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COMPACT CONTINUUM RADIO SOURCES IN THE ORION NEBULA[1]

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ABSTRACT

We mapped the Orion Nebula, searching for compact radio sources, using the VLA at 1.5, 4.9, 15.0, and 22.5 GHz. We detected 21 radio sources with flux densities greater than 4 mJy per beam area. All but one of the sources have either optical or infrared counterparts.

Fourteen of the radio sources are within 30″ of Θ^1 Orionis C (Θ^1C). Thirteen of these objects are probably neutral condensations surrounded by ionized envelopes that are excited by Θ^1C. If the temperature of the ionized envelopes is 10^4 K, and their electron densities decrease as the square of the distance from the core center, then a typical neutral condensation has a radius of 1×10^{15} cm and a peak electron density of 4×10^5 cm^{-3}. We suggest that the neutral condensations are dense fragments remaining from a massive molecular cloud after it was blown out by the action of the ultraviolet radiation and stellar winds from its young, massive, and luminous descendants. The remaining radio source within 30″ of Θ^1C is coincident with Θ^1A, an eclipsing binary in the Trapezium. Its radio emission is characterized by large flux density variations and by a flat spectrum.

Seven sources are in or near the Orion molecular cloud. Three of these sources are invisible optically. The radio emission from two of these (one of which is coincident with the BN object) is likely to arise in a dense ($n_e \geq 10^6$ cm^{-3}) ionized envelope surrounding and excited by an early B-type star deeply embedded in the Orion molecular cloud. The third optically invisible object, located $\sim$12″ east of BN, is variable and is not coincident with any of the infrared sources in the Orion-KL region. The last four objects all have optical counterparts. Two are highly variable radio sources and are associated with X-ray sources. They probably are pre–main-sequence (T Tauri) stars. The remaining two objects have radio spectra indicative of thermal emission. They probably are neutral globules surrounded by externally ionized envelopes.

In a more sensitive survey we detected radio emission from IRc2. Its flux density at 15 GHz is 2 mJy.

Subject headings: nebulae: H II regions — nebulae: Orion Nebula — stars: formation — stars: pre–main-sequence — stars: winds

I. INTRODUCTION

The Orion Nebula is a complex and fascinating region of star formation, exhibiting O and B stars, infrared sources, H II regions, masers, and molecular emission. Because it is only about 500 pc from the Sun, it has become a prototype for the study of star-forming regions and has been observed by most astronomical instruments. A summary of the physical characteristics and observational results for the Orion Nebula is given by Field (1982).

The Orion Nebula itself (M42, NGC 1976) is a cloud of ionized gas of $\sim$8′ in size with an electron temperature of $\sim$8000 K (Pankonin, Walmsley, and Harwit 1979) and an electron density in its central region (20″) of $\sim 10^4$ cm^{-3} (Lockman and Brown 1975). It is centered on the trapezium stars (Θ^1 Orionis), a cluster of luminous OB stars that excites and ionizes the nebula. About 1′ northwest of the Trapezium stars and behind the nebula is the Orion molecular cloud (OMC-1) core, a region of molecular gas with a temperature of about 100 K and a density of $\sim 10^6$ cm^{-3} (cf. Werner, Becklin, and Neugebauer 1977). Infrared observations have shown that, embedded in the molecular cloud core, there is a cluster of optically obscured infrared sources (Downes *et al.* 1981; Wynn-Williams *et al.* 1984).

We observed the Orion Nebula with the Very Large Array of the NRAO[2], in order to search for radio emission from compact H II regions indicative of embedded OB stars or from winds associated with pre–main-sequence, low-mass stars. The infrared sources embedded in the molecular cloud may be associated with young massive stars and therefore have internal energy sources of their own, or they may be high-density condensations heated by external energy sources. Our radio observations were designed to probe deeply into the Orion molecular cloud in order to determine which of the infrared sources are truly sites of massive star formation. Preliminary results of our early measurements in this program were discussed by Moran *et al.* (1982).

II. OBSERVATIONS

We observed the Orion Nebula with the VLA at several frequencies on 1981 August 9, 1982 April 25, 1983 February 17, and 1983 August 28. See Table 1. Typical integration times for each epoch were 60 minutes at each frequency obtained from 10 minute scans at different hour angles in order to provide

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TABLE 1

OBSERVATIONAL PARAMETERS

EPOCH (1)	CONFIGURATION (2)	FREQUENCY (MHz) (3)	SYNTHESIZED BEAMWIDTH (4)	BANDWIDTH (MHz) (5)	PHASE TRACKING CENTER α(1950) (6)	PHASE TRACKING CENTER δ(1950) (7)	FLUX CALIBRATOR (8)	MINIMUM (u, v) SPACING (kλ) (9)	RMS NOISE (mJy per beam) (10)
1981 Aug 9	B	4866	1".13	12.5	$05^h32^m50^s.0$	−5°25'30".0	3C 147 (7.9 Jy)	50	1.1
	B	15015	0.46	50.0	05 32 47.0	−5 24 23.0	3C 147 (2.4 Jy)	35	0.6
1982 Apr 25	A	4873	0.43	25.0	05 32 48.5	−5 25 20.0	3C 286 (7.4 Jy)	12	0.7
1983 Feb 17	C	14965	1.56	50.0	05 32 47.0	−5 24 45.0	3C 286 (3.4 Jy)	20	1.0
	C	22485	1.08	50.0	05 32 48.7	−5 25 15.0	3C 286 (2.5 Jy)	25	1.3
	C	22485	1.02	50.0	05 32 46.5	−5 24 20.0	3C 286 (2.5 Jy)	25	1.0
1983 Aug 28	A out[a]	1452	1.10	25.0	05 32 49.0	−5 25 10.0	3C 286(13.8 Jy)	30	0.3
	A in[b]	4873	1.43	25.0	05 32 49.0	−5 25 10.0	3C 286 (7.3 Jy)	30	1.4
	A in[b]	14977	0.51	25.0	05 32 49.0	−5 25 10.0	3C 286 (3.4 Jy)	35	0.8

[a] Configuration formed with the four outer antennas in each arm.
[b] Configuration formed with the five inner antennas in each arm.

good (u, v) plane coverage. The on-source observations were preceded and followed by observations for 3 minutes of the calibration source, 0539−057. The position of the calibrator was $\alpha(1950) = 5^h39^m10^s.99$, $\delta(1950) = -5°43'15''.1$, which has an accuracy of 0''.1 (Perley 1982). The data were edited and calibrated following the standard procedures described by Hjellming (1979).

Maps were made by Fourier transforming and CLEANing the interferometer data. Since the Orion Nebula itself is a strong source, which is not totally resolved on the shorter VLA spacings, we applied a minimum baseline cutoff in order to obtain a higher dynamic range to search for compact sources. The minimum baseline length used to map the region is given in column (9) of Table 1, and the noise level (per beam area) in the map is given in column (10).

We used a photograph of the Orion Nebula in the near-infrared passband 690–880 nm taken with the 120 inch (3.0 m) reflector of the Lick Observatory (Herbig 1982) to search for optical counterparts to the radio sources. The positions of 70 Parenago stars (Parenago 1954) distributed across the plate and of several unidentified optical sources within 2' of the Trapezium stars were measured on a measuring engine at the Smithsonian Astrophysical Observatory. Fifty-six of the Parenago stars have known coordinates and were used to determine the plate scale and the α–δ orientation. The accuracies of the optical position determination is about 0''.4 (1 σ error). Since the individual motions of most of the 56 Parenago stars are unknown, proper motion corrections could not be applied. The errors involved in neglecting proper motions can be estimated using the radial velocity dispersion of stars in the vicinity of the Trapezium of $\sim$4 km s^{-1} (Strand 1958). For a time span of $\sim$50 yr, we estimate an average proper motion of only 0''.2.

III. RESULTS

a) *Extended Radio Emission*

Figure 1 shows the radio continuum emission at 5 GHz of the Orion Nebula obtained with the VLA in the B configuration. In this configuration, the VLA is not sensitive to structures larger than 30''. Thus, most of the continuum emission that is observed with single antenna telescopes have been resolved. The radio map shown in Figure 1 was obtained by applying a Gaussian taper of 50 Kλ to the (u, v)-plane data, giving a synthesized half power beam width (FWHM) of 3''.

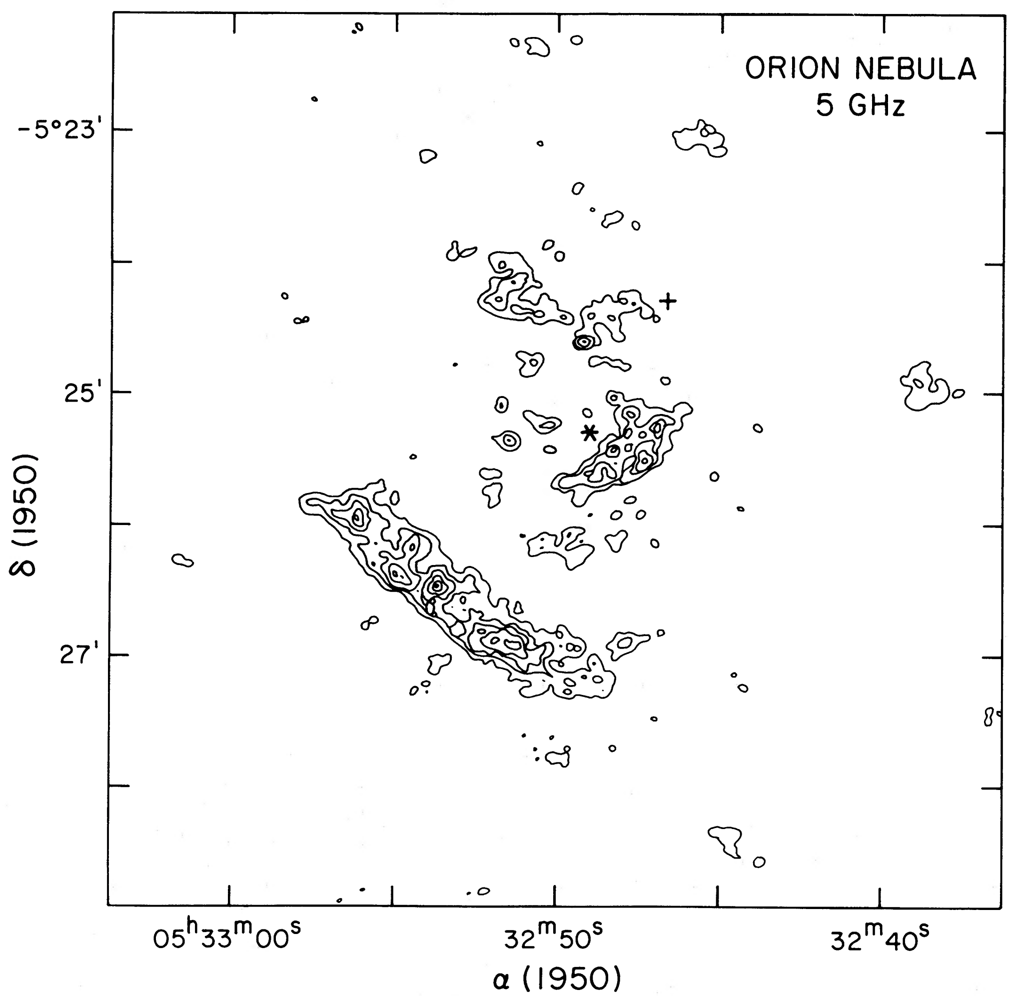

FIG. 1.—Map of the Orion Nebula at 5 GHz made with the VLA in the B configuration in 1981 August. A Gaussian taper of 50 Kλ was applied to the (u, v)-plane data giving a beamwidth of 3'' (FWHM). The contour levels are −20, 20, 35, 50, 65, 80, and 95% of the peak flux density of 95 mJy per beam area. The asterisk and cross indicate the position of the Trapezium star Θ^1C and of the BN object, respectively.

