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MASERS ASSOCIATED WITH TWO CARBON STARS: V778 CYGNI AND EU ANDROMEDAE

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ABSTRACT

We present several observations of the 22.2 GHz H_2O maser line from two C stars, V778 Cyg and EU And, and the 1665/67 MHz OH maser lines from V778 Cyg. For both sources the intensity of the H_2O line has varied by more than a factor of 5 over several months. We interpret the systems as being binaries, each with an M star component with a thick shell and a C star component.

Subject headings: masers — stars: carbon — stars: circumstellar shells — stars: individual (EU And, V778 Cyg)

I. INTRODUCTION

Seven carbon stars are associated with oxygen-rich circumstellar material (Little-Marenin 1986; Willems and de Jong 1986) as deduced from the presence of strong 10 μm and 18 μm emission features in their *IRAS* low-resolution spectra (Joint *IRAS* Science Working Group 1986). These stars are EU And (C4, 4), V778 Cyg (C5$^-$, 5), BM Gem (N), IRAS 08002−3803 (= CCCS 1003 = star 1003 in *Catalog of Cool Carbon Stars*, Stephenson 1973), IRAS 08577−6035 (= MaC 79, star 11 = star 11, Table 2, MacConnell 1979), IRAS 18006−3213 (= FJF 270 = star 270 of Fuenmayor 1981, erroneously labeled FJF 272 in Fig. 1 of Willems and de Jong), and IRAS 19139+5412 (= NC 83 = star 83 of Stephenson 1985). We exclude from the list two other stars mentioned by Willems and de Jong (1986). IRAS 10091−7049 = CCCS 1633 may be an S or MS star as mentioned by Stephenson (1973). Also its 10–11 μm emission feature is more typical of MS stars rather than M stars (Little, Little-Marenin, and Price 1987). IRAS 13442−6109 (may be = CCCS 2123) has an uncertain C position, and Stephenson (1973) could not confirm its C classification.

To better understand the unexpected phenomena of an oxygen-rich circumstellar shell near a carbon-rich photosphere, we searched the four C stars visible to the Haystack Observatory[2] 37 m telescope for H_2O emission. The 6_{16}–5_{23} H_2O maser emission line at 22,235.080 MHz was detected toward EU And (Benson and Little-Marenin 1987) and V778 Cyg (Little-Marenin, Benson, and Little 1987; Nakada *et al.* 1987). We also searched EU And and V778 Cyg for OH maser emission with the NRAO[3] 300 foot (91 m) telescope; the main-line 1665 and 1667 MHz OH maser lines were seen towards V778 Cyg but not EU And (<0.07 Jy [3 σ]).

II. OBSERVATIONS AND RESULTS

Since 1987 March we have monitored EU And and V778 Cyg at Haystack Observatory for H_2O maser emission. The spectra were automatically corrected by the Haystack computer for atmospheric attenuation and for variation in telescope gain with elevation. We observed the stars in total power mode with 5 minutes on-source and 5 minutes off-source. The first detections of EU And (1986 Dec 15) and V778 Cyg (1987 Mar 23) were obtained with an autocorrelator bandwidth of 16.67 MHz with 512 channels, resulting in a resolution of 0.53 km s^{-1} which only marginally resolved the H_2O lines. Later observations were usually made with a bandwidth of 5.55 MHz with 1024 channels, resulting in a velocity resolution of 0.09 km s^{-1}. Pointing was checked twice daily with observations of 3C 84 and 3C 374. We used a conversion factor of 12 Jy K^{-1} (Haschick 1986).

H_2O maser emission from V778 Cyg (R.A. = $20^h35^m07^s$; decl. = $+59°54'48''$ [1950]) was first detected on 1987 March 23 with a flux of 1.9 (0.5) Jy at $V_{LSR} = -16.8$ (0.1) km s^{-1}. The formal errors of the Gaussian fits are in parentheses. Since then the intensity of the maser has increased to a value of 11 Jy on 1987 June 9. Figure 1*a* displays the temporal sequence of the V778 Cyg spectra. At times the line has shown two additional components which are weaker by about a factor of 3–5 at −20.5 km s^{-1} and −15.1 km s^{-1}. Figure 2*a* plots the peak flux and integrated area for the three components as a function of Julian date. The intensity of the weaker components tends to vary in phase with the main water line. The parameters of the Gaussian fits to the observed lines are summarized in Table 1; for weak lines we estimated the peak flux only. Upper limits to the flux are estimated as being <3 σ. Table 1 and Figure 2*a* include the data from the independent detection of V778 Cyg by Nakada *et al.* (1987) on 1987 April 30 with a peak flux of 7 Jy.

