NEW MULTIPLE SYSTEMS IN MOLECULAR CLOUDS

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ABSTRACT

Twenty micron searches of the dense cores of the molecular clouds S140, S255, and Cepheus A have revealed the existence of multiple sources of infrared radiation which seem to be precursors to Trapezium-like clusters of OB stars. Two of the new sources are extended with unusually low color temperatures, less than 100 K. Observations with the Very Large Array with 1 m Jy sensitivity have shown that three and possibly four of the infrared sources are associated with small H II regions. Multiple systems appear to be the rule rather than the exception in molecular clouds.

Subject headings: infrared: sources — interstellar: molecules — nebulae: general

I. INTRODUCTION

As part of a larger program, we have used the 2.2 m telescope on Mauna Kea to examine `hot spots' in molecular clouds \( T^{12} \text{CO} \gtrsim 20 \text{ K} \) in search of infrared sources, presumed to be massive stars in the early stages of evolution (Werner, Becklin, and Neugebauer 1977). This search has been made at 20 \( \mu \text{m} \) for maximum sensitivity to cool sources. This letter reports the discovery of groups of infrared sources in three molecular clouds, all of which have \( ^{12} \text{CO} \) column densities \( \gtrsim 4 \times 10^{16} \text{ cm}^{-2} \).

The typical bolometric luminosities of the infrared objects found in this survey, \( 10^{4}-10^{5} L_{\odot} \), suggest that they are, or might become, late O or early B stars. There are theoretical reasons for expecting that, in the process of formation, protostars of this luminosity develop hot cores while continuing to accrete surrounding material (Larson and Starrfield 1971; Yorke and Krügel 1977). Very compact H II regions may therefore be associated with these objects. Observations of infrared recombination lines have demonstrated the existence of ionized gas around a few infrared sources (Grasdalen 1976; Hall et al. 1978), but extinction and low spectral resolution limit the sensitivity of these lines as a probe for ionized material. We have therefore used the Very Large Array (VLA) of the National Radio Astronomy Observatory1 to look for the 6 cm radiation from the infrared objects studied at Mauna Kea. The VLA data on S140 and S255 are 2 to 10 times more sensitive than earlier work (Israel 1976; W. Gilmore and R. L. Brown 1977, private communication cited in Blair et al. 1978), and 15 to 90 times more sensitive to ionized gas than the infrared recombination line studies of these objects (Dinerstein, Lester, and Rank 1979; Simon, Simon, and Joyce 1979) in those cases where the radio emission is not self-absorbed.

II. OBSERVATIONS

Infrared observations were made during 1977–1978 using the 2.2 m telescope at Mauna Kea with a liquid-helium-cooled bolometer and filters spanning 7.8–25 \( \mu \text{m} \) (Dyck and Simon 1977). Maps were made using the \( f/35 \) chopping secondary with two 7" beams separated by 15" in the north-south direction. The 20 \( \mu \text{m} \) maps are complete down to a sensitivity (to point sources) of 20 Jy. Positions were determined by offsetting from nearby SAO stars and are accurate to \( \pm 3'' \).

Observations of the 6 cm (4.8851 GHz) continuum were made using the VLA during a 24 hour run on 1979 January 11–12. Seven antennas were available out to 17 km on the southwest arm, six antennas out to 2 km on the southeast arm, and one antenna at 0.4 km on the north arm. For most of the day technical problems and maintenance requirements restricted the number of usable antennas to about 12. Both senses of circular polarization were observed and the data were combined for maximum sensitivity. The bandwidth for all observations was 50 MHz. The observing procedure was to look at a source for about 25 minutes and then go to a nearby standard for a 3 minute phase calibration. The flux calibration is based on an observation of 3C 286, whose 6 cm flux is 7.41 Jy. The sources were observed 6 to 8 times at a variety of hour angles to provide reasonable coverage in the UV plane. The beam shape and sensitivity varied with declination, but a typical beam diameter was 1.0 with a 3 \( \sigma \) noise level of 1 mJy after 3 hours. No "cleaning" algorithms were applied to the maps.

