THE ASTROPHYSICAL JOURNAL, **208**:390–395, 1976 September 1

INFRARED OBSERVATIONS OF MONOCEROS R2

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Received 1975 December 22

ABSTRACT

A cluster of compact infrared sources plus extended emission has been found at the peak of the molecular cloud in Mon R2. The extended emission is probably due to heated dust associated with PKS 0605−06, a compact H II region embedded in the molecular cloud. Several of the compact infrared sources have properties indicative of protostars. For one of these, the associated dust is apparently seen in projection against the H II region.

Subject headings: clusters: associations — infrared: sources — interstellar: molecules — nebulae: individual

I. INTRODUCTION

Radio observations have revealed a strong source of molecular emission (Kutner and Tucker 1975; Loren, Peters, and Vanden Bout 1975) in the direction of Mon R2, an association of reflection nebulae studied by van den Bergh (1966) and Racine (1968). Although CO emission is extended over an area ~3°.5 × 3°.5, the strongest peak in the CO emission lies between two reflection nebulae and marks a dense condensation ~10′ × 10′ in extent where HCN, CS, and H_2CO are seen in emission. At the peak of the HCN and CS emission the ^{12}CO line becomes broader and is apparently self-absorbed—further indications of an active region. Because the ^{12}CO emission has secondary peaks on several reflection nebulae, the molecular cloud is assumed to be at the same distance as the R association, 950 pc (Racine and van den Bergh 1970).

An H II region, PKS 0605−06 (Shimmins *et al.* 1966), a Type I OH maser, and an H_2O maser (Downes *et al.* 1975; Knapp and Brown 1976) are also associated with Mon R2; recent studies (Brown, Knapp, and Kuiper 1976; Downes *et al.* 1975) indicate that most of the radio continuum flux comes from a small spherical region ~20″ in diameter. The presence of the masers and a compact H II region suggests a site of active star formation.

In this paper infrared observations are presented which show the existence of extended emission plus compact sources. These observations are consistent with the idea that sources are in an early evolutionary state. Infrared observations of this region have also been made by Kleinmann (1975).

II. OBSERVATIONS

The observations were made at Cassegrain foci of the 1.5 m telescope at Mount Wilson and the 5 m Hale telescope. A helium-cooled germanium bolometer was the detector for all observations at $\lambda \geq 4.8\ \mu$; at $\lambda < 4.8\ \mu$ a liquid-nitrogen–cooled InSb detector operating in the photovoltaic mode was used. Wavelength ranges and calibrations are listed in Table 1.

Maps with 10″ resolution were made by scanning in declination at wavelengths of 10 μ and 20 μ at the 1.5 m telescope and at wavelengths of 2.2 μ and 1.65 μ at the 5 m telescope. The position of each map was determined with reference to a visual field star whose coordinates were determined by measurement of the Palomar Sky Survey plate of the region. In addition to the maps, single scans with 5″ resolution at 1.65 μ and 2.2 μ were made in right ascension and declination near the central portion of the maps. Photometric measurements, using the wavelength bands defined in Table 1, were made on most of the discrete sources found during mapping of the region.

In addition to the maps and photometry, declination scans of the two strongest discrete sources were made at 8.7, 9.5, 11.2, 12.5, and 20 μ on the 5 m telescope with a 0″.5 × 3″ slit (declination × right ascension) on a night of good seeing. By comparing scans across each source with scans across a nearby star it is possible to detect a source extension greater than 0″.1 full width at half-maximum.

