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INTERIM REPORT

The Non-Axisymmetric Milky Way
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The Dwek et al. (1995) model represents the current state-of-the-art model for the stellar structure of our Galaxy. The goal of the program supported by the prior ADP grant has been to improve on this model. These improvements take a number of forms: (1) the construction of a more detailed dust model so that we can extend our modelling to the galactic plane; (2) simultaneous fits to the bulge and the disk; (3) the construction of the first self-consistent model for a galactic bar; and (4) the development and application of algorithms for constructing non-parametric bar models.

Our improved Galaxy model has enabled a number of exciting science projects: In Zhao et al. (1995), we show that the number and duration of microlensing events seen by the OGLE and MACHO collaborations towards the bulge were consistent with the predictions of our bar model. In Malhotra et al. (1996), we constructed an infrared Tully-Fisher relation for the local group. We found the tightest TF relation ever seen in any band and in any group of galaxies. The tightness of the correlation places strong constraints on galaxy formation models and provides a independent check of the Cepheid distance scale.

1. Dust and Zodaical Light Modelling

Spergel et al. (1995) presents preliminary results of our modelling of the J,K,L and M band emission detected by the DIRBE instrument on the COBE satellite. Our model includes the contribution of Zodiacal light and a three-dimensional model for the distribution of dust based upon DIRBE observations of dust emission at 240 microns. Our approach enables us to construct dust removed maps of our Galaxy that we will use to model the structure of the bar, the spiral structure of Galaxy and the shape of the disk.

We are working on constructing an improved model for the infrared emission. We model the dust emission as distributed along the line-of-sight and are plan to use a non-parametric approach to modelling the shape of the bar. These changes allow us to model the disk shape (which requires using data below $3°$) and allows us to construct an improved model for the shape of the bar.

The data used for this modelling are the all sky DIRBE maps at solar elongation angle $\epsilon = 90°$ released by the DIRBE team. In most cases the observations were made at solar elongation angles near 90 degrees and the $\epsilon = 90°$ maps were constructed by the DIRBE team by interpolation/extrapolation (cf. DIRBE explanatory supplement 1995). The contribution of the zodiacal dust to NIR light was modelled and subtracted by fitting the analytic form given by Hauser(1993). At each ecliptic longitude bin the ecliptic latitude profile of the emission shows a very sharp lower cutoff; the upward scatter of points is due to Galactic contribution We fit a lower envelope to this emission, excluding the emission at galactic longitude $b < 25°$. The zodiacal emission is weak in these bands, so the residuals from the subtraction are estimated to be a few % of Galactic emission. The maps obtained after subtracting zodiacal emission were median filtered to remove point sources.

After removing the zodiac emission using the procedures outlined in Hauser (1993) and Weiland et al. (1994), the next step in the modelling program is to correct the infrared observations for dust absorption.

We use the COBE 240 micron observations as a tracer of the spatial distribution of the dust. Sodroski et al. (1993) found that the dust emission at 240 microns was optical thin throughout the Galaxy and that the dust temperature varied slowly from 22 K in the galactic center to 17 K in the outer Galaxy. The 240 micron emission is probably a better tracer of the dust distribution than the CO and HI emission as the H_2/CO ratio appears to vary by nearly an order-of-magnitude between the galactic center and the outer Galaxy (Blitz et al. 1985, Sodroski et al. 1994).

We model the 240 micron emission by first fitting an axisymmetric dust model to the data. We assume that the dust layer has a scale height that increases linearly with r:

$$\rho_d(r, z) = \rho_{dust} * \exp(-|r|/r_{dust}) * \exp(-|z|/z_{dust}) \tag{1}$$

where $z_{dust} = \beta * r + z_{min}$. This model was a significantly better fit to the data than a constant scale height model. The linearly increasing scale height is consistent with the gas having a constant azimuthal velocity dispersion, and the Galaxy having a flat rotation curve with a constant ratio of azimuthal to radial epicyclic frequencies. The best least square fit to the data was $\rho_{dust} = 1100.$, $r_{dust} = 3.82$ kpc, $\beta = 0.02$ and $z_{min} = 0.05$ kpc. This dust distribution is consistent with the HI vertical and radial distributions (Malhotra 1995).

