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MULTIFREQUENCY OBSERVATIONS OF THE REGION ASSOCIATED WITH THE COMETARY NEBULA GM24

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RESUMEN

Se presentan observaciones en los intervalos espectrales infrarrojo (1-20 μm) y de radio (6-cm y línea de CO) de la vecindad de la nebulosa GM24 = PP85 y del máximo de temperatura de una nube de CO reportada anteriormente. Con el "Gran Arreglo Interferométrico" (*VLA*) se dectectó la emisión de radio continuo (6-cm) proveniente de una región H II. Su posición coincide con un máximo de emisión en el intervalo 1-4 μm. Creemos que GM24 es la parte visible de una región H II obscurecida que comienza a emerger de la nube molecular en la que está embebida. Nuestros mapas infrarrojos hechos en el Observatorio Astronómico Nacional en San Pedro Mártir, muestran otros dos máximos (1-20 μm) localizados a distancias de $\sim$ 30 segundos de arco de la región H II compacta, todos rodeados de emisión extendida en el cercano infrarrojo (1-4 μm). También se obtuvo, con el Telescopio Milimétrico de la Universidad de Texas, un mapa detallado de la nube molecular completa. Se obtuvo, además, espectroscopía de alta resolución en la línea Hα con el telescopio Anglo-Australiano. Interpretamos nuestros resultados en términos de la formación reciente de tres estrellas masivas, una de las cuales, habiendo desarrollado una región H II, se encontraría en una etapa posterior de su evolución. La emisión de 1 a 4 μm extendida puede provenir de una nebulosa de reflexión similar a NGC 7538-Irs 9.

ABSTRACT

The faint nebulosity GM24 = PP85 was observed at infrared (1-20 μm) and radio (6-cm and CO line) wavelengths in the vicinity of a CO "hot spot" reported previously. Radio continuum (6-cm) emission from an H II region was detected with the Very Large Array. Its position coincides with a 1-4 μm emission peak. GM24 appears to be the visible part of an obscured H II region that is beginning to emerge from the molecular cloud. Our infrared maps made at the Observatorio Astronómico Nacional at San Pedro Mártir, show two additional (1-20 μm) peaks located at distances $\sim$ 30 arcsec from the compact H II region, all surrounded by extended near-infrared (1-4 μm) emission. A detailed CO ($J = 1 \rightarrow 0$) map of the whole molecular cloud was obtained with the University of Texas Millimeter-Wave Telescope. High resolution spectroscopy of the Hα line was also obtained with the Anglo-Australian Telescope. Our results are interpreted in terms of recent formation of three massive stars; one of which, having developed an H II region, is at a slightly later phase of its evolution. The extended near-infrared emission may arise in a reflection nebula similar to NGC 7538-Irs 9.

Key words: MOLECULAR CLOUDS – NEBULAE-INDIVIDUAL – INFRARED-SOURCES

I. INTRODUCTION

GM24 is a cometary-like nebula discovered by Gyulbudaghian and Markarian and listed (PP85) by Parsamian and Petrosian (1979). It is located some two degrees south of the massive star forming region NGC 6334 (e.g. Rodríguez, Cantó and Moran 1982) and was found to be associated with a CO "hot spot" by Torrelles *et al.* (1983). In their extensive CO line survey, GM24 was found to have the highest antenna temperature, comparable only to a few other known regions of star formation (cf. Wynn-Williams 1982), implying the existence of at least one O-type star heating the cloud. An extended and tenuous Hα emission region RWC 126 and an associated radio continuum source with a total flux of $\sim$ 10 Jy were found by Rodgers, Campbell, and Whiteoak (1960) and Altenhoff *et al.* (1970) respectively. A low spatial resolution far-infrared (40-350 μm) observation by Emerson, Jennings, and Moorwood (1973) yielded a flux of 9×10^{-14} W/cm^2. From energy arguments, Torrelles *et al*. (1983) deduced a total luminosity of $\sim 10^5$ $L_\odot$ for the exciting objects and found no evidence of strong radial mass outflows. Figure 1 (Plate 1) shows an enlargement of the region from the short-red UK Schmidt I/SR Atlas with coordinates with an estimated accuracy of 3 arcsec. Note that the coordinates in the blueprint published by Torrelles *et al* (1983) have an uncertainty of $\sim$ 15 arcsec.

In the present work, near and mid-infrared (1-20 μm) observations, new radio continuum and line-emission searches and measurements as well as high resolution spectroscopy in the Hα line spectral region of GM24 are presented. The observations are described and the results presented in Section II. Section III contains a discussion of the properties of the region and the individual sources. Finally, a description of the GM24 region and our conclusions are given in Section IV.

