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THE ORION RADIO ZOO: PIGS, DEERS AND FOXES

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ABSTRACT. Recent VLA radio observations of a $\sim 3' \times 3'$ region of the Orion Nebula, centered near the core of the KL nebula, revealing the presence of thirty-five ultracompact radio sources are discussed. Twenty-five of the radio sources are clustered near Θ^1C Orionis, the most luminous star of the Trapezium cluster, and have optical counterparts. Most of these objects are probably neutral condensations surrounded by ionized envelopes that are excited by Θ^1C. The partially ionized globules (PIGS) have (FWHP) sizes of $\sim 2 \times 10^{15}$ cm and if their electron densities have the form $n_e \propto r^{-2}$, then a typical neutral condensation radius is $\sim 6 \times 10^{14}$ cm and the electron density just beyond that radius is $\sim 10^6$ cm^{-3}. Four radio sources, the DEERS, are projected toward the dense core of the Orion molecular cloud and are invisible optically. Two of these are coincident with luminous infrared objects in the Orion-KL region. The DEERS are thus likely to be embedded in the molecular cloud and associated with young, recently formed luminous stars. Hence their acronym as Deeply Embedded Energetic Radio Sources. Three radio sources, the FOXES, are near the dark bay that indents the Orion Nebula. The FOXES exhibit variability in their radio emission and are associated with variable X-ray and optical objects. Hence their acronym as Fluctuating Optical and X-ray Emitting Sources. They probably are pre-main sequence (T Tauri) stars. A suggestion for the sequential formation of the Orion radio zoo species is made, as is for the triggering mechanism.

Key words: INFRARED-SOURCES — NEBULAE-ORION — RADIO SOURCES-IDENTIFICATION

I. INTRODUCTION

The Orion Nebula is a fascinating region of ionized gas, ~1 pc in size, containing a vast number of stars, many of them hiding in the brilliant nebular background in conventional photographs, but most impressively seen in near infrared photographs (cf. Herbig 1982). At the center of the nebula lies Θ^1 Orionis, a group of luminous massive early type stars, The Trapezium stars. Surrounding them, distributed over a region of ~0.5 pc in diameter, there is wealth of lower mass stars, the Trapezium cluster. It has an unusually high space density of ~560 pc^{-3}, two orders of magnitude larger than that of a galactic cluster (Herbig 1982).

Molecular radio observations towards the Orion region reveal the existence of two giant molecular clouds having masses of ~10^5 $M_\odot$ (Kutner et al. 1977). One of them, known as the Orion Molecular Cloud 1 (OMC-1), is associated with the Orion Nebula and extends by ~10° across the sky. The denser (>10^6 cm^{-3}) and hotter ($T_K \sim 100$K) region of this cloud, the OMC-1 core, is centered ~1' northwest of the Trapezium stars. Infrared observations of the core region show that it consists of several peaks surrounded by extended emission (Downes et al. 1981; Wynn-Williams et al. 1984). In addition, interferometric molecular line observations toward the OMC-1 region reveal a "hot core" component of ~15" in size (Genzel et al. 1982; Pauls et al. 1983) and a high-velocity gas component extending over ~30" (Wright et al. 1983; Masson et al. 1984).

Several papers discussing the Orion Nebula, and covering a wide range of wavelengths - from X-ray through UV, optical, infrared to radio - were recently published in the proceedings of a symposium on The Orion Nebula to honor Henry Draper. These contributions, nicely summarized by Field (1982), have significantly increased our present understanding of the Orion Nebula. A generally accepted interpretation of the morphology of the Orion Nebula is that it corresponds to a bubble of ionized gas being eroded in the molecular cloud by the ultraviolet radiation and stellar winds from the luminous Trapezium stars. Further, the ionization front has already overtaken the front edge of the molecular cloud producing a blister on its face, i.e. the sudden evacuation of the ionized gas inside the molecular cloud (cf. Pankonin et al. 1979). The cavity in the molecular cloud created around the luminous stars can be easily appreciated in Malin's skillfully processed color photographs of the Orion Nebula (Malin 1981). It is suggested that the Trapezium cluster represents a sample of the stellar content of the OMC-1 that has been suddenly revealed to us as a result of gas and dust being swept out of the cavity around the Trapezium stars (Herbig 1982).

On the other hand, a common interpretation of the OMC-1 core morphology is that it corresponds to a cluster of protostellar objects, with each infrared peak containing a young, massive star thus having luminosity of their own. However, the infrared peaks may just be high density condensations heated by an external energy source. The "hot core" molecular emission is thought to originate in an expanding disk of gas centered near the infrared source IRc2 (Plambeck et al. 1982). In addition, the high velocity gas is believed to arise from an outflow driven by IRc2. The nature and driving mechanism of the gas outflow are not yet understood.

Large turbulent velocities are observed in the central region of the Orion Nebula (Münch 1958). Since the decay of supersonic turbulence is rapid, an energy source is needed to maintain the turbulence. Dyson (1968) proposed that the source of the turbulence are dense, neutral condensations enclosed by externally ionized envelopes, stirring up the nebular gas around them. The envelope ionization is thought to be produced by the ultraviolet radiation from the massive, luminous OB stars located in the central region. In addition, the ionization-shock front surrounding these neutral cloud clumps can trigger their implosion that may eventually form low mass stars (Sandford et al. 1982). Thus, the effects of the turn-on of a large output of ionizing radiation, from the luminous Trapezium stars, on the surrounding medium might be of crucial relevance in understanding the present characteristics of the Orion Nebula.

To probe the stellar content of the core of the Orion molecular cloud we must resort to radio observations. Radio waves are not absorbed by the dust in the molecular cloud and thus can be used to unravel the self-luminous infrared objects and to reveal new objects deeply hidden in the molecular cloud and opaque at infrared wavelengths. In addition, to explore the Orion Nebula center, seeking to understand its evolutionary state and the processes occurring in early stages of star formation, we undertook VLA radio interferometric observations which provide large angular resolution, high sensitivities, and are not affected by the strong extended emission.

II. THE ORION RADIO ZOO

In this talk I will deal mostly with radio wavelengths and discuss recent high angular resolution VLA observations of the central region of the Orion Nebula. Garay, Moran and Reid (1987), hereafter GMR, reported the detection of twenty-one compact radio sources, with flux densities greater than 4 mJy per beam area, in a 3'×3' region of the Orion Nebula centered near the Kleinmann-Low nebula. These observations were confirmed by Churchwell, Felli, Wood and Massi (1987), hereafter CFWM, who mapped the central 90"×90" of the Orion Nebula at 2 cm with an rms of ~0.15 mJy per beam area. In addition, they detected six other compact radio sources with flux densities smaller than 4 mJy. The results reported here come from new observations, at 5 and 15 GHz, of the central region of the Orion Nebula that are an order of magnitude more sensitive than the observations of GMR and a factor of two more sensitive than those of CFWM. There are as many as 35 ultracompact radio sources in a 3'×3' region of the Orion Nebula centered near the Kleinmann-Low nebula. In Table 1 are given the positions of all objects with flux densities $\geq$ 0.5 mJy per beam area, together with their sizes and flux densities at 5 and 15 GHz. A radio map of the central region of the Orion Nebula, at 15 GHz, is shown in Figure 1. Clearly seen in Figure 1 are:

(1) A region (bottom left) of ~40" in size, centered on the Trapezium star Θ^1C Orionis, having an unusually large density of radio sources: The PIGS' habitat.

