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A WATER MASER ASSOCIATED WITH EU ANDROMEDAE: A CARBON STAR NEAR AN OXYGEN-RICH CIRCUMSTELLAR SHELL

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ABSTRACT

An H_2O maser emission line at 22.2 GHz has been detected toward the carbon star EU And, confirming the conclusion based on analysis of LRS *IRAS* spectra that this star is in the vicinity of an oxygen-rich circumstellar shell. We interpret the 24 km s^{-1} velocity difference between the H_2O maser, measured at -29.4 km s^{-1}, and the carbon star absorption line velocity of -53 km s^{-1} to be due to the orbital motion of the C star about an M star with a relatively thick circumstellar shell.

Subject headings: masers — stars: carbon — stars: circumstellar shells — stars: individual (EU And)

I. INTRODUCTION

Recently, Little-Marenin (1986) and Willems and de Jong (1986) have shown that at least three reliably classified carbon stars, and three or four others with less reliable classifications, are near oxygen-rich circumstellar dust shells as deduced from the presence of the 10 μm and 18 μm silicate emission features in their *IRAS* low-resolution spectra (hereafter LRS) (*IRAS* Science Team 1986). These three stars are EU And (C4, 4: Dean 1976), BM Gem (C4, 5J with strong C_2, ^{12}CN and ^{13}CN features: Yamashita 1972) and V778 Cyg (C4, 5J: Yamashita 1975). The three stars were first recognized as carbon stars on the Dearborn Observatory's objective prism survey of red stars in the early 1940s. The location of the stars listed by Little-Marenin (1986) in color-color plots based on the *IRAS* point source fluxes at 12, 25, 60 and 100 μm are also indicative of oxygen-rich circumstellar (hereafter CS) shells (Zuckerman and Dyck 1986). As an independent confirmation of the oxygen nature of the dust shells, we decided to search the semiregular carbon stars EU And (R.A.[1950] = $23^h17^m41^s$; decl.[1950] = $+46°58'00''$ and BM Gem (R.A.[1950] = $7^h17^m56^s$; decl.[1950] = $+25°05'35''$) for H_2O emission, since H_2O masers are often associated with the CS shells around Mira or semiregular (hereafter SR) variable M stars (Engels 1979; Reid and Moran 1981; Dickinson and Dinger 1982).

Neither star has a well-established period. The fourth edition of the *General Catalog of Variable Stars* (Kholopov 1985) lists EU And as a SR variable with a photographic magnitude range of 12.9–14.1. The classification for BM Gem in the fourth edition was revised to SRb-286:^{d} from Lb. Often SR and Lb designations are indicative of less well observed Miras.

II. OBSERVATIONS

Observations of the 6_{16}–5_{23} transition of H_2O at 22,235.080 MHz were carried out with the 37 m Haystack Observatory[2] telescope during 1986 December 13–15 and 1987 January 23. The system temperature averaged about 90 K. The spectra were automatically corrected by the Haystack computer for atmospheric attenuation and for variation in telescope gain with elevation. We used an autocorrelator bandwidth of 13.33 MHz with 512 channels for the 1986 December observations, resulting in a velocity window of 180 km s^{-1} and a resolution of 0.53 km s^{-1}. In 1987 January, we used a bandwidth of 4.44 MHz with 1024 channels, resulting in a velocity resolution of 0.09 km s^{-1}. The stars were observed in a total power mode with three sets of 5 minutes on source and 5 minutes off source.

III. RESULTS

The 1986 December 15 maser detection toward EU And is shown in Figure 1. The observed line was well fitted by a Gaussian with the following parameters: $T_A^* = 0.68\ (0.05)$ K, $V_{LSR} = -29.40\ (0.03)$ km s^{-1}, and ΔV(FWHM) = 0.67 (0.06) km s^{-1}. The formal errors in the Gaussian fit are given in parentheses. The rms noise in the off-peak channels is 0.047 K. Although the line width is only a little greater than one resolution element, the line appears to be real since it showed up on all three runs and is typical of many other H_2O masers. The integrated area of the feature is 0.62 K km s^{-1}. Using a conversion factor of 12 Jy per K, the line intensity is 8.2 Jy. No other H_2O maser line is visible with flux > 1 Jy (3 σ).

