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STELLAR WINDS AND MOLECULAR CLOUDS: A SEARCH FOR IONIZED STELLAR WINDS

L.F. Rodríguez and J. Cantó

Instituto de Astronomía
Universidad Nacional Autónoma de México

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RESUMEN

Observamos con el VLA a 20, 6 y 2-cm varias regiones con eyección de gas: LkHα 198, GL 490, HH 7-11, T Tau, HL Tau, GGD 12-15, GL 961, GGD 27-28, V645 Cyg, Cep A, y MWC 1080. En la mayoría de las regiones no detectamos, al nivel de 1 mJy, objetos a 6-cm que pudieran ser identificados como la fuente de energía de los flujos. Este resultado sugiere que en estos casos los vientos estelares que energizan los flujos son neutros, o que si están ionizados, tienen velocidades terminales grandes ($\sim 10^3$ km s^{-1}). T Tauri y la mayoría de las fuentes detectadas tienen espectros característicos de regiones H II ópticamente delgadas y no de vientos estelares simples. También medimos las posiciones de varios máseres de H_2O, asociados con regiones de eyección gaseosa: GL 490, OMC(2)2, OMC(2)1, Mon R2, GGD 12-15, S106, GL 2591, NGC 7129(2), S140, y Cep A.

ABSTRACT

We observed with the VLA several regions of mass outflow at 20, 6 and 2 cm: LkHα 198, GL 490, HH 7-11, T Tau, HL Tau, GGD 12-15, GL 961, GGD 27-28, V645 Cyg, Cep A, and MWC 1080. In most of the regions no continuum source was detected, down to the mJy level, at 6 cm that could be identified as the energy source of the outflow. This result suggests that in these cases the stellar winds powering the outflows are either neutral or, if ionized, have a large terminal velocity ($\sim 10^3$ km s,$^{-1}$). T Tauri and most of the other sources detected show spectra characteristic of an optically-thin H II region and not that of simple ionized winds. We measured the positions of several H_2O masers associated with mass outflow regions: GL 490, OMC(2)2, OMC(2)1, Mon R2, GGD 12-15, S106, GL 2591, NGC 7129(2), S140 and Cep A.

Key words: MASERS – NEBULAE-GENERAL – RADIO SOURCES-SPECTRA – STARS-PRE-MAIN-SEQUENCE – STARS-WINDS

I. INTRODUCTION

During the last few years the phenomenon of molecular mass outflow has been detected in many regions of star formation. Following the detection of high velocity CO wings in Orion (Zuckerman, Kuiper, and Rodríguez-Kuiper 1976; Kwan and Scoville 1976), cases of bipolar mass outflows in L1551 and Cep A were reported by Snell, Loren, and Plambeck (1980) and Rodríguez, Ho, and Moran (1980). Since then, more than twenty sources of high velocity molecular outflows have been detected and studied (cf. Rodríguez *et al.* 1982; Bally and Lada 1983). One of the most important aspects of the problem is the identification of the energy source of the outflow. Generally, there are one or more compact optical, infrared, or radio objects at or near the center of the outflow. Some examples of optically identified central objects are V645 Cyg (Rodríguez, Torrelles, and Moran 1981), T Tau (Edwards and Snell 1982; Calvet, Cantó, and Rodríguez 1983), R Mon (Cantó *et al.* 1981), MWC 1080 (Cantó *et al.* 1983), and PV Cep (Levreault 1983). Some mass outflows associated with infrared objects are Orion (Zuckerman, Kuiper, and Rodríguez-Kuiper 1976; Kwan and Scoville 1976), L1551 (Snell, Loren, and Plambeck 1980), GL 961 (Blitz and Thaddeus 1980), and GL 490 (Lada and Harvey 1981). Finally, central compact objects observed in the radio have been found in several of the sources mentioned and in Cep A (Rodríguez *et al.* 1980), GGD 12-15 (Rodríguez *et al.* 1982), NGC 2071 (Bally 1982; Lichten 1982), and GL 2591 (Torrelles *et. al,* 1983). It is important to emphasize that many of the outflow regions are associated with several compact objects of various characteristics that are detectable at different frequency domains. In most sources, the optical, infrared, and radio objects are *not* coincident in position, suggesting different stellar or protostellar objects in different stages of evolution or in different environments (Rodríguez *et al.* 1980; Haschick *et al.* 1980).

In this paper we report the results of a search for compact continuum sources in regions of CO outflows. The sources are expected to fall in one of the following categories, according to their spectral index α, where $S_\nu \propto \nu^\alpha$: (1) optically thick H II region, $\alpha \simeq 2$; (2) optically thin H II region, $\alpha \simeq -0.1$; (3) ionized stellar wind, $\alpha \simeq 0.6$; and (4) non-thermal source, $\alpha < -0.1$. This classification is broad and non exclusive, but it provides an indication of the nature of the source. Of course, our main interest was the detection of sources that could be identified as ionized stellar winds, $\alpha \simeq 0.6$, since this would make them strong candidates for the energy source of the CO outflows. Furthermore, the continuum flux in combination with the CO measurements could allow the determination of the mass loss rate, $\dot{M}$, and of the wind terminal velocity, v_∞. This can be done because the continuum flux gives information on the ratio $\dot{M}/v_\infty$, while the CO data allows an estimate of the product $\dot{M}v_\infty$. Combining this information it is possible to estimate separately $\dot{M}$ and v_∞.

We also measured, using the VLA, the positions of several H_2O masers to compare them with available positions of other compact sources in the region. In § II we describe the continuum and H_2O observations and in § III we make comments on the individual sources. A general discussion on the association between radio continuum sources and CO outflows is given in § IV and we present our conclusions in § V.