II. OBSERVATIONS AND RESULTS

a) *Infrared Observations*

The infrared observations were made during several runs between 1984 May and 1984 August on the 2.1-m telescope of the Observatorio Astronómico Nacional at San Pedro Mártir, Baja California, México. For measurements at wavelengths shorter than 4 μm, the InSb-based photometer described by Roth *et al.* (1984) was used while the longer wavelength observations were made with the Ge bolometer of the Istituto di Astrofisica Spaziale (cf. Persi *et al.* 1985).

Maps through the *H, K, L'* and *N* filters were made of a region of size 1.5 X 1.5 arcmin centred at $\alpha_{1950} = 17^h$ 13^m 41^s and $\delta_{1950} = -36° \; 17' \; 54''$ by performing three to five second integrations at successive points separated 7.5 arcsec with an aperture of 12 arcsec in diameter. The

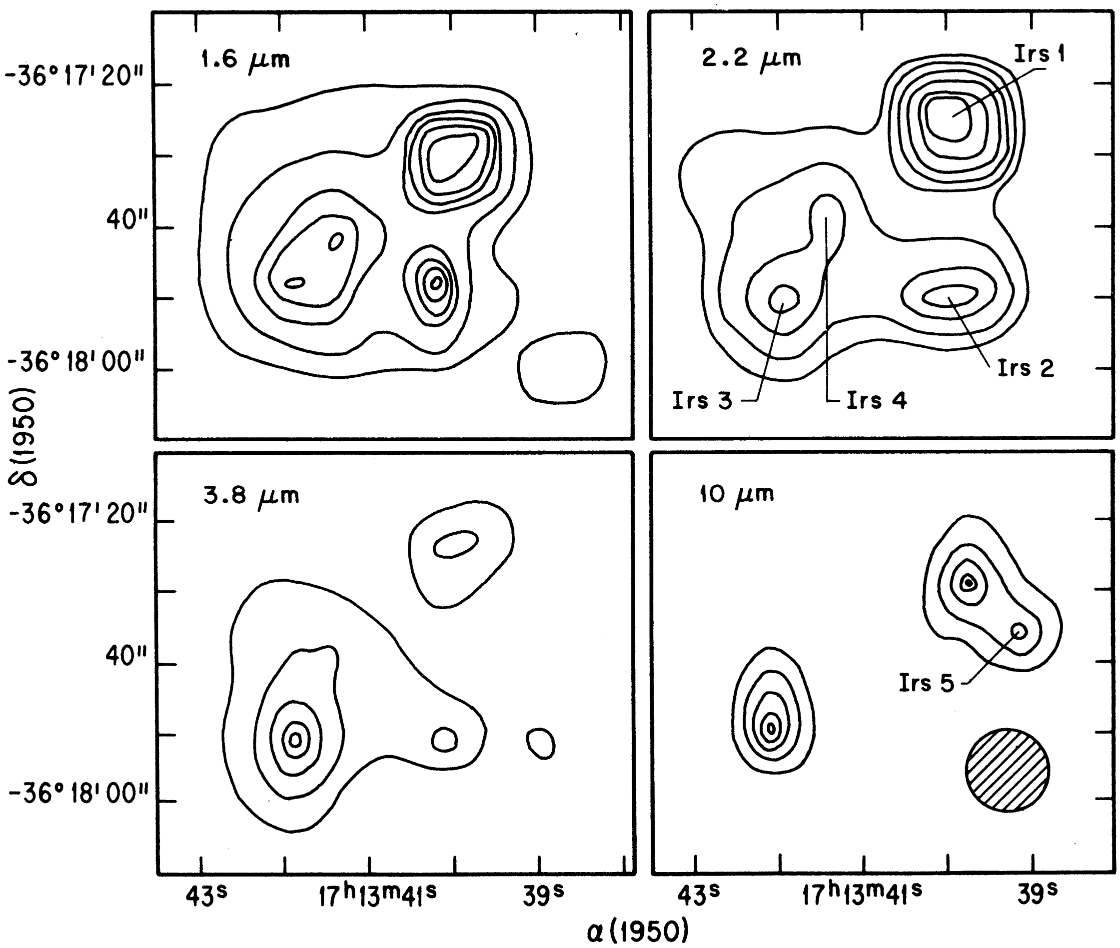

Fig. 2. Infrared maps of the central region of GM24 obtained with a 12" diaphragm (hatched circle). Contours are 0.2, 0.4, 06, 0.8 and 0.9 of the peak flux (corresponding to the magnitudes given in Table 2 for a 12" diaphragm) except in *H* and *K* where the 0.7 contours are also shown. The observational uncertainties of the relative positions in different maps is estimated to be ± 6".

chopper throw was ∿ 70 arcsec but additional maps with different throws were also made to avoid confusion with possible negative signals. The resulting contour maps are shown in Figure 2. The average positions of the five peaks in the central region as well as those of the two northern point sources also found are given in Table 1. The absolute coordinates were determined by offsetting from the nearby star SAO 208622 and have uncertainties of ±10 arcsec but relative positions in any single map are better than ±6 arcsec.

