THE ASTROPHYSICAL JOURNAL, 430:L61–L64, 1994 July 20

OBSERVATION OF A RING STRUCTURE IN SiO MASER EMISSION FROM LATE-TYPE STARS

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Received 1994 March 4; accepted 1994 May 4

ABSTRACT

We have used the NRAO Very Long Baseline Array (VLBA) to make the first full high-resolution synthesis images of 43 GHz SiO masers around late-type stars. Our observations of the stars TX Cam and U Her reveal well-defined rings of maser emission at ≈2–4 stellar radii. These images are in contrast to earlier, less accurate, fringe-frequency maps of SiO masers which suggested chaotic structures in similar stars. We can place the SiO masers in the so-called extended atmosphere of the star, where the dynamics are very complex and dust grain formation occurs. Our observations demonstrate that the SiO maser outflow is ordered, not random, and that the masers are being tangentially amplified. We are unable to distinguish between proposed models for radiative and collisional pumping of the SiO masers.

Subject headings: circumstellar matter — masers — stars: individual (TX Camelopardalis, U Herculis)

1. INTRODUCTION

Many evolved stars of low to moderate mass ($<8\ M_\odot$) undergo a period of mass loss in which the outer layers of the star are ejected. The circumstellar envelopes of these evolved stars contain many molecular species. Of particular interest are OH, H_2O, and SiO which exhibit strong maser emission. The SiO masers lie close to the stellar surface and should allow us to investigate the properties of this complex region.

Many interferometric observations of OH and H_2O stellar masers have been performed over the past 20 years, using connected-element, radio-linked and very long baseline interferometers. However, high-resolution interferometric observations of SiO masers have been much less common; only a few sources have been mapped using fringe-frequency mapping techniques (Moran et al. 1979; Lane 1982; McIntosh 1987). These observations demonstrated that the SiO masers in circumstellar envelopes were distributed over areas ≤80 mas in diameter. From visibility measurements the individual masers were thought to consist of relatively large spots $\approx 10^{13}$–10^{14} cm in size with either an extended halo or other weaker, smaller masers spread over areas of a few millarcseconds. Recently, Colomer et al. (1992) demonstrated that, with current technology, normalized fringe visibilities have structure on a much wider range of scales than previously detected.

TX Cam is a cool M-type star (M8–M10) with a period of 557 days. The distance is uncertain, with reported values in the range 450 pc (Olofsson et al. 1991) to 1200 pc (Bujarrabal, Planesas, & del Romero 1987). The former value may be the most probable since it is based on a recent period-luminosity relation for Mira variables (Hughes & Wood 1990). SiO maser emission was first reported in 1977 (Spencer 1977), and strong maser emission from higher energy states has also been detected (Jewell et al. 1987). Thermal emission from several other molecules has also been observed, including the first detection of CN in an oxygen-rich envelope (Olofsson et al. 1991). Surprisingly, no other types of masers are known to exist in the circumstellar envelope around TX Cam.

U Her is an M5e–M8e star with a 405 day period. Its estimated distance is 460 pc (Gomez Balboa & Lepine 1986). SiO masers from U Her were detected first in 1975 (Snyder & Buhl 1975), and it has been shown to emit strong SiO maser emission from several vibrational and rotational transitions (Engels & Heske 1989). U Her also contains relatively strong OH and H_2O masers (Sivagnanam et al. 1990; Lane et al. 1987).

2. OBSERVATIONS

The $v = 1, J = 1$–0 SiO masers around U Her were observed for 8 hr on 1992 May 21 using four antennas (Pietown, Los Alamos, Kitt Peak, and North Liberty) of the VLBA, a new facility of the National Radio Astronomy Observatory.[1] The TX Cam SiO masers were observed for 6 hr on 1992 August 10 using five antennas (Los Alamos, Kitt Peak, Fort Davis, North Liberty, and Brewster) of the VLBA. The data were recorded with a 2 MHz bandwidth and left circular polarization on the Mk II recording system and later correlated in Socorro, New Mexico. The synthesized beam resulting from these arrays was ≈1 mas and images of size 100 × 100 mas were made. The calibration and data reduction were performed using standard software. The techniques used will be described in more detail in a forthcoming paper.