II. OBSERVATIONS

a) *Continuum*

The observations at 20, 6 and 2 cm were made during 1981 October using the Very Large Array (VLA) of the National Radio Astronomy Observatory[1]. At the epoch of observation the maximum baseline was $\sim$ 2.5 km (C configuration). The parameters of the instrument at the three observed frequencies are given in Table 1. The sources observed and other information are listed in Table 2. We have corrected the fluxes to account for the primary beam response. When possible, we determined the spectral index of the source. Only the source in GGD 12-15 and Cep A showed resolved angular structure. The last column of the table contains a brief comment on the source classification. The fields were observed in the snapshot mode with one to three five-minute integrations made for each observed frequency. Each observation was preceded and followed by a three-minute integration on the calibrator. The data were reduced using the standard data analysis procedures (Hjellming 1982) and maps were made over the coherent field of view. In some cases, sources were detected close to the edge of the 20 cm field that could not be reached in the 6 cm field. Similarly, sources close to the edge of the 6 cm field were not reached in the 2 cm field. The signal-to-noise ratio of each map varies according to the observed wavelength and to the presence of strong sources in the field. At 6 cm, the rms noise level is 0.14 mJy for 5 minutes of integration. However, at 20 cm there is a 50 percent chance of having an extragalactic source with a flux of $\sim$ 50 mJy within the coherent field of view. Since in the snapshot mode the $(u\ v)$ coverage is modest, the sidelobes of the random extragalactic source will tend to lower the effective signal-to-noise ratio of the map. In any case, sources with several mJy are still detectable with a five-minute shapshot. Finally, at 2 cm the higher system temperature and the overall lower efficiency only allow detections of sources of tens of mJy in a five-minute integration. Due to time limitations we could not integrate at 20 and 2 cm for sufficiently long times and for many of the sources the upper limits at these frequencies are not stringent. Nevertheless, our results are relevant for several of the sources and improve our understanding of them.

TABLE 1

PARAMETERS OF THE VLA (1981 October)

Wavelength (cm)	Frequency (GHz)	Angular Resolution (arc sec)	Field of View[a] (arc sec)	System Temperature (K)
20	1.465	18	$\sim$ 1000	60
6	4.885	5	$\sim$ 540	60
2	14.965	2	$\sim$ 220	300

a. With 50-MHz bandwidth. At 20 cm we were limited by coherence and at 6 and 2 cm by primary beam size.

b) *Water Masers*

Spectral line observations were made at 1.3 cm with the VLA during 1982 September. The array was in the B configuration having a maximum baseline of $\sim$ 10 km and an angular resolution of $\sim 0''.3$. We used an effective bandwidth of 3.125 MHz spread over 32 channels giving a velocity coverage of ~ 42 km s^{-1} and a velocity resolution of ~ 1.6 km s^{-1} (unit weighting). The number of antennas was 18. Due to the poor weather we had unstable phases in the long baselines so we applied a Gaussian taper of 1 km, degrading the angular resolution of the interferometer to $\sim 3''$.. We made maps of the velocity channels having the strongest features. In Table 3 we give the positions, radial velocities, and fluxes of the features mapped. The fluxes have been corrected to account for the primary beam response. We estimate the positional errors to be $\sim 0''.2$.

III. COMMENTS ON INDIVIDUAL SOURCES

a) *LkHα 198*

This is an Ae-type star associated with nebulosity (Herbig 1960). Schwartz and Buhl (1975) reported a weak H_2O maser probably associated with this star. Cantó *et al.* (1983) found a low velocity bipolar molecular outflow associated with it. In the region we found three continuum sources, none of them coincident with the star. The nearest radio source, at α (1950) $= 00^h08^m52^s.2$; δ (1950) $= 58^\circ\ 33'\ 02''$, is about one arcmin away from the position of LkHα 198

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[1] NRAO is operated by Associated Universities, Inc., under contract with the National Science Foundation.

TABLE 2

OBSERVED SOURCES

Source	Calibrator	Center of Field		Position of Sources[a]		Flux (mJy)[b]			Spectral Index	Comment
		α(1950)	δ(1950)	α(1950)	δ(1950)	20 cm	6 cm	2cm		
LkHα 198	0133 + 476	00^h 08^m $47\overset{s}{.}5$	58° 33′ 06″	00^h 08^m $52\overset{s}{.}2$	58° 33′ 02″	4	3	⩽ 7	−0.2 ± 0.3	Thin H II region
"				00 08 32.2	58 34 36	3	3	–	−0.0 ± 0.3	Thin H II region
"				00 09 07.3	58 30 22	3	⩽ 2	–	⩽ −0.3	–
GL 490	0133 + 476	03 23 41.0	58 36 52	03 23 41.0	58 36 52	< 100[c]	⩽ 2	–	–	No detection
HH7-11	0400 + 258	03 25 56.4	31 05 20	03 25 56.4	31 05 20	< 6	2	⩽ 6	–	–
"				03 26 15.1	31 05 32	6	4	–	−0.3 ± 0.2	Extragalactic ?
T Tau	0400 + 258	04 19 04.2	19 25 05	04 19 04.2	19 25 05	5	5	⩽ 8	0.0 ± 0.2	Thin H II region
HL Tau	0400 + 258	04 28 44.4	18 07 37	04 28 44.4	18 07 37	⩽ 5	⩽ 1	⩽ 6	–	No detection
"				04 28 50.0	18 04 12	25	15	–	−0.4 ± 0.1	Extragalactic triple
GGD 12-15	0723−008	06 08 24.1	−06 11 08	06 08 24.1	−06 11 08	98	108	102	0.00 ± 0.1	Thin H II Region
GL 961	0723−008	06 31 58.0	04 15 30	06 31 58.0	04 15 30	⩽3	< 1	⩽ 8	–	No detection
"				06 31 44.4	04 14 27	4	2	–	−0.6 ± 0.3	Extragalactic
"				06 31 25.3	04 22 35	11	–	–	–	–
GGD 27-28	1908−202	18 16 13.0	−20 48 48	18 16 13.0	−20 48 48	⩽ 17[c]	7	⩽ 14	–	–
"				18 16 38.1	−20 37 50	255	–	–	–	Probably extragalactic
V645 Cyg	2352 + 495	21 38 13.2	50 00 01	21 38 13.2	50 00 01	20	8	⩽ 10	−0.8 ± 0.1	Extragalactic
"				21 37 35.3	50 03 21	28	–	–	–	–
Cep A	2352 + 495	22 54 19.0	61 45 48	22 54 19.0	61 45 48	∿ 100	~ 100	⩽ 50	0.0 ± 0.2	Complex, thin H II regions
MWC1080	2352 + 495	23 15 16.3	60 33 52	23 15 16.3	60 33 52	⩽ 30[c]	⩽ 2	⩽ 12	–	No detection

a. Positional accuracy is ∿ 1″.

b. Estimated flux errors are 1mJy (20 cm), 0.6 mJy (6-cm), and 4 mJy (2 cm).

c. Extended source in vicinity produced ripples in map.

