A NEW TOOL FOR STUDYING GALACTIC STRUCTURE

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ABSTRACT

We here describe a new synthetic catalogue generator, based on a statistical model of the Galaxy, and use it to model the spatial and kinematic distribution of a subset of the Hipparcos Catalogue, specifically OB stars in the plane of the Galaxy. To accurately model this stellar population a method is developed which does not make the usual assumption of uniformity across the field. This population is shown to be best described by a non-axisymmetric spatial distribution. Many of the Galactic parameters are found by a manual adjustment to recover the observed properties of the selected Hipparcos sample.

Key words: Galactic structure; OB stars.

1. MOTIVATION

Circumstances dictate that our determination of the large scale structure of our Galaxy be indirect, as we view it from an uniquely internal perspective. Therefore studies of the stellar components of the Milky Way have relied upon Galactic models that give a statistical description of the stellar distribution, and the synthetic catalogues produced from them (Bahcall & Soniera 1980, Robin & Crézé 1986, Ratnatunga et al. 1989). The parameters and components of the model will presumably describe physically meaningful stellar populations.

Here we present a model of a single stellar component of our Galaxy: the young OB stars in the direction of the anti-center. We have chosen this population in order to study the warp of the Galaxy, as we expect this young population to trace the gaseous warp that has long been known from HI observations. Evidence of the Galactic Warp is investigated in Smart et al. (1997, hereafter SDL), as well as a detailed description of the Hipparcos data set that was studied; here we present our synthetic catalogue generation program and the stellar distribution model upon which it is based.

The challenges of modeling this stellar component include its large field upon the sky ($70 < l < 290$), its sparseness (0.07 per square degree), its natural location at low galactic latitudes and the consequential importance of absorption. To meet these challenges we present a synthetic catalogue generation program which is designed to build stellar catalogues over large regions of the sky without the usual assumption of uniformity across the field or sub-fields, but instead generates the spatial distribution accurately throughout the entire volume. We also show that the distribution of our chosen young stellar population is better described by a non-axisymmetric distribution then the usual axisymmetric model. Absorption is calculated from a model of the galactic dust distribution.

In the following section we describe our method of arriving at the stellar distribution in observation space, and our model for the kinematic and spatial distributions. In the third section we compare a generated synthetic catalogue with the Hipparcos data set chosen in SDL for studying the galactic warp.

2. METHOD

2.1. Spatial Distribution

The total number of stars within a catalogue is determined by integrating over the luminosity function, $\Phi(M)$, and the number density of stars relative to the solar neighborhood, $n(\mathbf{x})$. Explicitly:

$$N = \int \Phi(M)dM \int n(\mathbf{x})dV \qquad (1)$$

However, rather than using the above equation to determine the number of stars in our synthetic catalogue, we generate the same number of stars as in our data set, interpreting the product $\Phi(M)n(\mathbf{x})$ as a probability density.

The method we employ to generate the spatial distribution is referred to as the exclusion method, and entails distributing the stars according to a generating function, $g(\mathbf{x})$, which is everywhere greater than $n(\mathbf{x})$, and then randomly 'excluding' $(1-g/n)$ of the stars at $\mathbf{x}$. The generating function we adopt is simply the uniform distribution $g = \max(n(\mathbf{x}))$, the maximum of the stellar density in the volume.

For a catalogue defined by an apparent magnitude limit, the volume over which stars are distributed is dependent upon absorption. We avoid this complication by first distributing the stars with the assumption that $A_v = 0$; after this preliminary catalogue is constructed, an absorption model is applied to calculate the observed apparent magnitudes of the stars, and a magnitude cut applied.

Before distributing the stars uniformly in space we generate the distribution of absolute magnitudes, using the luminosity function of Scalo (1986). Having generated the luminosity distribution with the assumption of a uniform stellar density, we then distribute the stars accordingly; a star of absolute magnitude M is placed within a distance $D(M) = 10^{(m_C - M + 5)/5}$ of the Sun with a uniform probability per unit volume. Once the stars are so distributed the desired stellar density $n(\mathbf{x})$ is achieved by implementing the exclusion step described above.

Typically synthetic catalogues are generated using an axisymmetric model for the stellar distribution, following the lead of Bahcall & Soniera (1980). This assumption, sufficient for deep fields at high galactic latitudes dominated by older stars, is not appropriate for describing the distribution of our chosen sample of stars. Instead we adopt the non-axisymmetric distribution:

$$n(r, \phi) = n_\circ \sinh^2\left(\frac{z}{h}\right) \sum_{i=1,2} e^{-(r-R_i)^2/w_i^2} \ , \qquad (2)$$

R_1 and R_2 being the galactocentric distance to two spiral arm centers, defined as $R_i = R_{0i} \exp(-a\phi)$. The widths w_i are made to vary with azimuth: $w_i = w_{0i} \exp(-a\phi)$. This distribution is compared with that of a typical axisymmetric exponential disk in the following section. If a galactic warp is included z is replaced by $(z - Z_w)$ in the above formula.