TABLE 1
WAVELENGTH BANDS AND FLUX CALIBRATION

λ (μ)	Δλ (μ)	F_ν of Zeroth Mag (Jy)
1.65...........	0.3	980
2.2............	0.4	620
3.4............	0.6	280
4.8............	0.6	150
8.7............	1.2	50
9.5............	1.5	42
10.............	5	37
11.2...........	1.5	30
12.5...........	1.3	24
20.............	9	10

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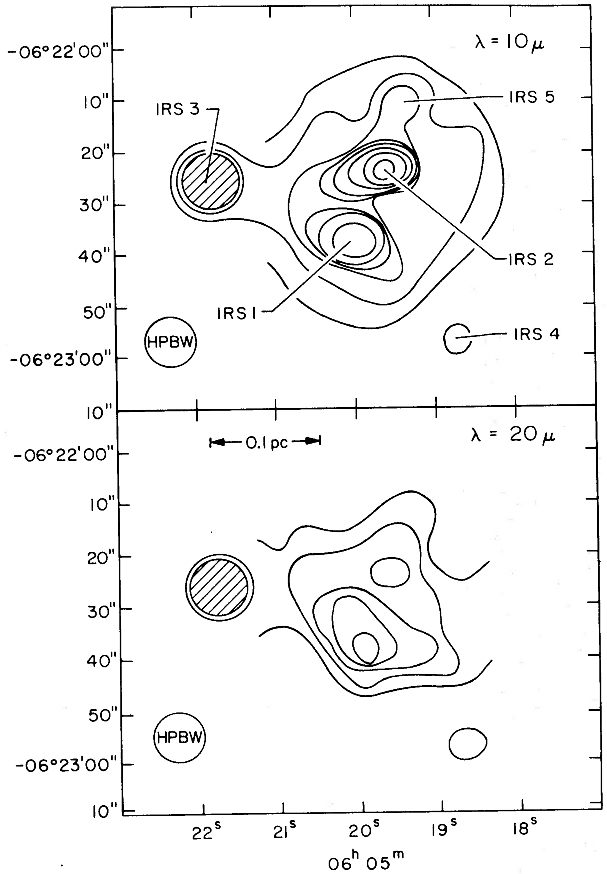

FIG. 1.—Maps of Mon R2 at 10 and 20 μ are given. The aperture at both wavelengths is 9″. The spacing for sky cancellation was 27″ at 10 μ and 40″ at 20 μ. The contours on the 10 μ map are (1.3, 2.7, 4.0, 5.3, 6.6, 13, 20, and 27) × 10^9 Jy sr^{-1}. On the 20 μ map the contours are (10, 20, 40, 60, and 80) × 10^9 Jy sr^{-1}. Neither map is complete east of $06^h05^m21^s$. IRS 3 has a peak flux of 120 Jy in a 9″ aperture at 10 μ and 450 μ in a 9″ aperture at 20 μ.

