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ON THE NATURE OF THE CENTIMETER CONTINUUM EMISSION FROM THE FU ORIONIS STARS V1057 CYG AND ELIAS 1-12

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RESUMEN

Utilizando el Conjunto Muy Grande (VLA=Very Large Array) de radiotelescopios observamos a 2 y 1.3-cm las estrellas FU Orionis V1057 Cyg y Elias 1-12. Detectamos ambas estrellas a 2-cm como fuentes puntuales y se obtuvieron límites superiores a sus flujos a 1.3-cm. Nuestros nuevos resultados, en combinación con los flujos a 3.6-cm publicados anteriormente, nos permiten establecer que en la región centimétrica estos objetos tienen índice espectral de $\sim$ 0.7, característico de emisión libre-libre de vientos ionizados. Las tasas de pérdida de masa ionizada para V1057 Cyg y Elias 1-12 son del orden de 10^{-7} $M_\odot$ año^{-1}, mucho menores que las tasas de pérdida de masa máximas observadas para los objetos FU Orionis. En el caso de V1057 Cyg los datos de la región visible sugieren que el viento podría estar ionizado solo en un 10%.

ABSTRACT

Using the Very Large Array we observed at 2 and 1.3-cm the FU Orionis stars V1057 Cyg and Elias 1-12. Both stars were detected as unresolved sources at 2-cm and upper limits for their flux densities were set at 1.3-cm. Our new results, combined with the published 3.6-cm flux densities, permit us to establish that the emission from these stars in the centimeter wavelengths has a spectral index of $\sim$0.7, characteristic of free-free emission from ionized outflows. The estimated ionized mass loss rates for both V1057 Cyg and Elias 1-12 are $\sim 10^{-7}$ $M_\odot$ yr^{-1}, much lower than the maximum mass loss rates observed from FU Orionis objects. In the case of V1057 Cyg, optical constraints suggest that the wind may be only about 10% ionized.

Key words: STARS-ACCRETION – STARS-CIRCUMSTELLAR SHELLS – STARS-PRE-MAIN SEQUENCE – STARS-WINDS

I. INTRODUCTION

Recently, the FU Orionis phenomenon has been ıe subject of several theoretical and observational .udies. At present, the most promising explanation f these outbursts is in terms of a large increase in ıe stellar accretion rate from a circumstellar disk -Iartmann & Kenyon 1985). Although FU Orionis bjects have been observed in detail in the optical nd infrared (see Hartmann, Kenyon, & Hartigan 992 for a review), there have been few studies : radio wavelengths. Rodríguez, Hartmann, & Chavira (1990) made a sensitive VLA search at 3.6-cm toward four FU Orionis stars: FU Ori, V1515 Cyg, V1057 Cyg, and Elias 1-12, detecting the last two sources. Given that measurements at only one frequency were available, these authors could not establish the nature of the cm emission from the detected FU Ori stars. In this paper we present continuum observations at 2 and 1.3-cm that allow a significant improvement in the identification of the mechanism responsible for the radio continuum emission in FU Ori stars.

II. OBSERVATIONS

The 2 and 1.3-cm continuum observations were made during 1990 November 24 using the Very Large Array of NRAO[1] in the C configuration. The angular resolution was ~ 1.7″ and ~ 1.1″ at 2 and 1.3-cm, respectively, for maps made with natural weighting. The observations were made with an effective bandwidth of 100 MHz. The on-source integration times for each source were approximately 3 hours at 2-cm and 1.5 hours at 1.3-cm. The absolute amplitude calibrator was 3C286 and the phase calibrators were 2005+403 (for V1057 Cyg), and 2200+420 (for Elias 1-12). The bootstrapped 2 and 1.3-cm flux densities of the phase calibrators were 2.94±0.05 and 2.66±0.07 Jy for 2005+403, and 2.27±0.04 and 2.08±0.06 Jy for 2200+420. The data were edited and calibrated using the standard VLA procedures and maps were obtained by Fourier transformation of the calibrated visibilities.

III. RESULTS AND DISCUSSION

At 2-cm we detected weak radio continuum sources in association with V1057 Cyg and Elias 1-12 (see Figures 1 and 2 and Table 1). Even though the detections are at the 4-σ level, we consider them to be statistically significant since, within positional error, the 2-cm radio sources coincide with the 3.6-cm radio sources detected by Rodríguez *et al.* (1990). The sources appear unresolved for the angular resolution of ~ 1.7″ of the maps. At 1.3-cm we could only set upper limits to the flux density (see Table 1).

