The Trapezium Radio Cluster of the Orion Nebula

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ABSTRACT. We review the characteristics and discuss the nature of a dense group of compact radio sources found projected toward the Trapezium cluster of the Orion nebula. There are twenty-six radio sources, with flux densities greater than 2 mJy, clustered within a region of 35" radius around Θ^1C Orionis, the most luminous star of the Trapezium. The density of radio objects, of 1.4×10^4 pc^{-3}, is extraordinarily high, about a thousand times greater than the density of stars in typical galactic clusters.

Most sources show flat, or slowly rising, spectra between 5 and 15 GHz, brightness temperatures smaller than 10^4 K, and flux densities that are constant on time scales of days to a few months. These characteristics suggest that the radio emission is free-free radiation from an HII region. The ionization must be external however, most likely produced by the UV radiation from Θ^1C. Possible models for these objects are: (1) neutral condensations surrounded by ionized envelopes; and (2) low mass stars surrounded by evaporating protostellar neutral accretion disks. The ionized gas flowing out from either the globules or the stellar disks and expanding into the surrounding medium is likely to produce the turbulence observed in the central region of the Orion nebula.

I. INTRODUCTION

The term "Trapezium radio cluster" is used here to refer to a dense group of compact radio sources, first discovered by Moran et al. (1982), found projected toward the Trapezium stars Θ^1 Orionis. From several VLA observations, made at different frequencies, spatial resolutions and sensitivities (Garay, Moran, and Reid 1987; Churchwell, Felli, Wood, and Massi 1987; Garay 1987), a total of 26 compact radio sources with flux densities greater than 2 mJy have been detected in a region of ~ 35" radius centered near Θ^1C, the brightest Trapezium star. A map of the radio sources at 5 GHz is shown in Figure 1. Assuming that the three-dimensional region is a sphere, with a radius of 0.076 pc (35" at 450 pc), the density of compact radio sources is ~ 1.4×10^4 pc^{-3}. This density is extraordinarily high, about seven times higher than the density of Trapezium stars brighter than $M(I_c)$ = 6.0 (Herbig and Terndrup 1986) and about a thousand times greater than the density of stars in Galactic clusters.

All but one of the Trapezium radio sources have optical and near infrared counterparts. Twenty are clearly appreciated in a multifrequency (1.6, 2.2, and 3.8 μ) near infrared image of the central region of the Orion nebula (Allen et al. 1984); eighteen are seen in short exposure plates taken in deep red (0.7-0.9 nm) light (Herbig 1982); and seven are associated with optically visible 'nebular condensations' observed by Laques and Vidal (1979) and Vidal (1982) (see Table 2 of Garay 1987, for a summary).

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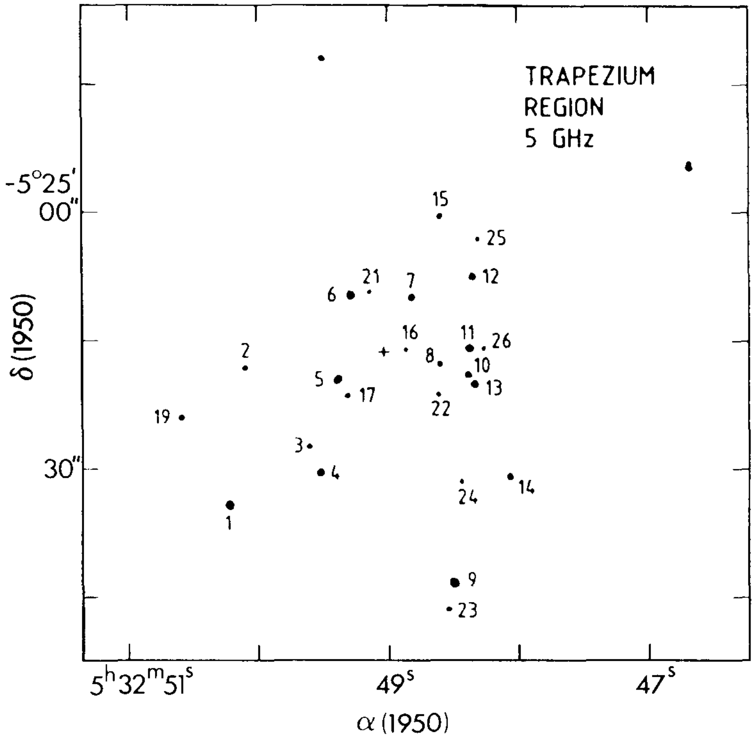

Figure 1. Map of the Trapezium compact radio sources at 5 GHz. The cross indicates the position of the Trapezium star Θ^1C.

