INFRARED PROPERTIES OF EXTRAGALACTIC HII COMPLEXES

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I. INTRODUCTION

Many galaxies emit significantly more infrared radiation than expected as directly observable photospheric emission. This emission is not restricted solely, or even predominantly, to the galactic nuclei. Rather, where detailed observations exist, they indicate that pronounced emission often originates throughout the disks and especially in the more extended central regions which are distinct from the nuclei. The process which invariably dominates the emission at wavelengths longer than a few microns is radiation from heated dust. At shorter infrared wavelengths, nebular continuum and line radiation, as well as the stellar photospheres, has been observed. In many cases, this emission has been unambiguously associated with HII complexes.

In this review, we focus first on infrared observations of relatively isolated giant HII complexes in the LMC and the spiral arms of M33 and M101. We then examine complexes which extend over several kiloparsecs near the galaxian centers. We will not consider the large body of data on extragalactic infrared emission which, although surely relevant to our discussion, is not straightforwardly attributable to HII complexes rather than unusual phenomena in the nuclei (see Rieke and Lebofsky 1979).

II. 30 DORADUS

Due to its proximity (55 kpc), 30 Dor is the best studied extragalactic HII region at infrared wavelengths. Werner et al. (1978) mapped the central 100 pc in several passbands at $\lambda > 30$ μm. The temperature of the far-infrared emitting dust decreases with increasing distance from R136 (Figure 1), clearly implicating that object and its neighbors as the sources which heat the dust and excite the nebula. The infrared luminosity throughout this region is 4×10^7 $L_\odot$, which is comparable to that of the observable stars at the position of R136. Thus, the luminosity from the region of R136 is converted efficiently into infrared radiation by dust in and near the visual nebula, and there is no need to invoke additional,

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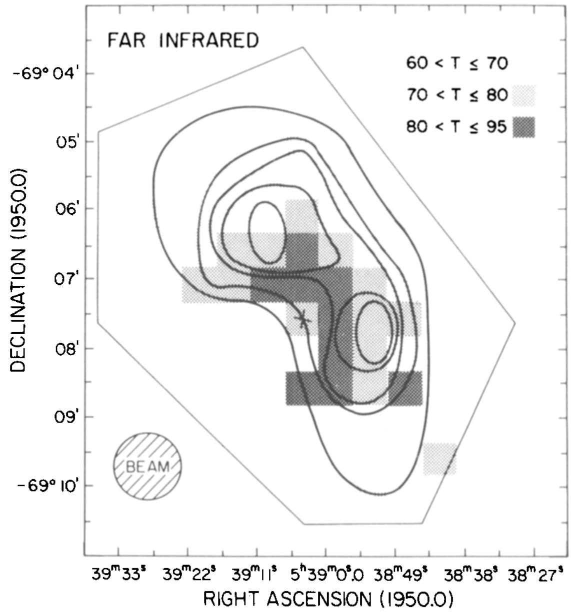

Figure 1. The variation of the 50-100 μm color temperature with position in the 30 Dor nebula, shown overlaid on the far-infrared luminosity contours. The cross marks the position of R136. From Werner et al. (1978).

obscured energy sources. The infrared luminosity is distributed in an arc northwest of, and concave towards, R136, which reflects the assymetric distribution of warm dust. The infrared brightness distribution resembles the distribution of ionized gas seen in Hα and the radio continuum, but the infrared ridge lies further away from R136 than do the regions of highest Hα and radio surface brightness. This suggests that R136 is heating dust located in neutral regions behind the ionization fronts, a result consistent with the "blister" model (Israel 1978) of evolved HII regions which heat and ionize the edges of adjacent molecular clouds.

30 Dor shares with Galactic HII regions the property of converting most of the stellar radiation into infrared emission. However, in addition to having a significantly higher infrared luminosity and larger size than Galactic HII regions like W51, there do not appear to be any high surface brightness infrared sources which are characteristic of embedded, heavily obscured younger objects (although a "protostar" has been detected elsewhere in the LMC by Gatley et al. 1981). This property is manifested partly in the infrared energy distribution of 30 Dor, which is characteristic of emission from dust with an average temperature higher than that usually identified with embedded sources in the Galaxy.

Particularly intriguing is the discovery that 30 Dor contains stellar populations from at least two bursts of star formation (Hyland, Thomas, and Robinson 1978; McGregor and Hyland 1981). The blue population, which includes numerous Wolf-Rayet stars, has an age of $\sim 10^6$ yr and appears to

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be exciting the nebula. Near-infrared observations, however, have revealed a large number of red supergiants which are older than 10^7 yr. Since these two populations appear to occupy the same region of space, scenarios of sequential star formation often invoked to explain the morphologies of Galactic HII complexes may not apply in 30 Dor.

III. THE DISKS OF M33 AND M101

The first infrared detection of an extragalactic HII region, IC 133 in the galaxy M33, was part of a 10 μm study of discrete extragalactic HII complexes (Strom et al. 1974). Since their observations, additional infrared studies have been made of M33, particularly of the giant spiral arm complex NGC 604. Because M33 is over an order of magnitude further away than the LMC (720 kpc), it is not surprizing that much less detailed information is available for NGC 604 than for 30 Dor. Detection of NGC 604 at 100 μm (Gatley, Harvey, and Thronson 1978) implies a far-infrared luminosity in the range $(0.4\text{-}1.4) \times 10^7\ L_\odot$, somewhat smaller than the stellar luminosity as estimated from the ultraviolet emission after correction for a magnitude of visual extinction (Israel et al. 1982); thus, like 30 Dor, there is sufficient dust in the HII region to convert a large fraction of the stellar flux into infrared radiation without totally obscuring the stars. Consistent with this is the fact that the far-infrared optical depth in the emitting region across the center of NGC 604 is $\sim 10^{-3}$, which is much less than that for embedded sources in the Galaxy. However, due to the large distance to M33, beam dilution could be significant for these observations (the far-infrared beam diameter was 40"); consequently, compact infrared sources with relatively large optical depths may be present in NGC 604. Observations near 10 μm with high spatial resolution should be able to determine if such regions, which are indicative of very early stages of stellar evolution, are present.

