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Detection of SiO Maser Emission in V838 Mon

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Abstract

We report on the detection of 43 GHz SiO maser emission in V838 Mon, a prototype of a new class of eruptive variables, in which a red supergiant was formed after a nova-like eruption in 2002. The detection of SiO masers indicates that the star formed after the eruption is indeed a kind of cool mass-losing object with circumstellar masers. The measured radial velocity and the intensity of maser emission are consistent with the object being located at a distance of about 7 kpc from the sun. It also suggests that a considerable percentage of SiO masing objects in the Galaxy are formed by the same mechanism as that which created V838 Mon.

Key words: radio lines: stars — stars: AGB and post-AGB — stars: circumstellar matter — stars: general — stars: novae, cataclysmic variables

1. Introduction

V838 Monocerotis is a star that erupted in the beginning of 2002 January. After developing an A–F supergiant spectrum at the optical maximum phase within a few months, it revealed a cool M-type supergiant spectrum, and remained bright in infrared (Munari et al. 2002; Crause et al. 2003), appealing to a prototype of a new class of eruptive variables (Kimeswenger et al. 2002). Though a spectacular discovery of a light echo and succeeding observations of expansion received much attention (Bond et al. 2003; Crause et al. 2005), it did not help much to derive an accurate distance to this object due to its model dependence (Tylenda 2004). Instead, based on kinematic and other information, the distance to this object has been estimated to be 8–10 kpc (Munari et al. 2005).

The presence of a B3V hot companion (Munari et al. 2005) at the post-outburst (and likely pre-outburst; Tylenda et al. 2005b) phase supports a binary-star model of the system. Soker and Tylenda (2003) found that thermonuclear models cannot explain the eruption, but a stellar merger can account for the outburst luminosity. Tylenda, Soker, and Szczerba (2005b) argued from the available observational data prior to the eruption that the progenitor of V838 Mon was not an evolved red giant, but a main-sequence star erupting into an M-supergiant.

A number of molecular bands, such as CO, H_2O, and TiO, have been detected in absorption in the infrared region (Evans et al. 2003; Lynch et al. 2004). More recently, Rushton et al. (2005) found variable SiO first-overtone emission at 4 μm, which indicates a characteristic of a cool supergiant. A search for circumstellar molecular emission at radio wavelengths (in the SiO $J = 2$–1 $v = 1$ line, and the ^{12}CO $J = 1$–0, 2–1, and 3–2 lines) gave negative results (Rushton et al. 2003).

In this paper, we report on SiO maser detection toward an unusual eruptive variable, V838 Mon. The observations, made during a two-month separation (2005 February and April), indicate that the SiO maser intensity is increasing at the current phase. The detection of SiO masers in this object implies that a considerable percentage of stellar maser sources, which have been considered to be mass-losing stars at the Asymptotic Giant Branch (AGB) phase (or occasionally post-AGB phase), can be created by the same mechanism as that which created V838 Mon. We discuss the implication of this result in section 3.

2. Observations and Results

The first observation of V838 Mon with the Nobeyama 45-m telescope was made on 2005 February 23 in the SiO maser lines ($J = 1$–0, $v = 1$ and 2) at 43.122 and 42.821 GHz, respectively. The half-power full beam width (HPFBW) was about 40$''$ at 43 GHz. We used a cooled SIS-mixer receiver ($T_{\rm sys} \sim 180$–250 K) and acousto-optical spectrometers with high (40 kHz; AOS-H) and low (250 kHz; AOS-W) resolutions having 2048 channels each. The spectrometer arrays covered velocity ranges of $\pm 390\,{\rm km\,s^{-1}}$ and $\pm 800\,{\rm km\,s^{-1}}$ in AOS-H and AOS-W with an effective velocity resolution of 0.3 and $1.8\,{\rm km\,s^{-1}}$ per binned channel, respectively. The conversion factor of the antenna temperature ($\equiv T_{\rm a}^*$) to the flux density was $\sim 2.9\,{\rm Jy\,K^{-1}}$. The details of observations with this system had been described elsewhere (Deguchi et al. 2000).

