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H_2O MASERS NEAR OB ASSOCIATIONS

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ABSTRACT

Four new water masers have been found in the vicinity of three OB associations. One of these, in Cep OB3, is among the most intense sources yet discovered and may be related to the most recent epoch of star formation in the OB association. Two others, one in CMa OB1, the other in M16, have large radial velocities relative to their associated molecular clouds. These results are discussed in the context of star formation and CO line self-reversal within the individual sources.

Subject headings: clusters: associations — interstellar: molecules — masers

I. INTRODUCTION

Water maser sources found in the vicinity of H II regions are generally considered to be indicative of activity related to the earliest stages of star formation (e.g., Lada 1978). Water masers are never spatially resolved with a single antenna, and VLBI observations show that typical interstellar masers consist of spatially separate emission spots of different velocity with sizes of the order of a few AU, clustered into centers of activity 10^{16}–10^{17} cm in extent (e.g., Genzel and Downes 1977; Genzel *et al.* 1978). The highly localized nature of H_2O maser sources makes them very accurate markers of positions of associated protostellar or neostellar (newly formed) objects in extended regions of star formation. It has recently become clear that knowledge of the relative locations of newly formed stars provides important information concerning the mechanism responsible for star formation.

We selected several OB associations for which extensive CO maps have been made and searched for H_2O masers in those regions where we suspected new stars are being formed. Similarly motivated studies have resulted in the discovery of new maser sources in S184 (Elmegreen and Lada 1978) and S252 (Lada 1978). In this study we extend our search to many more associations. We report the detection of four new maser sources found toward three associations. One maser may be related to the most recent burst of star formation in Cep OB3; two others have high velocities relative to the molecular clouds and may be unrelated to the star formation process in the corresponding associations.

II. OBSERVATIONS

The observations were made 1978 January 25–30 with the 37 m Haystack[1] telescope in Westford, Massachusetts. The system temperature ranged from 98 K to 150 K, and observations were made using the total power mode. The half-power beamwidth of the telescope at 22 GHz is 1'.4, and the beam efficiency is 25%. The receiver was a K-band maser similar to that described by Cheung *et al.* (1973). The spectrometer was a 1024 channel autocorrelator, and the searches were made using a bandwidth of 13.3 MHz (180 km s^{-1}). Integrations on source were usually for three minutes resulting in a typical rms noise temperature of 0.07 K.

[1] The Haystack Observatory is operated by the Northeast Radio Astronomy Corporation with support from the National Science Foundation.

III. RESULTS

We have found four new masers, the observational parameters of which are summarized in Table 1. Antenna temperatures and flux densities are corrected for atmospheric attenuation and elevation dependence on antenna gain. In all cases a linear baseline was removed from the data. The stated positional accuracies are 1 σ errors which include a 7" rms pointing error for the Haystack telescope. In the case of the Cepheus maser, the position was determined by taking drift scans across the source using a 200 kHz bandwidth continuum receiver. For the other masers, the position was interpolated from a five-point cross made at half-beamwidth intervals. The interpolated position was then checked to see if the flux was higher than at the other positions.

a) *Cepheus A*

We have discovered a very intense water maser within the molecular cloud associated with the Cep OB3 association (Sargent 1977*a*; Blaauw 1964); its spectrum is shown in Figures 1*a* and 1*b*. Only three other masers are known to be as strong: W49, Orion (KL), and W3 OH. Figure 1 shows the spectrum of the Cep A maser observed on 1978 January 26. Rich velocity structure is evident, and the unusually high