TABLE 1

POSITIONS OF INFRARED SOURCES IN GM24[a]

Source	α_{1950}	δ_{1950}
Irs 1	$17^h13^m40.0^s$	−36° 17′25″
Irs 2	17 13 40.0	−36 17 50
Irs 3	17 13 41.9	−36 17 50
Irs 4	17 13 41.4	−36 17 40
Irs 5	17 13 39.5	−36 17 34
Irs 6	17 13 39.9	−36 16 39
Irs 7	17 13 36.2	−36 15 45

a. Errors are ±10″.

Broad-band *J, H, K, L′, M, N* and *Q* photometry was performed individually for most of the objects. The results are given in Table 2 and in Figure 3 the corresponding spectral distributions are plotted. Photometric standards and the San Pedro Mártir absolute flux calibration were taken from Neri (1985). Spectrophotometry in the 10μm window of Irs 3 with a resolution of $\lambda/\Delta\lambda \simeq 50$ was obtained with the Ge bolometer containing a continously variable filter (*CVF*). The spectrum shows a deep silicate absorption feature with an optical depth of $\tau_{9.7} \simeq 3.4$ computed using the semi-empirical formula (Willner *et al.* 1982) ,

$$\tau_{9.7} = 1.4\, \ell n\, (F^{bb}_{9.7}/F^{abs}_{9.7}) + 1.6 \cong 3.4 \quad ,$$

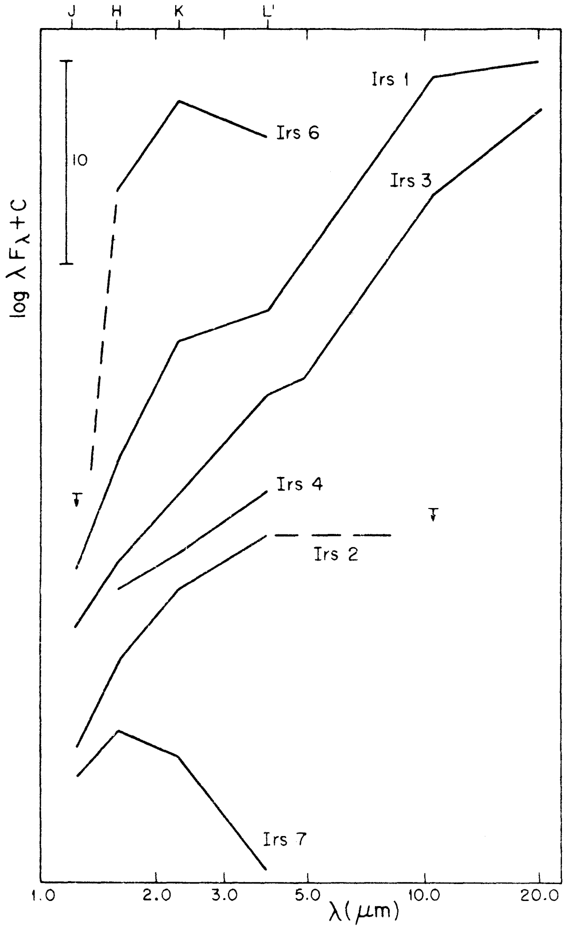

Fig. 3. Energy distribution of the infrared sources found in the present survey.

where $F^{bb}_{9.7}$ is the interpolated flux at 9.7 μm of a black body fitted to the observed 8.0 μm and 11.2 μm fluxes. The corresponding value of the total visual absorption in

TABLE 2

PHOTOMETRY OF INFRARED SOURCES IN GM24

Source	*J*	*H*	*K*	*L′*	*M*	*N*	*Q*
Irs 1	11.94 ± 0.06	9.41 ± 0.04	7.49 ± 0.04	5.50 ± 0.06	...	−0.6 ± 0.1	−2.8 ± 0.3
Irs 2	11.34 ± 0.06	9.53 ± 0.03	7.77 ± 0.06	5.51 ± 0.06	...	< 2.0	...
Irs 3	11.32 ± 0.04	9.73 ± 0.04	8.01 ± 0.04	5.12 ± 0.09	4.35 ± 0.09	−0.06 ± 0.10	−3.86 ± 0.14
Irs 4[a]	...	9.8 ± 0.2	8.5 ± 0.2	6.1 ± 0.2	...	< 2.0	...
Irs 5[a]	...	...	...	...	...	−0.3 ± 0.2	...
Irs 6	> 15.4	10.96 ± 0.03	8.96 ± 0.03	7.86 ± 0.14	...	...	...
Irs 7	10.45 ± 0.04	9.12 ± 0.04	8.58 ± 0.04	8.39 ± 0.49	...	...	...
Off[a,b]	...	11.1 ± 0.4	9.5 ± 0.4	7.0 ± 0.5	...	< 2.0	...

a. Photometry obtained from maps.

b. Offset position from Irs 3: 7″ to E and 21″ to N.

