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DIRBE EVIDENCE FOR A WARP IN THE GALAXY

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ABSTRACT

A large-scale warp in the surface brightness distribution of the Galactic disk has been found in the data of the Diffuse Infrared Background Experiment (DIRBE) of the Cosmic Background Explorer. In the far-infrared it is seen in seen in thermal emission by dust. In the near-infrared it is seen in starlight. The far-infrared warp matches that of the velocity-integrated HI. The near-infrared warp has approximately the same orientation, but has a smaller amplitude, which which increases with increasing wavelength. This is consistent with the stellar disk of the Galaxy being bent in the same way as the HI layer.

1. INTRODUCTION

While more attention is usually paid to the center of the Galaxy, the fact that the gravitational potential of the outer Galaxy is dominated by dark matter makes its structure of great interest (Binney 1992). It has long been known that the HI layer of the outer Galaxy, like that of many other galaxies, is warped (Burke 1957, Kerr 1957). It rises above the nominal plane in the direction of $l \sim 90°$ and falls below it at $l \sim 270°$ (Burton & Deul 1987). Molecular clouds and cool ($\sim 20K$) dust appear to exhibit the same behavior (Wouterloot *et al.* 1990, Sodroski *et al.* 1987), but the distribution of stars in the outer Galaxy is obscured by extinction. A warping of the gas and dust layer does not necessarily require a warping of the stellar disk. The warp may be a young phenomenon, confined to recently accreted gas and dust, or it may commence beyond the edge of the stellar disk.

Evidence for a warping of the population I stellar component has been obtained through studies of Cepheid and OB-type stars, and studies of WR stars, open clusters and SNR's (*e.g.* Miyamoto *et al.* 1991, Pandey *et al.* 1990). However, these objects, bright enough to be seen at great distances, are young enough to have formed within an already-warped gas layer.

Djorgovsky and Sosin (1989) have found relatively old stellar tracers in the form of (mostly) AGB and post-AGB stars of the IRAS Point Source Catalog at 12 and 25 μm, wavelengths at which extinction is negligible and these dust-

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shrouded stars are highly luminous. Djorgovsky and Sosin find a warp similar to that of the HI layer, though of lesser amplitude, a fact they tentatively ascribe to radial truncation of the stellar disk.

The DIRBE is a photometer with ten infrared spectral bands, covering the wavelength range of 1-240 μm (Hauser *et al.* 1990). The far-infrared bands are sensitive to interstellar dust, while the near-infrared bands, particularly those at 3.5 and 4.9 μm, provide complete, low-extinction views of the stellar component of the Galaxy.

2. METHOD

Latitudinal asymmetries in surface brightness have been calculated from equal-area cylindrical projection maps of the Galactic plane, $|b| < 7°$, at 1.25, 2.2, 3.5, 4.9, 100 and 240 μm. The first four bands are near-infrared (NIR) and their maps are dotted with bright stars, most of which lie relatively nearby. The bright resolved stars are removed using an iterative filtering algorithm. All but the 240 μm band have a significant foreground due to interplanetary dust. Strongest near the ecliptic, the interplanetary dust foreground tends to produce a distortion similar to a warp, but weaker and roughly opposite in sign to that of the HI layer. An empirical model (Hauser 1993) is used to remove this foreground. The latitude centroid of each column of pixels is calculated from the corrected maps, then robustly averaged over 12° bins of longitude.

The warp detected in the DIRBE surface brightness maps is not a subtle effect. Except for the 1.25 μm band, the signature of the warp is clear (though somewhat noiser) even before the removal of foreground and bright stars. It can be discerned by inspection of the maps themselves.