(2) A second region, about 1 arcmin northwest of Θ^1C, exhibiting a few radio sources: The DEERS' habitat.

(3) A small number of radio sources - about 40 arcsec northeast of Θ^1C: the FOXES' habitat.

It is upon these regions that I will intend to focus the following discussion. I will present the observed characteristics of the radio sources, discuss their nature and origin and speculate on what appears to be taking place within each cage of the Orion radio zoological garden.

TABLE 1. Ultracompact Radio Sources in the Orion Nebula

Source	Coordinates (1950) Right Ascension	Declination	Flux density[a] (mJy) 5 GHz	15GHz	Deconvolved Size (")
	a) TRAPEZIUM REGION (PIGS HABITAT)				
1	05h32m50s21	-05°25'34"1	12.9±1.5	7.7±0.6	0.4
2	50.10	18.2	3.8±1.1	4.8±0.4	0.2
3	49.61	27.3	4.4±0.5	4.8±0.4	0.2
4	49.52	30.3	9.9±0.5	9.0±0.4	0.3
5	49.39	19.6	12.0±1.8	15.0±0.9	0.2
6	49.29	09.8	16.6±0.9	26.3±1.0	0.2
7	48.82	10.0	8.1±0.5	10.6±0.4	0.1
8	48.60	17.7	4.0±0.6	6.3±0.4	0.1
9	48.49	43.1	14.8±0.9	10.8±3.0	0.6
10	48.39	18.9	6.2±0.6	5.4±0.8	0.4
11	48.37	15.9	10.5±0.9	11.8±0.4	0.2
12	48.35	07.5	v		-
13	48.33	20.0	9.1±0.8	10.0±0.6	0.3
14	48.06	30.9	6.7±0.5	5.0±0.8	0.4
15	48.60	00.5	4.1±0.6	3.6±0.4	0.2
16	48.87	16.0	2.1±0.5	4.0±0.8	<0.1
17	49.31	21.3	3.6±0.5	4.4±0.4	<0.1
19	50.58	24.0	5.3±0.6	4.7±0.4	0.3
20	49.38	19.3	b	4.4±0.5	<0.1
21	49.15	09.4	1.4±0.5	2.0±0.4	<0.1
22	48.61	21.2	2.3±0.5	-	0.2
23	48.54	46.4	4.0±0.7	-	0.4
24	48.44	31.4	1.4±0.5	4.4±0.4	0.2
25	48.30	3.3	1.4±0.5	1.4±0.4	<0.1
26	48.27	15.9	1.8±0.7	2.6±0.4	0.1
	b) KLEINMANN-LOW NEBULA (DEERS HABITAT)				
B	05h32m46s64	-05°24'16"5	1.1	8.0	<0"1
H	47.02	32.1	0.8	2.0	<0.1
I	47.02	24.0	<0.4	1.8	<0.1
D	47.41	19.0	v		
	c) MOLECULAR BAY (FOXES HABITAT)				
E	05h32m49s50	-05°24'41"9	v		
L	49.87	29.3	v		
G	50.47	38.7	v		
F	50.89	30.6	v		

[a] v denotes variable flux density.
[b] blended with source No 5.

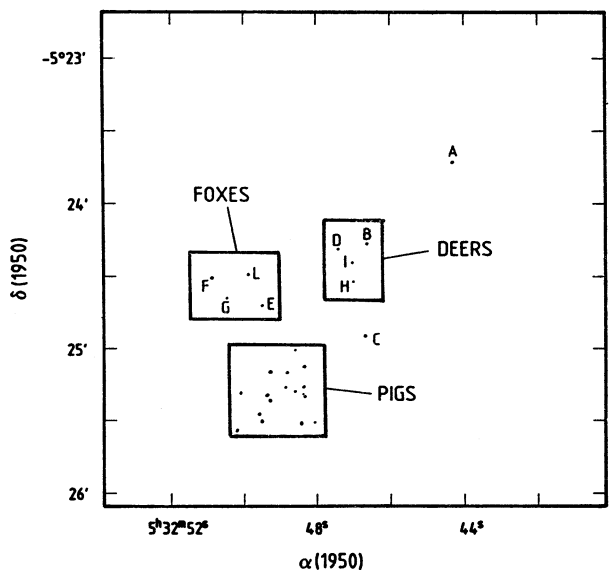

Fig. 1 - Map of the compact radio sources in the Orion Nebula at 15 GHz. The area of the circles is proportional to the total flux density.

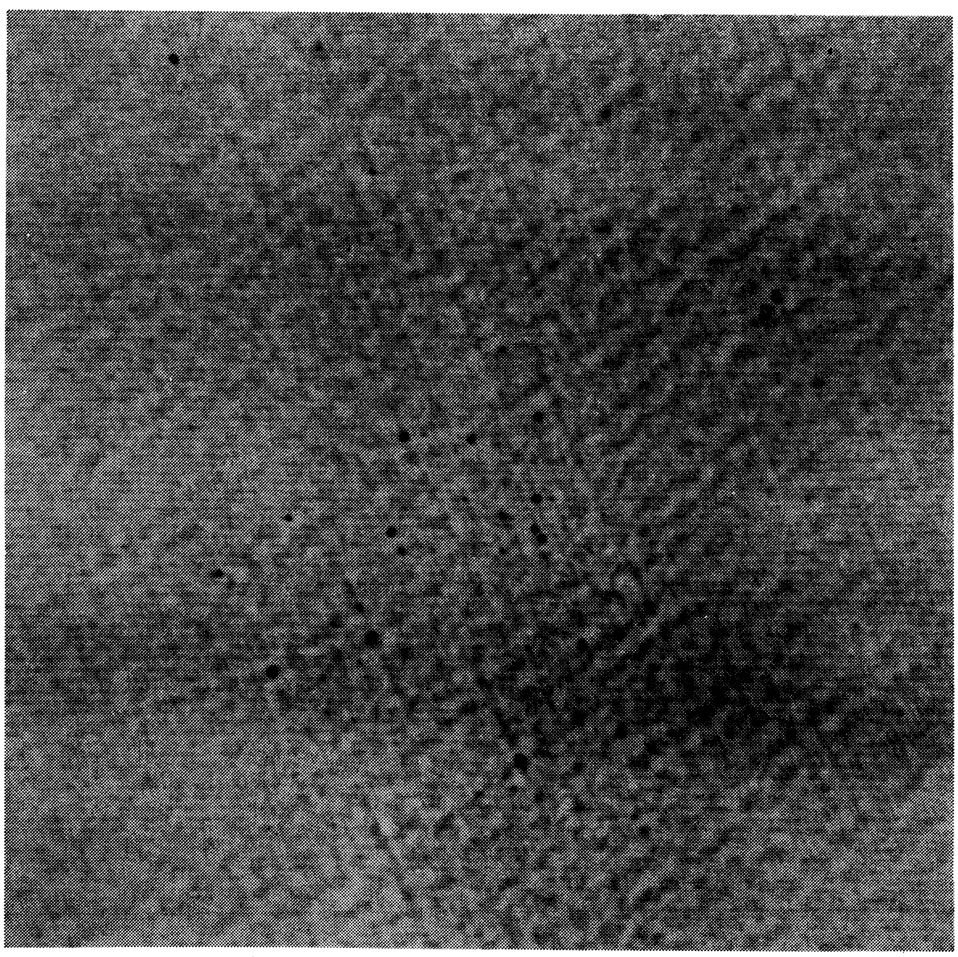

Fig. 2. Radio photograph of the PIGS region.

