RAPID FLUCTUATIONS OF WATER MASER EMISSION IN VY CANIS MAJORIS

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ABSTRACT

We report the observational results of short timescale monitoring of the 22 GHz water maser emission in VY CMa. A quasi-sinusoidal fluctuation has been detected with the relative flux intensity change of 20%–25% and a period of 10.3 day for two dominant features. This detected variability appears to be superimposed on the normal maser lines. We cannot easily explain the rapid fluctuation with the variation of the radiative input or the strong interstellar scintillation along the line of sight. The variation may be caused by the periodic shock.

Subject headings: circumstellar matter — masers — stars: individual (VY Canis Majoris)

1. INTRODUCTION

VY CMa is a well-known M5e irregular variable supergiant star immersed in a small reflection nebula and located at the interface of a large molecular cloud and the H II region S310 (Lada & Reid 1978). In the infrared, at 20 μ m, it is one of the brightest sources in the sky (Hyland et al. 1969) and at radio wavelengths it displays strong maser emission from OH, H₂O, and SiO maser molecules (Herbig 1969, 1972). In recent years a high number of rotational transitions, including the microwave transition of ²⁸SiO $v = 4$, $J = 5-4$ transition and the rotational lines of the rare isotope ²⁹SiO, have been detected with the IRAM radio telescope (Cernicharo et al. 1992). Moreover, five new water maser transitions ($4_{4,0}-5_{3,3}$ at 96 GHz; $5_{5,0}-6_{4,3}$ at 232 GHz; $7_{7,0}-8_{6,3}$ at 263.5 GHz; $10_{2,9}-9_{3,6}$ at 321 GHz; and $5_{1,5}-4_{2,2}$ at 325 GHz) have been observed (Menten & Melnick 1989, 1991; Yates 1992). The abundant lines from the source allow many authors to infer the structure of the envelope and the conditions of maser excitation. Comparing the line profiles of the well-studied 22 GHz water maser, the (sub)millimeter H₂O emission, and a high number of SiO masers, Menten & Melnick (1991) concluded that the vibrationally excited H₂O and SiO masers probably arise from a region with infalling motions of matter. Based on the clumps of relatively high velocity detected only at the $v = 3$, $J = 4-3$, and $v = 4$, $J = 5-4$ SiO lines, Cernicharo et al. (1992) proposed a rotating disk model since the highest rotational velocity is expected in the inner (more excited) regions of the rotating structures. Evidence for a disk and bipolar flow is clearly seen in the MERLIN maps of circumstellar 22 GHz H₂O masers around VY CMa (Yates et al. 1992).

The maser variability is an important probe in the dynamics of the circumstellar envelope. However, the availability of copious data on maser variability has not led to significant improvement of our understanding of the physics of the circumstellar environment. One of the first attempts to investigate in detail the long-term time variations of several stars was carried out by Cox & Parker (1979). They have monitored at irregular intervals the maser

emission from VY CMa from 1974 September to 1977 May. After analyzing the data they concluded that the proportional changes in intensity of the three main groups of features indicated the existence of a common pump source. Comparing their results with the spectra obtained by Knowles & Batchelor (1976) they also concluded that in long-term periods some components presented independent variability. Gomez Balboa, & Lepine (1986) extended their investigation of the variability of the water emission of VY CMa to 1981. They argued that a 350 day period seemed to be present in all three features and was possibly related to the common infrared pumping source. A monitoring observation of four sources of SiO maser emission was made by Pijpers et al. (1994). They failed to detect the variation in VY CMa.

With the objective of studying very short interval variation (days to hours) of water maser emission at 22 GHz, we undertook a monitoring program of 14 sources. Some interesting results of these observations will be presented elsewhere (Scalise, Han, & Zheng 1998). Here we present the results of the monitoring of the VY CMa emission and report the detection of a 10.3 day periodicity.

