TOWARDS AN IMPROVED MODEL OF THE GALAXY

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ABSTRACT

We use the Hipparcos survey to derive an improved model of the local galactic structure. The availability of parallaxes for all the stars permits direct determination of stellar distributions, eliminating the basic indeterminacy of classical methods based on star counts.

The observed joint distribution of parallaxes, colours and apparent magnitudes is well reproduced by a density model of the Bahcall-Soneira type but with modified luminosity/colour distribution and scale heights. The best fit to the data is obtained with a density law perpendicular to the plane that is intermediate between the two classical forms, the exponential and the sech^2 (isothermal). The solar distance from the plane is found to be low compared to previous estimates, especially those based on optical star counts.

The Hipparcos survey was intended to be a complete sample of some 50 000 stars, limited by apparent magnitude and colour. In reality, the faint part of the survey is incomplete, and the completeness factor is depending on many variables that are hard to reproduce in a model. The much more complete and homogeneous sample offered by the Tycho Catalogue can be used to constrain the model for the fainter stars.

Key words: space astrometry; galactic structure; Milky Way Galaxy.

1. THE HIPPARCOS SURVEY

Hipparcos gives for the first time a truly three-dimensional view of the solar vicinity, and a complete, homogeneous and highly accurate set of magnitudes and colours. This means that new techniques can be applied in the treatment of the data which places strong constraints on a model that tries to describe the local Galactic structure. In this paper we investigate how well a model of low complexity along the same lines as the models by Bahcall & Soneira (1980), Gilmore (1984) and Larsen (1996) can describe the Hipparcos observations. This model can then be compared to more elaborate evolutionary models as the ones described in Ng et al. (1996) and Haywood et al. (1997).

The Hipparcos survey is a major part of the input catalogue with about 52 000 stars out of the total 118 000 stars. A list of bright stars uniformly distributed over the sky was needed for the operation of the satellite, and this list was also extended to be statistically complete to well defined limits in order to facilitate studies of galactic structure. The survey selection criteria are defined for two different groups of stars:

$$V \leq 7.9 + 1.1 \sin |b| \quad (1)$$
$$V \leq 7.3 + 1.1 \sin |b| \quad (2)$$

The first criterion (1) was used for blue, mainly main-sequence stars with spectral type earlier than or equal to G5 (or $B-V < 0.8$ if no spectral type was known). The second criterion (2) was used for the later spectral type stars and gives mainly red giants. The reason for the division of the stars into two groups was to reduce the number of more distant red giants (with ill-defined distances), and to get more A, F and early G dwarf stars from which more astrophysics can be deduced. There are two error sources in the definition of the survey: erroneous spectral type and erroneous magnitude. Of the whole survey only 40 per cent had photoelectric photometry, and in the break region around G5 many stars lacked accurate MK classification and had only a HD spectral type. However the HD Catalogue lists G stars as only G0 or G5 and the correlation between MK and HD types has a considerable scatter. These errors leads to a survey containing many stars fainter than the formal survey limits, while other stars that are brighter than the survey limits were never included in the Hipparcos programme.

2. THE MODEL

The interpretation of the Hipparcos data is complicated by various observational errors and selection effects. This is especially the case with absolute magnitudes derived from parallaxes. If the error in the parallax is Gaussian, which is a fair approximation, the error in the absolute magnitude is not Gaussian and especially non-physical absolute magnitudes result from negative parallaxes. This, together with

