ROCKET MEASUREMENTS OF THE GALACTIC BACKGROUND AT 100 μ

JUDITH L. PIPHER*

Dept. of Physics and Astronmy, University of Rochester, Rochester, N.Y., U.S.A.

Abstract. Measurements of the diffuse background radiation in the 85–115 μ band are presented, as observed from altitudes close to 190 km with a rocket-borne, liquid helium cooled telescope. Evidence is given for detection of the galactic background due to thermal grain emission at galactic latitudes of 5–35°, and at a galactic longitude of $\sim 163°$. At small latitudes, the background intensity is measured to be $\sim 9 \times 10^{-11}$ W cm^{-2} sr^{-1}; the average number density of grains derived is consistent with the optically determined measure. The 100 μ data is compared with 20 μ data taken on the same flight, in order to draw some conclusions about the grain emissivity and temperature.

1. Introduction

Recent observations (Houck *et al.*, 1971; Hoffmann *et al.*, 1971; Soifer *et al.*, 1973; Harper and Low, 1971; Low and Aumann, 1970; Soifer, 1972). indicate that the galactic center, H II regions and dust clouds are strong infrared sources with peak intensity at 100 μ. Although the mechanism for such emission is not perfectly understood (partially because there is a lack of far infrared data with good spectral resolution), absorption of ultraviolet and optical radiation by dust grains and subsequent re-emission in the infrared has been suggested as a possible source for all of the above objects. It has been recognized for some time that a diffuse galactic background should be observable in the far infrared due to the re-emission of galactic interstellar grains. Stein (1966) first made rough predictions of the expected intensity. The temperature that the grains assume and the wavelength of peak emission depend on the heating mechanism and the grain characteristics. Most models, however, predict that the galactic grain emission should peak in the 70–300 μ range. The observed intensity will depend on the column density of grains along the line of sight, and will vary relatively slowly in brightness gradient. Since atmospheric constraints at wavelengths proximate to 100 μ make differential chopping necessary even at balloon altitudes, it is possible only at rocket altitudes and higher to make wide field observations of diffuse galactic grain emission.

We report here observations of a diffuse galactic background, in the 85–115 μ band, and give evidence that thermal grain emission is the most likely source of the radiation. The observations were made with a liquid helium cooled telescope carried above the atmosphere on Aerobee 170 rockets launched from White Sands. The observations reported here took place at about 01:32 MST on 1970 December 2, and some substantiation of these results were obtained from a flight at 21:53 on July 16, 1971. Pre-

* This work was done while the author was at Cornell University.

Greenberg and Van de Hulst (eds.), Interstellar Dust and Related Topics, 559–566.

liminary results of the July flight were previously (Houck *et al.*, 1971; Soifer *et al.*, 1973) reported as were more detailed accounts of the December flight (Pipher *et al.*, 1971; Soifer *et al.*, 1971; Pipher, 1971).

2. Observations

The cryogenic telescope used for the observations is described by Pipher *et al.* (1971) cited above. Although the main emphasis here will be on the 100 μ (85–115 μ) observations, reference will be made to the results from some of the other detectors flown.

On this flight, the telescope first scanned along the galactic plane, and then scanned perpendicular to the plane at an approximate galactic longitude of 163°. Because there were technical difficulties on the scan along the galactic plane, only the scan