TABLE 1

PARAMETERS FOR COMPONENTS OF DETECTED MASERS

Velocity (km s^{-1})	T_A (K)	Flux Density (Jy)	Resolution (km s^{-1})
Cepheus A: 22^{h}54^{m}20^s.0, 61°45′42″ (±12″) (1950)			
−33.2	1.1	12	0.22
−21.5	2.9	34	0.22
−19.7	1.0	12	0.22
−17.9	2.2	26	0.049
−11.36	140.8	1667	0.049
−8.36	241.4	2854	0.049
−6.72	47.1	558	0.049
−5.19	13.1	155	0.049
−3.01	38.9	461	0.049
+6.9	7.0	83	0.22
+13.7	1.0	12	0.22
GL 1074: 7^{h}05^{m}28^s.5, −10°39′18″ (±30″) (1950)			
42.8	3.6	43	0.88
45.0	2.0	24	0.88
48.5	0.6	7	0.88
54.7	0.8	9	0.88
56.9	0.3	4	0.88
M16 A: 18^{h}15^{m}19^s.4, −13°46′30″ (±30″) (1950)			
−65.4	1.8	21	0.88
M16 B: 18^{h}16^{m}33^s.8, −13°42′24″ (±30″) (1950)			
18.4	0.9	11	0.88
22.7	0.3	4	0.88
S106*: 20^{h}25^{m}25^s ± 1^s.6, 37°12′30″ ± 10″			
−4.0	0.6	7	0.22

* Quoted position errors are those of Cesarsky *et al.* 1978.

luminosity implies that the source of excitation of the maser is a very massive protostellar or neostellar object or a group of such objects (Genzel *et al.* 1978).

The molecular cloud associated with the maser and the Cep OB3 association has been studied by Sargent (1977*a*). The maser is located in a high-density fragment (designated Cep A by Sargent) near the interface between the molecular cloud and the H II region S155 which is excited by early-type stars in the youngest subgroup of Cep OB3 (Blaauw 1964). Self-reversed ^{12}CO spectra are evident in this region, and the maser is found where the self-reversed feature is deepest. The velocity of the ^{13}CO peak is −10.3 km s^{-1}, close to the mean of the velocities of the two strongest H_2O features. Within several arc minutes of the maser, there is a cluster of small emission nebulae visible on the red Palomar Observatory Sky Survey plate. These nebulae appear brighter on redder plates of the region and may be Herbig-Haro objects (Sargent 1978). An unconfirmed 20 μm infrared source, GL 2977s, is also found near the maser position.

Sargent suggested that Cep A is a region of ongoing star formation in the Cep OB3 association, and this suggestion seems to be confirmed by our detection of the intense maser source. The association appears to be an example of the sequential formation of massive stars. In this case, the sequential formation pattern is spatially delineated by the older visible subgroup, the younger visible subgroup, and the maser-CO source which all lie along a line in a temporal sequence terminating in the molecular cloud.

Whether or not the Cep A maser is a signpost of a third burst of star formation in Cep OB3 cannot yet be determined because of the large discrepancies between published estimates of the ages of the visible subgroups. Blaauw (1964) has estimated the ages from the H-R diagram to be 4 and 8 million years for the two groups. However, work on the kinematics of the stars by Garmany (1973) has been interpreted by Sargent (1977*b*) to give ages of 1–3 × 10^5 yr and 5–7 × 10^5 yr, respectively, for the two groups. If the age of the younger subgroup is closer to Blaauw's estimate, the Cep A maser probably represents a new burst of star formation in the complex.

Elmegreen and Lada (1977) obtained separations of about 13 pc and 3 million years in an idealized application of their sequential model. The projected separations between the two visible subgroups and between the youngest visible subgroups and Cep A are about 12 pc (Blaauw 1964) and 10 pc (Sargent 1977*a*) respectively. Application of the Elmegreen-Lada model therefore favors an age estimate for the two groups closer to Blaauw's. Furthermore, because the earliest spectral type in the older subgroup is B0, it is difficult to understand how the subgroup could have expanded to its present extent and so effectively dissipated the surrounding protostellar gas unless it is at least several million years old.