TABLE 3

PARAMETERS OF H_2O MASERS

Source	α(1950)	δ(1950)	v_{LSR}(km s^{-1})	S_ν(Jy)
GL 490	$03^h23^m39\overset{s}{.}29$	$58°36'35\overset{''}{.}0$	− 13	2
OMC(2)2	05 32 58.16	− 05 07 36.0	13	6
OMC(2)1	05 32 59.50	− 05 11 44.6	15	11
Mon R2	06 05 19.30	− 06 22 11.3	− 2,2	178,104
GGD 12-15	06 08 25.66	− 06 10 49.5	− 15, − 9	10,4
S106	20 25 32.54	37 12 50.8	− 12	13
GL 2591	20 27 35.93	40 01 15.4	− 2.5, − 10, − 8	18,18,21
NGC 7129(2)	21 41 57.03	65 53 10.8	− 15, − 7	3,11
"	21 41 57.22	65 53 08.6	− 19	6
S140	22 17 41.14	63 03 41.8	− 2,8	60,50
"	22 17 41.02	63 03 41.6	− 16	160
Cep A	22 54 19.00	61 45 47.5	11	110
"	22 54 19.26	61 45 44.1	− 4	230

given by Loren, Vanden Bout, and Davis (1973). Its spectral index is consistent with that of an optically thin H II region. If this source is indeed an H II region and is located at 1.7 kpc, the same distance of LkHα 198 (Cantó *et al.* 1983), it could be ionized by a B2 ZAMS star (Panagia 1973). The other two sources could also be optically-thin H II regions. Moran *et al.* (1982) found several flat spectrum radio sources in Orion which coincide spatially with optically observable stars or condensations. The LkHα 198 region could also be abundant in this type of sources.

b) *GL 490*

Simon *et al.* (1981) observed Brγ line emission from a compact IR source in this region. From their measurements they concluded that the Brγ emission is coming from a very compact region probably thick in the infrared and very thick in the radio. This conclusion is confirmed by the low upper limit ($\lesssim$ 2 mJy at 6 cm) obtained by us. Indeed, the Brγ line emission intensity indicates an ionizing rate equal or greater than 5×10^{45} s^{-1}. If the ionized volume were optically thin in the radio we would expect a flux, $S_{5GHz} > 56$ mJy (for a distance of 1 kpc), much greater than our upper limit. Recently, Simon *et al.* (1982) observed the region with greater sensitivity detecting a 3.2 mJy source at 1.3 cm and getting an upper limit of 1 mJy at 6 cm. These two measurements imply an spectral index $\alpha \gtrsim 0.8$. This index is consistent with an ionized stellar wind with $\dot{M}/v_\infty = 5 \times 10^{-9}\ M_\odot\ yr^{-1}\ (km\ s^{-1})^{-1}$ (Felli and Panagia 1981). however, an optically thick H II region cannot be ruled out. An H_2O maser in the region (Table 3) was detected by Torrelles (1982) in 1981 September at the Haystack Observatory. In Figure 1 we show a spectrum of the maser at that epoch. When observed with the VLA about a year later the dominant -13 km s^{-1} feature was much weaker. This H_2O maser is coincident (within $\sim 0''.1$) with the unresolved continuum source found by Simon *et al.* (1983) and described above. The IR source (Thompson and Tokunaga 1979, Simon *et al.* 1981) has a larger positional error ($\sim 1''$) and within this uncertainty it is also coincident with the H II/H_2O) source. Thus, in this region we may have an H II/H_2O/IR source, a rather rare correspondence.

c) *HH 7-11*

We detected two radio sources in the 20 cm field of view. One of them has a spectral index of $\sim -0.3 \pm 0.2$, which does not allow even a crude classification. The other detection confirms the radio source reported by Haschick *et al.* (1980). The 6 cm flux observed by us (2.0 ± 0.5 mJy) is, within error, equal to the value measured by these authors. Our upper limits at 20 and 2 cm allow a constraint to the spectral index ($-1.0 \leqslant \alpha \leqslant 1.0$), which rules out an optically-thick H II region.

d) *T Tau*

This is one of the most interesting sources observed. Cohen, Bieging, and Schwartz (1982) determined the flux of T Tau to be 5.8 ± 0.6 mJy at 6 cm in 1981 March, using the VLA. This measurement agrees with ours. However, (Cohen, Bieging, and Schwartz 1982) combined their VLA data with single-dish measurements at other frequencies (Spencer and Schwartz 1974; Schwartz and Spencer 1977; Cohen 1980) and suggested that the radio spectrum could be fitted with a spectral index, $\alpha \simeq 0.63$ characteristic of an ionized stellar wind. Bertout and Thum (1982) give a similar interpretation. However, our measurements at 20 and 6 cm and our upper limit at 2 cm give $\alpha \simeq 0.0 \pm 0.2$, consistent with an optically thin H II region. Such a discrepancy in the spectral index (for which a possible explanation will be presented later) is very important, since the two possibilities lead to very different conclusions. Under the stellar wind model, the rate of ionizing photons required to fully ionize a constant velocity wind should be equal or greater than a critical value given by (Felli and Panagia 1981):

$$\left[\frac{N_c}{s^{-1}}\right] \simeq 4.9 \times 10^{46} \left[\frac{S_\nu}{mJy}\right]^{1.5} \left[\frac{D}{kpc}\right]^{3} \times \left[\frac{\nu}{4.9\ GHz}\right]^{-0.9} \left[\frac{R_*}{10\ R_\odot}\right]^{-1} , \qquad (1)$$

where S_ν is the flux at the observing frequency ν, D is the distance to the source and R_* is the stellar radius, assumed to be the inner radius of the ionized envelope. We have taken the electron temperature to be 10^4 K. For T Tau, D = 0.16 kpc, $R_* = 6.7\ R_\odot$ (Cohen, Bieging, and Schwartz 1982), and taking $S_\nu = 5$ mJy at $\nu = 4.9$ GHz we obtain $N_c \simeq 3 \times 10^{45}\ s^{-1}$. This is a very large ionizing flux, corresponding to a B1 ZAMS star (Panagia