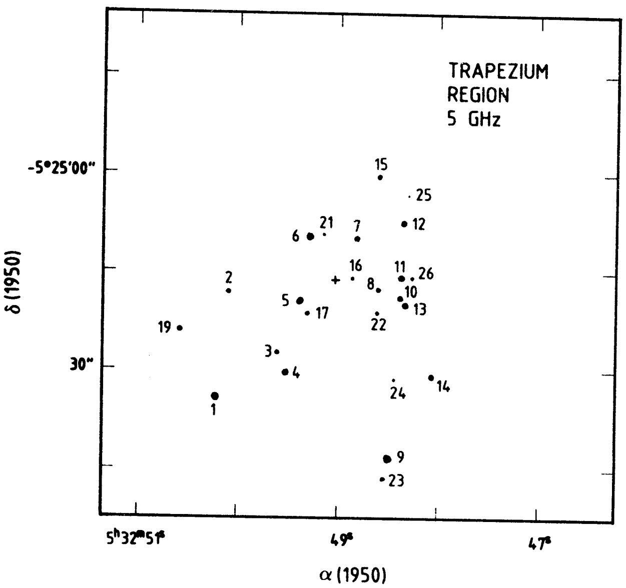

Fig. 3. Map of the compact radio sources near the Trapezium stars (PIGS' habitat) at 5 GHz. The cross indicates the position of the Trapezium star Θ^1C.

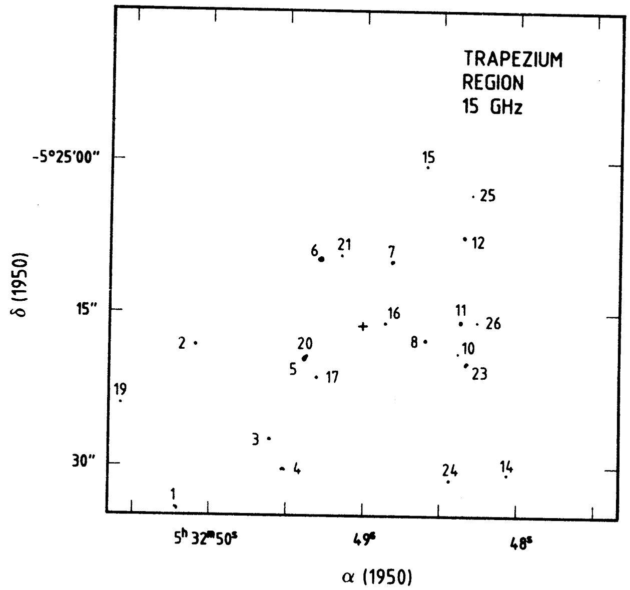

Fig. 4. Same as Figure 2, at 15 GHz.

1. PIGS

An unparalleled situation is seen at the center of the Orion nebula, around the Trapezium stars. There is a high surface density of compact radio sources: VLA radio images (see Plate 1) reveal ~25 sources, with flux densities per beam larger than 0.5 mJy/beam in a region of radius 30" centered in the Trapezium star Θ^1C Orionis. This radio photograph, with angular resolution of 0".4, shows a dramatic insensitivity to the extended emission from the nebula that usually frustrates the optical studies of this region. Radio maps toward the PIG's habitat, at 5 and 15 GHz, are shown in Figures 3 and 4. All the ultracompact radio sources detected at 5 GHz, in a region 30" in diameter centered in Θ^1C, were also detected at 15 GHz. Fourteen of these objects (Nos. 1 to 14) were reported by GMR which they referred to as the Trapezium sources. Three additional ultracompact radio sources in the Trapezium region (Nos. 15 to 17) were detected by CFWM. In Table 2 we compare the 2 cm detections of GMR, CFWM and the present 2 cm detections.

As we will argue below, several of these objects are likely to be Partially Ionized Globules surrounding molecular condensations. The PIGS' barn is brightly signalized, at optical wavelengths, by the luminous Trapezium star Θ^1C (shown as a cross in Figures 3 and 4) which is also likely to be the PIGS' feeding source. Not all sources within the PIG's habitat are likely to be PIGS however.

(a) Characteristics of the PIGS

All of the radio sources within a radius of 30" from Θ^1C have optical counterparts. Their identification is summarized in Table 2. The counterparts are best appreciated in a (multifrequency) near infrared image of the central region of the Orion nebula in which the nebular background is considerably suppressed (Allen, Bailey and Hyland 1984). The coincidence between a radio source and an object in this image is denoted as "ABH" in column 5 of Table 2. Sources 19 and 23 do not fall within the infrared image window, sources 1 and 22 are only marginally detected and source 16 falls within the bright stellar image wing of Θ^1C. Several of the radio objects within a radius of 10" from Θ^1C are associated with bright optical emission-line objects discovered by Lacques and Vidal (1979). These optical condensations are visible on the Hα, Hβ and [OIII] emission lines but invisible in (narrow) continuum plates. Objects at angular distances from Θ^1C larger than ~10" were not studied by Lacques and Vidal.

TABLE 2. Identifications

Source	Optical[a]	Optical[b]	Emission[c] Lines	Near[d] Infrared	X-ray[e]	2 cm detections GMR	CFWM	This Paper
	a) TRAPEZIUM REGION							
1		H		ABH:		Y	Y	Y
2		H		ABH		Y	Y	Y
3	π1893	H		ABH		Y	Y	Y
4	π1894	H		ABH		Y	Y	Y
5		wθ^1C	LV1	ABH		Y	Y	Y
6	π1890,θ^1G	H	LV2	ABH		Y	Y	Y
7		H	LV3	ABH		Y	Y	Y
8		wθ^1C	LV4	ABH		Y	Y	Y
9	π1869	H		ABH	KRS24	Y	f	Y
10		H	LV6	ABH		Y	Y	Y
11	π1867,θ^1H	H	LV5	ABH		Y	Y	Y
12	π1865,θ^1A	H		ABH		Y	Y	Y
13		H	LV6	ABH		Y	Y	Y
14		H		ABH		Y	N	Y
15		wθ^1B		ABH		N	Y	Y
16		wθ^1C		wθ^1C		N	Y	Y
17		wθ^1C		ABH		N	Y	Y
18						N	Y	N
19		H		g		N	N	Y
20		wθ^1C		ABH		N	N	Y
21		H		ABH		N	N	Y
22		H		ABH:		N	N	Y
23	π1870	H		g	KRS24	N	f	Y
24				ABH		N	N	Y
25	π1864,θ^1E	H		ABH	KRS23	N	N	Y
26	π1866,θ^1H^1	H		ABH		N	N	Y
	b) KLEINMANN-LOW NEBULA							
B				ABH,BN		Y	Y	Y
H						N	Y	Y
I				ABH,IRc2		N	Y	Y
D						Y	N	Y
	c) MOLECULAR BAY							
E		H		ABH		Y	N	Y
L	π1909	H		ABH	KRS35	N	N	Y
G	π1910	H		ABH	KRS31	Y	N	Y
F	π1925	H		g	KRS32	Y	Y	Y

[a] Parenago (1954).
[b] Herbig (1982) (w denotes that radio source is within the image wing of a nearby bright star).
[c] Lacques and Vidal (1979) (LV)
[d] Allen, Bailey and Hyland (1984) (ABH)
[e] Ku, Righini-Cohen and Simon (1982) (KRS)
[f] not mapped
[g] not within the infrared image

The radio spectra of most of the sources, having turnover frequencies near 4 GHz and being flat at frequencies above 10 GHz (GMR 1987), can be simply explained if the radio emission is free-free radiation arising in an ionized envelope that is optically thin above 10 GHz. The radio flux densities can be accounted for with an ionizing flux of $\sim 3 \times 10^{44}$ Lyman continuum photons per second, approximately that of a B2 star.

