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Prediction of the Diffuse Far-Infrared Flux from the Galactic Plane

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ABSTRACT:

A basic model and simple numerical relations useful for future far-infrared studies of the galaxy are presented. Making use of recent CO and other galactic surveys, we then predict the diffuse far-infrared flux distribution from the galactic plane as a function of galactic longitude ℓ for $4^{\circ} \leq \ell \leq 90^{\circ}$ and the far-infrared emissivity as a function of galactocentric distance. Future measurements of the galactic far-infrared flux would yield valuable information on the physical properties and distribution of dust and molecular clouds in the galaxy, particularly the inner region.

I. INTRODUCTION

Our picture of the state and distribution of interstellar gas in the galaxy has been rapidly changing with important implications for galactic structure theory (Burton 1976, Stecker 1976). These changes have come about as a consequence of important observational evidence of CO in molecular clouds at mm wavelengths (Scoville and Solomon 1975, Burton et al. 1975, Gordon and Burton 1976) and satellite observations at γ-ray wavelengths (Fichtel et al. 1975). The CO surveys show that the molecular cloud abundance in the galaxy exhibits a strong radial dependence with a broad maximum in the 5 to 6 kpc region. A strong increase in the γ-ray emissivity peaking in the 5 to 6 kpc region (Stecker et al. 1974, Puget and Stecker 1974) has now been associated with the strong increase in the molecular cloud concentration there (Solomon and Stecker 1974, Stecker et al. 1975). The recent observations imply that H_2 is by far the most abundant form of gas in the inner galaxy. These results are consistent with the basic concepts of density wave theory (Burton 1976, Stecker 1976).

Both the CO and γ-ray observations require some indirect analysis in obtaining parameters such as hydrogen densities. These analyses lead to different uncertainties so that the CO and γ-ray observations complement each other to some extent (Stecker et al. 1975).[1] Another promising technique for studying large-scale galactic structure lies in comparing the γ-ray and radio synchrotron observations (Paul et al.

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[1]See also Puget et al. 1976

1976) but again, this type of analysis should ultimately include independent observational determinations of the gas density.

Far-infrared observations provide a powerful alternative technique for exploring the physics and galactic distribution of cold molecular clouds. The basic source of far-infrared radiation in a molecular cloud or HII region is the reradiation of dust heated by light from early type stars or young stellar associations located in or near a cloud and having an evolutionary connection with it as extreme population I. Judging from measurements of CO excitation temperatures in these clouds (Scoville and Solomon 1975, for example), the dust temperature in them is expected to be of the order of 10-20 K and that they are expected to radiate most of their energy in the wavelength range between 100 μm and 300 μm in distinct contrast to the hotter strong infrared sources at shorter wavelengths (<100μm) which are primarily associated with HII regions. Stein (1966) and Pipher (1973) have previously proposed the existence of a diffuse infrared flux from the galactic plane due to thermal radiation by dust grains, but the recent CO observations now permit a more detailed prediction of the properties of this radiation.

In this Letter we will assume that the ratio of total gas to dust is roughly the same as that in more diffuse atomic clouds (Ryter et al. 1975) and that the physical properties of the dust are roughly uniform throughout the Galaxy. We will then propose a framework for future far-infrared surveys by suggesting some basic numerical relations for predicting flux distributions and emissivities. Using dust temperatures derived from CO and other measurements, we then predict the diffuse far-infrared flux distribution in the galactic plane as a function of galactic longitude ℓ in the range $4^{o} \leq \ell \leq 90^{o}$ and the far-infrared emissivity distribution as a function of galactocentric distance.

II. GALACTIC PLANE EMISSION

If we assume the dust is at an equilibrium temperature, T_d, and radiates with an absorbtivity, $Q_{IR,}$ then the energy emitted in the wavelength interval $d\lambda$ per unit volume of the dust cloud per second is given by

$$J_{IR}(\lambda)d\lambda=4\pi^2a^2n_dQ_{IR}(\lambda)B_\lambda(T_d)\ d\lambda \qquad (1)$$

where a is the radius of the dust grain, n_d the density of dust particles, and $B_\lambda(T)$ is the Planck function.