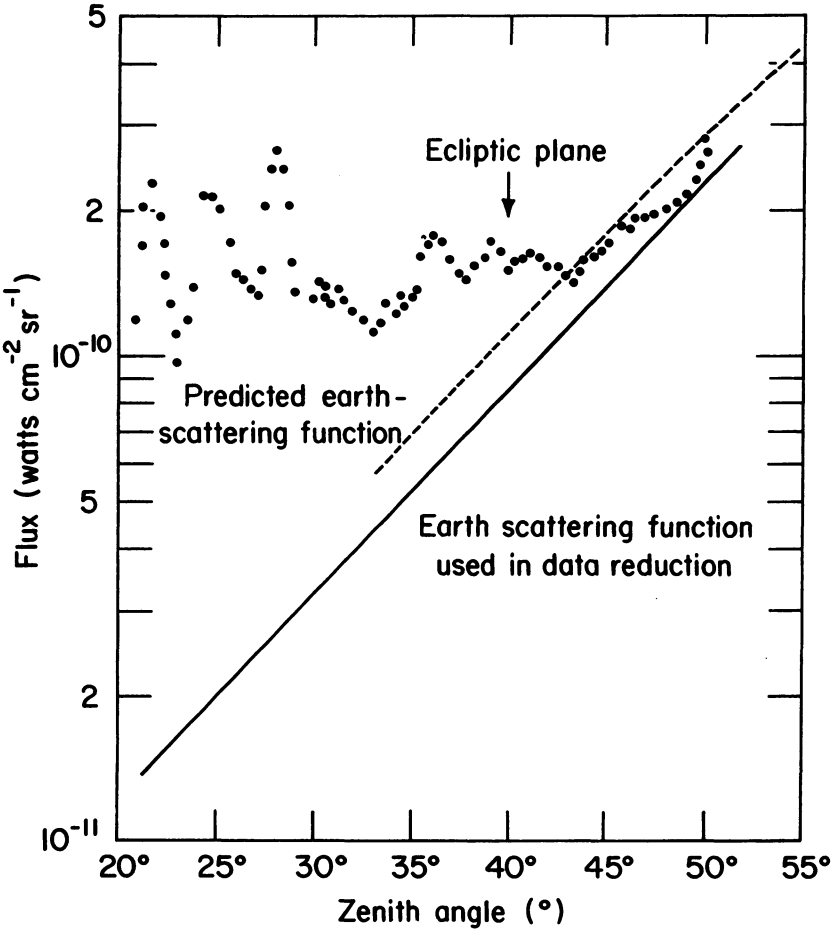

Fig. 1. Signal level observed by 85–115 μ detector as a function of zenith angle for a scan at $l^{II} = 163°$, and b^{II} ranging from 5°–35°. Predicted horizon shine (earth scattering function) and function used in data reduction are shown.

https://doi.org/10.1017/S0074180900054735 Published online by Cambridge University Press

perpendicular to the plane will be discussed here, for galactic latitudes ranging from 5° to 35°. Because of an attitude control system (ACS) failure 225 s into the flight, the path was passed over only once. The raw data for this scan are presented in Figure 1 as a function of zenith angle. At zenith angles greater than 42°, the contribution from scattered earthshine predominates over celestial signals. In order to obtain the celestial flux, the scattered earthshine component is subtracted from the raw data by the method outlined by Soifer *et al.* (1971) and Pipher (1971). Because the signal to noise ratio is large for these measurements, the major source of error is the absolute detector calibration, which is described in detail by Pipher *et al.* (1971). On the 1971 flight (Houck *et al.*, 1971), 100μ observations of the galactic center agreed well with previous studies from balloon altitudes (Hoffmann *et al.*, 1971), giving added confidence in the calibration techniques. Another source of error is the subtraction of the scattered earthshine. At galactic latitudes less than 30° this error is thought to be minimal. We estimate our subtracted intensity levels to be accurate to $\pm 50\%$ close to the galactic plane. Figure 2 contains a linear plot of the difference data as a function of both galactic and ecliptic latitude. As can be seen, the mean intensity decreases with increasing latitude, and peaks as the ecliptic plane is crossed. As well, discrete sources,