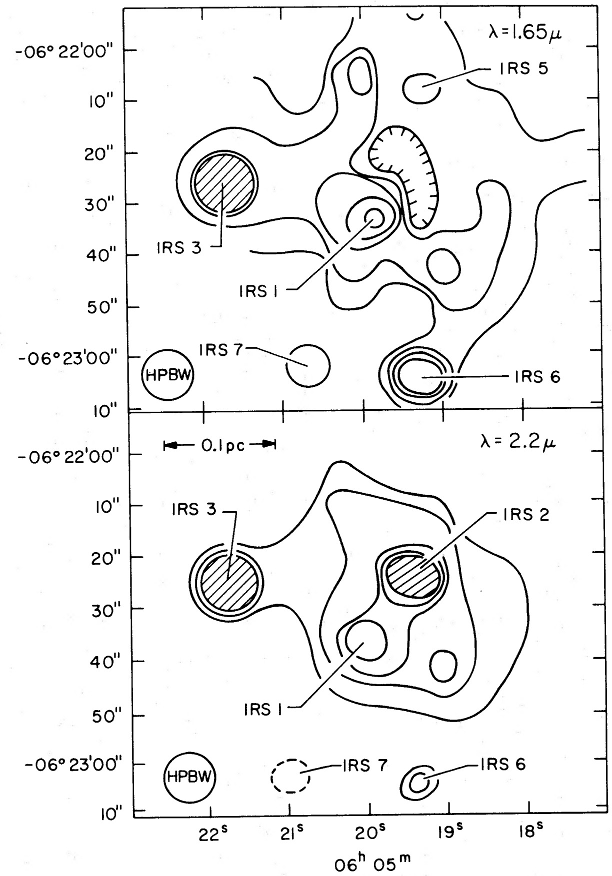

FIG. 2.—Maps of Mon R2 at 1.65 and 2.2 μ are given with apertures of 10″. Sky chopping with a north-south spacing of 42″ at 2.2 μ was used to cancel the background radiation; at 1.65 μ no sky cancellation was used. The contours are spaced by 4.7 × 10^6 Jy sr^{-1} on the 1.65 μ map and 1.6 × 10^7 Jy sr^{-1} on the 2.2 μ map; the dashed contour on the 2.2 μ map is at a level of 0.8 × 10^7 Jy sr^{-1}. The peak flux of IRS 3 in the apertures used is 0.15 Jy at 1.65 μ and 1.5 Jy at 2.2 μ. IRS 2 has a peak flux in a 10″ aperture of 0.3 Jy at 2.2 μ. The flagged contour on the 1.65 μ map around the position of IRS 2 represents an area of decreased flux. The maps are not complete east of $6^h05^m21^s$.

III. RESULTS

The 10 and 20 μ maps are shown in Figure 1; the 1.65 and 2.2 μ maps are shown in Figure 2. At all wavelengths there is emission extended over ~30″ × 30″ as well as discrete sources. Five discrete sources, denoted IRS 1 through 5, are seen at 10 μ. Figures 3 and 4 show the energy distributions of the discrete sources and the extended emission; Table 2 summarizes several parameters. Two additional discrete sources, labeled IRS 6 and IRS 7, appear on the 1.65 and 2.2 μ maps. Because only limited information is available on these sources, they will not be discussed further in this paper.

The slit scans of IRS 3 resolved the source at all wavelengths. At 8.7, 12.5, and 20 μ IRS 3 is extended with a full width for a Gaussian source on the order of 0″.4; within the silicate band at 9.5 and 11.2 μ the scans indicate an angular size on the order of 0″.2. The 8.7, 12.5, and 20 μ data can be fitted equally well if IRS 3 is assumed to consist of two point sources separated by about 0″.4. The slit scans failed to resolve IRS 2, putting a limit on its size of <0″.2 at 8.7 μ through 20 μ.

The right ascension and declination scans with 5″ resolution were positioned to cross IRS 2 and show structure consistent with Figure 1 but not resolved with the 10″ aperture used to produce the maps of Figure 1. In particular the 1.65 μ east-west scan through IRS 2 shows a definite minimum ~5″ east of IRS 2, while the declination scan with 5″ resolution shows a broad minimum to the south of IRS 2; the 1.65 μ flux at IRS 2 in a 5″ aperture is less than 3 mJy (5 × 10^6 Jy sr^{-1}). At 2.2 μ there is also a definite minimum at the same position in the background, although it is partially masked by IRS 2. At this minimum the 2.2–1.6 μ color is significantly redder than in the rest of the extended emission.