These radio sources are unlikely to be internally ionized. The required number of ionizing photons implies the presence of an underlying B2 star. The visual magnitude of a B2V star at a distance of 500 pc, assuming an absorption of ~2.3 mag (Johnson 1965; Penston 1973), should be ~8.3 mag. 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. We propose that these radio sources are externally ionized. However, they cannot be entirely ionized or they would have very short lifetimes. The electron density of the globules is much larger than that of the surrounding medium, therefore, because of the pressure difference, they will expand in the nebular medium in a dynamical time scale of $\sim R/v_s \sim 100$ years, where v_s is the speed of sound in an HII region and R is the size of the ionized region.

(b) Model

We suggest that the radio emission from these sources arises in the ionized envelopes surrounding dense molecular condensations. To determine the physical characteristics of the PIGS, we adopt a simple spherically symmetric model, sketched in Figure 5, in which the molecular condensation, of radius r_o, is surrounded by a dense ionized envelope with an electron density of the form $n_e \propto r^{-2}$, where r is the distance from the center of the condensation.

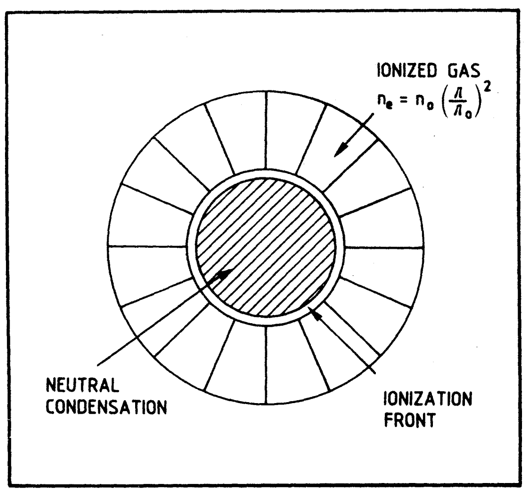

Fig. 5. A schematic representation of the proposed model for the PIGS.

The radio flux density from a source of ionized gas with an electron temperature T_e, an electron density n_e, at frequency ν in the optically thin regime is given by (cf. Moran 1983)

$$S_\nu = 3.4 \left(\frac{\nu}{GHz}\right)^{-0.1} \left(\frac{VEM}{10^{57}\ cm^{-3}}\right) \left(\frac{T_e}{10^4 K}\right)^{-0.35} \left(\frac{D}{Kpc}\right)^{-2}\ mJy \qquad (1)$$

where $VEM = \int n_e^2\, dV$ is the volume emission measure and D is the distance. For the electron density dependence with radius assumed above, we find $VEM = 4\pi\, n_o^2\, r_o^3$, where n_o is the electron density at radius r_o. Thus,

$$\left(\frac{S_\nu}{mJy}\right) = 10.7 \left(\frac{n_o}{5\times10^5\ cm^{-3}}\right)^2 \left(\frac{r_o}{10^{15}\ cm}\right)^3 \left(\frac{\nu}{GHz}\right)^{-0.1} \left(\frac{T_e}{10^4 K}\right)^{-0.35} \left(\frac{D}{Kpc}\right)^{-2} \qquad (2)$$

The observed size of the ionized gas, r_i, at an optically thin frequency, within the above model, is given by (GMR 1987)

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

In addition, the rate of Lyman continuum photons required to ionize the gas is $N_i = \alpha_B$ VEM where α_B is the recombination coefficient. For $\alpha_B = 2.6 \times 10^{-13} \left(\frac{T_e}{10^4 K}\right)^{-0.8}$ and in terms of the flux density

$$N_i = 7.6 \times 10^{43} \left(\frac{S_\nu}{mJy}\right) \left(\frac{\nu}{GHz}\right)^{0.1} \left(\frac{T_e}{10^4 K}\right)^{-0.45} \left(\frac{D}{Kpc}\right)^2 \ . \qquad (4)$$

Thus, from the observed flux density and ionized radius at an optically thin frequency we can derive, using relations (2), (3) and (4), the radius of the molecular condensation, the electron density at that radius and the Lyman continuum photon flux. They are given in Table 3. Also given in Table 3 is the turnover frequency

$$\nu_{to} = 5.9 \left(\frac{n_o}{5\times10^5 \ cm^{-3}}\right)^{0.95} \left(\frac{r_o}{10^{15} \ cm}\right)^{0.48} \left(\frac{T_e}{10^4 K}\right)^{-0.64} \ GHz \qquad (5)$$

predicted by this model. The turnover frequencies are consistent with the observed radio spectra.

(c) The energy source

Θ^1C is the most luminous star in the Trapezium region. It is a 06 ep star (Bohlin and Savage 1981) providing $\sim 1.7 \times 10^{49}$ UV photons s^{-1} (Panagia 1973) to the surrounding medium. Therefore, the obvious question that arises is: Can the Lyman continuum photon flux required to ionize the PIG's envelope be supplied by Θ^1C? The ionizing photon rate, N_i', incident on a PIG that subtends a solid angle Ω as seen by Θ^1C is

$$N_i' = N_o \frac{\Omega}{4\pi} e^{-\tau_{LC}} \ , \qquad (6)$$

where N_o is the total Lyman continuum photon rate emitted by Θ^1C.

In column 6 of Table 3 we give N_i' derived from equation (6), assuming $\tau_{LC} << 1$ and that $\Omega = 1.133 \left(\frac{\Theta_S}{\Theta_L}\right)^2$, where Θ_S is the FWHP angular size of the ultracompact radio source and Θ_L is its angular distance from Θ^1C. We assume for the position of Θ^1C $\alpha(1950) = 5^h32^m49^s.02$; $\delta(1950) = -5^\circ25'16''.3$. A comparison of the Lyman continuum photon flux derived from the observed radio continuum flux with N_i' (see Table 3) indicates that the PIG's ionization can, in most cases, be maintained by the ultraviolet photons from Θ^1C.

(d) Stability of the condensations

Consider an isothermal, spherical, non-magnetic, neutral condensation of mass M, radius r_o and temperature T, surrounded by an external medium applying a pressure p_o at the cloud surface. Not all of these condensations are possible in practice. If the external pressure is higher than (cf. Nakano 1984)

$$p_{cr} = \frac{1}{12\pi \ G^3 M^2 a^3} \left(\frac{9kT}{4\mu m_H}\right)^4 \ , \qquad (7)$$

then no equilibrium is possible and the condensation will collapse. Equivalently, if the mass of the neutral condensation is greater than M_{crit}, given by

$$\left(\frac{M_{crit}}{1\ M_{\odot}}\right) = 0.98 \left(\frac{p_o}{10^{-7}\ \text{dynes cm}^{-2}}\right)^{-1/2} \left(\frac{T}{100K}\right)^2 \left(\frac{2.3}{\mu}\right)^2 \left(\frac{1.0}{a}\right)^{3/2} , \quad (8)$$

then the forces due to the external pressure will lead to its collapse.

