(HC) 1.00
(MF) .50

INFRARED CONTINUUM FROM HII REGIONS

Recent observations of the planetary nebula IC418 by F. J. Low have indicated a measurable flux of about 10^{-16} watt cm^{-2} near a wavelength of 13 microns. This observation has been interpreted as emission from Ne^{+} at 12.8μ (Gould 1966). In order to investigate alternative explanations the expected flux of infrared free-free emission from planetary nebulae was calculated. The results show that the free-free flux, although not large enough to explain the observed flux from a nebula such as IC418 near 13μ, should be detectable from some planetaries at the shorter infrared wavelengths of 3 or 5 microns. Observations of the free-free emission from planetary nebulae would provide an alternative method to radio frequency observations of checking the recombination theory of emission of visible light. The possibility of further investigating other HII regions such as the Orion nebula and the compact thermal radio source at the galactic center (Lequeux 1962) through infrared free-free radiation is also of interest. The longer infrared wavelengths provide the possibility of making such measurements free of the problems of extinction by interstellar dust as well as at frequencies high enough to eliminate self-absorption by the thermal radio sources.

In order to determine the wavelengths at which free-free radiation might be observed from HII regions it was necessary to estimate the flux of radiation that might be observed due to other continuum radiation processes in the infrared. This discussion will ignore nonthermal processes such as synchrotron radiation since they are probably not of importance in thermal HII regions. At the shorter infrared wavelengths ($\lambda < 3\mu$) it might be expected that continuous radiation due to recombination of hydrogen and 2 photon emission from the 2S state of hydrogen could be significant.

Spitzer and Greenstein (1951) have shown that in the visible region of the spectrum the two quantum process contributes enough radiation to decrease the magnitude of visible recombination discontinuities at the series limits. It was shown that the two quantum process contributes less radiation at the Balmer and Paschen limits than the recombination process, however. In order to estimate the contribution of recombination and two photon emission in the infrared it seems justifiable to use as an approximate upper limit the upper bound to the intensity from recombination radiation at the series limits. This limit is obtained by setting $h\nu = \chi_1/n^2$ in the expression for the emissivity due to recombination radiation where χ_1 = ionization potential of state $n = 1$ of hydrogen. The expressions for the emissivity of an ionized gas due to free-free and recombination radiation are well known and need not be discussed here. If one considers the upper bound to the recombination radiation at all wavelengths, the result for the ratio of free-free to recombination continuum is given approximately by

$$\frac{P(\nu)_{f-f}}{P(\nu)_{f-b}} > \frac{10^{10}\ T}{\nu} \left(\frac{\chi_1}{h\nu}\right)^{\frac{1}{2}} e^{-h\nu/kT} \left(\frac{\bar{g}_{ff}}{\bar{g}_{f-b}}\right) .$$

where $\bar{g}_{ff}$ and $\bar{g}_{f-b}$ are the average Gaunt factors for the two processes. It was assumed for these calculations that $\bar{g}_{f-b} \approx 1$ and $\bar{g}_{f-f}$ was taken from Karzas and Latter (1961). The frequency in the infrared at which there would be no more than a ten percent contribution due to the other processes can then be found. For typical HII regions for which the temperature is 15,000 ^{o}K this frequency is about 10^{14} cps. In other words at wavelengths longer than about 3 microns the continuum flux from ionized hydrogen can be essentially all attributed to free-free emission.

Another possible source of infrared emission from galactic nebulae that contain dust is infrared emission by the grains. The unknown composition of the dust makes it difficult to construct meaningful models for the infrared emission by the grains. Therefore, for the present no such model of emission from grains in galactic nebulae will be constructed. It seems more reasonable to first understand the infrared continuous emission from planetaries where no dust exists. Comparison of planetary nebula results with observations of galactic nebulae where dust does exist could then perhaps be used in infer properties of the interstellar grains. An estimate of the flux of radiation from dust in a galactic nebula can be made assuming a star temperature of 20,000 $^{\circ}$K, a scattering optical depth at visible wavelengths of one and absorption efficiency for the grains of at least 0.1. If the distance of the nebula were 500 pc the flux from dust would be of the order of 3×10^{-10} watt m^{-2}. This is larger than the expected free-free flux in any attainable bandwidth. However, the spectral distribution of this radiation is unknown.