TABLE 2

TRAPEZIUM COMPACT RADIO SOURCES

Source	α(1950)[a]	δ(1950)[a]	Flux Density (mJy) 1.45 GHz	4.9 GHz			15.0 GHz			22.4 GHz	Deconvolved Size[b]
			1983 Aug	1981 Aug	1982 Apr	1983 Aug	1981 Aug	1983 Feb	1983 Aug	1983 Feb	
1........	05h32m50s22	−5°25′34″2	6.5 ± 0.3	16.0 ± 2.4	19.0 ± 1.4	23.2 ± 4.6	9.3 ± 2.1	14.5 ± 1.6	13.9 ± 0.6	14.3 ± 1.2	0″48 ± 0″18
2........	05 32 50.11	−5 25 18.2	<1	5.5 ± 0.9	7.3 ± 1.3	5.6 ± 0.9	<4	<5	5.0 ± 1.1	<5	0.39 ± 0.11
3........	05 32 49.61	−5 25 27.4	<1	~3	7.0 ± 1.2	<5	<4	<5	10.8 ± 0.6	<5	0.42 ± 0.06
4........	05 32 49.53	−5 25 30.3	4.9 ± 0.5	14.2 ± 1.6	13.2 ± 1.4	11.5 ± 1.1	9.0 ± 0.4	6.6 ± 1.0	14.0 ± 1.0	8.3 ± 1.4	0.41 ± 0.08
5........	05 32 49.39	−5 25 19.5	1.9 ± 0.3	15.1 ± 0.8	18.0 ± 0.5	12.5 ± 1.8	18.8 ± 0.5	32.7 ± 0.8	35.3 ± 0.8	23.5 ± 1.3	0.40 ± 0.06
6........	05 32 49.29	−5 25 09.8	4.7 ± 0.3	20.4 ± 2.1	26.6 ± 3.4	24.5 ± 1.7	27.9 ± 1.1	35.2 ± 1.6	39.0 ± 1.5	33.4 ± 1.7	0.34 ± 0.12
7........	05 32 48.83	−5 25 10.0	4.5 ± 0.5	7.2 ± 1.5	18.1 ± 2.0	10.5 ± 1.3	11.0 ± 0.4	17.7 ± 2.0	17.9 ± 1.1	10.3 ± 1.2	0.32 ± 0.18
8........	05 32 48.61	−5 25 17.7	<1	3.6 ± 0.9	6.9 ± 1.0	<5	5.9 ± 0.8	<5	3.9 ± 1.4	4.5 ± 1.2	0.34 ± 0.12
9........	05 32 48.50	−5 25 43.2	6.6 ± 0.8	18.0 ± 1.5	20.1 ± 1.2	13.7 ± 3.8	15.6 ± 4.3	10.5 ± 1.0	26.4 ± 0.6	10.3 ± 1.4	0.66 ± 0.11
10........	05 32 48.39	−5 25 18.9	[c]	[c]	8.7 ± 1.1	[c]	~4	[c]	6.9 ± 1.0	[c]	0.39 ± 0.10
11........	05 32 48.38	−5 25 15.9	1.6 ± 0.6	9.3 ± 0.9	11.1 ± 0.7	6.6 ± 1.5	12.2 ± 0.7	13.5 ± 1.6	15.2 ± 1.0	13.7 ± 1.2	0.32 ± 0.08
12........	05 32 48.36	−5 25 07.5	14.8 ± 0.5	13.9 ± 2.6	3.3 ± 1.7	10.6 ± 2.7	13.6 ± 0.2	73.9 ± 2.2	13.5 ± 1.4	74.3 ± 1.6	0.21 ± 0.06
13........	05 32 48.34	−5 25 20.0	11.9 ± 2.2	13.1 ± 1.2[d]	15.2 ± 0.7	19.2 ± 3.0[d]	15.7 ± 1.2	25.1 ± 1.6[d]	16.4 ± 1.0	15.8 ± 1.8[d]	0.52 ± 0.06
14........	05 32 48.07	−5 25 30.9	2.7 ± 0.5	9.8 ± 1.1	6.4 ± 0.7	10.4 ± 1.4	8.6 ± 0.8	12.2 ± 2.0	14.1 ± 1.0	18.8 ± 1.5	0.50 ± 0.14

[a] Positions are accurate to 0″1 (1 σ).
[b] Full width at half-maximum.
[c] Blended with source 13.
[d] Sources 10 + 13.

This radio map is remarkably similar to the well-known Lick Observatory photographs of the Orion Nebula seen in the light of hydrogen or oxygen emission lines (e.g., Herbig 1982). The most prominent features that appear in both the radio and optical are the bar ~100″ southeast and an ionized cavitylike structure ~30″ west of the Trapezium cluster.

The sharp drop in the flux density across the bar (to the southeast) suggests that it is an ionization front expanding away from Θ^1C and moving into the dense neutral molecular cloud. This interpretation is supported by both continuum infrared (Becklin *et al.* 1976) and molecular hydrogen (Hayashi *et al.* 1985) observations that show that hot dust and shock-excited molecular hydrogen lie just outside the ionized gas. The shock is probably driven by the expansion of the H II region.

b) *Compact Radio Structure*

We detected 21 compact radio sources with flux densities stronger than 4 mJy per beam area and sizes smaller than 5″ in the Orion Nebula. Fourteen of the sources are clustered around the Trapezium stars, that is, within an angular distance of 30″ from Θ^1C Orionis, the brightest star of the Trapezium. Since the physical characteristics of most of these 14 sources are similar, they have been listed separately in Table 2 and will be referred to as the Trapezium sources. The remaining sources are listed in Table 3. Maps of the radio sources at 15 GHz are shown in Figures 2–4.

In Tables 2 and 3 we give the flux densities and deconvolved angular sizes of the sources. The flux densities have been corrected to account for the primary beam response of the individual interferometer elements. The deconvolved angular sizes correspond to the average of sizes determined at 4.9 GHz with the A array (beamwidth ~0″.4) and at 15.0 GHz with an inner portion of the A array (beamwidth ~0″.5). Typical 1 σ errors are 1.5 mJy and 0″.1 for the flux density and angular size, respectively.

i) *Trapezium Sources*

All 14 Trapezium radio sources have optical counterparts. In Table 4 we summarize the identification of the compact radio sources. Six of these compact sources are identified with optically visible objects seen in Parenago's chart VA (Parenago 1954). One of these objects is Θ^1A, the westernmost member of the Trapezium cluster (Θ^1 Orionis). Θ^1A is an eclipsing binary, with a B0.5 V primary and period of 65.43 days (Baldwin and Mattei 1977). Seven of the compact radio sources (of which two are associated with Parenago objects) are associated with the nebular condensations identified by Laques and Vidal (1979) and Vidal (1982). We refer to these as LV objects. These condensations are characterized by strong Hα, Hβ, and [O III] optical emission lines, but they lack continuum emission and [S II] emission lines. The remaining three radio sources have also been identified with optical objects seen in 690–880 nm passband plates of Orion (Herbig 1982). None of the radio sources correspond to stars without Parenago numbers observed by Herbig and Terndrup (1986). In Table 5 we list the 1950 coordinates of the radio sources and the coordinates of their probable optical counterparts. The coordinates of the LV objects were obtained by measuring their relative positions from Figure 2 of Laques and Vidal (1979) and then referring them to the coordinates of Parenago stars in that figure.

Spectra of the Trapezium radio sources are shown in Figure 5. Most of the spectra are consistent with emission from compact H II regions that becomes optically thin between 5 and 15 GHz. The radio source associated with Θ^1A (source 12) showed large (~an order of magnitude) variations in its flux density. Its spectrum was flat at all observed epochs.

ii) *Molecular Clouds and Environs*

All but one of the radio continuum sources near the Orion molecular cloud are identified with either optical, infrared or radio line counterparts (see Table 4). Source A is near a peak in the NH_3 emission map of the Orion Nebula (Batrla *et al.* 1983). Source B is coincident with the Becklin-Neugebauer object. Sources C and E are associated with optical objects seen on Herbig's plates. Sources F and G are coincident with Parenago stars. Spectra of these sources are shown in Figure 6. Few spectral data points were available for source A since, at most epochs, it was not within the delay beam of the interferometer. The spectrum of source B (the BN object) between 15 and 22 GHz suggests that the emission is optically thick in that range. Sources F and G show significant flux density variations.

We have also made sensitive observations (below the limits of this survey) of the region around IRc2 and have detected a radio source close to the position of the compact infrared source. Its flux density at 5 GHz is 2 mJy and its position is $\alpha(1950) = 05^h32^m47^s.02 \pm 0^s.02$, $\delta(1950) = -5°24'24''.0 \pm 0''.1$. This position is 0″.6 south of the IRc2 position given by Lester *et al.* (1985). These results are discussed separately (Moran *et al.* 1983, 1986).

TABLE 3

MOLECULAR CLOUD AND ENVIRONS

			Flux Density (mJy)								
			1.45 GHz	4.9 GHz			15.0 GHz			22.5 GHz	
Source	α(1950)[a]	δ(1950)[a]	1983 Aug	1981 Aug	1982 Apr	1983 Aug	1981 Aug	1983 Feb	1983 Aug	1983 Feb	Deconvolved Size[b]
A	$05^h32^m44^s.33$	−05°23′43″.0	[c]	10.0 ± 1.0	[c]	[c]	11.0 ± 1.0	[c]	[c]	[c]	0″.19 ± 0″.12
B	05 32 46.65	−05 24 16.5	<1	<3	<3	<5	9.1 ± 0.6	7.6 ± 1.6	9.4 ± 1.0	13.6 ± 1.1	...
C	05 32 46.70	−05 24 54.5	3.9 ± 0.3	13.0 ± 1.2	26.1 ± 3.8	11.3 ± 1.8	13.7 ± 1.1	21.3 ± 2.2	14.1 ± 1.0	13.2 ± 1.9	0.75 ± 0.19
D	05 32 47.42	−05 24 18.9	<1	<3	<3	<5	7.5 ± 0.3	<5	<5	<4	...
E	05 32 49.50	−05 24 41.9	3.5 ± 0.3	5.9 ± 1.1	<3	<5	6.5 ± 1.2	~5	<4	<5	0.45 ± 0.13
F	05 32 50.89	−05 24 30.6	8.0 ± 0.5	5.2 ± 0.9	23.9 ± 0.4	17.3 ± 1.2	4.9 ± 0.7	3.9 ± 1.2	28.7 ± 1.1	<5	...
G	05 32 50.47	−05 24 38.7	4.8 ± 0.5	<3	8.9 ± 0.8	<5	<4	22.8 ± 1.0	<4	25.1 ± 1.2	...

