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RADIO OBSERVATIONS OF COMPACT SOURCES NEAR HERBIG-HARO OBJECTS

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ABSTRACT. The observations of masers and compact HII regions near Herbig-Haro objects are reviewed. H_2O masers and H-H objects are probably both manifestations of shocked gas in the outflowing envelopes of newly formed stars. H_2O masers have been detected near HH 1, HH 7-11 and HH 19-24 and near GGD 4, 5-6, 12-15, 16-17, 25, 27-28, 29, 32-35 and 37. Most of these masers have luminosities $\sim 10^{-7}$, which is substantially smaller than the luminosities of masers near massive OB stars. VLB observations show that the components in HH 7-11/H_2O(A) are very small, $\sim 2\times10^{12}$ cm in diameter and clustered within an area of diameter 3×10^{13} cm. The dispersal time for the maser is ~ 1 year. Hence, the masing cloud could not have travelled intact from a distant source, but is probably excited locally at the interface between the stellar wind and ambient cloud. It should be possible to measure proper motions of the HH/H_2O masers with either the VLA or VLB Network. Compact HII regions have been observed with the VLA at 5 GHz near HH 7-11, and GGD 5-6, 12-15, 25, 27-28, 29, and 37. If they are optically thin at 5 GHz they correspond to B0-B3 stars, whereas if they are stellar wind sources they would be substantially more luminous. The compact HII regions near HH 7-11, GGD 12-15, and GGD 37 could be ionized by embedded stars that are the energy sources for the associated bipolar molecular outflows. However, the momentum rates in the flows exceed those inferred for the radiation fields.

I. INTRODUCTION

The purpose of this paper is to review the observations of compact radio sources near Herbig-Haro Objects. These include H_2O masers and HII regions. All of the relevant data has been acquired since 1974 when the H_2O maser near HH 7-11 was discovered by Dickinson, Kojoian, and Strom (1974) and Lo, Burke, and Haschick (1975). The radio observations of extended sources near H-H objects, such as high velocity molecular outflows, have been reviewed by Snell in these proceedings, Bally and Lada (1983) and Rodríguez et al. (1982) and the observations of the ambient molecular medium have been discussed by Ho and Barrett (1980), Lada et al. (1974) and others. These observations will not be discussed in detail here.

It is now widely believed that H-H objects and H_2O masers are the result of radiation from shocked gas in the mass outflow occuring in the extended envelopes of newly formed stars (see recent observational reviews by Cohen (1982), Genzel and Downes (1983) and theoretical papers by Königl (1982), Cantó (1980), Norman and Silk (1979) and Schwartz (1978)). The large velocity dispersion of the spectral features in H_2O masers, up to ~ 300 km s^{-1}, provided the first evidence of unbounded expansion in molecular clouds. Strelnitskii and Syunyaev (1973) were the first to show that the maser spectra could arise from the radiation of many cloudlets being accelerated by winds from early-type stars. The detection of the high velocity CO outflow in Orion by Zuckerman, Kuiper, and Kuiper (1976) and Kwan and Scoville (1976) and other sources focused widespread attention on this phenomenon. Direct measurements of outflow in a molecular cloud were made by Genzel et al. (1981b) who observed the transverse motions of the H_2O masers in Orion over a two-year period. The proper motions of the maser components indicated an outflow of material from a central point, probably IRc2. The spatial distribution of velocities show that the mass outflow has been continuous for at least 10^3 years and could not have been produced by a single outburst. The results of this experiment show that proper motion studies of masers can provide important information about material flow around newly formed stars.

Proper motion measurements of H-H objects have convincingly shown that they are also part of mass outflows. Cudworth and Herbig (1979) showed that HH 28 and HH 29 are moving at tangential velocities of ~150 km s^{-1} away from the infrared source IRS5, the probable source of the high velocity molecular outflow in L1551 discovered by Snell, Loren, and Plambeck (1980). Herbig and Jones (1981) found that HH 1 and HH 2 are moving at velocities of ~150 km s^{-1} in opposite directions (see Figure 1). A faint star found by Cohen and Schwartz (1979) along the axis joining these H-H objects is probably the source of energy. The optical spectra of H-H objects are similar to those expected for cooling gas behind a shock front. However, it is unclear, at least from the