The 1665 and 1667 MHz OH observations of V778 Cyg

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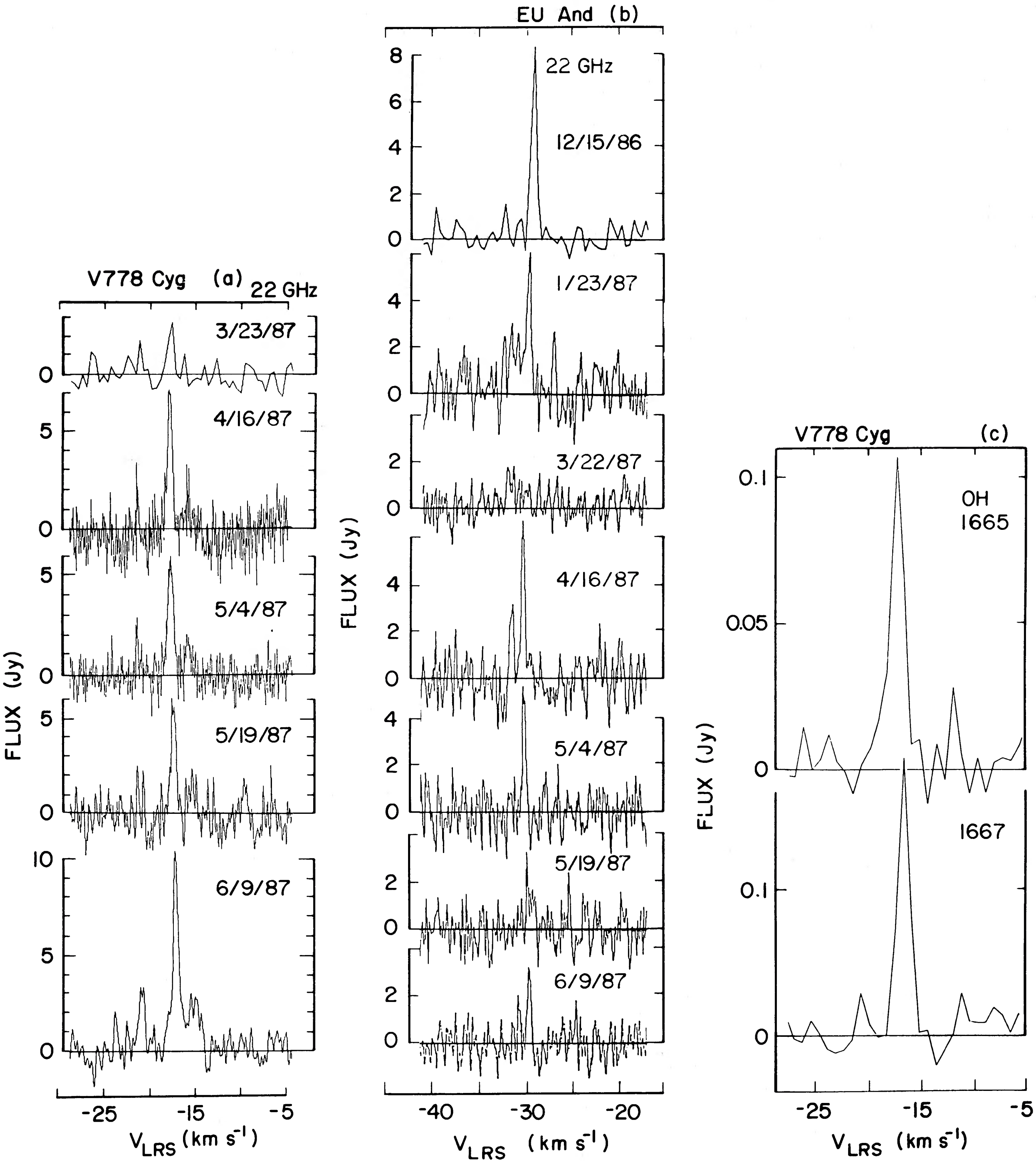