The detections at 2-cm and the upper limits at 1.3-cm allow a discussion of the nature of the centimeter radio continuum emission from these two FU Ori stars. In Figures 3 and 4 we show the continuum spectra of V1057 Cyg and Elias 1-12 for the cm and mm range, using data from Weintraub, Sandell, & Duncan (1991), Rodríguez *et al.* (1990), and this paper. We have fitted separate power law fits to the 3.6 and 2-cm flux densities and to the 1300 and 800 μ flux densities. The spectral indices for the cm and mm ranges are listed in Table 2.

The spectral indices derived from the 3.6 and 2-cm data, 0.7–0.8, are characteristic of ionized outflows (see, for example, Reynolds 1986), while those derived from the 1300 and 800 μ data, 2.7, are characteristic of emission from optically-thin dust (see, for example, Beckwith *et al.* 1990). From these results we propose that the transition where the continuum has comparable contributions from free-free emission possibly arising in an ionized outflow and from optically-thin dust emission possibl arising in a circumstellar disk occurs around 2 GHz, that is, 1.5-cm (see Figures 3 and 4).

1. NRAO is operated by Associated Universities, Inc., under cooperative agreement with the National Science Foundation.

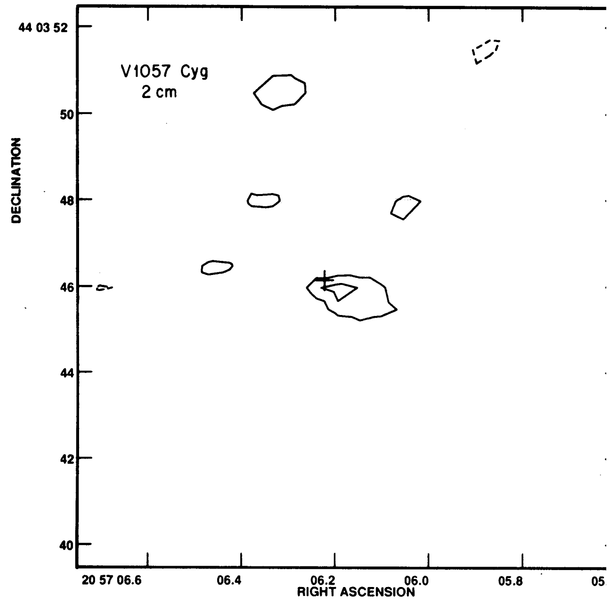

Fig. 1. Natural-weight VLA map of the 2-cm emissio from V1057 Cyg. Contours are −3, 3, and 4 times the rr noise of the map, 48 μJy beam^{-1}. The angular resolutio of the map is 1.7″. The cross marks the position c the 3.6-cm source detected by Rodríguez *et al.* (1990 Coordinates are for equinox 1950.

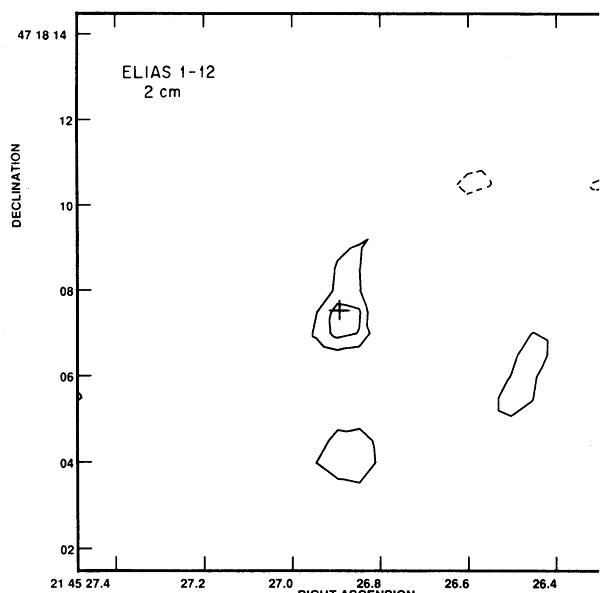

Fig. 2. Natural-weight VLA map of the 2-cm emissio from Elias 1-12. Contours are −3, 3, and 4 times the rr noise of the map, 45 μJy beam^{-1}. The angular resolutio of the map is 1.7″. The cross marks the position c the 3.6-cm source detected by Rodríguez *et al.* (1990 Coordinates are for equinox 1950.