The value of n_d is related to the total hydrogen density by

$$n_d = (3m_H/4\pi\rho a^3)\ (M_d/M_H)\ n_H \qquad (2)$$

where m_H is the mass of the hydrogen atom n_H the total hydrogen density (n_H=$2n_{H_2}$+n_{HI}), ρ is the grain density, and M_d/M_H the dust-to-gas mass ratio. The column density $N_H=\int n_H ds$ in any direction can be related to the CO emission in that direction as follows:

$$N_H = 4.6 \times 10^{20}\ I_{CO}\ \mathrm{cm}^{-2} \qquad (3)$$

where $I_{CO} = \int T_A dv$ is the integrated CO intensity in units of K km s^{-1} (Solomon 1973, Scoville and Solomon 1975, Gordon and Burton 1976).[2]

[2]Based on the CO measurements alone, eq. (3) is uncertain by a factor of 5 (Scoville and Solomon 1975). However, arguments taking into account infrared and x-ray absorption measurements reduce this uncertainty to within a factor of 2 (Stecker *et al*. 1975).

The dust parameters are ρ, a, and Q_{IR}. The value of ρa can be determined using a hydrogen column density at $\ell=0°$ (excluding the galactic nucleus) of $7 \times 10^{22} cm^{-2}$ (Stecker et al. 1975) and an optical depth in that direct $\tau_v = 28$, (Becklin and Neugebauer 1968, Spinrad et al. 1971). Then

$$\tau_v = 0.92\ A_v = \pi a^2 Q_v N_d \tag{4}$$

where A_v is the visual extinction in magnitudes, Q_v is the extinction efficiency at visible wavelengths and N_d is the column density of the dust. If we assume the canonical values $(M_d/M_H) = 10^{-2}$ and $Q_v = 1$, we find

$$\rho a = 3.1 \times 10^{-5}\ g\ cm^{-2} \tag{5}$$

This is consistent with the values given by Allen (1973) of $\rho = 1\ g\ cm^{-3}$ and $a = 3 \times 10^{-5}$ cm estimated from Q_v and which we now adopt. We then obtain from eq. (2)

$$N_d = 1.4 \times 10^{-13}\ N_H \tag{6}$$

The value of Q_{IR} is assumed to be of the form $A_1 \lambda^{-1}$ with $A_1 = 4.5 \times 10^{-5}$ cm (Pottasch 1973).[3] The optical depth of the dust is then

$$\tau_{IR} = Q_{IR} \pi a^2 N_d = 8.2 \times 10^{-6} \lambda^{-1}_{cm}\ I_{CO} \tag{7}$$

For the range of values for I_{CO} given by Scoville and Solomon (1975) and taking $\lambda = 300\ \mu m$, it is found that the galaxy is optically thin

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[3]The dependence $Q_{IR} \propto \lambda^{-n}$ with n = 1 is somewhat uncertain at long wavelengths. Pottasch (1973) and Soifer et al. (1972) find evidence in far of an overall dependence given by $n \simeq 1$. Scoville and Kwan (1975) and Leung (1975) suggest the dependence may be better represented by $n \sim 1.5$ for $\lambda \gtrsim 30\ \mu m$, although Leung also gives several examples of grains for which $n \simeq 1$. Andriesse (1974) suggests that n = 2 for $\lambda > \lambda_c$ with λ_c between 50 μm and 200 μm.

at far-infrared wavelengths.

