INFRARED SOURCES AND STAR FORMATION*

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The objects I intend to discuss are the recently discovered infrared sources which may be, by some definition of the term, protostars. Strom (1972) has recently reviewed the infrared properties of visible pre-main-sequence objects such as the T-Tauri stars; I shall therefore concentrate rather on those invisible objects, powerful in the wavelength range 2 - 20μ and often sources of OH and H₂O radiation, which may be precursors of O stars. I shall also talk about the infrared properties of some of the interstellar clouds associated with these objects. The best studied of these clouds at infrared wavelengths are generally H II regions, but there is a selection effect in operation here; the high resolution radio maps which are available of H II regions greatly encourage and facilitate the infrared exploration of such areas rather than, for example, of dark clouds, for which no such guiding data are available.

The infrared properties of H II regions have been summarized recently by Wynn-Williams and Becklin (1974). Most H II regions appear to emit the bulk of their energy in a broad wavelength band within the range 3 μ to 2 mm. This emission almost certainly arises from dust grains heated to a temperature of order 100 K by the absorption of ultraviolet photons close to or within the ionized region. The total infrared bolometric luminosity of an H II region generally agrees within a factor of two with that estimated, on the basis of the free-free emission, to be generated by the O stars in the nebula. This result indicates that most H II regions are associated with a sufficient quantity of dust to reabsorb most, if not all, of the photons produced by the stars and the nebula in the ultraviolet and visible wavelength ranges.

At wavelengths around 100 μ, where the energy distribution of a typical H II region has its peak, small airborne telescopes must be used with the result that the spatial resolution of such observations is limited to about 1 arc min by diffraction effects. At wavelengths in the 2 μ to 20 μ range, however, large ground-based instruments can be employed, making it possible to map H II regions with diaphragms as small as a few arc sec and thereby allowing detailed comparison with aperture synthesis radio maps. Maps at these shorter infrared wavelengths, for for example those of W 3 by Wynn-Williams, Becklin and Neugebauer (1972),

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have demonstrated the presence of heated dust within the compact ionized regions, and also the presence of thick layers of cold obscuring dust immediately outside them. This cold dust is presumably associated with the clouds of molecular hydrogen revealed by millimetre wave observations of such species as HCN and CO (e.g. Morris et al. 1974, Scoville and Solomon 1973). Infrared observations have also led to the discovery of the highly obscured exciting stars of some of these compact H II regions, providing confirmation of the view that such objects are internally heated by newly-formed O stars. Simple dynamical considerations (e.g. Mathews 1969) indicate timescales of evolution of the order of $10^4$ years for these regions.

The H II region W 3 also contains a powerful unresolved infrared source called W3-IRS5 which, though coincident with an H2O maser source, is not associated with any radio continuum emission feature. Its infrared energy distribution is unlike that of a compact H II region, and resembles that of a black-body at 350 K modified by the presence of a strong 10 μ silicate absorption feature. The bolometric luminosity of W3-IRS5 is at least $3 \times 10^4 L_\odot$, but could be significantly higher, depending on the amount of extinction assumed towards the object (Aitken and Jones 1973). It is clearly surrounded by a great deal of dust. If the energy source for W3-IRS5 is a normal star its high luminosity requires that it be either an evolved late supergiant or an O star. The first alternative seems unlikely, since the presence of an old star in such a young region is not readily explicable except as a coincidence. If W3-IRS5 contains an O star, then the star must be surrounded by a very dense shell of dust, that inhibits the formation of an H II region. Such a shell of dust, if it exists, would probably be a remnant of the cloud out of which the star formed, so it is therefore profitable to compare the observations of W3-IRS5 with the predictions of models of protostellar evolution.

Models of the evolution of high-mass protostars have been described by Larson (1973) and, in more detail, by Appenzeller and Tscharnuter (1974). The latter authors consider the collapse of a 60 $M_\odot$ spherical, non-rotating non-magnetic cloud from an initial density of $10^{-19}$ g cm$^{-3}$. After about $4 \times 10^5$ y a hydrostatic core is formed in the centre which, by rapid accretion of infalling material, becomes hot enough to start hydrogen burning $2 \times 10^4$ y later. After another $2.5 \times 10^4$ y the heat flow from the core becomes so great that the collapse of the outer layers is halted and mass outflow disperses the remainder of the protostellar matter, leaving behind a 17 $M_\odot$ ZAMS star. The luminosity and surface temperature of W3-IRS5 are compatible with such an object at some time after hydrogen burning has started but before complete dispersal of the circumstellar material. It is encouraging that the time scale for the evolution of this stage of the model is of the same order as that of the compact H II regions nearby.