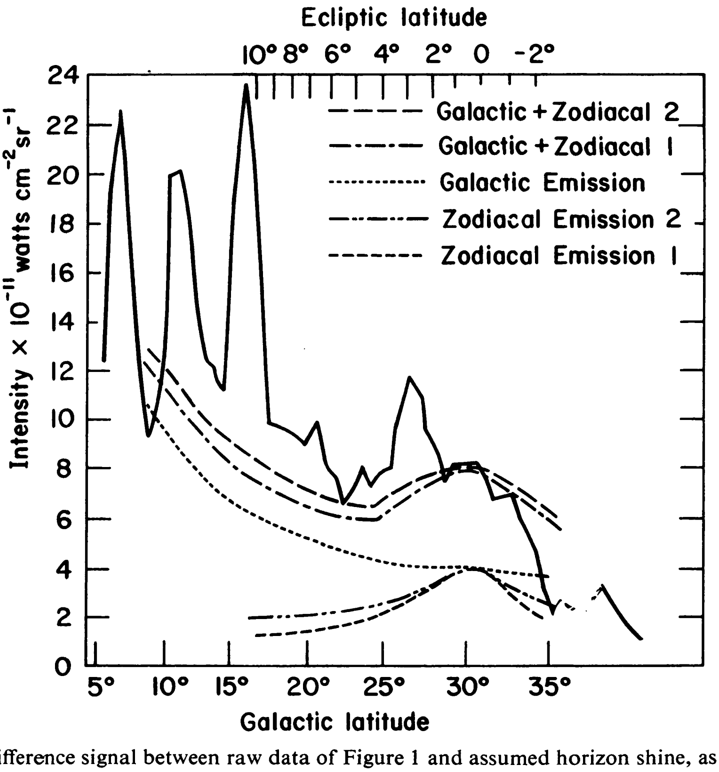

Fig. 2. Difference signal between raw data of Figure 1 and assumed horizon shine, as a function of galactic latitude, ecliptic latitude and zenith angle. A csc(b^{II}) galactic emission and two zodiacal emission models are scaled so that their sum best fits the 100 μ average background data. Discrete sources (corresponding to dust clouds, an H II region and nebulosity) are also evident.

https://doi.org/10.1017/S0074180900054735 Published online by Cambridge University Press

which can be identified with dark clouds, reflection nebulae (Pipher *et al.*, 1971), and an H II region (Soifer *et al.*, 1973; Pipher *et al.*, 1971) are superimposed on the background signal; these will be discussed in a separate article.

Unfortunately, it is not an unambiguous exercise to separate the galactic and zodiacal dus emission in the 100 μ data shown in Figure 2. Soifer *et al.* (1971) have measured the thermal emission from zodiacal particles at 5–6 μ, 12–14 μ and 16–22 μ on this rocket flight. They find the spectrum of measured radiation in these bandwidths appropriate to a dilute 280 K blackbody. At these shorter wavelengths, the zodiacal emission has fallen in intensity by a factor of two to three by the time an ecliptic latitude of 10° is reached. For want of a more plausible model for the 100 μ zodiacal component, similar scaling laws with ecliptic latitude are assumed. As discussed in the next section, galactic grain emission seems to be the most plausible explanation for the radiation that decreases in intensity with increasing galactic latitude, at $l^{II} \sim 163°$. If the distribution of grains is approximately uniform, the radiation at 100 μ should be optically thin. The total optical depth along the line of sight can be written as

$$\tau_{100} = \int n\,\mathrm{d}l \cdot \pi a^2 \cdot \varepsilon_{100}, \tag{1}$$

where n is the number density of grains, dl is an increment of path length along the line of sight, a is the grain radius, and ε_{100} is the emissivity of the grain at 100 μ. For reasonable assumptions about the grain size and column density at $l^{II} \sim 163°$, the small value of the 100 μ grain emissivity for any plausible grain type ensures that the radiation is optically thin, and that a csc(b^{II}) scaling law should hold for the galactic grain emission for $b^{II} \geqslant 5°$ if one assumes a disc model of the Galaxy. An attempt was made to fit the data with a csc(b^{II}) law and the two adopted models of zodiacal emission and the best fit curves are shown on Figure 2. The fit is fairly good for latitudes larger than 10°, but the intensity falls off more slowly than csc(b^{II}) at small latitudes. This discrepancy probably reflects the inadequacies of a uniform disc model of the Galaxy. At zenith angles greater than 42° the greatest errors in subtracting the scattered earthshine occur, and a discrepancy with adopted models is expected.

The July 1971 flight was not designed to make galactic background measurements. The telescope first scanned south along the plane to the galactic center region. During this portion of the flight, the galactic emission is confused with the increasing horizon shine as the telescope points at increasingly larger zenith angles. In the region of the galactic center, not only does the horizon shine confuse observations of the background, but also the strong and extended sources at 100 μ make observations of the background difficult. However, on a scan perpendicular to the plane, an ACS pointing error resulted in a crossing of the plane some 2–3° away from the galactic center, beyond the extended 100 μ source (Houck *et al.*, 1971). As a consequence, the increasing intensity depicted at that time in Figure 3 is identified with thermal emission from grains. The detector field of view was $1\frac{1}{4}°$, so that the galactic disc at 20 kpc would be smaller than the beam size. If the grain density typical of the solar neighbor-