From equations (1) and (3) the infrared brightness can be computed as a function of galactic longitude ℓ

$$i_{IR}\, d\lambda = \frac{d\lambda}{4\pi} \int J_{IR} ds = 0.97 \times 10^{-10} \tag{8}$$

$$\times \{ I_{CO}(\ell)\, d\lambda\, \lambda^{-6} (\exp(1.44/\lambda T) - 1)^{-1} \}$$

$$\text{erg cm}^{-2}\text{s}^{-1}\text{Sr}^{-1}$$

with λ in cm. The total infrared brightness is

$$I_{IR} = \int_0^\infty i_{IR} d\lambda = 3.8 \times 10^{-13} T_d^{\,5}\, I_{CO}(\ell)\ \text{wm}^{-2}\ \text{Sr}^{-1} \tag{9}$$

The total emission per grain is

$$\varepsilon_g = n_d^{-1} \int J_{IR}\, d\lambda = 7.7 \times 10^{-24}\ T_d^{\,5}\ \ \text{w} \tag{10}$$

The temperature of the dust can be derived by relating it to the CO kinetic temperature, $T_{CO.}$ Goldreich and Kwan (1974) and Scoville and Kwan (1975) have investigated the thermal coupling between radiatively heated dust and ambient molecular gas (H_2) and indicate that the gas will approach thermal equilibrium with the dust ($T_{H_2} \rightarrow T_d$) via collisions of H_2 with grains for $n_{H_2} > 10^4 \text{cm}^{-3}$. However, at $n_{H_2} = 10^4\ \text{cm}^{-3}$ the collision rate is sufficient to give only $T_{H_2} = 1/2\ T_d$. Observational evidence, however, suggests the coupling may be stronger. Scoville and Solomon derive an average value of T_{CO} of 6.6K. We shall assume that a lower limit to T_d is ~7K.

An upper limit to the dust temperature can be derived by assuming the dust particle absorbs all the incident visible and ultraviolet radiation and reradiates it in the infrared. At equilibrium:

$$4\pi^2 a^2 \int_0^\infty Q_{IR}\ B_\lambda(T_d)\ d\lambda = \pi\ a^2 c u_\gamma \tag{11}$$

where u_γ is the density of radiation in interstellar space ≃ 7 x 10^{-13} erg/cm^3 (Allen, 1973). Solving for $T_{d,}$ we get T_d = 15K. Kaplan and

Pikelner (1970) and Greenberg (1971) obtain similar estimates. u_γ may vary somewhat throughout the galaxv but eq. (11) gives only a slight $u_\gamma^{0.2}$ dependence for T_d.

In presenting our results in graphical form, we shall assume a value T_d=10K. In figure 1 we have plotted the total infrared brightness, I_{IR} as a function of galactic longitude derived from eq. (9) using the data of Scoville and Solomon for I_{CO} and excluding the galactic center. Of particular importance is the predicted large peak at $\ell = 30^o$ tangent to the maximum interstellar gas density near 5 kpc.

A further consequence of our model which can be used as an experimental test is the prediction that the width of the galactic far-infrared disk should be comparable with that of the molecular cloud disk. The full width of the cloud disk is given by Scoville and Solomon to be $\sim 1°$ at $\ell \simeq 30°$.

The infrared spectrum can be obtained from equation (8). The maximum in the spectral curve is given by

$$\lambda_m \simeq (hc/5.98T_d) \simeq 0.24\ T_d^{-1}\ \text{cm} \tag{12}$$

where for T_d = 10K, λ_m = 240 μm. With Q_{IR} of the form $A_n\lambda^{-n}$ (n>0).

$$\lambda_m \simeq hc/\{(n+5)\ kT_d\} \simeq \frac{1.44\ \text{cm}}{(n+5)T_d} \tag{13}$$

In the Raleigh-Jeans approximation hc <<λkT, the far infrared spectrum takes the power-law form

$$I_{IR}(\lambda)\ d\lambda \propto \lambda^{-(4+n)}d\lambda \tag{14}$$

It follows from eq. (11)(also Andriesse (1974)) that assuming n > 1 would result in higher T_d estimates and smaller differential fluxes at long wavelengths, although the total infrared flux integrated over all λ as shown in the figures remains unchanged (Greenberg 1971). For example, Andriesse (1974) with n = 2, obtains $T_d \sim$ 24K with $\lambda_m \sim$ 85 μm. For the intermediate case, n = 1.5 $\lambda_m \sim$ 150-200 μm. Future spectral measurements over the galactic plane in the far-infrared could thus help determine the wavelength dependence of Q_{IR}.