FIG. 1.—The temporal sequence of maser spectra: (*a*) the 22 GHz spectra of V778 Cyg between 1987 March 23 and June 9; (*b*) the 22 GHz spectra of EU And between 1986 December 15 and June 9; (*c*) the 1665 and 1667 MHz OH spectra of V778 Cyg.

were made at the 300 foot (91 m) NRAO Greenbank telescope on 1987 July 13. The spectra were taken simultaneously in two different polarizations for each line using the 384 channel autocorrelator split into four 92 channel sections. Standard calibrations were used and the two polarizations were averaged. The system temperature averaged about 20 K. The bandwidth of 625 kHz for each segment provided a velocity window of 113 km s^{-1} and a resolution of about 1.5 km s^{-1}. We detected the 1665 and 1667 MHz lines at about the same velocity as the H_2O line. The intensity of the 1667 line of 0.26 K = 0.195 Jy at $-15.3 +/-1$ km s^{-1} is almost twice as intense as the 1665 line of 0.15 K = 0.113 Jy at $-16.5 +/-1$ km s^{-1} see Figure 1*c*.

The 22 GHz flux of EU And (R.A. = $23^h17^m41^s$; decl. = $+46°58'00''$ [1950]) has varied by at least a factor of 8 between 1986 December and 1987 June (Fig. 1*b*) with the main component being below the detection limit of about 1.5 Jy on