b) M16

Two new maser sources have been detected toward the M16 H II region–molecular cloud complex. Extensive CO maps of this source (Lada and Baliunas 1978) have uncovered a large, massive molecular cloud with numerous peaks of bright CO emission. Far-infrared emission has also been detected at various locations in this source by balloon-borne telescopic observations (Fazio and Wright 1978). We searched M16 at two suspected positions of star-forming activity. The first position is near a weak far-infrared source which appears embedded in the molecular cloud very close to a sharp ionization front. We found a relatively weak H_2O maser at this position (M16 A), the spectrum of which is shown in Figure 2. The velocity of the maser source (−70 km s^{-1}) is considerably different from either the molecular CO emission (~22 km s^{-1}) or the hydrogen recombination line emission from nearby ionized gas (~25 km s^{-1}). No detectable CO emission is found at the velocity of the maser (Cohen 1978). This large velocity difference suggests that the maser may not be related to M16, although its positional coincidence with the infrared source is striking. High-velocity H_2O emission is not common in H II region sources; but in all cases where such emission is found, it is accompanied by considerably stronger ($\gtrsim$10×)

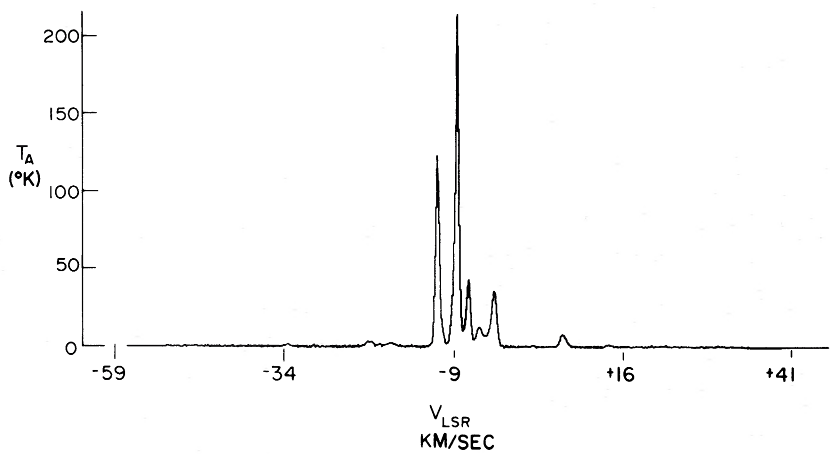

FIG. 1a

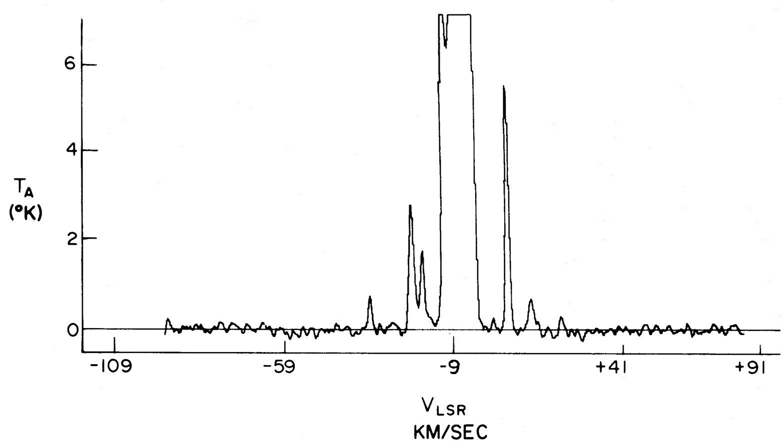

FIG. 1b

FIG. 1.—(*a*) Spectrum of the Cep A maser taken on 1978 January 26, at a resolution of 0.22 km s^{-1}. The maser is not quite resolved. (*b*) Spectrum of the Cep A maser taken on 1978 January 28, showing the six weaker components. The resolution is 0.88 km s^{-1}.

emission at the velocity of the associated source (Genzel and Downes 1977). No H_2O emission was seen toward M16 A at velocities within ± 50 km s^{-1} of the molecular cloud velocity.