Using the relations derived by Stecker et al. (1975) in conjunction with equations (6) and (10) and employing the data of Scoville and Solomon on the molecular cloud distribution in the galaxy, the total far-infrared emissivity from molecular clouds as a function of galactocentric distance was calculated. The results are given in figure 2.

III. GALACTIC CENTER REGION

In the galactic center region $|\ell| \leq 3°$, Scoville, Solomon and Jefferts (1974) have already shown that a correlation exists, as a function of galactic longitude, between the 100 μm flux and the maximum CO brightness temperature at each longitude. These authors conclude that the CO and dust coexist in nearly thermal equilibrium.

The CO measurements indicate that the molecular cloud disk surrounding the galactic nucleus has a radius of ∿ 600 pc and that the total mass of molecular gas, mostly H_2, within the cloud is ∿ $5 \times 10^7 M$.

In accordance with our assumed gas-to-dust ratio, the implied dust mass is then $M_d \sim 5 \times 10^5 M_\odot$ or about 10^{39} g. The total number of grains is then

$$N_g = (3M_d/4\pi a^3\rho) \simeq 10^{52} \quad (15)$$

and, from equation (10), the total luminosity of the galactic center source is estimated to be

$$L_{G.C.} = N_g\varepsilon_g \simeq 8 \times 10^{28}\ T_d^5\ w \quad (16)$$

which, using the data given by Hoffman, Frederick and Emery (1971), yields an estimated temperature $T_{d,G.C.}$ of the order of 25 K. The mean temperature of the CO gas, expected to be somewhat cooler, is of the order of 20 K (Scoville, Solomon and Jefferts 1974) so that our model gives reasonable results for the galactic center source.

IV. CONCLUSIONS

Our results indicate that much can be learned about the physics and conditions of interstellar dust and molecular clouds as well as the galactic dust and cloud distribution by making far-infrared studies of the galactic plane. In the inner galaxy, most of the interstellar medium is in the form of the cold clouds. Far-infrared surveys, in conjunction with other observations, will enable us to get better estimates of quantities like N_H, N_d and T_d. In this paper, we have predicted the intensity, angular distribution and spectrum of the diffuse far-infrared radiation over that region of the galactic plane where sufficient CO data are available ($4° \leq \ell \leq 90°$) using the data of Scoville and Solomon (1975). Comparison of our model with 100 μm observations of the galactic center source, which is expected to be about three times hotter than the average galactic molecular cloud, gives us confidence in the basic relations given in this Letter. We believe the flux estimates calculated here to be reasonable predictions, however, one should bear in mind the assumptions made, in particular the wavelength dependence of Q_{IR}, the uncertainty in the relationship between I_{CO} and n_H and the assumption of a uniform value of T_d = 10 K since the predicted flux has a steep temperature sensitivity.