The HII complex NGC 5461 in M101 (at 6 Mpc) has also been studied in some detail in the infrared (Blitz et al. 1981). These data, consisting of 1-20 μm photometry and low spectral resolution observations of the Brγ recombination line of hydrogen at 2.16 μm, present a reasonably consistent picture of an HII region similar to W51 and W3.

IV. EXTENDED CENTRAL COMPLEXES

HII complexes near the centers of galaxies and with sizes of several kiloparsecs have been found to be powerful sites of infrared emission and star formation. Although the occurance of such regions has been known for some time, the recent emphasis on detailed observations of face-on galaxies has clarified considerably the relationship of the infrared emission with the visual complexes. The first galaxy in which a large-scale spatial correlation of visual HII regions and infrared emission was observed is the barred spiral NGC 1097 (Telesco and Gatley 1981). Strong 10 μm emission originates at the nucleus and in a visually bright ring which is ~ 2 kpc in diameter (Figure 2). Optical emission-line data and the presence of photospheric absorption lines in the ring indicate abun-

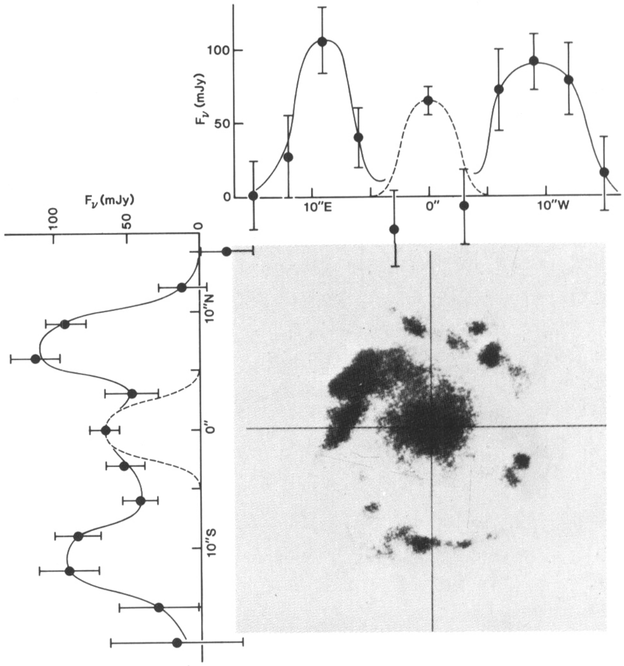

Figure 2. Comparison of 10 μm scans through the nucleus of NGC 1097 to a visual photograph. Enhanced infrared emission occurs at the nucleus and at the ring of HII regions ∿1 kpc from the nucleus (Telesco and Gatley 1981).

dant early-type stars and normal HII regions. The mid-infrared colors are consistent with the emission being from dust, and the spatial correlation between the 10 μm and visual distributions demonstrates that the emitting dust is located near the giant HII complexes. In terms of luminosity, do these regions qualify as giant HII regions? Most certainly; even with reasonable uncertainties in the ratio of total infrared to 10 μm flux for young-star regions, the infrared luminosity of any of the positions observed on the ring is $>10^9$ $L_\odot$ in a region ∿500 pc in diameter.

The large-scale spatial correlation of infrared and visual distributions has now been observed in several other galaxies including the Seyfert NGC 1068 (Telesco, Becklin, and Wynn-Williams 1982). Mapping of NGC 1068 at 10 μm has shown that, in addition to the bright nuclear infrared source (diameter ∿100 pc), extended emission originates across a visually bright disk ∿3 kpc in diameter which emits a total infrared luminosity of 1.8×10^{11} $L_\odot$ (the Seyfert nucleus emits an additional 1.4×10^{11} $L_\odot$). Of particular interest is the fact that the visual and ultraviolet flux attributable to young stars across this disk (and excluding the Seyfert nucleus) is only 13% of the infrared flux, even if generous allowance is made for blue stars emitting in the far-ultraviolet. Thus, nearly all of the young-star activity evident at infrared wavelengths in the disk of NGC 1068 is visually obscured. This conclusion is in marked contrast to results for the isolated giant HII complexes 30 Dor and NGC 604 in which most of the stellar luminosity is converted into infrared radiation without totally obscuring the stars.

As we look to the future, among the questions which infrared astronomers will be able to address is the relationship between giant spiral arm HII regions like NGC 604 and central complexes like the 3 kpc infrared disk in NGC 1068; we expect that differences in age and possibly the large-scale mechanisms of star formation are manifested at infrared wavelengths by, for example, the relative fraction of hidden and visible young stars and the efficiency of star formation. Clearly, extragalactic infrared astronomy is in its infancy, but we anticipate explosive progress to accompany the advent of mapping with infrared arrays, the increased focus of infrared spectroscopy on galaxies, and the launching of major new facilities like the Infrared Astronomical Satellite and the Shuttle Infrared Telescope Facility.

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