Figure 1 shows the total power spectra of the SiO maser emission toward the two stars. The TX Cam spectrum covers a velocity range of ≈ 8 km s^{-1} centered on ≈ 9 km s^{-1}. Observations of the $v = 0$ transition of SiO (Bujarrabal et al 1986) suggest that the velocity of the star with respect to the local standard of rest (LSR) is 8.9 km s^{-1}, although the CO and CS

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[1] The National Radio Astronomy Observatory is operated by Associated Universities, Inc., under cooperative agreement with the National Science Foundation.

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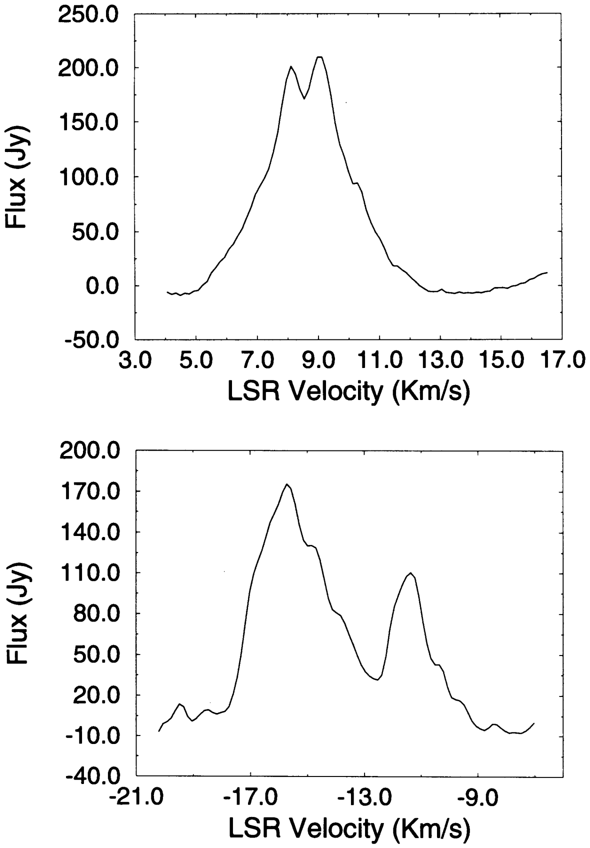

FIG. 1.—Total power spectra of the 43 GHz SiO $v = 1$, $J = 1\text{–}0$ masers from the stars TX Cam (*top*) and U Her (*bottom*). The TX Cam spectrum was taken with the Los Alamos VLBA antenna on 1992 August 10; the U Her spectrum was taken with the Kitt Peak antenna on 1992 May 21.

spectra of Olofsson et al. (1991) tend to have line center velocities ranging from 9.6–12.5 km $\mathrm{s^{-1}}$. The U Her spectrum covers a velocity range of 11 km $\mathrm{s^{-1}}$ centered on -13.4 km $\mathrm{s^{-1}}$. The LSR velocity of the star, as determined by observations of the SiO $v = 0$ emission, is -13.4 km $\mathrm{s^{-1}}$ (Morris et al. 1979).

Figure 2 shows an image integrated over all velocity channels containing emission from TX Cam. The masers form a partial ring of emission of 28 mas diameter (12.6 AU assuming a distance of 450 pc). The masers appear to be absent from the southern portion of the ring. In fact, there are very weak masers in the south, but they are not seen clearly owing to the dynamic range of the composite image. There is also an obvious radial nature to the maser emission, with most maser groups appearing to point away from the center of the image. This structure may be due to velocity gradients within the maser groups; group A (Fig. 2) exhibits a total change in line of sight velocity of 3.2 km $\mathrm{s^{-1}}$ across its length of 4.7 mas. However, within each individual velocity channel the maser emission is essentially pointlike. The ring of masers has an average width (FWZP) of ≈ 2.7 mas, implying a narrow zone within which inversion occurs.

Figure 3 shows a composite image for the SiO masers around U Her. The U Her masers were weaker than those of TX Cam at the epoch of observation, and so the image is somewhat noisier. However, an elongated ring structure is clear, being 21 mas (≈ 9.7 AU) north-south and 16 mas (≈ 7.4 AU) east-west, with an average width of 2.6 mas.