For this preliminary investigation, the primary purpose of which is to establish the presence of a warp in the DIRBE data, the centroid has been taken as the mean latitude, weighted by surface brightness. Unfortunately, a mean is not resistant to outliers, which in this case are usually nearby sources. Limiting the range to $|b| < 7°$ avoids the most prominent local sources, the clouds in the Taurus, Orion and Ophiuchus regions, but also causes the systematic underestimation of true large-scale asymmetries. The latitude limits are imposed symmetrically with respect to $b = 0°$. If the latitude profile is shifted with respect to $b = 0°$, however, the tail of the profile farthest from $b = 0°$ is truncated more than the other, introducing a bias against large displacements. Other means of determining the centroid are being explored.

A more basic problem in using surface photometry is that it provides no distance information. The asymmetries detected are asymmetries integrated over distance. An analysis of point-sources, like that performed by Djorgovsky and Sosin, could be attempted, but the DIRBE's large (.7°-square) beam makes it difficult to find distant sources uncontaminated by less-distant emission.

3. THE FAR-INFRARED: HI AND DUST

At 100 and 240 μm the DIRBE is sensitive to the thermal emission of cool dust. Fig. 1 shows the latitude centroids vs l at 240 μm. The centroids of a velocity-integrated HI map (Weaver & Williams 1973) are included, showing a strong correlation between gas and dust. The warp at 100 μm is very similar.

The same analysis was applied to a map of the optical depth at 240 μm (Sodroski *et al.* 1993), with similar results, demonstrating that the warp seen

at 240 μm is not due to variations in dust emissivity. The results of Sodroski *et al.* (1987), who measured the latitude distribution of the IRAS 100 μm data for $|b| < 4°$, have also been verified.

The clumpy distribution of nearby dust leads to irregular structure in surface brightness maps. The relative smoothness and clearly sinusoidal shape of the warp in Fig. 1, and the fact that there is virtually no extinction to limit range in the outer Galaxy, argue that local emission is unlikely to play a major role in our results. Emission from Gould's belt could form a warp-like distortion of the surface brightness, but Gould's belt has a line of nodes at $l \sim 265°$, while that of Fig. 1 is at $l \sim 160°$. The "big dent," a two-kpc vertical depression in the interstellar medium delineated by Alfaro *et al.* (1991), does roughly coincide with the trough in Fig. 1, but they describe no feature matching the peak, and it does not seem likely that this feature would stand out in the velocity-integrated HI map. The sign and line of nodes of the warp shown in Fig. 1 are consistent with those of the distant HI layer. The fact that the two extrema are less than 180° apart is also consistent with the geometry of the HI warp. The approximate north/south symmetry of the warp is to be expected if most emission comes from within $\sim$ 17 kpc of Galactic center, a distance beyond which the southerly displaced edge of the HI layer begins to curve back toward the nominal plane (Burton & Deul 1987).

4. THE NEAR-INFRARED: STARS

NIR photometry is dominated by the older stars of the disk, in particular the G and K giants. Within one kpc of the Sun these stars seem to be more or less uniformly distributed (McCuskey 1965). Older stars in general show little correlation with small- and medium-scale structure of the ISM.