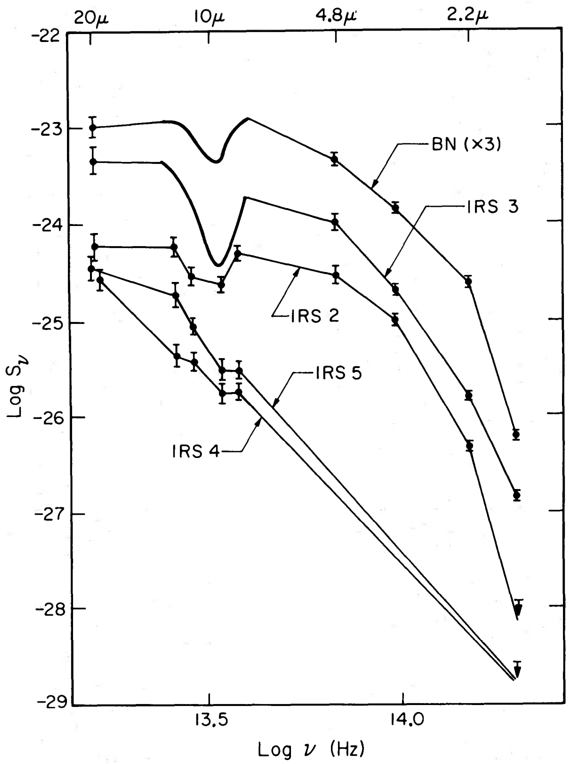

FIG. 3.—The infrared energy distributions of IRS 2 through IRS 5 are given. The spectrum of the Becklin-Neugebauer object in Orion at 3 times the actual flux density is plotted for comparison (Becklin, Neugebauer, and Wynn-Williams 1973). IRS 2 and IRS 3 were measured at the Mount Wilson 1.5 m with a 9″ aperture and 13″ sky separation; IRS 4 and 5 were measured at the 5 m telescope with a 4″ aperture and 10″ sky separation. The heavy line in the energy distribution of IRS 3 represents a spectrum obtained with 1 percent spectral resolution by S. Willner (1975). S_ν in W m^{-2} Hz^{-1}.

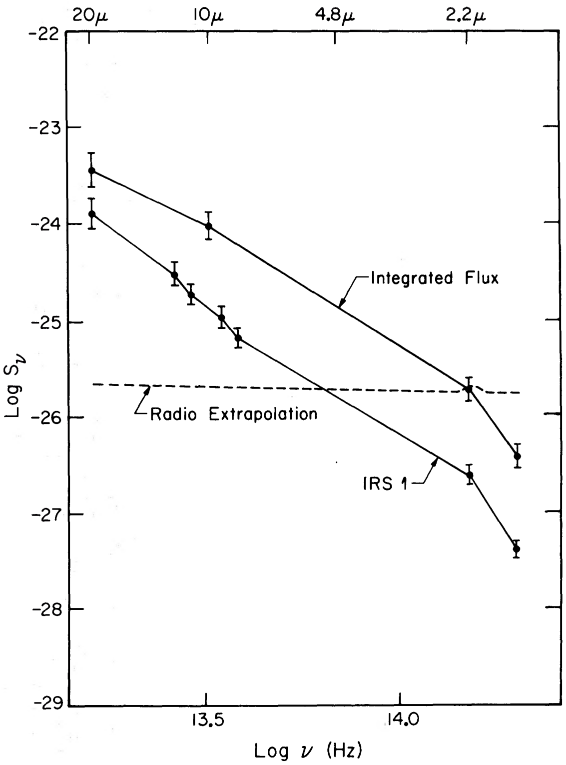

FIG. 4.—The infrared energy distributions of IRS 1 and of the total extended emission, removing the contribution of IRS 2 and IRS 3, are plotted. The dashed line indicates the infrared flux expected from the ionized gas, based on an extrapolation of the radio data. S_ν in W m^{-2} Hz^{-1}.

In contrast to IRS 2 and IRS 3, IRS 1 is extended at 10 μ by about 10″; its extent at 20 μ is about 15″ to 20″. The 1.65–20 μ spectrum of IRS 1 is close to a power law, with no turnover at 20 μ. The absence of a silicate feature in IRS 1 should be contrasted with the presence of the silicate absorption at 10 μ in the nearby IRS 2 and IRS 3. Figure 4 shows the spectrum of the total extended emission around IRS 1 and IRS 2 obtained by integrating the entire flux from the maps; the fluxes from IRS 2 and IRS 3 have been excluded. The spectrum of the extended emission is very similar to that of IRS 1.

IV. DISCUSSION

The infrared emission from the direction of the dense molecular cloud in Mon R2 consists of emission from

TABLE 2

SUMMARY OF PARAMETERS

Object	Observed 1–25 μ Luminosity ($L_\odot$)	$\tau_{9.5}$*	Color Temperature† (K)	10 μ Size‡ (× 10^{15} cm)
IRS 1...............	500 ± 200	< 0.3	...	140
IRS 2...............	700 ± 200	1	400	< 3§
IRS 3...............	3000 ± 10000	2	400	5§
IRS 4...............	< 100	...	< 400	< 28‖
IRS 5...............	< 200	...	< 400	< 28‖
Extended source......	4000 ± 1000	...	...	420

* Estimated from the depth at 9.5 μ below a blackbody fit to the 1–20 μ data.