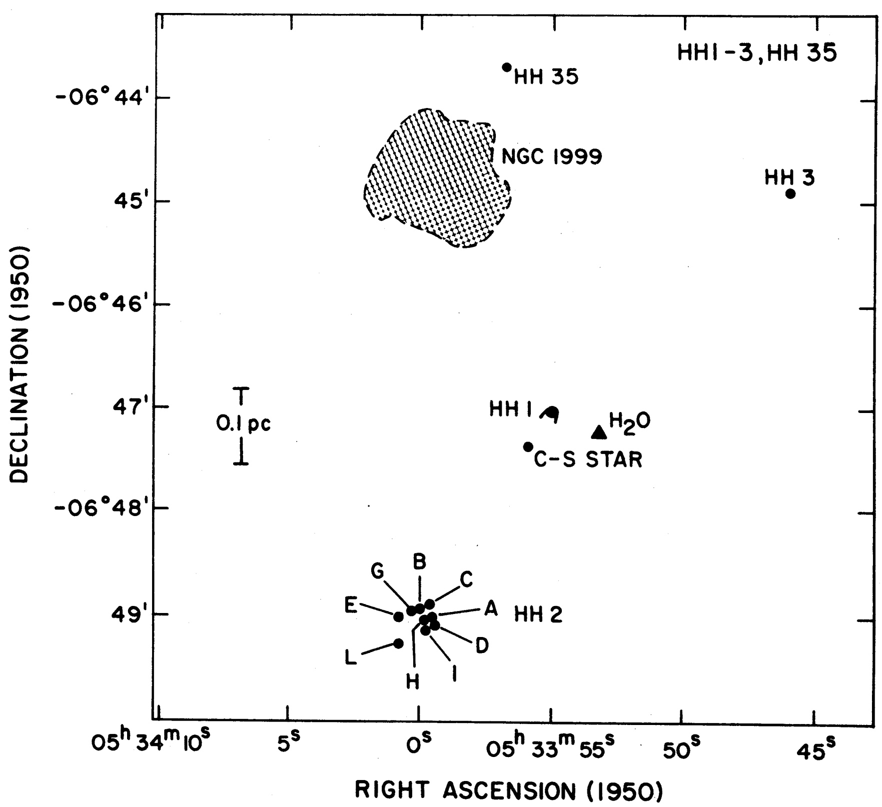

FIGURE 1. Herbig-Haro Objects 1, 2, 3 and 35, the Cohen-Schwartz (C-S) star and the H_2O maser. Maser position from Ho et al. (1982). Figure adapted from Haschick et al. (1983).

proper motion measurements, whether the shock is created as the H-H objects are accelerated by stellar winds or decelerated due to impact with the ambient molecular cloud.

II. OBSERVATIONS OF H-H OBJECTS

A. Survey Results

The earliest survey of H-H objects for H_2O masers was made by Lo, Burke, and Haschick (1975) who found masers near HH 1-2 and HH 7-11. A much more extensive survey was made by Haschick et al. (1983) with the Haystack Observatory. The survey consisted of 600 spectra covering 900 square arc-minutes in 20 regions at a sensitivity of about 10 Jy (5σ). HH 1-43, 55, 100-101 and several other objects were observed, most with a coverage of at least $\pm 2'$ (± 0.3 pc at 500 pc distance). New masers were found towards HH 19-27 (near NGC 2068) and the Serpens object, which is near GGD 29. The detection rate of $\sim 20\%$ (4 masers in 20 regions) is about the same as for other classes of objects with masers. For example, about 10% of evolved stars and compact HII regions show maser emission. The four HH/H_2O masers are weak compared to those found near newly formed OB stars, and have luminosities of $\sim 10^{-7}$ $L_\odot$. There is some evidence that maser luminosity is correlated with stellar luminosity (Genzel and Downes, 1979) which would indicate that the exciting stars for HH/H_2O masers have luminosities of about 10^2 - 10^3 $L_\odot$.

B. HH 7-11

The masers toward HH 7-11 are the best studied. Spectra have been published by Dickinson, Kojoian, and Strom (1974), Lo, Burke, and Haschick (1975), Lo et al. (1976), White and Little (1975), Genzel and Downes (1979), Haschick et al. (1980, 1983) and Sandell and Olofsson (1981). The most complete work was done by Haschick et al. (1980) who monitored the masers for 5 years and made VLBI measurements. As shown in Figure 2, there are 4 sites of maser emission. There is an IR source (Cohen and Schwartz, 1980), the brightest source in the region at 100μ, that is coincident within 1" with H_2O(A). Maser H_2O(B) is close to a compact HII region which has a flux density of 1.5 mJy corresponding to a B3 ZAMS star (Panagia, 1973) if the radio emission is optically thin. The CO profiles show high velocity wings, ± 20 km s^{-1}, about the cloud velocity of 8 km s^{-1} with a clear spatial separation of red- and blue-shifted emission (Snell and Edwards, 1981). The center of the flow is near H_2O(A) and H_2O(B) with the strongest blue shifted lobe covering the region of HH 7-11. All four of the H_2O masers are blue shifted with respect to the ambient cloud velocity and are probably part of the molecular flow.

The VLBI observations (Haschick et al., 1980) of H_2O(A) show that it can be most readily understood as a dense cloud that is rapidly dispersing. The angular diameter of the principal velocity component at -7 km s^{-1} was 0.35 milliarcseconds (mas), or 2×10^{12} cm at 500 pc, making it the smallest maser component ever measured. Other components at -15 and -17 km s^{-1} were about the same size and coincident with it to within 5 mas or 3×10^{13} cm, which is remarkable. The velocity shifts among the components must be kinematic because there are no other viable line splitting mechanisms. For example, the hyperfine splitting spans only 6 km s^{-1}, a Zeeman splitting of 10 km s^{-1} would require a magnetic field of 400 G, and the Stark effect is negligible in the maser radiation field (Genzel et al., 1979). The dynamical time scale for the maser is less than one