3. DISCUSSION

One important question is, "How far from the star do the masers lie?" Accurate determinations of stellar diameters for Mira variables are not common. The diameters of both TX Cam and U Her have so far not been determined observationally. Cahn & Elitzur (1979), using a period-luminosity spectral type scheme for Mira variables, estimated the photospheric diameters of TX Cam (450 pc) and U Her (460 pc) to be 3.6 and 4.8 AU, respectively. There are only a few actual measurements available for stars with SiO emission; VLA observations (Reid & Menten 1993) of the Mira variable W Hya reveal a photospheric diameter of ≈ 9 AU and optical interferometry of the stars R Aql, R Aqr (Tuthill, Haniff, & Baldwin 1993), and R Leo (Tuthill et al. 1994) suggest diameters of ≈ 6.4, 4.6, and 4.6 AU, respectively. The measurements for all three stellar diameters are about twice the predicted values (Cahn & Elitzur 1979) (corrected for different distance estimates), implying that the theoretical diameters are only accurate to a factor of 2 and are probably low. This therefore implies that the masers around TX Cam are situated between 2 and 4 R_* from the center of the star, while those around U Her appear to be at ≤ 2 R_*. Thus, we suggest that the $v = 1$, $J = 1\text{–}0$ SiO masers do not reside in the stellar photosphere as had been suggested for one model of maser pumping (Elitzur 1980). Instead, they appear to lie in the so-called extended atmosphere, the region between the photosphere and dust formation point.

Observations of OH masers toward evolved stars demonstrate that, in general, the OH emission lies in spherically symmetric shells in the outer reaches of the envelopes where the gas has reached its terminal velocity (e.g., Norris, Diamond, & Booth 1982). Since this is the case, the OH masers are amplified in the radial direction, and the line of maximum maser gain lies in the same direction as the exciting star. The situation with the SiO masers is clearly different; there is no maser emission visible inside of the area enclosed by the rings. This observation argues strongly against radial amplification in a spherically symmetric shell and is indicative of tangential amplification, i.e., the masers appear to lie perpendicular to the radial direction. Tangential amplification can be produced if any of three conditions are met (Bujarrabal & Rieu 1981; Rosen et al. 1978): (1) the masers lie in a flattened ellipsoid or disk, (2) there is a large radial velocity gradient in a spherically symmetric shell, or (3) the gas has a rotational velocity component. Western & Watson (1983) suggest that the observed linear polarization in SiO masers may also be due to tangential amplification. Our observations provide the first direct evidence that such a process may be occurring.

The extended atmosphere of a variable star is a region of complex interaction between the dynamics of the pulsating atmosphere and the dust complex at a few stellar radii. The region is permeated by shocks, with outflow being the dominant kinematic component but inflow also being present (Fleischer, Gauger, & Sedlmayer 1991; Hinkle, Scharlach, & Hall 1984). We have investigated the kinematics in this inner part of the circumstellar envelope by fitting a generalized ellipsoidal model (a generalization of that described by Bowers 1991) to the TX Cam outflow. Our model assumes that the gas is confined to a hollow ellipsoidal region around the star with a velocity field that has components of outflow, rotation (either solid body or Keplerian) and acceleration and that can vary with latitude within the ellipsoid. No model uniquely describes the TX Cam data, but a plausible fit is provided by an ellipsoid of radii 15 × 18 × 8 mas with a normal vector inclined at 10°–15° to the line of sight and an isotropic radial outflow of