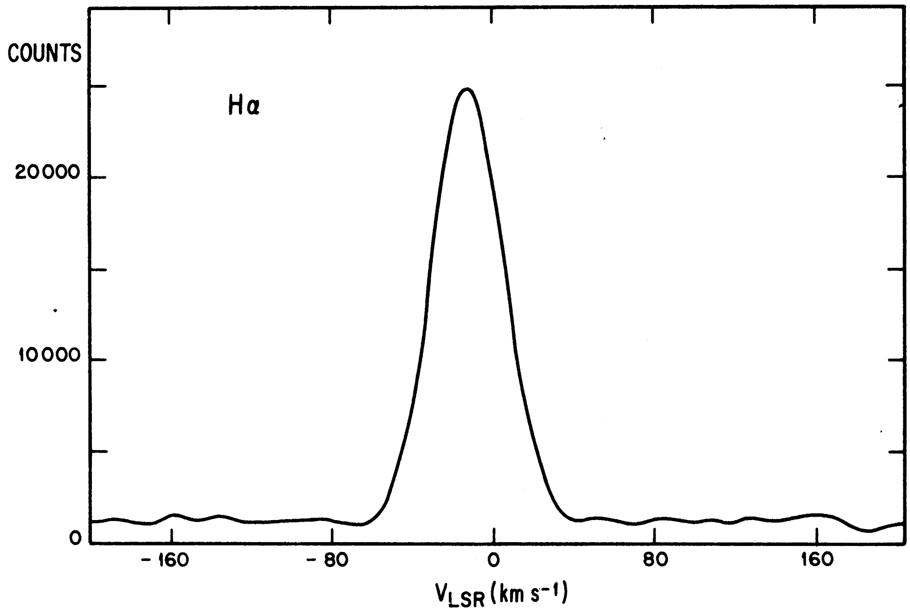

Fig. 4. Smoothed profile of the Hα emission line of GM24.

front of the region where the 10 μm continuum is originated is $A_V \cong 56$, assuming the relationship

$$A_V = 16.6\ \tau_{9.7}$$

(Rieke and Lebofsky 1985).

b) *Optical Spectroscopy*

Previous low dispersion spectroscopy of GM24 was obtained by López (1984), where an anomalous blue continuum superimposed on a G-type spectrum was reported. After a re-analysis of the observations, it was discovered that the data were biased by an accidental too large setting of the slit width, which apparently let moonlight in and produced internal scattering in the spectrograph. New high dispersion spectra have been kindly obtained by Dr. J. Meaburn at our request. The spectra, covering the λλ6540-6590 A region, were taken with an Echelle spectrometer (Meaburn *et al.* 1984) at the f/8 Cassegrain focus of the 3.9-m Anglo-Australian Telescope with the Image Photon Counting System as detector. A frame of 120 data-taking windows (each 1.425 arcsec long) was placed along the slit and 1020 pixels (each of size ∿ 30 μm) in the direction of the dispersion were exposed. The slit width was 150 μm (≅ 1 arcsec) and the instrumental resolution, as determined by measuring the FWHM of arc lines, was ∿ 3 channels corresponding to 0.21 A or 9.6 km s^{-1} at Hα. The orientation of the slit was N-S with a total length of 171 arcsec. The centre of the slit was placed halfway between GM24 and the extended nebula RWC 126 located ∿ 1 arcmin south of the cometary-like nebulosity in order to obtain spectra of both objects. The Hα and [NII] emission lines are present in almost all positions along the slit. Furthermore, no significant kinematical differences were found among the two regions. The FWHM of the Hα profile from the core of GM24 (x-sections 94 + 95) shows a ∿ 9 km s^{-1} broader profile than the corresponding one for RWC 126 (x-sections 29-31). The V_{LSR} of the Hα emission for GM24 peaks at -12.3 ± 1.5 km s^{-1}. This velocity is similar to the -10 km s^{-1} obtained from the $J = 1 \rightarrow 0$ CO measurements by Torrelles *et al.* (1983) and to the one reported here for the local molecular cloud. The similarity and continuity of the spectra suggest that GM24 and RWC 126 are physically connected. Figure 4 shows the Hα profile from the core of GM24.

The optical data and the proximity of the nebula to the radio peak, suggest that GM24 is the visible part of an embedded H II region that is beginning to emerge from the cloud.

c) *Radio Observations*

i) Continuum.