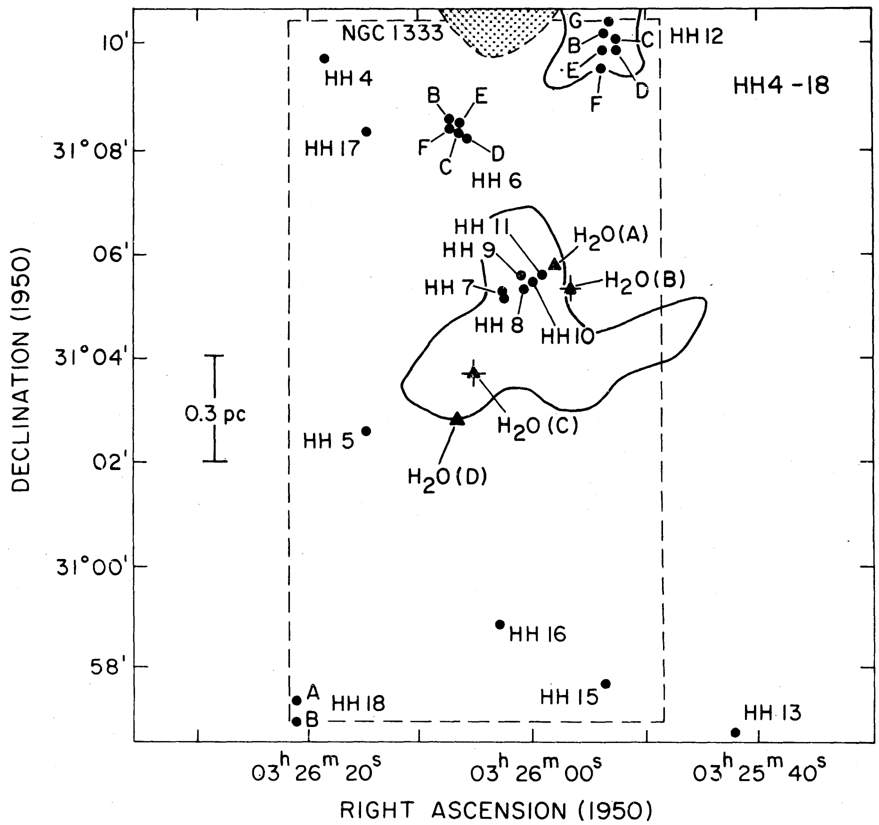

FIGURE 2. Map of region containing Herbig-Haro Objects 4-18 and four H_2O masers. The IR source SSV 13 (Cohen and Schwartz, 1983) is coincident with H_2O(A) and a compact HII region is near H_2O(B). Position of H_2O(D) is from Ho et al. (1982). The contour defining the local NH_3 peak is shown. The dashed box is the region searched for H_2O masers. Figure adapted from Haschick et al. (1983).

year, which is about the duration of individual maser features. This phenomenon of rapid dispersal of masing features is common in H_2O masers. It is dramatically evident in W51 where proper motions have been measured showing that the "southern high velocity complex" is dispersing on a time scale short with respect to the travel time from the source of the wind (Genzel et al., 1981a).

The short dispersal time of the masers in HH 7-11/H_2O(A) suggests that violent interaction between the wind and ambient cloud may be the source of the maser excitation. Such a model was first discussed by Lo et al. (1976) and developed by others (cf. Königl, 1982). One might imagine small wind-driven clumps smashing into the dense ambient medium and being rapidly torn apart. The kinetic energy dissipated in such a collision is sufficient to pump the maser. It is difficult to calculate accurately the kinetic energy of the masing clouds because the measured angular size and flux density are not uniquely related to the true size and particle density. For cylindrical or filamentry geometry the measured size of a masing cloud is the true cross sectional diameter but the axial length is unknown, although it is unlikely to be greater than 20 times the cross sectional diameter. For spherical masers, the ratio of true to measured diameter varies from ~5 for an unsaturated maser to ~50 for a fully saturated maser where a small unsaturated core persists (Goldreich and Keeley, 1972; Litvak, 1973). The separation between the spots and the diameters of the spots observed suggests that this ratio cannot be greater than ~15. We adopt this value and assume the masers are spherical so that the true maser cloud radius, R, is $\sim 2\times10^{13}$ cm. The maximum luminosity from a maser having a population inversion density, ΔN_o, occurs when it is saturated and is approximately

$$L_m = h\nu\Delta N_o \Gamma V \text{ (erg/s)}, \qquad (1)$$

where h is Planck's constant, ν is the maser frequency, Γ is the inverse lifetime of the maser states, $\sim 1\ s^{-1}$, and V is the volume. Since the -7 km s^{-1} feature has $L_m \sim 3\times10^{-7}\ L_\odot$, then $\Delta N_o \sim 250\ cm^{-3}$. This rather large population inversion density is required because of the maser's small size. Assuming that the pump efficiency is 3%, the fraction of H_2O molecules in the masing levels is 3%, and the ratio of molecular hydrogen to H_2O number density is 4×10^4, brings the total gas density, n_m, to $10^{10}\ cm^{-3}$. The mass of the maser cloud is about $10^{-6}\ M_\odot$. The kinetic energy dissipation rate is

$$L = \frac{\pi}{2} R^2 n_c m_{H_2} v^3, \qquad (2)$$

where n_c is the ambient cloud density, m_{H_2} is the mass of hydrogen, and v is the maser cloud velocity. If the maser features have a lifetime of ~1 year and $v \sim 30$ km s^{-1} (the radial velocity difference is ~20 km s^{-1}) then $n_c \sim n_m/10 \sim 10^9\ cm^{-3}$ and $L \sim 0.01\ L_\odot$. The minimum pump luminosity, L_p, assuming one pump photon in the H_2O band ~40μ per microwave photon, will be $\sim 1\times10^{-4}\ L_\odot$. Hence ~1% of the cloud kinetic energy must be radiated in the IR lines of H_2O that pump the maser. Recently, Hollenbach and McKee (1979) showed that cooling in molecular lines, and H_2O lines in particular, is very efficient in a post-fast-shock regime. Hence, there may be adequate kinetic energy available to pump the maser. In general the ratio of pump luminosity to kinetic luminosity is $L_p/L \sim 10^3 (\frac{n_m}{n_c}) \frac{R}{v^3}$, so that moderately high velocities are needed. The pump requirement is reduced if the maser is beamed.

