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Detection of the ^{29}SiO v=1, J=1–0 Maser from TX Camelopardalis*

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Abstract

The maser emission from the $v = 1$, $J = 1$–0 transition of ^{29}SiO has been detected for the first time toward the Mira variable star TX Cam among 54 surveyed late-type stars. The line was fairly narrower than the ^{29}SiO $v = 0$, $J = 1$–0 transition, and slightly redshifted compared to the $v = 0$ line. In addition, the ^{28}SiO $v = 2$, $J = 2$–1 transition has also been newly detected in this star. Based on the line intensity, the pumping mechanism for the ^{29}SiO $v = 1$, $J = 1$–0 maser is discussed. The simple large velocity-gradient model and the line overlap of H_2O can not be adopted for this maser.

Key words: Masers: SiO — Stars: circumstellar shells — Stars: long-period variables

1. Introduction

The ground-state rotational transition of isotopic silicon monoxide, ^{29}SiO and ^{30}SiO, occasionally appears as masers in evolved stars (Deguchi et al. 1983; Cho et al. 1986; Barcia et al. 1989) and in the star-forming region Orion-KL (Olofsson et al. 1981). The ^{29}SiO masers show spiky spectra which are more intense than the ^{28}SiO $v = 0$ lines in spite of the much lower abundance of ^{29}SiO; $(^{28}\mathrm{SiO})/(^{29}\mathrm{SiO}) \approx 20$ (Geballe et al. 1979; Tsuji et al. 1994). Alcolea and Bujarrabal (1992) made a systematic study of the characteristics of the ^{29}SiO $v = 0$, $J = 1$–0 masers. Based on a good correlation between the ^{29}SiO $v = 0$, $J = 1$–0 intensities and the 8 μm flux, they argued that this maser is pumped by stellar radiation. The ^{29}SiO rotational transitions in the vibrationally excited states(the $v = 1$, $J = 3$–2 to 6–5 lines and $v = 2$, $J = 2$–1, $J = 6$–5 lines) have also been detected in evolved stars (Cernicharo et al. 1991; Chernicharo, Bujarrabal 1992). However, some rotational transitions in the vibrational states of ^{29}SiO, especially the lowest rotational transition in the first vibrational excited state ($v = 1$, $J = 1$–0), have not been detected in any source (Alcolea, Bujarrabal 1992; Cho et al. 1993). In the case of ^{28}SiO masers in late-type stars, the $v = 1$, $J = 1$–0 line is the strongest among the rotational lines in the vibrational states. It is curious that the ^{29}SiO $v = 1$, $J = 1$–0 line was not detected in spite of detecting the even more excited $J = 6$–5 transition in this vibrational state.

In this letter we report on the first detection of the ^{29}SiO $v = 1$, $J = 1$–0 transition in the Mira-type variable star TX Cam. The implication of this observation concerning the pumping mechanism of a ^{29}SiO maser is discussed.

2. Observations

The observations were made with the 45 m telescope of the Nobeyama Radio Observatory (NRO) in 1993 December and 1994 March. Two SIS receivers, S40 (32–50 GHz) and S100 (86–116 GHz), tuned at the frequencies of the ^{28}SiO $v = 2, 3$, $J = 1$–0, ^{29}SiO $v = 0, 1$, $J = 1$–0 and ^{28}SiO $v = 1, 2$, $J = 2$–1, ^{29}SiO $v = 0$, $J = 2$–1 transitions were used simultaneously. The two receivers were polarized linearly. The SSB system temperature was 180–210 K for S40 and 250–320 K for S100, respectively. We used acousto-optical spectrometers (AOS) with 37 kHz resolution (0.26 km s^{-1} at 43 GHz) and a bandwidth of 40 MHz. The aperture efficiencies were estimated to be 53 and 39% at 43 and 86 GHz, respectively. The intensity scale is the antenna temperature(T_{A}^{*}), corrected for atmospheric and ohmic losses (Ulich, Haas 1976). The antenna temperature was converted to flux density by a factor 3.3 and 4.5 Jy K^{-1} at 43 and 86 GHz, respectively. The pointing was checked every two hours by the sources themselves, using the S40 receiver. The pointing accuracy during our observations was within 5$''$ in azimuth and elevation.

We selected 54 evolved stars (50 Mira variables, 1 semiregular variable, and 3 supergiants), all known to be $v = 1$ and $v = 2$ line emitters.

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* Based on observations made at the Nobeyama Radio Observatory (NRO). NRO is a branch of the National Astronomical Observatory, an inter-university research institute operated by the Ministry of Education, Science and Culture of Japan.