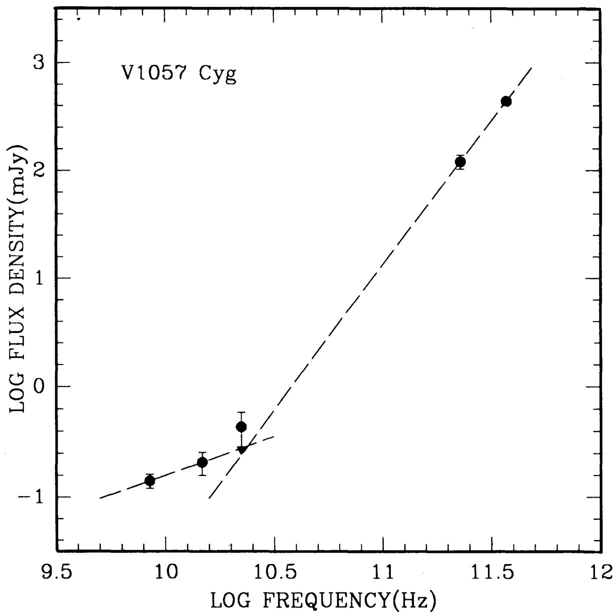

Fig. 3. Continuum spectrum of V1057 Cyg in the cm and mm range. Data points are from Weintraub *et al.* (1991), Rodríguez *et al.* (1990), and this paper. Dashed lines are fits to the 3.6 and 2-cm points (left) and to the 1300 and 800-μ points (right).

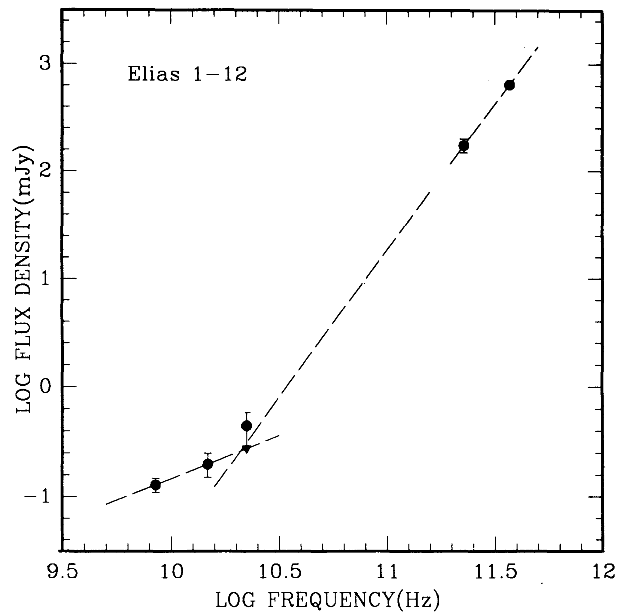

Fig. 4. Continuum spectrum of Elias 1-12 in the cm and mm range. Data points are from Weintraub *et al.* (1991), Rodríguez *et al.* (1990), and this paper. Dashed lines are fits to the 3.6 and 2-cm points (left) and to the 1300 and 800-μ points (right).

TABLE 1

CENTIMETER FLUX DENSITIES FOR V1057 CYG AND ELIAS 1-12

Star	α (1950)[a]	δ (1950)[a]	$S_{3.6cm}$ (mJy)	S_{2cm} (mJy)	$S_{1.3cm}$ (mJy)
V1057 Cyg	$20^h\ 57^m\ 06.22^s$	+44° 03′ 46.1″	0.14±0.02	0.21±0.05	≤ 0.44[b]
Elias 1-12	21 45 26.89	+47 18 07.5	0.13±0.02	0.20±0.05	≤ 0.45[b]

[a] Positions from 3.6-cm observations of Rodríguez, Hartmann, & Chavira (1990). Error is ~ 0.1″.

[b] Three-sigma upper limits.

TABLE 2

SPECTRAL INDICES

Star	3.6cm–2cm[a]	1300μ–800μ[b]
V1057 Cyg	0.7±0.5	2.7±0.3
Elias 1-12	0.8±0.5	2.7±0.3

[a] Data from Rodríguez, Hartmann, & Chavira (1990) and this paper.

[b] Data from Weintraub, Sandell, & Duncan (1991).

For a spherically-symmetric, steady, isothermal outflow at constant velocity, the ionized mass loss rate is related to the radio frequency flux by

$$\dot{M}_{ion} = 0.29 \times 10^{-5}\, S_\nu^{3/4}\, \nu_{10}^{-0.45}\, T_4^{-0.075} \times$$
$$\times\, \mu_{1.2}\, V_3 Z^{-1/2}\, d^{1.5}\, M_\odot\, yr^{-1} \quad (1)$$

(Panagia & Felli 1975), where S_ν is measured in mJy, ν_{10} is the frequency in units of 10 GHz, T_4 is the temperature in 10^4 K, Z is the charge of the ion, $\mu_{1.2}$ is the mean molecular weight in units of 1.2 hydrogen masses, V_3 is the (constant) wind velocity in units of 10^3 km s^{-1}, and d is the distance in kpc. Adopting $d = 0.6$ and $V_3 \sim 0.3$ for V1057 Cyg (see below), we find an ionized mass loss rate of $\dot{M}_{ion} \sim 10^{-7}$ M$_\odot$ yr^{-1}from the 3.6 cm flux.

