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DIRBE OBSERVATIONS OF GALACTIC STELLAR POPULATIONS AND EXTINCTION

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ABSTRACT

The short wavelength bands of the Diffuse Infrared Background Experiment (DIRBE) on NASA's Cosmic Background Explorer (COBE) mission allow us to examine the integrated near-infrared emission of various stellar populations within the Galaxy. The results of a preliminary analysis at 1.25, 2.2, 3.5, and 4.9 μm are presented. The characteristic colors of the bulge and disk populations are determined. The derivation of the line-of-sight extinction in these bands yields a mean interstellar reddening law. Comparison of the near-infrared extinction with that for the longer wavelength bands (140 and 240 μm) allows separation of the relatively nearby obscuration from that caused by more distant clouds.

1. INTRODUCTION

The near infrared region of the spectrum (1 – 5 μm) is an excellent window in which the stellar content of the Galaxy can be studied. At shorter wavelengths, extinction by dust prohibits observation of the full Galactic distribution of stars. At longer wavelengths, the diffuse Galactic light becomes dominated by the emission from dust in H II regions and in H I and molecular clouds.

The DIRBE instrument has mapped the full sky with a 0°.7 square beam at wavelengths from 1 to 240 μm (Hauser *et al.* 1991, Boggess *et al.* 1992), and has measured polarization from 1 to 3.5 μm (Berriman *et al.* 1993). DIRBE maps of the Galaxy at 1.25, 2.2, 3.5, and 4.9 μm clearly show a smooth Galactic disk of starlight surrounding an elliptical bulge. Extinction still significantly influences the appearance of the Galaxy at 1.25 μm (*e.g.* a dust lane is visible across the bulge of the Galaxy), but it quickly becomes less significant with increasing wavelengths in accord with the known properties of interstellar extinction (*e.g.* Rieke & Lebofsky 1985). It also polarizes starlight in the Galactic plane through selective absorption by magnetically aligned grains.

This paper examines the colors of the stellar populations and the characteristics of the interstellar extinction and polarization as observed in the short wavelength DIRBE bands. Questions regarding the spatial structure of the stellar bulge and the disk of the Galaxy are addressed in other papers in these proceedings (Weiland *et al.* 1993,

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Freudenreich *et al.* 1993, Sodroski *et al.* 1993).

2. DATA

The data used here consist of observations spanning the six month interval from Dec 1989 to May 1990. All observations were then interpolated to 90° solar elongation, so that the signal contributed by interplanetary dust could be uniformly removed using an empirical fitting function (Hauser 1993). The estimated inaccuracies in our removal of this local emission are $\lesssim 1-2\%$ (at $1-4$ μm) and $\lesssim 5\%$ (at > 4 μm) of the median brightness of the inner Galaxy.

3. COLOR-COLOR DIAGRAMS

Color-color diagrams of I(1.25 μm) / I(2.2 μm) vs. I(2.2 μm) / I(3.5 μm) and of I(2.2 μm) / I(3.5 μm) vs. I(3.5 μm) / I(4.9 μm) were generated for various longitude ranges along the Galactic plane. The correlations between these colors were investigated by examining the colors in each DIRBE pixel (~0.32° square).

For the inner Galaxy, all three near-IR colors are linearly correlated with one another. The dispersion of points *along* these linear trends decreases towards the outer Galaxy and at higher latitudes. The range of colors is greatest for the I(1.25 μm) / I(2.2 μm) color and decreases with increasing wavelength. The correlations as a function of longitude in the 4th Galactic quadrant show good symmetry with those observed in the 1st quadrant. The Cygnus Region ($l = 70° - 90°$) and the Carina Region ($l = 270° - 290°$) show a greater range of colors than suggested by the general trend with longitude, and in the shorter wavelengths the trend has a significantly steeper slope.

4. EXTINCTION

The correlations between near-IR colors are strongly suggestive of extinction effects. We have quantified these trends by comparison with reddening lines calculated in three different ways: a) calculating a linear least squares fit to the data with the assumption that all sources are seen through the same amount of foreground extinction; b) using the Rieke-Lebofsky reddening law (Rieke & Lebofsky 1985) with the assumption of only foreground extinction; and c) using the Rieke-Lebofsky reddening law assuming that the sources of emission (stars) are embedded uniformly in an absorbing medium (dust).

The DIRBE-derived extinction law [method (a)] is consistent with the Rieke-Lebofsky reddening law [method(b)]. Other tabulated reddening laws (*e.g.* Mathis 1990, Koornneef 1983) do not fit the DIRBE data as well, particularly in the redder colors.

In the direction of the inner Galaxy and bulge ($70° < l < 290°$, $-5° < b < 5°$), the reddening is too large and too linear to be caused by a mixture of dust and stars along the line of sight [method (c)]. With uniformly mixed dust and stars, the observed colors will always be dominated by relatively nearby unreddened emission. Apparently the observed emission is actually dominated by that of the inner Galaxy and bulge as seen through up to 4 magnitudes of extinction (at 1.25 μm). The optical depth at 1.25 and 2.2 μm reaches 1.0 within ~2° of the Galactic plane at these longitudes. This means that the different wavelengths used here will sample different path lengths in the Galactic plane, complicating any detailed analysis.

