# INFRARED EMISSION FROM H II REGIONS

C. G. WYNN-WILLIAMS*

*California Institute of Technology, Pasadena, Calif., U.S.A.*

**Abstract.** Most H II regions emit large amounts of energy at infrared wavelengths. Dust grains absorb a major fraction of the total energy emitted by the O stars, and this is reradiated in the infrared. The dense H II condensations seen by aperture synthesis radio observations are strong 20-$\mu$m infrared sources. The dust is probably mixed with the ionized gas in these sources. There are also infrared sources that are not radio sources; these may be protostars. Infrared emission has also been found from many OH/$H_2O$ maser sources associated with H II regions.

In the past two or three years it has become clear that most H II regions emit large quantities of energy at infrared wavelengths. Dust grains within and around the H II region absorb stellar and nebular photons and are thereby heated to temperatures in the range 50 to 200 K. Figure 1 shows the overall energy distribution of W3, a source with features common to many H II regions. It may be seen that the flux density at 100 $\mu$m is about three orders of magnitude greater than is produced by free-free and free-bound transitions in the ionized plasma.

The infrared energy distribution deviates from that of a black-body at both long and short wavelengths. At short wavelengths this effect is probably due to real variations in the dust temperatures of different parts of the source, while at long wavelengths the effect is due to the decrease in the emissivity of the dust particles with increasing wavelength. The deficit of emission shortward of 3 $\mu$m as compared to the expected free-free flux density must be attributed to extinction by dust grains. Very large amounts of extinction have been found this way, including a value in excess of 50 mag in the visible for part of W3.

Because of the opacity of the Earth's atmosphere at wavelengths near 100 $\mu$m, measurements of the total energy emitted at infrared wavelengths have to be made from small telescopes carried to high altitude by aircraft or balloons (Harper and Low, 1971; Emerson *et al.*, 1973). The results of these measurements indicate that the total infrared luminosity of an H II region is closely related to its total rate of ionization and, moreover, that the dust grains absorb and re-emit a major fraction of the total energy emitted by the O stars inside the H II region. In general, however, the dust grains do not absorb a significant number of Lyman-continuum photons direct from the star (Wynn-Williams and Becklin, 1974).

Infrared maps of H II regions may be made at wavelengths of 20 $\mu$m or shorter using large optical telescopes and beamwidths of a few arcseconds. These maps indicate that most of the dense H II condensations seen by aperture synthesis radio observations are strong 20-$\mu$m infrared sources (Figure 2). This result strongly sug-

* Now at Mullard Radio Astronomy Observatory, Cambridge, United Kingdom.

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gests that the dust giving rise to the emission at this wavelength is coextensive with the ionized gas; there are, however, indirect arguments that indicate that much of the emission at around 100 $\mu$m comes from cooler dust grains associated with atomic or molecular hydrogen exterior to the ionized region.