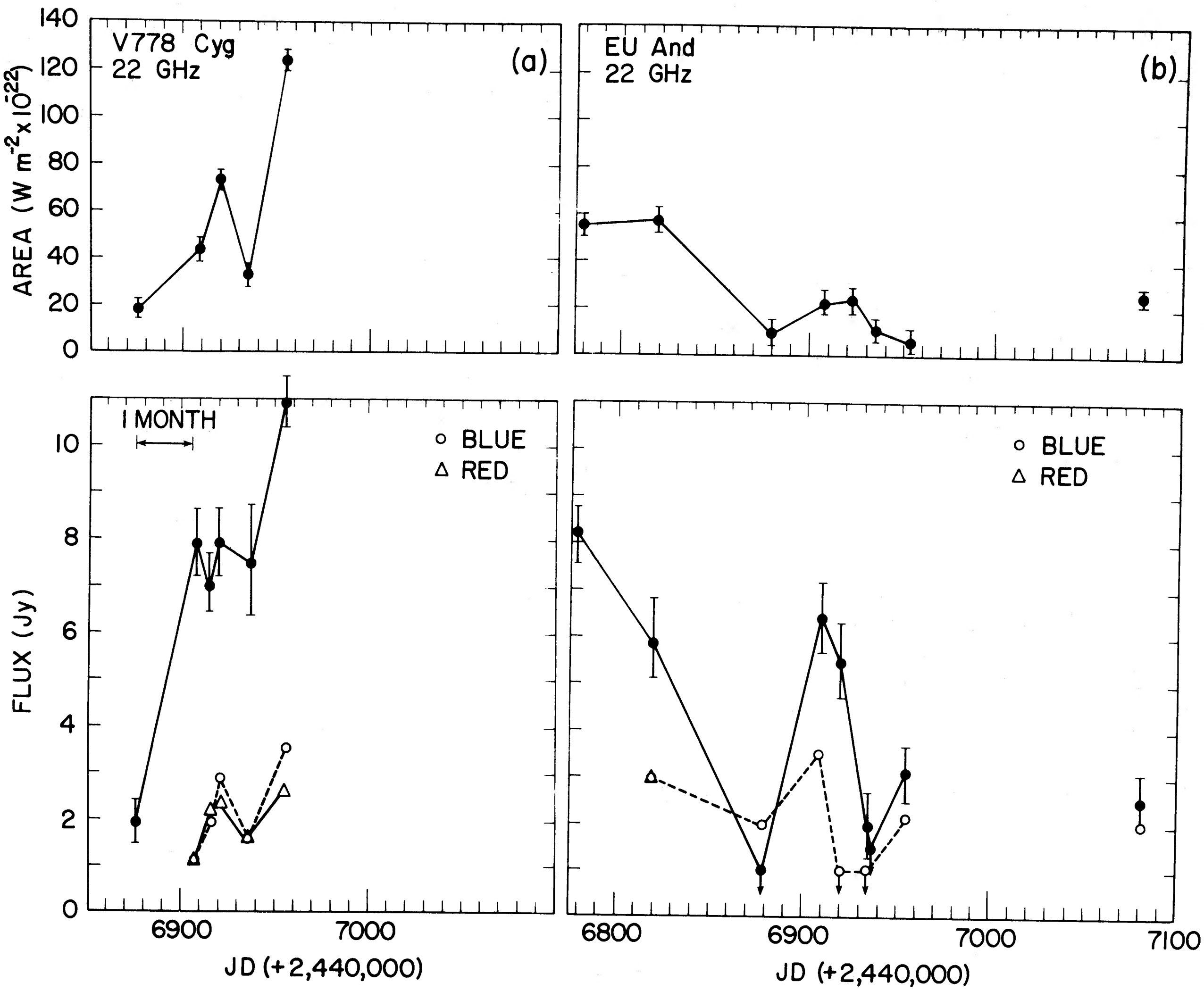

FIG. 2.—The variation of the 22 GHz maser flux as a function of Julian Date. Fig. 2*a* (*top*) shows the integrated area of the V778 Cyg 22 GHz line from 1987 March 23 to June 9. In Fig. 2*a* (*bottom*), the solid circles show the peak flux of main component at -16.9 km s^{-1} (*solid line*). Open circles show the peak flux of the blueshifted component at -20.5 km s^{-1} (*dotted line*). Triangles show the peak flux of the redshifted component at -15.1 km s^{-1}. Fig. 2*b* (*top*) shows the integrated area of the EU And 22 GHz lines from 1986 December 15 to 1987 October 20. In Fig. 2(*b*) (*bottom*), the solid circles show the peak flux at -29.7 km s^{-1}. Open circles show the blueshifted component at -31.1 km s^{-1}. Triangles show the redshifted component at -26.0 km s^{-1}.

1987 March 22 and very weak ($\sim$2 Jy) on 1987 May 19. On 1987 May 22, Nakada *et al.* were unable to detect EU And at the 1.5 Jy level. At times EU And has shown at least one other component at -31 km s^{-1}, once possibly another at -26 km s^{-1} and on 1987 October 20 a possible component at -12.4 km s^{-1}. EU And shows greater temporal variations than V778 Cyg in the intensity of the main component as can be seen in Figure 2*b*. The integrated flux has primarily been decreasing for EU And (Fig. 2*b*) and primarily been increasing for V778 Cyg (Fig. 2*a*) since we have been observing these sources. The water maser receiver was unavailable at Haystack Observatory from 1987 mid-June until 1987 early October. Optically, both stars are quite faint with $m_p \approx 12$–13. Their optical variability types are only poorly established with EU And being classified as SR and V778 Cyg as Lb. It is not known if their maser variability correlates with optical variability.

BM Gem (R.A. = 07^{h}17^{m}56^s; decl. = +25°05′03″ [1950]) has been searched over a velocity range of 10–190 km s^{-1} three times and IRAS 19139+5412 (R.A. = 19^{h}13^{m}55^s; decl. = +54°12′06″ [1950]) over a velocity of -180 to $+180$ km s^{-1} three times with negative results. Considering the variability of the H_2O emission from EU And and V778 Cyg and the fact that both were detected during our first try, we expect that both BM Gem and IRAS 19139+5412 have a very high probability of being detected as maser sources if observed often enough.

III. DISCUSSION

Stellar water masers are located in expanding circumstellar shells around M Miras or semiregular variables (Kleinmann, Dickinson, and Sargent 1978; Reid and Moran 1981; Dickinson and Dinger 1982; Bower and Hagen 1984). H_2O emission is highly variable in intensity both in space and in time (Gomez, Balboa, and Lepine 1986; Johnston, Spencer, and Bower 1985) with the various velocity components of the masers being located in different parts of the circumstellar shell. Interferometric observations of the spatial distribution of H_2O maser spots indicate that the maser regions range from <9 to 100 AU (average about 50 AU) in total extent around giants and from 300 to 720 AU around supergiants and show