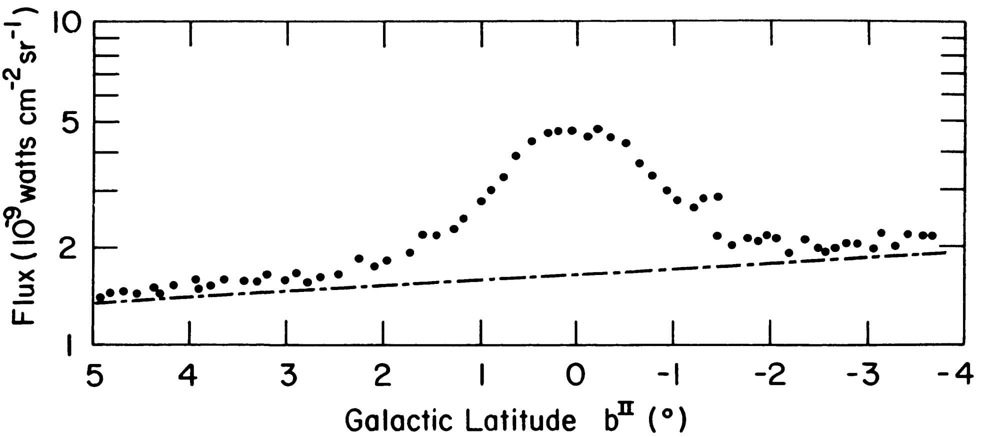

Fig. 3. Signal level observed by 85–115 μ as a function of galactic latitude for a scan at $l^{II} \sim 2\overset{\circ}{.}5$, and b^{II} ranging from $-5° - +5°$. The horizon shine predominates over celestial signals except close to $b^{II} = 0°$.

hood persists throughout the Galaxy within an order of magnitude, the total optical depth over this path length would still be less than unity. The intensity as the plane was crossed is some 30 times the value observed at $l^{II} \sim 163°$ and $b^{II} = 5°$. This intensity, within reasonable error, corroborates the December 1970 observation reported here.

3. Possible Mechanisms for the 100 μ Galactic Emission

There are several possible mechanisms for production of the 100 μ galactic emission. Thermal radiation from dust grains appears to be the most likely source.

By extrapolation from the radio data, several authors (Lequeux, 1970; Partridge and Peebles, 1967) have shown that synchrotron radiation, Inverse Compton radiation and free-free emission are not expected to be strong sources of 100 μ radiation, and in fact are all at least an order of magnitude down in strength from the observed signal in the galactic anticenter direction close to the plane. Synchrotron emission in the far infrared as the primary energy (Cavaliere *et al.*, 1970) requires moderately high magnetic fields; normal synchrotron emission not only would require high magnetic fields (Burbridge and Stein, 1970) but also a low frequency galactic absorption mechanism to reconcile the radio data with the 100 μ data. The density of relativisitic electrons required by an Inverse Compton mechanism is too high.

Fine structure line emission in the Galaxy is expected to be of limited concern in the 85–115 μ band (Petrosian, 1970). The only possible candidate, the 88.16 μ line of O III, is predicted to be strong only in H II regions. Hence, this mechanism is not considered likely.

Molecular line radiation in the 85–115 μ band, or resonance radiation from oscillators trapped in grains are possible sources of the 100 μ galactic background. The latter possibility is the more likely; however, without observations with increased spectral resolution, a specific model will not be examined in detail.

The mechanism of thermal emission from dust grains within the Galaxy seems to be the most attractive possibility. The observed energy density of the 100 μ radiation ($4\pi I/c$, where I is intensity) close to the plane is $3 \pm 1.5 \times 10^{-13}$ ergs cm^{-3}. This number should be compared with the energy density in starlight, including the near IR sources, 8×10^{-13} ergs cm^{-3} (Allen, 1964). The similarity of these energy densities lends credence to the idea that efficient absorption of starlight by the grains and subsequent re-emission at a wavelength dependent on the temperature the grains assume (which in turn depends on the size and type of grain) accounts for much of the radiation produced in the far infrared.

