INFRARED OBSERVATIONS OF STAR FORMATION REGIONS

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1. INTRODUCTION

This review is divided into three parts. The first section gives a brief introduction to the different infrared wavelength ranges and to the various kinds of infrared objects seen in regions of star formation. The second section reviews the recent progress in infrared observations, concentrating on the three years since the review by Wynn-Williams and Becklin (1974) was written. The third section describes in more detail four varied examples of star formation regions.

1.1 Infrared wavelength ranges

For astronomical purposes it is convenient to divide the infrared spectrum into four wavelength ranges. This differentiation is necessitated by the wide variations in technique which are imposed by detector and, in particular, by atmospheric limitations.

The "near" or "photographic" infrared is effectively an extension of the visible wavelength range as far as it is possible to use photographic emulsions and image tubes. Currently this limit is about 1μm; at all wavelengths longer than this, single element detectors, such as photoconductors or bolometer elements, must be used. Between 1μm and about 40μm there are a number of atmospheric windows through which observations may be made from ground-based observatories using large optical or infrared telescopes. The windows at 2.0-2.4μm and 8-13μm, for example, are relatively transparent and much used, while the 20μm and 34μm windows are sensitive to water vapour fluctuations and require the use of high altitude observatories.

Between about 40μm and 350μm infrared observations are impossible from the ground, and telescopes must be mounted in aircraft or under balloons. The chief disadvantage of these techniques, apart from their expense, is that spatial resolving power is limited by diffraction effects in the small telescopes which must be used. Longward of 350μm

T. de Jong and A. Maeder (eds.), Star Formation, 105-132. *All Rights Reserved.*

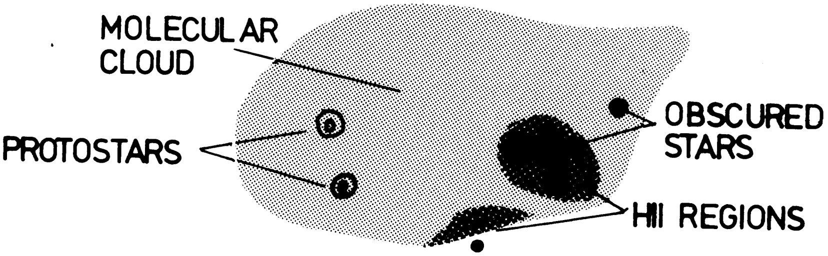

Figure 1. Schematic representation of the relative dispositions of the various types of infrared sources described in this paper.