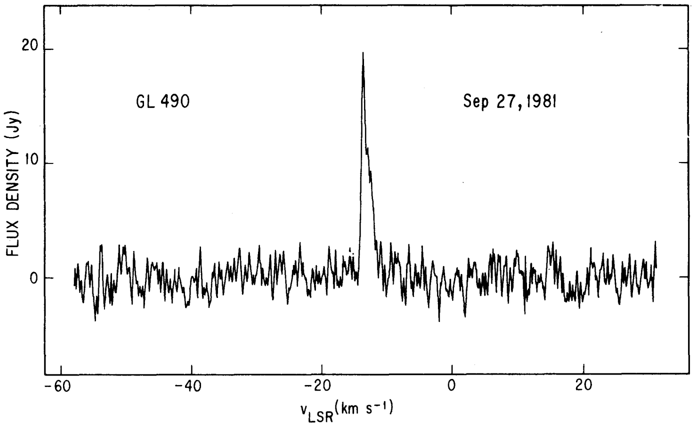

Fig. 1. The spectrum of the H_2O maser associated with GL 490 measured at the Haystack Observatory. The velocity resolution is 0.22 km s^{-1} (Hanning weighting). The velocity axis is referred to the local standard of rest.

1973). Furthermore, the required ionizing luminosity ($\gtrsim$ 19 $L_\odot$) would be comparable with the bolometric luminosity of T Tau ($\sim$ 28 $L_\odot$, practically all of it in non-ionizing photons; Cohen and Kuhi 1979) and much larger than the mechanical power in the wind ($\sim$ 0.3 $L_\odot$ for $\dot{M} \simeq 10^{-7}$ $M_\odot$ yr^{-1} and $v_\infty \simeq 200$ km s^{-1}). Thus, an unknown, highly efficient ionizing mechanism would appear to be required.

If we assume on the other hand, that the radio emission of T Tau is coming from an optically thin plasma such difficulties disappear. In this case the required rate of ionizing photons is given by (Schraml and Mezger 1969):

$$\left[\frac{N_i}{s^{-1}}\right] \simeq 9.0 \times 10^{43} \left[\frac{S_\nu}{mJy}\right]\left[\frac{D}{kpc}\right]^2 \times \left[\frac{\nu}{4.9\ GHz}\right]^{0.1} , \qquad (2)$$

where again we have taken the electron temperature to be 10^4 K. For T Tau we obtain $N_i \simeq 1 \times 10^{43}$ s^{-1} (or an ionizing luminosity of $\sim$ 0.07 $L_\odot$), more than two orders of magnitude less than under the ionized-stellar wind assumption. This modest ionizing rate could be obtained by thermalizing a small fraction ($\sim$ 20%) of the kinetic energy of the wind (assumed to be neutral when leaving the stellar surface). T Tau is a recently formed star an it is probably still surrounded by circumstellar clumps of matter, as suggested by its associated H_2O maser emission (Knapp and Morris 1976); Genzel and Downes 1977) and circumstellar reddening (Mendoza 1966); Rydgren, Schmelz, and Vrba 1982). If these clumps intersect a small percentage of the stellar wind of T Tau, the mechanical energy of the wind will be thermalized and ionization will occur.

We would like to point out a plausible explanation for the discrepancy between the single-dish and interferometer flux measurements. Although there is an unresolved source with 5 mJy at 6 cm coincident with T Tau, cleaning of a region of about 1′ around it revealed the presence of low-level extended emission adding 4 mJy to the flux of the region. The total flux of 9 mJy is probably what is being measured by the single-dish observations.

Finally, our discussion is based on the assumption that T Tau is a single source. However, recent infrared (Dyck, Simon, and Zuckerman 1982) and radio (Schwartz, Simon, and Zuckerman 1983) observations indicate that T Tau has an obscured close companion which dominates the radio emission. Thus our results most probably apply to the obscured companion rather than to the visible star.

e) *HL Tau*

We did not detect a source at the position of the star to an upper limit of $\sim$ 1 mJy at 6 cm. This result agrees with the upper limit of Cohen, Bieging and Schwartz (1982). About 3′ to the south of HL Tau we detected a triple component source which is probably extragalactic because of its spectral index and therefore lies in the background of the redshifted CO lobe detected in this cloud (L1551) by Snell, Loren, and Plambeck (1980). In Figure 2, we show a 6 cm map of this extragalactic source.

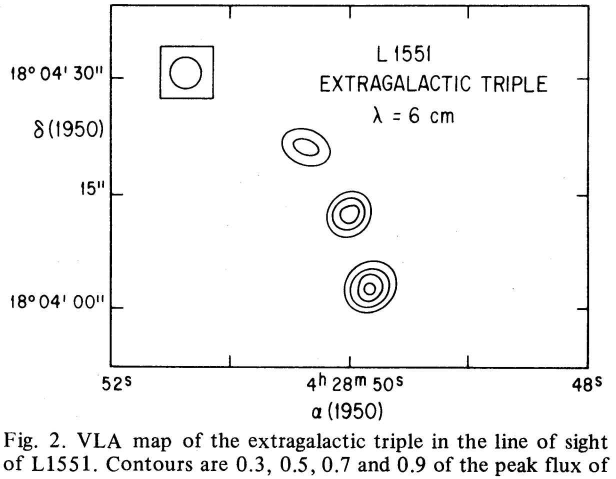

Fig. 2. VLA map of the extragalactic triple in the line of sight of L1551. Contours are 0.3, 0.5, 0.7 and 0.9 of the peak flux of 4.6 mJy per beam area.

f) *Mon R2*

The H_2O position reported by us corresponds to a new maser in the region located between the masers Mon R2 (1) and Mon R2 (2) (Genzel and Downes 1977). This new maser was dominating the H_2O emission of the region at the epoch of the observation. We did not search for continuum sources in this region.

g) *GGD 12-15*

We measured at the three frequencies the flux of the radio source detected by Rodríguez *et al.* (1980). It is a typical optically-thin, compact H II region with an angular diameter of $\sim$ 2″. In Figure 3 we show its spectrum which includes a VLA measurement made by Torrelles (1982) at 1.3 m and a RATAN-600 measurement made by Kononov and Pyatunina (1981) at 7.6 cm. The CO bipolar outflow appears to center at an H_2O maser displaced about 30″ from the H II region. Our VLA position for the H_2O maser coincides within $\sim$ 0″.5 with the VLBI position of Rodríguez *et al.* (1980). Apparently, the star powering the H_2O maser is not a detectable source of continuum, but may be powering the outflow. The H II region requires at least a B0.5 ZAMS star for its ionization (Rodríguez *et al.* 1980). The CO antenna temperature peaks at the position of the H II region (Rodríguez *et al.* 1982), which suggests that its ionizing star is the dominant energy source However, the CO outflow