3. Results

The seven observed lines toward TX Cam are shown in figure 1 where the ^{29}SiO $v = 1$, $J = 1$–0 maser emission has been detected for the first time. The ^{29}SiO $v = 0$, $J = 2$–1 and ^{28}SiO $v = 2$, $J = 2$–1 maser lines have also been newly detected in TX Cam. The ^{28}SiO $v = 3$, $J = 1$–0 line was not detected at this time. The observational results for the seven transitions of SiO are summarized in table 1. Fifty three surveyed sources, except for TX Cam, were not detected for the $v = 1$, $J = 1$–0 of ^{29}SiO within a 3 rms noise level of 0.12–0.38 K (Cho, Ukita in preparation).

The ^{29}SiO $v = 1$, $J = 1$–0 line profile (half width $= 0.6$ km s^{-1}) is more sharply peaked than the profile of ^{29}SiO $v = 0$, $J = 1$–0 (half width $= 1.3$ km s^{-1}); its peak velocity (9.2 km s^{-1}) is redshifted by about 0.3 km s^{-1} from the velocity of ^{29}SiO $v = 0$, $J = 1$–0. The peak velocity of 9.2 km s^{-1} is well consistent with the peak velocity of the red component of the ^{28}SiO $v = 2$, $J = 2$–1 double peaks, and is similar to the line center velocity 9.6 km s^{-1} of ^{13}CO ($J = 2$–1) (Olofsson et al. 1991). The peak antenna temperature 3.2 K is about one fifth that of the peak antenna temperature of ^{29}SiO $v = 0$, $J = 1$–0 ($T_A^* = 15.7$ K). The ^{29}SiO $v = 0$, $J = 1$–0 line is very strong (51.7 Jy) compared to that of Mira variables detected until now. In addition, the ^{29}SiO $v = 0$, $J = 2$–1 line profile consists of a broad pedestal component shown from $V_{\rm LSR} = -12$ km s^{-1} to 32 km s^{-1} and a narrow spike at 5.4 km s^{-1}, similar to the profiles found in other stars by Leguchi et al. (1983) and Nguyen-Q-Rieu et al. (1988). It has been deduced that the broad pedestal component is the thermal emission and that the spike is the maser emission. The peak velocity of the spike is shifted to the blue side with respect to the peak velocity of the ^{29}SiO $J = 1$–0 lines by about 4 km s^{-1}, and it is close to that of the lower velocity component of the ^{28}SiO $v = 2$, $J = 2$–1 double peaks, as shown in table 1. TX Cam is the fourth known source with the ^{28}SiO $v = 2$, $J = 2$–1 maser emission after previously known sources, χ Cyg (Olofsson et al. 1981, 1985), R Cas (Clark et al. 1981), and R Leo (Olofsson et al. 1985). This line shows a sharp double peak at 9.2 km s^{-1} and 5.6 km s^{-1}. Although the ^{28}SiO $v = 2$, $J = 1$–0 and $v = 1$, $J = 2$–1 profiles show ordinary maser characteristics, the peak velocity of the ^{28}SiO $v = 2$, $J = 1$–0 line(10.8 km s^{-1}) is redshifted compared to the other lines by a few km s^{-1}. The ^{28}SiO $v = 3$, $J = 1$–0 line was not detected at this time. It was detected at 11.0 km s^{-1} (phase 0.21, Cho et al. 1993) and 9.4 km s^{-1} (phase 0.10, Alcolea et al. 1989), respectively.