Figure 2 shows that in W3 there also exist infrared sources which are not radio

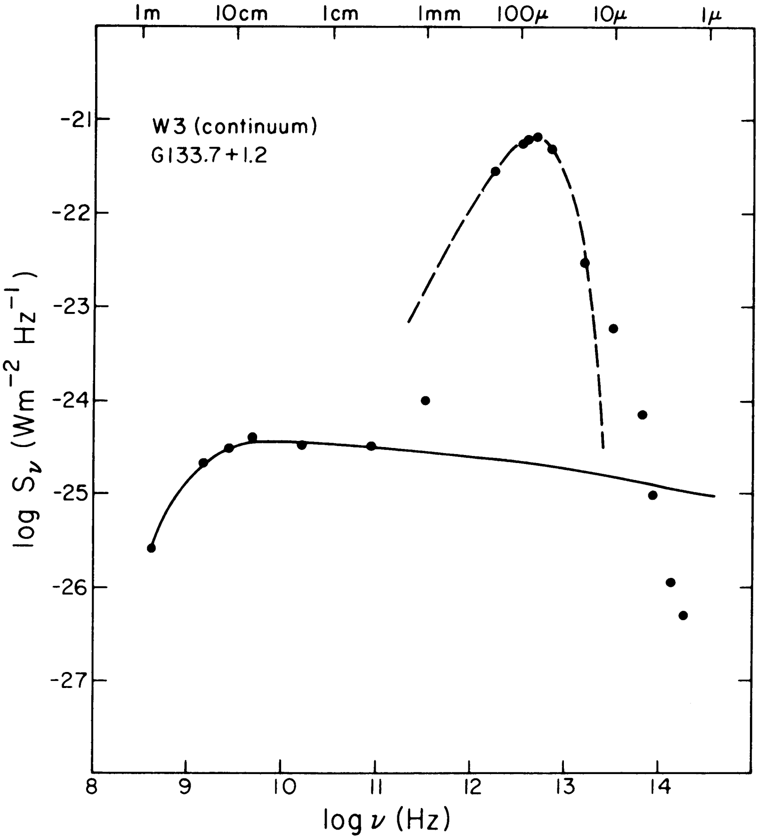


Fig. 1. The radio and infrared energy distribution of W3. Radio data are from Webster and Altenhoff (1970), Wynn-Williams (1971), Schraml and Mezger (1969) and Hobbs, *et al.* (1971). The 1-mm point is by Harvey (1973) using the Hale 200-in. telescope, the 30- to 300-$\mu$m data is by Harper (1973), and the remainder of the infrared data is from Wynn-Williams, *et al.* (1972). The solid line shows the emission expected from transitions in the H II plasma, calculated according to the relationships given by Willner *et al.* (1972), and the dashed line is a black-body curve at 70 K.

sources. IRS2, for example, seen at 2.2 $\mu$m in W3, is probably the early-type exciting star of W3(A)/IRS1. IRS5, on the other hand, is associated with the $H_2O$ maser source and has the energy distribution shown in Figure 3. It resembles that of a black-body at 350 K except that it has a strong 'silicate' absorption at 10 $\mu$m (Aitken and Jones, 1973). This object has a luminosity of at least $3 \times 10^4$ $L_\odot$ and a black-body diameter

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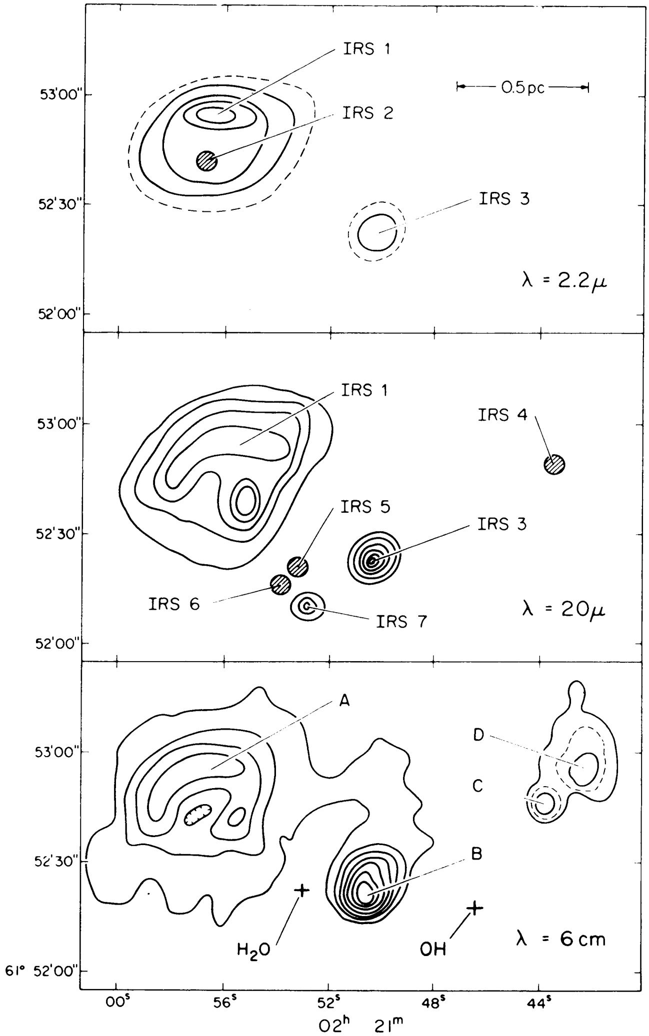


Fig. 2. W3 (G133.7 + 1.2) mapped at 2.2 $\mu$m, 20 $\mu$m and 6 cm wavelength (Wynn-Williams, *et al.*, 1972; Wynn-Williams, 1971) with resolutions in the range 5 to 10″. The $H_2O$ maser position is from Hills *et al.* (1972) and the OH position is from Wynn-Williams *et al.* (1974).

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of 600 AU. It is tempting to speculate that W3-IRS5 is a massive protostar since an O star with this luminosity should produce a detectable H II region. Several other rather similar objects have been found in other H II regions, including one in NGC 7538, although the latter appears to be associated with faint continuum radio emission (Wynn-Williams *et al.*, 1973; Martin, 1973).