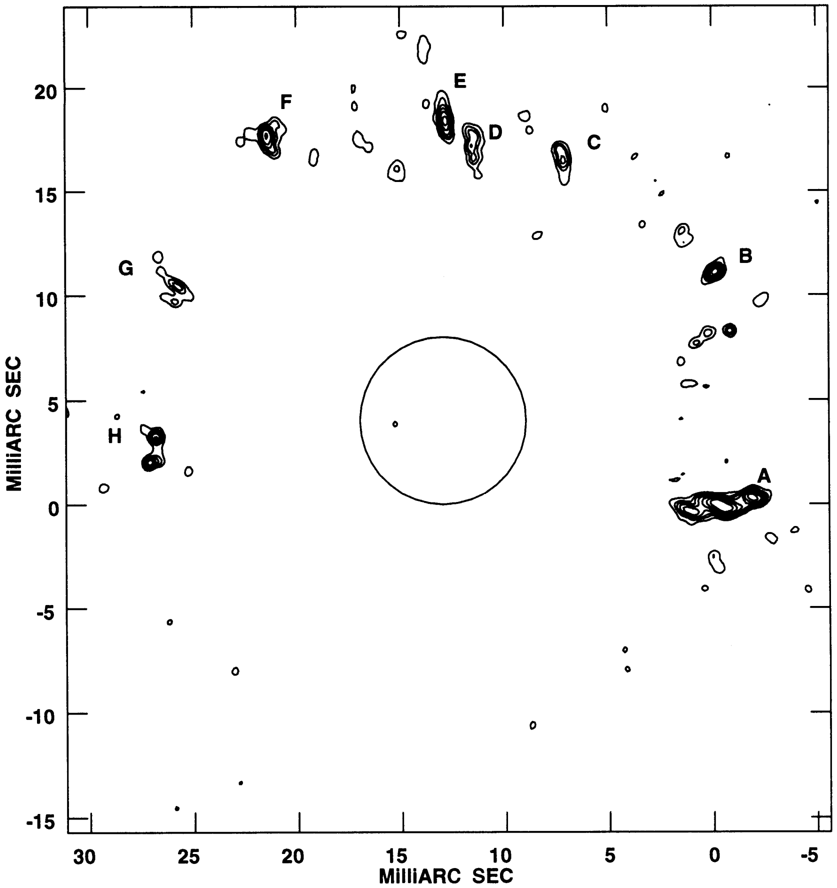

FIG. 2.—A composite image of the 43 GHz SiO masers around the star TX Cam, formed by summing all channels with emission above a threshold of 0.5 Jy. Since the channel images are limited by missing Fourier spacings, the summed image still contains artifacts from the strongest features, which mask some of the weaker components. The image covers a velocity range from 5–13 km s^{-1}. The circle in the center represents a star with a photospheric diameter of 3.6 AU at an adopted distance of 450 pc (see text), assumed to lie at the centroid of the maser emission. The letters adjacent to the maser complexes denote a key to their LSR velocity ranges: A = 5.1–8.3 km s^{-1}; B = 7.4–8.3 km s^{-1}; C = 8.4–9.1 km s^{-1}; D = 7.7–8.7 km s^{-1}; E = 8.4–9.9 km s^{-1}; F = 9.0–10.3 km s^{-1}; G = 10.1–11.2 km s^{-1}; H = 8.4–10.9 km s^{-1}. Note that the most blueshifted masers lie on the western side of the image, the most redshifted on the eastern side.

$\approx$5–6 km s^{-1}. There is some evidence for gravitational-type deceleration. Future proper motion studies will provide important additional constraints on kinematic models. Examination of the TX Cam image shows that there is a systematic variation of component velocity from west to east across the source. One possibility is that this is due to a $\approx$2 km s^{-1} rotation ($v \sin i$) of the envelope. However, our model fits demonstrate that this effect can be explained by orientation alone without necessarily invoking rotation.

Lockett & Elitzur (1992) have recently studied both radiative and collisional pumping of SiO masers around stars. They conclude that the predominant pump is collisional, since such pumps can produce maser emission over much broader ranges of location and conditions than radiative pumps. Collisional pump models can also explain the observations of other vibrational and rotational transitions. Using nominal parameters for the conditions around late-type stars (viz., $n_{\mathrm{H}_2} \approx 3 \times 10^9$ cm^{-3}; $X_{\mathrm{SiO}} = n_{\mathrm{SiO}}/n_{\mathrm{H}_2} = 5 \times 10^{-5}$), they find that the maser emission should peak at a distance of $\approx$25 AU from the star. This is much larger than the distances we observe. The radius at which peak emission occurs can, however, be lowered by adjusting the values of n_{H_2} and/or X_{SiO}. Lockett & Elitzur (1992) also state that the only radiative pump capable of producing the required emisson is that of Deguchi & Iguchi (1976). That particular mechanism requires a very steep velocity gradient ($d \log V/d \log R \approx 5$) and that the masers be located at $\approx$2–4 R_*. Unfortunately the radiative pump model has difficulty producing maser emission from higher energy states. Our observations show that the SiO masers in TX Cam and U Her do lie at the required distance from the star but are unable to directly confirm a large velocity gradient. Without more extensive monitoring and polarization observations our current data are not able to distinguish between radiative or collisional pumps for these two stars.