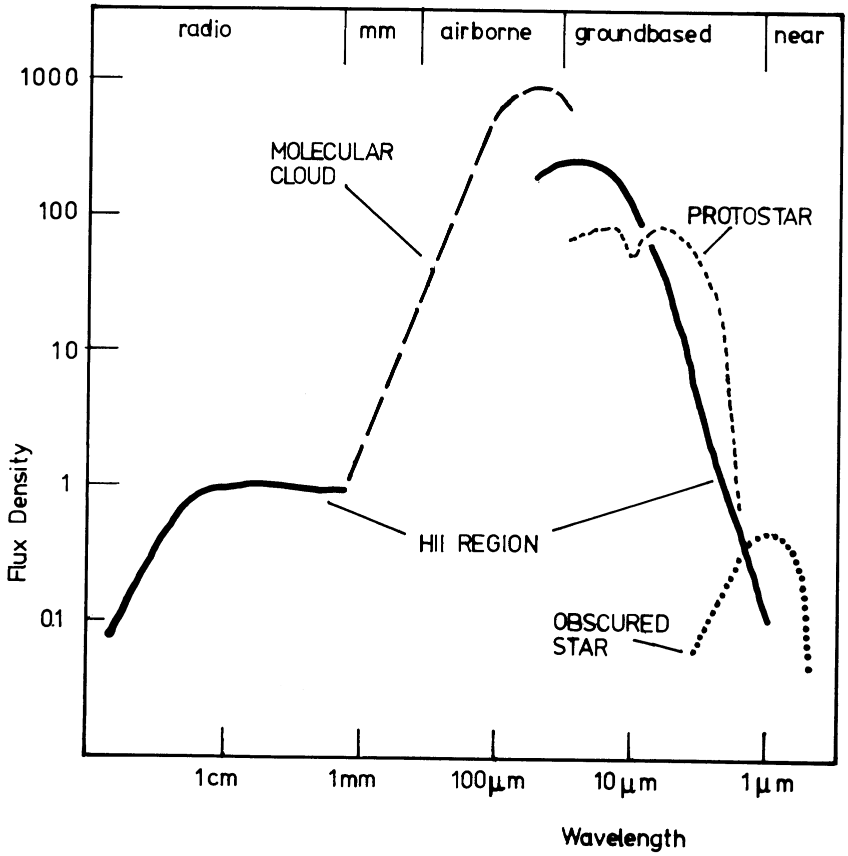

Figure 2. Schematic energy distributions of the various types of infrared sources described in this paper.

the atmosphere gradually becomes transparent enough for ground-based observations. The two commonly used bands are the "submillimetre" band at 350μm and the "millimetre" band between 0.7 mm and 1.4 mm.

The spatial resolution possible in the infrared depends very much on wavelength. Shortward of about 20μm the limit is set by atmospheric seeing to a few arc seconds, between 40μm and 2 cm it is set by diffraction to somewhat less than 1 arc min, while longward of 2-cm aperture synthesis telescopes allow one second resolution again.

1.2 Types of Infrared Source

The infrared objects observed in regions of star formation fall into four main classes: obscured stars, compact HII regions, protostars and molecular clouds. These are illustrated schematically in Figure 1, while their typical energy distributions are shown in Figure 2. The infrared properties of pre-main sequence objects such as T-Tauri and Herbig-Haro objects are discussed in S.E. Strom's article elsewhere in this volume.

Obscured Stars. Since, at infrared wavelengths, the extinction due to interstellar dust is much smaller than at visual wavelengths, infrared searches will often disclose stars hidden behind dust clouds. Two sorts of star are of particular interest: the exciting stars of HII regions (e.g. Beetz et al. 1976) and young stars embedded in dark clouds. A good example of the latter situation, namely the 2.2μm infrared sources associated with the ρ Ophiuchi dark cloud, is described in P. Thaddeus' article in this volume, and by Vrba et al. (1975). The flux densities from the hot photospheres of these stars decreases with increasing wavelength longward of 1μm; for this reason there are few observations of dust-embedded stars at wavelengths longer than 3μm.

Compact HII Regions. As a result of various selection effects, the best studied HII regions are those having diameters in the range 0.05 to 0.5 pc and electron densities 10^3 to 10^4 cm^{-3}. As described by Wynn-Williams and Becklin (1974) the dust grains which emit over the wavelength range 2 to 20μm appear to be coextensive with the ionized gas and produce an approximately power-law energy distribution over this wavelength range. At longer wavelengths it is unclear, except in a few cases such as the Orion Nebula (section 3.1), how much of the infrared emission comes from dust within the ionized gas and how much comes from the molecular clouds surrounding or very close to the HII region. Inadequate spatial resolution at 100μm is the main cause of this uncertainty. The question of the ways in which the dust grains are heated in and around HII regions has led to much theoretical calculation. An extensive series of models for dusty HII regions is described by Natta and Panagia (1976).

"Protostars". There is now a rapidly increasing number of 2 to 20μm infrared sources which have properties which suggest that they may be of protostellar origin. The earliest known examples are the BN source in Orion (Becklin, Neugebauer and Wynn-Williams 1973) and W3-IRS5 (Wynn-Williams, Becklin and Neugebauer 1972), but Werner, Becklin and Neugebauer (1976a) list 13 objects which are probably of this type. Their typical characteristics are small angular size (< 2 arcsec), an energy distribution resembling a black body at a few hundred degrees Kelvin with a strong silicate absorption, H_2O and/or OH maser emission, but no visual counterpart. Usually the objects have no radio emission themselves, but are in the vicinity of compact HII regions. The objects range in luminosity from about 100 $L_\odot$ for OMC2-IRS3 (Gatley et al. 1974) to 4×10^4 $L_\odot$ for RCW57-IRS1 (Frogel and Persson 1974).