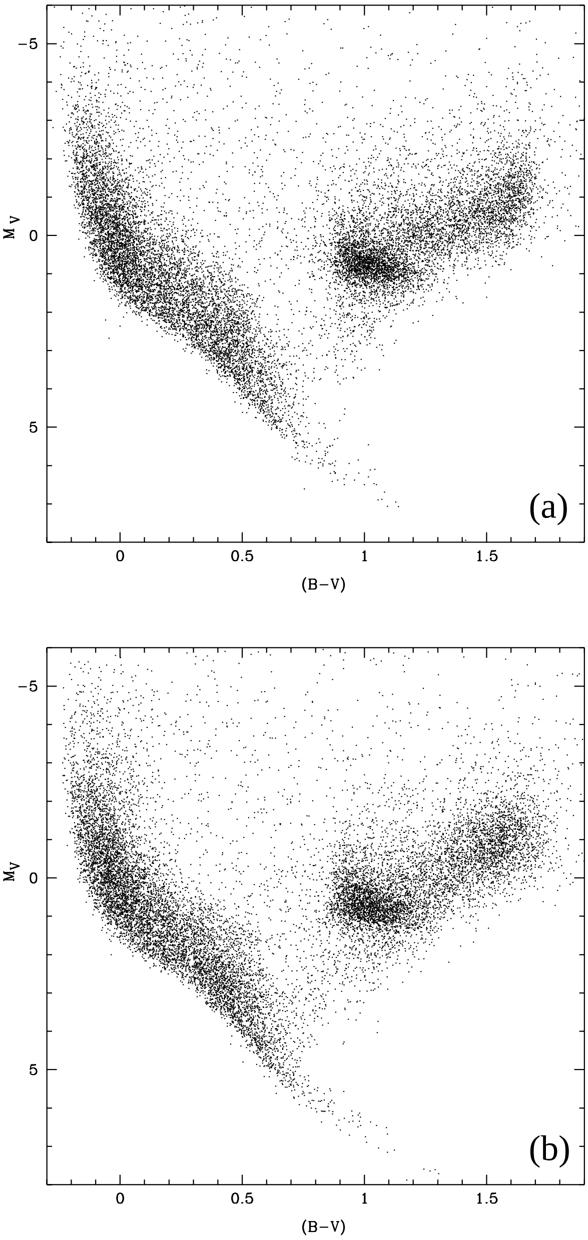

Figure 1. Distribution of stars with $V < 7$ in the HR diagram for the Hipparcos Catalogue (a) and for a simulated model catalogue (b).

the strong gradient in the number of stars versus true distance, produces a bias in the estimated distances or magnitudes that has to be corrected for. An alternative way is not to try to correct the data, but instead use a model and subject this model to the same observational errors and selection effects. A model catalogue is created that can be compared with the observed catalogue directly in the observational domain, thereby eliminating the effects from various biases.

We employ a full three component model with a disk, a thick disk and a halo, and in order to be able to work close to the plane of the Galaxy our model uses

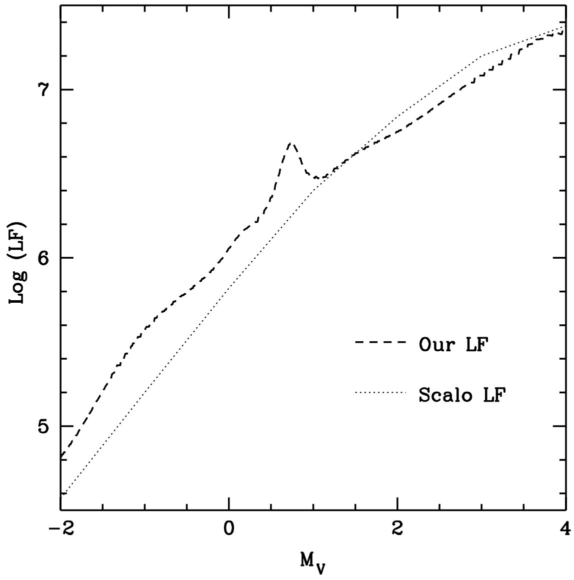

Figure 2. The disk luminosity function (LF) used in our model, compared with Scalo(1986). The vertical scale is $\log_{10}(stars/pc^3)$ + 10.

the extinction distribution described in Arenou et al. (1992). In the Hipparcos survey the disk stars are off course completely dominating, and it is hard to deduce parameters for the other components from the Hipparcos data alone. This investigation therefore concentrates on improving the description of the thin disk. The density distribution in the radial direction is modelled in the classical way as an exponential with a scale length of 3.5 kpc, whereas in the Z direction we have employed the generalized form:

$$\rho(Z) = \rho(0)\ \mathrm{sech}^{2/n}(nZ/2Z_e) \tag{3}$$

which was presented by van der Kruit (1988) in order to give a representation of density distributions between the exponential ($n \to \infty$) and the isothermal ($n = 1$). Here $\rho(0)$ is the density in the plane and Z_e the exponential scale height at large Z. For the scale height of main-sequence stars we use a relation depending on absolute magnitude, similar to Scalo (1986) but with new parameters and single scale heights for the red giants and super giants.