It is noteworthy that none of the simple reddening models used here adequately describe the color-color diagrams of star-forming regions like Cygnus. Possible

explanations for this are discussed below (§7).

5. INTRINSIC POPULATION COLORS OF THE INNER DISK AND BULGE

With the assumptions that the signal is predominantly from stars and that all the extinction lies in front of the stars which contribute to the short wavelength emission, we can examine lines of sight with low expected extinction and extrapolate reddening lines to $\tau = 0$ to find the intrinsic colors of the stellar populations along different lines of sight. In order to characterize the integrated emission of the stellar populations, the observed colors were compared with those of isolated bright stellar sources that were detected by DIRBE.

The unreddened Galactic light at 1.25 – 4.9 μm exhibits colors similar to those of late K and M giants and supergiants. The bulge stars appear to have I(2.2 μm) / I(3.5 μm) color $\lesssim$5% bluer than the disk stars, which is in accord with the finding that the bulge stars are ~ 400 K hotter than their disk counterparts (Terndrup, Frogel, & Whitford 1991). Difficulty in accurately determining the limit of $\tau \rightarrow 0$ prevents clear distinction between the I(1.25 μm) / I(2.2 μm) colors of the bulge and disk populations.

6. MORE EXTINCTION AND POLARIZATION

From the ratio of I(1.25 μm) / I(2.2 μm) we have constructed an optical depth ($\tau_{1.25}$) map of the Galaxy, neglecting the influence of any possible intrinsic source color differences between the inner and outer Galaxy or between the disk and the bulge. Features in this map are clearly anti-correlated with the intensity at 1.25 μm. The $\tau_{1.25}$ map also has been compared with the optical depth map at 240 μm constructed from the dust emission in the 140 and 240 μm DIRBE bands (Sodroski *et al.* 1993). Where $\tau_{1.25} \lesssim 1.0$, it is well correlated with the DIRBE 240 μm optical depth, implying that where the line of sight is optically thin at 1.25 μm, the same dust is observed in both absorption and emission. The DIRBE data indicate that $\tau_{1.25} / \tau_{240} \approx 0.0010$, which is roughly 2/3 of the value tabulated by Mathis (1990).

The 1.25 μm extinction map has also been compared with the DIRBE polarization maps at 1.25 and 2.2 μm (Berriman *et al.* 1993). Both wavelengths show similar gross polarization characteristics. In the Galactic plane, the amplitude of the polarization vector near the Galactic center (l = 5° – 350°) correlates with $\tau_{1.25}$. At 2.2 μm, the Galactic center is more strongly polarized than the rest of the plane. North of the Galactic plane (l = 1°, b = 5°), a distinct region of polarized light is seen at 1.25 μm and 2.2 μm, which correlates very well with high opacity structures in the $\tau_{1.25}$ map. This region is part of a complex of dust clouds near θ Oph which includes B 78 and other dark clouds. Extinction by dust in these clouds gives rise to the polarization and the apparent peanut shape of the bulge North of the galactic plane as observed at 1.25 μm (Hauser 1993).

7. CYGNUS AND OTHER STAR-FORMING REGIONS

The different character of the color-color diagrams in Cygnus and Carina is also seen in the ρ Oph region, Orion A, and the Rosette Nebula. Thus, the effect seems linked to star forming regions that are observed at locations that are not dominated by the bright light of the stellar Galactic disk and the bulge.

Simple modeling suggests that the trends can be characterized by various mixtures of stellar light and emission from very hot dust ($T_{dust} \approx 1000$ K). However, the high dust temperatures required would be hard to maintain if the grains were at equilibrium

temperatures. Such hot dust would be found only very close to stars (« 1 pc), implying a very high density of very dusty stars. It seems more likely that the high color temperatures are due to small, transiently heated grains or PAHs such as observed in reflection nebulae (*e.g.* Sellgren, Werner, & Dinerstein 1983; Sellgren 1984). Models incorporating excess emission from very small grains and/or PAHs are under investigation.

On the basis of simple models it is found that the trends are not caused by stellar light mixed with line or continuum emission from ionized gas. Estimates of near-IR emission based on the observed Hα intensities of H II regions in Cygnus (Dickel, Wendker, & Bieritz 1969), suggest that the gaseous component of the ISM should not influence the DIRBE observations.

8. CONCLUSIONS

The reddening in the inner Galaxy can be effectively described by foreground extinction rather than extinction intermixed with the dominant stellar populations. This extinction strongly influences the appearance of the Galactic bulge at 1.25 μm and to lesser degrees at longer wavelengths. The extinction at 1.25 μm correlates with the 240 μm optical depth where $\tau_{1.25} \leq 1.0$, *e.g.* at latitudes $|b| \gtrsim 3°$. Infrared polarization signals are correlated with extinction, demonstrating that extinction gives rise to polarization of starlight from the Galactic bulge.

In the inner Galaxy ($|l| < 70°$), the integrated starlight seen by DIRBE at 1.25 – 4.9 μm matches the colors of late K and M giants. The bulge population seems to exhibit slightly different (bluer) 2.2 μm – 3.5 μm colors than the disk stars.

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