After the stars are distributed in $(M, \mathbf{x})$ space an absorption model is used to calculate the apparent magnitude of the stars, and stars below the magnitude cut are then discarded. The absorption model that we adopt here is that of Spergel et al. (1997), which describes the dust distribution of the galaxy as an axisymmetric disk, whose parameters are determined from COBE data. The absorption is found for each star by integrating the dust density along the line of sight to the star.

2.2. Velocity Distribution

After the stars have been distributed in space, a velocity distribution model is applied. For this preliminary work we assume a linear function for the rotation curve of the Galaxy: $V_c = 220$ km s$^{-1} + c \times r$, where c is the slope of the rotation curve. Peculiar velocities V_p are based on the velocity ellipsoid prescription; the velocity dispersion in z is set to the solar neighbourhood value, $\sigma_z(R_\odot)$ and is not varied spatially, whereas the velocity dispersion in r and ϕ are varied according to: $\sigma^2 = \sigma_\odot^2 \exp\{(R_\odot - r)/\tau_r\}$.

The solar values for the velocity ellipsoid components were found from the observed data set (see next section). Each component of a star's peculiar velocity is determined by randomly sampling a normal (Gaussian) distribution whose standard deviation is equal to that component's velocity dispersion. After the peculiar motions are determined each synthetic star is given a circular velocity, consistent with V_c and the velocity dispersion model assumed above, by means of an axisymmetric drift equation derived from the collisionless Boltzmann equation.

If a systematic velocity $V_s(\mathbf{x})$ is desired, such as that due to a warp, then it can be added as an additional component of the motion. The final velocity of a star is then: $\mathbf{V}_* = \mathbf{V}_\theta + \mathbf{V}_s + \mathbf{V}_p$.

2.3. Observed Quantities

The spatial and velocity distributions are generated in galactocentric coordinates, then transformed into the physical quantities measured by the observer, i.e. heliocentric galactic coordinates and proper motions. Once this transformation is made a model of the significant observational errors existent in the observed catalogue is applied to the synthetic catalogue. Finally, any selections (cuts) made to define the observed catalogue, with respect to observed quantities, are likewise applied to the synthetic catalogue.

Our observed catalogue is a subset of the Hipparcos catalogue. Errors in the positions of the stars are neglected, as are the errors in measured apparent magnitudes. Our data set is partially defined using a measured parallax (see SDL), we therefore calculate a parallax for each star, add the estimated observational error of 1.2 mas, and keep those entries (synthetic stars) which satisfy the selection criterion $\pi \leq 2$ mas. We also add observational error to the proper motions. Our model for these errors are $\sigma_{\mu_b} = 0.8$ mas and $\sigma_{\mu_l} = 1.2$ mas $\times \cos$ b, which gives a satisfactory estimate for $b < 30$ degrees. These errors are based on the error estimates given by Mignard (1997). Photometric distances were also derived for our observed catalogue (see SDL) and the error of these distances are estimated as 20 per cent relative. An observed distance was generated for each synthetic star by adding such an error to the distances based on the generated positions.

The generation of a final synthetic catalogue entails several cuts: two cuts are made to generate the distribution in luminosity and in space, a cut is made after absorption is applied, and a cut based on observed parallax is made. As there is no way to know beforehand how many stars will be excluded in these cuts an iterative method is employed until the number of stars in the synthetic catalogue is greater than that in the data set, at which point excess stars are discarded.

3. COMPARISON WITH AN HIPPARCOS DATA SET

Here we compare an Hipparcos data set of OB stars with synthetic catalogues based on an unwarped Galactic model. The data set is a nearly complete sample of OB stars (894 with $m < 8$), and represents a subset of the entire dataset used by SDL. The values adopted for the model parameters, to which a galactic warp is added in SDL, are given in Tables 1 and 2. This model also serves as a control case to see what features are and are not explained by a galactic warp. In other words, this set of parameters are

Table 1. Spatial Parameters: those indicated with a dagger were not adjusted.

Sun's Coordinates:			
†distance to Galactic Center	$R_\odot$	8.	kpc
height above Galactic Plane	$z_\odot$	.02	kpc
Stellar Distribution:			
scale height	h	.09	kpc
distance to 1^{st} spiral arm	R_{01}	8.22	kpc
†distance to 2^{nd} spiral arm	R_{02}	9.72	kpc
width to 1^{st} spiral arm	w_{01}	.3	kpc
†width to 2^{st} spiral arm	w_{02}	.36	kpc
tangent of pitch angle	a	.277	
†scale length (axisymmetric case)	r_s	2.3	kpc

Table 2. Kinematic Parameters: those indicated with a dagger were not adjusted.