The infrared energy distributions of these objects indicates that they consist of a thick layer of hot dust surrounding some energy source. Some authors (e.g. Penston, Allen and Hyland 1971) have suggested that the central objects are highly evolved stars, but the frequency with which these infrared sources are found near to the centres of molecular clouds makes this alternative statistically implausible. If the central objects are main sequence stars they would in most cases by of type O; to account for the absence of radio emission it is therefore necessary to conjecture that the star is surrounded by such a thick layer of dust that the formation of an HII region in inhibited. It is difficult to explain the existence of such a thick "cocoon" surrounding the star unless the material was connected with the recent formation of the star; it would therefore seem reasonable to allow the term protostar to include such a configuration.

The use of the term "protostar" to describe these infrared sources is perhaps contentious in view of how little is known about their structure and dynamics. From an observational point of view, however, it is convenient to use the term to refer to a compact infrared source whose major observable characteristics are believed to be a consequence of its current or its very recent accretion of matter. The value of this definition is that it relates to the external, observable properties of the object rather than to its internal constitution; the word used in this sense would not necessarily exclude ultra-compact HII regions such as NGC7538-IRS1 (Wynn-Williams, Becklin and Neugebauer 1974), and would certainly include Kahn's (1974) cocoon stars. The question of whether the objects have started nuclear burning is left open (see e.g. Appenzeller and Tscharnuter 1974). If the word "protostar" is not to be used to describe this class of infrared source, another word must be coined. Whether a term such as "Dustar" would appeal to the astronomical community must be considered doubtful.

Molecular Clouds. At wavelengths longward of about 50μm, emission is seen mainly from extended, comparatively cool molecular clouds. These are the same objects as are studied by molecular line astronomers (see P. Thaddeus' article in this volume), and a close correlation has been found in some cases between molecular line and 1-mm continuum emission (Harvey et al. 1974). Radial density and temperature gradients suggestive of collapse have been found in some clouds

(Westbrook et al. 1976), and in almost all cases the density peak coincides with one or more protostars or compact HII regions.

2. PROGRESS IN INFRARED OBSERVATIONS

2.1 "Near" infrared ($\lambda \lesssim 1\mu m$)

The Heidelberg infrared group has been studying several HII regions at photographic infrared wavelengths (Beetz et al. 1976). Using a cooled image tube working at 0.70μm and 0.92μm they were able to find obscured probable ionizing stars in several HII components in W3. They also discovered an obscured star cluster nearly coincident with the peak of the extended infrared and radio emission in M17, as well as a near-infrared counterpart to the Kleinmann-Wright infrared object. Near-infrared photography has the advantage of permitting large areas to be surveyed fairly quickly; it is an excellent method of finding stars obscured by 5-15 magnitudes of visual extinction, and of investigating dust clouds with extinctions in this range.

2.2 Mapping and photometry at $1\mu m < \lambda \lesssim 20\mu m$

Many infrared groups are now involved in mapping and photometry of HII regions and other infrared sources in this wavelength range. The main improvements in the last three years have been in the limiting sensitivity of ground-based observations as a result of the introduction of new types of detector. Table 1 gives very approximate values for the current minimum detectable flux densities in one second of integration at 2.2μm and 10μm using a large instrument such as the Palomar 5m telescope. For comparison, limits are also given at 100μm for the C-141 aircraft and at 1 mm for the 5m telescope. Longer integrations can reduce these limits by factors of about 100 at 2.2μ, and 20 at the longer wavelengths before systematic effects dominate; in at least some areas of the galactic plane, however, confusion by faint field stars appears to set the practical sensitivity limit at 2.2μm, even with diaphragms as small as 5 arcsec in diameter.

Table 1. Minimum detectable fluxes at infrared wavelengths in 1 second integration. (Becklin, private communication). 1Jy = 10^{-26} W m^{-2} Hz^{-1}.

Wavelength	Limit in 1sec
2.2μm	1mJy (14.5 mag)
10μm	150mJy (6 mag)
100μm	200Jy
1 mm	30Jy

2.3 The window at 34μm

At a few high altitude observatories it is sometimes possible, on very cold dry nights, to make observations in the rather murky 30-40μm atmospheric window. Measurements of HII regions in this wavelength range have been reported by Low, Rieke and Armstrong (1973), using Mount Lemmon, by Sutton, Becklin and Neugebauer (1974), using Las Campanas and by Dyck and Simon (1976) using Mauna Kea. Because of atmospheric problems, observations in the 34μ window are difficult and photometric accuracy is low. The ground-based observations at these wavelengths are, however, extremely important, since they provide a link between the short-wavelength/high-spatial-resolution observations made from the ground and the long wavelength/low-spatial-resolution observations made from the air; with a 2.5 m ground-based telescope the diffraction limit at 34μm is about 4 arcsec, several times less than that of the C-141 airborne observatory. In the study of compact HII regions the high spatial resolution at this wavelength can help solve the question of how much of the $\lambda > 30\mu m$ radiation from the vicinity of compact HII regions comes from dust coextensive with the ionized gas and how much comes from the surrounding molecular clouds. In this context Dyck and Simon (1976) showed that much of the 34μm radiation attributed to W3(A) must come from regions exterior to the ionized gas.

