ON THE OBSERVED INFRARED FLUXES FROM EXTRAGALACTIC H II REGIONS

K. V. K. IYENGAR and K. S. KRISHNA SWAMY
Tata Institute of Fundamental Research, Bombay, India

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Abstract. We have calculated for extragalactic H II regions, the expected relationship between the radio flux at 11 cm and the infrared flux at 11 and 20 μm based on the grain models and the parameters which fit the observations of galactic H II regions. It is shown that the measured infrared fluxes of extragalactic H II regions are consistent with the expected infrared fluxes for these objects.

1. Introduction

Most of the galactic H II regions emit a large amount of infrared radiation over and above the free–free emission from the ionized gas (Wynn-Williams and Becklin, 1974). The extragalactic H II regions also seem to emit a large amount of infrared radiation (Strom *et al.*, 1974), although the observations are limited at the present time. It is generally believed that this excess of observed infrared radiation arises from the thermal re-radiation by dust grains. If the heating of the grain is due to Lymanα (Lyα) photons, then one expects a linear relation between the radio flux and the infrared flux. Even with limited observations Harper and Low (1971) did find a correlation of this type although the energy contained in Lyα was found to be smaller by a factor of five or so compared with the observed total infrared radiation (see Wynn-Williams and Becklin, 1974). Strom *et al.* (1974) have given in their paper a linear relation between the radio flux at 11 cm and the infrared flux at 11 and 20 μm for galactic H II regions based on the AFCRL infrared sky survey (Walker and Price, 1975). It may be noted that the AFCRL infrared sky survey carried out at 4, 11 and 20 μm, is an extensive compilation of infrared measurements which suffers less from nonobjective selection criteria. Attempts are being made at the present time to verify and also to identify the sources from this Catalogue (Low *et al.*, 1976; Lebofsky *et al.*, 1976; Gehrz and Hackwell, 1976; Cohen and Kuhi, 1976; Allen *et al.*, 1976). Some of these studies have not been able to confirm many of the sources listed in the AFCRL Catalogue. However, the H II regions considered by Strom *et al.* in their study were those identified by comparing the AFCRL source list with the 11 cm survey of Altenhoff *et al.* (1970). It is therefore safe to assume that their analysis is based on genuine sources and not on sources of spurious nature.

In the present paper, we will first calculate the expected relation between the radio flux at 11 cm and the infrared flux at 11 and 20 μm based on the particle models for galactic H II regions. We then use parameters which give a good fit to the observed

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relation for galactic H II regions to calculate the relation to be expected for the extragalactic H II regions. These results are compared with the infrared observations of extragalactic H II regions of Strom *et al.* It is shown that the infrared observations of extragalactic H II regions are consistent with the expected infrared fluxes for these objects.

2. Method of Calculation

The thermal emission from the grains in H II regions is calculated using the model given by Krishna Swamy and O'Dell (1968) and Krishna Swamy (1969). Here we refer only to those points which are relevant to this paper.

The factors $(3f)^{1/4} \equiv F^{1/4}$ which occurs in the temperature calculation is treated as a parameter. We use for the infrared absorptivity I, the mean value defined by the relation

$$I = \frac{\int Q(\lambda) B(\lambda, T_g)\, d\lambda}{\int B(\lambda, T_g)\, d\lambda},$$

where $B(\lambda, T_g)$ is the Planck function and $Q(\lambda)$ the absorption efficiency of the grain. The Lyα flux is calculated from a knowledge of the radio flux (Osterbrock, 1964, 1974). An electron temperature of 10 000° K is assumed for all H II regions. Since the composition of grains in H II regions is still far from certain, we perform calculations for two types of possible grain models, namely, graphite and silicate.