We detected SiO maser emission in both $J = 1$–0, $v = 1$ and 2 transitions at $V_{\rm LSR} \sim 54\,{\rm km\,s^{-1}}$ in V838 Mon in about 11 min of on-source integration time. The spectra taken in AOS-H are shown in figure 1. The detections were confirmed in AOS-W spectra in all cases. The line properties are summarized in table 1, which contains the source name, observed positions, observed transitions, radial velocities ($V_{\rm LSR}$), peak antenna temperatures ($T_{\rm a}$), integrated intensities, and rms noise levels for both transitions from the AOS-H spectra. The MSX

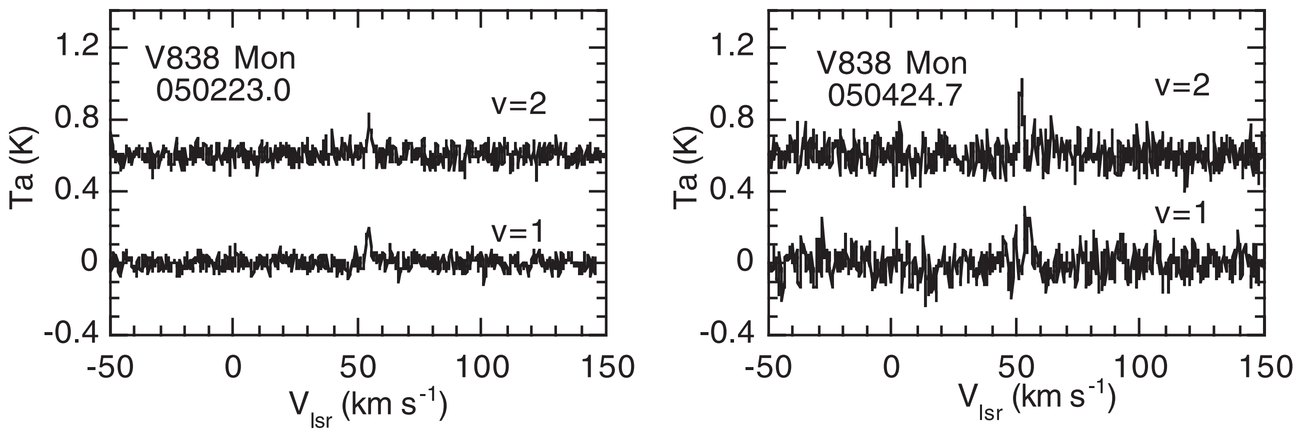

Fig. 1. Spectra of the SiO J = 1–0, v = 2 (top) and v = 1 line (bottom) in V838 Mon. The observation dates are 2005 February 23 (left panel) and 2005 April 24 (right panel).

6C catalog (Egan et al. 2003) gives no point source detected within 10′ of V838 Mon in all of the observed bands, although the MSX imager shows a slight enhancement of emission in the A (8.3 μm) band at the position of IRAS 07015−0346 (= V838 Mon; F_{12} = 0.25 Jy; see van Loon et al. 2004). The 2MASS images (Cutri et al. 2003) do not show any contaminating bright-red objects within 1′ of V838 Mon. Therefore, there is no chance of contamination by other objects emitting SiO masers within a telescope beam.

A short follow-up observation with the same telescope was made on 2005 April 24 for V838 Mon in the SiO J = 1–0, v = 1 and 2, and J = 2–1, v = 1 (86.243 GHz) lines. The AOS-H spectrometer arrays covered the radial velocity range between $\pm$75 km s^{-1} in the 86 GHz SiO maser observation. The system temperature was approximately 240 K at 86 GHz. The conversion factor of the antenna temperature to the flux density was inferred to be approximately 4.4 Jy K^{-1} at 86 GHz. The J = 1–0 v = 1 and 2 maser lines around 43 GHz were found to become slightly stronger than before, but the J = 2–1 v = 1 line was not detected.

Figure 1 and table 1 indicate that the SiO maser intensity in V838 Mon apparently increased with time over a two-month span. Though the calibration of the line flux involved an uncertainty of about $\pm$20% in the NRO 45-m telescope system (e.g., see Kamohara et al. 2005), and the noise level was high in the 2005 April observation due to a time restriction, the maser intensity in 2005 April seems to have increased by about 50% compared with the intensity in 2005 February. It is consistent with the fact that the 4 μm SiO first-overtone emission was first developed in a periphery of the extended atmosphere during 2002–2003 (Rushton et al. 2005), and the outflowing gas made SiO masers at the outer envelope a year or two after. An outflow velocity of 20 km s^{-1} gives a crossing length of about 6×10^{13} cm over a year, when the gas reaches to a radius of $\sim 1.6 \times 10^{14}$ cm if it started at the photospheric radius of 1.0×10^{14} cm, which was measured by a near-IR interferometer at 2.2 μm (Lane et al. 2005).

In addition, we observed the same type of eruptive variable, V4332 Sgr (Martini et al. 1999; Banerjee et al. 2004), on 2005 March 9 and 10 by the SiO J = 1–0 v = 1 and 2, and added the negative results in table 1. This star, V4332 Sgr, erupted in 1994 February, developing an early M-type spectrum involving TiO bands (Tylenda et al. 2005a). The distance was inferred to be a few kpc away from the Sun. No maser was detected in this star. The 2MASS database shows a faint red star with K = 10.99 and $H - K$ = 0.61 at this position.