2.4 Ground-based spectroscopy

Infrared spectroscopy of objects related to star formation now embraces molecular, atomic, ionic and solid-state phenomena. Almost all the observations have been made from the ground, most frequently at Kitt Peak, and in most cases involve variable-thickness interference filters or grating spectrometers with typical spectral resolutions of $\lambda/\Delta\lambda \approx 100$. Much higher resolving powers are now becoming available, however, as a result of the development of Fourier Transform Spectrometers.

Molecular Hydrogen. Gautier et al. (1976) used a Fourier Transform Spectrometer to detect seven lines of the 1-0 vibration-rotation quadrupole spectrum of H_2 in emission from the vicinity of the BNKL sources in Orion. Their resolution was about 3 cm^{-1} at 2μm. The remarkable feature of this discovery is the high strength of the lines, which require a temperature of about 2000K for their excitation. The authors estimate that the lines are produced in a region with a column density of 10^{19} to 10^{20} molecules cm^{-2}. The OMC1 molecular cloud has a temperature of about 70K and a column density of about 10^{23} cm^{-2}, so the region where the 2μm lines are formed must be rather special, and is perhaps associated with a shock front.

Atomic and Ionic Lines. The most commonly observed lines are some of the higher recombination lines of hydrogen such as the Brackett-α line at 4.05μm and the Brackett-γ line at 2.17μm. Measurement of the strengths of these lines in HII regions can help to disentangle the contributions of the gas and the dust to the infrared continuum and, in the case of visually obscured HII regions, can allow the extinction to be estimated by comparison with the radio flux density. The 2.06µm line of neutral helium is strong in HII regions, but is very sensitive to optical depth and density variations. Fine structure lines of several ions have now been detected in HII regions including [NeII] at 12.8µm (Aitken and Jones 1974), [ArIII] at 8.99µm (Soifer and Pipher 1975) and [SIV] at 10.52µm (Willner 1976). The wide range in ionization potential of these species may make them useful tools in obtaining a better understanding of the ionization structure of dust-embedded HII regions.

Silicates and Ices. A feature at 9.7µm attributed to silicate grains is seen in emission in the Trapezium region of the Orion Nebula (Forrest, Gillett and Stein 1975) and in absorption in front of a large number of compact HII regions and protostars (e.g. Gillett et al. 1975a; Aitken and Jones 1973; Willner 1976a; Persson, Frogel and Aaronson 1976). Most authors have interpreted their 10µm spectra in terms of a warm emitting region behind a layer of cool dust that produces the silicate extinction. Kwan and Scoville (1976), on the other hand, show that a depression at 10µm may arise naturally as a result of radiative transport effects in an object with a radially decreasing temperature, and that the strength of the 10µm feature is not easily related to the visual extinction in front of the object. Their model correctly predicts a correlation between the colour temperature of a protostar and the depth of its 10µm feature, and can account for the weakness of the 20µm silicate absorption in the Orion BNKL sources (Forrest and Soifer 1976).

Comparison of celestial infrared spectra with those of laboratory materials favours identification of the 9.7µm feature with amorphous, hydrated types of silicates (Day 1974; Penman 1976), but the interpretation of this feature is made more complicated by the fact that the infrared absorption properties of silicates are found to vary significantly with temperature (Day 1976).

After the 9.7µm silicate feature the strongest absorption band usually seen at infrared wavelengths is the "ice" band at 3.1µm, which is believed to be a blend of H_2O and NH_3 features (Merrill, Russell and Soifer 1976). Gillett et al. (1975b) found large variations in the ratio of the strengths of the ice and silicate features in different directions, from which they inferred that ice grains are found only in molecular clouds, not in interstellar space. Kwan and Scoville (1976), however, show that the apparent variation in the ice/silicate ratio may be partly attributable to radiative transport effects.