The calculation of the grain temperature involves a knowledge of the ultraviolet and infrared absorptivities. The ultraviolet absorption cross-section is calculated using the Mie theory (van de Hulst, 1957). In the infrared and far infrared regions, where $a \gg \lambda$ is valid (a being the radius of the grain), we have used the corresponding asymptotic expression for the absorption cross-section (van de Hulst, 1957). We have used the values of refractive index of Taft and Phillipp (1965) to calculate the absorptivities of graphite grains. We use the dielectric constants (ε_1, ε_2) of Perry *et al.* (1972) to compute the infrared absorptivity of the silicate grains. They have obtained these constants for a large number of lunar samples of Apollo 11, 12 and 14 from an analysis of infrared reflectance spectra. As the results for various samples are similar in nature, we used as representative the results obtained for two rocks, viz., 14321 and 12009. Since the refractive index of these samples in the ultraviolet region is not available, we set the ultraviolet absorptivity equal to unity. The calculations were performed for typical graphite and silicate grains of radii 0.02 and 0.2 μm, respectively.

3. Results and Discussion

The listing of the radio sources of Altenhoff *et al.* that were identified with the AFCRL sources by Strom *et al.* was not available to us. We have therefore selected a sample of sixty galactic H II regions from the source listings of Altenhoff *et al.* at 11 cm to cover

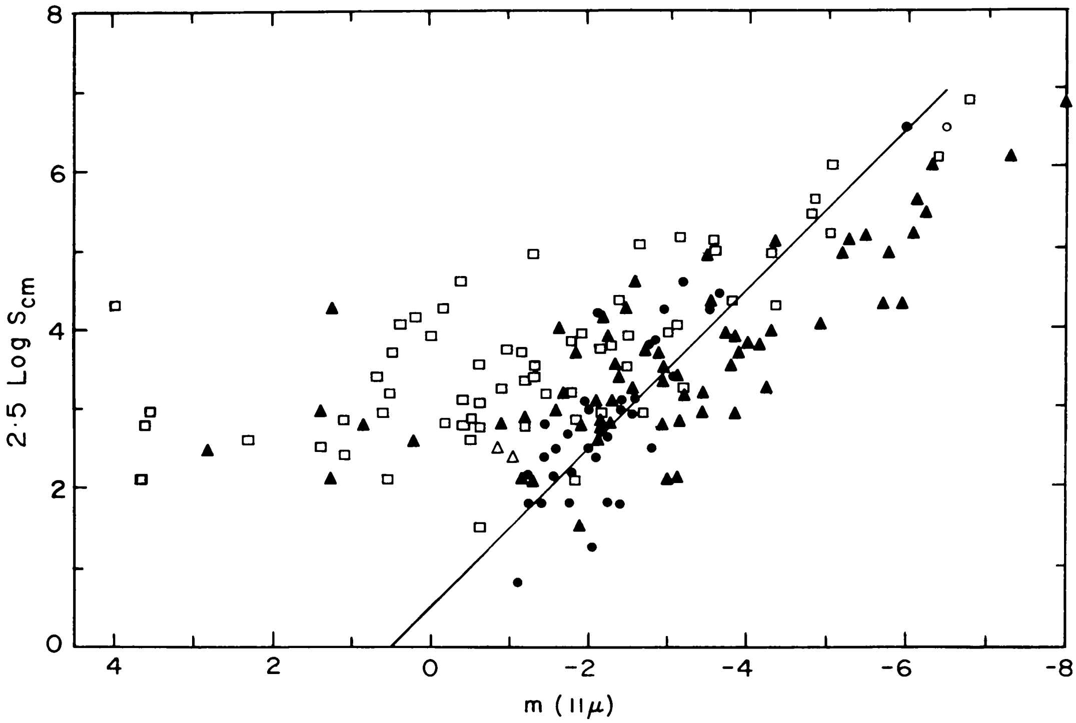

Fig. 1. Comparison of the radio flux in flux units at 11 cm (S cm) versus m (11 μm) for graphite model with F=30. M=3 (□), M=7 (▲) and observations (●). The line shown in the figure is that drawn by Strom *et al.* to pass through the observational points.