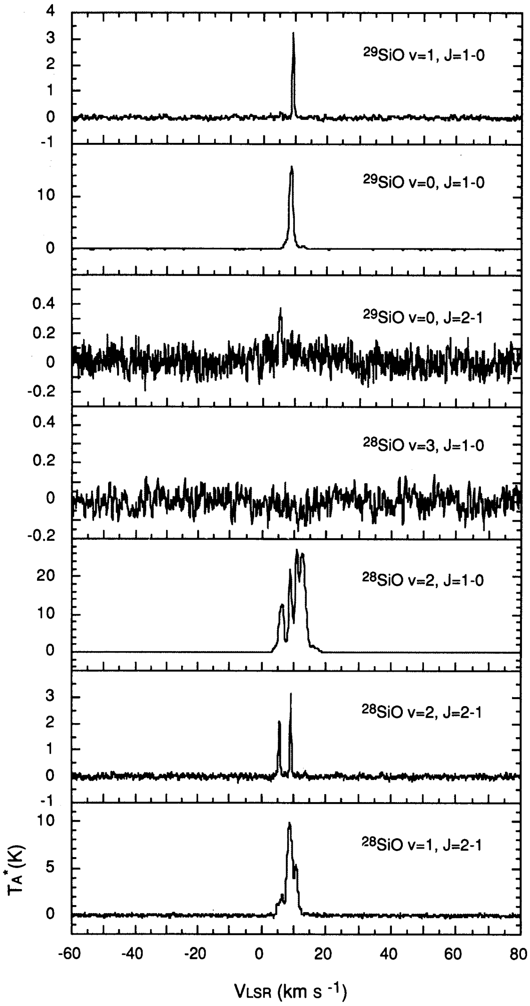

Fig. 1. Simultaneously observed spectra of ^{28}SiO and ^{29}SiO from TX Cam on 1994 March 27.

4. Discussion

The ^{29}SiO $v = 1$, $J = 1$–0 line has been detected only in TX Cam among the 54 surveyed sources. TX Cam has shown a normal feature as a Mira variable star. It has a spectral type of M8–M10, and an optical variation from $V_{\rm max} = 11.60$ to $V_{\rm min} = 16.20$ in magnitude with a period of 557 d (Kholopov et al. 1985). The mass-loss rate estimated from the CO $J = 2$–1 line is $3 \times 10^{-6} M_\odot$ yr^{-1} (Wannier, Sahai 1986). However, TX Cam shows unusual infrared and chemical characteristics as a known oxygen-rich star. The IRAS flux ratio S(60)/S(25) of TX Cam is relatively large, putting this star in region VII of van der Veen and Habing (1988) where the proportion of stars with carbon-rich circumstellar shells is large. TX Cam is also rich in molecular lines(CO, CS, CN, HCN, HNC, SiO, SiS, and SO), as studied by Lindqvist et al. (1988,

Table 1. Line parameters of TX Cam.

Source	Transition	Peak antenna temperature	RMS (K)	Peak velocity (km s^{-1})	Integrated temperature (K km s^{-1})
TX Cam	^{29}SiO $v = 1$ $J = 1$–0	3.2	0.05	9.2	2.5
	^{29}SiO $v = 0$ $J = 1$–0	15.7	0.04	8.9	25.9
	^{29}SiO $v = 0$ $J = 2$–1	0.3	0.05	5.4	2.0
	^{28}SiO $v = 3$ $J = 1$–0	<0.1	0.03		
	^{28}SiO $v = 2$ $J = 1$–0	27.2	0.04	10.8	145.9
	^{28}SiO $v = 2$ $J = 2$–1	3.1	0.06	9.2	2.0
	....	2.1	0.06	5.6	1.5
	^{28}SiO $v = 1$ $J = 2$–1	9.9	0.09	8.9	29.9

Note: Observing date is 1994 March 27. An antenna temperature of 1 K corresponds to a flux density of 3.3 and 4.5 Jy at 43 and 86 GHz, respectively.

1992) and Olofsson et al. (1991). The abundances of carbon-bearing molecules are particularly high. However, neither OH (Olnon et al. 1980) nor H_2O (Bower, Hagen 1984) have been detected. It is interesting how these characteristics in TX Cam are related to the rare maser of the ^{29}SiO $v = 1$, $J = 1$–0 line.

The ^{29}SiO $v = 1$ maser lines detected in evolved stars, are only the $v = 1$, $J = 3$–2 to 6–5 lines. It is most surprising that the lowest rotational transition in the first vibrational excited state of ^{29}SiO has not been detected in any evolved stars, including VY CMa. Based on the normal inversion mechanism of SiO masers, the lowest rotational transition is expected to have the strongest intensity, as shown in the case of the ^{29}SiO $v = 0$ and ^{28}SiO $v = 1$ masers. Thus, the ^{29}SiO $v = 1$, $J = 1$–0 transition was considered to be intrinsically very weak ($\sim$ 130-times weaker than that of the ^{28}SiO $v = 1$, $J = 1$–0 masers; Alcolea and Bujarrabal 1992). The present detection of the ^{29}SiO $v = 1$, $J = 1$–0 line in TX Cam (only $\sim$ 8-times weaker than the ^{28}SiO $v = 2$, $J = 1$–0 line) shows that the non-detection of this line in other M stars can not be accounted for based on its intrinsic strength.

