Dark Matter in Galaxies
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Galactic Disk Surface Density in the Solar Neighbourhood

William F. van Altena, Vladimir I. Korchagin, Terrence M. Girard, Dana I. Dinescu,

Yale University, Department of Astronomy, New Haven, USA

Tatiana V. Borkova

Institute of Physics, Rostov-on-Don, Russia

Abstract. Using parallaxes and proper motions of a kinematically and spatially unbiased sample of old bright red giant stars from the Hipparcos catalog with measured radial velocities from Barbier-Brossat & Figon (2000), we have re-estimated the surface density of the Galactic disk in the solar neighbourhood within ±0.4 kpc of the Sun. We determine the vertical distribution of the red giants as well as the vertical velocity dispersion of the sample, (14.4±0.26 km/sec), and combine these to derive the surface density of gravitating matter in the Galactic disk. Using these data, we determine the surface density of the galactic disk as a function of the galactic coordinate, z. The surface density of the disk increases from 10.5 ± 0.5 $M_\odot/pc^2$ within ±50 pc to 42 ± 6 $M_\odot/pc^2$ within ±350 pc. The volume density of the galactic disk within ±50 pc is 0.105 ± 0.005 $M_\odot/pc^3$, which is only marginally greater (within 2 sigma) than the volume density estimates of observed baryonic matter in the solar neighbourhood.

1. Introduction

A measurement of the density of gravitating mass of the Milky Way disk allows us to make a conclusion as to the presence of dark matter in the Galactic disk by comparing it with the observed density of visible matter. Starting from Oort's (1932) first attempt to determine this quantity, this problem was readdressed later on by a number of authors (see e.g., Holmberg & Flynn 2000 for the references). We re-address here the question of the mass density distribution perpendicular to the galactic disk in the solar neighbourhood. For this investigation we choose a subsample of old red giant stars from the Hipparcos catalog which is about 93 percent volume complete within $\sim \pm$ 0.4 kpc of the Sun. The new element in our study is the use of a kinematically unbiased subsample of red giants from the Hipparcos catalog with measured radial velocities. We demonstrate that with the catalog of Barbier-Brossat & Figon (2000) and the Hipparcos catalog a kinematically unbiased subsample of red giants can be extracted. Such a subsample has measured 3-D velocities and is used in the present study for the analysis of the kinematics of stars in the solar neighbourhood. Use of the volume-complete sample of red giants at distances extending $\sim$ 0.4 kpc from the Sun, in combination with the kinematically unbiased sub-

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sample of these stars, allows us to make a robust estimate of the integral surface mass density of the Milky Way disk in the solar neighbourhood

2. The Method

The total surface density Σ of all gravitating matter can be determined by estimating the spatial distribution and the kinematical distribution for a subsample of test stars. If the test sample is nearly isothermal, the surface density of gravitating matter in the disk can be evaluated by measuring the vertical distribution of the test sample of stars, and by measuring its vertical velocity dispersion:

$$\Sigma_{out}(z_{out}) = -\frac{\overline{v_z^2}}{2\pi G}\Big(\frac{1}{\rho_i}\frac{\partial \rho_i}{\partial z}\Big)\Big|_{z_{out}} + \frac{2z_{out}(B^2 - A^2)}{2\pi G} \tag{1}$$

Here v_z^2 is the vertical velocity dispersion of the test stars, G is the gravitational constant, ρ_i is the volume density of the test stars, and A and B are the Oort constants.

3. Selection Criteria

To determine the surface density of the Milky Way disk, one needs to measure the spatial distribution of the test stars together with the velocity dispersion of a kinematically unbiased sample. To satisfy these criteria, we choose as our basic sample of study old red giant stars from the Hipparcos catalog. The absolute magnitude cut-off ($M_V < 0$) and Yale-Yonsei isochrones allow us to form a sample of 1476 red giants older than $\sim$ 3 Gyr, nominally assuming their metallicity to be solar.