Table 1. Observational parameters

Date 1985	Config.	Frequency (GHz)	Bandwidth (MHz)	HPBW (")	rms noise (mJy/beam)
Jan 18....	A	4.86	100.	0.43x0.37	0.45
Jan 19....	A	4.86	100.	0.44x0.37	0.27
		14.94	100.	0.13x0.12	0.20
Feb 2....	A	4.86	100.	0.44x0.39	0.61
		14.94	100.	0.31x0.23	0.47
Feb 16....	A	4.86	100.	0.44x0.39	0.42
		14.94	100.	0.15x0.15	0.30
Mar 1....	A	4.86	100.	0.52x0.50	0.51
		14.94	100.	0.20x0.15	0.26
Mar 6....	A	4.86	100.	0.42x0.36	0.29
		14.94	100.	0.15x0.12	0.22
Mar 8....	A	4.86	100.	0.40x0.35	0.31
		14.94	100.	0.13x0.12	0.21
Mar 15....	A	4.86	100.	0.57x0.49	0.59
		14.94	100.	0.15x0.12	0.37

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II. CHARACTERISTICS OF THE RADIO EMISSION

From the data of GMR (Tables 2 and 3) and CFWM (Table 2) it appears that several of the compact radio sources show variability in their flux density on time scales of a year. It is not clear if these variations, which are typically of 40% about the mean, are intrinsic to the sources or extrinsic, such as for instance due to calibration errors, the use of different array configurations (hence different angular resolutions and sensitivities to extended structure) and/or the use of different image processing.

We report here observations that were designed to look for variability in the flux density of the Trapezium compact radio sources on time scales ranging from days to a few months. The data were obtained with the VLA of the NRAO[1] during the first quarter of 1985, a period in which the array was in the A configuration. Table 1 gives the observing dates and instrumental parameters.

In order to study variability, and to take into account the slight difference in the size of the synthesized beams between the different epochs, we decided to compare brightness temperatures. Assuming that the brightness temperature, T_b, is uniform over the synthesized gaussian beam, then $T_b = 1.22\times10^3\ \nu^{-2}\ \Theta_b^{-2}\ S_\nu$, where ν is the frequency in GHz, Θ_b is the HPBW in arcsec, and S_ν is the observed peak flux density per beam in mJy. The derived brightness temperature at 6 cm of the sixteen strongest radio sources within the Trapezium radio cluster are given in Table 2. Most of these sources appear to be constant (1σ rms variations about the mean < 20%). Source No. 12 is clearly variable, while sources 1, 9, and 14 are probably variable. Among the weaker sources, Nos 22, 23, and 25 are probably variable. We will assume that the rest of the Trapezium radio sources are constant. The variability observed on time scales of years will be assumed, until demonstrated otherwise, as due to extrinsic reasons.

The observational parameters of the Trapezium radio sources are listed in Table 3. The data used to derive these parameters were obtained by combining, in the (u,v)-plane, all data from the individual observations. The deconvolved angular diameters of the sources, given in columns 6 and 7, are typically between 0"1 and 0"4. The sizes derived from the observations at 5 and 15 GHz are in good agreement, in spite of the fact that the synthesized beam at 5 GHz (0"39) is about three times larger than that at 15 GHz (0"12). There is a significant difference between the deconvolved angular diameters at 15 GHz given here and those reported by CFWM, even though they were derived from observations with similar angular resolutions. Several of the sources not resolved by CFWM appear extended to us. The peak brightness temperatures observed by us are consistent with the sources being resolved.

The spectra, between 5 and 15 GHz, of most of the Trapezium radio sources are either flat or rising toward the higher frequency. In addition, their brightness temperatures are smaller than 10^4 K (mean average of 2000

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Table 2. 6 cm brightness temperature ($\times 10^3$ K)