The external pressure p_o at the neutral condensation surface is given by $p_g + p_r$, where p_g is the ionized gas pressure and p_r is the radiation pressure from Θ^1C. Assuming $n_o \sim 4 \times 10^5$ cm^{-3} and $T_e = 10^4$K, we find $p_o \simeq p_g = 1.1 \times 10^{-6}$ dynes cm^{-2}. The radiation pressure of $\sim 2 \times 10^{-9}$ dynes cm^{-2} at 10" from Θ^1C, does not contribute significantly to the total pressure. Substituting the above value of p_o in relation (8) we find that, for a uniform density spherical condensation at T = 100 K, $M_{crit} \simeq 1\ M_{\odot}$. This leads to the suggestion that low mass star formation at the center of the Orion Nebula may have been triggered by the ionizing radiation from the young, massive OB stars. The pressure generated by the ultraviolet radiation, from these luminous stars, on dense molecular clumps might be enough for the clumps to become gravitationally unstable and collapse.

Table 3. Neutral Condensation Parameters

Source	r_o 10^{15} cm	n_o 10^6 cm^{-3}	ν_o GHz	N_i 10^{44} photons s^{-1}	N_i' 10^{44} photons s^{-1}
1	0.8	0.3	3.6	1.9	3.1
2	0.4	0.9	6.2	1.2	1.4
3	0.3	1.0	6.8	1.2	1.7
4	0.7	0.5	4.7	2.2	5.3
5	0.4	1.6	10.7	3.7	9.1
6	0.5	1.4	10.8	6.6	11.
7	0.3	1.8	11.1	2.6	5.2
8	0.2	2.1	11.3	1.6	3.6
9	1.3	0.2	2.9	3.3	6.0
10	0.8	0.3	3.1	1.3	20.
11	0.3	1.6	10.4	2.9	3.5
13	0.7	0.4	4.5	2.5	14.
14	0.8	0.3	3.0	1.2	4.6
15	0.3	0.9	5.9	0.9	1.2
16	<0.2	>1.7	-	1.0	<28.
17	<0.2	>1.8	-	1.1	< 3.4
19	0.6	0.4	3.8	1.2	1.8
20	<0.2	>1.8	-	1.1	< 3.9
21	<0.2	>1.2	-	0.5	< 2.9
22	0.5	0.3	3.0	0.5	13.
23	0.9	0.2	2.2	0.9	2.6
24	0.4	0.7	5.4	1.1	1.6
25	<0.2	>1.0	-	0.3	< 0.5
26	0.3	0.9	5.7	0.6	2.0

(e) Lifetime of the condensations

These condensations are continuously evolving as they are being eroded by the advancing ionization front from Θ^1C. However, because of the large density ($\sim 10^6$ cm^{-3}) of the ionized gas near the neutral condensation radius, the electron-proton recombination rate is appreciable and the flux of ultraviolet photons reaching the ionization front is highly reduced. Therefore, the ionization front moves slowly (~ 0.05 km s^{-1}) into the condensation (Dyson 1968). The lifetime of the condensation can be estimated as $M/\dot{M}$, where M and $\dot{M}$ are respectively the mass and the mass-loss rate by ionization of the neutral condensation. For the condensation parameters derived in section (b) and the flux of ionizing photons from the Θ^1C Orionis star reaching them, the derived mass-loss rates are typically $\sim 10^{-7}$ $M_\odot$ yr^{-1} (GMR 1987). Thus, neutral condensations with masses larger than 0.03 $M_\odot$ will have lifetimes consistent with the age of the Trapezium stars of $\sim 3 \times 10^5$ years (Strand 1958).

As we pointed out before, not all ultra compact radio sources in the Trapezium region are likely to be globules with partially ionized envelopes. Source 12 is coincident with Θ^1A Orionis, its radio emission is characterized by large flux density variations and a flat spectrum. Possible interpretations of this object have been discussed by Garay et al. (1985) and CFWM. Objects 9 and 23 are associated with known X-ray sources (Ku, Righini-Cohen and Simon 1982) that are probably pre-main sequence stars. Their radio emission is extended, however, and thus it is unlikely to have a non-thermal origin. It is possible that the radio emission from sources 9 and 23 arises in an ionized protostellar disk surrounding a low mass pre-main sequence star as suggested by CFWM. Source 3 does show small, but significant, variability in its radio emission. Finally, objects 16, 17, 20, 21 and 25 were unresolved at 15 GHz with angular resolution of 0.″12. Their nature is ambiguous. They could be PIGS, evaporating protostellar disks or non-thermal stellar objects.

2. DEERS

There are four ultracompact radio sources projected towards the Becklin-Neugebauer-Kleinmann-Low (BN-KL) cluster of infrared sources. All of these radio objects have been previously detected (Moran et al. 1982; Moran et al. 1983; GMR; CFWM); their observed parameters are summarized in Table 1. To facilitate comparison we designate them with the same names as those of GMR and CFWM. None of the sources projected toward the core of the OMC-1 have optical counterparts. We assume that they are deeply embedded in the molecular cloud. Further, their radio emission indicates that they are primary energy sources. Hence, we refer to them as DEERS, an acronym for Deeply Embedded Energetic Radio Sources. Source B is coincident with the BN object, source I is associated with IRc2, and sources H and D are not coincident with any of the infrared objects in the Orion-KL region.

The habitat of the DEERS has been recently probed with angular resolution of arcseconds at infrared and millimeter wavelengths. Here, I will summarize the current status of our knowledge of the distribution and physical conditions of the dust and molecular gas within this region. Infrared maps, between 2 and 30μ, show that there are seven peaks within a region of ~25" in diameter, with the BN object being the most prominent feature at all wavelengths (Wynn-Williams et al. 1984; see also references therein). These observations suggest that at least two infrared sources, BN and IRc2, are self-luminous with IRc2 possibly providing the bulk of the luminosity of the BN-KL region ($\sim 10^5$ $L_\odot$). On the other hand, millimeter observations of the molecular gas, at few arcsec resolution, show that there is a "hot core" (T ~200 K) component of ~12" in size and a "plateau" component extending over ~30" and having velocities up to ~100 km s^{-1} (Masson et al. 1984). The high velocity emission is believed to arise from an outflow which is powered by one of the infrared sources. The hot core coincides with a depression in the 20μ infrared map, and a region devoid of infrared sources at all wavelengths. It is likely to be a very dense ($N_{H_2} \sim 5 \times 10^7$ cm^{-3}) molecular condensation, with a dust opacity of ~0.01 at 3.4mm (Wright and Vogel 1985) and thus optically thick to infrared radiation.