In order to get a complete model, this description of how the stars are distributed geometrically has to be complemented with a description of how they are distributed in absolute magnitude and colour. We therefore apply a luminosity function giving the total density of stars as a function of M_V together with a description of how the stars are distributed in colour. The parameters of the model are then derived from the best fit to the joint distribution of parallaxes, colours, apparent magnitude and galactic latitude and longitude of the stars in the Hipparcos survey. Details of this procedure will be published elsewhere.

3. RESULTS

3.1. The structure of the HR Diagram and the Luminosity Function

The model distribution of stars in M_V and $B-V$ was constructed such that, after application of all selection effects and observational errors according to the model, the observed distribution of stars in the HR diagram was reproduced. Figure 1a is the observed HR diagram from the Hipparcos Catalogue, using all stars brighter than $V=7$. (This conservative limit was used to avoid problems with the definition of the survey near its formal completeness limit; cf. Section 3.4.) Many features in the HR diagram are for the first time seen in field stars thanks to Hipparcos. A very obvious example is the slanted red giant clump, the metal rich stars equivalent to the horizontal branch of core helium burning stars, at $M_V \simeq 0.75$, $B-V \simeq 1.0$. This structure is also seen in rich old open clusters such as Berkeley 18 (Kaluzny 1997).

Figure 1b is the corresponding HR diagram for the model catalogue. As can be seen, most features of the observed HR diagram are well reproduced by the model thanks to the rather detailed modelling of the joint $M_V/B-V$ distribution. Actually, separate distributions were derived for the three different components, using the kinematic characteristics of the components to discriminate between them. The marginal distribution of the joint $M_V/B-V$ distribution, for the disk component in the galactic plane, gives the luminosity function shown in Figure 2. For comparison, the luminosity function from Scalo (1986) is also shown.

3.2. Vertical Density Distribution

For galaxies other than the Milky Way the vertical distribution of light in nearly edge-on galaxies was studied by de Grijs & van der Kruit (1996). They find that the most probable distribution function has a form between the two ones usually employed: the exponential and the sech^2 (isothermal). We have found the same to be true for our own Galaxy as observed by Hipparcos. From the family of density laws for the vertical mass (Equation 3) we found that $n=3$ gave the best representation of the stellar distribution in the Hipparcos catalogue.

In order to study the density distribution in Z we counted the number of stars in cylinders of height $\Delta Z = 10$ pc and radius 100 or 200 pc centered on the Sun's position in the XY-plane. This was done both for the stars in the Hipparcos Catalogue and for stars in a simulated catalogue model. In order to reduce statistical scatter in the model counts, they were computed as the averages from 10 simulated catalogues.

Figure 3a shows the distribution of stars with $B-V$ between 0.3 and 0.6 and $V<7$ in a cylinder with radius 100 pc, mostly containing F-stars. Figure 3b shows a similar comparison for a sample with $B-V>0.8$ and $V<7$ in a cylinder with radius 200 pc that almost entirely consists of red giants. The radii of the cylinders where chosen in order to roughly correspond to the completeness volumes of the stellar sample and to minimize the impact of reddening. In both cases the fit is god, and especially in the red giant case an exponential density distribution would predict far too many stars close to the plane.