Date 1985	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	19
Jan 18	2.4	1.1	1.3	2.1	2.4	3.6	1.8	1.3	1.9	1.3	2.2	2.9	1.7	1.0	0.9	1.3
Jan 19	1.8	1.2	1.2	2.0	2.4	3.6	2.0	1.3	1.7	1.3	2.2	6.7	2.1	1.2	1.1	1.1
Feb 2	0.9	1.4	1.3	2.1	2.1	4.4	1.7	---	---	---	2.5	4.6	1.3	---	---	1.5
Feb 16	1.7	1.3	1.0	2.0	2.6	3.4	2.4	1.3	1.7	1.2	2.1	4.4	2.3	1.1	1.4	1.2
Mar 1	1.6	1.3	0.8	1.9	2.4	3.1	2.3	1.0	2.5	1.3	2.4	4.6	1.8	2.2	1.5	1.2
Mar 6	1.7	1.1	1.1	1.9	2.6	3.7	2.0	1.0	1.5	1.4	2.4	2.7	2.0	1.3	1.1	1.2
Mar 8	1.7	1.3	1.1	1.9	2.5	3.5	2.1	1.3	1.9	1.4	2.5	6.0	1.8	1.3	1.2	1.1
Mar 15	1.9	---	1.0	2.1	2.8	3.4	1.2	0.8	2.5	1.5	2.0	2.5	2.2	1.4	1.2	0.9

Table 3. Trapezium radio cluster

Source	Coordinates(1950)		Flux density (mJy)		Deconvolved size[c] (")	
	R.A.	Dec.	5 GHz	15 GHz	5 GHz	15 GHz
	$5^h\ 32^m$	$-5°\ 25'$				
1	$50^s.21$	34".1	12.9	7.7	0.48	0.36
2	50.10	18.2	3.8	4.8	0.16	0.16
3	49.61	27.3	4.4	4.8	0.20	0.15
4	49.52	30.3	9.9	9.0	0.34	0.30
5	49.39	19.6	12.0	15.0	0.30	0.16
6	49.29	9.8	16.6	26.3	0.30	0.21
7	48.82	10.0	8.1	10.6	0.21	0.13
8	48.60	17.7	4.0	6.3	0.14	0.10
9	48.49	43.1	14.8	10.8	0.56	---
10	48.39	18.9	6.2	5.4	0.31	0.36
11	48.37	15.9	10.5	11.8	0.31	0.15
12	48.35	7.5	---a	---a	u	u
13	48.33	20.0	9.1	10.0	0.31	0.33
14	48.06	30.9	6.7	5.0	0.40	0.36
15	48.60	0.5	4.1	3.6	0.18	0.15
16	48.87	16.0	2.1	4.0	u	u
17	49.31	21.3	3.6	4.4	0.20	u
19	50.58	24.0	5.3	4.7	0.30	0.27
20	49.38	19.3	---b	4.4	---	0.12
21	49.15	9.4	1.4	2.0	u	u
22	48.61	21.2	2.3	---	0.23	---
23	48.54	46.4	4.0	---	0.41	---
24	48.44	31.4	1.4	4.4	u	0.18
25	48.30	3.3	1.4	1.4	u	u
26	48.27	15.9	1.8	2.6	u	0.13

[a] variable flux density; [b] blended with source No. 5; [c] u means unresolved (HPBW of 0."39 and 0."12 at 5 and 15 GHz, respectively)

and 300 K, at 5 and 15 GHz, respectively). These characteristics suggest that the radio emission is free-free radiation arising from a compact HII region.

The number of Lyman continuum photons needed to ionize each source is $\sim 4\times10^{44}$ s^{-1}, which could be supplied by B2 ZAMS stars. However, the presence of such stars is doubtful, owing to: (1) the weakness of the optical continuum associated with the radio sources; and (2) the absence of strong near-infrared emission, which argues against their being embedded in the cloud.

III. NATURE OF THE COMPACT RADIO SOURCES

Because of its proximity, at a distance of 450 pc, the Orion region has become the prototype of a star forming site in our Galaxy. The discovery of the compact radio sources embedded in the Orion nebula should add new information for studying the process of star formation; therefore to establish their nature should be of considerable interest. Since the high density of radio sources is found only in the vicinity of Θ^1C (no similar cluster was found within a 9'×9' region of the Orion nebula), the existence of the Trapezium radio cluster must be intimately related to the presence of such a luminous star. We suggest that the radio emission from most of the Trapezium radio sources is thermal bremsstrahlung from ionized gas that is externally excited by the UV radiation from Θ^1C. The Trapezium radio cluster represents, thus, an aspect of the early interaction of a young, luminous star with its surroundings.