† For IRS 2 and IRS 3 a best-fit blackbody to 1–20 μ points.

‡ Assuming a distance to the source of 950 pc.

§ From 0″.5 slit scans at 8.7 μ and 12.5 μ.

‖ From scans with 5″ circular aperture.

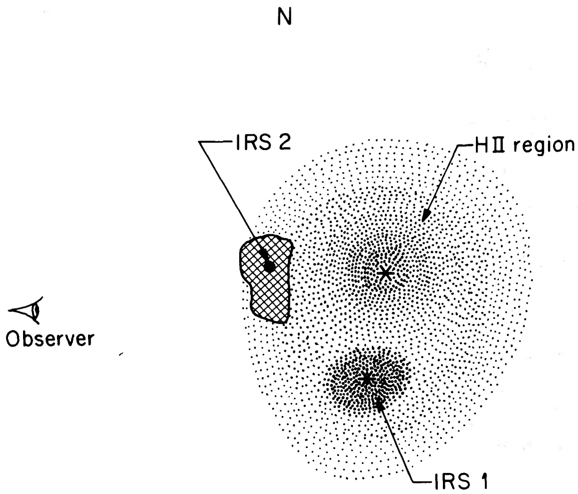

FIG. 5.—The drawing gives a very schematic representation of the model postulated for the H II region, IRS 1 and IRS 2; north is up. The dust associated with IRS 2 obscures the 1.65 μ radiation of the H II region. The asterisks show two possible positions of the exciting star.

both an extended source and several compact objects. It is argued below that most of the extended emission, including that from IRS 1, is due to dust associated with an H II region. The compact infrared sources are best explained by stellar or protostellar objects, each embedded in its own dust cloud. A suggested geometry is shown in Figure 5 and will be discussed below.

a) The Extended Emission and IRS 1

The extended emission of Figure 1 appears to be similar in size and position to the H II region PKS 0605−06. Furthermore, since the spectra of both IRS 1 and the extended emission are similar to each other and to the spectra of other H II regions (Becklin *et al.* 1973), these two sources will be considered together. We will interpret the extended infrared emission, including IRS 1, as due to dust and gas associated with the H II region.

Brown, Knapp, and Kuiper (1976), using the NRAO interferometer at 11 cm, find a 6 Jy source which they model as a spherical H II region 20″ in diameter, centered on IRS 1. Downes *et al.* (1975) at Westerbork find a region of similar size as well as an unresolved ($<4''$) source of 0.3 Jy at the center of the more extended radio emission. If the H II region is at 950 parsecs and at a temperature of 10^4 K, the number of Lyman continuum photons from the exciting star needed to produce a 6 Jy source is 5.6×10^{47} s^{-1} (cf. Rubin 1968). Following Panagia (1973), this number implies a total stellar luminosity $> 3.5 \times 10^4\ L_\odot$ for an exciting star on or above the main sequence. Measurements of this region with a 1′ beam in the 30–120 μ range by Harper (1975) and in the 1 mm continuum by Werner (1975), together with the data presented here, yield a total infrared luminosity of $2.5 \times 10^4\ L_\odot$; this agrees with the expected value for the stellar luminosity.

b) The Compact Objects IRS 2–IRS 5

The energy distributions of the compact objects IRS 2–IRS 5 are grossly similar to each other in containing an absorption feature at $\sim 10\ \mu$, and differ qualitatively from those of IRS 1 and the extended emission. The characteristics of IRS 2 and IRS 3 are readily explained if the infrared radiation is assumed to originate from dust heated to temperatures on the order of 500 K by a source embedded inside the dust, and it will henceforth be assumed that the infrared radiation from IRS 2 and IRS 3 is, in fact, thermal radiation from dust. Since they are compact and very red, IRS 4 and IRS 5, for which only limited photometry is available, will be assumed to be similar in nature to IRS 2 and IRS 3, but less luminous. This assumption is not crucial to the picture of Mon R2 presented below.