The survey portion of the Hipparcos catalog was designed to be complete to a limiting visual magnitude which would be a function of Galactic latitude, and colour. For red stars, $(B-V > 0.8)$, the completeness limit is $V \leq 7.3 + 1.1 sin|b|$. In order that our sample traces the density distribution of the disk to large enough distances, we apply an absolute magnitude cut of $M_{lim} < 0.0$. This cut-off, in combination with the visual magnitude limit determines the boundary of our volume of study, which has a heliocentric radius given by the expression:

$$R \leq 10^{0.2(7.3+1.1 sin|b| - M_{lim})+1.0} \tag{2}$$

The completeness limit together with the absolute magnitude cut-off allow us to choose virtually *all* the bright old red giants which are inside the volume of study in the Milky Way.

4. Systematic Corrections

In order to properly determine the vertical scale height of the test stars, several corrections must be applied. First, there is a purely geometrical correction due to the shape of the volume of study. We make this correction by re-scaling the number of stars in an elementary volume between z and $z + dz$ to the corresponding number of stars in a cylinder of radius 300 pc centered at the position of the Sun. The stellar distribution also must be corrected for extinction and for the systematic error arising from the statistical errors in the parallax measurements. We apply extinction corrections using the $E(B-V)$ extinction model published by Chen et al. (1999) which is based on COBE/IRAS all sky reddening maps and uses the 'infinity' reddening maps obtained from Schlegel et al (1998).

Distance errors have been corrected using a Monte-Carlo approach. A population of synthetic stars is generated based on an assumed spatial distribution. An absolute magnitude is assigned to each star, randomly drawn from a known luminosity function. A parallax measurement error is similarly assigned, from an error distribution which models that of the Hipparcos catalog. From these quantities are derived the star's apparent magnitude, 'observed' parallax, and 'observed' absolute magnitude. A sample is then trimmed from this population using an apparent magnitude limit, observed absolute magnitude range and corresponding observed distance cutoff, similar to those used to form our real sample of red giant stars from the Hipparcos data.The ratio of the sample's z-distribution based on the input 'true' parallaxes with that based on the 'observed' parallaxes defines the correction function which, applied to the observed z-distribution, recovers the true z-distribution

5. Results

Figure 1 shows the extinction and distance-error corrected z-distribution of old red giants within ± 400 pc (dotted line) which has been created using a Gaussian kernel function of 50 pc. Figure 1 shows also the best fits to this distribution with exponential (dashed line), sech^2 and sech-distributions (thin solid lines). The scale height of the best-fit sech^2 distribution is 280 pc with an uncertainty in the scale height determination of 15 pc. We note that this value is in good agreement with other recent determinations of the sech^2 scale height of the stellar thin disk in the solar neighbourhood.

A kinematical study must be based on a kinematically unbiased sample of stars. We use in our study the sample of red giants older than $\sim$ 3 Gyr, that are brighter than $M_V = 2.0$, and that have measured radial velocities and well-measured parallaxes. We demonstrate that this sample of stars is kinematically unbiased, as judged by their physical velocities.

In order to estimate the surface density of the gravitating matter in the Galactic disk we need to measure the velocity dispersion of our test sample of stars. We have explored several methods for estimating the velocity dispersion of our sample; a probability plot method, least-squares fit with a general two-component Gaussian distribution, and a fit to our kinematical sample trimmed on the velocity range $-30 < v_z < +20$ km/sec. The trimmed distribution has a best fit to a Gaussian distribution with velocity dispersion 14.6 ± 0.3 km/sec, which after taking into account broadening due to the measuring errors, gives a value for the intrinsic velocity dispersion of 14.4 km/sec. Our final estimate for the velocity dispersion of the red giant sample of stars is therefore $\sigma_z = 14.4 \pm 0.3$ km/sec.