Solar Motion:	$U_\odot$	-9.0	km s^{-1}
	$V_\odot$	5.0	km s^{-1}
	$W_\odot$	7.0	km s^{-1}
velocity ellipsoid:	$\sigma_r(R_\odot)$	12.0	km s^{-1}
	$\sigma_\phi(R_\odot)$	10.0	km s^{-1}
	$\sigma_z(R_\odot)$	7.0	km s^{-1}
†LSR Velocity		220.0	km s^{-1}
dispersion scale length	τ_r	2.3	kpc^{-1}
slope of rotation curve	c	-3.0	km s^{-1} kpc^{-1}
ellipsoid tilt parameter	η	0.5	

found to produce synthetic catalogues as consistent with the selected OB stars from the Hipparcos catalogue as the assumption of no warp being present allows. Some of the parameters of the galactic model are taken from the literature, while the majority are the result of adjustment in an effort to reproduce features in the data set; the non-adjusted quantities are indicated in the Tables.

Rather than comparing the total distributions of particular observed quantities with the corresponding distributions in the synthetic catalogue, we show the mean variation of observed quantities across the defined 'field'. Because our field is not of telescopic dimensions we believe this is more meaningful, as a given observed quantity will significantly vary across the sky.

Figures 1 and 2 show how the number of stars varies across the field of the catalogue with respect to galactic longitude and latitude. These smoothed profiles are found by counting the number of stars within a moving bin. The distribution in latitude (Figure 2) is primarily determined by the scale height of the stars and the height of the Sun above the plane of the Galaxy, and is reproduced without difficulty by the program. In contrast, the distribution in longitude (Figure 1) shows clear evidence of the non-axisymmetric distribution of this population. In particular, the minimum in the number of the stars is offset from the anti-center direction, which is a natural consequence of a spiral arm, but can not be reproduced by an axisymmetric distribution. For comparison we show the profile of the number of stars that a typical axisymmetric exponential disk produces. While the minimum can be made smaller by decreasing the scale length of the disk, such a distribution will not produce an offset of the minimum. The parameters for the closest spiral arm were manually adjusted in an effort to produce the observed variation with longitude, while a second spiral arm with similar parameters was necessary to generate stars at large distances.

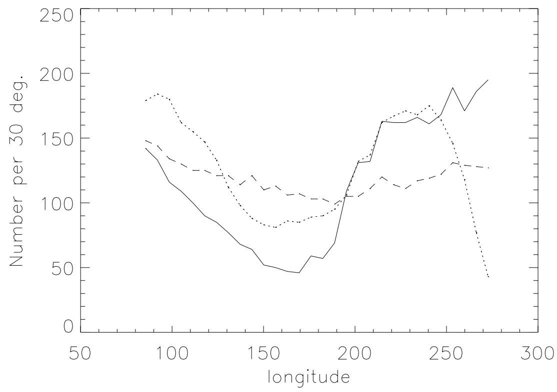

Figure 1. The number of stars in a 30 degree moving bin is shown for the data (solid line), and synthetic catalogues generated from a non-axisymmetric (dotted line) and axisymmetric (dashed line) stellar density distribution, the latter with an exponential scale length of 2.3 kpc.

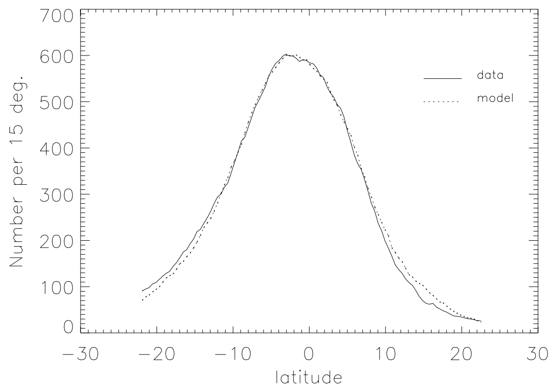

Figure 2. The distribution of stars with respect to latitude, calculated as in Figure 1, but with a 15 degree moving bin, for the data and a catalogue based on the non-axisymmetric model.