Observations at 6-cm of the region were made with the Very Large Array (*VLA*) of the National Radio Astronomy Observatory[1] in 1984 May. At the epoch of the observations the *VLA* was in the C configuration, providing an angular resolution of ∿ 3″ at 6-cm. We obtained a snapshot of the source using 1730–130 as phase calibrator and 3C286 as amplitude calibrator. The data were reduced following the standard *VLA* procedures. A strong source was detected and a map of it is shown in

1. NRAO is operated by Associated Universities, Inc., under contract with the National Science Foundation.

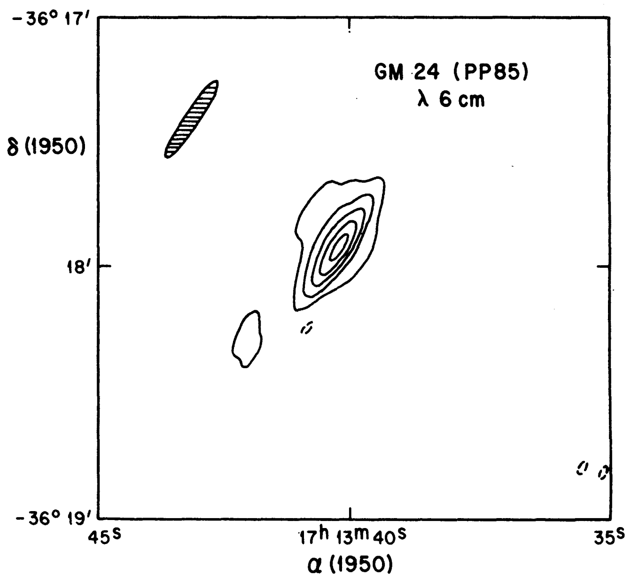

Fig. 5. *VLA* map of the GM24 compact H II region. Contours are −0.1, 0.1, 0.3, 0.5, 0.7 and 0.9 of the peak flux per synthesized beam, 1.20 Jy/beam. The integrated flux is 3.60 Jy. The angular size of the synthesized beam is 3″ X 22″. The NW-SE elongation of the beam is due to the low declination of the source.

Figure 5. Since the beam is very elongated in the NW-SE direction the source was not resolved in this direction. However, it is clearly resolved in the NE-SW direction. We have assumed that the source is a compact H II region associated with the GM24 cloud, since it coincides within ∿ 15″ with the hot CO spot detected by Torrelles *et al.* (1983). Its parameters are given in Table 3.

ii) Carbon Monoxide.

Observations of the J = 1 → 0 rotational transition of CO and ^{13}CO were obtained with the Millimeter Wave Observatory's[2] 4.9-m radio telescope in 1983 October and 1984 July. At the observed frequencies the beam has a HPFW of ∿ 2$'$.3. The data were obtained with a horn-fed cooled receiver and calibrated using an absorbing chopper. As a spectrometer we employed two filter banks of 128 X 62.5 kHz and 256 X 250.0 kHz in parallel. Torrelles *et al.* (1983) mapped in CO the core (∿ 5′) of the molecular cloud associated with GM24 with a higher angular resolution (∿ 1$'$.1). Our more extensive CO map, shown in Figure 6, indicates that the CO cloud has dimensions of ∿ 12′ X 24′ (∿ 6 X 12 pc at a distance of 1.7 kpc). We also obtained ^{13}CO spectra in 14 positions around the CO peak. The CO and ^{13}CO spectra at the

2. The MWO is operated by the Electrical Engineering Research Laboratory of the University of Texas at Austin, with support from the National Science Foundation and McDonald Observatory.

TABLE 3

PARAMETERS OF THE COMPACT H II REGION NEAR GM24[a]

Right Ascension (1950)	$17^h13^m40^s.3 \pm 0^s.1$
Declination (1950)	−36°17′56″ ± 2″
Flux density at 4.9 GHz	3.6 ± 0.2 Jy
Angular diameter at half maximum	6″ ± 1″
Physical diameter at half maximum	1.5×10^{17} cm
Electron density	2.4×10^4 cm^{-3}
Mass of ionized gas	1.2×10^{-1} $M_\odot$
Emission measure	4.4×10^7 cm^{-6} pc
Optical depth at 4.9 GHz	0.53
Required number of ionizing photons	9.4×10^{47} s^{-1}
Equivalent ZAMS star	O9

a. Assuming the source is a homogeneous sphere of ionized hydrogen with an electron temperature of 10^4 K. A distance of 1.7 kpc was adopted. The parameters were derived following Schraml and Mezger (1969) and Panagia (1973).