We then improve on the axisymmetric model by rescaling it it along each line of sight to fit the 240 emission data:

$$\rho_{disk}(r, z, \phi) = \rho_d(r, z) \frac{I_{observed}(l, b)}{I_{axi}(l, b)} \tag{2}$$
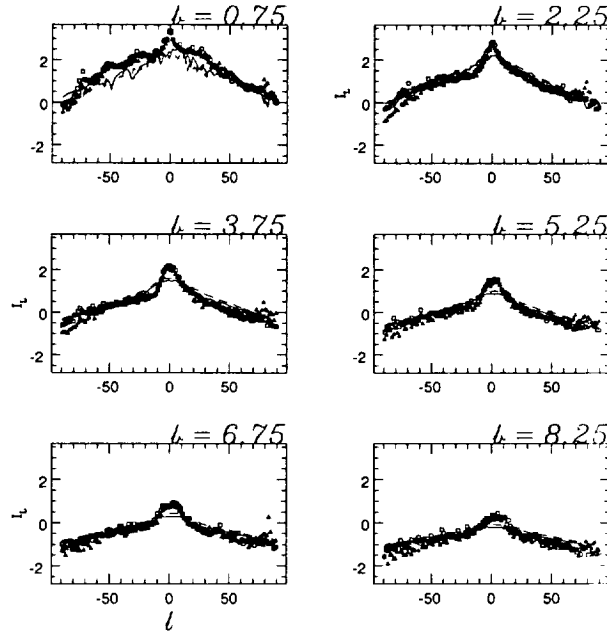
FIG. 1. This plot compares the L band data based on the results of a model consisting of the Dwek et al. (1995) bulge plus a stellar disk. The triangle are the data for $+b$ and the squares are the data for $-b$. The solid line is the model for $+b$ and the dashed line is the data for $-b$. (Figure from Spergel et al. 1995)

where $I_{observed}$ is the observed intensity and I_{axi} is the intensity predicted by the axisymmetric model. This rescaling as the effect of adding extra dust in the direction of nearby spiral arms. This approach significantly improved our fit to the observed reddening.

We then simultaneously fit the emission at K,L, and M bands using our dust model together with a multiparameter model for the disk and bulge:

$$I_\nu(l,b) = \int_0^\infty ds \rho_\nu(s) \exp(-\tau_\nu(s))$$ (3)

where $\rho_\nu(s) = C_\nu(\rho_{disk}(r,z) + \rho_{bulge}(x,y,z)]$ and τ_ν is the optical depth at each wavelength. In estimating the optical depth, there was only one free parameter, A_V/I_{240}, the ratio of V band extinction to the intensity measured at 240 microns. The Rieke & Lebofsky (1985) values for A_K/A_V, A_L/A_V and A_M/A_V were used in the analysis. In our analysis, we used the Dwek et al. (1995) G2 parameterization for the bulge and modelled the disk stellar distribution as

$$\rho_{disk}(r,z) = \exp(-r/r_{disk}) * \mathrm{sech}^2(z/z_{disk})$$ (4)

The model has six parameters to fit the three color data at 1800 positions: the overall normalizations in K, L and M, the disk scale length and scale height and the ratio of the extinction in V to the emission at 240 microns. The best fit parameters were found using a conjugate gradient minimization scheme (Press et al. 1991) to minimize the least square fit to the K, L and M magnitudes. In order to avoid local minima, the minimization was repeated with 10 different starting positions. The best fit model parameters are $r_{disk} = 2.8$ kpc, $z_{disk} = 0.276$ pc and $A_V/I_{240} = 0.0215$. Note that the stellar disk appears to be significantly more centrally concentrated than the dust layer. This small scale length is consistent with Bahcall et al. (1995) analysis of the M dwarfs detected by HST and with Kent et al. (1991) analysis of their IRT data.