It is possible that this high-velocity H_2O emission originates in the circumstellar shell of an evolved star which happens to be along the line of sight to M16. If this is the case, the velocity of -70 km s^{-1} need not be the stellar velocity. The OH maser emission from such evolved objects usually consists of at least two maser components whose velocities are symmetrically placed around the stellar velocity. Typical separations of velocity components range from 5 to 40 km s^{-1} (Dickinson, Kollberg, and Yngvesson 1975). Water maser spectra from these objects usually show a smaller spread in velocity (Dickinson and Kleinmann 1977), although often only one velocity component is detected. The velocity of the exciting source of M16 A could thus lie in the range between -50 and -90 km s^{-1}.

A second maser (M16 B), the spectrum of which is shown in Figure 3, was detected at a strong CO emission peak within the molecular cloud east of the H II region. The velocity of this maser is close to that of the molecular cloud, suggesting an association between the two objects. This maser source may mark the location of a region of very recent star formation. The brightness of the maser emission is considerably less than that of Cep A, and we cannot be certain that a massive object is forming here. The location of this maser source near the interface between the H II region and the molecular cloud is reminiscent of the close

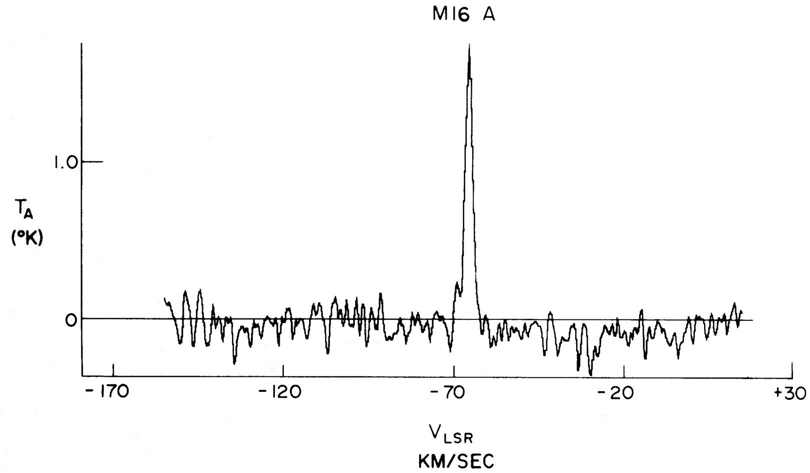

FIG. 2.—Spectrum of the M16 A maser taken on 1978 January 28, at a resolution of 0.88 km s^{-1}

proximity of maser sources and ionization fronts in numerous other well known sources (Orion, W3, M17, S184 [see, e.g., Elmegreen and Lada 1977]; S252 [Lada 1978]; NGC 7538 [Habing, Israel, and de Jong 1972]; and Cep OB3) and may suggest a causal relationship between ionization fronts and star formation (Lada 1976; Elmegreen and Lada 1977).

Other promising regions in M16 have yet to be searched; the existence of masers in the only two regions we searched suggests that M16 may be a very prolific star-forming source.

c) GL 1074

This maser is found at the edge of a CO cloud complex mapped by Blitz (1978) in the region of CMa OB1 and the related association of reflection nebulae CMa R1; its spectrum is shown in Figure 4. Blitz's observations show what appear to be two distinct cloud complexes of comparable mass: one related to the H II region S292 and the other related to the H II region S296 and CMa R1. If the maser is embedded in the molecular material, it occurs in the cloud complex associated with CMa R1, but is about 10–15 pc from the nearest star in the R association. If the maser is a signpost of recent star formation, it may therefore not be related to the mechanism responsible for CMa R1. The maser is, however, located in the part of the cloud which faces the center of expansion of a shell of ionized gas reported by Reynolds and Ogden (1978) and is less than half a degree (~ 10 pc projected distance) from the O6.5 star HD 54662 which is responsible for most of the ionization of S296. Consequently, the GL 1074 maser could be related to the expansion of S296 into the molecular cloud as appears to be the case in M16 and possibly Cep A. Note, however, that the velocities of the maser components are 30–40 km s^{-1} longward of the molecular cloud velocity (15 km s^{-1}) and, as in M16 A, may not be related to the molecular material. There is no component of CO