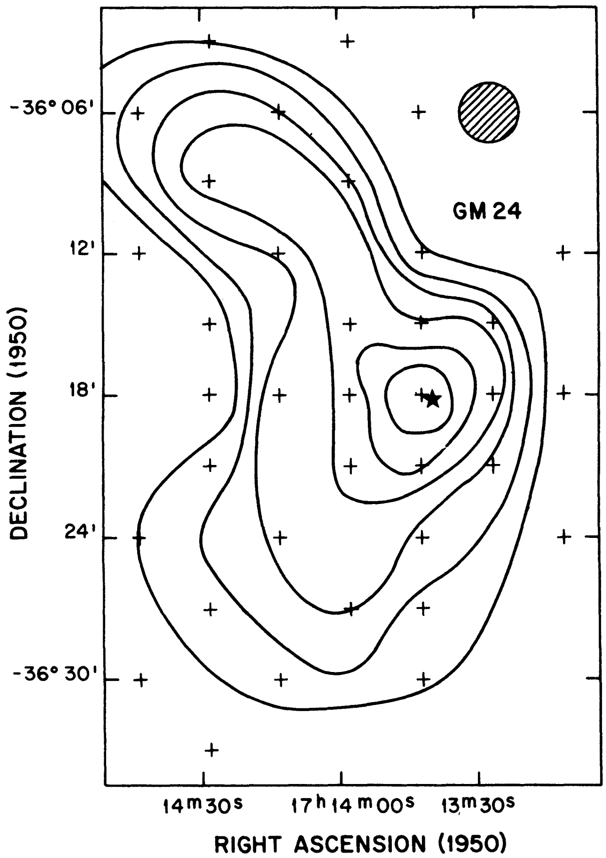

Fig. 6. Contour map of the peak CO radiation temperature (as defined by Kutner and Ulich 1981) for the GM24 region. Contours are 5, 10, 15, 20, 25 and 30 K. The star represents the position of the infrared multiple system and the compact radio H II region and the crosses (+) show the observed positions.

central position, $\alpha_{1950} = 17^h\ 13^m\ 42^s.0$, $\delta_{1950} = -36°\ 18'\ 00''$, have parameters T_R (CO) = 34 K, ΔV(CO) = 5 km s^{-1} V_{LSR} (CO) = −10 km s^{-1}, and T_R (^{13}CO) = 14 K, ΔV(^{13}CO) = 4 km s^{-1}, V_{LSR} (^{13}CO) = − 10 km s^{-1}, where T_R is the peak radiation temperature, ΔV is the full width at half maximum, and V_{LSR} is the radial velocity with respect to the local standard of rest. From these parameters and using the formulation of Dickman (1978) we derive N(^{13}CO) $\simeq 1.5 \times 10^{17}$ cm^{-2}, N(H_2) $\simeq 7.5 \times 10^{22}$ cm^{-2} and $A_V \simeq 60$ mag as average values for the column of gas observed in our beam ($\sim 2'.3$). Assuming that the cloud has a physical depth of ~ 6 pc, equal to its projected width, we obtain a density of n(H_2) $\simeq 4.0 \times 10^3$ cm^{-3}. We have ^{13}CO observations for the central $9' \times 9'$ of the cloud and from them we derive a mass for this region of $\sim 5 \times 10^3\ M_\odot$. We conservatively estimate a total mass of $\sim 10^4\ M_\odot$ for the whole cloud.

iii) Lack of H_2O and OH Maser Emission.

Using the 37-m radio telescope of the Haystack Observatory[3] we searched in 1984 May for H_2O maser emission around GM24 making a seven-point map (cf. Rodríguez *et al.* 1978). No H_2O maser emission was detected at a level of ~ 20 Jy (3σ) for the velocity range −135 to 135 km s^{-1}. This upper limit is not very stringent as a result of the low elevation of the source, but rules out the presence of strong H_2O maser emission.

In his OH survey, Turner (1979) observed a position that includes GM24 within the antenna beam. Only weak absorption was detected, and the presence of strong OH maser emission can also be ruled out.

III. DISCUSSION

a) *The Infrared Multiple System*

Four near-infrared (1-4 μm) emission peaks were found in a 1 arcmin diameter region centred on the brightest optical nebula GM24, very close to the CO "hot spot" observed by Torrelles *et al.* (1983). Figure 2 shows the presence of an extended emission at 1.65, 2.2 and 3.8 μm with four well defined maxima. The extended emission is not seen at 10 μm and 20 μm but a possible fifth source is revealed at these wavelengths.

With our spatial resolution, the brightest sources Irs 1 and 3 are not resolved at the longer wavelengths. These sources exhibit similarities in their infrared spectral distribution (see Figure 3); both rise steeply with wavelength. The black body temperatures fitted to the *MNQ* colours are 200 K < T < 400 K for Irs 1 and 150 K < T < 350 K for Irs 3 depending on the correction for interstellar extinction. These should represent the average temperatures of dust particles in dense circumstellar shells around Irs 1 and 3. The far-infrared emission reported by Emerson *et al.* (1973) and IRAS, most probably arises in these shells. Irs 1 and 3 and possibly Irs 5 are examples of the commonly observed massive, very young stellar objects embedded in the densest part of molecular clouds. The lack of bright H_2O and OH maser emission in their vicinity suggests that active star formation stopped about 10^5 years ago (Genzel and Downes 1979) in this region.