Table 2 summarizes the relevant information derived from the spectra. The 1–20 μ luminosities for IRS 2 and IRS 3 will be assumed to be their total luminosities, since the energy distributions have essentially turned over at 20 μ. The 10 μ absorption features in these energy distributions are normally attributed to the presence of silicates in the material in front of the source; this absorption has not been taken into account in the luminosities of Table 2. Since the absorption is present in IRS 2 but is absent in IRS 1, it is assumed to be localized within the compact source.

The declination scans of IRS 3 can be fitted equally well by the convolution of the seeing profile with either a single extended source or with two point sources, and there is no direct evidence from the scans to discriminate between the two. If IRS 3 is a single extended source with a diameter $\sim 0''.4$ and a temperature of ~ 400 K—its 2–20 μ color temperature—then its emissivity would be ~ 0.1. There are, however, two lines of reasoning which argue that the source function consists of two discrete sources. First, if IRS 3 contains a single source of $L \approx 3000\ L_\odot$ embedded in and illuminating gray particles, the temperature of the particles at a distance of 2×10^{15} cm from the embedded source would have an equilibrium temperature of ~ 150 K rather than the observed color temperature of 400 K. This discrepancy can be resolved if the emissivity of the grains decreases with increasing wavelength, since this both raises the physical temperature of the grains and tends to make the color temperature an overestimate of the physical temperature. Second, a model with two discrete sources, each surrounded by its own dust cloud with a characteristic silicate feature, offers a ready explanation for the apparent change in size with wavelength throughout the 9.5 to 11.2 μ silicate absorption feature. This situation is reminiscent of W3 IRS 5, a source which has been clearly resolved into two discrete sources with differing amounts of silicate absorption in each (Becklin and Neugebauer 1976). Neither of the above arguments is convincing proof that IRS 3 is composed of two separate sources, but the possibility certainly cannot be ruled out.

Figure 5 shows a proposed geometry for the H II region, IRS 1, and IRS 2; a unique feature of the geometry of Figure 5 is the placement of IRS 2 and its associated dust cloud between the H II region and the observer, as deduced from the decreased 1.65 μ emission observed from the neighborhood of IRS 2. In particular, for an area with dimensions $\sim 10''$, the 1.65 μ flux expected from this H II region, if unobscured, is much greater than the flux observed from the area of IRS 2. We therefore deduce that there must be an absorbing cloud of material roughly $10''$ in size between the H II region and the observer. In the proposed model this cloud is associated with IRS 2 and is located in front of the H II region. An alternative configuration will be described in § IV*c*.

If the infrared radiation comes from heated dust, the nature of the internal heat sources can be determined only on the basis of plausibility arguments. Since the infrared cluster is embedded in a molecular cloud and is associated with an H II region, a Type I OH maser, and a H_2O maser, it is likely that the compact sources are young objects.

If the proposed model is correct, it is possible to study, for the first time, the density distribution of dust around an infrared star through its attenuation of the 1.65 μ flux of the H II region. In particular, the luminosity and wavelength of maximum emission of IRS 2 agree well with Larson's (1972) models for a protostar of 5–10 $M_\odot$ which has accreted half its mass. According to that author, the density profile of a 10 $M_\odot$ protostar at this stage is $1.4 \times 10^6 r^{-3/2}$ g cm^{-3}, where r is the distance in cm from the central star. If the opacity law is proportional to $\lambda^{-3/2}$, as suggested by Larson, the diameter of the region that will be optically thick at 1.65 μ is $\sim 10^{17}$ cm or $6''$; this is comparable to the observed size. A more general prediction of Larson's model is that the size of the optically thick region will vary inversely as the cube of the wavelength. The scans with $5''$ resolution indicate that at 2.2 μ the region which is optically thick has a size comparable to that at 1.65 μ. Since this prediction depends only on the forms of the opacity and density laws, this application of this Larson's model is oversimplified.