In addition, proper motions of compact H_2O maser cloudlets in the BN-KL region reveal two outflows of features from a common origin between IRc2 and IRc4 (Genzel et al. 1981). There is a low velocity (~20 km s^{-1}) flow along a NE/SW direction and a flow with velocities of up to 80 km s^{-1}, the plateau flow, roughly orthogonal to the first one. Downes et al. (1981) and Genzel et al. (1981) suggested that both outflows originate from IRc2 which, they hypothesized, is undergoing a continuous mass-loss rate of $\sim 10^{-3}$ $M_\odot$ yr over the past 10^4 years. However, this interpretation encounters some difficulties. Interferometric maps of the CO plateau emission (i.e. high velocity outflow) show that it is closely centered near the BN object (Masson et al. 1984). Further, the mass estimated in the plateau component is ~20 $M_\odot$ and there is no clear way a star can inject such an amount of mass into the surrounding medium. Undoubtedly, the region is complex and additional observations with high angular resolution are required to unravel its secrets. In the following we discuss new sub-arcsec resolution radio results that strongly constrain the physical characteristics of the IR sources in the BN-KL region.

(a) Radio Characteristics of the DEERS

i) Sources H and D

Sources H and D might be either luminous objects that are heavily extincted by the gas and dust of the hot core source (Wright and Vogel 1985) and thus hidden at infrared wavelengths, or they could be low luminosity radio emitting young objects (cf. Snell and Bally 1986). Source H exhibits a flat radio spectrum indicative of optically thin, thermal emission. We suggest that the radio emission from this object may arise in a photoionized gas surrounding a luminous central star. The flux of Lyman continuum photons, needed to explain the observed radio flux densities, is 5×10^{43} photons s^{-1} which can be provided by a B3 ZAMS (Panagia 1973). On the other hand, source D shows variability in its radio flux density on time scale of few months or shorter. We suggest that the radio emission from source D might be non-thermal radiation from a low mass pre-main sequence star such as DoAr 21 in the ρ Ophiuchi cloud (Feigelson and Montmerle 1985). However, since no information is available on the above two objects, other than their radio emission properties, it is difficult to determine the nature of these sources and they will not be discussed any further.

ii) BN and IRc2

The detection of radio emission associated with BN and IRc2 definitively shows that these infrared objects contain energy sources of their own, probably in the form of a young luminous star or protostar. In the following discussion we will assume that the radio emission from these objects is due to free-free radiation.

The radio spectra of BN and IRc2 are shown in Figure 6. The data is taken from Moran et al. (1983), GMR (1987), CFWM (1987) and Moran et al. (1987). The spectra are rather similar. The spectral index of BN, calculated using average values of the flux density, is 1.8 ± 0.2 between 5 and 15 GHz and 1.6 ± 0.9 between 15 and 22.5 GHz. IRc2 was undetected at a 3σ flux density limit of 0.4 mJy at 5 GHz. Its spectral index between 15 and 22.5 is 1.3 ± 0.6. The spectra of both sources suggest that the emission is optically thick below 15 GHz but turns over at a frequency of ~35 GHz. The radio spectrum can be explained by two models. The radio emission could arise from either a compact uniform density HII region or an ionized stellar wind with a finite recombination radius.

In the case of the constant density homogeneous model, the size of the HII region can be derived from the optically thick part of the spectrum. For an electron temperature of 10^4 K, the observed flux density, at 5 GHz for BN and 15 GHz for IRc2, implies source radii of 3.3×10^{14} cm and 1.4×10^{14} cm, respectively. The electron densities, calculated from the above derived radius and a turnover frequency of 35 GHz, are 6.1×10^6 and 9.4×10^6 cm^{-3} for BN and IRc2, respectively. The number of Lyman continuum photons required to ionize the constant density gas are 1.5×10^{45} and 2.6×10^{44} photons s^{-1} for BN and IRc2, respectively.

(b) The nature of BN

A decade after the discovery of this object at 2.2μ by Becklin and Neugebauer (1967), various spectroscopic observations at near infrared wavelengths began to question the simple model for BN as an accreting protostar. First, the Brackett α line was detected in emission towards BN (Grasdalen 1976). Afterwards, several other infrared atomic hydrogen emission lines were reported by Hall et al. (1978), who also detected broad wings on the Brα line. The IR lines could be explained either as arising in the photosphere from a star with temperature in the range 5000 to 20000 K, or arising in an extended ionized envelope surrounding a hot young star (Downes et al. 1981).

The detection of the radio emission associated with BN strongly constrains the physical conditions of the ionized gas. The emission is optically thick between 5 and 15 GHz and implies a source radius of 3.3×10^{14} cm (~20 AU) for an electron temperature of 10^4 K. Thus, the radio observations reveal that the free-free emission arises in an extended envelope which is probably excited by a young, massive, hot central star.

The simple model of a spherical ionized envelope of uniform density described in section (a) is, however, inconsistent with several other observations. The Brα line flux predicted in this model, assuming it is an optically thin line, is $\sim 2 \times 10^{-12}$ ergs cm^{-2} s^{-1}, about 30 times smaller than the observed, corrected by extinction, Brα flux density of 6×10^{-11}

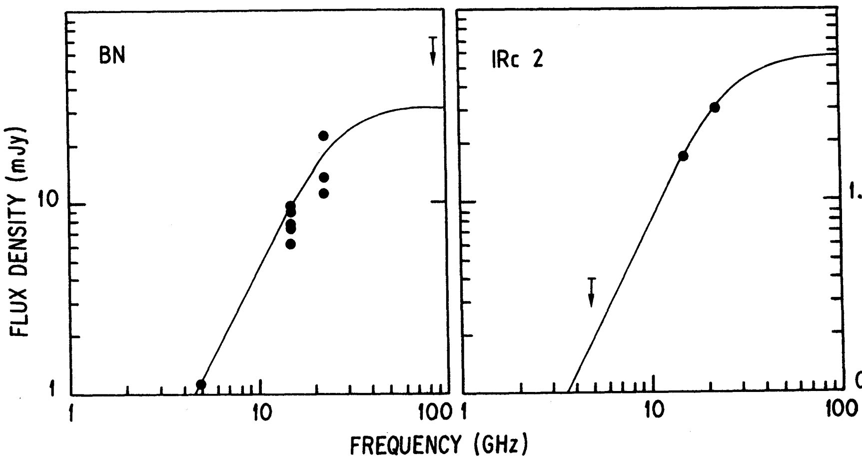

Fig. 6. Microwave spectra of the radio sources associated with BN and IRc2.

ergs cm^{-2} s^{-1}. Further, the Brackett line profiles show broad wings indicative of velocities of ±100 km s^{-1}. Finally, the highly excited CO emission at 2.3μ associated with BN is thought to arise within only a few AU from the central star (Scoville et al. 1979). Since the dissociation energy of CO is less than the ionization potential of H, the CO and ionized hydrogen cannot be co-extensive and thus the derived CO source size is in conflict with the radio source size if both are assumed to arise in a spherically symmetric envelope around the star. One possible way to reconcile the CO and radio data is to assume that BN have a complex structure. The molecular gas, around BN, may be confined to a circumstellar disk, while the ionized gas may arise in a bipolar flow along the disk axis, thus also explaining the broad wings of the Brackett lines (Moran et al. 1982; Scoville et al. 1982).

