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Scale Length of the Galactic Thin Disk

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Abstract. This paper presents an analysis of the first 2MASS (The Two Micron All Sky Survey) sampler data as observed at lower Galactic latitude in our Galaxy. These new near-infrared data provide insight into the structure of the thin disk of our Galaxy, The interpretation of star counts and color distributions of stars in the near-infrared with the synthetic stellar population model, gives strong evidence that the Galactic thin disk density scale length, h_R, is rather short (2.7 ± 0.1 kpc).

Key words. Galaxy: stellar content—Galaxy: structure.

1. Introduction

Within the plane of the Galactic thin disk, the radial density function can be expressed in terms of the distance from the Galactic center, the Solar distance from the center, and the Galactic disk scale length. The latter parameter is poorly known at present but can be a major discriminant of theories of thin disk formation. The scale length of thin disk varies as a function of Galactic morphological type (Freeman 1970). For the Milky Way, published values of the scale length of thin disk range from 1.8 to 6 kpc (McCuskey 1969; De Vaucouleurs & Pence 1978; Knapp *et al.* 1978; Robin *et al.* 1992; Ruphy *et al.* 1996). It should also be noted that one way of constraining the value of the Hubble constant involves comparing the radial scale lengths of external disk galaxies, which are dependent on distance and hence the Hubble constant, with that of the Milky Way; thus the radial structure of the disk is also relevant for large-scale structure. Therefore it is of great interest to know the radial structure of the Galactic disk.

The 2MASS near-infrared data provide, for the first time, deep star counts on a large scale, in the J, H, K_s photometric bands. These surveys offer new inputs to determine the radial structural parameters in our Galaxy. Apart from the benefit of a lower interstellar extinction, the near-infrared data present another advantage on optical ones: they trace more reliably the total mass distribution, and therefore should be preferred to investigate the stellar distribution, specially at large distances from the Sun.

In this paper, we present the first analysis of star counts in the J and K_s bands in one of the 2MASS fields at lower Galactic latitude of our Galaxy. The counts are compared to the results of the model of stellar population synthesis of the Galaxy, in order to derive some constraints on the radial structure of the Galactic thin disk.

2. Observational data

We have used the first 2MASS sampler data, public release of point source catalogue, in J (1.25 μm), H (1.65 μm) and K_S-band (2.17 μm) for our analysis. The sampler data are drawn from observations obtained at the Northern 2MASS facility on the night of November 16th, 1997. 2MASS uses two new, highly-automated 1.3 m telescopes, one at Mt. Hopkins, AZ, and one at CTIO, Chile. Approximately 63 deg^2 of northern sky were covered by these observations. The data are complete to 16.0 in J, 15.5 in H and 15.0 in K_S. The 2MASS sampler point source catalog contains position and brightness information for 227,197 objects. We have used one of the 2MASS fields at lower Galactic latitude, which covers approximately 5.958 deg^2 area for our analysis. The positions of the field covered by the observations are: α_{2000} = $07^h05^m36^S$; = δ_{2000} = $+20^o49'30''$; l = 196°; b= +12°.

3. Analysis

3.1 *Stellar population synthesis model*

The Besançon model of stellar population synthesis was used to interpret the 2MASS near-infrared counts. Robin & Crézé (1986) started to build a self-consistent Galaxy model using an evolutionary model from Rocca-Volmerange *et al.* (1981), then they introduced the dynamical constraints (Boltzmann and Poisson equations) allowing the determination of the scale heights of the disk according to the potential (Bienaymé *et al.* 1987). The kinematical parameters of Galactic thin and thick disk were described in Robin & Oblak (1987); Robin *et al.* (1996) and Ojha *et al:* (1996). In order to check the Initial Mass Function (IMF) and the Star Formation Rate (SFR) history in the Galaxy, recently Haywood (1994, 1997ab) redesigned the evolution scheme from Rocca-Volmerange to a more detailed one using the most recent evolutionary tracks and gave strong constraints on the slope of the IMF, the history of the SFR in the past and on the age-velocity dispersion relation for the disk stars.