The vertical velocity dispersion σ_z and the vertical scale height of the sample stars $(1/\rho_i)(\partial\rho_i/\partial z)$ allow us to estimate the surface density of the disk's

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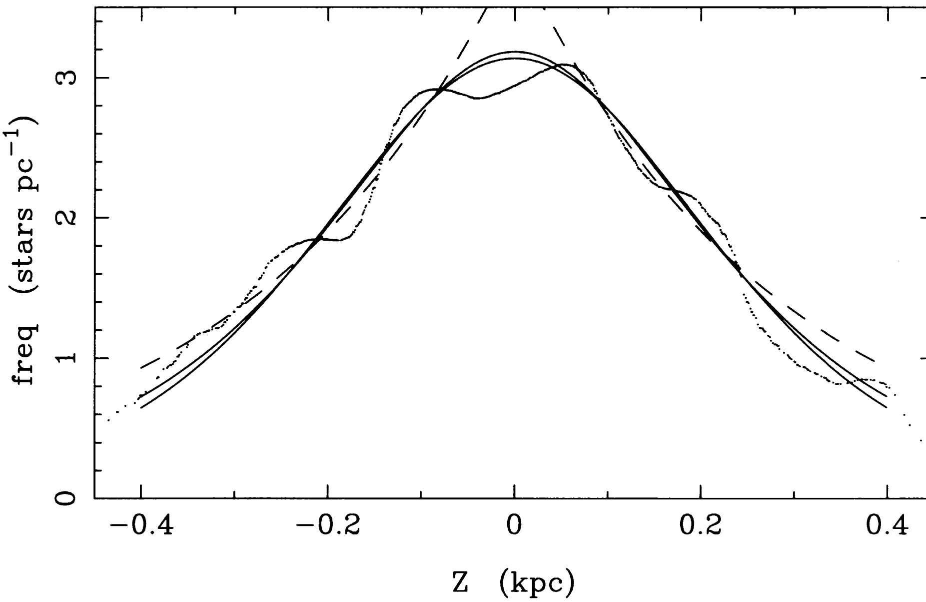

Figure 1. The extinction and distance error corrected z-distribution of old red giants represented by the red giant sample (dotted line). Also shown are the best fits to this distribution with exponential (dashed line), sech^2 and sech-distributions (thin solid lines). The spatial distribution functions are created with the use of a 50-pc Gaussian kernel function.

gravitating matter. The scale height (i.e. logarithmic derivative) can be determined directly from the z-distribution of the test sample. Figure 2 shows the numerically determined scale height function for the red giant sample (thick solid line). The scale height of the red giants is scaled by the square of their velocity dispersion, σ_z^2, and thus shows the z-dependence of surface density of gravitating matter in the disk. Also shown are the smooth curves corresponding to the sech^2, sech, and exponential functions fit to the red giants z-distribution which were shown in Figure 1. The vertical lines are error bars in the surface density determinations which arise from the uncertainties in the scale height determinations, and from the uncertainty in the velocity dispersion of the red giant sample.

The surface density of gravitating matter in the disk as 'seen' by the red giant sample of stars increases with z up to $|z| \sim 400$ pc. The surface density approximately follows the sech^2 or sech functional distributions, and is inconsistent with an exponential density profile perpendicular to the Galactic disk. Using the values of the Oort's constants taken from Olling & Dehnen (2003), we evaluate the second term of Equation (1) to be roughly 0.1 ± 0.02 M$_\odot$/pc^2 at $|z| \sim 50$ pc, and 0.8 ± 0.2 M$_\odot$/pc^2 at $|z| \sim 350$ pc. Combining these with the surface density estimate shown in Figure 2 yields values for the surface density

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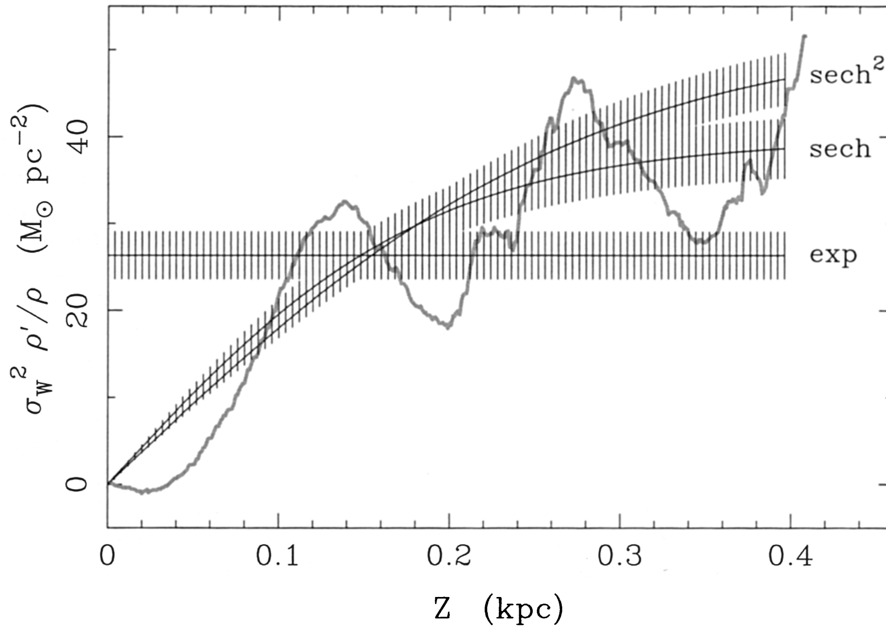