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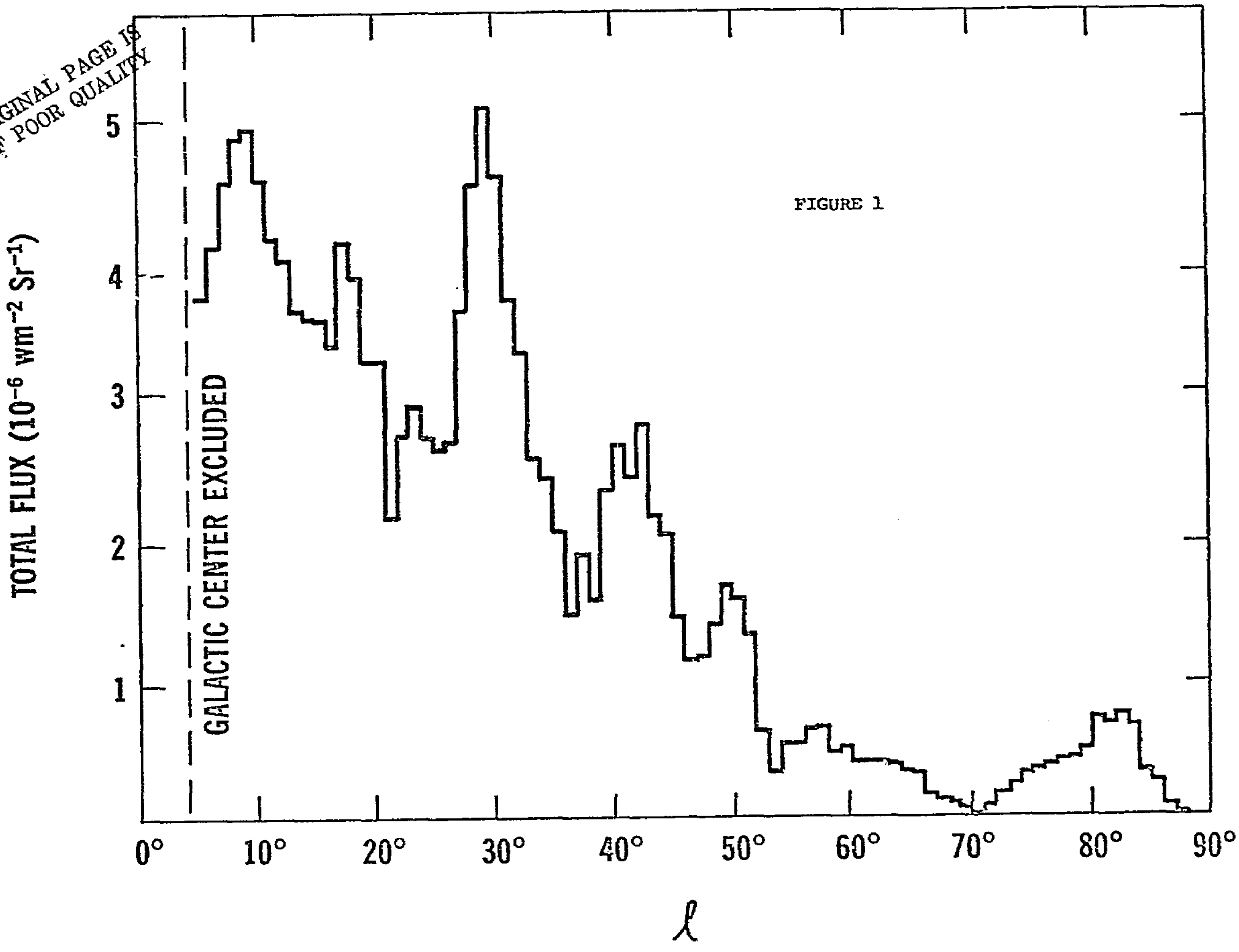
FIGURE CAPTIONS

Fig. 1. Predicted longitude dependence of the galactic far-infrared flux based on the model in the text (equation 9) using the CO data of Scoville and Solomon (1975) and a temperature of 10K.

Fig. 2. Predicted galactic far-infrared emissivity distribution using equations (6) and (10) together with the data of Scoville and Solomon (1975) and the values of n_{H_2} derived by Stecker *et al.* (1975). Again, a cloud temperature of 10K has been assumed.