TABLE 1

OBSERVATIONS OF THE 22 GHz H_2O MASER LINE

A. H_2O EMISSION DETECTED

Date (1987)	JD+ 2,400,000	V_{main} (km s^{-1})	ΔV (FWHM)	Flux (Jy)	V_{blue} (km s^{-1})	Flux (Jy)	V_{red} (km s^{-1})	Flux (Jy)	Area (Wm^{-2} × 10^{-22})	RMS (Jy)
				EU And						
Dec 15[a,b]	46778	−29.40	0.67	8.2	...	...	...	...	53	0.6
Jan 23	46819	−29.67	0.52	5.6	−31.2	3.0	−26.0	3.0	57	0.9
Mar 22	46877	...	...	<1.5	−31.4	2.0	...	...	10	0.5
Apr 16	46908	−29.79	0.49	6.4	−31.0	3.5	...	...	23	0.8
May 4	46920	−29.82	0.45	5.5	...	...	...	...	24	0.8
May 19	46935	−29.8:	...	3.6:	...	...	...	...	12	0.7
May 22[b]	46938	...	...	<1.5	...	...	...	...	...	...
June 9	46955	−29.87	0.46	3.1	−30.9	2.2:	...	...	7	0.6
Oct 20	47089	−29.96	0.65	2.5	−31.0	1.9	−12.4	2.6	28	0.6
				V778 Cyg						
Mar 23[b]	46878	−16.82	1.1	1.9	...	...	...	...	18	0.5
Apr 16	46908	−16.93	0.63	7.9	−20.5	1.2:	−15.1	1.2	43	0.7
Apr 30[c]	46916	−16.9	1.0	7.0	−20.5[c]	1.9[d]	−15.1[d]	2.3[d]	...	...
May 4	46920	−17.01	0.76	7.9	−20.6	2.9	−15.1	2.4	73	0.6
May 19	46935	−16.91	0.64	7.5	−20.9:	1.6	−15:	1.6	35	1.2
Jun 9	46955	−16.94	0.66	10.9	−20.7	3.6	−15.1	2.7:	124 err +/−5	0.6

B. NO H_2O EMISSION DETECTED

Date (1987)	Flux (Jy)
BM Gem	
Mar 23	<2.7
Apr 16	<2.6
Apr 30[c]	<2.1 (= 3 × rms)
Oct 20	<1.5
IRAS 19131+5412[e]	
Mar 23	<1.3
Apr 16	<1.5
Oct 20	<1.2

NOTES.—Colons are used to indicate uncertain measurements. Velocity resolution = 0.09 km s^{-1} unless otherwise indicated.

[a] 1986.

[b] Velocity resolution = 0.53 km s^{-1}.

[c] Observations by Nakada *et al.* 1987.

[d] Data read from Fig. 1 of Nakada *et al.* 1987.

[e] NC star 83; Stephenson 1985.

elongated structures as well as spherical symmetry (Lane *et al.* 1987). Assuming that the masers in V778 Cyg and EU And are located in expanding shells, then half of our observed maser velocity range of about 3 km s^{-1} should be the lower limit to the expansion velocity of the shell in the masing region. Theoretical models of H_2O masing regions around giants (Cooke and Elitzur 1985) predict expansion velocities of about 3–6 km s^{-1} which correspond to a terminal velocity of about 10 km s^{-1}, in agreement with our observations. The relatively simple structure and small velocity difference between the H_2O maser components argue strongly for the masers being located around giants rather than supergiants. The galactic latitudes of V778 Cyg and EU And ($b = 12°$ and $-13°$, respectively) also support these stars being giants since, in general, supergiant OH/IR stars tend to be strongly concentrated towards the galactic plane with $b < 4°$.

The mapping of the 1665/67 MHz OH and 22 GHz H_2O masers around the supergiant VX Sgr shows that the two maser sources are at very similar distances and have very similar outflow velocities (Chapman and Cohen 1986) unlike the 1612 MHz OH emission which is about a factor of 10 farther out. Although we estimate that the H_2O and OH masers for V778 Cyg are located around a giant rather than a supergiant, we interpret the agreement between our observed H_2O and OH velocities for V778 Cyg as indicating that both types of masers are located at roughly the same distance from the central star. Other OH velocity components which correspond to the weaker H_2O components are not detectable at the OH velocity resolution of 1.17 km s^{-1}.