In the model, the Galactic thin disk in the z-direction is represented by a sum of 7 components with different scale heights, the 6 oldest components of which are isothermal. This model employs a constant SFR, a three-slope IMF, and a 21 km/s maximum velocity dispersion. The model also gives the thin disk a vertical metallicity gradient according to age-metallicity and age-scale height relations. In the model, the key parameter is the density law of the Galactic thin disk, which is an Einasto density law (Einasto 1979) for $R \leq R_{\max}$ (radial cutoff), and is equal to 0 beyond $R_{\max}$. The Einasto law is close to a sech^2 law in the vertical direction (see Bienaymé *et al.* 1987, for details), and close to an exponential law in the radial direction, in such a way that the parameter h_R is similar to a radial exponential scale length.

Since we are dealing with the field at lower Galactic latitude, the effect of extinction along the line of sight must be investigated. The effect of extinction on K_S star counts is limited, however J-K_S color distributions are significantly sensitive to the extinction. The fit of the position of the observed and model predicted distribution peaks allows to adjust the spatial extinction law in the model. This fit gives a value of

0.2 mag/kpc for the coefficient of the local diffuse visual absorption for the lower Galactic latitude field.

While examining the various parameters of the Galactic disk, we have started with the best fit Besançon model (as in Robin *et al.* 1996; Ojha *et al.* 1996).

3.2 *Scale length of Galactic thin disk*

In order to constrain the scale length of the Galactic thin disk, h_R, we produced a grid of models, with different values of the disk scale length. For each disk model, we simulate catalogues of data similar to the observed data set, including photometric errors. To avoid too large Poisson noise in the Monte Carlo simulations, we computed at least five simulations of 30 square degrees for each of the models tested in our analysis. The data are binned with a step of 1 mag in K_S, and 0.1 in J-K_S. We determine the best value of the density scale length using a maximum likelihood technique, applied on a set of bins of K_s and J-K_S to the whole set of data, for stars brighter than 15 in K_S. The likelihood of each model is computed as described in Bienaymé *et al.* (1987):

Let q_i be the number of stars predicted by the model in bin i and f_i be the observed number. In case the deviations of $f_i^{'}$s with respect to q_i just reflect random fluctuations in counts, each f_i would be a Poisson variate with mean q_i. Then the probability that f_i be observed is:

$$\mathrm{d}P_i = \frac{q_i^{f_i}}{f_i!}\exp(-q_i).$$

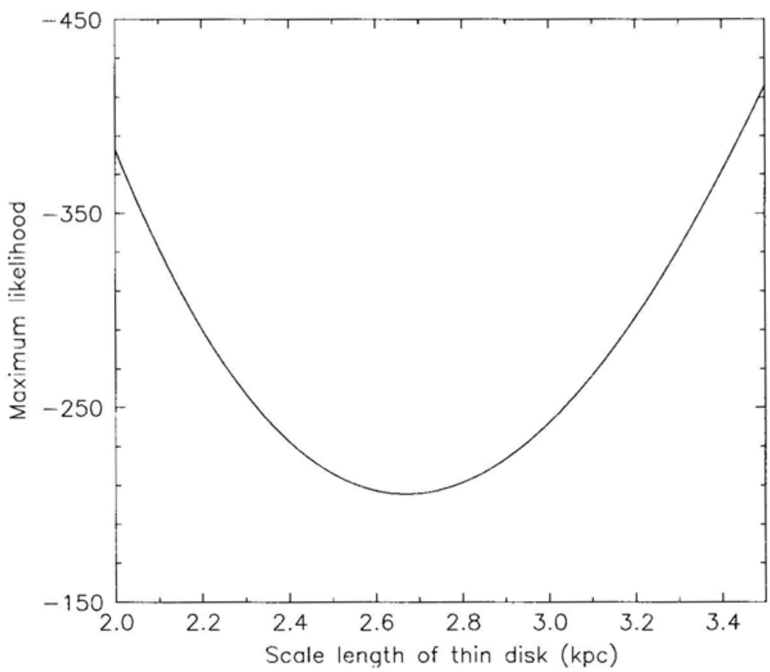

Figure 1. Maximum-likelihood curve for the density scale length, h_R, of the thin disk.