Observations were made at 30–200 \( \mu \text{m} \) of S255 using the Kuiper Airborne Observatory and the photometer described by Gatley et al. (1977). Data taken with a 1' beam in a 3' cross around the position of peak emission were combined to give the total luminosity of the 3' diameter region (Table 1).

III. RESULTS

Figures 1–3 show infrared and radio maps of the three regions discussed in this Letter. Figure 4 shows the 7.8–25 \( \mu \text{m} \) energy distributions in a 6.5 beam at the positions of maximum 20 \( \mu \text{m} \) emission. Table 1 gives the integrated 5 GHz flux densities and sizes for the sources, together with the photoionization rate, \( N_{\gamma} \), derived from Rubin's (1968) formula for an optically

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1 The National Radio Astronomy Observatory is operated by Associated Universities, Inc., under contract with the National Science Foundation.
TABLE 1

<table>
<thead>
<tr>
<th>Source</th>
<th>$S_{1.4}$ (mJy)</th>
<th>6 cm size (arcsec)</th>
<th>$N_L$ ($10^{24}$ s$^{-1}$)</th>
<th>$L_{20 \mu m}$ ($10^8 L_\odot$)</th>
<th>$L_{tot}$ ($10^9 L_\odot$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cep A 1</td>
<td>15±4</td>
<td>4×1</td>
<td>7</td>
<td>0.3</td>
<td>50±</td>
</tr>
<tr>
<td>Cep A 2</td>
<td>6±2</td>
<td>2×1</td>
<td>3</td>
<td>0.7</td>
<td>...</td>
</tr>
<tr>
<td>Cep A 3</td>
<td>4±2</td>
<td>2×1</td>
<td>2</td>
<td>1.4</td>
<td>44±</td>
</tr>
<tr>
<td>S140 IRS 1</td>
<td>6±1</td>
<td>2×1</td>
<td>4</td>
<td>4.2</td>
<td>...</td>
</tr>
<tr>
<td>S140 IRS 2</td>
<td>2±1</td>
<td>1</td>
<td>1.5</td>
<td>0.2</td>
<td>14±</td>
</tr>
<tr>
<td>S140 IRS 3</td>
<td>&lt;0.8</td>
<td>&lt;0.6</td>
<td>0.4</td>
<td>0.4</td>
<td>...</td>
</tr>
<tr>
<td>S140 NW</td>
<td>1±0.5</td>
<td>&lt;1</td>
<td>0.7</td>
<td>1.0</td>
<td>...</td>
</tr>
<tr>
<td>S255 IRS 1</td>
<td>&lt;1.6</td>
<td>...</td>
<td>&lt;9</td>
<td>9.4</td>
<td>...</td>
</tr>
<tr>
<td>S255 IRS 2</td>
<td>6±3</td>
<td>3</td>
<td>2.7</td>
<td>80</td>
<td>...</td>
</tr>
</tbody>
</table>

*Koppenaal et al. (1979) in a 4.5' beam.

The 6 cm map of the region (Fig. 1) shows three extended radio sources apparently associated with the infrared emission. The radio objects are probably not extragalactic, as fewer than one 1 mJy source per 5' diameter field is expected at 6 cm (Wall and Cooke 1975). The separation of the three radio sources is of the same order as the size of the infrared object, suggesting that the infrared extent might be due to the observation of multiple sources at low spatial resolution. The difference in position between the centroids of the radio and infrared emission is no larger than the infrared positional uncertainty.