It is also possible that the compact objects are evolved stars that have ejected mass to form dust shells; late-type giants and supergiants often possess such dust shells (see, e.g., Humphreys and Ney 1975). Although the infrared properties of any given compact object could be explained by such a star, the simultaneous presence of at least four such objects with the wide range of luminosities indicated in Table 2 is implausible because of the great differences in evolution time scales associated with stars of differing luminosity. Furthermore, the luminosities of IRS 2, 4, and 5 are such that they require stars less massive than 5 $M_\odot$, whose main-sequence lifetimes exceed 6×10^7 years (cf. Iben 1967). This is much longer than the free-fall time T_{FF} of the dense portion of the molecular cloud, $T_{FF} \leqslant 4 \times 10^5$ years if the density $\geq 10^4$ cm^{-3}.

c) *Reddened Star Model for Compact Objects*

Penston, Allen, and Hyland (1971) and Allen and Penston (1974) have explained W3 IRS 5 and the Becklin-Neugebauer and other infrared point sources in Orion as background stars reddened by as much as 90 magnitudes of visual extinction by foreground material. A similar explanation could be forwarded for the compact sources in Mon R2. This model, however, requires a geometry with a highly luminous star behind the densest portion of a molecular cloud. Such special conditions make this model less and less plausible as more such sources are found. In any case, IRS 2 is an especially dubious candidate for such an explanation. As discussed in § III, IRS 2 lies at a local minimum in the 1.65 μ emission, indicating that the H II region is obscured at 1.65 μ. Thus there must be a chance alignment of the distant star and the obscuring cloud. In contrast, the observations find a natural explanation if the radiation from IRS 2 is due to heated dust near the center of the absorbing cloud. We conclude that the infrared radiation from the compact sources in Mon R2 is not from reddened background stars.

d) *The Exciting Star of the* H II *Region*

On the basis of its derived Lyman continuum flux, the spectral type of the exciting star is B0 (ZAMS); the 1.65 μ flux from such a star is 1.2 Jy. Because this flux is 3 times greater than the average radiation from the gas in the H II region into a $10''$ beam, the star should be seen at 1.65 μ. The locations of IRS 3, 6, and 7 make them implausible candidates for the exciting star. The only strong 1.65 μ source within the H II region is IRS 1. From the observations, any star must have an observed 1.65 μ flux of less than 0.04 Jy. A star with 1.2 Jy thus requires at least 3.7 magnitudes of extinction at 1.65 μ. If the observed 1.65 μ flux from the extended source is all recombination radiation, the average extinction at 1.65 μ would be ~ 2.0 magnitudes. Since this is a lower limit to the extinction and because IRS 1 peaks on the center of the H II region, it is likely that the exciting star is contained in IRS 1. It is also possible that the exciting star lies behind a dust condensation with an extinction much higher than the average extinction to the H II region. Because of its location in front of the H II region, the dust cloud around IRS 2 presents a possible source for the obscuration.

It should be noted that a star is visible on the Palomar Sky Survey print near the peak of IRS 1. The required 3.7 magnitudes of extinction at 1.65 μ implies at least 22 magnitudes of visual extinction, thus ruling out this star as a possible exciting star for the H II region.

V. CONCLUSIONS

A cluster of compact infrared sources has been found within the densest portion of the molecular cloud associated with Mon R2. In addition, an extended infrared component is apparently associated with a compact H II region embedded in the cloud. The compact sources have properties similar to compact infrared sources associated with molecular clouds in Orion and W3, areas where star formation is believed to be taking place.

For one of the compact objects, an associated dust concentration is apparently seen in projection against the compact H II region. Hence, for the first time, one has the potential of mapping the dust distribution around a possible protostar by studying the shadowing of the 1–2 μ radiation from the H II region.

We are grateful for comments and help by Jay Frogel, Ian Gatley, Peter Goldreich, Keith Matthews, Eric Persson, Mike Werner, and Steve Willner. We would also like to thank Juan Carrasco, Jim Frazier, Howard Lanning, and Gary Tuton for assistance with the observations. This work was supported in part by National Aeronautics and Space Administration grant NGL 05-002-207 and National Science Foundation grant MPS 74-18555A01. N. J. E. was supported by National Science Foundation grant MPS 73-04677A01.

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