Because interstellar grains are thought to be small (0.05–0.2 μ in radius) they cannot emit efficiently at $\lambda \gg 2\pi a$ where a is the grain radius. The far infrared emissivity falls off approximately as $1/\lambda^{\beta}$ where β is thought to lie between 1 and 2. (See e.g., Greenberg, 1971). The specific wavelength dependence is a function of the grain composition, and the interstellar medium may very well contain a range of grain sizes, shapes and compositions. The 'free space' temperatures that the grains can attain are given by the radiative equilibrium of the grains with their environment

$$\int_0^{\infty} R(\lambda)\varepsilon(\lambda)\,d\lambda = \int_0^{\infty} \varepsilon(\lambda)B(\lambda, T_g)\,d\lambda\,, \tag{2}$$

where T_g is the grain temperature, $\varepsilon(\lambda)$ is the emissivity of the grain, radius a, at wavelength λ, $B(\lambda, T_g)$ is the Planck distribution of temperature of the grain, $R(\lambda)$ is the radiation field of the environment. The two integrals in Equation (2) generally refer to different wavelength regions. For grains in free space, or in clouds of moderate opacity, the ultraviolet optical and near infrared wavelengths dominate the left hand side of the equation, while the low grain temperatures attained imply the right hand integral covers far infrared wavelengths. If F is the flux of energy, in W cm^{-2}, emitted from a grain surface in the 85–115 μ bandwidth, then under the assumption of isotropic emission and a single grain size, the intensity observed at earth above the atmosphere along a line of sight is

$$I_{100} = F \cdot a^2 \cdot \int n\,dl\,(W\,\mathrm{cm}^{-2}\,\mathrm{sr}^{-1})\,. \tag{3}$$

Because the actual parameters describing galactic grains are quite uncertain, several extreme models of grains are considered here. F was calculated for these models, using free space grain temperatures and infrared emissivities appropriate to the grain, and assuming the stellar radiation field as the sole source of grain heating. A single representative grain size was adopted for each model. The important grain size ranges have been given by Greenberg (1971) as

$a_{\text{ice}} = 0.05 - 0.3\,\mu$
$a_{\text{graphite}} = 0.05 - 0.1\,\mu$
$a_{\text{silicate}} = 0.05 - 0.1\,\mu$
$a_{\text{core}} = 0.05\,\mu$, $a_{\text{grain}} = 0.1 - 0.2\,\mu$ for core-mantle grains.

TABLE I
Grain parameters

Grain type	T_g (K)	a (μ)	$\int n\,dl$ (cm^{-2})	$\bar{n}$ (cm^{-3})	Source of grain parameters
pure graphite	43	0.05	4×10^{10}	1.3×10^{-11}	Werner and Salpeter (1969)
dirty ice	15	0.2	2×10^{9}	7×10^{-13}	Stein (1966)
core-mantle	17	0.05, 0.15	2×10^{9}	7×10^{-13}	Greenberg (1971) and Werner and Salpeter (1969)

The value of I_{100} is 9×10^{-11} W cm^{-2} sr^{-1}, and corresponds to a total path length along the line of sight of roughly 1 kpc. On the assumption of a uniform distribution of grains along this path, the average number density of grains was calculated. These values are tabulated along with the relevant grain parameters in Table I. Silicate grains are not included, because the far infrared emissivities for such grains are very uncertain (Kushna Swamy, 1971): it is expected that the column and number densities derived for the silicate grains would be larger than those for the ice grains, because the grain temperature expected ($\sim$ 9 K) shifts much of the radiation out of the detector bandwidth.

Both the dirty and core-mantle grain models give reasonable agreement with the optically determined measure of the average number density of 2×10^{-13} cm^{-3} (Allen, 1964). Impure graphite grains, and graphite grains with moderate numbers of resonances near 100 μ (see e.g., Werner and Salpeter, 1969) could reduce the column density of grains required to produce the observed 100 μ intensity, both because the grain temperature would be reduced, shifting the peak wavelength of emission closer to the acceptance band of the detector system, and because the resonance might fall within the band. Although such possibilities are interesting, detailed calculations do not appear to be warranted until further spectral information on the radiation becomes available.