[a] Positions are accurate to 0″.1 (1 σ).
[b] Full width at half-maximum.
[c] Not mapped.

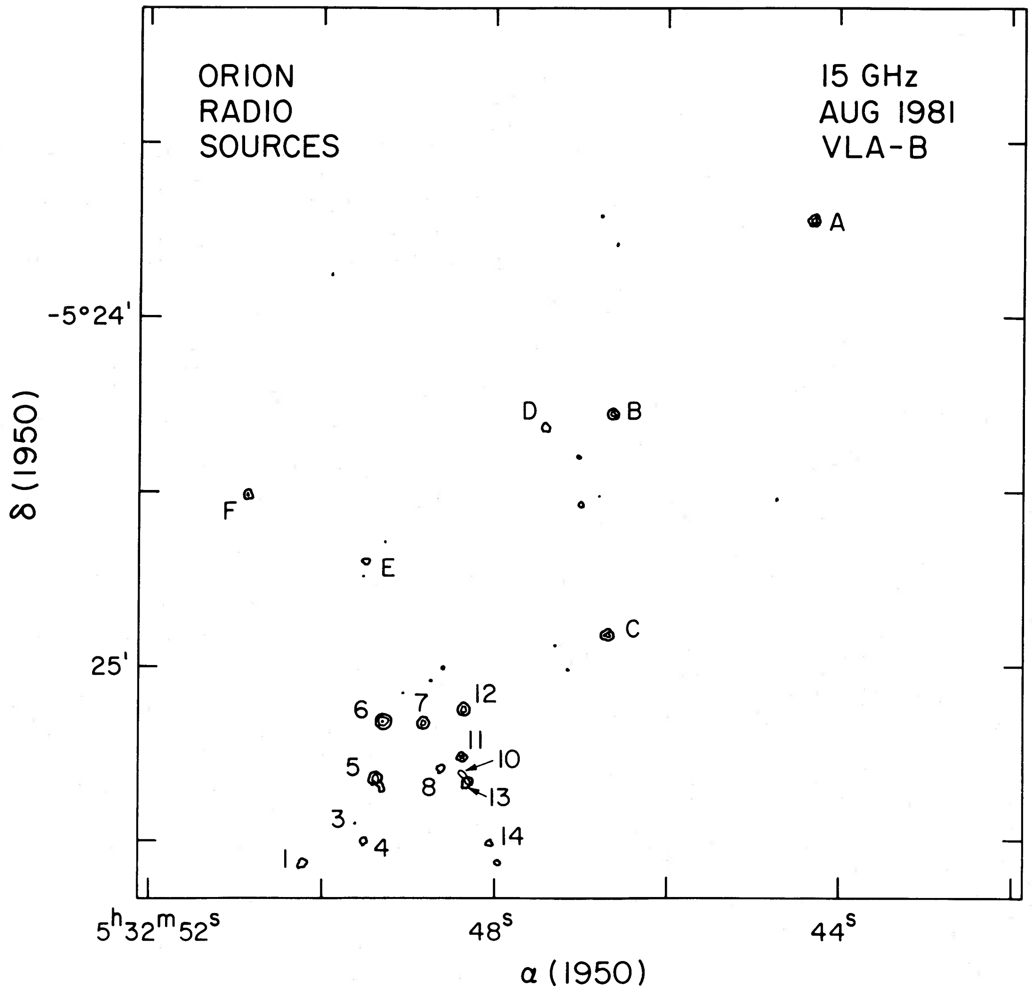

FIG. 2.—Map of the compact radio sources in the Orion Nebula at 15 GHz made with the VLA in the B configuration in 1981 August. A 35 kλ minimum baseline spacing was used to remove structure larger than 6″. The areas of the circles are proportional to flux density.

IV. DISCUSSION

Stellar photospheres with angular diameters of $\sim 10^{-4}$ arcsec and temperatures of ~ 5000 K would be undetectable by the VLA. Most of the compact radio sources we detected were resolved with the VLA, having angular sizes of $\sim 0\farcs4$. The compact radio sources have diameters much larger than photospheric diameters of stars and brightness temperatures smaller than 10^4 K. This result suggests that we are detecting thermal emission produced by bremsstrahlung in an ionized gas. Further classification among thermal radio sources requires the understanding of the physical nature of the ionized circumstellar envelope as well as that of the exciting source.

Thermal bremsstrahlung sources include quasi-static H II regions and mass-loss objects. Mass-loss stars, such as OB stars, have a relatively steady mass-loss rate driven by stellar winds, while symbiotic stars show short outbursts of mass ejection. H II regions can be internally ionized, usually by an OB star, or externally ionized, in which case they appear as neutral condensations surrounded by an ionized envelope. With the presently available data on the compact radio sources, it is difficult to discriminate among the different types of thermal radio sources. Optical, infrared, and ultraviolet observations may help distinguish among them. Nonetheless, in the remainder of this section, we discuss the characteristics of the different models that can explain the radio emission from the newly detected compact radio sources.

Two of the Orion cloud environs radio sources (sources F and G) were not resolved with our resolution of $\sim 0\farcs4$ and have brightness temperatures exceeding 5×10^3 K. Furthermore, their radio emission shows large flux density variations. These variations suggest that the radio emission has a nonthermal origin. Possible interpretations of their radio emission are discussed at the end of this section.

a) Trapezium Sources

One of the radio objects in the neighborhood of Θ^1C, source 12, shows exceptional characteristics: (1) its radio emission shows dramatic flux density variations; (2) its spectrum is flat at all observed epochs; and (3) it is associated with Θ^1A Orionis, a luminous member of the Trapezium cluster. This source is clearly different from the rest of the Trapezium sources, and it will not be considered in the following discussion. A detailed discussion of the characteristics of the radio emission associated with Θ^1A was presented elsewhere (Garay, Moran, and Reid 1985).

i) *The Case against Internal Ionization*

The spectra of most of the Trapezium sources turn over near 4 GHz and become flat at higher frequencies. This might poss-

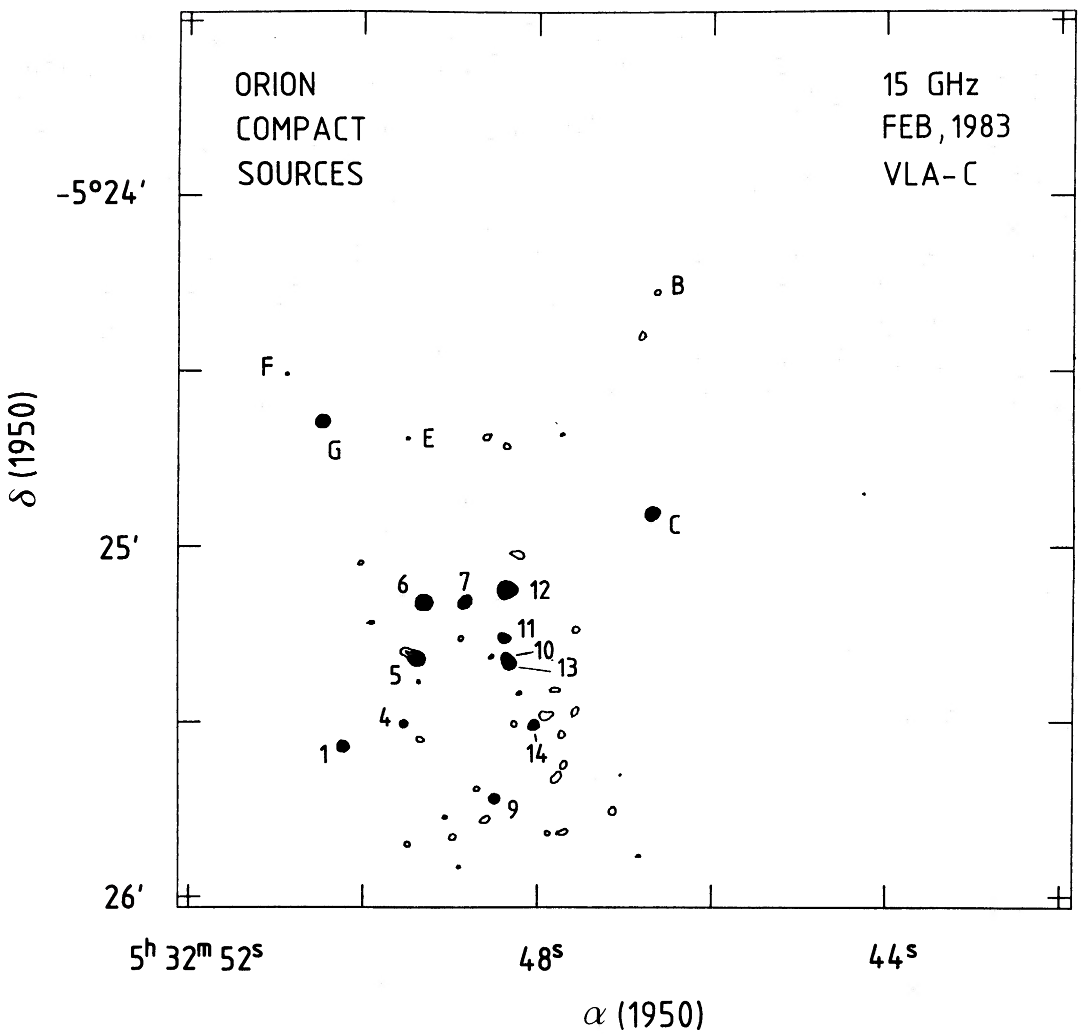

FIG. 3.—Map of the compact radio sources in the Orion Nebula at 15 GHz made with the VLA in the C configuration in 1983 February. A minimum baseline spacing of 20 kλ was used to remove structure larger than 10″.

ibly be explained by a simple model in which these objects are ZAMS stars surrounded by an ionized envelope of constant density and temperature. Figure 5 shows the observed flux density as a function of frequency for each of the Trapezium sources. Also shown for each source is the theoretical spectrum of a spherical H II region, having constant density and an electron temperature of 8000 K, that best fits the data. The fitted parameters (i.e., density and radius) and the derived parameters, namely the emission measure, the number of ionizing photons, and the optical depth for the homogeneous spherical H II region model are given in Table 6. All the model H II regions are very dense ($n_e \approx 2 \times 10^5$ cm^3) and extremely small ($d \approx 0.001$ pc or 200 AU). Source 3 is not included in Tables 6 and 7 since its flux density shows small, but probably significant, variations. Thus, the model discussed here may not be suitable for this object.