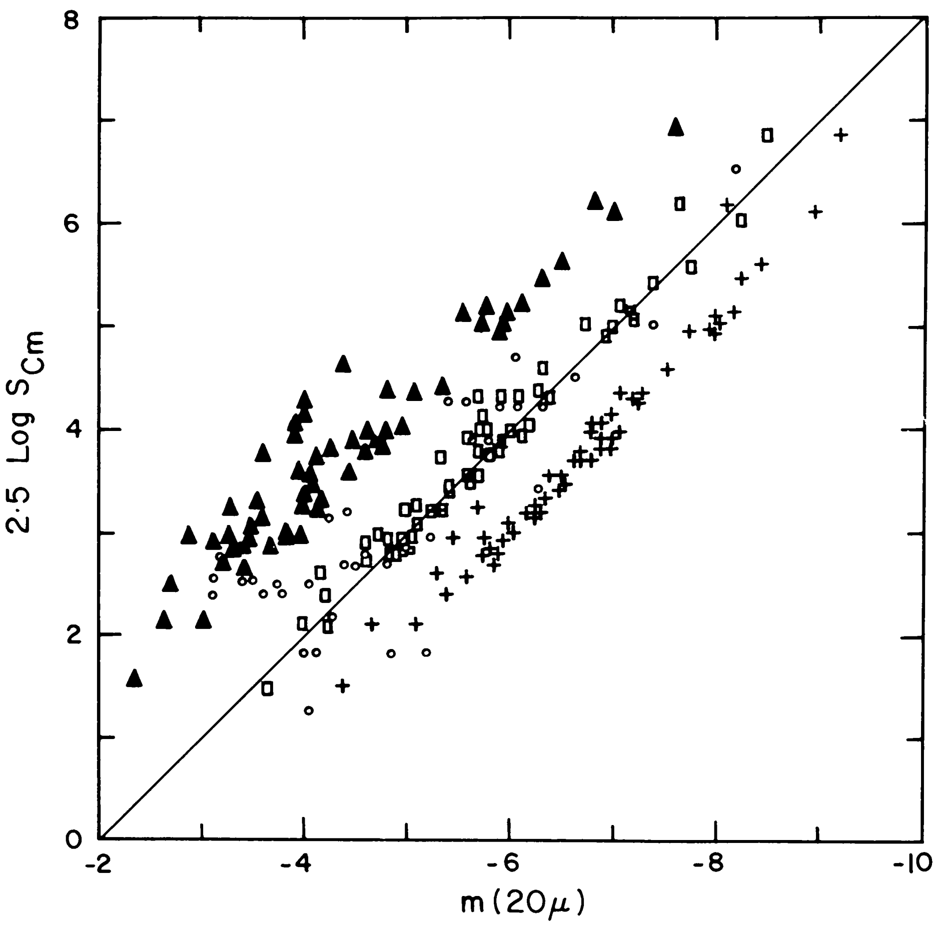

Fig. 2. Same as Figure 1, but for 20 μm. M=1 (▲), M=3 (□), M=7 (+) and observations (○).

the flux range from 4 to 552 Jy. The calculated infrared fluxes were converted to infrared magnitudes using the calibration of Walker and Price (1975). It was found that the calculated infrared magnitudes were always fainter than those of observations for all values of F, for both the graphite and silicate models. Therefore we introduce a parameter M, a factor by which Lyα flux is to be enhanced to bring an agreement with the observations. In Figures 1 and 2, the results are shown for different values of M with F set equal to 30 for the graphite model. To get an agreement between the calculations and observations, one requires $M \approx 3$ to 5, although 11 μm data fit better for $M \sim 5$ and 20 μm data for $M \sim 3$. This implies that the Lyα heating of the grain by itself is not sufficient to explain the observed infrared fluxes from H II regions. This is consistent with other investigations based on the total infrared luminosity. The calculations also show that the 11 μm magnitudes depend both on the variables F and M, while the 20 μm magnitudes depend primarily on the factor M. It is also found that the graphite model seems to fit the observation better than that of the silicate model.