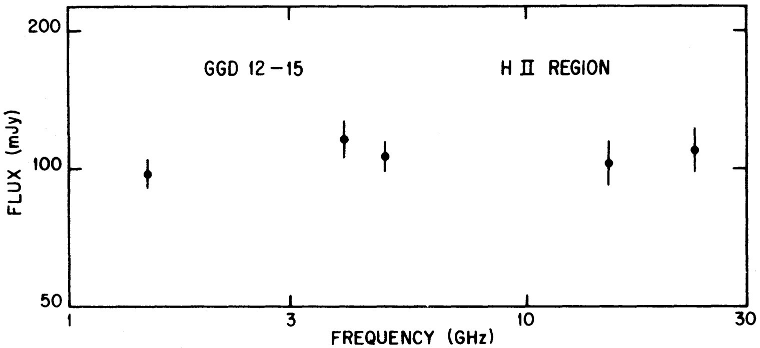

Fig. 3. Radio spectrum of the compact H II region associated with GGD 12-15. The source has the flat spectrum characteristic of optically thin plasma.

appears to be centered on a less luminous object. This result substantiates the conjecture that the energy source of the outflows does not necessarily have to be the most luminous object in the region (Ho, Moran, and Rodríguez 1982).

h) *GGD 27-28*

We confirmed the radio source detected by Rodríguez *et al* (1980). Within observational error, the 6 cm flux has not changed. As in the source probably associated with HH 7-11, the lack of significant time variability favors a thermal nature for both sources.

i) *S106*

We improved the position of the H_2O maser detected by Stutzki, Ungerechts, and Winnewisser (1982). The H_2O maser is ~ 15″ west of the compact H II region found by Bally and Predmore (1983).

j) *GL 2591*

The VLA position for the H_2O maser agrees within ∿ 1″ with the VLBI position of Walker *et al.* (1978). This H_2O maser is associated, within the IR observational error (~ 2″), with the 3.5μm peak measured by Wynn-Williams *et al.* (1977).

k) *V645 Cyg*

There is no detectable 6 cm continuum source ($\leqslant$ 1 mJy) at the position of V645 Cyg, as first observed by Kwok (1981) and Rodríguez, Torrelles, and Moran (1981). The source displaced ∿ 50″ to the southeast of V645 Cyg reported by these authors has a non-thermal spectrum and most probably is an extragalactic source unrelated to this star-forming region. There is another continuum source in the region which was detected only at 20 cm.

l) *NGC 7129 (2)*

This source has two H_2O centers of activity. One of the two centers coincides with the star LkHα 234 (Cohen and Schwartz 1983). This is one of the few pre-main-sequence objects that is visible and coincident with an H_2O maser.

m) *S140*

The two H_2O centers of activity are located at the north edge of the compact (~ 2″) radio source of elongated shape detected by Beichman, Becklin, and Wynn-Williams (1979). We speculate that radio continuum studies of higher resolution may show the elongated radio source to resolve into two separate H II regions, each one associated with one H_2O maser. We did not observe this region in the continuum.

n) *Cep A*

Beichman *et al.* (1979) and Rodríguez *et al.* (1980) mapped this region at 6-cm with the VLA finding two compact (~ 1″) H II regions. VLBI measurements of Lada *et al.* (1981) show two H_2O maser clusters coincident with the H II regions, while Norris (1980) found the OH maser in the region to coincide with one of them. Our VLA maps of H_2O maser emission are consistent with the results of Lada *et al.* (1981). At lower spatial resolution (~ 30″), Hughes and Wouterloot (1982) found two main H II regions, the eastern one contains as subcomponents the two compact H II regions found by Beichman *et al.* (1979) and Rodríguez *et al.* (1980). The main western H II region coincides with the suspected HH object GGD 37 (Gyulbudaghian, Glushkov and Denisyuk 1978). Our 20 cm map made with intermediate resolution (~ 18″) confirms the spatial coincidence between GGD 37 and the western H II region. This map is shown in Figure 4. However, our 20 cm map shows that the eastern H II region which appears as single in the Hughes and Wouterloot (1982) map, actually breaks into two, probably three, components. A more recent map by Hughes and Wouterloot (1983) with angular resolution of ~ 8″ also shows that the eastern H II region is multiple. Finally, our 6 cm map with a resolution of ~ 4″ (Figure 5) whows further fine structure and 7 indi-

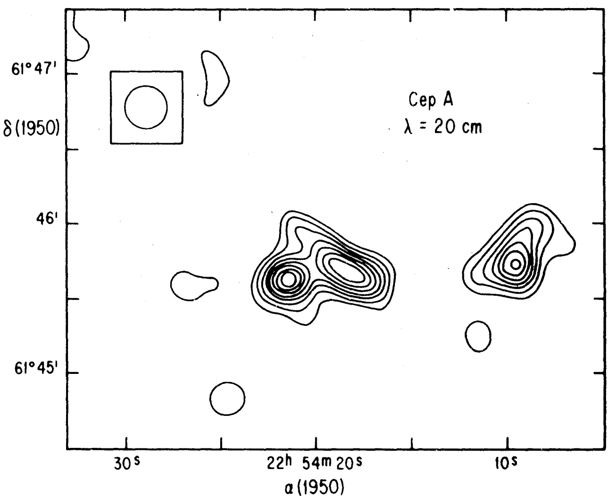

Fig. 4. VLA map at 20 cm of the H II regions in Cep A. The first contour is 0.2 and increments are 0.1 of the peak flux per beam (16.3 mJy).