Then the likelihood of a set of q_i's given the relevant f_i is:

$$L = \ln \sum \mathrm{d}P_i = \sum_i (-q_i + f_i \ln q_i - \ln f_i!).$$

In search of the models that maximise *L,* it is convenient to use the reduced form:

$$L - L_0 = \sum_i f_i \left(1 - \frac{q_i}{f_i} + \ln \frac{q_i}{f_i}\right)$$

where L_0 is constant and $L - L_0 = 0$ for a model which would exactly predict all fi's.

Fig. 1 shows the maximum likelihood curve for different values of h_R for our data set. The maximum likelihood is obtained with a scale length, h_R, of 2.7 kpc.

3.3 *Confidence interval*

The confidence interval of our fit comes from the estimation of the variation of the likelihood due to the Poisson noise on the data. The likelihood of two realizations of the same model, differing just by the Poisson statistics, gives the value to add to the maximum likelihood to get the confidence level. We thus obtained an uncertainty of ±0.1 kpc for h_R. These uncertainties account only for Poisson errors, but do not account for other sources of errors that are very difficult to quantify, such as the uncertainties on the extinction model or on the luminosity function.

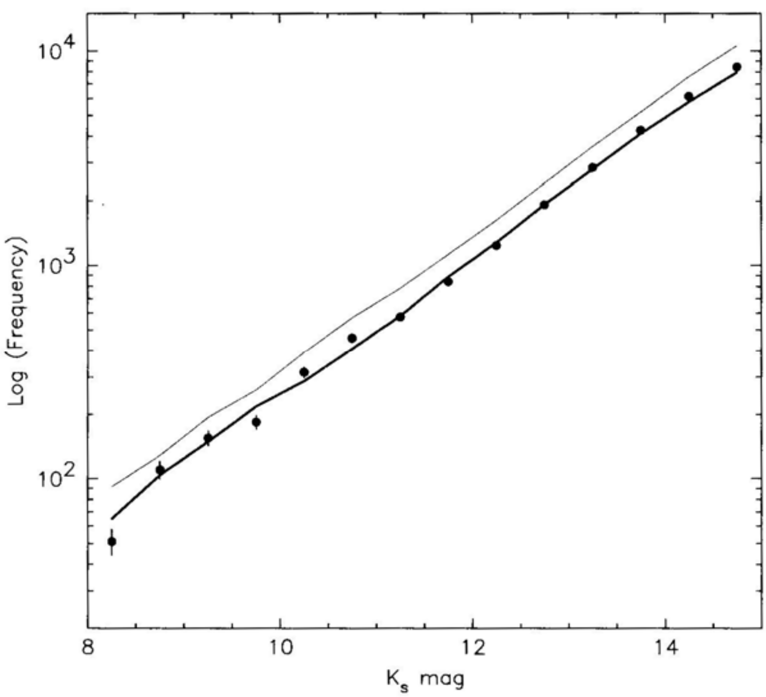

Figure 2. K_S star counts in 2MASS field. **Filled circle:** Observed counts with 1σ error bars (Poisson noise only). **Thick line:** Predicted counts assuming a density scale length, h_R, of 2.7kpc. **Thin line**: Predicted counts with h_R of 3.5 kpc.