Since, in these models, the central part of the protostar becomes hydrogen burning while the outside layers are still collapsing, the hypothesis that W3-IRS5 is a dust-embedded O star may be seen as a special case of the hypothesis that it is some kind of protostar. We have no way as yet of knowing whether the outer layers of W3-IRS5 are in a state of collapse or in one of re-expansion.

Several other infrared sources have recently been discovered with properties
broadly similar to W3-IRS5, in that they possess an energy distribution close to that of a black-body at a temperature of a few hundred K, show strong 10 μm silicate absorption, are less than 3 arc sec in diameter and have no detectable radio emission apart from OH or H2O maser radiation. These objects have so far been found associated with the Orion Nebula, which is discussed in more detail below, Sharpless 228 (Frogel and Persson 1973), RCW57 (Frogel and Persson 1974) and NGC6334 (Becklin and Neugebauer 1974).

The protostellar model discussed above has the feature that its central core is becoming continuously hotter and more luminous as it accretes matter from the infalling envelope. The possibility therefore arises that some of the inner parts of the cloud may become ionized while the outer parts are still collapsing, leading to the existence of a very small H II region surrounded by a strong infrared source, as in Davidson and Harwit's (1967) cocoon-star model. Such objects, resembling protostars in most respects, but associated with weak continuum radio sources, have been associated with NGC 7538 (Wynn-Williams, Becklin & Neugebauer 1974, Martin 1973), and with a strong infrared source in Cygnus (Merrill and Soifer 1974, Wendker and Baars 1974). The source W3(OH) (Wynn-Williams et al. 1972, Harper 1974) may also be an object of this type.

Observations of a different kind have revealed a pair of very interesting regions in W75. One of these contains at its centre the bright, compact H II region DR21, while the other, 3 arc min away, contains the W 75(S)OH maser, but produces less than 10^{-3} of the radio flux density of DR21. Despite this disparity in the objects in the centre both sources appear to have almost identical outer layers since the isophotes of the HCN molecular line emission (Morris et al. 1974) and of the 1-mm dust emission (Elias et al. 1974) are essentially the same for the two regions on a scale of a few arc min. Whether the OH source and the H II region represent different stages in the evolution of the same kind of object, or different possible consequences of collapse of this kind of cloud, is at present uncertain.

By far the best studied infrared sources are those associated with the Orion Nebula. The extended emission from this region has been mapped recently by Lemke, Low and Thun (1974) at 20 μm, by Harper (1974) at 91 μm, and by Harvey et al (1974) at 1 mm. The small scale structure has been observed by Rieke, Low and Kleinmann (1973) and Wynn-Williams and Becklin (1974). These data reveal the presence of a small cluster of infrared sources about 1 arc min distant from the Trapezium, associated with OH or H2O maser sources but with no obvious optical or radio continuum feature. Infrared observations at different wavelengths indicate that the temperature of the dust rises towards the centre of the cluster, while observations of molecular species of different excitation (e.g. Buhl 1974) reveal an increase of gas density in the same sense. The general picture is one of a cloud of gas and dust with a total mass of about 500 m_{\odot} (Harvey et al. 1974) heated by a recently forming cluster of stars at its centre. The eventual size and luminosity of this new cluster will probably be about the same as those of the Trapezium itself.

More recently Gatley et al (1974) have discovered a new cluster of possible
protostars 12 arc min north of the Orion Nebula. This cluster, called OMC2, contains about 5 compact objects within an extended molecular cloud. The infrared luminosity of this cluster is only about 1% of that of the Orion Nebula cluster, a fact which may be related to the lower average density in the OMC2 region (Werner et al. 1974). OMC2 is not closely associated with an H II region, and its infrared sources may be precursors of stars of a later spectral type than those hitherto described in this review.

The OMC2 region is unusual and particularly important in that it was discovered by a fortunate accident rather than as a result of an infrared search of a known interstellar cloud. We may hope that as infrared surveys improve a larger sample of such regions will become available, so that the bias towards studying radio emitting regions, and hence the bias towards the study of the formation only of massive stars, can be reduced.

References


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