Infrared emission has been found from many, but not all, of the OH/$H_2O$ maser sources associated with H II regions. In contrast to the situation found for the 1612-

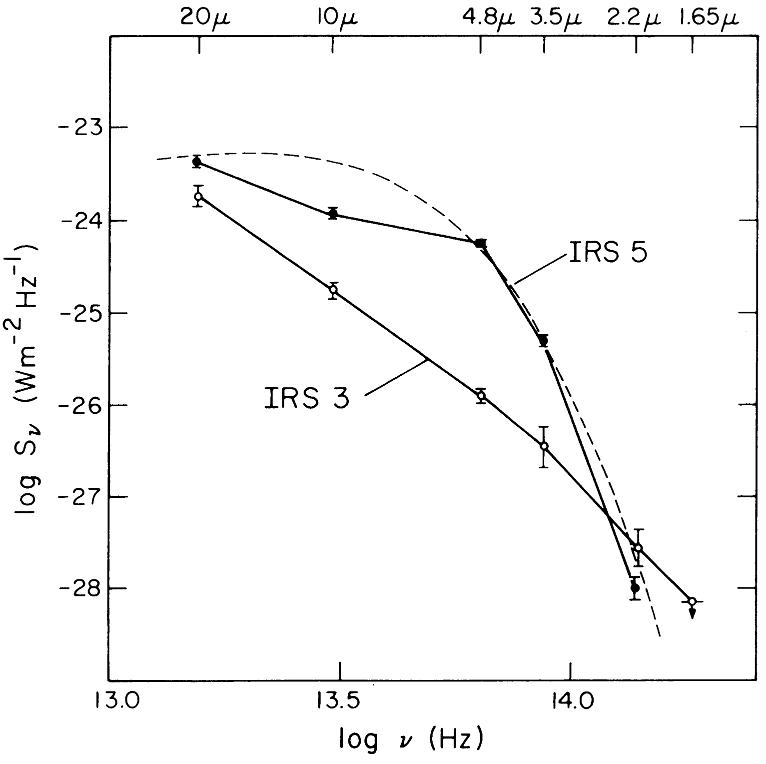


Fig. 3. Infrared energy distributions of W3-IRS5 and W3-IRS3. (from Wynn-Williams *et al.*, 1972) The dashed line is a black-body curve at a temperature of 350 K.

MHz OH/IR stars, no quantitative relationships have yet been found between the infrared and microwave properties of these sources, except that there is perhaps a tendency for infrared sources which are associated with OH/$H_2O$ masers to be hotter and more compact than are most H II components (Wynn-Williams and Becklin, 1974).

Figure 4 shows the Orion nebula at 20 $\mu$m. Most noticeable is the cluster of small sources about 1′ from the Trapezium O star cluster. These objects, which include the Becklin-Neugebauer and Kleinmann-Low infrared sources, are closely associated with the OH and $H_2O$ masers, show deep silicate absorption features in their spectra, are highly polarized at infrared wavelengths and lie at the center of a more extensive cool dust cloud which is seen by 1-mm continuum and by 2-cm formaldehyde observations (Figure 5). The infrared observations indicate that the temperature of the cloud increases inwards towards the most compact part of the infrared cluster; it