Unidentified features. Two unidentified emission features, also seen in the planetary nebula NGC7027, have been found in the Orion Nebula and M17 by Grasdalen and Joyce (1976). Their wavelengths are 3.28µm and 3.4µm. The lines are also seen as a blend by Soifer, Russell and Merrill (1976). A possible identification of one of the features with the CH^+ molecule was suggested by Grasdalen and Joyce.

2.5 Polarimetry

Strong linear polarization has been detected from the Orion BN object at wavelengths between 1.6μm and 10μm (Breger and Hardorp 1973; Loer, Allen and Dyck 1973; Dyck et al. 1973). The polarisation is strongest at the wavelengths where the extinction is strongest, namely shortward of 2μm and in the 3.1μm and 9.7μm ice and silicate absorption bands. Circular polarization of 0.9 per cent at 3.4μm from the same object has been found by Serkowski and Rieke (1973). Dyck and Beichmann (1974) show that the observations can be satisfactorily explained by invoking the Davis-Greenstein mechanism in a cold uniform medium in front of the BN object. Linear polarization at 2.2μm has also been reported in CRL2591, another infrared protostar, by Oishi et al. (1976).

2.6 "Airborne" infrared mapping (30μm $\leqslant \lambda <$ 350μm)

The number of HII regions surveyed by comparatively small balloon-borne telescopes has been greatly increased by the surveys of Furniss, Jennings and Moorwood (1974) and Olthof (1974). The reflection nebula NGC2023 was studied at 40-350μm by Emerson, Furniss and Jennings (1975). The most significant recent advance at these wavelengths, however, has been the introduction of much larger diameter telescopes, in particular the 1.02 m diameter Harvard-Smithsonian-Arizona balloon-borne telescope (Fazio et al. 1974) and the NASA 0.92 m telescope mounted in a C-141 aircraft. These telescopes have permitted greatly improved spatial resolution at these wavelengths; Harvey, Campbell and Hoffmann (1976), for example, have mapped several HII regions with a spatial resolution of 17 arcsec at 53μm using the C-141 instrument.

2.7 "Airborne" spectroscopy

Until now, only one spectral feature has been detected in the wavelenth range 30μm $\leqslant \lambda <$ 350μm, namely the 88.16μm line of [OIII] in M17 (Ward et al. 1975). Several groups have made observations delineating the continuum spectra of strong far infrared sources; Erickson et al. (1976a, 1976b), for example, have used a Michaelson interferometer aboard the C-141 aircraft to measure the spectra of the central 1.4 arcmin regions of SgrB2 and OMC1 in Orion between 30 and 250μm. The spectra are smooth, indicating dust temperatures of about 30K and 80K respectively for the two sources.

2.8 Submillimetre and millimetre observations ($\lambda \geqslant$ 350μm)

The 350μm window suffers greatly from variable atmospheric attenuation, but successful observations have been made at Mauna Kea (Rieke et al. 1973; Righini, Simon and Joyce 1976) and Mount Lemmon (Soifer and Hudson 1974). All the objects so far observed have their spectral energy peaks consierably shortward of 350μm, so that measurements in the submillimetre range can be used to estimate the gradient of the "Rayleigh-Jeans" part of the spectrum (see Figure 2). The measured spectral indices generally lie in the range 3-4, significantly steeper than the black-body slope of +2, indicating that the objects are optically thin and that the emissivity of the warm grains decreases with increasing wavelength, as expected for small particles.

Atmospheric problems are much less severe at a wavelength of 1 mm, but since the spatial resolution at this wavelength is usually set by diffraction, large dishes must be used. The Kitt Peak 11 m radio telescope has been used by Clegg, Rowan-Robinson and Ade (1976) for a brief look at many sources, while the Palomar 5 m telescope has been used for more extensive studies of a number of objects (e.g. Werner et al. 1975). The importance of 1 mm observations is that the emission, being optically thin, is uncomplicated by radiation transfer effects and is not very temperature dependent (only linearly, not exponentially). As discussed by Westbrook et al. (1976) continuum maps at 1 mm provide a much better guide to the distribution of matter in molecular clouds than do maps of the molecular line emission or shorter wavelength infrared emission. The clouds studied by Westbrook et al. (1976) have typical masses of 1000 $M_\odot$ and column densities corresponding to a visual extinction of about 100 magnitudes. Several have density profiles similar to those expected in a collapsing cloud, and each contains at least one compact HII region or protostar at its centre.

