosphere of the AGB star, or in the equatorial disk in the binary. The previous example of R Aqr clearly indicates that the jet is created by an accretion disk. Therefore, it is highly likely that these jets are created in the accretion disk of the compact star associated with the AGB or post-AGB star. We have also to pay attention to the totally different idea of the stellar evolution of red giants, which has been proposed recently for some peculiar stars such as V838 Mon. The binary phenomena and stellar mergers seem to produce rare but interesting deviations in stellar evolution. In contrast, understanding the kinematics of evolved stars in the Galaxy seems to be considerably difficult, but the field has matured sufficiently to explore this issue using masers as a tool. Information on the complete 3D velocities of stellar motions is absolutely necessary and will be obtained by future VLBI measurements.

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