The Trapezium compact radio sources can be modeled as neutral condensations surrounded by ionized envelopes (GMR). If the temperature of the ionized envelope is 10^4 K and if its electron density decreases as the square of the distance from the core center, then a typical neutral condensation has a radius of 7×10^{14} cm and an electron density just beyond that radius of 5×10^5 cm^{-3}. The mass loss rate by ionization is $\sim 10^{-7}$ $M_\odot$/yr. In order to have lifetimes greater than the age of the cluster, the initial mass of the globules would have to be > 0.02 $M_\odot$. A detailed discussion of the structure and stability of neutral globules immersed in an ionized medium has been given by Dyson (1968).

Some of the Trapezium radio sources are associated with optical objects with apparent visual magnitude of ~ 15 mag (see GMR, Table 4). If the optical luminosity is due to the presence of an optically visible low mass star, as suggested by CFWM, the neutral condensation model encounters problems since the star should be obscured by the globule. CFWM proposed that these radio sources might correspond to evaporating protostellar accretion disks surrounding low mass stars. The physical properties derived from the observations, such as density, total mass and mass loss rate of the ionized gas, are about the same for the protostellar disk and neutral condensation models.

Not all the Trapezium radio sources are likely to be globules or disks, however. The radio emission from source No. 12, which is associated with the binary system Θ^1 Ori A, shows strong variability on a time scale of days, suggesting that the radiation arises in flare events. The non-thermal origin of this emission was conclusively established by Felli et al. (1989), who derived a brightness temperature > 4×10^7 K and suggested that the emission probably arises from the T Tauri component of the binary system. Source No. 25 is associated with the star θ^1 Ori E which is a strong and variable source of X-ray emission, hence its unresolved and probably variable radio emission could well be attributed to non-thermal emission. Sources 9 and 23 are associated with young pre-main sequence stars which show variable optical and X-ray emission. A pure non-thermal interpretation for the origin of their radio emission is problematic however, since both radio sources appear to be extended. A possible interpretation might be that the radio emission arises from both a central T Tauri star and a surrounding accretion disk.

Several observations toward the Orion nebula have shown the presence of large turbulent motions (Münch 1958; Wilson et al. 1959; Castañeda and O'Dell 1987). Castañeda and O'Dell (1987) concluded that the input scale of the turbulence is smaller than ~ 0.3 pc and is probably introduced at several sizes. Since the decay of supersonic turbulence is rapid, energy sources are needed to maintain it. Wilson et al. (1959) suggested that the eddies containing energy are secondary ionization fronts arising from the non-uniform growth of the HII zone into the surrounding molecular cloud.

The globules and stellar disks, which act as sources of ionized gas flowing out into, and stirring up, the surrounding nebula, are natural sources of turbulence. We thus propose that the Trapezium compact radio sources are a major source of turbulence within the Trapezium region. It was Dyson (1968) who first proposed, based on theoretical work, that partially ionized globules were the source of turbulence in the central region of the Orion nebula. The parameters of the (smaller) condensations predicted by him are in good agreement with the ones derived from the observations.

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REFERENCES

Allen, D., Bailey, J., and Hyland, A.R. 1984, Sky Teles., **67**, 222.
Castañeda, H.O., and O'Dell, C.R. 1987, Ap. J. (Letters), **315**, L55.
Churchwell, E., Felli, M., Wood, D.O.S., and Massi, M. 1987, Ap. J., **321**, 516.
Dyson, J.E. 1968, Ap. Space Sci, **1**, 388.
Felli, M., Massi, M., and Churchwell, E. 1989, Astr. Ap., in press.
Garay, G. 1987, Rev. Mex. Astron. Astrof., **14**, 489.
Garay, G., Moran, J.M., and Reid, M.J. 1987, Ap. J., **314**, 535.
Herbig, G.H. 1982, Symposium on the Orion Nebula to Honor Henry Draper, eds. A.E. Glassgold et al. (New York: New York Academy of Science), p.64.
Herbig, G.H., and Terndrup, D.M. 1986, Ap. J., **307**, 609.
Lacques, P., and Vidal, J.L. 1979, Astr. Ap., **73**, 97.
Moran, J.M., Garay, G., Reid, M.J., Genzel, R., and Ho, P.T.P. 1982, Symposium on the Orion Nebula to Honor Henry Draper, eds. A.E. Glassgold et al. (New York: New York Academy of Science), p.204.
Münch, G. 1958, Rev. Mod. Phys., **30**, 1035.
Vidal, J.L. 1982, Symposium on the Orion Nebula to Honor Henry Draper, eds. A.E. Glassgold et al. (New York: New York Academy of Science), p.176.
Wilson, O.C., Münch, G., Flather, E.M., and Coffeen, M.F. 1959, Ap. J. Suppl., **4**, 199.