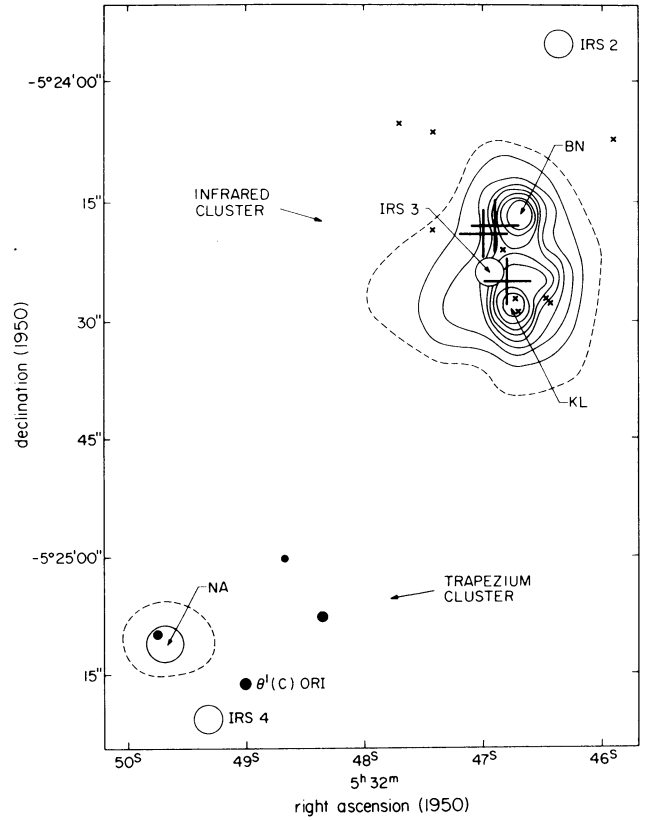


Fig. 4. The Orion nebula mapped at 20 $\mu$m with a 5″ diaphgram on the Hale 200-in telescope by Becklin, Neugebauer and Wynn-Williams (inpublished). The contour interval is $3 \times 10^{-15}$ W m$^{-2}$ Hz$^{-1}$ sr$^{-1}$, with the dashed line at half this interval. The three large crosses are the OH positions of Raimond and Eliasson (1969), while the nine small crosses are the $H_2O$ maser positions of Moran *et al.* (1973); the whole group of nine is subject to a possible 5″ absolute position error, which is not shown in the figure.

therefore again seems very plausible that these objects are other protostars or stars formed so recently that they are still accreting matter from the surrounding clouds of gas and dust.

A much more extensive review of the infrared properties of H II regions is currently in press (Wynn-Williams and Becklin, 1974).

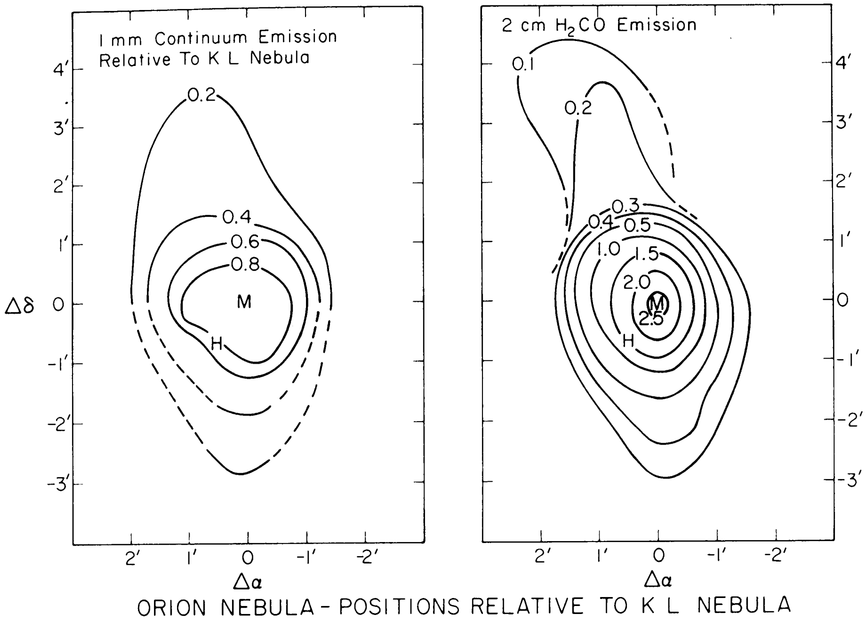


Fig. 5. The Orion nebula at 1 mm (750 to 1500 μm) as mapped with 100″ resolution on the 200-in. telescope by Harvey *et al.* (1973), and in the formaldehyde line by Evans *et al.* (1973). The peak of the H II emission, which coincides with the Trapezium cluster, is denoted *H*, while the center of the molecular emission, which coincides with the infrared cluster, is denoted by *M*.

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C. G. Wynn-Williams
*Mullard Radio Astronomy Observatory, Cavendish Laboratory,*
*Free School Lane, Cambridge, CB2 3RQ, United Kingdom*

# DISCUSSION

*Churchwell:* Is there any unambiguous way to distinguish between IR radiation from protostars and from evolved M supergiants?

*Wynn-Williams:* Not really, but coincidences of late type M supergiants with the most interesting parts of H II regions must be rather unlikely.

*Townes:* In answer to the question whether there is a definite way of distinguishing between a new star and a red giant surrounded by dust, I would like to note the possibility of discrimination on the basis of the $^{12}C/^{13}C$ ratio in circumstellar material. Geballe, Wollman, and Rank have recently applied this technique in examining IRC + 10216. Old stars characteristically show a low ratio (4–10), whereas new stars presumably would show a high ratio (50–100) since interstellar gases do. In particular, it appears practical to determine this ratio from the CO absorption spectrum for such sources as the brighter Orion sources.