The ionizing flux inferred for each of the three radio sources corresponds to a ZAMS B2 star, according to Panagia's (1973) calculations. The total luminosity of three such stars would be about 1.0 $\times$ 10$^8 L_\odot$, a factor of 5 less than the total infrared luminosity observed from the region by Koppenaal et al. (1979) in a 4.5' beam.

b) Sharpless 140

Blair et al. (1978) discovered and studied at 1–20 $\mu$m a bright infrared object (hereafter designated S140 IRS 1) in the Sharpless 140 molecular cloud, 0.9 kpc away (Crampton and Fisher 1974). Scans of a 1.0 $\times$ 1.5' region around S140 IRS 1 at 20 $\mu$m from Mauna Kea have led to the discovery of two additional sources of radiation which we have named S140 IRS 2 and S140 IRS 3 (Fig. 2). As can be seen in the energy distributions of Figure 4, the new sources are redder and a factor of 7–10 times fainter than S140 IRS 1 at 20 $\mu$m. All three sources show silicate absorption at 10 $\mu$m. The absolute position of S140 IRS 1, determined at 2.2 $\mu$m $\alpha(1950) = 22^h 17^m 41^s 5, \delta(1950) = 63^\circ 03' 40'' \pm 3''$, agrees within the errors with that determined by Dinerstein et al. at 4 $\mu$m. S140 IRS 1 also coincides with the brightest region of 0.9 $\mu$m emission found by the latter authors.

VLA observations (Fig. 2) show two radio sources, one extended and one unresolved, coincident, within the uncertainties, with S140 IRS 1. An extended radio source lies within 3' of S140 IRS 2; while a marginally

thin gas at 10$^4$ K. Also shown are the 7.8–25 $\mu$m luminosities (integrated over the source if extended) of the infrared sources described in this Letter as well as the 30–200 $\mu$m luminosities determined from airborne observations.

a) Cepheus A

Sargent (1977) has made extensive molecular line observations within the Cepheus OB3 association and has found several clouds, the densest of which she designated Cep A. The distance to the association is 0.73 kpc (Garmany 1973). Our 20 $\mu$m searches of the central 2' of Cep A revealed the existence of an extended source which lies close to a group of very strong H2O masers (Blitz and Lada 1979; Lada et al. 1979). The source has a 12–25 $\mu$m color temperature of 88 K, making it one of the coldest objects yet detected from a ground-based infrared telescope. Although the object was too faint to map in detail, repeated scans across the source in both north-south and east-west directions showed it to be extended on a scale of 9'.

Fig. 1.—A 6 cm map of the Cep A region with contours drawn at 20%, 40%, 60%, and 80% of the peak flux of 3.5 mJy in a 1.2 by 0.7 beam. The dashed circle indicates the approximate extent of the 20 $\mu$m emission. The shaded ellipse corresponds to the half-power size of the synthesized radio beam. The two crosses mark the VLBI positions of the two main concentrations of H2O maser sources (Lada et al. 1979).
significant fourth source, called S140 NW, coincides with the northwest patch of 0.9 μm nebulosity; S140 IRS 3 coincides with some 0.9 μm nebulosity, but shows no pointlike 6 cm counterpart brighter than 0.8 mJy.

On the assumption that S140 IRS 1 is responsible for most of the observed energy output, then its bolometric luminosity is comparable to that of a ZAMS B0 star. The observed radio flux is a factor of 50 less than the amount expected from such a star, coming closer to that expected from a B2 star.

The 0.9 μm fluxes from S140 IRS 1 and 3 are compatible with the idea that this light represents either the direct or scattered light from B stars hidden behind 20–30 mag of visual extinction. This amount of extinction is also consistent with the depths of the silicate features seen toward the two objects.

**Fig. 2.**—Twenty micron and 6 cm maps of the S140 region. The 20 μm contours are drawn at 5%, 10%, 20%, 40%, 60%, and 80% of the peak flux of 690 Jy in a 6.5 beam (FWHM). Contours on the 6 cm map are shown at 20%, 40%, 60%, and 80% of the peak flux of 2.6 mJy in a 1.7 by 1.0 beam. The dotted contours are at the −20% level. The dashed areas correspond to the 0.9 μm nebulosity observed by Dinerstein et al. The large cross marks the position of the H₂O maser (Genzel and Downes 1979).