4. Discussion

It appears that pure graphite grains are excluded on the grounds that too large a grain density is required to give the appropriate 100 μ intensity. In fact, graphite grains sufficiently pure to achieve a free space temperature of 43 ° K are not expected to exist in space. These grains are excluded on another ground as well. On the same flight, a 16–23 μ detector was also flown. Using the grain column density from 100 μ data, an intensity of 2.4×10^{-11} W cm^{-2} sr^{-1} is predicted in this band due to thermal emission from pure graphite grains. The observed intensity, with the horizon-shine subtracted out, was at this time in the flight, 1.3×10^{-11} W cm^{-2} sr^{-1}. At first glance, these values seem fortuitously close; however, Soifer *et al.* (1971) have presented very convincing evidence that most if not all of this signal is due to zodiacal emission. As a consequence, we can conclude that the 16–23 μ observation supports the conjecture that pure graphite grains are ruled out. The 16–23 μ observation, however, is compatible with less pure graphite grains of free space temperatures of 33 K (Greenberg, 1971); however, the column density of grains required by the 100 μ observations is still rather high ($\sim 1 \times 10^{10}$ cm^{-2}), and it is concluded tentatively that such grains are only marginally allowed by the observations.

On the other hand, core-mantle grains and dirty ice grains, attaining lower free-space temperatures, are attractive not only because of the more reasonable column density required to explain the observation, but also because an upper limit of 1.4×10^{-10} W cm^{-2} sr^{-1} to the galactic emission observed at this time by a detector sensitive at 230–330 μ, does not conflict with this conclusion.

We conclude that grain temperatures of 15- $\leq$ 33 K are allowed by the observations for the grain types and sizes indicated. It is not a particularly restrictive conclusion; graphite grains with impurities and resonances can achieve temperatures within this range (Werner and Salpeter, 1969), as well as dirty ice and core-mantle grains. Wide-band observations at 200 μ and 40 μ would do much to restrict the allowable grain types and temperatures. Narrow band measurements are required to define the role that impurity resonances play in grains.

Acknowledgements

The author would like to thank B. T. Soifer, M. Harwit and J. R. Houck for helpful discussions. She held a National Research Council of Canada Graduate Fellowship during the time the experimental work was executed.

The research reported on was sponsored by AFCRL contract F 19628-70-C-0128, and KPNO rocket branch supplied excellent support.

References

Allen, C. W.: 1964, *Astrophysical Quantities*, University of London, The Athlone Press, 2nd ed.
Burbidge, G. R. and Stein, W.: 1970, *Astrophys. J.* **160**, 573.
Cavaliere, A., Morrison, P., and Pacini, F.: 1970, *Astrophys. J.* **162**, L133.
Greenberg, J. M.: 1971, *Astron. Astrophys.* **12**, 240.
Harper, D. A. and Low, F. J.: 1971, *Astrophys. J.* **165**, L9.
Hoffmann, W. F., Frederick, C. L., and Emery, R. J.: 1971, *Astrophys. J.* **164**, L23.
Houck, J. R., Soifer, B. T., Pipher, J. L., and Harwit, M.: 1971, *Astrophys. J.* **169**, L31.
Krishna Swamy, K. S.: 1971, *Astrophys. J.* **163**, 63.
Lequeux, J.: 1970, *Astrophys. J.* **159**, 459.
Low, F. J. and Aumann, H. H.: 1970, *Astrophys. J.* **162**, L79.
Partridge, R. B. and Peebles, P. J. E.: 1967, *Astrophys. J.* **148**, 377.
Petrosian, V.: 1970 *Astrophys. J.* **159**, 883.
Pipher, J. L.: 1971, Ph.D. Thesis.
Pipher, J. L., Houck, J. R., Harwit, M., and Jones, B. W.: 1971, *Nature* **231**, 375.
Soifer, B. T.: 1972, Ph.D. Thesis.
Soifer, B. T., Houck, J. R., and Harwit, M.: 1971, *Astrophys. J.* **168**, L73.
Soifer, B. T., Pipher, J. L., and Houck, J. R.: 1973, to be published in *Astrophys. J.*
Stein, W.: 1966, *Astrophys. J.* **144**, 318.
Werner, M. W. and Salpeter, E. E.: 1969, *Monthly Notices Roy. Astron. Soc.* **145**, 249.