There is an alternative model to the one just described. Each of the 4 masing regions could be in the envelope of an individual star, like the masers in late-type stars or the "shell" features around IRc2 in Orion. In this case the maser spots would flare as clumps flowed out in the individual winds. Maser H_2O(A) is exactly coincident with an infrared source, SSV13, that Cohen (1982) suggests is the exciting source for the bipolar flow and HH 7-11. The H-H objects and the H_2O/IR source are aligned to within a few degrees. Similarly, H_2O(B) is near a compact HII region which could correspond to another star. In this view one dominant star would power the molecular flow but other low-mass stars would be present.

III. OBSERVATIONS OF GGD OBJECTS

Gyulbudaghian, Glushkov and Denisyuk (1978) found 37 objects (GGD objects) that look like H-H objects on the Palomar Sky Survey. Spectroscopic observation of six of them showed characteristic low excitation spectra but no observations shortward of 5000 Å were made. Some of these objects are undoubtably reflection nebula, as, for example, GGD 14, which shows no emission lines (Cohen and Schwartz, 1980). Rodríguez et al. (1980) surveyed the 24 fields containing the GGD objects and found H_2O masers in 9 of them (GGD 4, 5-6, 12-15, 16-17, 25, 27-28, 29, 32-35, and 37). Most of the masers have simple spectra with features substantially shifted, ~30 km s^{-1}, from the ambient molecular cloud velocity. Six (GGD 5-6, 12-15, 25, 27-28, 29, and 37) of the nine fields with H_2O masers contained compact continuum radio sources, probably compact HII regions powered by early B stars. The H_2O masers are closer to the compact HII regions (mean projected separation ~0.15 pc) than the GGD objects are (mean projected separation ~0.6 pc) suggesting that, if the H_2O masers and GGD objects are both clumps in flows, the masers occur closer to the exciting star than the GGD objects.

Two of the GGD fields have bipolar CO outflows: GGD 12-15 (Rodríguez et al., 1982) and GGD 37 (Cepheus A) (Ho, Moran, and Rodríguez, 1982). The compact HII region near the center of the flow in GGD 12-15 is probably powered by a ~B0.5 star (see Figure 3). This is one of the rare cases where the radiative momentum rate is almost as large as the mechanical momentum in the flow. The maser and GGD objects are not well-aligned with the flow.

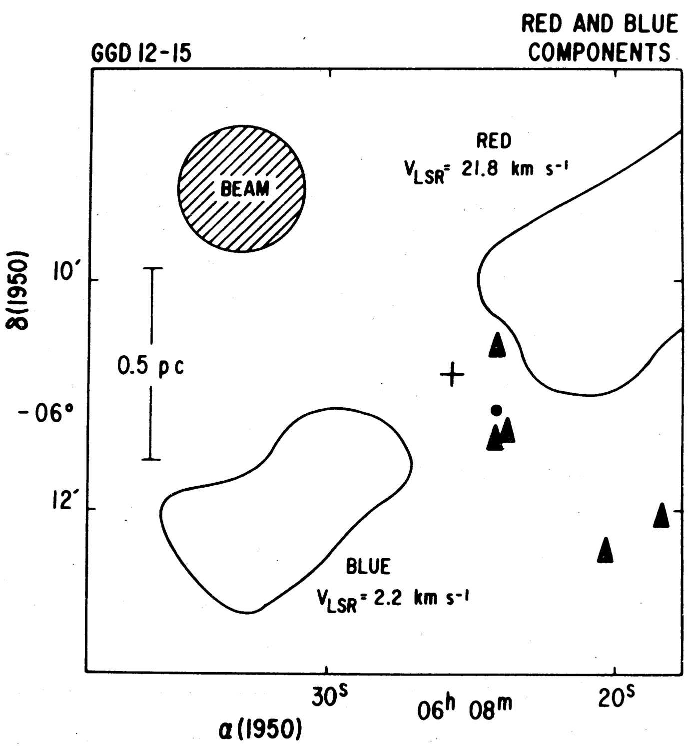

FIGURE 3. Region of GGD 12-15 with contours showing the high velocity red- and blue-shifted emission of CO. The (+) marks the position of the H_2O maser, the (•) the compact HII region, and the (▲)'s the GGD objects (the most southerly GGD object, GGD 13, is LKHα338, an emission line star). Reipwith and Wamsteker (1983) found seven 2μ sources in the field.