If the molecular outflow seen towards the BNKL region does not originate from BN (cf. Genzel et al. 1981), there are no compelling reasons to rule out the notion that this object may be an accreting protostar. An argument supporting this point of view is the presence of an absorption feature, in the ^{12}CO v:0 → 1 line profile towards BN, at a velocity of ~30 km s^{-1} redshifted by ~ 9 km s^{-1} from the systemic velocity of BN (Scoville et al. 1982). Thus, prompted by this point of view, we consider here a model in which the radio emission from BN arises in a remnant accreting envelope surrounding a protostar. The gas might be excited by the ultraviolet radiation from either or both, the central protostar and the accretion shock surrounding the protostellar core. We assume that the ionized gas is a gravitationally dominated spherical accretion flow, thus the density varies as $r^{-3/2}$ and the velocity as $r^{-1/2}$. Further, we assume it has an outer cutoff radius r_o. In this case, for frequencies below ν_a, where

$$\nu_a = 6.0 \left(\frac{r_o}{10^{14}\ cm}\right)^{0.48} \left(\frac{n_o}{10^6\ cm^{-3}}\right)^{0.95} \left(\frac{T_e}{10^4 K}\right)^{-0.64} \left[\ln\left(\frac{r_o}{r_c}\right)\right]^{0.48} GHz\ , \qquad (9)$$

the radio emission will be optically thick and the spectral index will be 2. Here, n_o is the density at radius r_o, and r_c is the radius of the accretion shock. For $\nu > \nu_a$ the radiation is optically thin and the spectral index is ~ -0.1 (Felli et al. 1982). The observed radio spectrum of the BN object can be well explained by this model. Assuming an electron temperature of 10^4 K the optically thick portion of the spectrum implies an outer radius of 3.3×10^{14} cm. In addition, assuming $r_c = 10^{12}$ cm, the turnover frequency of 35 GHz implies an electron density of 1.5×10^6 cm^{-3} at the outer radius. The model spectrum is shown in Figure 6. The observed line wings of the Brackett lines can also be explained in this model as due to the motions of the accreting material reaching velocities up to a few 100 km s^{-1}.

(c) The nature of IRc2

i) Stellar wind

Prompted by the outflow associated with IRc2 (Downes et al. 1981; Genzel et al. 1981) we will consider here an ionized stellar wind as the origin of the radio emission associated with the infrared object. If the flow were ionized to infinity, the radio flux would be proportional to $\nu^{0.6}$ at all frequencies (Panagia and Felli 1975; Wright and Barlow 1975). Thus, both the molecular outflow and the observed radio spectrum suggest that the envelope cannot be fully ionized. We assume that the radio emission arises from a stellar wind source of finite recombination radius (Marsh 1975; Felli and Panagia 1981). In this case, the radio emission is optically thick virtually to the outer ionized cutoff r_o and the spectral index is 2 for frequencies below ν_o, given by (cf. Moran 1983)

$$\nu_o = 6.2 \left(\frac{\dot{M}}{10^{-6}\ M_\odot\ yr^{-1}}\right) \left(\frac{v}{100\ km\ s^{-1}}\right)^{-1} \left(\frac{r_o}{10^{15} cm}\right)^{-1.4} \left(\frac{T_e}{10^4 K}\right)^{-0.6}\ GHz \qquad (10)$$

Further the flux density of an optically thick source of radius r_o, electron temperature T_e, observed at frequency ν, is given by (cf. Moran 1983)

$$S_\nu = 0.41 \left(\frac{\nu}{10\ GHz}\right)^2 \left(\frac{r_o}{10^{14} cm}\right)^2 \left(\frac{D}{500\ pc}\right)^{-2} \left(\frac{T_e}{10^4 K}\right)\ mJy\ . \qquad (11)$$

The observed radio flux density at 15 GHz of 1.7 mJy gives a value of 1.4×10^{14} cm for the outer radius of IRc2. In addition, the radio spectrum of IRc2 suggests that the turnover frequency, ν_o, is ~35 GHz. Substituting this and the value of r_o derived above, in relation (10) gives

$$\left(\frac{\dot{M}}{10^{-6}\ M_\odot\ yr^{-1}}\right) = 0.3 \left(\frac{v}{100\ km\ s^{-1}}\right)\ . \qquad (12)$$

Genzel et al. (1981) suggested a model in which the molecular outflows in the BN-KL region originates from the source IRc2. In their view IRc2 is a luminous young OB star undergoing a strong mass loss rate of $\sim 10^{-3}\ M_\odot\ yr^{-1}$ at velocities of ~ 20 km s^{-1}. The mass-loss rate, of $\sim 10^{-3}\ M_\odot\ yr^{-1}$, cannot be driven by radiation pressure even if the luminosity of IRc2 is as high as $10^5\ L_\odot$. They suggest it might be driven by loss of rotational, magnetic or gravitational energy. The detection of radio emission associated with IRc2 is however inconsistent with this model, since the high rate of mass loss should have prevented the formation of a compact HII region. For an object with a stellar luminosity of $10^5\ L_\odot$ and a flow velocity of ~ 20 km s^{-1} the critical mass-loss rate, above which the flow is ionized to only an exceedingly small region around the star (cf. Wright and Barlow 1975), is $\sim 10^{-6}\ M_\odot\ yr^{-1}$. The large stellar mass-loss rate from IRc2 demanded in the Genzel et al. model implies that only a thin shell near the stellar surface is ionized, and therefore that the radio flux should be undetectable.

ii) Hydromagnetic winds from disk

Pudritz and Norman (1983, 1986) suggest that hydromagnetic disk wind, arising from a large rotating disk through the action of magnetic wind torques, drives the bi-polar outflows associated with protostars. The outflow of disk material consists of two components, an outer molecular outflow, radii $> 10^{15}$ cm, with typical mass-loss rate of $\dot{M}_{mol} \sim 10^{-4}\ M_\odot\ yr^{-1}$ and an inner ionized gas outflow, radii $\lesssim 10^{15}$ cm, with $\dot{M}_{ion} \sim 10^{-6}\ M_\odot\ yr^{-1}$. The luminosity of the protostellar core is produced by accretion of disk matter, with accretion rates of $\sim 10^{-3}\ M_\odot\ yr^{-1}$. The associated accretion shock produces ultraviolet radiation that ionizes an inner disk envelope. Free-free radio continuum emission is thus expected to arise from both the ionized inner disk and the mass-loss gas associated with it.

The observed radio emission from IRc2 and the high molecular mass loss rate associated with it can be reconciled in a reasonable way within the hydromagnetic wind model. Pudritz and Norman (1986) and Pudritz (1985) models predict that the ionized mass loss rate $\dot{M}_{ion}$, the molecular mass loss rate $\dot{M}_{mol}$, and the radius of the ionized inner disk envelope R_i, depend on the disk mass M_d, the specific angular momentum h, and the Lyman continuum photon rate N_i. The disk parameters required to explain the observed properties of IRc2, namely an ionized radius of 1.4×10^{14} cm, a radio flux density of 3.0 mJy at 22.5 GHz and a molecular mass loss rate of $10^{-3}\ M_\odot\ yr^{-1}$, are $M_d \sim 170\ M_\odot$, $h = 0.8 \times 10^{22.5}\ cm^2\ s^{-1}$ and $N_i \sim 2 \times 10^{48}\ s^{-1}$ (Moran et al. 1987).

The existence of a dense disk around IRc2, with similar characteristics to those derived above, has been suggested by several observations (Hasegawa et al. 1984; Vogel et al. 1985). We thus favor the hydromagnetic disk wind model to explain the radio emission and molecular outflows associated with IRc2.

3. FOXES

The radio sources belonging to this group are spatially confined within a small region of the nebula which is close to the molecular bay that indents the ionized cavity. They are all associated with optical objects. The radio positions and identifications are given in Tables 1 and 2, respectively.