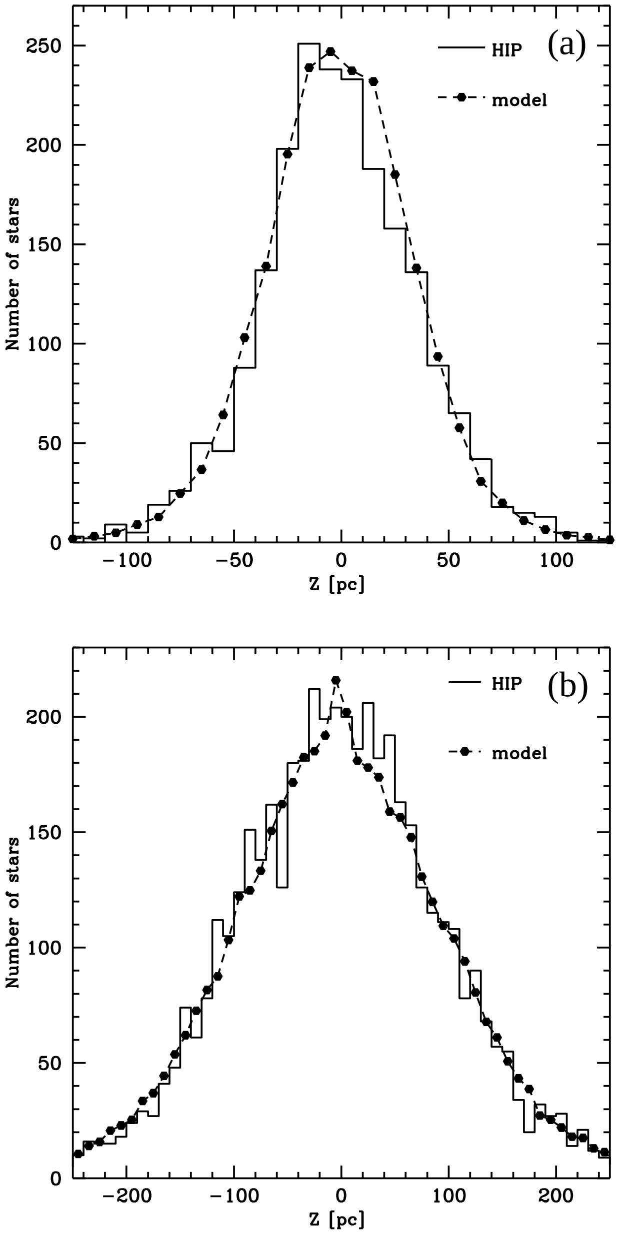

Figure 3. (a) The height distribution for stars with $0.3 < B-V < 0.6$ and $V<7$ (roughly F stars) within a radial distance of 100 pc from the Sun. (b) The height distribution for stars with $B-V > 0.8$ and $V<7$ (almost exclusively red giants) within a radial distance of 200 pc from the Sun. The diagrams give the counts from the observed or simulated catalogues, including all selection effects, and therefore do not represent the true distribution of stars.

3.3. The Sun's Distance above the Galactic Plane

Most studies agree that the Sun is not exactly at the plane of the Galaxy, but some distance above it. Before Hipparcos measured values of $Z_\odot$ ranged between 10–20 pc (mostly from studies of gas, dust and young stars) and 20–40 pc (mostly from optical stars counts). An alternative way is to interpret the latitude of Sgr A* (-0.05 degrees) as a projection effect $= -Z_\odot/R_\odot$, giving $Z_\odot \simeq 7$ pc (Ratnatunga et al. 1989). Hipparcos finally solves the question in a very convincing way by placing the Sun at $Z_\odot \simeq 8 \pm 4$ pc.