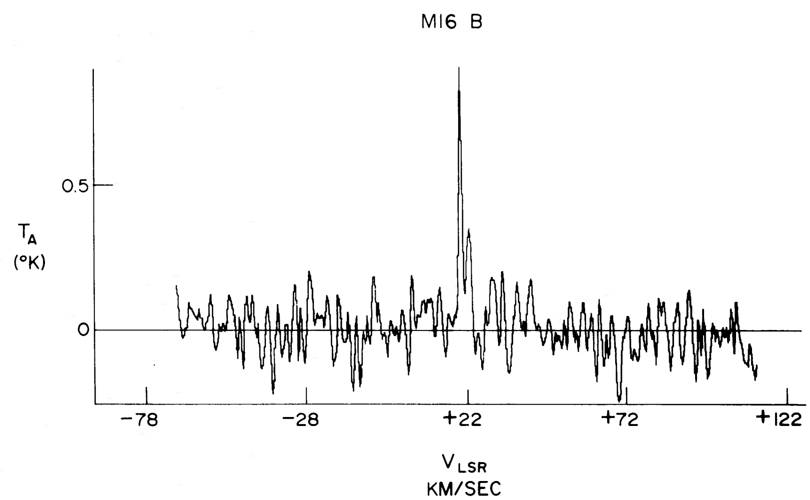

FIG. 3.—Spectrum of the M16 B maser taken on 1978 January 29, at a resolution of 0.88 km s^{-1}

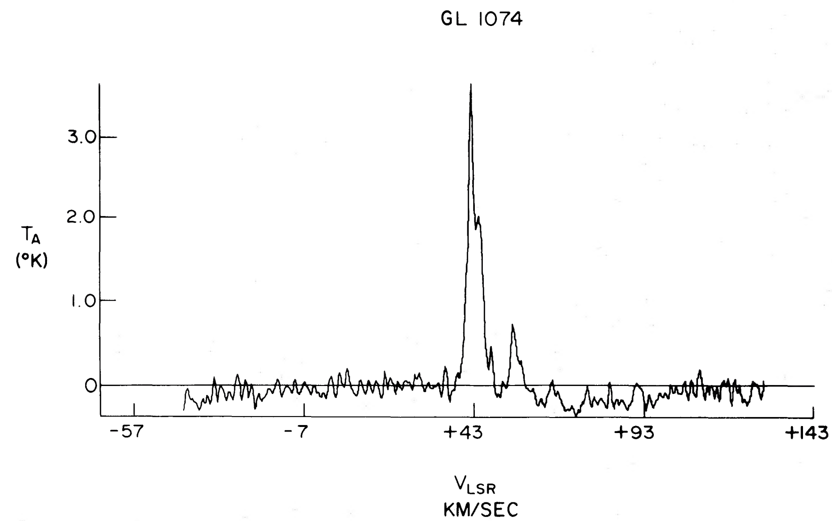

FIG. 4.—Spectrum of the GL 1074 maser taken on 1978 January 28, at a resolution of 0.88 km s^{-1}

emission at the maser velocity (Morris 1978) toward GL 1074. Furthermore, although the maser is found in a region of recent star formation, there is no CO enhancement toward this maser at a resolution of 8′ (Blitz 1978). This implies that the source of excitation for the maser is probably an evolved star, but none has as yet been identified with the infrared source. Observations have been planned to obtain a more accurate position for the infrared source and to determine whether any OH maser emission is also present. These observations should determine conclusively whether or not the origin of the maser is an evolved star.