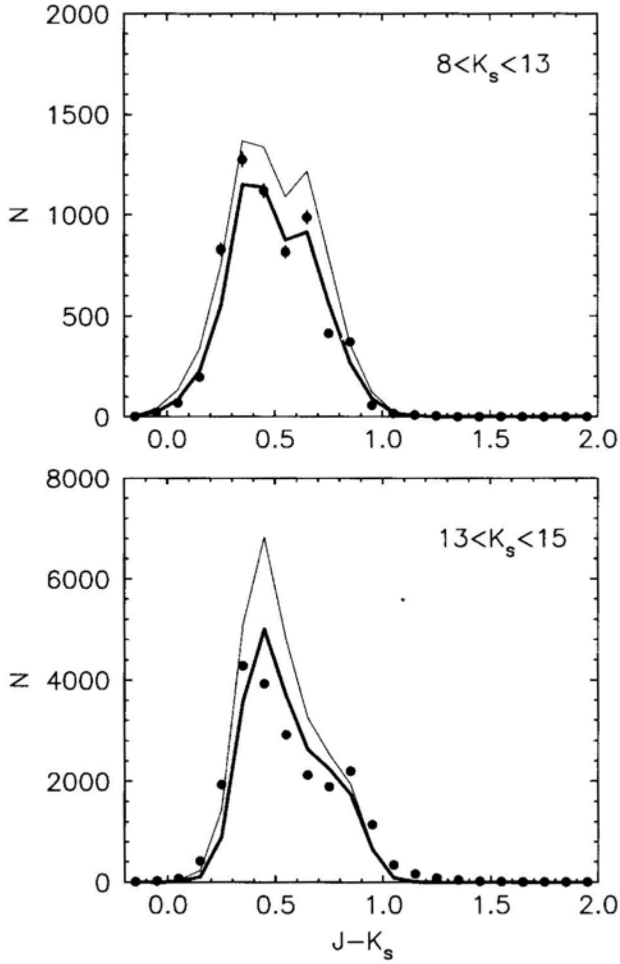

Figure 3. J-K_S distributions of sources brighter than K_S = 15 in 2MASS field. The symbols are as in figure 2.

3.4 *Comparison with observed data*

In Fig. 2, the observed apparent K_S magnitude distribution is compared with the model predictions with thin disk scale lengths of 2.7 and 3.5 kpc. The total observed counts are in good agreement with the model predictions assuming the thin disk scale length, h_R, of 2.7 kpc. Fig. 3 shows J-K_S distributions alongwith model predict-tions for two different thin disk scale lengths, h_R = 2.7kpc and h_R = 3.5 kpc. The excess of stars seen on Figs. 2 and 3 for h_R = 3.5 kpc, is significantly reduced with the new value of h_R. The model fit with data is not, however, completely satisfactory in J-K_S, which might be improved by a slight change of SFR history in the model. One expects that the Galactic evolution parameters will be better known after the analysis of the Hipparcos and Tycho catalogues. The Besançon model is in a further improvement phase by using the data from Hipparcos and Tycho (Robin *et al.* 1999).

4. Discussion and conclusion

There have been several determinations of the radial scale length in the thin disk of the Milky Way either from photometric or kinematic approach. The many different determinations based on photometry or star counts give possible values in a large range (Kent *et al.* 1991 give a recent review; see also Robin *et al.* 1992). To add to this apparent confusion, many published density scale lengths are deduced from kinematic data using the asymmetric drift relation, but generally the expressions used for the asymmetric drift are simplified without any strong theoretical support. For example, it is frequently assumed that the kinematic and density scale lengths are equal. Only in a recent contribution (Fux & Martinet 1994), the term including the shape (spherical, cylindrical...) of the potential is adjusted.

Here, we have presented a direct measurement of density scale length of thin disk by analysing the data using a synthetic model, reproducing observable quantities (magnitude and color counts). This method is expected to avoid systematic bias that can be encountered in inversing the process. The resulting density scale length of 2.7 ± 0.1 kpc has to be compared to some recent works: the value of 2.3 ± 0.1 kpc obtained by Ruphy *et al.* (1996) by analysing the DENIS near-infrared data towards anticenter direction; Robin *et al.* 1992: 2.5 ±0.3 kpc, from optical star counts towards the Galactic anticenter; Fux & Martinet 1994: $h_R = 2.5\ ^{+0.8}_{-0.6}$ kpc, based on a rigorous analysis of the asymmetric drift relation; Porcel *et al.* 1998: 2.1 ± 0.3 kpc, from the near-infrared K-band counts from the TMSG (Two Micron Galactic Survey); Bienaymé (1999) finds out that the scale density length of the Galactic disk is 1.8 ± 0.2 kpc, using the neighbouring stars in Hipparcos catalogue. This quite short scale length is also fully compatible with star counts at median latitude regions of the Galaxy (Ojha *et al.* 1996).

We also notice that an increase of h_R (~ 0.8 kpc) predicts a significant excess of stars (in Figs. 2 and 3). It follows that the present 2MASS data are clearly incompatible with the larger values of h_R for thin disk, such as those found by van der Kruit (1986) (h_R = 5.5 ± 1 kpc); Lewis & Freeman (1989) (h_R = 4.4 ± 0.3 kpc, based on kinematics of disk K giants).

We conclude that the scale length of the Galactic thin disk is rather short (2.7 ± 0.1 kpc). Additional information will be gained when other 2MASS surveys in different directions of the Galaxy will be analyzed globally by using the Besançon model.

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