GGD 37 lies in the red-shifted lobe of the CO outflow from Cep A (see Figure 4). The blue-shifted lobe coincides with the local NH_3 peak (Ho, Moran, and Rodríguez, 1982) and appears compressed with respect to the red-shifted lobe. This may be a case where the ambient cloud shapes the outflow. As shown in Figure 5, the H_2O maser spots in the velocity -22 to +4 km s^{-1} are projected directly onto a double compact HII region near the center of the outflow (Lada et al., 1981). There are a few high velocity features that were not measured. Such a close coincidence between a water maser and a compact HII region is unusual.

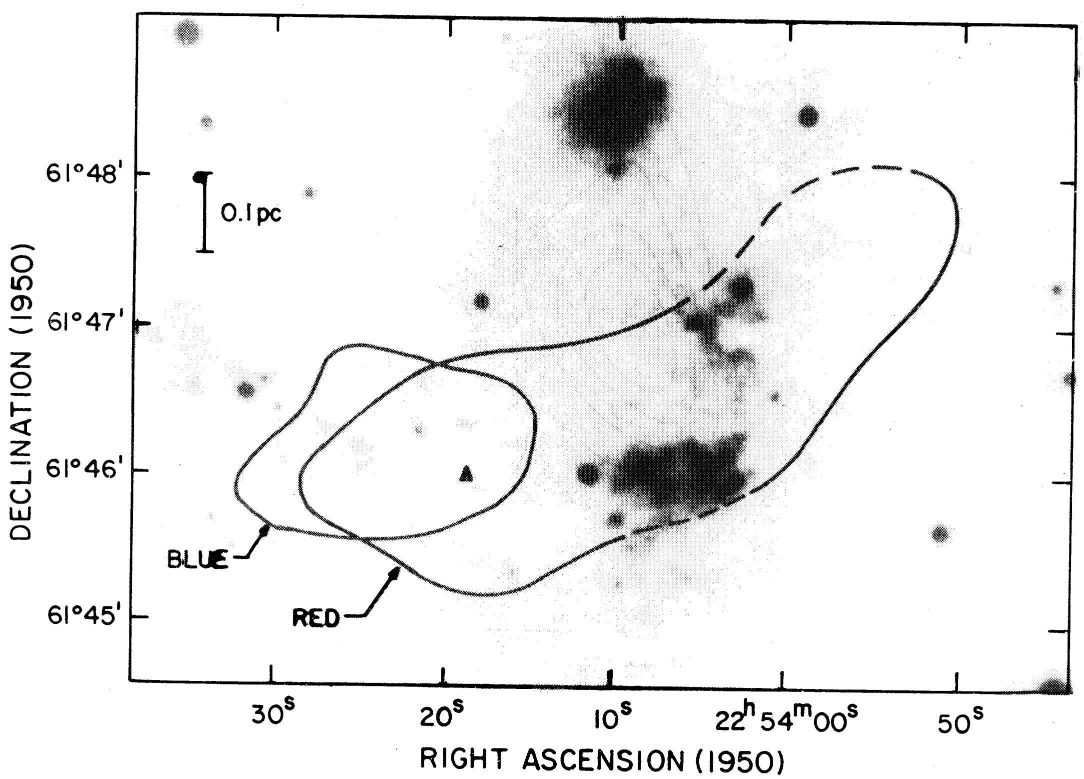

FIGURE 4. Half power contours of the red- and blue-shifted CO wings superimposed on a reproduction of the Palomar Sky Survey plate. (Copyright (1960) by the National Geographic Society - Palomar Sky Survey. Reproduced by permission from the California Institute of Technology.) The triangle marks the site of the compact HII region and masers shown in Figure 5. The suspected H-H object GGD 37 is near $\alpha = 22^h54^m05^s$, $\delta = 61°46'00''$. From Ho et al. (1982).

IV. FLUX DENSITIES OF CONTINUUM RADIO SOURCES

The thermal radio emission from newly formed stars in molecular clouds can be detected if the star ionizes a sufficient amount of its circumstellar gas. We assume that the ionization is due to the stellar radiation alone. The number of Lyman continuum photons required depends on the electron density model assumed. The flux density of an optically thick source of radius r_o will be

$$S = 0.1\left(\frac{T_e}{10^4\,K}\right)\left(\frac{r_o}{10^{15}}\right)^2\left(\frac{D}{kpc}\right)^{-2}\left(\frac{\nu}{GHz}\right)^2\ mJy, \quad (3)$$

where T_e = electron temperature, ν is the frequency and D is the distance. The flux density in the