3. Discussions

3.1. *Radial Velocity, Maser Intensity, and Kinematic Distance of V838 Mon.*

The radial velocity of SiO maser emission is known to coincide with that of the central star within a few km s^{-1} (Jewell et al. 1991). It directly indicates the velocity of a cool

Table 1. Observed line intensities.

Object	RA(J2000.0)* h m s	Dec(J2000.0)* ° ′ ″	Transition mol, J_u–J_l, v	V_{LSR} (km s^{-1})	Peak T_a (K)	Integ. int. (K km s^{-1})	rms (K)	Obs. date yymmdd.d
V838 Mon	07 04 04.85	−03 50 51.1	SiO 1–0, 1	54.6	0.197	0.577	0.034	050223.0
			SiO 1–0, 2	54.2	0.251	0.396	0.042	050223.0
			SiO 1–0, 1	53.5	0.330	0.813	0.070	050424.7
			SiO 1–0, 2	54.1	0.419	0.681	0.065	050424.7
			SiO 2–1, 1	···	···	···	0.034	050424.7
V4332 Sgr	18 50 36.70	−21 23 29.6	SiO 1–0, 1	···	···	···	0.052	050310.3
			SiO 1–0, 2	···	···	···	0.068	050310.3

* Positions were taken from the SIMBAD database [originally from Brown et al. (2002) for V838 Mon, and Downes et al. (2001) for V4332 Sgr].

M-supergiant, which was formed after eruption. The relatively narrow ($\sim 5\,\mathrm{km\,s^{-1}}$) widths of both maser lines suggest that the turbulence in the outflowing envelope of the M-supergiant is relatively mild. The SiO maser lines are normally formed at a few stellar radii of the photosphere for M-type stars ($\sim 10^{14}$ cm; Cotton et al. 2004), but for supergiants, VLBA observations indicate that it is a slightly outer part of the envelope (Miyoshi 2003). The SiO maser line profiles of V838 Mon do not show any indication of the broad line width that is common for supergiants (Cernicharo et al. 1997). This is partly due to the low signal-to-noise ratio of the detected lines, in which the profile is not sufficient to reveal the weak broad pedestal feature often seen in supergiants.

The radial velocity of V838 Mon was not accurately known, though it has been estimated from P-Cygni-type optical spectra (Kipper et al. 2004; Tylenda et al. 2005b) as V_{helio} = 55–65 $\mathrm{km\,s^{-1}}$ (corresponding to V_{LSR} = 42–52 $\mathrm{km\,s^{-1}}$). The SiO radial velocity found in the present paper, $V_{\mathrm{LSR}} = 54\,\mathrm{km\,s^{-1}}$, coincides with the high end of the optical velocities, establishing an accurate stellar radial velocity. Tylenda, Soker, and Szczerba (2005b) listed the radial velocities of interstellar clouds within $\sim 1.5^{\circ}$ from V838 Mon. From their table 3, we find that two molecular clouds, G217.6 + 2.4 and G218.7 + 1.8 (= IC 466, S 288), which have the highest radial velocities in the table (V_{LSR} = 55 and 57 $\mathrm{km\,s^{-1}}$), have similar radial velocities to that of V838 Mon. The kinematic distances to these clouds were evaluated to be 7.02 and 7.17 kpc, respectively (Wouterloot, Brand 1989). Jiang et al. (1996) estimated the kinematic distances of SiO maser sources in this direction using a rotation curve derived by Burton (1988). Their figure 8 gives a kinematic distance of about 7 kpc for $V_{\mathrm{LSR}} = 54\,\mathrm{km\,s^{-1}}$, suggesting that V838 Mon is located at a similar distance with these molecular clouds (if V838 Mon is a disk population).

The intensity of SiO maser lines, 0.6–1.2 Jy, is comparable with the intensities of masers found in the galactic center and bulge (e.g., see Deguchi et al. 2002, 2004a). Therefore, this fact also supports the large distance ($\sim$ 7 kpc) of V838 Mon, provided that the M-supergiant of V838 Mon emits the same intrinsic maser flux as the bulge SiO maser sources do. However, because only the maximum (upper limit) of SiO maser line intensity relative to the IRAS 12 μm flux density (i.e., normalized by the luminosity and the distance of the object) is meaningful in general (because of time variation of maser intensity; Jewell et al. 1991), we cannot completely deny the possibility of a smaller distance merely based on the line fluxes. The measured flux density is nearly equal to the value expected from the maximum photon fluxes of the usual SiO sources at a distance of 7–8 kpc, indicating that the envelope of an M-supergiant in V838 Mon radiates SiO masers at a nearly maximum flux among masing objects.