If V778 Cyg and EU And are giants, then the material outflowing from the central star will transit through the H_2O and OH masing region (about 50/2 = 25 AU; Lane *et al.* 1987) in about 40 yr if a conservative estimate of 3 km s^{-1} for the expansion velocity in the masing region is assumed [t(yr) = D(AU) ∗ 4.74/v(km s^{-1})]. The transit time of material through the silicate emitting region is estimated to be about 20–30 yr for a similar expansion velocity since circumstellar shell (hereafter CS) models predict that the 10 μm emission comes primarily from a distance of about $10R_*$ or about 15–20 AU for M star Miras (Rowan-Robinson and Harris 1983; Dyck *et al.* 1984).

There are two principal interpretations possible for the extraordinary situation of having an oxygen-rich CS associated with a carbon-rich photosphere.

1. We are observing a binary system with a C star and an M star companion with a relatively thick CS. The CS of the M star produces the 10 and 18 μm emission, and the H_2O and OH maser lines. However, the CS absorbs the visible light of the M star so that only light from the carbon star is seen in the visible and near infrared region.

2. We are observing the transition of an M star to a C star so that we still observe the O-rich material in the CS for a brief time after the central star has already become C-rich.

We favor interpretation (1), the binary system hypothesis, since the time scales for hypothesis (2) to be correct are not compatible with the observations of the outflow velocities and of the evolutionary time scales available to transform M to C stars.

First, V778 Cyg (= MSB 38) and EU And (= DO 42999) were first recognized as a carbon star in 1933 (Merrill, Sanford, and Burwell 1933) and before 1947 (Lee, Gore, and Bartlett 1947), respectively. The outflowing material at 3 km s^{-1} has traveled at least 30 AU since then and should have passed through the silicate emission region by the time the *IRAS* observations were made and is likely to have passed through the H_2O and OH maser region. Only in the very unlikely situation that both stars in 1933 and 1940 were observed at the instance when the photosphere became carbon-rich without going through an S and SC phase would we still see the remnant oxygen-rich shell in the *IRAS* and maser data.

Second, the *IRAS* low-resolution spectra of V778 Cyg and EU And are indistinguishable from other M star spectra which show strong silicate emission and are also H_2O and OH masers, e.g., R Cet and WX Ser. On the other hand, S and SC star spectra are significantly different from M star spectra (Little, Little-Marenin, and Price 1987) suggesting very strongly that we are observing the 8–22 μm spectrum of an M star and not an S or SC star.

Third, abundance analyses of S and SC stars (Dominy and Wallerstein 1983; Smith and Wallerstein 1983; Smith and Lambert 1986; Mathews *et al.* 1986; Winters and Macklin 1987; Wallerstein and Dominy 1988) show that the distribution of the observed *s*-process photospheric abundances imply several dredge-up episodes during the asymptotic giant branch (AGB) lifetime of these stars which takes on the order of 10^5–10^6 yr. Similarly, since the observed *s*-process enhancements in C stars are produced during several dredge-up episodes, it would take longer than the transit time of material through the CS to produce a C star from an M star. The location in an H-R diagram of Magellanic Cloud AGB stars of intermediate-age globular clusters indicate a progression with increasing luminosities of M → MS → S → (SC) → C (Wood 1985), i.e., there is no evidence for a direct transition from M to C. Hence, we consider the scenario of an instantaneous transition from an M to C star highly unlikely. This does not mean that the scenario *could* not happen only that there is no evidence that it *has happened* either from evolutionary considerations or transit times of material through the CS.

Fourth, Willems and de Jong (1986) argue that all C stars with strong 10 μm emission are J-type C stars, i.e., stars with low $^{12}C/^{13}C$ ratios. However, Utsumi (1985) finds that galactic C stars rich in ^{13}C show no *s*-process enhancements nor does the J-type star Y CVn show lines of the radioactive element technetium (Peery 1971). This suggests very strongly that the carbon enrichment needed to produce J-type C stars must have occurred before the stars reached their AGB phase of evolution and that it occurred more than 5×10^5 yr ago so that ^{99}Tc had time to decay away. Hence, no C-rich shell should yet be observable around J-type stars.