2. OBSERVATIONS

The monitoring observations of the short time variation of the water maser were carried out in 1993 from August 26 through September using the 13.7 m telescope at the Qinghai Station of Purple Mountain Observatory (PMOQH). This antenna is located in the Gobi Desert, a very dry and arid region at 3200 m above the sea level in western China. It is a classic Cassegrain telescope and has a pointing accuracy better than 20" and at 22 GHz a HPBW of 4'.2. The front end operates with a cooled Schottky mixer and a 1.4 GHz FET IF amplifier. The local oscillator was a phase-locked Gunn diode. A high-resolution 1024 channel AOS was employed as a back end, having a channel spacing of 12 kHz, or a velocity resolution of 0.16 km s⁻¹ at the observed frequency. Observations were made in position-switching mode and a 120 K noise diode was used as a second calibrator. To check the stability of the noise diode a number of continuum sources were observed. During the entire observation period the weather conditions at the site were excellent. We estimate that the atmospheric attenuation at zenith during the entire period was about 0.01. The absolute calibration for flux density was about 20%.

In order to eliminate any gain dependence effect of the radio telescope all the observations were carried out at the

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FIG. 1.—Spectrum of the 22 GHz water maser emission from VY CMA. The on-source integration time is 120 s ($1\sigma = 0.9$ K). Velocity resolution of the spectrum is 0.16 km s^{-1} . The lower panel displays the spectrum on an expanded scale.

same sidereal time, i.e., at the same parallactic angle and elevation angles. To discriminate the instrumental effects and the real changes in the flux density, the monitoring program included several sources with different spectral features in order to understand the telescope properties.

3. RESULTS OF THE OBSERVATION

A spectrum of the water maser emission from the supergiant star VY CMA is given in Figure 1. The rms noise level (1σ) in the plot is about 0.9 K, obtained after 240 s integration (120 s on-source). At this noise level, we found that the maser lines spread from -10 to 30 km s^{-1} . The velocity range is similar to that in spectra observed by many authors (Yates 1992; Menten & Melnick 1989; Cox & Parker 1979; Rosen et al. 1978). The central group of features in the velocities from 10 to 25 km s^{-1} appears to consist primarily of two prominent peaks located at 14 and 20 km s^{-1} , respectively. The observed characteristics and the ratio of these two components are very similar to those reported by Yates et al. (1992), although Yates quoted 16 and 22 km s^{-1} for these two peaks. The origin of this discrepancy might be caused by the frequency calibrations. These two components are approximately symmetric about the stellar velocity of 17.6 km s^{-1} (Reid & Dickinson 1976). There are many weaker features around the base of these peaks. Other two groups near 35 to 45 km s^{-1} and -10 to 0 km s^{-1} have varied considerably over the past twenty years. For example, in the spectrum from 1976 September given by Rosen et al. (1978), the component at -4 km s^{-1} was one of the brightest features, but it has almost disappeared in our spectrum at the 0.9 K noise level.

Figure 2 shows the flux density variations of these two peaks as function of time scaled by 1 day. The intensity variation amplitudes were about 60 K for the feature at 14 km s^{-1} and 15 K for the feature at 20 km s^{-1} , respectively. The relative changes in the intensity for these two features are approximately the same, about 30%. The fluctuations appear to be sinusoidal with a period of 10.3 days. The

variation of the line profile integration also follows the period. The average error for the Gaussian fit to the spectra is about 0.5 K. It should be noted that during our observations more than one scan was obtained on several

FIG. 2.—Variation curves of the radio flux densities for two peaks at velocities of 14 km s^{-1} (top) and 20 km s^{-1} (bottom), respectively. Flux densities are corrected by atmospheric attenuation, antenna gain variations, and pointing error. The average error for the fitting Gaussian line profiles to the spectra is about 0.5 K. The sinusoid overlaying on the plot is in the same period, 10.3 days, with different amplitudes: 60 K for the feature at 14 km s^{-1} and 15 K for one at 20 km s^{-1} . The monitoring observations were carried out in 1993 August 26 through September 24.

occasions. The error of the flux density between different scans was not greater than 20 K for the feature at 20 km s^{-1} and 5 K for the feature at 14 km s^{-1} . We also examined carefully the shifts of radial velocities for these two components. The systematic shifts of 0.01 km s^{-1} per day are probably caused by the instrumental frequency axis. It is difficult to identify a phase lag between these two curves of variations in Figure 2.