We suggest that Irs 2 is most probably associated with the compact radio H II region and with GM24. Its *JHKL'* energy distribution is consistent with free-free emission reddened by $A_V \simeq 12$ and an excess at $\lambda \geq 2.2$ μm due, most probably, to dust particles at 450 K < T < 600 K. The above parameters were computed by fitting the *(J–H)* colour index to the extrapolated free-free λ 6-cm flux (assuming a frequency dependence $S_\nu \propto \nu^{-0.1}$), a normal reddening and a black body. As shown in Table 3, the required ionizing photons for the radio H II region correspond to those provided by a ZAMS O9 star. The fact that Irs 2 has developed an H II region and that it is much less reddened than Irs 1 and 3 suggests that it is at a later stage of evolution and may be located in the outer part of the parental molecular cloud in the direction of the Sun. The total infrared (1-350 μm) flux of the cluster from the present observations and those by Emerson *et al.* (1973) is $3 \times 10^4\ L_\odot$ (at a distance of 1.7 kpc) which corresponds to three B0 ZAMS stars. The recently published IRAS fluxes (F_ν (12 μm) = 247 Jy, F_ν (25 μm) = 2505 Jy, F_ν (60 μm) = 10931 Jy and F_ν (100 μm) = 13512 Jy) are consistent with this total flux.

In view of the quite different mid-infrared (10-20 μm) behaviour of Irs 1, 3 and 5 on the one hand and Irs 2 and 4 on the other, it is surprising that all of them exhibit similar *JHKL'* colours.

The extended nature of the near-infrared (1-4 μm) emission and the fact that the emission also peaks strongly at Irs 1 and 3, can be interpreted in terms of a reflection nebula which scatters light from the central stellar objects which escapes through "cracks" or "holes" in their circumstellar dust shells. This near-infrared radiation may also come from small particles heated at large temperatures 700 K < T < 1100 K by Irs, 1, 2 and 3 as proposed by Sellgren (1984) for visual reflection nebulae. Irs 4 may be seen as a clump or "hole" in this picture. The small differences in the *JHKL'* energy distribution of Irs 1 and Irs 3 are explained by their different shell morphology. Similar infrared reflection nebulae have been proposed in NGC 7538-Irs 9 (Werner *et al.* 1979; Tokunaga, Lebofsky and Rieke 1981), NGC 6334V (Harvey and Wilking 1984; Simon *et al.* 1985) and GGD 12-15 (Harvey *et al.* 1985).

b) *Irs 6 and Irs 7*

These sources are located some 1 and 2 arcmin north of the infrared multiple system respectively. Their *JHKL'* colours suggest that both sources are background red-

3. Radio Astronomy at Haystack Observatory of the Northeast Radio Observatory Corporation is supported by the National Science Foundation under grant AST-82-10570.

dened stars. The fitted values for the visual extinction are $A_V \simeq 55$ for Irs 6 and $A_V \simeq 8\text{-}11$ (depending on its spectral type) for Irs 7; the former has no optical counterpart even on the deep IV Schmidt plates while Irs 7 is clearly visible in the short red plate Figure 1 (Plate 1).

c) *The H II Region*

The radio, infrared and visual data of GM24 are consistent with the presence of a symmetrical H II region ionized by an early (O9-B0) type star. Its association to the larger RWC 126 region seems clear from Hα spectroscopy.

IV. SCHEMATIC PICTURE OF GM24 AND CONCLUSIONS

In Section III we outlined the problem of the extended near-infrared emission. Were it not for the fact that Irs 1 and 3 peak sharply at 1.6, 2.2 and 3.8 μm, the extended emission could be attributed to the H II region. In any case, the size of the extended near-infrared emission exceeds by far the radio H II region. Therefore, we have to explain the presence of cool and warm dust around Irs 1 and 3.

It can be assumed that Irs 1 and 3 are formed deeper into the core of the cloud as compared to Irs 2. Due to the size of our beams (∿ 12″) our maps show a superposition of the point-like sources and their surroundings. If in addition we assume that the shrouds of Irs 1 and 3 are breaking up in a clumpy way, allowing some of the star's radiation to escape in random directions, the observed combined structures would resemble those observed in the maps and spectral distributions. The extended near-infrared emission has to be thought of, in this picture, as an infrared reflection nebula.

From all the above, we see GM24 and its surroundings as a molecular cloud of intermediate mass, in which a core has collapsed and has given way to the recently formed massive stars. The star formation process seems to have stopped in the near past (10^5 years).

Several observations are suggested: infrared polarization measurements should allow a better understanding of the extended near-infrared flux. Radio continuum observations obtained with a higher dynamical range, could reveal faint compact H II regions at the positions of Irs 1 and 3.