Figure 1 compares the model to the L band data. Outside of the bulge region, the model is a good fit to the data. The discrepancy in the bulge regions suggests that the Dwek et al. (1995) model, which was fit to data only outside of $|b| > 3$ is not a good fit to the central region of the bulge. The Dwek model is clearly not steep enough in the inner Galaxy. The model also underestimate the L band luminosity at b = 0.75. This may be due to our representing the stellar distribution as a single population. The light in L band is likely a combination of a thin supergiant population and a thicker giant population.

We have recently improved our modelling by replacing the Dwek et al. bulge with a more centrally concentrated bulge density distribution. Our new model represents the bulge density distribution as
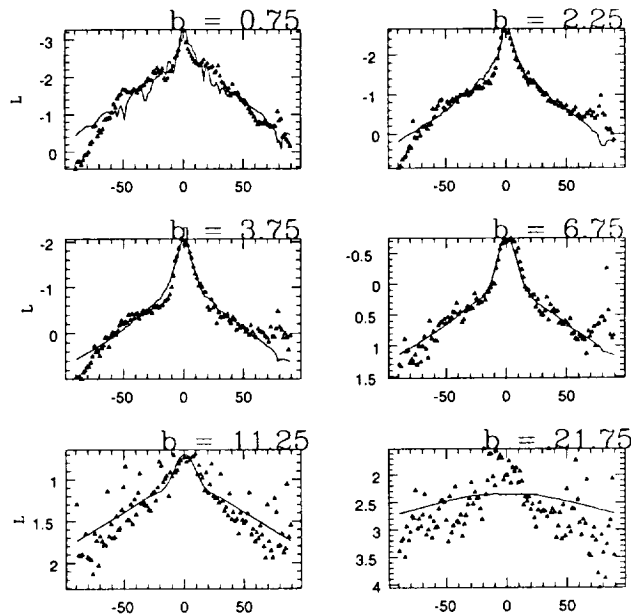
FIG. 2. This plot compares the L band data based on the results of a model consisting of our new bulge model plus a stellar disk. The triangle are the data for $+b$ and the squares are the data for $-b$. The solid line is the model for $+b$ and the dashed line is the data for $-b$.

$$\rho_{bulge} = r_s^q \exp(-r_s^2/r_0^2) \tag{5}$$

where $r_s^2 = \sqrt{(x^2 + y^2/b^2 + z^2/c^2)}$. Our best fit has $b = c = 0.4$, $q = -2.3$ and $r_0 = 3$ kpc. The fit is shown in figure 2. While this density profile is a much better fit to the bulge density, the model still does not properly reproduce the observations in the galactic plane. We have found that we can remove this discrepancy by adding a stellar ring at a galactocentric radius of 3 kpc. This is likely the infrared emission from a ring of supergiants detected by IRAS (Wainscoat et al. 1992).

Figure 3 compares the predicted reddening in K-L with the observed reddening for our improved model. Similar fits are obtained for J-K and L-M colors. This suggests that we have a reasonably accurate model of dust effects. While we believe our stellar model is a significant improvement over earlier work, there are still a number of additional possible improvements, such as inclusion of spiral arms and the application of non-parametric techniques that we hope to apply to the data in the coming year. These additional steps are outlined in the *future work* section of the proposal.