The variation of the proper motions, with respect to galactic longitude and latitude, we show in SDL (Figure 6). There we describe how the solar motion and slope of the rotation curve was arrived at using these distributions. We point out here, however, that our value for $V_\odot$, which deviates significantly from the traditional value, agrees well with other kinematic studies using Hipparcos stars (Binney et al. 1997, Upgren & Ratnutunga 1997). Here we show the distribution of the standard deviations of μ_l and μ_b with respect to l and b, which result from the velocity dispersions of this population (Figure 3). Matching these distributions entailed the adjustment of primarily the velocity dispersion components in

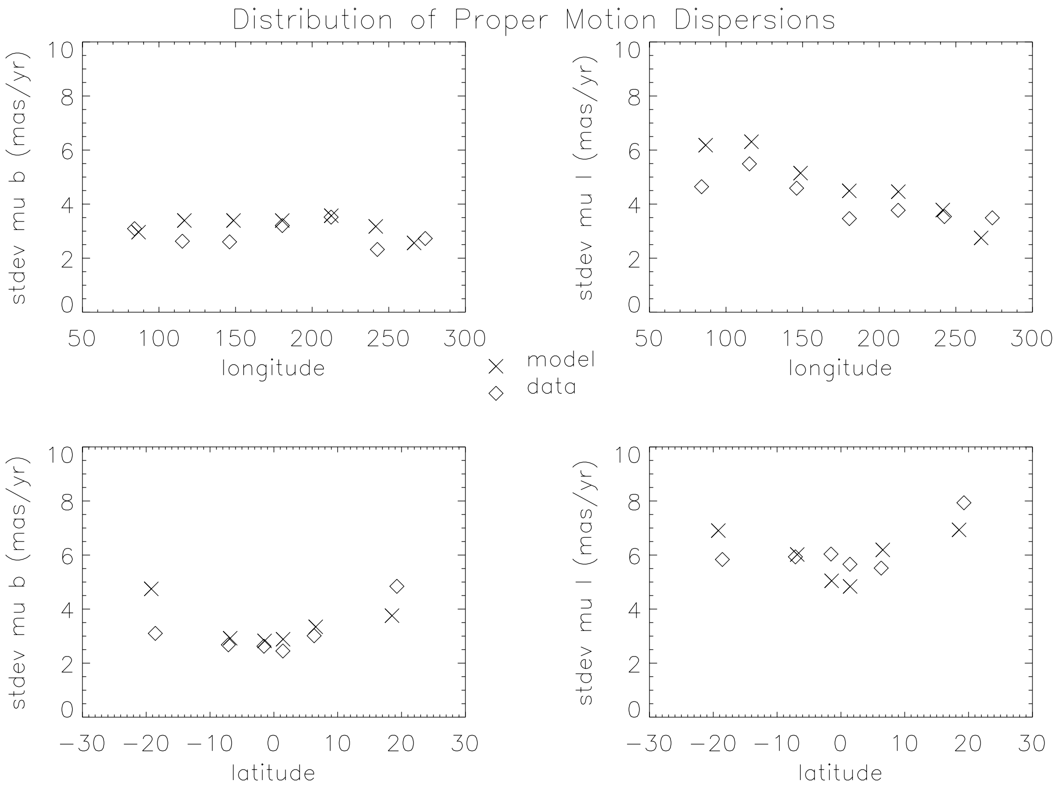

Figure 3. The distribution of the dispersion of the proper motion components, with respect to galactic longitude and latitude, for the data (diamonds) and a synthetic catalogue (X's).

the solar neighbourhood. Though the variation of the proper motion distribution with respect to galactic coordinates allows us to adjust various kinematic parameters, it is important to note that these distributions are also sensitive to the distribution of the stars across the sky, their distribution in distance.

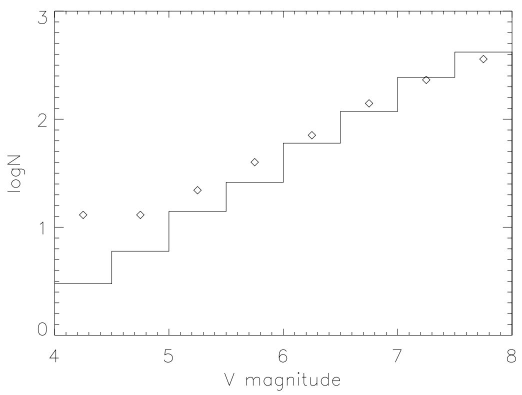

Figure 4. Apparent magnitude distribution for the data (diamonds) and a synthetic catalogue (histogram).

We also show, for general interest, the distribution in apparent magnitudes for a typical catalogue (Figure 4). This shows that our model underestimates the number of bright stars, while over estimating the number of faint stars. This is most likely due to an inadequacy in the absorption model, which will be improved by including non-axisymmetric structures in the dust distribution. That such an enhancement is necessary is shown both by the distribution of measured absorptions and the COBE IR data, which shows clear evidence of spiral structure in the longitude emission profiles at 240μ.

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