**Fig. 3.**—Twenty micron and 6 cm maps of the S255 region. The 20 μm contours are drawn at 10%, 20%, 40%, 60%, and 80% of the peak flux of 120 Jy in a 6.7 beam. Contours on the 6 cm map are shown at 50% and 90% of the peak flux of 1.6 mJy in a 1.2 by 1.0 beam. Dotted contours are at the −50% level. The large cross in the northwest marks the position of the H₂O maser (Lo and Burke 1973; Genzel and Downes 1977).
The level of radio emission from S255 is several hundred times less than the maximum possible on the assumption that the far-infrared luminosity of $8 \times 10^4 L_\odot$ is produced by a pair of ZAMS O9.5 stars.

**IV. Discussion and Conclusions**

*a* Searching regions of high $^{12}$CO temperature and high $^{13}$CO column density at 20 $\mu$m is a very fruitful method of finding embedded or highly obscured infrared sources. In at least two cases, Cep A and S255, sources were discovered whose color temperatures were so low that searches with current sensitivities at 10 $\mu$m would be unsuccessful. It is possible that other molecular clouds contain infrared sources of as low, or lower, color temperature.

*b* The new data strongly support the tendency for infrared sources in molecular clouds to occur in groups of two or more with a characteristic separation of the order of 0.1 pc. Besides the three examples given in this Letter, we note clustering on this scale in OMC-1 (Rieke, Low, and Kleinmann 1973; Wynn-Williams and Becklin 1974), OMC-2 (Gatley et al. 1974), CRL 437 (Kleinmann et al. 1977), NGC 7538 (Werner et al. 1979), Mon R2 (Beckwith et al. 1976), and W3 IRS 5, 6, and 7 (Wynn-Williams, Becklin, and Neugebauer 1972). Radio continuum observations suggest similar behavior in CRL 2591 (Wynn-Williams et al. 1977). This clustering of infrared sources is very reminiscent of the tendency of OB stars to be found in Trapezium-like groupings (Sharpless 1954), furthering the idea that these infrared objects are OB stars at an early stage in their evolution.

*c* A significant number of infrared sources in molecular clouds show radio continuum emission from ionized gas. Although the weakness of the radio emission opens the possibility that nonradiative ionization mechanisms, such as shocks, are operating, the high bolometric luminosities of these objects, $>10^4 L_\odot$, suggest that the most probable mechanism is ultraviolet photoionization. Comparison of the infrared and radio luminosities, however, indicates that in all cases the rate of ionization is far less than that expected from main-sequence stars of the appropriate luminosities (Panagia 1973). The apparent location of the observed sources above the main sequence could be due to a variety of factors, such as self-absorption at radio wavelengths, dust absorption at ultraviolet wavelengths, uncertainties in the stellar atmosphere models, or to the inappropriateness of assuming that the objects at the cores of the infrared sources closely resemble main-sequence stars.

*d* The compact infrared sources in molecular clouds show a wide variety of observable properties, even within a single cluster. Part of the variation may be due to the fact that the shapes of the continua of deeply embedded infrared objects are very much affected by intervening extinction, even at wavelengths as long as 20 $\mu$m. Some of the variations in observed infrared properties must, however, be intrinsic to the sources. S140 IRS 2, for example, has the weakest silicate feature of the three sources detected in S140.
yet its spectrum is significantly redder than that of S140 IRS 1 or 3. More evidence for intrinsic differences comes from the fact that, while the luminosity of S140 IRS 2 shortward of 25 μm is only 1/20th that of S140 IRS 1, the 6 cm emission from S140 IRS 2 is almost one-third that of S140 IRS 1.

The radio and infrared observations suggest it may be very difficult to account for all of the observed properties of these objects in terms of spherically symmetric systems. It would appear likely that asymmetrically radiating models such as those invoked in NGC 2264 (Harvey, Campbell, and Hoffmann 1977) and NGC 7538 IRS 9 (Werner et al. 1979) will be required before objects such as those discussed in this Letter can be understood.

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REFERENCES


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