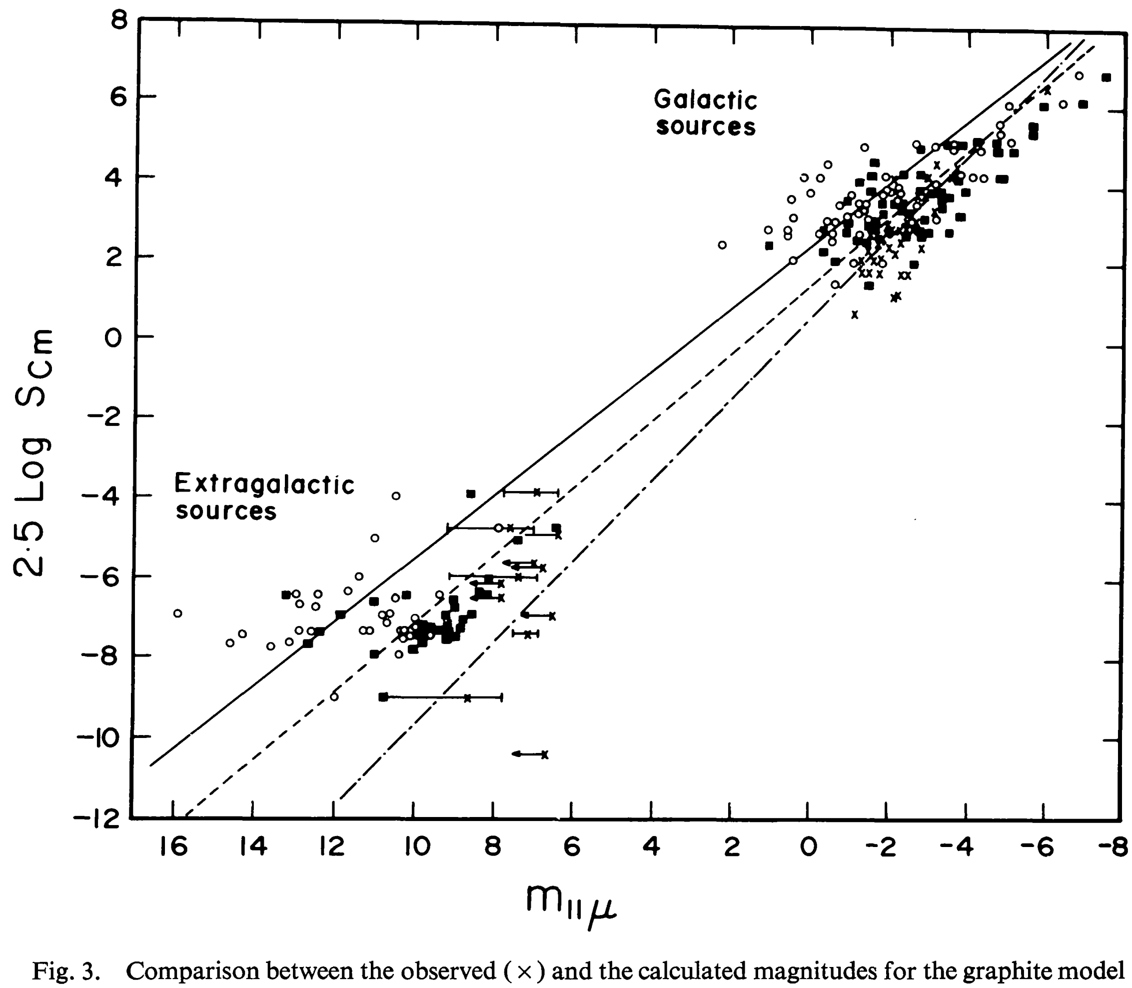

Fig. 3. Comparison between the observed (×) and the calculated magnitudes for the graphite model with $F = 30$ and for $M = 3$ (○) and $M = 5$ (■) respectively. Dot-dashed, continuous and dashed lines represent the linear square fits to, observational data of galactic and extragalactic sources, calculated values for the selected galactic and extragalactic sources for $M = 3$ and 5 respectively.