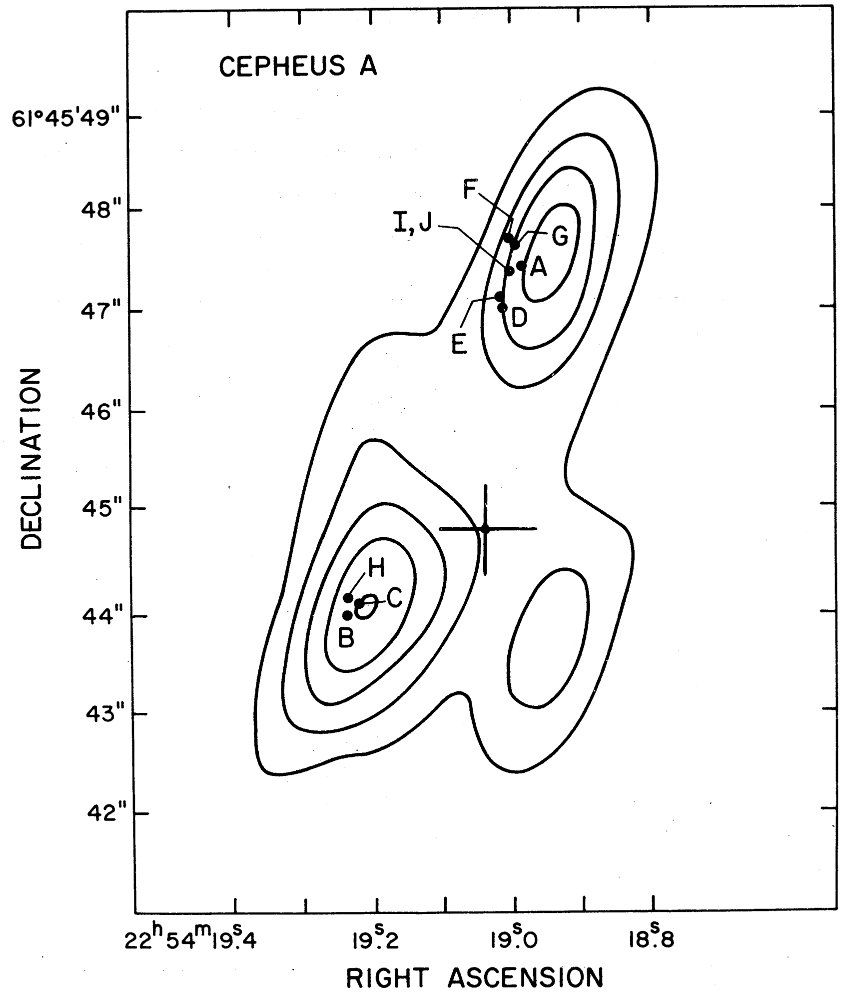

FIGURE 5. Map of the positions of H_2O masers (lettered spots) and the continuum emission at 5 GHz (contours) in Cep A. Relative alignment accuracy between H_2O masers and continuum map is ±0".5. The source with error bars is the OH maser (Norris, 1980). Adapted from Lada et al (1981).

optically thin regime, with the power law opacity formulation (cf. Mezger and Henderson, 1967), is

$$S = 3.4\left(\frac{T_e}{10^4\,K}\right)^{-0.35}\left(\frac{VEM}{10^{57}\,cm^{-6}}\right)\left(\frac{D}{kpc}\right)^{-2}\left(\frac{\nu}{GHz}\right)^{-0.1}\ mJy, \qquad (4)$$

where VEM = volume emission measure. The Lyman continuum flux necessary to ionize the gas is $N_c = \alpha_B VEM$ where α_B is the recombination coefficient. For $\alpha_B = 2.6\times10^{-13}\ (T_e/10^4\,K)^{-0.8}$,

$$N_c = 8\times10^{43}\left(\frac{S}{mJy}\right)\left(\frac{T_e}{10^4\,K}\right)^{-0.45}\left(\frac{D}{kpc}\right)^{2}\left(\frac{\nu}{GHz}\right)^{0.1}\ s^{-1}. \qquad (5)$$

If the electron density has the form $n_e = A\,r^{-2}$ where A is a constant and r is the radius, the radiation along the central ray will be optically thick. This case, appropriate for a stellar wind with constant velocity v and mass loss $\dot{M}$ where $A = \dot{M}/4\pi v$ has been analyzed by Wright and Barlow

(1975), Olnon (1975), Panagia and Felli (1975) and others. The spectrum has the form

$$S = 1.3\left(\frac{T_e}{10^4\,K}\right)^{0.1}\left(\frac{\dot{M}}{10^{-6}M_{\odot}yr^{-1}}\right)^{4/3}\left(\frac{v}{10^2 km\ s^{-1}}\right)^{-4/3}\left(\frac{D}{kpc}\right)^{-2}\left(\frac{\nu}{GHz}\right)^{0.6}\ mJy. \qquad (6)$$

The observed angular size varies as $\nu^{-0.7}$. There are a few well-documented cases of sources with this spectrum such as P Cygni (Newell, 1981) and MWC 349 (Olnon, 1975). If the ionized flow has an inner cutoff r_i then for $\nu > \nu_i$, where

$$\nu_i = 2.3x10^6\left(\frac{T_e}{10^4\,K}\right)^{-0.6}\left(\frac{\dot{M}}{10^{-6}M_{\odot}yr^{-1}}\right)\left(\frac{v}{10^2 km\ s^{-1}}\right)^{-1}\left(\frac{r_i}{10^{11}}\right)^{-1.4}\ GHz, \qquad (7)$$

the radiation becomes thin and the spectral index is -0.1. If r_i is the stellar radius then ν_i is above radio frequencies but in sources such as V1016, a planetary nebula, $r_i \sim 10^{15}$ cm and $\nu_i \sim 70$ GHz (Marsh, 1975). If the flow has an outer cutoff r_o, then for $\nu < \nu_o$, where

$$\nu_o = 6.2\left(\frac{T_e}{10^4\,K}\right)^{-0.6}\left(\frac{\dot{M}}{10^{-6}M_{\odot}yr^{-1}}\right)\left(\frac{v}{10^2 km\ s^{-1}}\right)^{-1}\left(\frac{r_o}{10^{15}}\right)^{-1.4}\ GHz, \qquad (8)$$