*Van Woerden:* The 50 magnitudes of extinction refer, I suppose to the visual and are estimated from the infrared on the basis of a particular model?

*Wynn-Williams:* The ratio of the measured 2.2 $\mu$m flux density to the expected free-free or free-bound transition radiation as calculated on the basis of the radio flux density leads to a lower limit to the extinction at 2.2 $\mu$m. An assumed interstellar extinction law, such as Whitford's, is then used to estimate the visual extinction.

*F. D. Kahn:* An IR source without a detectable H II region might also be produced in the following way. An early-type star, already on the main sequence, may still be accreting material at a higher rate. This leads to a high gas density around the star. Any H II region forming in this gas will have a very small surface area and will be strongly self absorbing in the radio range. The H II emission would therefore not be detectable at radio wavelengths.

*Mezger:* It is unfortunately the case that the density where the dust absorbs most of the Lyman continuum is also the density where the H II region becomes optically thick in the free-free continuum. So you cannot discriminate between the two possibilities that the H II region is so compact that the turn-over frequency is in the millimeter wavelength range or that the dust soaks up all the Lyman continuum.

*H. J. Habing:* I do not like the term 'protostar' for an object that emits sufficient UV photons to ionize a detectable H II region. This object is probably already rather close to the main sequence; I would prefer to call 'protostars' those objects still in their contraction phase, without nuclear burning.

*Mezger:* The best explanation for the use of 'protostar' in the context of H II regions is that everything that you can't explain in ordinary terms is called a 'protostar'. This has certainly turned out to be the case.

*Price:* You note that at a few hundred microns the radiation falls off more rapidly than you would expect for black bodies. Can you infer something about particle sizes from this?

*Wynn-Williams:* All it says is that particle sizes are less than 100 $\mu$m.

*Baldwin:* The present upper limit to the 5-GHz flux density of IRS5 in W3 of 10 mJy from the 5-km telescope does not yet put a very tight limit on the absence of a compact H II region. An optically thick region of 0.2″ diameter would have the flux density close to this limit, and 0.2″ is only a little smaller than compact regions we already know.

*Habing:* We may have detected the $H_2O$ source at the level of 5–7 mJy at 6 cm, but this is uncertain. We are fairly certain that the OH measure in the same W3 area is below 10 mJy. In the Orion case one should be extremely careful in stating that there is no radio phenomenon associated with the Kleinman-Low nebula and all the rest because really good data are lacking.

*Zuckerman:* What fraction of the IR emission in Orion comes from the Kleinman-Low nebula, and what is its temperature?

*Wynn-Williams:* It's not the Kleinman-Low nebula itself but a region centered on the Kleinman-Low nebula that is doing the emitting. Its diameter depends somewhat on the wavelength. The peak temperature is about 75–100 K, and it cools off outwards. Rieke reckons that two-thirds of the emission cannot be explained as coming from this small area but must come from a larger region.

*Terzian:* It seems to me that the similar brightness distribution of a source in the radio and infrared is a necessary but not sufficient condition for saying that the gas and dust are well mixed together. Is there other evidence on this problem?

*Wynn-Williams:* It is unnecessary to assume any special characteristics or concentration for the dust within the ionized region; an interstellar concentration of interstellar-type particles appears to be more than sufficient to cause the infrared emission. The assumption that the dust and ionized gas are mixed is therefore the simplest assumption you can make, and the observations seem to support it.

*Donn:* At infrared wavelengths up to 100 $\mu$m, when grains are smaller as you indicated, probably less than 1 $\mu$m, emissivity depends strongly on wavelength. How is this taken into account in deriving temperatures from the observed energy distribution?

*Wynn-Williams:* Since the H II regions contain dust grains at a variety of temperatures, the derived color temperatures in the 10 $\mu$m to 20 $\mu$m range are uncertain anyway. Changing the emissivity law to $\varepsilon \propto \lambda^{-1}$ or $\varepsilon \propto \lambda^{-2}$ still gives temperatures broadly in the 100 to 200 K range for these wavelengths.

*Radhakrishnan:* Do you think it is possible that the shape of the long wavelength end of the spectrum has something to do with the type of a particle?

*Wynn-Williams:* Yes, I think it is just the emissivity decreasing with increasing wavelength, and you can easily get up to a slope of up to 4 on the $d\varepsilon_\nu$ versus $\nu$ curve.