The major objection to this model is that stars exciting the H II region should be optically bright, if we assume that the ionization is from stellar UV photons. The required number of ionizing photons per second, $\sim 4 \times 10^{44}$ s^{-1}, implies the presence of an underlying ZAMS star of spectral type $\approx$B2 (Panagia 1973). The visual magnitude, m_V, of a B2 V star (absolute visual magnitude of -2.5) at a distance of 500 pc is $m_V = 6.0 + A_V$, where A_V is the absorption in magnitudes. For the Trapezium stars, Johnson (1965) derived $R_V = 5.7$, where $R_V = A_V/E_{B-V}$ and E_{B-V} is the color excess. Since the mean value of the color excess of several early type stars in the Trapezium region is 0.4 mag (Penston 1973), we obtain $A_V \approx 2.3$ mag, which we assume to be valid for the whole region. Thus, B2 stars should have $m_V \approx 8.3$ mag. Such a star should be easily seen in photographic plates of the Orion Nebula. However, the observed visual magnitude of two of the LV objects is 15.5 mag, in clear disagreement with the expected value if they were early B-type stars. It is unlikely that these sources are B2 stars deeply embedded in the molecular cloud and therefore heavily obscured in the optical wavelengths. The total luminosity of a B2 V star is in excess of $5 \times 10^3\ L_\odot$, which should appear primarily as infrared radiation if the star is embedded in a molecular cloud. Such an object would be easily seen in infrared maps (as is the case for the BN object). However, only one of these objects (source 11) has been detected as an infrared emitter (2.2 μm mag less than 12) (Becklin *et al.* 1976; Lonsdale *et al.* 1982).

The compact sources in the Trapezium region cannot be

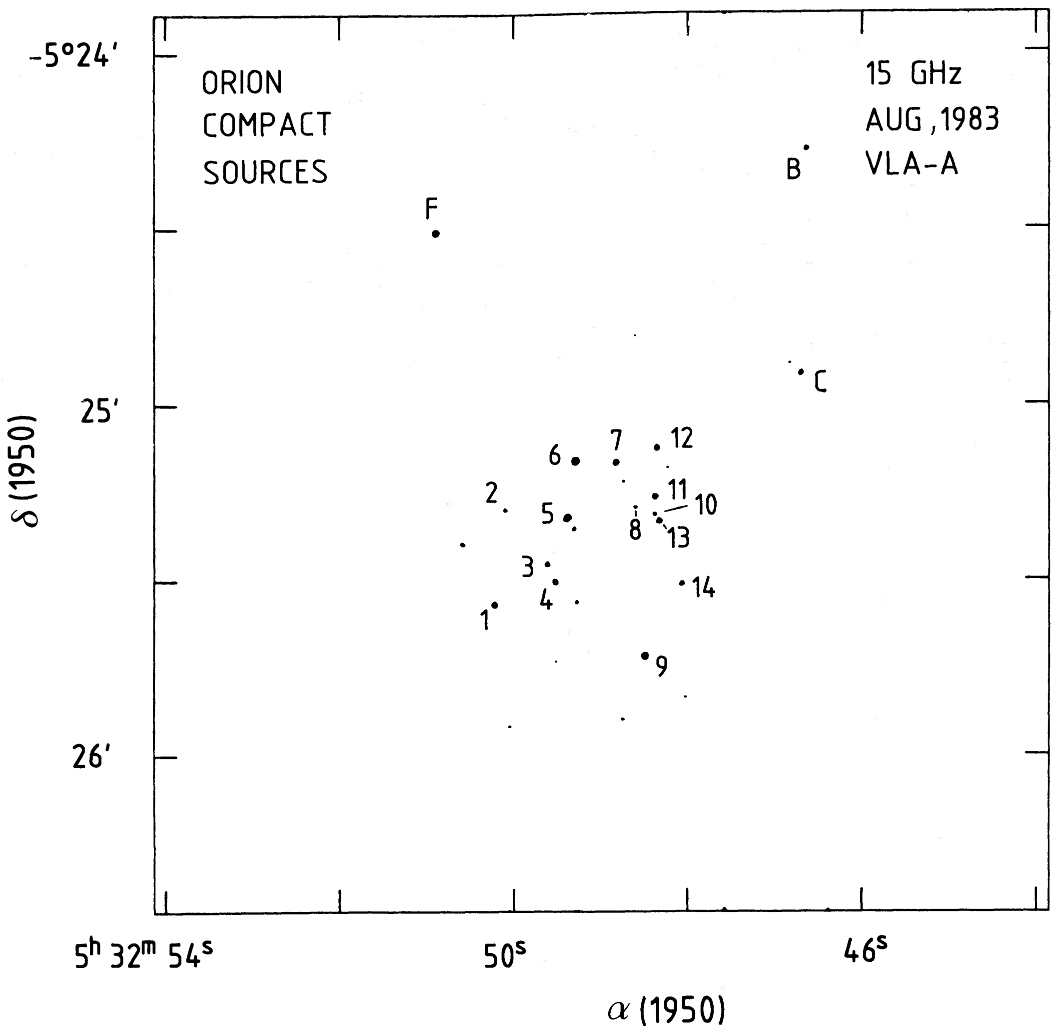

FIG. 4.—Map of the compact radio sources in the Orion Nebula at 15 GHz made with the VLA in the A configuration in 1983 August. Filled circles denote radio sources detected above the limit of 4 mJy per beam area.

stellar wind sources whose envelopes are ionized by central stars. First, the spectral indices are not equal to 0.6, as would be expected for a r^{-2} density profile. Second, the required ionizing rates are too high. The rate of ionizing photons for an optically thick wind source is given by (cf. Moran 1983)

$$\left[\frac{N_i}{\mathrm{s}^{-1}}\right] = 2.8 \times 10^{47}\left[\frac{S_\nu}{\mathrm{mJy}}\right]^{1.5}\left[\frac{\nu}{\mathrm{GHz}}\right]^{-0.9} \times \left[\frac{r_0}{5 \times 10^{11}\ \mathrm{cm}}\right]^{-1}\left[\frac{T_e}{10^4\ \mathrm{K}}\right]^{-0.95}\left[\frac{D}{\mathrm{Kpc}}\right]^3, \quad (1)$$

where S_ν is the radio flux density at frequency ν, r_0 is the inner radius of the ionized envelope, T_e is the electron temperature, and D is the distance from the Sun. For the Trapezium sources, $D = 0.5$ Kpc, $S_\nu \approx 15$ mJy at $\nu = 4.9$ GHz, and taking $r_0 = 5 \times 10^{11}$ cm, we obtain $N_i \approx 5 \times 10^{47}\ \mathrm{s}^{-1}$. This ionizing flux requires a O9.5 ZAMS star (Panagia 1973) and would be expected to be a very strong optical or infrared source. Even if the ionized envelope were optically thin throughout the observed frequency range so that the spectral index is -0.1, the ionizing flux would be $4 \times 10^{44}\ \mathrm{s}^{-1}$ corresponding to a B2.5 star.

ii) *Externally Ionized Neutral Condensations*

An alternative to the models described above is the one in which the Trapezium sources are externally ionized. The flux density of an optically thin nebula, with the power law formulation (Mezger and Henderson 1967), can be written as (cf. Moran 1983)

$$\left[\frac{S_\nu}{\mathrm{mJy}}\right] = 3.4\left[\frac{\nu}{\mathrm{GHz}}\right]^{-0.1}\left[\frac{T_e}{10^4\ \mathrm{K}}\right]^{-0.35} \times \left[\frac{\mathrm{VEM}}{10^{57}\ \mathrm{cm}^{-3}}\right]\left[\frac{D}{\mathrm{kpc}}\right]^{-2}, \quad (2)$$

where VEM is the volume emission measure. The rate of ionizing photons necessary to ionize the gas is $N_i = \alpha_B\mathrm{VEM}$, where α_B is the recombination coefficient. For $\alpha_B = 2.6 \times 10^{-13}(T_e/10^4\ \mathrm{K})^{-0.8}$, N_i can be written, in terms of the flux density, as

$$\left[\frac{N_i}{\mathrm{s}^{-1}}\right] = 7.6 \times 10^{43}\left[\frac{S_\nu}{\mathrm{mJy}}\right]\left[\frac{\nu}{\mathrm{GHz}}\right]^{0.1} \times \left[\frac{T_e}{10^4\ \mathrm{K}}\right]^{-0.45}\left[\frac{D}{\mathrm{Kpc}}\right]^2. \quad (3)$$

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TABLE 4

SUMMARY OF IDENTIFICATIONS

Source	Optical[a]	m_V	Emission[b] Lines	Optical[c]	X-Ray[d]	Other
			Trapezium			
1	…	…	…	H	…	…
2	…	…	…	H	…	…
3	π1893	14.2	…	…	…	…
4	π1894	15.2	…	…	…	…
5	…	…	LV 1	…	…	…
6	π1890, Θ[1]G	15.5	LV 2	…	…	…
7	…	…	LV 3	…	…	…
8	…	…	LV 4	…	…	…
9	π1869	14.1	…	…	KRS 24	…
10	…	…	LV 6[e]	…	…	…
11	π1867, π1866, θ[1] H/H′	15.5/16.0	LV 5	…	…	IR[f]
12	π1865, Θ[1]A	7.0	…	…	…	IR[f]
13	…	…	LV 6[e]	…	…	…
14	…	…	…	H	…	…
			Molecular Cloud and Environs			
A	…	…	…	…	…	NH_3[g]
B	…	…	…	…	…	BN
C	…	…	…	H	…	…
D	…	…	…	…	…	…
E	…	…	…	H	…	…
F	π1925	14.1	…	…	KRS 32	…
G	π1910	…	…	…	KRS 31	…

[a] Parenago 1954 (π denotes number in Parenago catalog).
[b] Laques and Vidal 1979 (LV).
[c] Herbig 1982 (H).
[d] Ku, Righini-Cohen, and Simon 1981 (KRS).
[e] LV 6 has been optically resolved in two components (Vidal 1982).
[f] Lonsdale *et al.* 1982.
[g] Batrla *et al.* 1983.