3. RECENT STUDIES OF SOME PARTICULAR REGIONS

3.1 The Orion Nebula and molecular cloud

The Orion region is the nearest and best studied HII region/molecular cloud complex. Both the HII region, centred close to the Trapezium stars, and the molecular cloud OMC1, about 1 arc minute away, are strong infrared sources (see, e.g. Wynn-Williams and Becklin 1974; Zuckerman and Palmer 1974). The Trapezium stars and the cluster of protostars near the centre of OMC1 both contribute to the heating of the dust. Figure 3 shows a 1 arc minute map of the Orion Nebula made by Werner et al. (1976b) at 100μm, using the C-141 aircraft. The main peak coincides with the centre of the molecular cloud, but there is an extended subsidiary maximum near the ionization front to the lower left of Figure 3. The infrared emission from this ionization front has been studied in detail by Becklin et al. (1976), who show that this warm dust is associated with neutral gas just outside the HII region itself. They also show that there must be a factor of ten increase in the dust density between the HII region and the neutral matter into which the ionization front is moving. Emission from warm dust just outside of the HII region appears to comprise a significant fraction of

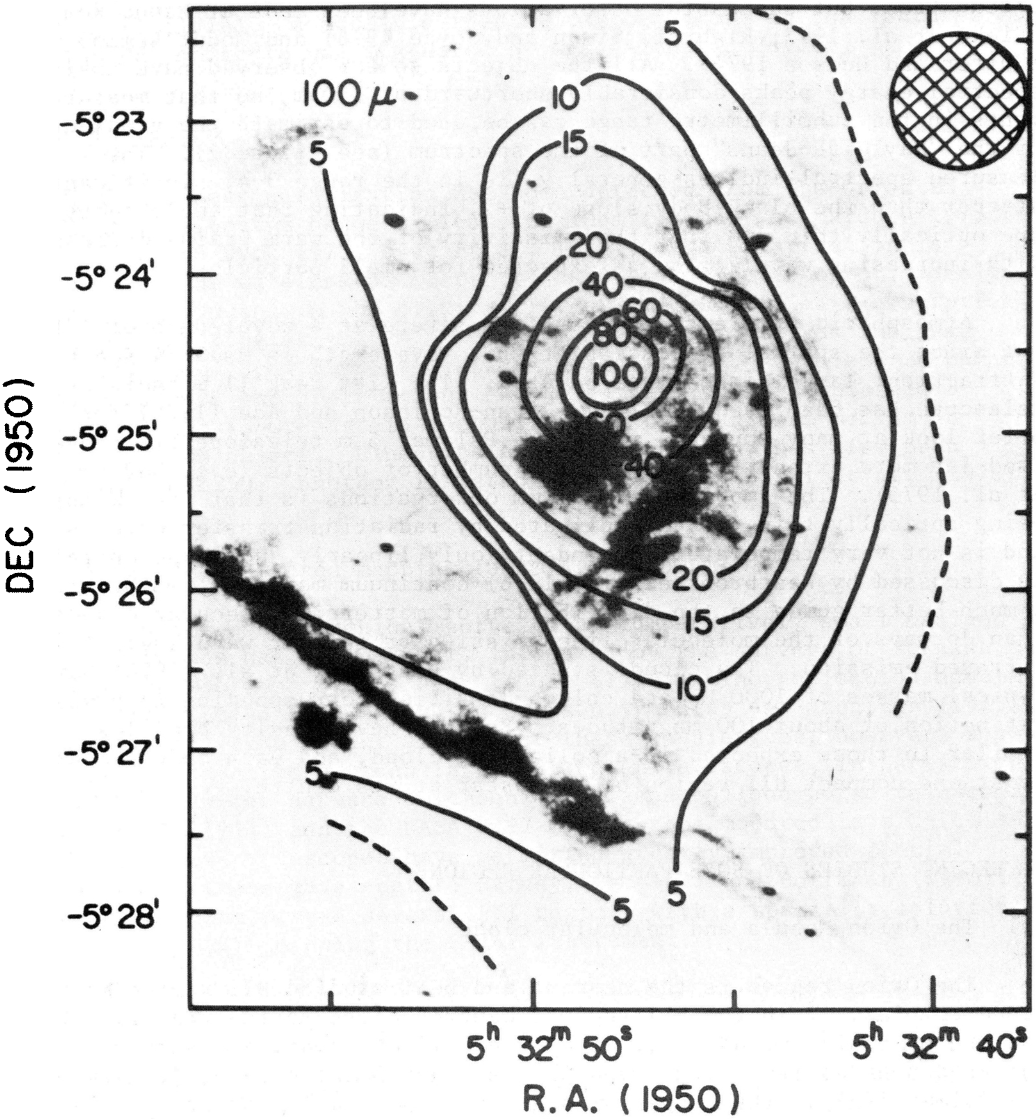

Figure 3. Map of the 100μm emission from the Orion Nebula (Werner _et al._ 1976b). The shaded circle shows the half-power beamwidths. The optical photograph, by T.R. Gull, is in the λ6300 line of OI and emphasises ionization fronts. The Trapezium cluster is at $05^h\ 32^m\ 49^s$, -5^o 25.2'.

the total flux at 100μm; in contrast the 20μm emission is concentrated within the HII region.

The strongest region of emission seen in Figure 3 coincides with the molecular cloud OMCI and includes at its centre the compact BN and KL sources. Grasdalen (1976) has reported detection of the Brackett-α hydrogen emission line in the BN object, and Gautier et al. (1976) have found molecular hydrogen emission at 2μm from this region (see Section 2.4). From the variation of infrared colour temperature Werner et al. (1976b) show that the Orion molecular cloud must be heated from within by an energy source of at least 1.2 x 10^5 $L_\odot$. The cluster of infrared protostars seen at the centre of the cloud is almost certainly responsible for this heating.

3.2. Sharpless 106. The HII region Sharpless 106 is another optically visible nebula, but in this case most of the radio flux comes from a group of visually obscured HII regions (Pipher et al. 1976). The most interesting feature of Sharpless 106, however, is a compact infrared source (Sibille et al. 1975), particularly prominent at 3.5μm, which is coincident with a faint patch of nebulosity seen at 0.8μm. Pipher et al. (1976) show that the object may be a Trapezium-like exciting cluster, in which case it would be one of the youngest star clusters known.