With $F=30$ and $M=3$ to 5, which gives a good fit for the galactic H II regions, we have calculated the expected relation between the radio flux at 11 cm and the infrared flux at 11 and 20 μm for extragalactic H II regions. The 11 cm radio fluxes were estimated from the radio fluxes at 21 cm (Israel and Van der Kruit, 1974) by assuming a power law relation of the type $S_\nu = k\nu^\alpha$ with $\alpha = -1$. We have selected 29 sources from the table of Israel and Van der Kruit for M33 covering the flux range 0.14 to 27 mfu. For other sources we have taken the 21 cm fluxes given in the table of Strom *et al.* The calculated results are compared with the observations of Strom *et al.* in Figures 3 and 4. Strom *et al.* have given for many sources only the upper limits for the infrared fluxes at 11 μm. The infrared measurements at 20 μm are given only for two sources and that too only for upper limits. In view of this, we have calculated the least square fit for the following three cases: (1) infrared observations of galactic and extragalactic H II regions; (2) expected infrared fluxes of galactic and extragalactic sources for $M=3$ based on the graphite model; and (3) similar to (2) except for $M=5$. The results obtained for these three cases are shown as dot–dashed, continuous and dashed lines respectively in Figures 3 and 4. The cases (2) and (3) are shown essentially to cover the range in values of M that fit the data of galactic H II regions. It may be

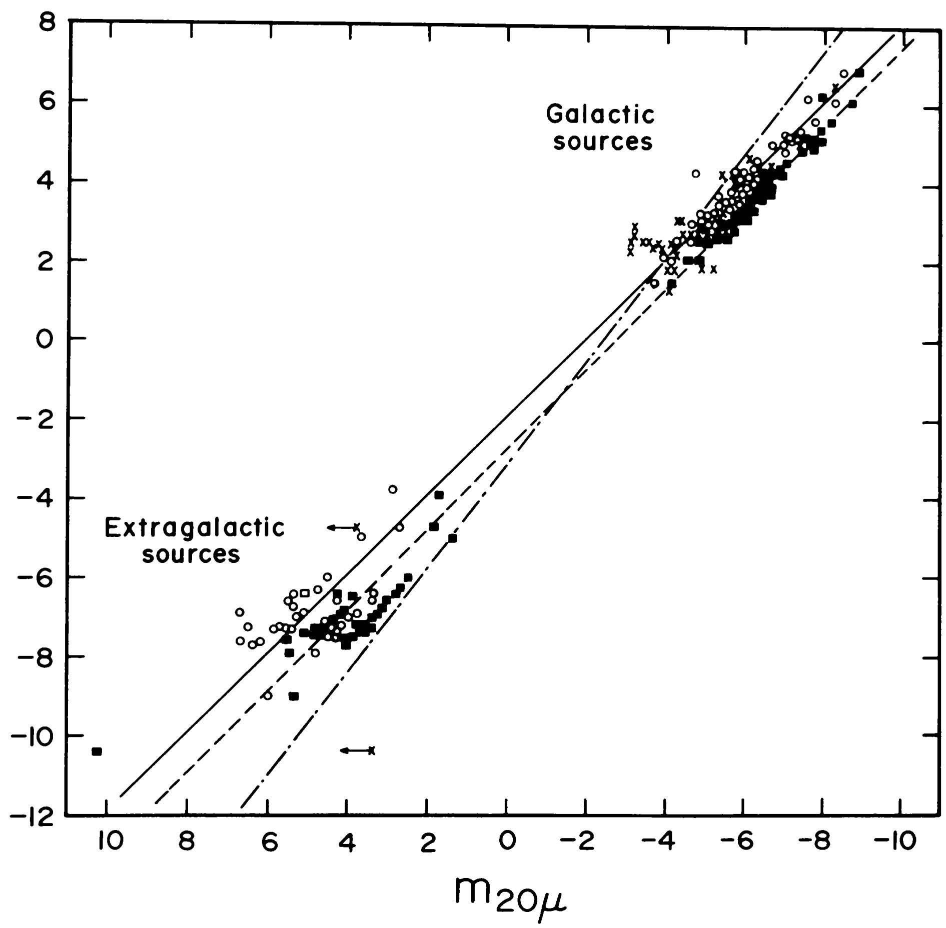

Fig. 4. Same as Figure 3, but for 20 μm.

pointed out that the least square fit line passing through the observations of galactic and extragalactic sources is based on many of the observations of extragalactic sources for which only upper limits are available. Therefore the line should move in the direction of the calculated lines when definite values of the infrared fluxes for these sources become available. Figures 3 and 4 show that the measured infrared fluxes of extragalactic H II regions are consistent with the expected infrared fluxes for these objects. Further observations of these objects are urgently needed.

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