TABLE 5

RADIO AND OPTICAL POSITIONS

SOURCE	RADIO		PARENAGO		LV[a]		HERBIG[b]	
	α(1950)	δ(1950)	α(1950)	δ(1950)	α(1950)	δ(1950)	α(1950)	δ(1950)
				Trapezium				
1	5h32m50s.22	−5°25′34″.2	…	…	…	…	5h32m50s.25	−5°25′34″.2
2	5 32 50.11	−5 25 18.2	…	…	…	…	5 32 50.13	−5 25 18.3
3	5 32 49.61	−5 25 27.4	5h32m49s.61	−5°25′27″.1	…	…	π	…
4	5 32 49.53	−5 25 30.3	…	…	…	…	5 32 49.55	−5 25 30.5
5	5 32 49.39	−5 25 19.5	…	…	5h32m49s.42	−5°25′19″.3	…	…
6	5 32 49.29	−5 25 09.8	…	…	5 32 49.28	−5 25 9.2	5 32 49.31	−5 25 10.0
7	5 32 48.83	−5 25 10.0	…	…	5 32 48.80	−5 25 9.7	5 32 48.86	−5 25 9.8
8	5 32 48.61	−5 25 17.7	…	…	5 32 48.64	−5 25 17.6	…	…
9	5 32 48.50	−5 25 43.2	5 32 48.52	−5 25 43.4	…	…	π	…
10	5 32 48.39	−5 25 18.9	…	…	5 32 48.40	−5 25 19.5	5 32 48.40	−5 25 19.0
11	5 32 48.38	−5 25 15.9	…	…	5 32 48.38	−5 25 15.8	5 32 48.43	−5 25 15.5
	…	…	…	…	…	…	5 32 48.34	−5 25 15.4
12	5 32 48.36	−5 25 07.5	5 32 48.37	−5 25 7.7	…	…	π	…
13	5 32 48.34	−5 25 20.0	…	…	5 32 48.38	−5 25 19.9	5 32 48.35	−5 25 20.2
14	5 32 48.07	−5 25 30.9	…	…	…	…	5 32 48.09	−5 25 30.8
				Molecular Cloud and Environs				
A	5 32 44.33	−5 23 43.0	…	…	…	…	…	…
B[c]	5 32 46.65	−5 24 16.5	…	…	…	…	…	…
C	5 32 46.70	−5 24 54.5	…	…	…	…	5 32 46.73	−5 24 54.3
D	5 32 47.42	−5 24 18.9	…	…	…	…	…	…
E	5 32 49.50	−5 24 41.9	…	…	…	…	5 32 49.54	−5 24 42.2
F	5 32 50.89	−5 24 30.6	5 32 50.91	−5 24 31.2	…	…	…	…
G	5 32 50.47	−5 24 38.7	5 32 50.48	−5 24 39.3	…	…	…	…

[a] Measured from Fig. 2 of Laques and Vidal 1979.
[b] Measured from photograph of plate taken with the Lick Observatory by Herbig 1982. π denotes Parenago position. These positions were used to calibrate Herbig's plate.
[c] Becklin-Neugebauer object.

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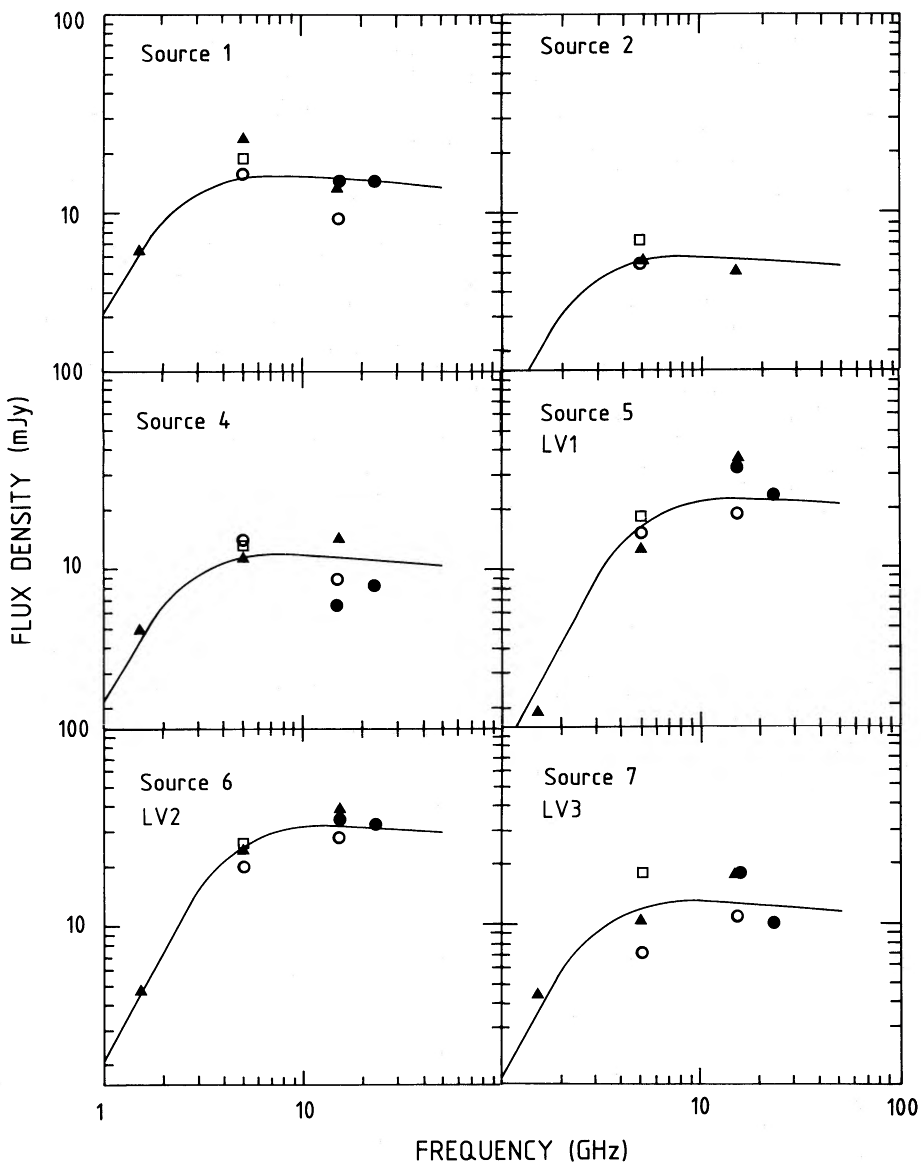

FIG. 5.—Microwave spectra of the Trapezium radio sources. Circles, squares, black dots, and triangles refer to flux density values in 1981 August, 1982 April, 1983 February, and 1983 August, respectively.

TABLE 6

H II REGION PARAMETERS

Source	Radius[a] (10^{15} cm)	n_e[a] (10^5 cm^{-3})	E.M. (10^7 pc cm^{-6})	N_i (10^{44} photon s^{-1})	ZAMS
1	3.1	1.1	2.4	4.6	B2
2	1.7	1.6	2.8	1.6	B2.5
4	2.6	1.2	2.4	3.3	B2
5	1.9	2.8	9.4	6.5	B2
6	2.5	2.1	7.2	9.3	B1.5
7	2.3	1.5	3.4	3.6	B2
8	1.7	1.4	2.2	1.3	B2.5
9	3.5	0.9	1.8	4.4	B2
11	1.5	2.9	8.1	3.5	B2
13	3.1	1.1	2.4	4.6	B2
14	2.2	1.5	3.2	3.0	B2

[a] Radius and electron density of a constant density spherical H II region at a temperature of 8000 K and located at a distance of 500 pc, that best fit the observed values of the flux density vs. frequency given in Table 2.

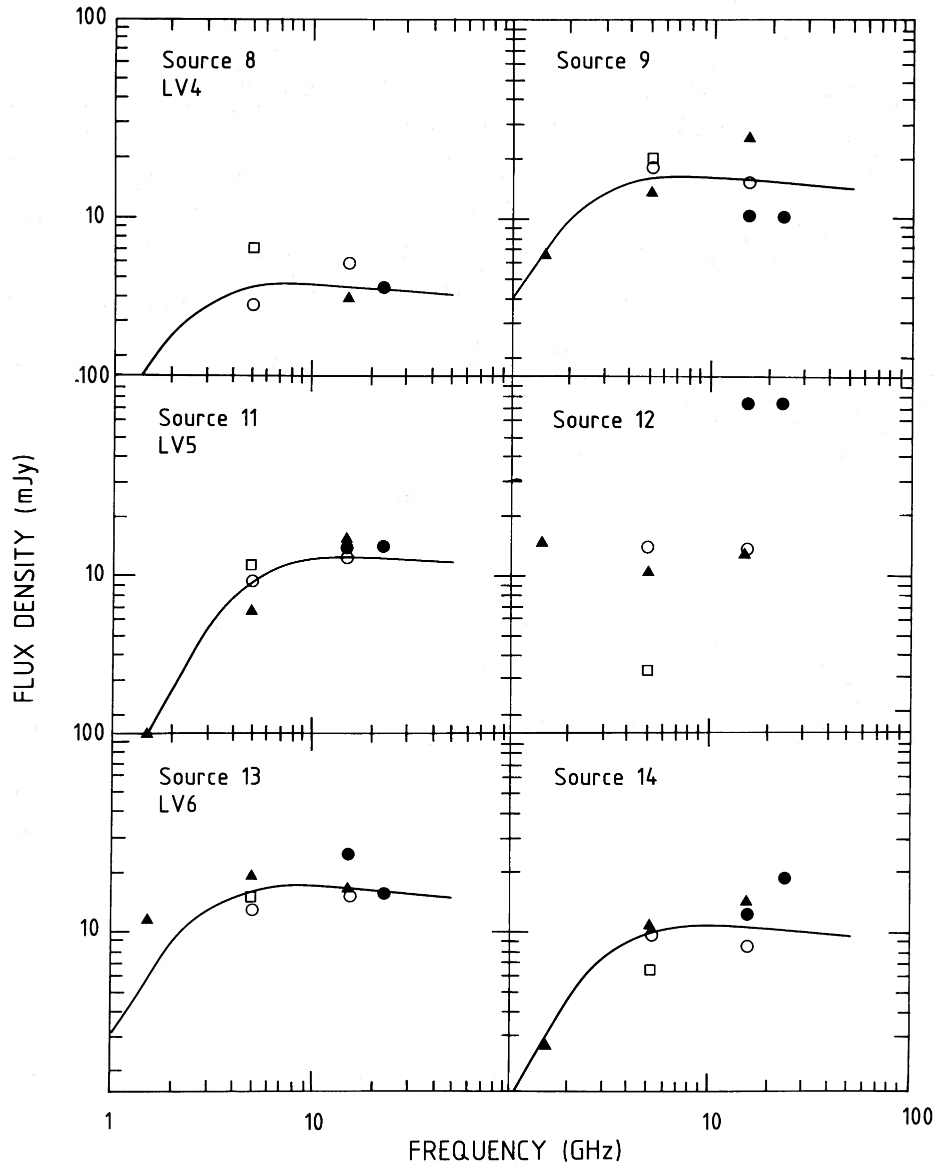

FIG. 5.—*Continued*

The average flux density at 15 GHz for the Trapezium compact radio sources is ~ 15 mJy, thus the number of ionizing photons per second required by the compact radio sources, assuming they are photoionized, is typically $\sim 4 \times 10^{44}\ \mathrm{s}^{-1}$.