the radiation will be optically thick and the observed radius will be $\sim r_o$ and the spectral index will be 2. An example of such behavior is VY 2-2 (Marsh, 1975) and possibly the BN object (Moran et al., 1982). Hence the general spectrum has three parts with the spectral index decreasing from 2 to 0.6 to -0.1 with increasing frequency. The number of Lyman continuum photons required to ionize the flow is

$$N_{cw} = 2.2x10^{48}\left(\frac{\dot{M}}{10^{-6}M_{\odot}yr^{-1}}\right)^2\left(\frac{T_e}{10^4\,K}\right)^{-0.8}\left(\frac{10^{11}}{r_i} - \frac{10^{11}}{r_o}\right)\left(\frac{v}{10^2 km\ s^{-1}}\right)^{-2}\ s^{-1}, \qquad (9)$$

which in terms of flux density when $r_o >> r_i$ is

$$N_{cw} = 1.5x10^{48}\left(\frac{S}{mJy}\right)^{1.5}\left(\frac{T_e}{10^4\,K}\right)^{-0.9}\left(\frac{D}{kpc}\right)^3\left(\frac{r_i}{10^{11}cm}\right)^{-1}\left(\frac{\nu}{GHz}\right)^{-0.9}\ s^{-1}. \qquad (10)$$

The best instrument for detecting and localizing the emission from weak compact thermal radio sources is the VLA. The sensitivity of the VLA to compact sources at the four operating frequencies is given in Table 1. Optically thick sources as small as $2x10^{14}$ cm at 10^4 K and 1 kpc can be detected in 6 hours of integration and optically thin emission from stars as late as B3.5 can be detected. Stellar wind sources with $\dot{M} > 10^{-7}\ M_{\odot}\ yr^{-1}$ can be detected at 1 kpc. Observations tend to concentrate at 5 GHz because this frequency provides the maximum sensitivity. Also, observations at 1.5 GHz are hampered by confusion and extended emission while observations at 15 and 22 GHz are degraded by phase noise. Therefore, many observations result in threshold detections at 5 GHz and hence it is impossible to obtain spectral data. In this situation the two basic models of uniform density and stellar wind cannot be readily distinguished. The distinction is important because the inferred Lyman continuum flux, based on a single frequency measurement, can be as much as three orders of magnitude greater for the wind model than for the homogeneous model. The only radio source among the H-H and GGD objects with good spectral data is GGD 12-15 which is optically thin above 1.5 GHz (Rodríguez et al., 1983).

TABLE 1. Sensitivity of VLA to Compact Thermal Sources

ν[1]	S_{min}[2]	r_o[3]	N_c[4]	ZAMS[5]	$\dot{M}$[6]	N_{cw}[7]	ZAMS[8]
GHz	mJy	10^{15}cm	$10^{43}s^{-1}$		$10^{-7}M_{\odot}/yr$	$10^{46}s^{-1}$	
1.5	0.2	1.0	1.6	B3.5	2.1	3.1	B0.5
5.0	0.12	0.2	1.1	B3.5	0.8	0.5	B0.5
15.0	0.9	0.2	9.2	B2.5	2.3	3.7	B0
23.0	1.4	0.2	15	B2	2.6	4.9	B0

(1) frequency
(2) minimum detectable signal (6σ) in 6 hours integration
(3) radius of smallest detectable optically thick source with $T_e = 10^4$K (eq. 3)
(4) Lyman continuum flux for optically-thin (e.g. uniform-density) HII region with smallest detectable emission measure and $T_e = 10^4$K, D = 1 kpc, recombination coefficient = 2.6×10^{-13} (eq. 5)
(5) model calculation of Panagia (1973) for N_c
(6) minimum detectable mass loss rate for stellar wind source with $T_e = 10^4$K, D = 1 kpc, v = 100 km s^{-1} (eq. 6)
(7) minimum Lyman continuum flux to ionize stellar wind to infinity, with $r_i = 3 \times 10^{-11}$cm, radius of an early ZAMS B star (eq. 10)
(8) model calculations of Panagia (1973) for N_{cw}

There may be fundamental difficulties with the photo-ionization model. For example, the radio source at the center of the outflow in L1551 has a flux density of 3.5 mJy at 5 GHz (Cohen, Bieging, and Schwartz, 1982) which requires $N_c = 8 \times 10^{42}$ s^{-1} or $N_{cw} = 7 \times 10^{44}$ s^{-1} for the homogeneous and wind models respectively. The luminosity of IRS5, the associated infrared source, is not large enough to supply the required UV flux. Hence, other processes, such as collisional ionization, may be important in ionizing the gas.

V. PROPER MOTIONS OF H_2O MASERS

The transverse velocities of several H-H objects at 0.5 kpc have been determined to an accuracy of ~ 10 km s^{-1} from position measurements spanning ~40 years (Herbig and Jones, 1981). Velocities of masers must be estimated on a much shorter time base because of their rapid variability. Hence an experiment involving ten measurements over a two year span of the position of a maser, located 0.5 kpc from the earth, to an accuracy of 0".01 would yield a velocity with an error of 10 km s^{-1}. This is a realistic goal. Unlike the very complex masers near massive OB stars, masers near H-H objects usually consist of only a few features. Hence positions must be measured relative to quasars, which may be >10° away. However, in the HH 7-11 complex there are 4 maser groups, whose relative positions could be measured. Relative maser positions have been measured to 10^{-4}" (Genzel, 1981a) but absolute positions have been reported to only 0".1 accuracy (cf. Lada et al., 1981). Absolute accuracies better than 0".01 should be possible, since this level has been reached in astrometric VLBI observations of extragalactic sources. The resolution of a transcontinental VLBI is better than 10^{-3}" so that the spatial structure of the masers can be determined and tracked with time. Since the maser components are less than 10^{-3}" in diameter it is unlikely that excitation effects could cause apparent motions on the level of 10^{-2}" (see Genzel et al. (1981a) for a discussion of the "Christmas tree effect").