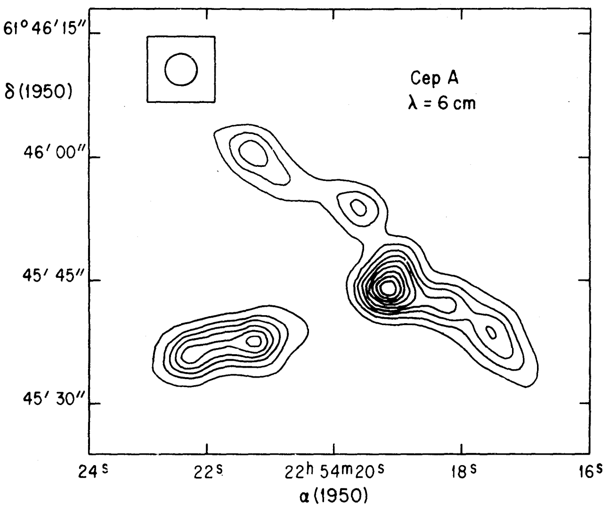

Fig. 5. VLA map at 6 cm of the H II regions in Cep A. The first contour is 0.1 and increments are 0.1 of the peak flux per beam (9.9 mJy).

vidual peaks can be distinguished. The integrated flux from these H II regions is consistent with optically-thin ionized gas. However, a VLA 1.3 cm map made by Torrelles (1982) suggests that the source at $\alpha(1950) = 22^h54^m19^s\!.0$; $\delta(1950) = 61°45'48''$ (Rodríguez *et al.* 1980) is partially thick.

Hughes and Wouterloot (1982) suggest that the suspected HH object (GGD 37) may not be related to the OH and H_2O masers and the compact H II regions. However, the high-velocity CO maps of Rodríguez, Ho and Moran (1980) and Ho, Moran and Rodríguez (1983) clearly show that there is a redshifted lobe of gas that connects the compact objects in the eastern H II region with GGD 37, which could be the western H II region. This suggests a relation, unfortunately poorly understood, between both H II regions.

o) *MWC 1080*

This is a B0 continuum star associated with nebulosity listed in Herbig (1960). Star and nebulosity lie projected against a small molecular cloud of about 6′ in diameter. Carbon monoxide observations by Cantó *et al.* (1983) reveal the presence of molecular material moving at large supersonic velocities (∿ ± 20 km s^{-1}) in the vicinity of the star. The dynamically affected region is quite large, 2-3 arc min across, with the redshifted and blueshifted emission spatially coincident and peaking at the star. Cantó *et al.* (1983) give a distance of 2.5 kpc for MWC 1080, which combined with the luminosity/(distance)^2 parameter given by Cohen and Kuhi (1979) implies a ZAMS luminosity class.

Assuming a B0 ZAMS spectral type for the star, we would then expect a rate of ionizing photons of about 2.3×10^{47} s^{-1} (Panagia 1973).

If the star is ionizing a dust-free medium of density ∿ 300 cm^{-3} (Cantó *et al.* 1983), the radius and emission measure of the expected Strömgren sphere are ∿ 0.43 pc (∿ 35″ at 2.5 kpc) and ∿ 3.9×10^4 cm^{-6} pc, respectively. Such an H II region would be optically thin in the observed frequency range with a flux of ∿ 400 mJy at 4.9 GHz. This value is much higher than the upper limit determined by us and given in Table 2. Even if dust were taken into account, we estimate from Spitzer (1978) that the optically thin flux could not be lowered more than a factor of ∿ 10. A possible explanation of this discrepancy is to assume that MWC 1080 possesses a stellar wind, as suggested by the CO results. As discussed in §IId, an ionized stellar wind could absorb a large rate of ionizing photons and still remain as a weak radio source. The minimum rate of ionizing photons required to fully ionize a constant velocity wind can be expressed also as (Felli and Panagia 1981):

$$\left[\frac{N_c}{s^{-1}}\right] = 2.9 \times 10^{47} \left[\frac{\dot{M}}{10^{-5}\, M_\odot\, yr^{-1}}\right]^2 \times \left[\frac{v_\infty}{10^3\, km\, s^{-1}}\right]^{-2} \left[\frac{R}{10 R_\odot}\right] \qquad (3)$$

For ZAMS stars, one knows the rate of ionizing photons and radius. Thus, for a given spectral type, we can estimate the *maximum* $\dot{M}/V_\infty$ ratio of a wind that the star can fully ionize. Combining equations (1) and (3), one finally obtains the maximum expected flux from a stellar wind ionized by a given spectral type, given by

$$\left[\frac{S_\nu}{\text{mJy}}\right] = 3.3 \left[\frac{\nu}{4.9\ \text{GHz}}\right]^{0.6} \left[\frac{\dot{M}}{10^{-5}\ M_\odot\ \text{yr}^{-1}}\right]^{4/3} \times \left[\frac{v_\infty}{10^3\ \text{km s}^{-1}}\right]^{-4/3} \left[\frac{D}{\text{kpc}}\right]^{-2} . \qquad (4)$$

In Table 4 we give the rates of ionizing photons, radii, and maximum $\dot{M}/V_\infty$ ratios and fluxes (at 4.9 GHz and a distance of 1 kpc) for ZAMS stars. For comparison purposes we also give the expected flux from optically thin plasma. For MWC 1080 (B0 ZAMS) we expect a flux of ~ 400 mJy (at a distance of 2.5 kpc). Clearly, our upper limit is consistent with the presence of a wind, either fully ionized or neutral, but not with the absence of a wind, since we should then have detected an extended H II region.

IV. ON THE NATURE OF THE COMPACT RADIO SOURCES IN REGIONS OF MASS OUTFLOW

The continuum sources observed by us can be grouped in three categories. In this discussion we are excluding the non-thermal sources detected which we assume to be field extragalactic sources, as well as the sources away from the center of the outflow, whose nature requires further study. First, there is a group of outflow regions with either no detectable or very weak ($\leqslant$ 1 mJy) compact source at 6 cm that could be identified as directly associated with the outflow. In this group fall LkHα 198, GL 490, HL Tau, GL 961, V645 Cyg, and MWC 1080. We included in this group GL 490 since the 1.3 cm source detected by Simon *et al.* (1982) is weaker than 1 mJy at 6 cm. We also included GL 961, since the 6 cm source detected by Bally and Predmore (1982) is also weaker than 1 mJy. A second group is formed by sources that have a flat spectrum characteristic of optically thin H II regions. These sources are T Tau, GGD 12-15, and Cep A. Finally, there is a third group of sources detected only at one wavelength (6 cm) for which there is no slope determination. These sources are HH 7-11 and GGD 27-28.