TOTAL FLUX (10^-6 wm^-2 Sr^-1)
5
4
3
2
1
GALACTIC CENTER EXCLUDED
0°
10°
20°
30°
40°
50°
60°
70°
80°
90°
ℓ

FIGURE 1

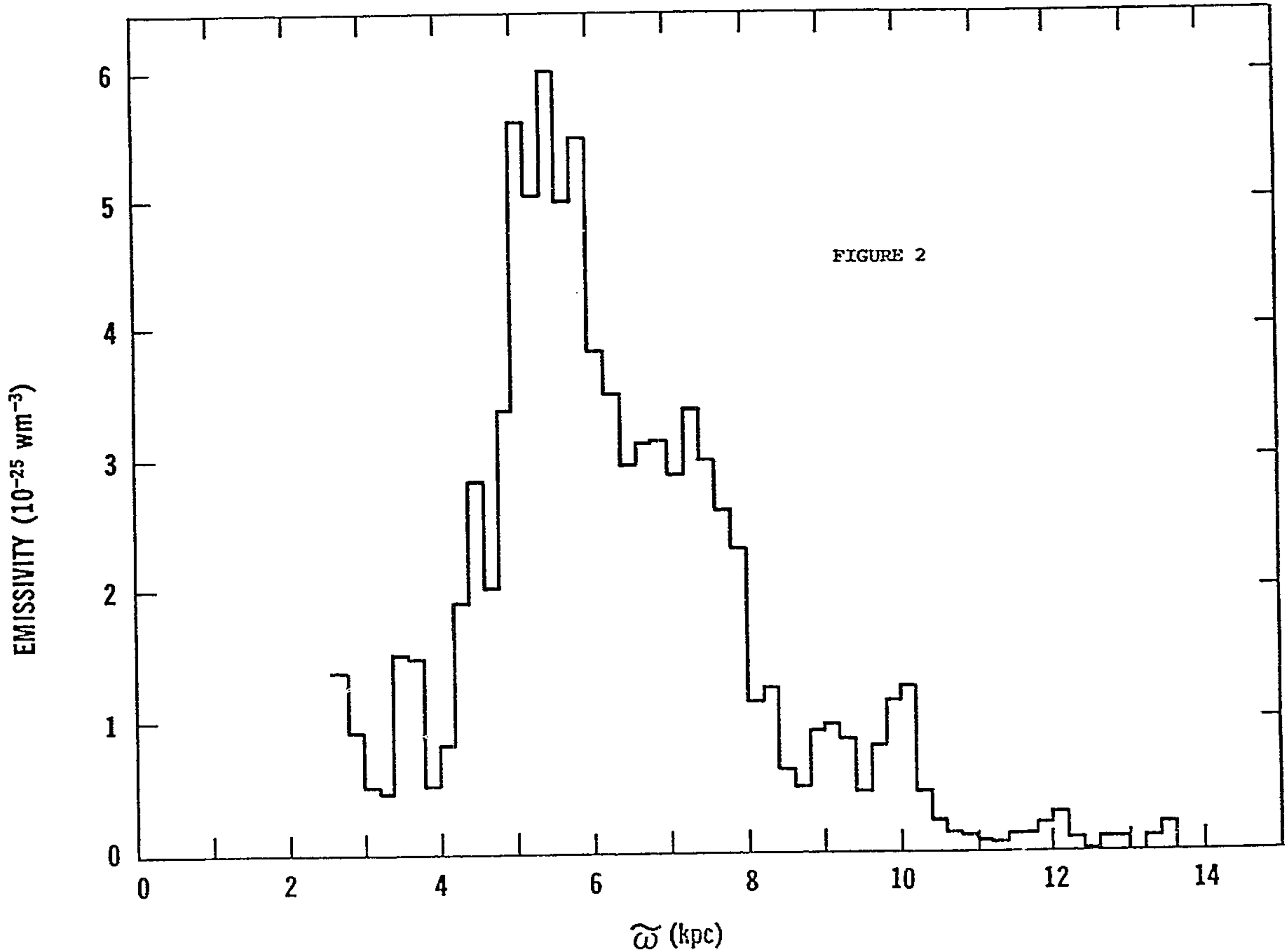


FIGURE 2
EMISSIVITY (10^{-25} wm^{-3})
6
5
4
3
2
1
0
0
2
4
6
8
10
12
14
$\tilde{\omega}$ (kpc)