As mentioned by Alcolea and Bujarrabal(1992), the inversion model of SiO $v = 0$ masers (Robinson, Van Blerkom 1981; Deguchi, Nguyen-Q-Rieu 1983) can not explain the observed ^{29}SiO and ^{30}SiO masers. Cernicharo et al. (1991) and Chernicharo and Bujarrabal (1992) suggested that the line which overlaps between ^{29}SiO and another species (^{28}SiO, ^{30}SiO) play an important and very selective role in pumping all of the vibrationally excited state masers of the rare isotopes, and in pumping of the ^{29}SiO $v = 0$ masers. Olofsson et al. (1981) also suggested the line overlap between ^{28}SiO and ^{29}SiO to explain the observation of SiO isotopes in Orion-KL. Cernicharo et al. (1991) adopted it to explain their observational results. Among the four simultaneously observed lines of ^{29}SiO ($v = 1$, $J = 2$–1 to 5–4), they detected only the $v = 1$, $J = 4$–3 line in W Hya, R Leo, R LMi, U Ori, IK Tau. Based on the standard large velocity-gradient(LVG) calculations for the ^{29}SiO molecule, they showed that the $J = 4$–3 line dominates in a narrow column density range. However, it was difficult to explain the observed intensity ratios. Consequently, they adopted the line overlap between the $J = 9$–10, $v = 1$–0 line of ^{28}SiO and the $J = 4$–5, $v = 1$–0 line of ^{29}SiO, and showed that only the $J = 4$–3 line could be efficiently pumped for moderate column densities. For TX Cam, although we have detected the ^{29}SiO $v = 1$, $J = 1$–0 maser, and we could not find any selective excitation of a certain level in the observational results of Cernicharo et al. (1991). Therefore, we can not directly adopt their line-overlap mechanism for the ^{29}SiO line of TX Cam without testing the normal inversion mechanism. However, we expect from their LVG calculations for ^{29}SiO molecule that the intensity of the $v = 1$, $J = 4$–3 line is about 300-times the intensity of the $v = 1$, $J = 1$–0 line. Since the detected peak antenna temperature of the ^{29}SiO $v = 1$, $J = 1$–0 line is 10.7 Jy, the peak antenna temperature of the $v = 1$, $J = 4$–3 line would be very strong ($\sim$ 3000 Jy). Still Cernicharo et al. (1991) did not detect this line toward TX Cam within the upper limit of $\sim$ 1 Jy, although its time variation was considered. Thus, the simple LVG model for ^{29}SiO can not be adopted for TX Cam.

Concerning the other rare maser, the ^{28}SiO $v = 2$, $J = 2$–1 line, Olofsson et al. (1981, 1985) suggest that the general weakness of the $v = 2$, $J = 2$–1 line in oxygen-rich stars(except for the S-type star χ Cyg) can be explained by a line overlap of H_2O with the $v = 1, J = 0 \rightarrow v = 2$, J=1 line of SiO causing an overpopulation of the $v = 2$, J=1 level. They proposed that in χ Cyg, as an S-star, and therefore water deficient compared to other SiO maser stars, the overpopulation of the $v = 2$, J=1 level is lower and the $v = 2$, $J = 2$–1 line shows moderate strength. Since an H_2O maser has not been detected in TX Cam, the above proposition can be adopted for the $v = 2$, $J = 2$–1 maser of this source. We may also adopted this proposition concerning the weakness of the ^{29}SiO $v = 1$, $J = 1$–0 line in oxygen-rich stars, because we could not detected this line in 53 oxygen-rich stars, except for TX Cam, where no H_2O maser has been detected. These 53 surveyed oxygen-rich stars has the H_2O maser detection rate of $\sim 72\%$ (Benson et al. 1990). In relation to this hypothesis, we investigated the possible overlaps between a line of H_2O and the ^{29}SiO $v = 0$, $J = 1 \rightarrow v = 1$, J=0 line (overpopulating the ^{29}SiO $v = 1$, J=0 level) and the ^{29}SiO $v = 1$, $J = 1 \rightarrow v = 2$, J=0 and/or the $v = 1$, $J = 1 \rightarrow v = 2$, J=2 lines (depopulating the $v = 1$, J=1 level). Such lines of H_2O could not be found within ± 5 km s^{-1} (Guelachvili et al. 1986). However, further investigation of the possible line- overlap pairs between this rare maser and other molecular lines would be valuable for understanding the pumping mechanism of SiO maser lines in relation to the chemical composition of evolved stars. In addition, surveys of both the ^{28}SiO $v = 2$, $J = 2$–1 and ^{29}SiO $v = 1$, $J = 1$–0 lines in S-star are needed. For TX Cam, it is necessary to confirm its spectral type with optical spectroscopic observations. TX Cam may be included in a transition object between oxygen and carbon stars by its chemical and infrared characteristics.

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