EU And was reobserved on 1987 January 23 with better velocity resolution (0.09 km s^{-1}). The intensity appears to

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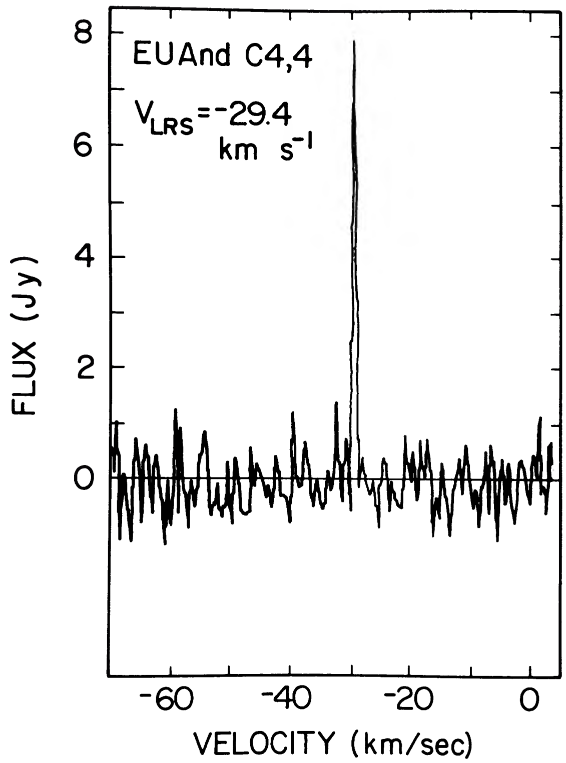

FIG. 1.—Spectrum of the H_2O maser emission in EU And

have decreased to about 5.5 Jy. The unsmoothed spectrum has rms noise equal to 0.125 K and the Gaussian fit gives values of $T_A^* = 0.46$ (0.04) K, $V_{LSR} = -29.67$ km s^{-1} (0.02), and ΔV(FWHM) = 0.52 (0.06) km s^{-1}. The FWHM is narrow (on the order of the previous resolution), which indicates that the line probably was not fully resolved in December, and we may have underestimated its intensity. The Hanning-smoothed spectrum (with rms = 0.076) shows the possibility of a second feature with Gaussian parameters $T_A^* = 0.16$ (0.02), $V_{LSR} = -31.21$ km s^{-1} (0.15), and ΔV(FWHM) = 1.83 (0.38) km s^{-1}. The total integrated area for both features is 1.242 K km s^{-1}.

BM Gem was observed 1986 December 14 with the velocity window centered on the optically determined radial velocity of 98 km s^{-1} (Abt and Biggs 1972), covering velocities from 8 km s^{-1} to 188 km s^{-1}. No H_2O lines were detected. The rms of the spectrum was 0.036 K, implying an upper limit of about 1 Jy (3 σ).

IV. DISCUSSION

The detection of the H_2O maser emission line confirms the presence of oxygen-rich material in the vicinity of EU And but leaves the physical relationship between the O-rich circumstellar shell and the C-rich photosphere unexplained. Willems and de Jong (1986) have argued that we are observing the transition from an M to a C star while the star is on the asymptotic giant branch (AGB). During helium shell flashing for AGB stars carbon-rich material can be dredged up, turning the oxygen-rich material of the M star into the carbon-rich material of a C star (Iben and Renzini 1983). Hence, it is theoretically possible to still see the oxygen-rich material in the CS shell for a brief period after the photosphere has already turned into a C star. However, the transit time for material to move through the shell is so short that it would be very difficult to observe this transition phase (Little-Marenin 1986). Theoretical models of CS oxygen-rich shells (Rowan-Robinson and Harris 1982, 1983*a*) indicate that the majority of the silicate emission comes from a region around 10 R_* in agreement with observations (Dyck *et al.* 1984). Based on typical outflow velocities of about 15 km s^{-1} obtained from CO observations of carbon stars (Knapp and Morris 1985), the material will transit through the region of strong silicate emission in 3–15 yr if a typical C star is assumed to have a radius of 1–5 AU. Even a 2 km s^{-1} outflow velocity implies a transit time of only 15–45 yr, which is marginally compatible with the time since EU And, BM Gem, and V778 Cyg were classified as carbon stars.

Dean (1976) determined a photospheric absorption-line velocity for EU And of $V_r = -62$ km s^{-1} ($V_{LSR} = -53$ km s^{-1}). This value is blueshifted by 24 km s^{-1} relative to that for the H_2O maser. Theoretical models of H_2O masers around giant long-period variables (hereafter LPV) (Cooke and Elitzur 1985) show that typical outflow velocities in the H_2O masing region are about 3–6 km s^{-1} when the terminal velocity is about 10 km s^{-1}. The H_2O emission lines may be either blueshifted or redshifted relative to the stellar lines implying that the masing region can be either in the near or the far side of the expanding envelope. Dickinson *et al.* (1978) point out that the photospheric absorption lines are often redshifted by 0–8 km s^{-1} relative to systemic velocities determined from thermal SiO lines. The same trend seems to apply to the mean of the H_2O maser lines if two components are observed. Hence, if EU And is a usual type of LPV giant, the EU And water maser velocity would be $(-53 + 8) \pm 6$ km s^{-1} or no greater than -39 km s^{-1} compared to the observed velocity of -29.4 km s^{-1}.