Is there an object in the Trapezium neighborhood compatible with the ionization requirements? The most luminous source in Θ^1 Orionis is Θ^1C, the southernmost member of the Trapezium. It is an O7 V star (Conti and Alschuler 1971) providing $\sim 7 \times 10^{48}$ UV photons s^{-1} (Panagia 1973) to the surrounding medium. The ionizing photon rate, N_i', incident on a source that subtends a solid angle Ω as seen by Θ^1C, is

$$N_i' = N_{i0} \frac{\Omega}{4\pi} e^{-\tau_{\mathrm{Lc}}} , \quad (4)$$

where τ_{Lc} is the Lyman continuum optical depth from Θ^1C to the source in question, and N_{i0} is the Lyman-continuum photon rate from Θ^1C. For a source with a radius of 0$''$.3 and at distance of 20$''$ from Θ^1C, $\Omega = 0.7 \times 10^{-3}$ sr and N_i' is $\sim 5 \times 10^{44}$ photons s^{-1}, if we assume $\tau_{\mathrm{Lc}} \sim 0$. Thus Θ^1C can account for the ionization of the radio sources in the Trapezium neighborhood within a radius of ~ 0.05 pc (angular distance of $\sim 20''$) from Θ^1C, provided that $\tau_{\mathrm{Lc}} \lesssim 1$. This result suggests that the properties of the radio sources in the Trapezium neighborhood are intimately associated to Θ^1C, that is, these sources could be externally ionized by the UV radiation from Θ^1C.

If the compact radio sources in the Trapezium are *completely* ionized globules, then they will not be in pressure equilibrium with their surroundings. Pressure disturbances will propagate at the speed of sound ($\sim 10\ \mathrm{km\ s}^{-1}$) in the less dense medium. Thus the globules would expand and disappear in the surrounding medium in about 500 yr. Since this time is very short compared with the estimated age of the Trapezium stars of $\sim 10^5$ yr (Strand 1958; Vandervoort 1963), we conclude that the globules are not completely ionized.

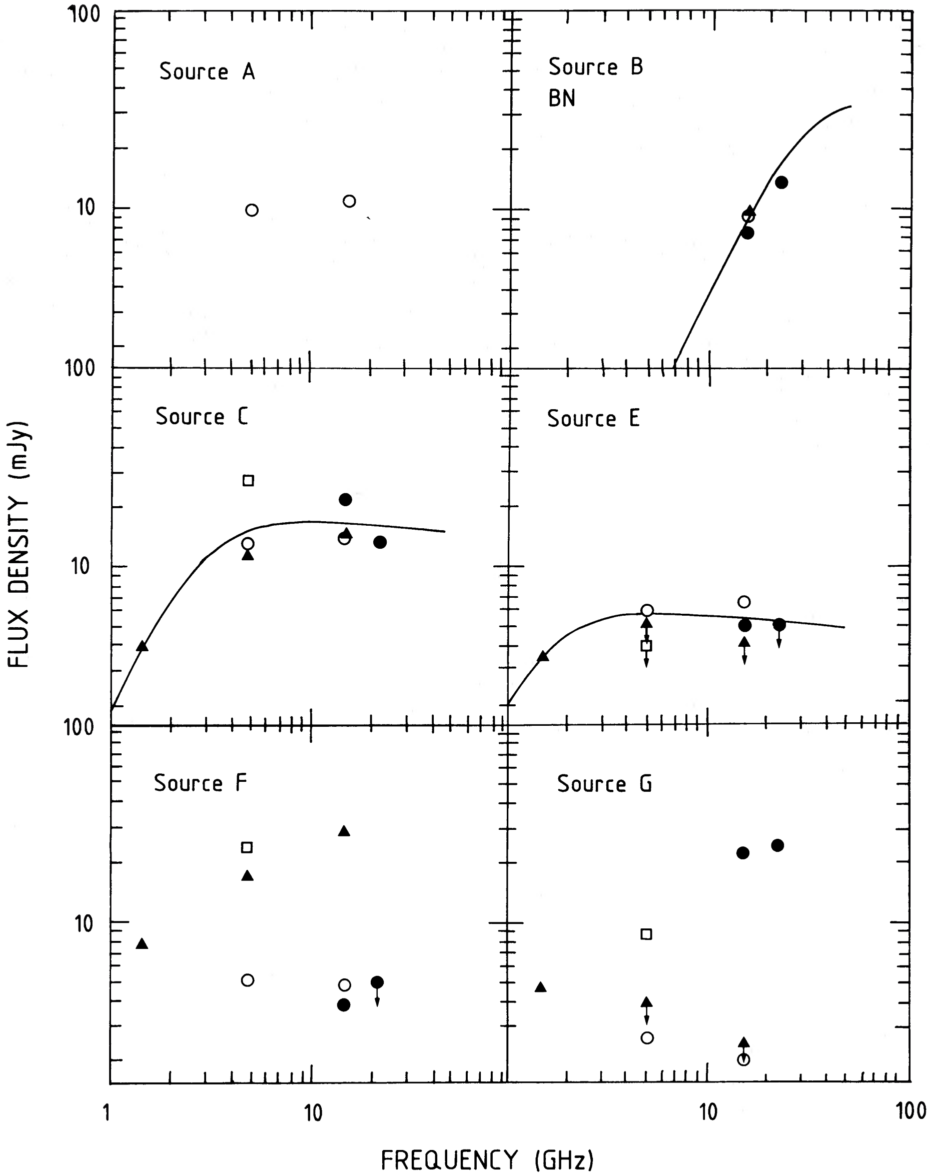

FIG. 6.—Microwave spectra of the molecular cloud and environ sources. The symbol meaning is the same as in Fig. 5. Upper limits are indicated by symbols with arrows.

The compact radio sources in the Trapezium can be modeled as partially ionized condensations created when neutral hydrogen is immersed in an ionizing medium that progressively consumes the neutral material (Dyson 1968). These objects are sometimes called partially ionized globules (PIGS). The density just behind the ionization front moving into the neutral gas is much larger than the density in the large-scale nebular medium. The resulting difference in pressure causes the ionized envelope to expand into the surrounding medium. For a spherical expansion, the density will be proportional to r^{-2}, and we can write

$$n_e(r) = n_0\left(\frac{r_0}{r}\right)^2 , \qquad (5)$$

where n_0 is the electron density at the ionization front, and r_0 is the radius of the ionization front (or radius of the neutral condensation). The volume emission measure is therefore

$$\mathrm{VEM} = \int_{r_0}^{\infty} n_e^2 dV = 4\pi n_0^2 r_0^3 . \qquad (6)$$

For an optically thin nebula, the radius of the ionizing front can be expressed in terms of a characteristic size, r_i, the observed radius (HWHM) of the ionized envelope, from the relation $\mathrm{EM}(r_i) = \mathrm{EM}(0)/2$, where EM(0) and $\mathrm{EM}(r_i)$ are the emission measures along the central ray and along the ray of projected distance r_i, respectively. For the electron density given in equation (5), we find $\mathrm{EM}(r_i) = (\pi/2)n_0^2 r_0^4/r_i^3$ and $\mathrm{EM}(0) = \frac{2}{3}n_0^2 r_0$. Thus,

$$r_0 = \left(\frac{2}{3\pi}\right)^{1/3} r_i . \qquad (7)$$

In Table 7 we give the observed and derived parameters for

TABLE 7

NEUTRAL CONDENSATION PARAMETERS

Source (1)	Observed θ_s (2)	r_i (10^{15} cm) (3)	S_{15GHz}[b] (mJy) (4)	VEM (10^{57} cm^{-3}) (5)	Derived[a] r_0 (10^{15} cm) (6)	n_0 (10^5 cm^{-3}) (7)	N_i (10^{44} s^{-1}) (8)	F(Hα) (10^{-11} ergs cm^{-2} s^{-1}) (9)
1	0″48	1.8	12.6 ± 2.8	1.21	1.1	2.9	3.1	1.4
2	0.39	1.5	5.0 ± 1.1	0.48	0.9	2.4	1.2	0.5
4	0.41	1.5	9.9 ± 3.8	0.95	0.9	3.3	2.5	1.1
5	0.40	1.5	28.9 ± 8.9	2.79	0.9	5.6	7.2	3.2
6	0.34	1.3	34.0 ± 5.6	3.28	0.8	7.5	8.5	3.7
7	0.32	1.2	15.5 ± 3.9	1.49	0.7	5.7	3.9	1.7
8	0.34	1.3	4.9 ± 1.4	0.47	0.8	2.8	1.2	0.5
9	0.66	2.5	17.5 ± 8.1	1.69	1.5	2.1	4.4	1.9
10	0.39	1.5	6.9 ± 1.0	0.67	0.9	2.8	1.7	0.8
11	0.32	1.2	13.6 ± 1.5	1.31	0.7	5.4	3.4	1.5
13	0.52	1.9	16.1 ± 0.5	1.55	1.1	2.9	4.0	1.8
14	0.50	1.9	11.6 ± 2.8	1.12	1.1	2.5	2.9	1.3

[a] We assume $T_e = 10^4$ K.

[b] Average value.

the Trapezium sources assuming they are neutral condensations of radius r_0 surrounded by an ionized gas shell of radius r_i. The volume emission measure is obtained from equation (2) with the observed radio flux density at 15 GHz and is given in column (5) of Table 7. The radii of each neutral condensation, r_0, is determined from the observed size of the ionized globule, r_i, by use of equation (7). The electron density at r_0 is then calculated from that radius and the volume emission measure, by use of equation (6).

Dyson (1968) modeled the structure and stability of neutral condensations immersed in an H II region and proposed the existence of these objects in the center of the Orion Nebula to explain the turbulence of the nebular medium. The parameters of the condensations predicted by Dyson's model for the center of the Orion Nebula are similar to the ones derived from the observations. Laques and Vidal (1979) also suggested the presence of externally ionized sources in the core of the Orion Nebula. In the vicinity of the Trapezium they found seven objects, all located within an angular distance of 10″ from Θ^1C, which they characterized as "nebular condensations" because they show emission in the Hα, Hβ, and [O III] λ5007 lines but no detectable emission in the continuum near λ6440. All seven condensations of Laques and Vidal can be identified with compact continuum radio sources detected in our study. Moreover, all of the compact radio sources (except the radio source coincident with the Trapezium star Θ^1A) within an angular distance of 10″ from Θ^1C may also be nebular condensations. The Hα flux density expected from the ionized envelope is

$$F(\mathrm{H}\alpha) = \frac{4\pi}{D^2}\int_{r0}^{\infty} j(\mathrm{H}\alpha) r^2 dr \,, \qquad (8)$$

where j(Hα), the emission coefficient of the Hα line (cf. Vidal 1976; Osterbrock 1974) for Menzel's case B, is given by

$$j(\mathrm{H}\alpha) = 1.35 \times 10^{-22} T_e^{-0.92} n_e^{2} \ (\mathrm{ergs\ cm^{-3}\ s^{-1}\ sr^{-1}}) \,. \quad (9)$$

Using the electron density dependence with radius given in equation (5), we can write the Hα flux density as

$$F(\mathrm{H}\alpha) = 1.35 \times 10^{-22} T_e^{-0.92} D^{-2} \mathrm{VEM} \ (\mathrm{ergs\ cm^{-2}\ s^{-1}}) \quad (10)$$

or

$$F(\mathrm{H}\alpha) = 1.1 \times 10^{-12} S(15\ \mathrm{GHz})\ (\mathrm{ergs\ cm^{-2}\ s^{-1}}) \,, \quad (11)$$

where S(15 GHz) is the flux density at 15 GHz in mJy. The predicted Hα flux densities from the partially ionized globules using equation (11) are given in column (9) of Table 7. For the six objects where Hα flux densities are available (Laques and Vidal 1979), the observed values of F(Hα) are about a factor of 30 larger than those predicted by equation (11), when extinction correction of 2.3 mag is made. However, except for the factor of 30, the observed values of F(Hα) and S(15 GHz) are well correlated. The excess values of F(Hα) may be due to a difference in excitation mechanism for the line from the standard formulation.

iii) *Evolutionary Model for the Trapezium Sources*

We suggest that most of the radio sources around Θ^1C are neutral and dense ($> 10^6$ cm^{-3}) condensations surrounded by externally ionized envelopes. Most of the ionizing photons are likely to be provided by Θ^1C, the most luminous member of the Trapezium star cluster. The formation of these dense and compact globules might be explained in the following sequence for the evolution of a massive molecular cloud. Due to a sudden increase in the external pressure (e.g., supernova explosion, galactic density waves, etc.), a dense, inhomogeneous molecular cloud, initially in hydrostatic equilibrium, is forced to contract and collapse. A collapsing cloud is likely to undergo several fragmentation stages with the most dense fragments giving birth to massive OB stars (cf. Bodenheimer 1978). These young and luminous stars will dominate the subsequent evolution of the parent molecular cloud. Their ultraviolet radiation will ionize the less dense molecular gas that surrounds them. This ionized gas will expand and stream away, creating a cavity around the newly formed stars. However, the most dense fragments of gas near the stars are not easily destroyed, and they will remain as neutral condensations with externally ionized envelopes for a considerable length of time.