Our first conclusion is that we could not detect an unambiguous case of an ionized stellar wind (i.e., $S_\nu \propto \nu^{0.6}$). The three sources with determined slopes (T Tau, GGD 12-15, and Cep A) show spectra consistent with optically thin H II regions (i.e., $S_\nu \propto \nu^{-0.1}$). Furthermore, in two of these regions there is evidence that the outflow is not centered on the observed radio sources. In GGD 12-15, Rodríguez *et al.* (1982) note that the bipolar outflow seems to center on an H_2O maser displaced ∿ 30″ to the northeast of the H II region. In Cep A, Rodríguez, Ho, and Moran (1980) also point out that the gaseous outflow seems to center in a position displaced ~ 30″ to the east of the compact H II regions. Similarly, in HH 7-11 the CO outflow (Snell and Edwards 1981) centers in an H_2O/IR source (Haschick *et al.* 1980; Strom, Vrba, and Strom 1976) again displaced ∿ 30″ to the northeast of the compact radio source. Although these displacements are only two to three times the positional accurancy with which the location of the CO lobes are determined (10 to 15 arc sec), we consider them to be significant when taken as a group. Thus, it appears reasonable to propose that the winds of the compact objects powering the outflow are either neutral or, if ionized, are weak radio continuum sources. Another example of a source with a powerful wind but no detectable radio continuum is IRc2 in Orion, identified as the energy source of one of the outflows in the region (Genzel *et al.* 1979), and again lacking detectable continuum (Moran *et al.* 1982). If the stellar winds powering the CO outflows are neutral they

TABLE 4

EXPECTED MAXIMUM FLUXES FOR STELLAR WINDS IONIZED BY ZAMS STARS

Spectral Type	Rate of Ionizing Photons[a] (s^{-1})	Radius[a] ($R_\odot$)	Maximum $\dot{M}/v_\infty$ ($10^{-5}\ \dot{M}\ yr^{-1}$ / 10^3 km s^{-1})	Maximum flux[b] (mJy)	Optically thin Plasma[b] (mJy)
O4	8.5×10^{49}	15.1	2.1×10^{1}	1.9×10^{2}	9.4×10^{5}
O5	4.2×10^{49}	12.6	1.4×10^{1}	1.1×10^{2}	4.7×10^{5}
O6	1.2×10^{49}	9.5	6.3×10^{0}	3.8×10^{1}	1.3×10^{5}
O7	4.2×10^{48}	7.2	3.2×10^{0}	1.6×10^{1}	4.7×10^{4}
O8	2.2×10^{48}	6.5	2.2×10^{0}	9.4×10^{0}	2.4×10^{4}
O9	1.2×10^{48}	6.0	1.6×10^{0}	6.2×10^{0}	1.3×10^{4}
B0	2.3×10^{47}	5.5	6.6×10^{-1}	1.9×10^{0}	2.6×10^{3}
B1	1.9×10^{45}	4.8	5.6×10^{-2}	7.1×10^{-2}	2.1×10^{1}
B2	4.5×10^{44}	4.3	2.6×10^{-2}	2.5×10^{-2}	5.0×10^{0}
B3	4.9×10^{43}	3.4	7.6×10^{-3}	4.9×10^{-3}	5.4×10^{-1}

a. Data from Panagia (1973).

b. At 4.9 GHz, a distance of 1 kpc and for an electron temperature of 10^4 K.

should be searched for using high angular resolution HI or CO observations. However, the winds could be ionized but still remain as very weak continuum sources. The radio flux of an ionized stellar wind is given in equation (4). From the high velocity CO data it is possible to estimate the product $\dot{M}v_\infty$. Thus, having a value for v_∞ allows a determination of $\dot{M}$ and of the expected radio flux. For early-type stars on the main sequence one could adopt $V_\infty \simeq 10^3$ km s^{-1}. However, for recently formed stars, the IR results of Simon *et al.* (1982) favor lower values, $v_\infty \simeq 10^2$ km s^{-1}. In Table 5 we list estimates for $\dot{M} v_\infty$ taken from the literature as well as the fluxes expected at 6 cm if the stellar wind powering the outflow is fully ionized to infinity for the cases $V_\infty \simeq 10^3$ and 10^2 km s^{-1}. Clearly the case of a fully ionized, slow (10^2 km s^{-1}) wind is ruled out since the expected flux greatly exceeds the measured flux or upper limit in most of the sources. Furthermore, it can be shown that the minimum ionizing photon rates required to fully ionize slow winds ($\sim 10^2$ km s^{-1}) exceeds, in several cases, the value of even the most luminous stars known. This is shown in Table 5, where we give the minimum ionizing photon rates for $v_\infty = 10^2$ and 10^3 km s^{-1}. Those rates were obtained using equation (3) and assuming a stellar radius of 10 $R_\odot$. On the other hand, for much higher wind velocities ($v_\infty \simeq 10^3$ km s^{-1}), the required ionizing rate and expected flux for a given $\dot{M} v_\infty$ are much smaller and a fully ionized, fast wind is still a possible model.

We can conclude that the winds powering the mass outflows are either neutral or if ionized have large ($\geqslant 10^3$ km s^{-1}) terminal velocities. Simon *et al.* (1982) give considerable evidence favoring a stellar wind that remains ionized only within several AU from the star, becoming neutral farther away. This is a result difficult to reconcile with the constant-velocity, steady-state stellar wind model (Wright and Barlow 1975; Panagia and Felli 1975; Olnon 1975). In this model, the radius of the ionized region is either very close to the stellar surface (if the number of available ionizing photons, N_i, is smaller than the critical value, N_c) or goes to infinity (if N_i equals or exceeds N_c). In Figure 6, we show the radius of the ionized volume as a function of N_i. In this figure it can be seen that for a randomly given N_i we tend to have a small ionized radius, $R_* \leqslant R \leqslant 10\, R_*$, or to ionize to infinity. Thus it is very improbable to "tune" N_i to produce an ionized volume of radius of, let us say, 100 R_*.