Typically H_2O masers are located in an expanding gas shell between 10^{14}–10^{15} cm (7–70 AU) from an exciting M star, usually a Mira or a semiregular variable giant or supergiant (Reid and Moran 1981; Bowers and Hagen 1984; Johnston, Spencer, and Bowers 1985). VLBI observations by Johnston, Spencer, and Bowers (1985) of four LPVs suggest that the H_2O masing region is located outside the silicate emission region. Although the OH emission measured by Bowers, Johnston, and Spencer (1983) appears to come from spherically symmetric envelopes, such spherical symmetry is not as well established in the H_2O data. The distribution of H_2O maser emission is quite complex and highly variable in time—both in intensity and location (Gomez Balboa and Lepine 1986; Johnston, Spencer, and Bowers 1985; Berulis *et al.* 1983). In general, the emission profiles show a greater degree of complexity around supergiants than giants. Zuckerman (1980) indicates that C stars appear to have nonspherical envelopes more often than M stars and suggests that such geometry is influenced by a companion.

We interpret the H_2O maser emission as coming from a CS envelope around an M star which has at least a 10 km s^{-1} redshift with respect to the C star companion. We suggest that EU And is a binary system in which the visible light in the 6000–7000 Å region is dominated by the C star, while the

10 μm flux and H_2O emission originates in the CS shell of the M star. Thus, EU And may be the first radio spectroscopic binary (Cohen 1987).

In order to check the plausibility of this deduction, we plot in Figure 2 a CS dust shell model by Rowan-Robinson and Harris (1983*b*) for HV Cas (C4, 3–C5, 4; M-527^d), a C star of similar spectral class to EU And, as well as the M star model for WX Ser (M8; M-425^d), which has a 10 μm feature similar in strength to EU And as observed by the *IRAS* LRS. A relatively thick CS shell ($\tau_{uv} = 10$) is predicted by the M star model which absorbs a large fraction of the visible light and reradiates the energy in the infrared. The Rowan-Robinson and Harris (1983*b*) C star models do not include the SiC emission which is observed at moderate strength in the LRS of HV Cas. Rowan-Robinson *et al.* (1986) have modified their models slightly in order to improve the predicted 60 and 100 μm *IRAS* fluxes, but these differences are at wavelength > 20 μm and therefore will have little effect on the present analysis. We assume that the C star is at least two magnitudes brighter at 6000–7000 Å since the M star is not visible in this region. We accordingly normalize the two spectra at 0.9 μm (*upper dashed curve for WX Ser*). The circumstellar dust shell around the M star is then approximately 5 mag brighter at 10 μm as shown in Figure 2. Photometry of the 1.0–3.7 μm region of BM Gem shows the typical 3 μm HCN and C_2H_2 absorption feature of a carbon star (Noguchi *et al.* 1981). The typical spectra of M stars in the 3 μm region show a smooth continuum (Noguchi *et al.* 1977). Hence, if the energy distribution of EU And is similar to BM Gem in the 3 μm region, we would expect the C component to be only about 0.5 mag or so brighter than the M star in this region. If we normalize the flux of WX Ser and HV Cas at 5 μm (*lower dashed curve for WX Ser*), we find that the M star is still brighter at 10 μm by about 2 mag. The shaded area on the graph therefore indicates the possible range of the M star fluxes compatible with the observations. The contribution of 11.2 μm SiC emission to the strong 10 μm silicate emission feature would not be observable. Therefore a model of a C star and a late M star with a circumstellar shell can explain the observed energy distribution in the 0.6–0.7 μm region, the 8–10 μm region, and 22 GHz H_2O emission.