Croswell, Hartmann, & Avrett (1987) constructed wind models to explain the optical Hα and Na I

P Cygni line profiles of FU Ori, and estimated a mass loss rate of $\sim 10^{-5}$ $M_\odot$ yr^{-1}. V1057 Cygni has much weaker blueshifted Na I absorption than FU Ori (Bastian & Mundt 1985; Croswell *et al.* 1987) suggesting that it has a lower mass loss rate. Unfortunately, both the $H\alpha$ and Na I lines in V1057 Cyg show distinct shell components rather than a smooth flow, which makes it difficult to assess the mass loss rate from continuous flow models. Moreover, the choice of wind terminal velocity V is similarly uncertain; most of the shell components have velocities $\sim$ a few hundred km s^{-1}, but occasionally one can observe blueshifted absorption in $H\alpha$ out to velocities as high as 400 km s^{-1} (Bastian & Mundt 1985).

The model results of Croswell *et al.* (1987) indicate that no blueshifted Na I absorption can be seen for continuous mass loss rates $\lesssim 10^{-6}$ $M_\odot$ yr^{-1} Thus we would estimate a time-averaged mass loss rate for V1057 Cyg slightly greater than 10^{-6} $M_\odot$ yr^{-1}. Alternatively, one might suppose that the deep Na I absorption in shells corresponds to instantaneous mass loss rates as high as 10^{-5} $M_\odot$ yr^{-1}, as in FU Ori, but in bursts which only occur $\sim$ 10 - 20 % of the time. In any event, it appears quite likely that the wind of V1057 Cyg has a sufficiently large time-averaged mass loss rate to comfortably explain the observed radio fluxes. Our estimates suggest that the wind need only be $\sim$ 10% ionized to explain the 3.6 cm flux, similar to the finding of Croswell *et al.* (1987) that the wind of FU Ori is only weakly ionized.

If the cm radio emission of V1057 Cyg arises from its wind, why was FU Ori not detected (Rodríguez *et al.* 1990), even though it has a higher mass loss rate than V1057 Cyg? We suggest that the dense wind of FU Ori has a smaller ionization fraction than the wind of V1057 Cyg. Croswell *et al.* (1987) calculated an ionization fraction $\sim 10^{-3}$ in the outer regions of a typical wind model (their Table 1), in which case the *ionized* mass loss rate is $\dot{M}_{ion} \sim 10^{-8}$ $M_\odot$ yr^{-1}. Since FU Ori is at roughly the same distance as V1057 Cyg, such a low ionized mass loss rate would produce a radio flux well below the detection limit of 0.05 mJy at 3.6 cm found by Rodríguez *et al.* (1990) (cf. equation 1).

Application of Eq. (1) to the measured flux of Elias 1-12 also indicates $\dot{M}_{ion} \sim 10^{-7}$ $M_\odot$ yr^{-1}. Detailed Na I line profiles are not available for Elias 1-12, so it is difficult to make even crude estimates of the mass loss rate. The high-dispersion $H\alpha$ spectrum of Bastian & Mundt (1985) indicates much weaker $H\alpha$ absorption than in FU Ori. Low-dispersion spectra suggest that the Na I lines are substantially weaker than in FU Ori (e.g., Elias 1978). As in V1057 Cyg, a low total mass loss rate may imply a more highly ionized wind.

We note that it would not be possible for the wind of FU Ori to be completely ionized, because the energy requirements for maintaining such ionization with such a high mass loss rate are much larger than the total system luminosity (Hartmann & Kenyon 1991). The energy requirements for ionizing the wind obviously decrease with decreasing mass loss rates. Paradoxically, weaker winds can be more easily observable in thermal free-free emission.

IV. CONCLUSIONS

Using the VLA we made sensitive observations of the 2 and 1.3-cm continuum emission toward the FU Orionis objects V1057 Cyg and Elias 1-12. Both stars were detected at 2-cm. The derived spectral indices for the cm range, 0.7–0.8, suggest that the emission mechanism is free-free radiation from an ionized outflow. For both V1057 Cyg and Elias 1-12, the required ionized mass loss rate is $\sim 10^{-7}$ $M_\odot$ yr^{-1}. In the case of V1057 Cyg, optical constraints suggest that the wind may be only about 10% ionized.

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