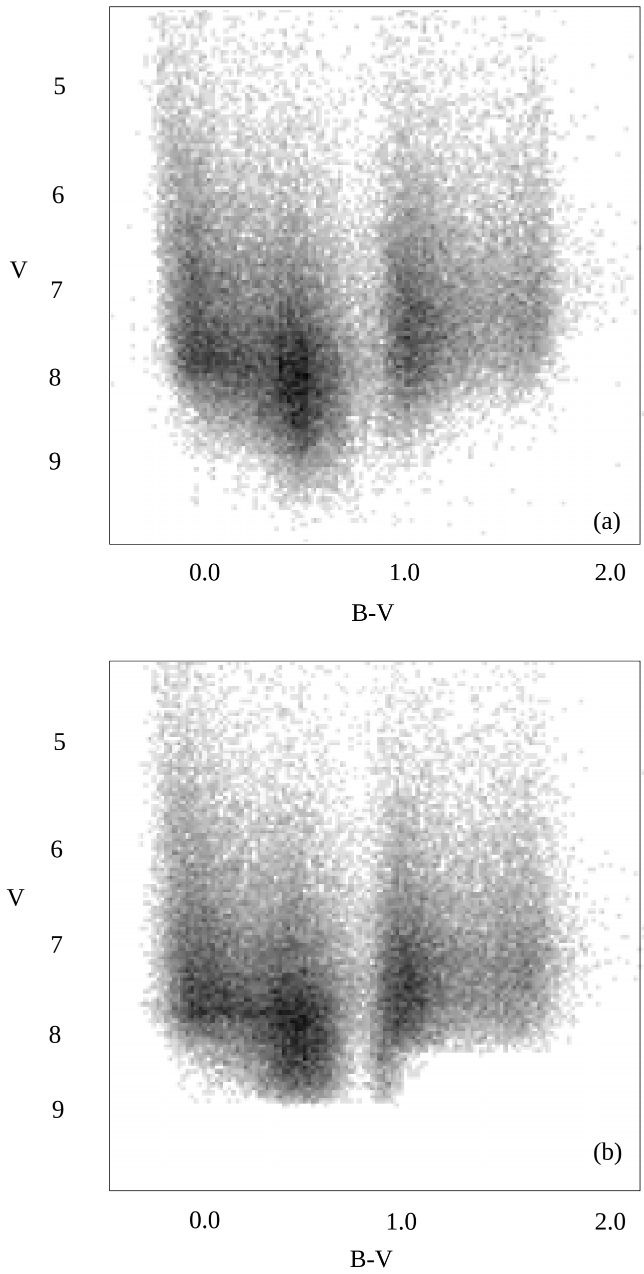

Figure 4. A comparison between the stellar distribution in the Hipparcos survey (a) and in the model (b).

3.4. Total Star Counts

Figure 4 is a comparison of the distributions of stars in apparent V magnitude and $B-V$ colour in the Hipparcos survey, and for stars in the model that pass the formal survey magnitude limits. It can be seen that the survey contains stars more than a full magnitude below the formal selection limits. This makes the use of the fainter part of the survey much more difficult, and in order to work on a truly complete sample, only stars brighter than $V = 7$ mag have been considered in this study. For this magnitude range the model is totally consistent with the stellar distribution seen from Hipparcos. For instance, in Figure 5 the total star counts of Hipparcos stars brighter than $V = 7$ mag, divided into colour bins, is compared with the model.

In order to check the model also for fainter stars we used the much richer, but not so accurate Tycho Catalogue. This is a very good complement to the Hipparcos survey, since it is truly complete to much fainter magnitudes. The completeness is at the 99.9 per cent level down to $V_T \simeq 10$, and somewhat fainter in B_T. Is this study only the total counts in 0.5 mag bins of B_T and V_T are compared with the model, and the fit is excellent. Figure 6 shows the comparison in the V_T and B_T photometric systems. Here the model is calculated for stars down to $V = 11.5$ and it can be clearly seen where the counts in the Tycho Catalogue begin to be fall below the model beyond $V_T \simeq 10$ and $B_T \simeq 10.5$ due to incompleteness.