Figure 2. The scale height, $1/\rho_i(\partial\rho_i/\partial z)$, as a function of z for the vertical distribution of the old red giant sample (thick curve). The smooth, narrow-lined curves represent the fits to the red giant sample illustrated in Figure 1. The scale heights are scaled by the square of the velocity dispersion of the sample, and thus give a measure of the surface density of gravitating matter in the disk.

of the Galactic disk within $\pm$ 50 pc of 10.5 $\pm$ 0.5 $M_\odot/pc^2$, and 42 $\pm$ 6 $M_\odot/pc^2$ within $\pm$ 350 pc.

Our results allow us to make a rough estimate of the volume density of gravitating matter in the Galactic disk. We find that the surface density of gravitating matter in the disk is about 10.5 $\pm$ 0.5 $M_\odot$ / pc^2 within $\pm$ 50 pc. This gives a value for the volume density of gravitating matter of about $\sim$ 0.105 $\pm$ 0.005 $M_\odot/pc^3$ under the conservative assumption that the gravitating matter is distributed homogeneously. This value should be compared to the estimated volume density of visible disk matter 0.095 $M_\odot/pc^3$ (Holmberg & Flynn 2000). Our dynamical estimate of the volume density of the Galactic disk is thus well comparable with the identified matter in the solar neighbourhood, and, at the 1 - σ level, is 5 – 20 percent larger than the volume density of identified matter. If, however, the volume density is distributed non-homogeneously within $\pm$ 50 pc, this would lead to a larger discrepancy between the observed, and the dynamical volume density estimate close to the mid-plane of the disk. We concur, however, with the conclusion of Holmberg & Flynn (2000) that there is no compelling evidence for a significant amount of dark matter in the disk.

6. Conclusions

We have used Hipparcos parallaxes and proper-motion measurements to form a kinematically unbiased sample of red giant stars that have measured radial velocities taken from the catalog of Barbier-Brossat & Figon (2000). A determination of the surface density of the Galactic disk requires measurement of the first derivative of the spatial distribution of the test stars above the plane in combination with the measurement of the velocity dispersion of the sample. Using the density profile for these red giants and a determination of the velocity dispersion of a similar sample, we re-determine the surface density of the Galactic disk within ± 0.4 kpc of the Sun. An estimate of the first derivative of the distribution of red giants together with our estimate of the intrinsic velocity dispersion of the sample of 14.4 km/sec yields a surface density of gravitating matter in the Galactic disk that varies from 10.5 ± 0.5 $M_\odot$ / pc^2 within ± 50 pc to 42 ± 6 $M_\odot$ / pc^2 within ± 350 pc. An estimate of the volume density of gravitating matter gives, at the 1-σ level, a value 0.1 – 0.11 $M_\odot/pc^3$ under the conservative assumption that the gravitating matter is distributed homogeneously. This is 5 – 20 percent larger than the volume density of identified matter in the solar neighbourhood 0.095 $M_\odot/pc^3$. The discrepancy might be larger if the volume density of gravitating matter is distributed non-homogeneously close to the mid-plane of the Galactic disk.

A detailed version of this paper can be found in Korchagin et al. (2003). This study was supported by the NSF under grant AST 00-98687.

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