3.3. K3-50 and ON-3. New infrared observations of the K3-50 region have been made by Wynn-Williams et al. (1976). They show that the visible nebula K3-50 is significantly displaced from its infrared and radio counterpart and probably lies at the edge of a molecular cloud some 2,500 $M_\odot$. The OH source ON-3 lies within or behind a second molecular cloud, and suffers several hundred magnitudes of visual extinction. The K3-50 region is a good example of the clustering of compact HII regions; five such regions are seen associated with two molecular clouds.

3.4. NGC7538. Observations of NGC7538 from the C-141 aircraft (Thronson et al. 1975) together with unpublished ground-based and millimetre observations by the Caltech group have shown that the compact group of sources NGC7538-IRS1/2/3 discovered by Wynn-Williams et al. (1974) are, in fact, part of a larger region of star formation which extends southwards and eastwards from NGC7538. In particular there is a new protostar whose properties closely resemble those of NGC7538-IRS1, except in the absence of radio or maser emission. NGC7538 contains an extremely rich variety of young objects, including at least two O stars, two maser sources, three compact HII regions, one extended HII region and two protostars. Together they comprise at least seven distinct and different manifestations of new stars within a radius of a few arc minutes. Whether this activity extends over a larger area than this is the subject of a further study.

4. CONCLUSIONS

The infrared study of star formation is, in some sense, still in its infancy. The objects that have been found and studied are more or less what had been predicted to exist, although this is partly because the predictions have been vague. The phenomena seen are: molecular clouds, as luminous and as massive as star clusters with density and temperature gradients suggestive of collapse: fragmentation, both in the grouping of molecular clouds and in the existence of groupings of protostars and compact HII regions at their centres: protostars, or, at least, cocoon stars, and young star clusters still embedded in dust clouds.

The main trends in the next few years are likely to be a great increase in the resolution, sensitivity and quantity of spectroscopic observations, better spatial resolution, especially at 1 mm wavelength, and the reduction of selection effects by the use of CO and infrared surveys rather than optical or radio signposts to look for infrared signs of star formation.

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