d) *S106*

This maser, associated also with GL 2584, was first detected by Cesarsky *et al.* (1978). The molecular cloud complex which accompanies this source is part of the Cyg OB1 association in the Cygnus X region and has recently been mapped in CO by Cong (1977). Cesarsky *et al.* reported a feature with a V_{lsr} of -1.1 km s^{-1} at a flux density of 19 Jy. We were not able to detect this component. Instead, as can be seen in Figure 5, we detect a component whose velocity is -4.0 km s^{-1} at the same position as that of Cesarsky *et al.*, a result illustrating the high variability of this maser source.

e) H_2O *Masers Related to* CO *Self-Absorption*

Self-reversed ^{12}CO line profiles are a rare phenomenon, and only eight examples have been reported in the literature. With the possible exception of ρ Oph, the self-reversal always occurs where there is other evidence of ongoing star formation such as infrared sources, but the relationship between the self-reversal and the process of star formation is not clear. Of the five self-reversed CO sources for which H_2O emission

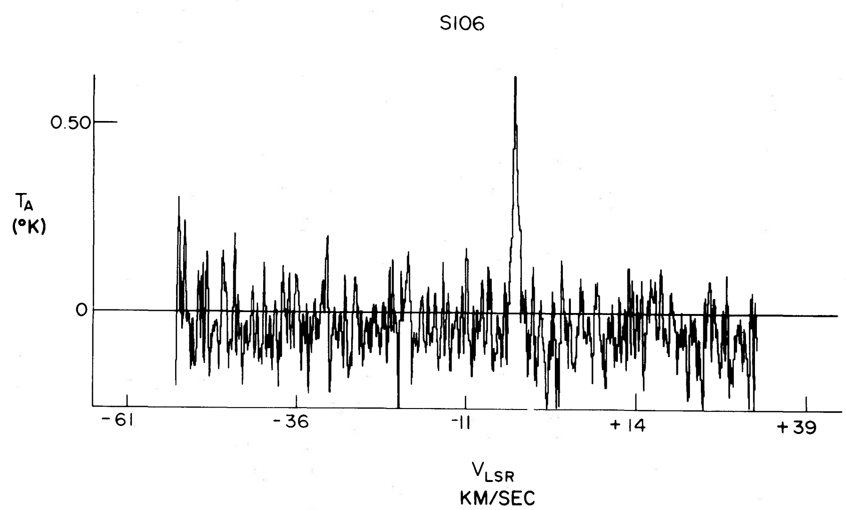

FIG. 5.—Spectrum of the S106 maser taken on 1978 January 29, at a resolution of 0.22 km s^{-1}