Simon *et al.* (1982) suggest that these ionized winds of finite radius could be due to the presence of a dust envelope around the ionized region. This could explain the truncation in the ionization but makes it difficult to understand how the wind is not stopped by the dust envelope, but flows freely to power the large-scale outflows. A possible model that should be explored further and could reconcile, at least in part, the radio and IR results, is that of a *clumpy envelope.* The number of clumps could be made large enough so as to intersect and absorb most of the stellar photons within, let us say, $\sim$ 10 AU from the star. Of course, also the stellar wind

TABLE 5

EXPECTED AND OBSERVED FLUXES UNDER THE IONIZED STELLAR WIND HYPOTHESIS

Source	Distance (kpc)	Observed $\dot{M}v_\infty$ ($M_\odot$ km s^{-1} yr^{-1})	Expected Flux[d] at 6 cm (mJy) $v_\infty = 10^2$ km s^{-1}	Flux or Upper limit at center of outflow[b] ($\lambda = 6$ cm)	Minimum Ionizing Photon Rate required to fully ionize the wind[c] $v_\infty = 10^2$ km s^{-1}	References[a]
LkHα 198	1.7:	6×10^{-6}	3×10^{-2}	$\leqslant 1$	1.1×10^{45}	5, 14
GL 490	0.9	6×10^{-2}	2×10^{4}	$\leqslant 1$	1.0×10^{53}	6, 13
HH7-11	0.5	2×10^{-3}	7×10^{2}	$\leqslant 1$	1.1×10^{50}	2, 3, 14
T Tau	0.16	2×10^{-6}	9×10^{-1}	5	1.8×10^{44}	4, 10, 14
HL Tau	0.16	2×10^{-7}	3×10^{-2}	$\leqslant 1$	1.2×10^{42}	4, 14
GGD 12-15	1.0	3×10^{-4}	15	$\leqslant 10$	2.5×10^{48}	1, 11, 14
GL 961	1.6	7×10^{-3}	4×10^{2}	0.9	1.4×10^{51}	7, 12
GGD 27-28	1.7	1×10^{-3}	20	7	2.3×10^{45}	1, 11, 14
V 645 Cyg	6.0	1×10^{-3}	2	$\leqslant 1$	2.7×10^{49}	8, 14
Cep A	0.7	2×10^{-2}	8×10^{3}	$\leqslant 10$	1.2×10^{52}	9, 11, 14
MWC 1080	2.5	2×10^{-3}	29	$\leqslant 2$	1.1×10^{50}	5, 14

a. 1) Rodríguez *et al.* 1982; 2) Haschick *et al.* 1980; 3) Snell and Edwards 1981; 4) Calvet, Cantó, and Rodríguez 1983; 5) Cantó *et al.* 1983; 6) Lada and Harvey 1981; 7) Lada and Gautier 1982; 8) Rodríguez, Torrelles, and Moran 1981; 9) Rodríguez, Ho, and Moran 1980; 10) Cohen, Bieging, and Schwartz 1982; 11) Rodríguez *et al.* 1980; 12) Bally and Predmore 1983; 13) Simon *et al.* 1982; 14) this paper.

b. In HH7-11, GGD 12-15, V645 Cyg, and Cep A there are in the field stronger sources than the upper limits given, but they were considered not to be the source of energy of the outflow.

c. This rate corresponds to a stellar radius of 10 $R_\odot$. The results scale as R_*^{-1} and V_∞^{-4}.

d. The results scale as $V_\infty^{-8/3}$.

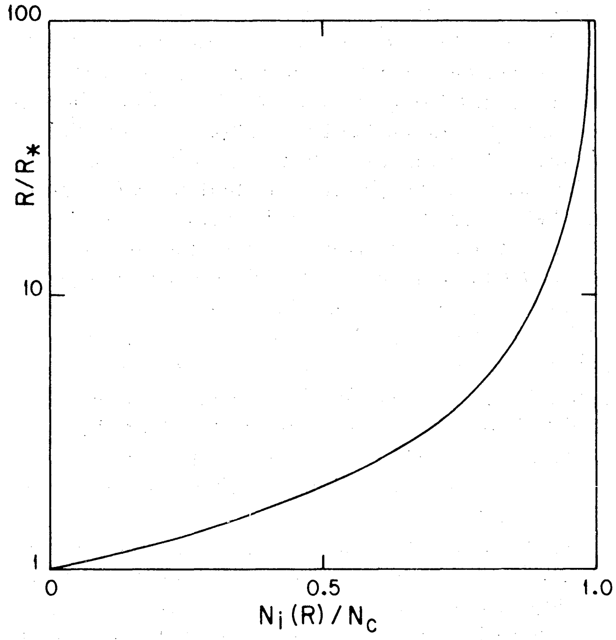

Fig. 6. The Strömgren radius of a stellar wind as a function of the ionizing photon rate of the central star, from Wright and Barlow (1975). R_* is the stellar radius and N_c is the critical ionizing photon rate. As the ionizing photon rate increases, the Strömgren radius increases, slowly at first. It is very difficult to produce an ionized zone of considerable radius ($R/R_* \simeq 10$), since small variations in the ionizing flux will make the Strömgren radius either shrink considerably or go to infinity.

would be intersected by the clumps, but it will tend to slide around them, escaping from the clumpy envelope. The resulting ionized region will be very small, self-absorbed in the radio, and consequently hard to detect.

V. CONCLUSIONS

Our main conclusions are summarized as follows:

1. We could not detect an unambiguous case of an ionized stellar wind, that is, none of the sources with a spectral index determination gave $\alpha \simeq 0.6$. This includes T Tau, which shows the flat spectrum characteristics of an optically-thin plasma.

2. Most of the CO outflow sources do not show a continuum source at its center to a level of ~ 1 mJy at 6 cm. This suggests that the stellar winds powering the outflows are either neutral, at least far from the star, or have a high $v_\infty \geqslant 10^3$ km s^{-1}) terminal velocity. Whether the winds are ionized or neutral could be settled observationally. If they are ionized, continuum observations at several wavelengths made with higher sensitivity and dynamic range should detect them. If the winds are neutral they may be detectable via high angular resolution observations of CO (if molecular) or H I (if atomic).

3. The H_2O masers in GL 490, S140, and Cep A are spatially associated with the compact H II regions found in the zone. Since this type of association is rare, it may be characteristically related to the mass outflow phenomenon. One of the H_2O masers observed in NGC 7129 may be spatially coincident with the star LkHα 234.

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J. Cantó and L.F. Rodríguez: Instituto de Astronomía, UNAM, Apartado Postal 70-264, 04510 México, D.F., México.