Our main conclusions are the following:

1. The present radio, infrared and optical observations of the environment of the GM24 = PP85 nebula reveal the presence of a region of recent star formation.

2. This region is embedded in a typical molecular cloud with a dimension of ∿ 10 pc and mass of ∿ 10^4 $M_\odot$.

3. A compact radio H II region associated with GM24 and an infrared peak were detected. The nebula is most probably the visible part of an embedded H II region that is starting to burst out of the cloud. Two other infrared peaks found in its vicinity are probably associated with less evolved objects.

4. The nature of the extended near-infrared flux is not clear but it may arise in a reflection nebula. Further observations are required.

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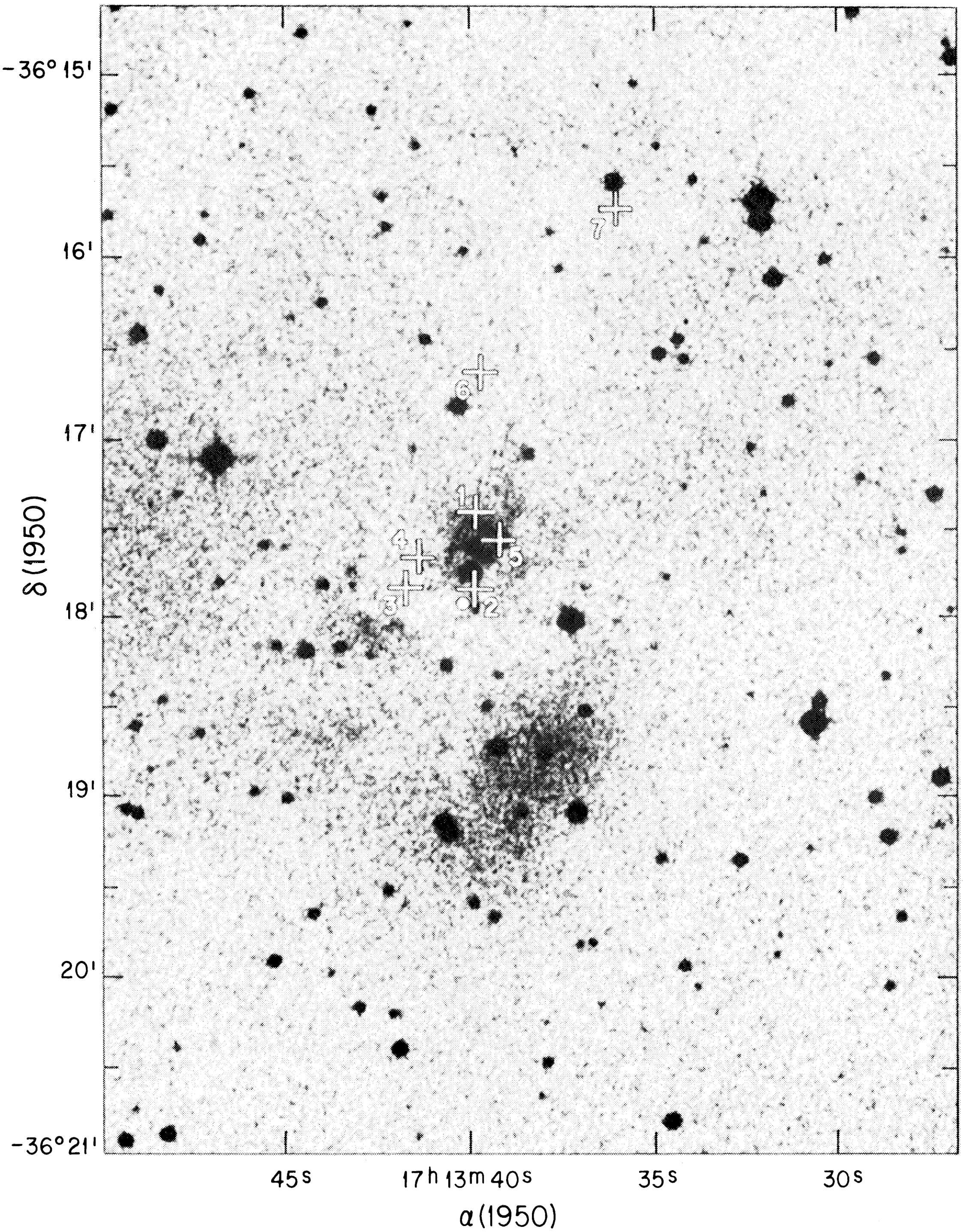

Fig. 1 (Plate 1). Enlarged copy of the Short Red UK Schmidt I/SR Atlas. The coordinates for the 1950 Epoch are indicated. These were determined by measuring the position of a number of stars in the area shown using as reference several *SAO* stars. The numbered crosses mark the position of the IR sources observed in the region. The dot marks the position of the compact radio H II region.

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