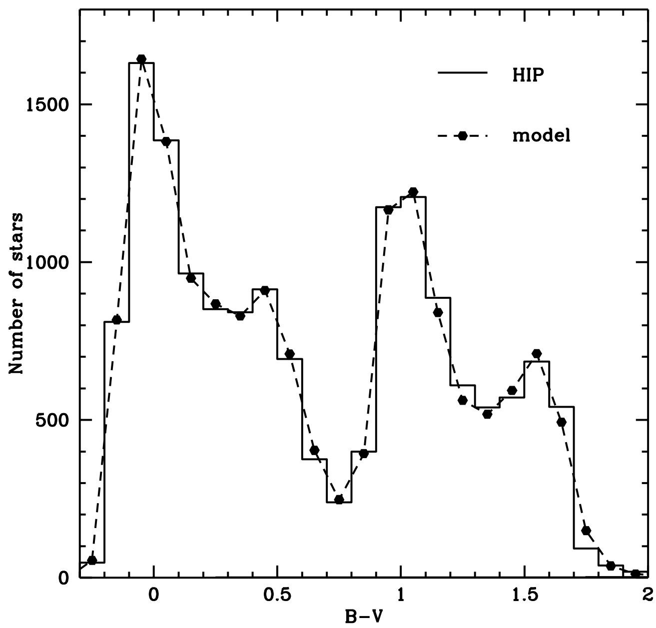

Figure 5. A comparison between the total number of stars with $V < 7$ in the Hipparcos Catalogue (histogram) and according to the model (dashed curve).

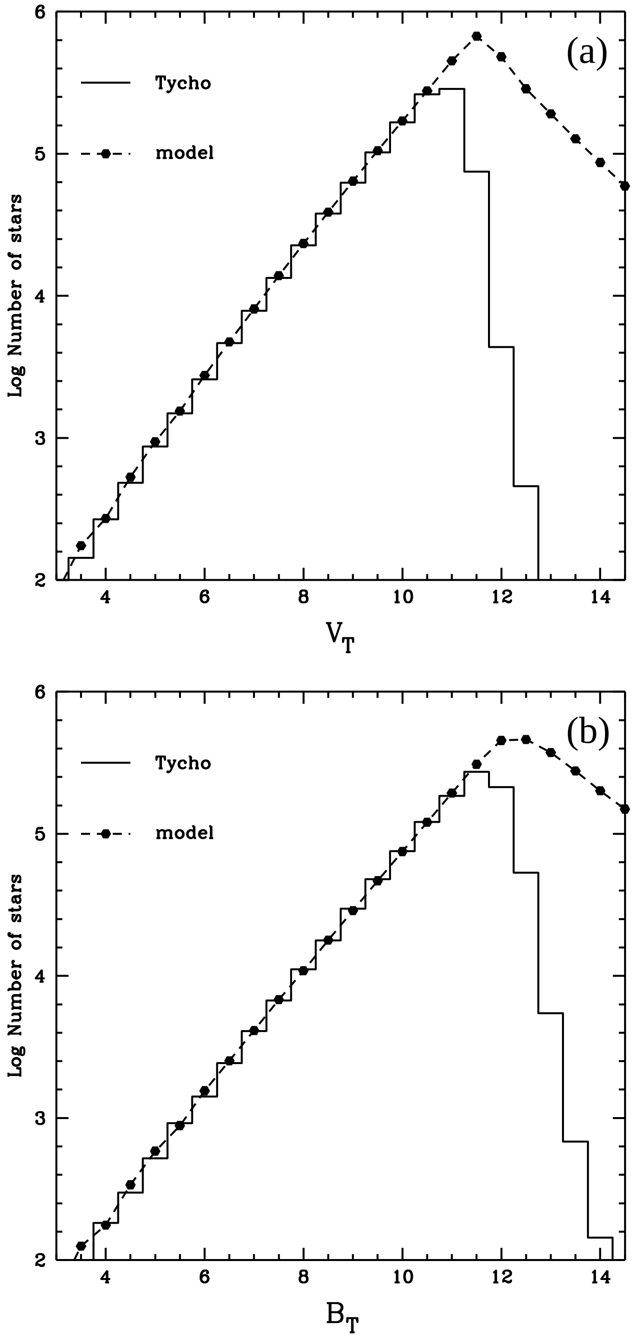

Figure 6. (a) A comparison between Tycho visual counts and the model. (b) A comparison between Tycho blue counts and the model. The Tycho Catalogue is complete to $V_T \simeq 10$ and $B_T \simeq 10.5$. The model used in this comparison was designed to be complete to $V = 11.5$.

4. CONCLUSION

Comparison of our model with the distribution of stars in the Hipparcos survey shows that main features of the local Galactic structure in the solar vicinity can be well represented by a model of low complexity.

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