We find support for the binary star hypothesis in the observed flux of V778 Cyg at 1, 12, 25, and 60 μm. V778 Cyg shows the typical strong CN absorption features of an Lb C star in the 0.8–1.08 μm region (Baumert 1972). The observed flux of about 11 Jy at 1.08 μm and 8 Jy at 0.78 μm (*triangles* in Fig. 3) and the *IRAS* color-corrected fluxes of 26 Jy at 12 μm, 14 Jy at 25 μm, and about 1.5: Jy at 60 μm (*open circles* in Fig. 3) can be modeled quite well with a composite M and C star spectrum as can be seen in Figure 3. Using the Rowan-Robinson and Harris dust shell models (1983*a*, *b*) for a typical J-type carbon star (Y CVn) and a typical M star Mira (WX Ser) with strong 10 and 18 μm silicate and H_2O and OH maser emission, we find that the C star will dominate the emission shortward of about 5 μm, and the M star with its shell will dominate longward of 5 μm. The 100 μm flux of 9.8 Jy (uncorrected) may be contaminated by infrared cirrus. No composite model can be calculated for EU And since no information on the near-infrared spectrum of EU And is available.

The binary hypothesis is also supported by the observed V_{LSR} of the EU And maser emission which differs from that of the C star by 24 km s^{-1}. We interpret this as due partly to the orbital velocity of the two components. Benson and Little-Marenin (1987) estimate the minimum orbital velocity difference in the EU And system is 10 km s^{-1}. However, for V778 Cyg the water maser velocity agrees with the velocity of the C star and may indicate that the orbital plane of the system is more highly inclined and/or that the M and C star components are presently moving across our line of sight and/or that the two components are more widely separated. Deguchi *et al.* (1988) have confirmed that the position of the water maser source around V778 Cyg agrees with the photographic position of the C star within 0″.5, implying that the two components of V778 Cyg could be separately seen if more than 50–500 AU apart at a distance of 10^2–10^3 pc. Peery's (1975) estimate of a 1.4 kpc distance for V778 Cyg makes it even less likely that the binary components could have been separately seen. Assuming typical C and M star Mira masses of $< 3\ M_\odot$ ($M_1 + M_2 < 6\ M_\odot$) (Willson 1982) and a separation of around 2×30 AU (so that the water masing region will be gravitationally bound to the M star), we estimate $P_{orb} > 200$ yr. This value is reasonably consistent with $P_{orb} <$ about 190 yr for EU And if we assume a $v_{orb} > 10/2$ km s^{-1} and $a = 30$ AU in a circular orbit.

IRAS color-color plots separate O-rich from C-rich circumstellar material. The *IRAS* colors defined by Olnon *et al.* (1984) (see Table 2) place the four C stars among those with O-rich CS; specifically they lie on the blueward extension of the newly

TABLE 2

IRAS COLORS

Object	$\log \nu S_\nu(60)/\log \nu S_\nu(25)$	$\log \nu S_\nu(25)/\log \nu S_\nu(12)$
EU And	−1.337	−0.417
V778 Cyg	−1.336	−0.543
BM Gem	−1.220	−0.571
19139+5412	−1.327	−0.560