The question that arises concerns the feasibility of the coexistence of neutral condensations and massive luminous OB stars within a radius of ~0.07 pc. The neutral condensations are not static but are continuously evolving since they undergo mass loss by ionization from their surfaces. Thus, if neutral condensations are present in the Trapezium neighborhood, then their lifetime must be greater than the age of the Trapezium stars. We can estimate the lifetime, τ, of the partially ionized globules as $\tau \approx M/\dot{M}$, where M is the mass of the neutral condensation and $\dot{M}$ is its mass-loss rate by ionization. The change of neutral mass per unit time must be equal to the rate at which gas is ionized at the ionization front, thus

$$\dot{M} = \pi r_0{}^2 J \mu_i \,, \tag{12}$$

where r_0 is the radius of the ionization boundary, μ_i is the mean mass of gas per atom ionized, and J is the flux of ultraviolet photons reaching the ionization front. Because of the large density ($\sim 10^6$ cm^{-3}) of the recombining gas that streams away from the condensation, J will be greatly reduced below J_0, the flux of ultraviolet photons per second from the star when it first reaches the cloud. Assuming that the ionized gas streams away with a velocity equal to the sound speed, $C_{\rm II}$ in the H II region (i.e., D critical front), it can be shown that (cf. Spitzer 1978, eq. [12-35])

$$J = 2J_0 \bigg/ \left[1 + \left(1 + \frac{4\alpha}{3} J_0 \frac{r_0}{C_{\rm II}{}^2}\right)^{1/2}\right], \tag{13}$$

where α is the total recombination coefficient. A typical value of r_0 for the neutral condensations is 1×10^{15} cm, and if this value is used in equation (13) with $\alpha = 4 \times 10^{-13}$ cm^3 s^{-1}, $C_{\rm II} = 10$ km s^{-1}, and $J_0 = 10^{14}$ cm^2 s^{-1} we find $J = 9 \times 10^{11}$ cm^2 s^{-1}. Inserting this value in equation (12), we find $\dot{M} \approx 10^{-7}$ $M_\odot$ yr^{-1}. Thus, neutral condensations with masses greater than 0.03 $M_\odot$ will have lifetimes $\gtrsim 3 \times 10^5$ yr, the estimated age of the Trapezium stars (Strand 1958; Vandervoort 1963).

A crude estimate of the mass of the neutral condensation can be made if we assume that it is in a state of (quasi)equilibrium with the surrounding medium. For an isothermal sphere in equilibrium with its surroundings, and neglecting magnetic fields, the virial theorem gives (cf. Spitzer 1978)

$$4\pi r_0{}^3 p_0 = 3\,\frac{MkT}{\mu} - \gamma\,\frac{GM^2}{r_0}\,, \tag{14}$$

where p_0 is the external pressure, M, r_0, and T are the mass, radius, and kinetic temperature of the neutral condensation, respectively; γ is a constant of order unity related to the gravitational energy of the condensation; and μ is the mean molecular weight. Assuming a condensation with temperature ~ 100 K, radius of 1×10^{15} cm, $\mu = 2.3 m_{\rm H}$, and an external pressure of 10^{-6} ergs cm^{-3} (i.e., $n_e \approx 4 \times 10^5$ cm^{-3}, $T_e \approx 10^4$ K), we find $M \approx 0.1$ $M_\odot$. The average density of the neutral gas is therefore 4×10^{10} cm^{-3}. Such a neutral condensation would have a lifetime for evaporation by ionization of $\sim 1 \times 10^6$ yr.

b) *Molecular Cloud and Environs*

i) *Molecular Cloud*

Sources A, B, and D appear projected onto hot molecular cores within the Orion molecular cloud that are most likely sites of current massive star formation. None of these radio sources has an optical counterpart; thus, they are likely to be deeply embedded in the molecular cloud and associated with young, recently formed stars.

Source A.—This radio source is at the center of one of eight strong ammonia peaks detected toward the OMC-1 and OMC-2 regions (Batrla *et al.* 1983). The ammonia spectrum toward this source (source 5 of Batrla *et al.*) shows two velocity components at 8 and 10 km s^{-1}, suggesting the presence of two clouds with kinetic temperatures, derived from several line intensity ratios, of 25 and 95 K, respectively.

The radio spectrum of source A is flat (spectral index of 0.1) between 5 and 15 GHz and is consistent with the radio emission being optically thin free-free radiation. We suggest that the radio emission from source A arises in a small ionized envelope surrounding a newly formed star embedded in one of the molecular clouds. If the source is an ionized sphere of uniform density at 10^4 K that is optically thin at 15 GHz, then the observed angular size of 0".19 and the measured flux density of 11 mJy imply a source radius of 1×10^{15} cm^{-3} and an electron density of 5×10^5 cm^{-3}. The Lyman-continuum photon rate, necessary to ionize the gas, is $\sim 3 \times 10^{44}$ s^{-1}, which can be supplied by a B2 ZAMS star. Since this source is optically invisible, it may be deeply embedded in the molecular cloud.

Recently formed stars are the most likely energy sources for the heating of the molecular gas that surrounds them. We suggest that source A is the energy source of, and thus is associated with, the hotter of the two cloud components of source 5 of Batrla *et al.* (1983). Further, $\sim 4''$ towards the west of the radio source lies the Herbig-Haro object M42–HH 1 that contains two distinct nuclei separated by 5" (Munch 1977). The [O I] λ6300 line toward one nuclei is blueshifted by 240 km s^{-1} with respect to the other. The large angular distance of these HH objects from previously known energy sources imposed serious problems in explaining their kinematics and energetics. Source A may be the energy source of this particular HH object.

Source B (the BN Object).—The position of this radio source is coincident within 0".3 with the infrared position of the Becklin-Neugebauer object (Downes *et al.* 1981). Radio measurements of BN were already presented elsewhere (Moran *et al.* 1983). The radio emission may arise from either a homogeneous H II region or a stellar wind provided the ionized flow recombines at a finite distance from the star. Our observations of BN on 1983 February 17 (see Table 3) give a spectral index of 1.4 ± 0.6 between 15 and 22 GHz, somewhat lower than, but statistically consistent with, the previous value of 2.3 ± 0.7. BN was not detected at 88 GHz to a limit of 70 mJy by both Moran *et al.* (1983) and Wright and Vogel (1985), which suggests that radio emission becomes optically thin at or near 30 GHz.

Source D.—Source D, located $\sim 12''$ east of BN, is not coincident with any of the strong infrared sources in the Orion-KL region. Nevertheless, it is within 1" of a weak local maximum in the 30 μm map of Wynn-Williams *et al.* (1984). The radio source was detected in 1981 August with a flux density of 7.5 mJy at 15 GHz; however, it was below our detection limits (see col. [10] of Table 1) at all the other epochs. This object could be a low-mass pre–main-sequence star, either a T Tauri or a red dwarf that is embedded in the cloud and going through its flare phase of evolution (see Kuipjers 1985 for a review of possible physical processes involved).

ii) *Environs*

Under this heading we group sources C, E, F, and G that are neither in the immediate vicinity of the core of OMC-1 nor in the neighborhood of the Trapezium stars. Their spectra are shown in Figure 6.

Sources C and E.—Sources C and E are at projected distances from Θ^1C of 41" and 35", respectively. The radio spectrum of source C suggests that the radio emission is due to free-free radiation that becomes optically thin at $\sim$4 GHz. If the radio emission arises in a spherical, uniform density H II region at 10^4 K, then a fit to the observed radio spectrum implies a source radius of 2×10^{15} cm and an electron density of 2×10^5 cm^{-3}. The Lyman-continuum photon rate needed to ionize the gas is 4×10^{44} s^{-1}.

Object E is one of the weak radio emitters among our sources and at some epochs its radio flux density was below the detection limits. Nevertheless, the observed radio spectrum (detections and upper limits) is consistent with being flat above 5 GHz and is thus indicative of thermal emission. A model of the radio spectrum as free-free emission from a compact spherical H II region of uniform density at 10^4 K gives a radius of 2×10^{15} cm and an electron density of 9×10^4 cm^{-3}. The Lyman-continuum flux necessary to excite the gas is 2×10^{44} s^{-1}. The Lyman-continuum photon rate required to excite sources C and E can be supplied by B2 ZAMS stars. However, both of these sources are associated only with optically faint objects that are unlikely to be luminous B2 stars embedded in the molecular cloud since they are not seen in the infrared. Alternatively, it is possible that these are neutral condensation surrounded by an externally ionized envelope. Although the number of Lyman-continuum photons intercepted by sources C and E from Θ^1C is about three and two times smaller than the number needed to excite the respective radio sources, the model may be viable if we relax the requirement of spherical symmetry.

Sources F and G.—The radio sources F and G are associated with the Parenago stars π1925 ($V = 14.1$) and π1910 ($V = 12.1$), respectively. π1910 is known to be a variable star designated as MT Orionis. Both F and G are also associated with near infrared sources brighter than 11.8 mag at 2.2μ (Lonsdale *et al.* 1982). Thus, these objects have a large excess of infrared emission. Further, they are associated with X-ray sources detected in the Orion cloud with the *Einstein X-Ray Observatory* (Ku, Righini-Cohen, and Simon 1982). MT Ori, one of the brightest X-ray sources in the Orion Nebula, shows significant X-ray intensity variations on a time scale of a few thousand seconds. The X-ray emission, infrared excess and optical variability associated with sources F and G suggests that they are pre–main-sequence or T Tauri stars.