IR interferometry (Bester et al. 1991) reveals that dust can condense at a few (3–5) stellar radii, where the temperature can be as high as 1200 K. It is significant that we observe no SiO maser emission beyond 4 R_*; presumably, this is the radius at which the Si begins to condense into dust.

4. CONCLUSIONS

We have produced the first VLBI synthesis images of SiO masers around the Mira variables TX Cam and U Her. These images have revealed the surprising result that the masers lie in rings at $\approx$2–4 stellar radii and are probably tangentially amplified. The masers around TX Cam fit a model of a hollow, expanding ellipsoid. Unfortunately, we are unable to dis-

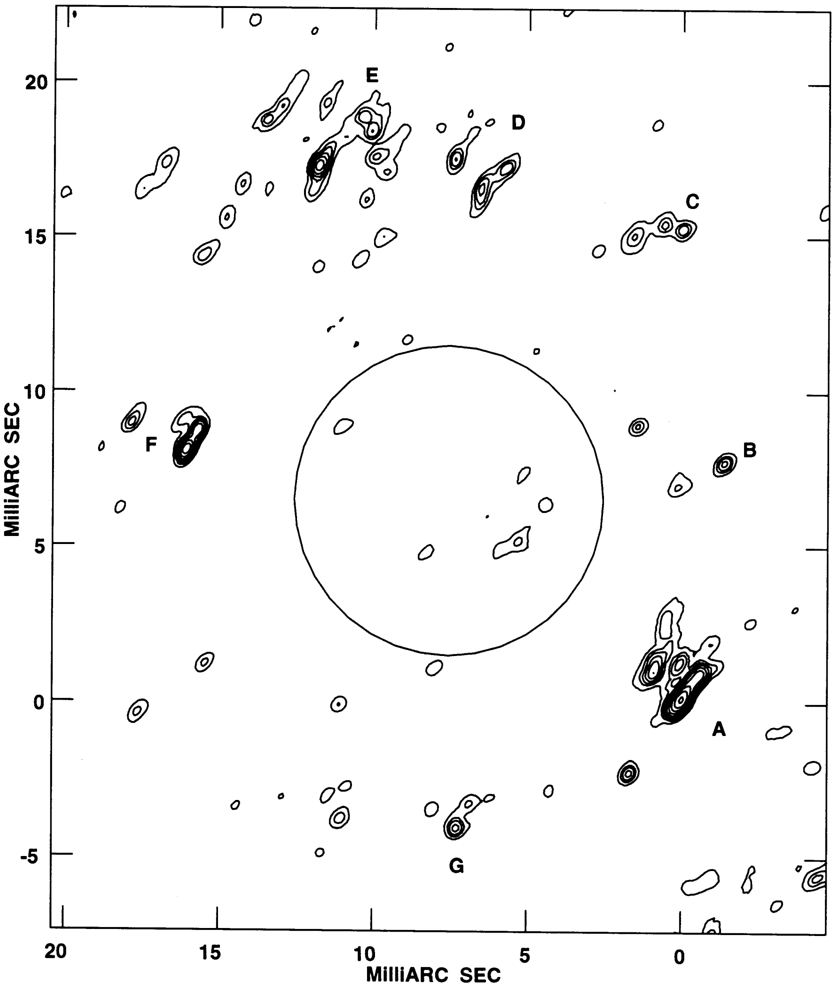

FIG. 3.—A composite image of the 43 GHz SiO masers around the star U Her; the image covers a velocity range from -18 to -9 km s^{-1}. The circle represents a star with a photospheric diameter of 4.8 AU at an adopted distance of 460 pc (see text). The letters adjacent to the maser complexes denote a key to the average LSR velocity of each group; A = -11.8 km s^{-1}; B = -12.8 km s^{-1}; C = -12.2 km s^{-1}; D = -11.6 km s^{-1}; E = -14.5 km s^{-1}; F = -11.4 km s^{-1}; G = -15.6 km s^{-1}. Note that the most blueshifted masers lie in the north and south of the image

tinguish between radiative or collisional pump models for the SiO masers. Monitoring observations, currently in progress, should enable us to answer such questions in the near future.

We wish to thank Alain Baudry, Moshe Elitzur, and Roy Booth for helpful comments that much improved the text.

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