TABLE 2

NEGATIVE RESULTS

Second Name	α (1950)	δ (1950)	Central Search Velocity (LSR) (km s^{-1})
S187	1h19m48s	61°36′0″	−15
W4 A	2 24 05	61 16 0	−40
W4 B	2 24 30	61 15 0	−40
W5 A	2 45 43	60 32 18	−40
W5 B	2 57 17	60 16 54	−40
IC 348	3 40 48	31 52 42	−10
IC 2087	4 26 49	25 39 10	−10
S222	4 26 59	35 10 42	−10
S239	4 28 25	18 0 51	−10
IC 410	5 19 06	33 18 0	−10
Ori OB2	5 28 38	12 07 27	0
S252 E	6 06 54	20 30 55	−8
Mon OB2:			
Rosette 6	6 26 58	4 58 0	16
Rosette 7	6 27 28	4 55 30	16
Rosette 5	6 27 48	4 45 30	16
Rosette 8	6 29 38	3 58 0	16
Rosette 3	6 30 38	4 33 0	16
Rosette 4	6 30 48	4 48 0	10
Rosette 2	6 31 28	4 28 0	16
GL 961	6 31 48	4 15 30	12
Mon OB1:			
Mon R1–3	6 24 49	10 04 0	0
Mon R1–2	6 28 48	10 28 0	0
2264–2	6 37 20	10 04 30	7
2264–3	6 38 24	10 44 30	7
2264–1	6 38 25.2	9 32 17	10
GL 1028	6 50 07	8 27 54	10
GL 1043	6 55 10	3 21 48	10
CMa OB1:			
Z CMa	7 01 22	−11 28 42	18
CMa–2	7 02 44	−10 48 30	18
CMa–3	7 02 54	−10 58 30	18
VY CMa–1	7 22 01.6	−25 49 13	13
VY CMa–2	7 22 02	−25 40 13	13
IC 4601	16 17 30	−20 2 30	3
ρ Oph	16 23 15	−24 19 30	3
M8 E	18 01 53	−24 27 54	13
DR 20 (GL 2616)	20 35 39	41 21 42	0
DR 23 (GL 2632)	20 38 51	41 40 12	0
IC 5146 A	21 51 30	47 02 10	10
Cep OB3:			
Cep F	21 51 14	62 36 57	−10
Cep B	22 57 27	62 18 37	−12
Cep C	23 03 38	62 12 23	−10
Cep OB4 (W1):			
GL 3193	23 57 15	67 04 24	−16
W1–2	23 58 32	67 14 24	−16
GL 4305	23 59 12	67 06 54	−10

has been previously observed, four showed positive detections. These are W3 OH (Knowles *et al.* 1969), NGC 1333 (Dickinson, Kojoian, and Strom 1974), NGC 2071 (Lada and Gottlieb 1974), and Mon R2 (Knapp and Brown 1976). Only LkHα 101 (S222, NGC 1579) showed no maser emission (Knapp and Morris 1976). The Cep A maser occurs at a position of maximum CO self-absorption; but two other self-absorbed sources we searched, ρ Oph (Encrenaz, Falgarone, and Lucas 1975) and GL 961 (Blitz and Thaddeus 1977; Blitz 1978), showed no evidence of maser emission. Thus five of the eight self-reversed CO sources showed H_2O maser emission. It may be that CO self-reversal and water masers are always found together, but the variability of the water masers is such that they were not detected in ρ Oph, GL 961, or LkHα 101 when these sources were observed. Further monitoring of these sources would test this hypothesis.

IV. NEGATIVE RESULTS

Negative results are summarized in Table 2. The 3 σ flux limit for the search is 6 Jy. A velocity range of ±90 km s^{-1} about the center velocity given in the table was searched for each source. The positions given are generally positions of CO maxima, but are sometimes the positions of infrared sources. The extent of the search around a particular source was dependent primarily on the CO maps and was therefore quite irregular. Note that Genzel and Downes (1977) detected water emission at the position of 2264–1 in Mon OB1, but Cesarsky *et al.* (1978), using the same instrument, did not detect this maser.

V. SUMMARY

We have found four new maser sources, each of which is seen toward a molecular complex related to an OB association. All are found near H II regions and may be related to star formation induced by the expansion of H II regions into the accompanying molecular material. However, the masers related to M16 A and GL 1074 are observed at anomalous velocities and may originate in the outer layers of evolved stars. The intense maser in Cep A is related to ongoing star formation in Cep OB3, and may signal a new burst of star formation in the association. A maser in S106, previously detected by Cesarsky *et al.* (1978), showed no evidence of the velocity component that they report, but was seen at another velocity, indicating a great deal of variability in this source. We note the positional coincidence of maximum CO self-reversal, infrared sources, and H_2O masers in five sources out of eight, suggesting that CO self-reversal is intimately tied to the earliest stages of star formation.

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Note added in proof.—Le Squeren, Baudry, Brillet, and Darchy have found a type II OH maser at the position of the water maser associated with GL 1074, apparently confirming that the source of excitation is a late type star.

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