2. Understanding the Source of the Infrared Emission

James Rhoads, a Princeton graduate student working under the supervision of Spergel, has been studying the origin of the near infrared light probed by DIRBE. K band observations of external galaxies (Rix & Zaritsky 1995 [RZ]) find strong spiral arms. This suggest either old stars participate in a very strong spiral pattern or that young supergiants make a significant contribution to the K band light. Rhoads (1996) measures the CO index both on and off the spiral arms in NGC 1309, one of the nearby spirals studied by RZ. Since supergiants have strong CO absorption, this index can determine the dominant stellar population contributing to the K band light. Rhoads found that in the arms K band light comes primarily from supergiants, while off the arms, the giant stars were the dominant stellar population. Rhoads has observing time at the ARC telescope to measure the CO index in other nearby spirals: observations that have significant implications for our understanding of the DIRBE observations fo the Milky Way. These new observations would be partially supported by this proposal.
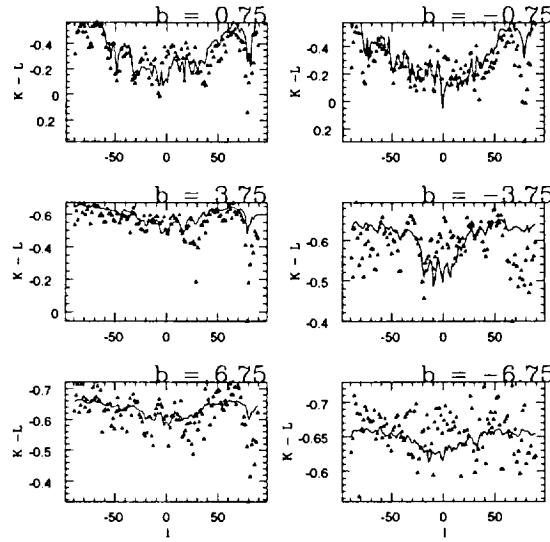
3. Infrared Tully-Fisher Relation

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FIG. 3. This plot compares the K-L reddening predicted from modelling the 240 μm emission (solid line) with the observed reddening (triangles).

Using the DIRBE infrared J(1.25 μm) K (2.2 μm) & L (3.5 μm) bands maps, S. Malhotra (IPAC), Spergel, Rhoads and Li (IPAC) have constructed a Tully-Fisher diagrams for the local group (see Figure 4). The fluxes for external galaxies are measured from DIRBE weekly flux maps, and published Cepheid distance are used to derive the absolute magnitudes. The dispersions in the Tully-Fisher relation are the smallest found at any wave band: σ_J = 0.09 magnitudes, σ_K = 0.13 magnitudes and σ_L = 0.20 magnitudes. For J and K bands, Monte Carlo simulations give a 95% confidence interval upper limit of σ_J = 0.35 and σ_K = 0.45. These small scatters are the sum of the intrinsic Tully-Fisher scatter, the scatter in the and the errors in estimates of fluxes, inclination angles, dust absorptions and circular speeds of Local Group galaxies.

We use a Galaxy model to determine the Milky Way's luminosity and place it in the Tully-Fisher diagram. For "standard" values for the size and circular velocity of the Milky Way (R_0 = 8.5kpc and Θ_0 = 220 km/s), it deviates less than 1.5-σ on these fairly tight TF relations giving credence to the Cepheid distances of these galaxies and to the rotation velocity and the size of the Milky Way as scaled by R_0, the sun-Galactic center distance. We can use the TF relation and the Cepheid distances to Local Group galaxies to constrain the R_0 and the MW rotation velocity: $\log(R_0/8.5\text{kpc}) + 1.63 \log(\Theta_0/220\text{km/s})$ = 0.07 ± 0.03. Alternatively, we fix the parameters of the Galaxy, ignore the Cepheid zero-point, and use the Tully-Fisher relation to determine the Hubble Constant directly: H_0 = 66 ± 12.

The K band is probably the longest wavelength band where we can minimize extinction without a significant contribution from interstellar dust. L band is expected to get some contribution from the 3.3 μm PAH feature. However, this contribution seems to be small since the L band data follows the Tully Fisher relation whereas the longer bands dominated by dust emission (e.g. 60, 100 μm) do not. The dispersion in the Tully-Fisher correlation is small: in J band σ_J = 0.13 magnitudes, in the K band σ_K = 0.13 magnitudes and in L band σ_L = 0.20 magnitudes. The Galaxy's luminosity can be used to set an independent zero-point for the Tully-Fisher relation and a measurement of the Hubble parameter that does not depend on the Cepheid distances (Wright 1994).