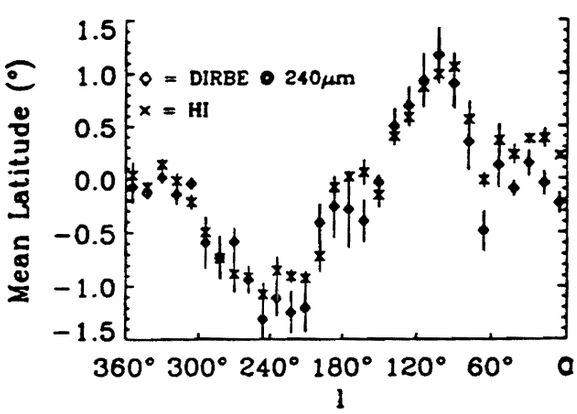

Fig. 1. HI and DIRBE FIR

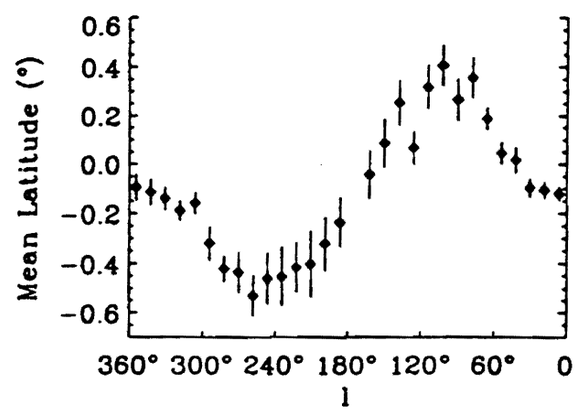

Fig. 2. DIRBE at 3.5 μm

The signature of the warp is visible in all NIR bands. The peak-to-peak amplitude increases with increasing wavelength: .35°, .65°, .9°, 1.0°, going from 1.25 to 4.9 μm. This is consistent with a stellar disk that curves away from $b = 0°$ beyond the solar circle. The longer the wavelength, the smaller the extinction, and the greater the contribution of distant–and more highly displaced–stars to the surface brightness. Fig. 2 shows the latitude centroids at 3.5 μm. The mean plane of the inner ($330° < l < 30°$) Galaxy seems to be at $b \approx -.1°$. Others (Djorgovsky and Sosin 1989, Pandey *et al.* 1990, Weiland *et al.* 1993) find the same effect, plausibly due to the Sun's z height above the Galactic plane.

The DIRBE results at 4.9 μm and $|b| < 7°$ have been compared with those of Djorgovsky and Sosin (1987), who use the latitude range $|b| < 10°$. Good agreement with their "basic" sample is found except for $270° < l < 220°$, where their centroids are $\approx .2°$ below ours. Local sources, perhaps young, highly reddened stars, may contaminate their sample in this region; or using $|b| < 7°$ may exclude more of the warped disk. The DIRBE results agree qualitatively with those of Pandey *et al.* (1990), who studied the locations of open clusters, WR stars and SNR's. They find a larger amplitude for the warp than is shown in Fig. 2, but this may be due to the bias of our centroid calculations.

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REFERENCES

Alfaro, E.J., Cabrera-Cano, J., & Delgado, A.J., 1991, ApJ, 378, 106
Binney, J., 1992, Ann. Rev. A&A, 30, 51
Burke, B.F., 1957, AJ, 62, 90
Burton, W.B., & Deul, A.R., 1987, in The Galaxy, eds. G. Gilmore & R. Carswell (Dordrecht: D. Reidel) p.141
Djorgovsky, S., & Sosin, C. 1989, ApJ, 341, L13
Hauser, M.G., Kelsall, T., Moseley, S.H., Jr., Silverberg, R.F., Murdock, T., Toller, G., Spiesman, W. & Weiland, J., in After the First Three Minutes, eds. S. Holt, C Bennett & V. Trimble, AIP 222, p 161
Hauser, M.G., 1993, this volume
Kerr, F.J., 1957, AJ, 62, 93
McCuskey, S.W., 1965, in Galactic Structure, eds. A. Blaauw & M. Schmidt, (Chicago: Univ. of Chicago Press) p 1
Miyamoto, M., Yoshizawa, M., & Suzuki, S., 1991, Ast. & Sp. Sci., 177, 399
Pandey, A.K., Bhatt, B.C., & Mahra, H.S., 1990, A&A, 234, 128
Sodroski, T.J., Dwek, E., Hauser, M.G., Kerr, F.J., 1987, ApJ, 322, 101
Sodroski, T.J., *et al.*, 1993, this volume
Weaver, H.F., & Williams, D.R.W, 1973, A&A Suppl., 8, 1
Weiland, J.L., *et al.*, 1993, this volume
Wouterloot, J.G., Brand, J., Burton, W.B. & Kwee, K.K., 1990, A&A, 230, 21