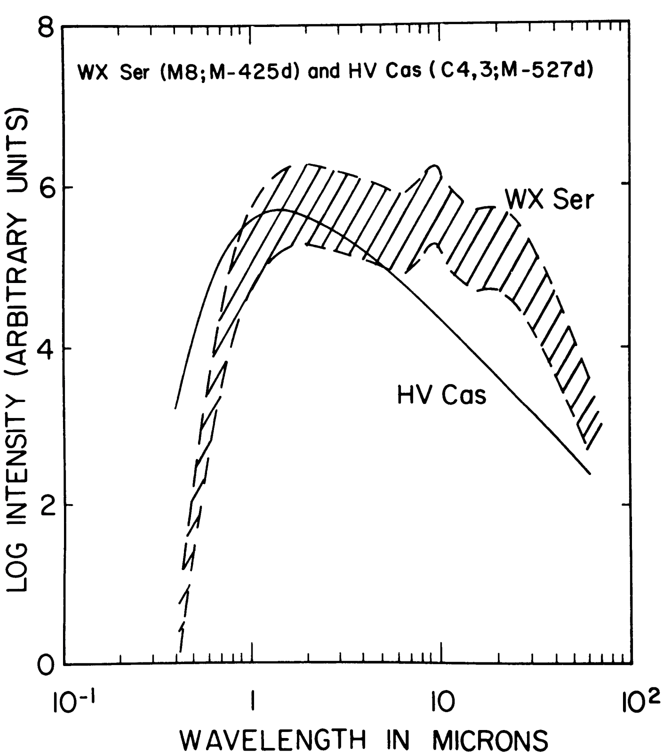

FIG. 2.—A possible model for EU And: a C star (HV Cas; *solid curve*) + an M star with a relatively thick CS shell (WX Ser; *dashed curves*). The spectra of HV Cas and WX Ser are normalized at 0.9 μm (*upper dashed curve of WX Ser*) and at 5 μm (*lower dashed curve of WX Ser*). The shaded area indicates the possible range of relative flux of the M star compatible with observations.

We expect M and C star components in a highly evolved binary system to have very similar masses and luminosities in order for both to be on the AGB. Since the more evolved C star should be slightly more luminous, we conclude that the lower curve for WX Ser, together with the solid curve for HV Cas, is a more realistic representation of the relative energy distribution for the two stars. As can be seen in Figure 2, the less luminous M star dominates the radiation in the infrared because a large fraction of its visible light is absorbed and reradiated by the CS shell.

A search through the LRS spectra shows that more than half of the LPVs with strong silicate emission like EU And are Miras with fairly long periods ($\langle P \rangle = 400^d$), another 25%–30% are semiregular variables, and the rest are either irregular variables or poorly observed stars. Only two short-period Miras R Cet ($P = 166^d$) and Sv Pup (168^d) show a very strong 10 μm silicate feature. An H_2O maser has recently been detected in R Cet (Benson *et al.* 1987). Hence, by analogy the companion to EU And should be a SR or a Mira with a period around 400^d.

About 10% of the LPVs with strong silicate emission are classified as supergiants, with expansion velocities of around 20–50 km s^{-1} in their CS shells as determined from OH, SiO, and H_2O observations. The difference between the absorption-line velocities of the carbon star and the H_2O maser velocity could then be due to the expansion of the CS shell around a single supergiant carbon star. There are several arguments which can be made against the latter interpretation. First, no supergiant C stars with large outflow velocities are known (anonymous referee 1987, private communication), in part due to the fact that no spectroscopic luminosity criteria for C stars exist. Second, the silicate and H_2O maser emission regions are predicted to be located roughly a factor of 5–10 further from a supergiant than a giant (Rowan-Robinson and Harris 1983*a*). However, the expansion velocities are larger by roughly the same factor (Bowers, Johnston, and Spencer 1983; Gomez Balboa and Lepine 1986), making the transit time of material through a supergiant silicate emission region less than about 50 yr, which is too short to be compatible with the C star classification. Third, the galactic latitude of EU And ($b = 12°$) is larger than for most supergiants. Fourth, the H_2O maser line is quite narrow and shows only one component which is more typical of CS shells around giants than supergiants. Of course none of these arguments is conclusive. As a better test for distinguishing between binary giants and a single supergiant, we suggest that EU And, as well as BM Gem and V778 Cyg, be searched for OH and SiO emission, since most CS shells with H_2O maser activity are also OH and SiO masers. Often the emission (especially in OH) is double-peaked with the mean velocity corresponding to the systemic velocity and the velocity difference between the peaks corresponding to the expansion velocity. Observations of a double-peaked maser should immediately tell us the systemic velocity.

V. CONCLUSION

We observed 22 GHz H_2O maser emission toward the C star EU And. The velocity of the line ($V_{LSR} = -29.4$ km s^{-1}) is redshifted by about 24 km s^{-1} relative to the photospheric absorption lines of the star ($V_{LSR} = -53$ km s^{-1}). We interpret EU And as the first detected radio spectroscopic binary system with C and M star components. The carbon star is seen and classified in the 6000–7000 Å region, whereas the O-rich CS shell around the M star is seen at 10 μm as silicate emission and at 22 GHz as an H_2O maser line. We hypothesize that EU And, along with the other carbon stars that show strong silicate emission in their spectra (BM Gem, V778 Cyg) are H_2O, as well as OH and SiO maser sources, and we plan to search them for periodic shifts in spectral line velocities in order to establish or disprove the binary nature of these systems.

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