The radio emission from the compact sources F and G undergoes large flux density variations on time scales of months or shorter (see Fig. 6). The radio emission from T Tauri stars is usually attributed to free-free emission arising in an extended stellar wind envelope (Felli *et al.* 1982). However, for sources F and G, the stellar wind interpretation encounters several difficulties:

1. Their large observed flux densities, $\sim$25 mJy at 15 GHz, requires an ionizing source supplying a Lyman-continuum photon rate of $\sim 5 \times 10^{47}$ s^{-1}. This corresponds to that of an O9.5 star, a very luminous star that would be very much brighter than observed.

2. Their variability time scales, smaller than months, are far shorter than the expected time scale of variation in stellar winds of years or greater.

Fifty percent of the X-ray sources in the central Orion region are identified with nebular variables or pre–main-sequence stars (Ku *et al.*) Furthermore, observations of pre–main-sequence stars in the ρ Ophiuchi region show that X-rays are usually detected only during flares (Montmerle *et al.* 1983). The radio and X-ray variability of sources F and G suggests nonthermal processes giving rise to flares near the stellar surface.

The peak observed luminosity of sources F and G at 5 GHz of $\sim 7 \times 10^{18}$ ergs s^{-1} Hz^{-1} is $\sim 10^6$ times greater than that produced by the strongest solar flares. Highly energetic solar flares ($\sim 5 \times 10^{12}$ ergs s^{-1} Hz^{-1}) are rare, associated with proton production and are confined to small regions on the Sun (Shimabukuro 1978). Thus, even under the assumption that activity takes place over the entire stellar surface, the radio emission from sources F and G cannot be explained as due to nonthermal emission from strong solarlike flare events (cf. Felli *et al.* 1982). On the other hand, they are similar to the peak luminosity seen in major radio flares in RS CVn stars at 10 GHz of $\sim 2 \times 10^{18}$ ergs s^{-1} Hz^{-1} (Feldman 1983). This suggests that the radio emission from objects F and G may arise in processes similar to those occurring in RS CVn or dMe stars.

Recently Feigelson and Montmerle (1985), during a radio survey of the ρ Ophiuchi star-forming cloud, found a pre–main-sequence star (DoAr 21) with similar radio characteristics to those of sources F and G. It shows rapid radio variability, a steeply inverted spectral index ($S \propto \nu^{1.2}$ between 1.4 and 4.9 GHz) during maximum emission, and a peak luminosity of $\sim 2 \times 10^{18}$ ergs s^{-1} Hz^{-1} at 4.9 GHz. They suggest that the radio emission is synchrotron emission arising from energetic (MeV) electrons in large ($\sim 10^{12}$ cm) magnetic loops. Sources F and G may join DoAr 21 in a new class of low-mass pre–main-sequence stars with extremely high levels of magnetically induced surface activity.

V. SUMMARY AND CONCLUSIONS

Our main observational results and conclusions are summarized as follows.

a) Trapezium Sources

We detected 14 compact radio sources in the vinicity of the Trapezium stars. Typically, the angular sizes are $\sim$0".4, and the brightness temperatures are less than 10^4 K. These results suggest that the radio emission is produced by bremsstrahlung in an ionized gas. All the radio sources are coincident with optically identifiable objects. Six sources correspond to Parenago's stars (Parenago 1954). Seven of the compact radio sources coincide with emission line objects of Laques and Vidal (1979). The remaining radio objects have been identified in optical plates taken by Herbig with the 120 inch reflector of the Lick Observatory.

The radio spectra (1.4–22.4 GHz) of most (12) of the Trapezium sources can be modeled as compact, uniform-density H II regions that become optically thin between 5 and 15 GHz. The Lyman-continuum photon flux necessary to ionize each H II region is $\sim 4 \times 10^{44}$ s^{-1}, which could be supplied by B2 V stars. However, the presence of such stars is doubtful, owing to (1) the weakness of the optical continuum associated with the radio sources; (2) the absence of strong near-infrared emission, which argues against their being embedded in the cloud; and (3) identification at optical wavelengths, which suggests that these objects are not deeply buried in the molecular cloud where they might be missed by near-infrared observations.

These sources are likely to be neutral condensations surrounded by externally ionized envelopes. The source of the ionization is probably Θ^1 Orionis C, an O7 star in the Trapezium. If the electron density in the ionized envelopes surrounding the neutral condensations has the form $n_e \propto r^{-2}$

where r is the radius, then the neutral condensation radius and electron density just beyond that radius have typical values of 1×10^{15} cm and 4×10^5 cm^{-3}, respectively.

One Trapezium source is associated with Θ^1 Orionis A, the western member of the Trapezium. Its radio emission shows dramatic flux density variations on a time scale of months but none on a time scale of hours. Its radio spectrum was flat in all observed epochs.

b) *Molecular Clouds and Environs*

Seven radio sources were detected in the Orion Nebula outside the Trapezium region. Four are coincident with optical objects and are within 60″ from Θ^1C. Of these sources, two are associated with X-ray objects and exhibit large radio frequency flux density variations. The radio and X-ray emission could arise close to the stellar surface in very energetic flare events associated with low-mass pre–main-sequence activity. The other two sources are possibly neutral globules surrounded by externally ionized envelopes.

The three radio sources that are not identifiable with optical objects are projected onto hot molecular peaks in the Orion cloud. Source A is associated with a hot ammonia peak, while sources B and D are in the immediate vicinity of the Orion-KL region. Source B is coincident with the BN object, but source D is not associated with any of the infrared objects in the Orion-KL region. The radio emission from sources A and B could be excited by an early B-type star and arise from a uniform density H II region or an ionized stellar wind with a finite recombination radius. The radio emission from source D was detected in only one of the four observing epochs. We also detected radio emission from IRc2, at a level below that of the general survey.

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REFERENCES

Baldwin, M., and Mattei, J. 1977, *J. R. A. S. Canada*, **71**, 475.
Batrla, W., Wilson, T. L., Bastien, P., and Ruf, K. 1983, *Astr. Ap.*, **128**, 279.
Becklin, E. E., Beckwith, S., Gatley, I., Matthews, K., Neugebauer, G., Sarazin, C., and Werner, M. W. 1976, *Ap. J.*, **207**, 770.
Bodenheimer, P. 1978, *Ap. J.*, **224**, 488.
Conti, P. S., and Alschuler, W. R. 1971, *Ap. J.*, **170**, 325.
Downes, D., Genzel, R., Becklin, E. E., and Wynn-Williams, C. G. 1981, *Ap. J.*, **244**, 869.
Dyson, J. E. 1968, *Ap. Space Sci.*, **1**, 388.
Feigelson, E. D., and Montmerle, T. 1985, *Ap. J. (Letters)*, **289**, L19.
Feldman, P. A. 1983, *in IAU Colloquium 71, Activity in Red-Dwarf Stars*, ed. P. B. Byrne and M. Rodono (Dordrecht: Reidel), p. 429.
Felli, M., Gahm, G. F., Harten, R. H., Liseau, R., and Panagia, N. 1982, *Astr. Ap.*, **107**, 354.
Field, G. 1982, *in Symposium on the Orion Nebula to Honor Henry Draper*, ed. A. E. Glassgold *et al.* (New York: New York Academy of Science), p. 290.
Garay, G., Moran, J. M., and Reid, M. J. 1985, in *Radio Stars*, ed. R. M. Hjellming and D. M. Gibson (Dordrecht: Reidel), p. 131.
Hayashi, M., Hasegawa, T., Gatley, I., Garden, R., and Kaifu, N. 1985, *M.N.R.A.S.*, **215**, 31P.
Herbig, G. H. 1982, *in Symposium on the Orion Nebula to Honor Henry Draper*, ed. A. E. Glassgold *et al.* (New York: New York Academy of Science), p. 64 (H).
Herbig, G. H., and Terndrup, D. M. 1986, *Ap. J.*, **307**, 609.
Hjellming, R. M. 1979, An Introduction to the Very Large Array, NRAO Internal Report, Charlottesville, Va.
Johnson, H. L. 1965, *Ap. J.*, **141**, 923.
Ku, W. H. M., Righini-Cohen, G., and Simon, M. 1982, *Science*, **215**, 61 (KRS).
Kuipjers, J. 1985, *in Radio Stars*, ed. R. M. Hjellming and D. M. Gibson (Dordrecht: Reidel), p. 3.
Lacques, P., and Vidal, J. L. 1979, *Astr. Ap.*, **73**, 97 (LV).
Lester, D. F., Becklin, E. E., Genzel, R., and Wynn-Williams, C. G. 1985, *A.J.*, **90**, 2331.
Lockman, F. J., and Brown, R. L. 1975, *Ap. J.*, **201**, 134.
Lonsdale, C. J., Becklin, E. E., Lee, T. J., and Stewart, J. M. 1982, *A.J.*, **87**, 1819.
Mezger, P. G., and Henderson, A. P. 1967, *Ap. J.*, **147**, 417.
Montmerle, T., Koch-Miramond, L., Falgarone, E., and Grindlay, J. 1983, *Ap. J.*, **269**, 182.
Moran, J. M. 1983, *Rev. Mexicana Astr. Ap.*, **7**, 95.
Moran, J. M., Garay, G., Reid, M. J., and Genzel, R. 1983, *Bull. A.A.S.*, **15**, 989.
———. 1986, in preparation.
Moran, J. M., Garay, G., Reid, M. J., Genzel, R., and Ho, P. T. P. 1982, *Ann. N.Y. Acad. Sci.*, **395**, 204.
Moran, J. M., Garay, G., Reid, M. J., Genzel, R., Wright, M., and Plambeck, R. 1983, *Ap. J. (Letters)*, **271**, L31.
Munch, G. 1977, *Ap. J. (Letters)*, **212**, L77.
Osterbrock, D. C. 1974, *Astrophysics of Gaseous Nebulae* (New York: Freeman), p. 69.
Panagia, N. 1973, *A.J.*, **78**, 929.
Pankonin, V., Walmsley, C. M., and Harwit, M. 1979, *Astr. Ap.*, **75**, 34.
Parenago, P. P. 1954, *Trudy Shternberg Astr. Inst.*, **25**, 1.
Penston, M. V. 1973, *Ap. J.*, **183**, 505.
Perley, R. A. 1982, *A.J.*, **87**, 859.
Shimabukuro, F. I. 1978, in *The Solar Output and its Variation*, ed. O. R. White (Boulder: Colorado Associated University Press), p. 133.
Spitzer, L. 1978, *Physical Processes in the Interstellar Medium* (New York: John Wiley and Sons).
Strand, K. A. 1958, *Ap. J.*, **128**, 14.
Vandervoort, P. O. 1963, *Ap. J.*, **138**, 294.
Vidal, J. L. 1976, *Astr. Ap.*, **48**, 55.
———. 1982, in *Symposium on the Orion Nebula to Honor Henry Draper*, ed. A. E. Glassgold *et al.* (New York: New York Academy of Science), p. 176.
Werner, M. W., Becklin, E. E., and Neugebauer, G. 1977, *Science*, **197**, 723.
Wright, M. C. H., and Vogel, S. N. 1985, *Ap. J. (Letters)*, **297**, L11.
Wynn-Williams, C. G., Genzel, R., Becklin, E. E., and Downes, D. 1984, *Ap. J.*, **281**, 172.

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