Proper motions can also be measured with the VLA. "Snap shot" observations routinely yield positions of 0"05 accuracy (Perley, 1982). Repeated observations with nearby calibrators may produce results with accuracies approaching 10^{-3}". However, the intrinsic resolution of the VLA is only ~0"1 so that milliarcsecond accuracies can be achieved only by measuring to a small fraction of the fringe spacing. If a maser contains subcomponents which are spatially separated, then changes in relative luminosities of these components will be observed as a shift in the centroid position. This could present serious difficulties for VLA experiments. Preliminary observations of HH 1 (see Figure 1) and HH 7-11 have been made on several occasions over a period of 3 months with the VLA in the B configuration which show position differences up to 0"05, possibly due to unresolved analysis problems or changes in brightness distribution (Ho et al., 1982). This work is continuing. Definitive results may have to await the construction of the VLB array.

VI. SUMMARY

H-H objects and H_2O masers are probably both manifestations of the outflowing envelopes of newly formed stars. Careful observation of regions such as HH 7-11 have led to the detection of many sites of maser emission. VLBI observations show that these masers appear to be violently dispersing on time scales of ~1 year. Interferometric observations should allow the measurements of transverse velocities to an accuracy of ~10 km s^{-1} for objects at 500 pc. Radio emission from compact HII regions have been detected near the center of several mass outflows. It is difficult to measure the spectra of these sources. Based on the 5 GHz flux, the inferred volume emission measure is about three orders of magnitude larger for a wind source than for a homogeneous source of uniform density.

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(This paper was read by P.T.P. Ho)

DISCUSSION

Cohen: It is not true that none of the H_2O masers you talked about today coincide with HH-objects, and that only one (component "A" near HH 7-11) coincides with a suspected exciting star of HH-objects?

Ho: That is correct. The intrinsic properties of the optical condensations and the H_2O masers are quite different, so that the non-coincidence is perhaps not surprising.

Herbig: Would you expect to find very large proper motions from those H_2O masers in view of the fact that they do not have very large radial velocities?

Ho: Only if the motion is in the plane of the sky (as in the case of HH 1-2). One might argue that the sources that would show large proper motions are the ones with low radial velocities.

Krautter: You found three masers in regions containing HH-objects. In how many regions did you *not* find any H_2O maser emission?

Ho: The detection rate was about 10% for all the classical HH-regions that we surveyed.

Franco: With such high densities and temperatures of a few hundred degrees, the masers are over-pressured and should have short lifetimes. Can you comment on the formation rate and detection probability of the masers?

Ho: There are too many variables that determine the probability of detection. We have surveyed the regions a number of times so that the detection rate of $\sim$ 10% is probably not too bad. However, we cannot rule out a population of weaker masers, or if our sampling in time was too poor to pick up rapidly varying sources.

Königl: The observations of the Orion KL region suggest that OH masers are generally associated with low-velocity flow, and H_2O masers more often with high velocity flow. Could you say whether a similar correlation applies also to other regions?

Ho: In general, OH masers appear to be associated with a later stage of evolution, such as after the development of compact H II regions. Known OH masers also appear to be associated with more massive OB stars rather than the type of low mass sources that apparently excite the HH-objects. This may explain the low detection rate (∿ 1 out of 25) among GGD objects. I am not aware of OH maser results for the classical HH-objects. In any case, the trend which is evident in Orion KL is difficult to interpret because (1) excitation requirements for OH and H_2O masers are very difficult, (2) possibility of more than one exciting source, and (3) the region is very complicated with too many things going on.

Appenzeller: You searched star formation regions with much higher sensitivity than earlier H_2O maser surveys. Therefore, one may expect to pick up more "background objects" (i.e., weak H_2O masers related to other interstellar flows). Can you say anything on the surface density of such weak masers in star formation regions outside the surroundings of HH-objects?

Ho: No, we do not have a very good "control" group. This can be attributed to the fact that most observatories would not like to devote a week of observing time to blank-field studies. However, it is a good idea. Of course, one could never be sure of the connection between the masers, whenever observed, and HH-objects. That is one of the reasons why we are trying to do the proper motion experiment. In the absence of detected proper motions for the H_2O masers that agree with those of the HH-objects, one can only appeal to spatial proximity, agreement in velocities, and the lack of independent exciting sources.

Zealey: Do you find H_2O masers aligned with the proposed outflow i.e., between HH-object and source; or perpendicular to this, possibly in the confining disc around the star?

Ho: There are only 2 cases where the association between H_2O masers and HH-objects seems safe enough even for the pessimist. These are HH 7-11 and HH 1-2. There, the alignment is more along the axis defined by the optical condensations. Other cases such as masers associated with GGD objects are complicated enough that alignment is difficult to define.

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