3.2. *Eruptive Formation of Maser Stars*

Though the interstellar matter revealed in the light echo of V838 Mon and a diffuse middle infrared emission found in MSX map were claimed to be a past activity of the AGB phase of the progenitor of V838 Mon (van Loon et al. 2004), a current understanding of photometric data of the progenitor star and a modeling of the light echo seem to conflict with the RGB/AGB/post-AGB hypothesis of the progenitor (Tylenda et al. 2005b). Rather, considering various possibilities, Tylenda, Soker, and Szczerba (2005b) argued that the progenitor of V838 Mon was a binary system of two main-sequence stars, such as B1.5V and B3V, and that the interstellar material, which was brightened by a light echo, did not originate from V838 Mon.

It is interesting to consider a scenario of the binary evolution, which produces an SiO maser star (late M-supergiant) by an eruptive event. From the fact that we already know two examples of the eruptive formation of an M-supergiant in the Galaxy, V838 Mon and V4332 Sgr (e.g., Banerjee et al. 2004), we can estimate that the formation rate of this type of a new class of nova events, creating an M-supergiant after eruption, is roughly one every 10 yr in the Galaxy. Because we could not detect any SiO maser emission in V4332 Sgr in the present work, we assume that one of these two events creates an SiO maser star. It is hard to estimate the lifetime of the maser-emitting phase in V838 Mon. However, let us assume a rather buoyant value of 2000 yr. In this case, we should observe 100 such maser stars of this kind in the Galaxy at any epoch of time. Furthermore, we know approximately 1500 SiO maser-emitting objects in the Galaxy (Deguchi et al. 2004b) and about 1000 OH/IR sources (Sevenster et al. 2001). Therefore, about 5–10% of these objects have the eruptive origin.

This is, of course, a very rough estimate, merely giving an order of magnitudes for such a percentage. Furthermore, it is difficult to estimate the galactic nova rate, because of the patchy interstellar extinction (Shafter 1997). The largest uncertainty in the previous estimate seems to be involved in the time span of SiO maser emitting phase in V838 Mon at present. Because the SiO masers are emitted at just a few stellar radii of the photosphere, it terminates within a few years when the mass loss ceases. If once an AGB star is created (as a single star), its lifetime at the AGB phase would be longer than 10^5 yr (depending on the mass). Therefore, it is not expected that the SiO maser terminates quickly unless the formed AGB-like structure is quite unstable and transient. It would be quite interesting to know how long the SiO masers are detectable in V838 Mon and whether or not H_2O and OH masers will follow in the future.

We have considered the eruptive origins of maser stars based on the view point of a binary merger model of V838 Mon for the sake of simplicity. However, it should be noted that the above arguments are equally applied to an alternative scenario, i.e., the post-AGB progenitor being born again as an AGB star (Lawlor, MacDonald 2003), though the life span of the maser-emitting phase must be significantly altered in such a scenario.

Spectroscopic observations suggested that V838 Mon is slightly metal deficient, except with enhanced abundances of *s*-process elements (Kipper et al. 2004; Kaminsky, Pavlenko 2005). Among metallic species, Kipper et al. (2004) gave the Si abundance as being 1/10 of the solar value, which does not seem to be consistent with the later finding of rich SiO infrared band emission (Rushton et al. 2005) and the SiO maser detection in the present work. These facts may imply that the abundance analysis from transient optical spectra is a work of extreme difficulty. Alternative evidence of binary mergers in slightly metal-poor environments was recently found in bulge globular clusters (Matsunaga et al. 2005); some SiO maser sources toward globulars are likely to be cluster members. Because the luminosities of these objects slightly exceed the AGB luminosity limit of the low-mass objects expected in aged globular clusters, these stars must be objects created by binary mergers. When accounting for these SiO maser sources in globulars, observations of maser sources do not necessarily constrain the mechanism as to whether it is a sudden, eruptive formation of an M-supergiant, or whether it is a merger event in which a merged star evolved into the AGB phase in a certain period later. Statistics of SiO maser sources and blue stragglers in globulars may provide the answer to this question.

4. Conclusion

SiO maser emission from the eruptive variable, V838 Mon, was detected with the Nobeyama 45-m telescope, confirming the formation of a mass-losing M-supergiant after nova eruption. The obtained radial velocity of masers, $V_{\rm LSR} \sim 54\,{\rm km\,s^{-1}}$, gives the first reliable evaluation of the radial velocity of this star, suggesting a kinematic distance of about 7 kpc for this object. If the SiO maser phenomenon in this star is persistent at a certain length, a considerable percentage of the SiO maser stars in the Galaxy may originate through the same mechanism, i.e., the eruptive formation of maser stars from merged binaries. This observation is consistent with evidence of the SiO maser phenomenon occurring in diversely different types of objects.

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