For the purposes of this discussion the expected infrared free-free emission from five of the brightest small planetaries has been based on observed Hβ fluxes. Predictions of radio fluxes from planetaries were first made by Osterbrock (1964). Observations of planetaries (Menon and Terzian 1965) show that in many cases spectra at radio frequencies are dominated by self-absorption in the nebulae. It would therefore be incorrect to determine predicted infrared fluxes from these radio measurements. The calculation of the expected flux of free-free radiation from the Hβ flux need be made at only one frequency, for example 1400 Mc. Then the ratio of the infrared flux to the radio flux is given simply by

$$\frac{P(\nu)_{IR}}{P(\nu)_{Radio}} = \frac{\bar{g}_{IR}}{\bar{g}_{radio}} \quad e^{-h\nu_{IR}/kT}$$

since $\nu_{IR} >> \nu_{radio}$. The average Gaunt factors at radio wavelengths were calculated from the formula of Brussard and Van de Hulst (1962) while the average Gaunt factors for infrared wavelengths were obtained from Karzas and Latter (1961). The results for five of the brightest small planetary nebulae are given in Table 1 for wavelengths from 3 microns to 1 mm.

In addition to the expected results from five planetaries, Table 1 lists the expected flux from the Orion Nebula (based on radio observations summarized in Howard and Maran 1965) and the expected flux from the thermal source in the Galactic nucleus (Lequeux 1962). Again the average Gaunt factor as a function of frequency was used to get the predicted infrared free-free fluxes.

Comparing the results of Table 1 with known infrared sources such as 3C273 (Johnson and Low 1964), it seems that it would presently be possible to detect the free-free emission from the brightest planetaries at 3 or 5 microns wavelength. The presently detectable flux at 5 microns is in the range of 1 to 2 x 10^{-26} watt m^{-2} cps^{-1} (Low, 1966). In addition, it should eventually be possible to detect the free-free emission from the galactic nucleus source and galactic nebulae such as Orion. The latter sources present a somewhat different observational problem than the planetaries because they are extended sources compared with the planetaries. Of course observations of the galactic nucleus should be done at relatively long infrared wavelengths to eliminate the problem of interstellar extinction.

Observations of the Orion nebulae have been made at very short infrared wavelengths (.85 - 1.7μ) by Moroz (1964). Moroz concludes that the observed flux from Orion is entirely explained by free-free and recombination radiation and that scattering by dust probably is not important at these wavelengths. However, the wavelengths near 1 micron are probably too short to expect to observe infrared emission by dust in the nebula.

It has been shown that the infrared free-free emission from several HII regions should be detectable. The results of such measurements on planetary nebulae at wavelengths greater than 3μ offer an alternative method of checking the recombination theory of visible light from planetaries. Such measurements would be free of problems of interstellar extinction in the visible and self-absorption by the source at radio wavelengths. The understanding of the continuum from planetaries in the infrared is an essential preliminary step to the understanding of the infrared continuum from alleged thermal sources such as the compact radio source in the galactic nucleus and galactic nebulae from which emission from interstellar grains is expected.

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TABLE 1

Object	Angular diameter	Infrared free-free flux (watt/m^{2}cps)				
		λ = 1 mm ν = 3x10"cps	$\lambda = 20\mu$ $\nu = 1.5\times10^{13}$cps	$\lambda = 10\mu$ $\nu = 3\times10^{13}$cps	$\lambda = 5\mu$ $\nu = 6\times10^{13}$cps	[illegible]
IC 418	12"	2.4×10^{-26}	1.3×10^{-26}	1.1×10^{-26}	9.0×10^{-27}	$7.7 \times 10^{[illegible]}$
NGC 6543	20"	9.5×10^{-27}	4.5×10^{-27}	4.0×10^{-27}	3.2×10^{-27}	2.6×10^{-27}
NGC 6572	15"	1.5×10^{-26}	7.4×10^{-27}	6.0×10^{-27}	4.7×10^{-27}	3.9×10^{-27}
NGC 7027	14"	4.7×10^{-27}	2.4×10^{-26}	2.1×10^{-26}	1.6×10^{-26}	1.4×10^{-26}
NGC 7662	15"	7.9×10^{-27}	4.1×10^{-27}	3.5×10^{-27}	2.5×10^{-27}	2.3×10^{-27}
Galactic nucleus	3.5'	1.6×10^{-24}	8.2×10^{-25}	6.9×10^{-25}	5.4×10^{-25}	4.6×10^{-25}
Orion	10'		approx. same as galactic nucleus			

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