Near infrared Tully-Fisher relations may be very useful for cosmology. The extinction corrections at 2.2 μ and 3.5μ are about half and one-third as large as for the H-band at 1.65μ, so these bands may be usefully exploited for distance estimation. One expects the K corrections to these bands to be lower so they could be used for intermediate redshift studies using the Tully-Fisher relation. With the advent of imaging IR instruments and two major all sky surveys DENIS and 2MASS there is also potential to estimate the distances and hence the peculiar velocity flows for many more galaxies ($\sim 10^6$) in a greater part of the sky and nearer to the plane of the Milky Way.

4. A Self-Consistent Galaxy Model & Gravitational Lensing

HongSheng Zhao, who received his Columbia Ph.D. under the joint supervision of Spergel and M. Rich (Columbia), built a three dimensional steady state stellar dynamical model for the Galactic bar using an extension of the Schwarzshild (1979) technique (Zhao 1996). The stellar density distribution in this model fits the Dwek et al. (1995)
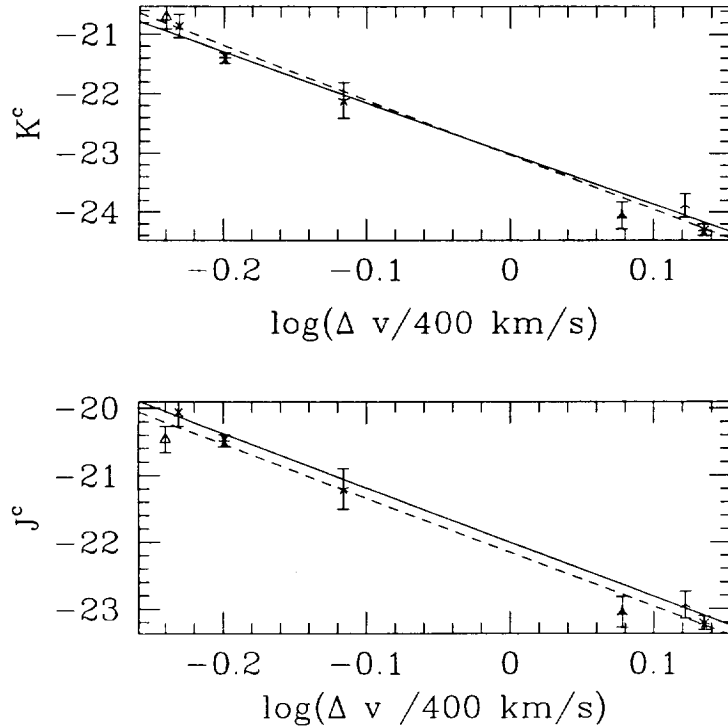
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FIG. 4. Local Group Infrared Tully-Fisher Relationship. The symbols are the dust-corrected J and K band magnitudes for the Local Group galaxies in the sample. The 3, 4, 5, 6 and 7 pointed stars are M81, NGC300, NGC 2403, M33 and M31. The open triangle is NGC 247, which falls just below our magnitude limit. The solid triangle is the Galaxy, where we have assumed a galactocenteric distance of 8.5 ± 0.5 kpc and $\Theta_0 = 220 \pm 10$ km/s. The errors on the points in the figures include only the reported uncertainties in Cepheid distances. The solid line is the fit to the 5 galaxy sample and the dashed line is the fit to the full 7 galaxy sample. (From Malhotra et al. 1996)

density distribution as well as measurements of stellar kinematics in Baade's window and a number of low extinction windows. Zhao (1996) shows that this model is stable and provides tables of predicted velocity dispersions and rotation velocities so that observers can test the model with observations in other windows.

Zhao et al. (1995, 1996) used this self-consistent model to predict microlensing events rates towards the galactic bulge. The predicted event rates and durations are consistent with the observations by the OGLE (Udalski et al. 1994) and MACHO (Alcock et al. 1995) collaborations. Zhao et al. (1996) showed that the observed lens event distribution could be used to constrain the mass function of the bulge and rule out the presence of large numbers of brown dwarfs in the bulge.

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