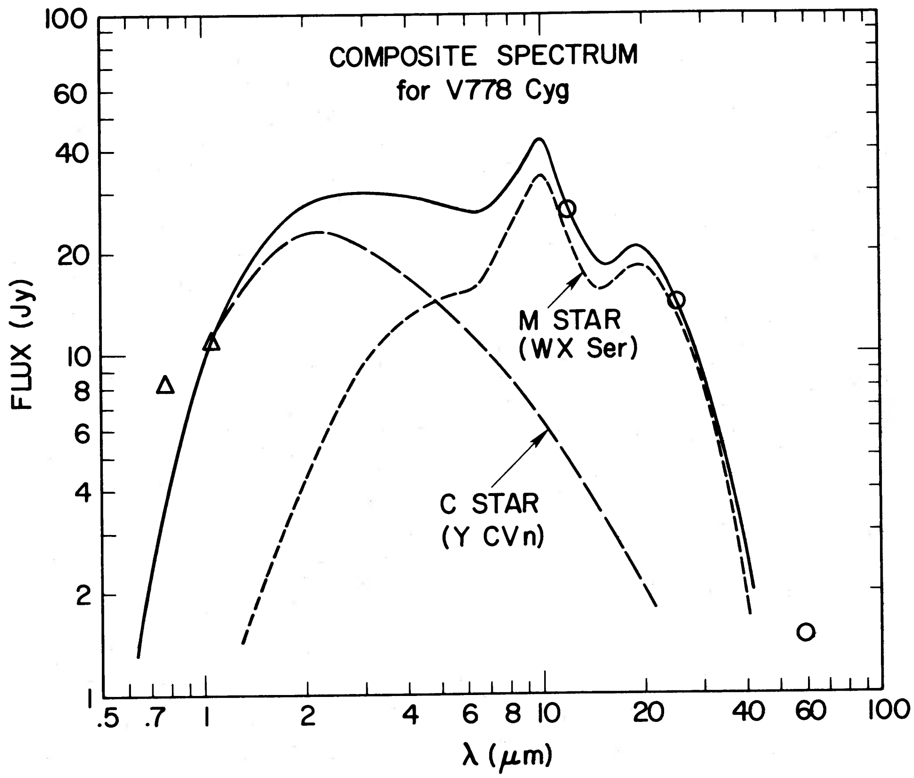

FIG. 3.—Composite flux calculated from the dustshell models for Y CVn and WX Ser. Triangles show the observed 0.78 μm and 1.08 μm flux (Baumert 1972). Solid circles show the *IRAS* fluxes at 12, 25, and 60 μm of V778 Cyg.

discovered OH masers with similar colors (Lewis, Eder, and Terzian 1985) close to or within the location of the optical Miras with periods usually $<500^d$. This suggests that the M stars associated with the water masers in the V778 Cyg and EU And systems are likely to be Mira variables with periods in the 400^d—500^d range. A similar conclusion was reached by Benson and Little-Marenin (1987) from an analysis of other stars with similar strong 10 and 18 μm emission features as V778 Cyg and EU And.

Deguchi *et al.* (1988) suggest that V778 Cyg is probably not a binary system because companions may perturb the CS enough to inhibit maser emission. The examples they give, *o* Cet and R Aqr, have (probably) hot white dwarf companions and their weak H_2O and SiO maser emission is likely to be due to their hot companions. However, we note that H_2O and OH masing regions are found around some binary M Miras, e.g., X Oph, R Hya, and W Hya (Proust, Ochsenbein, and Pettersen 1981), and we suggest that EU And V778 Cyg are systems more like the binary M Miras.

IV. SUMMARY

The presence of H_2O maser emission and strong 10 and 18 μm silicate emission features towards EU And and V778 Cyg and 1665/67 MHz OH maser emission toward V778 Cyg indicate the presence of oxygen-rich material in the vicinity of a carbon-rich photosphere. We interpret the observations as being due to a binary system with a C star and an M star component. The CS of the M star absorbs the visible light of the star and allows the detection of the C star in the optical and near infrared region. This interpretation is aided by the observed 1, 12, 25, and 60 μm fluxes of V778 Cyg, which successfully fit a composite M and C star spectrum, and the >10 km s^{-1} difference between the radial velocity of EU And and the H_2O maser velocity. We find the suggestion that we are observing the transition from an M star to a C star to be unlikely since the time scales of material in transit through the silicate and maser emission region is too short for oxygen-rich material still to be found in this region. This scenario also assumes that the MS, S, and SC stages of stellar evolution are bypassed in these stars. Abundance analyses of these types of stars suggest the contrary.

The arguments presented above are suggestive but do not constitute a definite proof of the binary hypothesis over the $M \rightarrow C$ transition model. We suggest the following two observations which could help to resolve this issue.

1. The detection of SiO maser emission from any of these C stars would greatly weaken the $M \rightarrow C$ transition model because SiO masers are located in the closer warmer part of the CS shell, usually within $2R_*$ (<10 AU). Material would transit through this region in about 10 yr, which is incompatible with the 40 yr since classification. SiO emission has been searched for with negative results in EU And, V778 Cyg, and BM Gem by us and Nakada *et al.* (1987). However, considering the variability of maser emission from these sources, we suggest that they be monitored.

2. Spectroscopic observations in the 3 and 4 μm region should show evidence for the presence of an M star companion, since we estimate that the crossover in flux between an M and a C star should occur between 2 and 5 μm (Fig. 3). Around 4 μm, photospheric absorption bands of SiO are observed in oxygen-rich M stars but not in C and SC stars (Rinsland and Wing 1982), whereas absorption bands due to C_2H_2 and HCN are found around 3.1 μm in C stars and not in M stars (Noguchi *et al.* 1981). The detection of the 3.1 μm absorption

bands, e.g., in BM Gem, does not exclude the presence of a M star since in this region M stars show featureless continua. Even if an M star contributes a large amount to the total flux (say <50%), we should still detect the absorption features from the C star.

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