The optical counterparts to three of the radio sources (objects G, L and F) show some of the classical characteristics of low mass pre-main sequence stars, such as optical variability, emission lines and infrared excess, and also exhibit their modern distinction: strong and variable X-ray emission (cf. Feigelson 1984). Hence, their acronym as Fluctuating Optical and X-ray Emitting Sources. The classical characteristics of T Tauri stars are usually attributed to stellar winds of $\sim 10^{-8}$ $M_\odot$ yr^{-1} which are corroborated by the observed P Cygni profiles. However, several PMS stars do not show line emission, indicating weak or absent winds, and exhibit high levels of X-ray emission that is variable on a timescale of minutes to hours (Mundt et al. 1983; Montmerle et al. 1983). These properties suggest that the emission from some PMS stars arise in flare events in active chromospheres (Feigelson 1984).

The radio emission from the FOXES is variable on a timescale equal to or less than a day. Their peak radio luminosities at 15 GHz are $\sim 8 \times 10^{18}$ ergs cm^{-2} s^{-1} Hz^{-1}. Interpretation of the radio emission from these young objects as free-free radiation arising in a stellar wind is doubtful due to both the large observed flux densities, requiring very luminous star to photo-ionize the envelope, and the short timescales of variability. Taking S_{15GHZ} = 25 mJy and a stellar radius of 4×10^{11} cm, the number of Lyman continuum photons required to ionize the gas (cf. Moran 1983) is 5×10^{47} s^{-1}, approximately that of a B0 star. The radio emission from a wind should vary on timescales $t > R/v_w \sim$ year, much longer than the observed timescale of less than a few days. The characteristics of the radio emission points instead to non-thermal process. The radio luminosities of the FOXES are comparable to, although somewhat larger than, the largest radio flare seen in RSCVn stars (Feldman 1983) for which the emission is believed to be synchrotron radiation (Hjellming and Gibson 1980). The flares from these PMS stars may be produced in a magnetic loop several times larger than the star, as already suggested by Feigelson and Montmerle (1985).

Infrared observations of the bay (Allen et al. 1984) show the presence of several infrared stars, which are neither radio nor X-ray sources and presumably correspond to an old population of low mass stars. The strong chromospheric activity of the FOXES might suggest that these sources are PMS stars in an earlier evolutionary stage than the infrared bay stars. Further, the spatial location of the FOXES, just arcseconds west of the molecular bay, and their youth suggest that their formation may have been triggered by the compression forces by the radiation from the OB central stars on the bay's edge. Optical investigations of these objects might be of great importance in understanding the evolution of the pre-main sequence stars.

III. DISCUSSION

The large density of stars within the Orion Nebula core raises the questions of "How is it that stars are produced with such efficiency at the core of the nebula?" and "Which is this very efficient mechanism of star formation?". Herbig (1982) proposed that the Trapezium cluster represents a sample of the stellar content of the OMC-1 that has been revealed by the recent formation of luminous OB stars in the near side of the cloud. However, the age of the stars in or around the Trapezium cluster periphery ranges from 10^4 to 3×10^7 years (Isobe and Sasaki 1982), suggesting several generations of star formation.

We suggest that the most recent episode of star formation in the Trapezium region may have been triggered by the ultraviolet radiation, from an early generation of OB stars (i.e., the Trapezium stars), propagating into the surrounding molecular cloud. Clumps of neutral gas may implode due to the compressional forces exerted by radiation driven ionization shock fronts (Klein, Sandford and Whitaker 1983) leading to the formation of a new generation of stars. This view is supported by the large density of PIGS found near the Θ^1C Orionis star.

(a) A scenario of the evolution of the Orion Nebula core.

Schematically, we propose the following scenario for the evolution of the core of a massive molecular cloud. A dense inhomogeneous molecular cloud, initially in hydrostatic equilibrium, is compressed for example from a galactic density wave or by the expanding gas of a supernovae. The densest region(s) of this cloud is then forced to contract and collapse giving birth to a few massive OB stars. These young and luminous stars (the Trapezium stars) will dominate the subsequent evolution of the surrounding gas. Their ultraviolet radiation and stellar winds will disrupt and dissipate the less dense molecular gas of the parental cloud creating a cavity around the newly formed stars.

However, the most dense fragments of the placental cloud, possibly created by fragmentation processes during the primordial collapse, are not easily destroyed and their fate is determined by their total mass. The most massive clumps may become gravitationally unstable under the external pressure forces induced by the ionization front from the luminous stars, and therefore will collapse to form stars. The less massive fragments remain as molecular condensations with externally ionized envelopes for a considerable length of time. In addition, the ionized gas in the envelope streams away from the neutral condensation flowing into the surrounding nebula producing supersonic turbulence (Dyson 1968). Thus the PIGS might also explain the turbulence observed toward the central region of the Orion nebula.

(b) Sequential formation of the Orion radio fauna?

Star formation may be sequential in nature proceeding through a series of consecutive events. On a length scale of ~ 50 pc, Blaauw (1964) showed that OB associations in the Orion constellation are sequentially ordered by age. Possible mechanisms driving the sequential star formation are ionization fronts, supernovae, stellar winds and spiral density waves (cf. Lada, Blitz and Elmegreen 1979).

It is interesting to speculate that the Orion radio zoo population might also have been sequentially formed, their formation being triggered by the effects of the ionizing radiation, from the OB Trapezium stars, propagating through the parental molecular cloud. The PIGS, spatially located near the Θ^1 Ori cluster and excited by the ultraviolet radiation from these luminous stars, were thus born shortly after the turn-on of a large output of UV radiation from the Trapezium stars. We suggest then that the PIGS might be the oldest species of the Orion zoo, having ages of $\sim 10^6$ years, close to the main sequence age of the Θ^1 Ori stars.

Second in rank in the hierarchical "age ladder" we place the FOXES which, we suggest, are probably $\sim 10^5$ years old, their formation being a result of the implosion of dense neutral condensations located near the edge of the molecular bay, due to ionization shock fronts from the OB central stars (see model of Klein, Sandford, and Whitaker 1983). This view is supported by the recent discovery of four large molecular condensations, lying along the western edge of the bright central part of the Orion nebula (Mundy et al. 1986), suggesting they may be large neutral clumps embedded in the ionized gas. Their densities of $\sim 10^6$-10^7 cm^{-3} and masses of ~ 50 $M_\odot$ suggest that they are likely to collapse on a short time scale ($\sim 2 \times 10^4$ years). The youth of the FOXES is supported by their observed X-ray, optical and radio properties which are similar to those of young low-mass pre-main sequence stars.

Finally, the youngest objects in the Orion zoo are the DEERS whose formation, we suggest, may have been triggered by the passage in the molecular cloud of shock waves driven by the ionization front produced by the Trapezium stars. Their ages are probably ~ 10^4 years.

Lastly, I wish to emphasize the speculative character of the above discussion. Clearly, we need more observational evidence to confirm (or deny) the points of view suggested here. In particular, spectrographic observations of the PIGS and FOXES, at optical and near infrared wavelengths, are of urgent necessity to firmly establish their nature. Similarly, valuable data to better determine the physical characteristics of the DEERS should be provided by infrared photometry and high angular resolution submillimeter wavelength observations. Clearly, there is still much to be done before we can use the Orion Nebula as the prototype region for the study of star formation.

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