4. COMMENTS OF THE RESULTS

It is likely that the apparent maser fluctuations are mostly real and are not caused by instrument effects. The amplitudes of these two sinusoidal curves are different, and instrument effects could not be responsible for such percent variations in different channels. In addition, observations of 13 other masers including W3(OH), W51N, and WHya done on the same days as part of our short time variation study of the water maser variability, do not reveal any periodic variation (Scalise et al. 1998). The 4.2" primary beam is much larger than the 20" pointing accuracy, so pointing errors could not cause the apparent variability for the maser structures located in the envelope of the VY CMa supergiant star. The half-power width of these two peaked features are over more than seven channels. Hence there was no undersampling of spectral lines which might have caused the variations. Any polarization effects are not significant because all observations were made at approximately the same sidereal time.

The same period of the flux variation for two features at 14 and 20 km s^{-1} indicates the existence of a common source of the "seed" variation. Approximately the same percent of variation for these two features may come from the same physical factors in different regions. In the absence of other data such as IR and visual observations it is difficult to identify the origin of the maser variability; however, based on our radio observation, we tentatively make the following points.

Three mechanisms could produce the maser variability in the circumstellar envelope of VY CMa: a quasi-sinusoidal input signal, a quasi-sinusoidal pumping rate, or the interstellar scintillation.

If the maser is unsaturated, the maser output would be expected to follow the sinusoidal input variation. It is, however, hard to explain the 10.3 day sinusoidal oscillation of the maser. For variable supergiant stars like VY CMa, the period of oscillations always scales inversely proportional to the square root of the mean density (Cox 1980). The supergiant stars have a characteristic period of about 300 days. Harmonic oscillations near 10 days must be weak. Moreover, it is difficult to explain the linear changes in the two features in terms of the input variability.

Intermolecular collisions are generally thought to be responsible for the pumping mechanism of the water masers

in the late-type stars. The changes in the collision rates produced by periodic shock waves could introduce the apparent maser variability. The photosphere acts as a pulsating piston and injects a large-amplitude shock wave into the gas envelope once each pulsation cycle. The inner layers close to the star may be driven outwardly by directed shock fronts and drawn back to the photosphere surface by gravity (Wood 1979; Hill & Willson 1979). This phenomenon may provide a satisfactory explanation of the quasi-sinusoidal fluctuation of the intensities of the maser emission. For the saturated maser, the linear and periodically simultaneous variation can be explained by an expanding shell with 3 km s^{-1} velocity at a distance of 10^{16} cm .

Interstellar scintillation caused by a scattering medium along the line of sight may play an important role for the explanation of the short time fluctuation of the 22 GHz water masers. For the strongly diffractive scintillation, the correlation timescale is $t_d \sim \lambda/2\pi\theta_s v_t$ for a source of angular size θ_s , observing wavelength λ , and a relative transverse velocity v_t (Simonetti 1992). For $D = 1.5 \text{ kpc}$ (Herbig 1969), the diameter of maser spot $d_s = 1.5 \times 10^{13} \text{ cm}$ (Rosen et al. 1978) and $v_t = 60 \text{ km s}^{-1}$, the diffractive timescale is about 10 s. It is too short compared to our observing time amplitude. The correlation timescale of refractive interstellar scintillation is $t_r \sim d_0/v_t$, where d_0 is the observed angular size. For the assumption $d_0 = d_s$, the refractive timescale is about 29 days, 3 times longer than our observations. Therefore, the interstellar scintillation is difficult to explain in 10.3 day variations.

Based on the above discussion, we tentatively conclude that the maser variability may be caused by the periodic shock. If the idea is true, the maser emission probably arises from a region close to the star. For the outer layers the matter driven by the shock does not return to its original position before the arrival of the next shock wave and superperiods may be established. If our observing variations are correct short time periodical variability of these two features originated from the same stellar optical or IR radiation in the pumping of the water maser. To better understand whether there is real periodicity present in the short timescale of VY CMa and to provide reasonable analysis for the origin of variation, a monitoring program with much longer duration is needed, with both the infrared and optical data.

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