THE KINEMATICS OF MAIN-SEQUENCE STARS FROM HIPPARCOS DATA

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ABSTRACT

We analyze a kinematically unbiased sample of 5610 stars around the south celestial pole that (i) have MK spectral types in the Michigan catalogues with luminosity class V and (ii) had photometric parallaxes that placed them within 80 pc of the Sun. We bin the stars by $B-V$ and determine for each bin the solar motion from proper motions alone. As expected, the U and W components of the derived solar motions do not vary significantly from bin to bin, while the V component varies systematically. As the classic Strömberg relation predicts, V is a linear function of the variance S^2 within each bin around the solar motion. Extrapolating $V(S^2)$ to $S = 0$ we determine the solar motion with respect to the LSR, obtaining a significantly smaller value of V than is usually employed. Parenago's discontinuity in the dependence of S^2 on spectral type emerges with exceptional clarity.

Key words: Stars: main-sequence; Galactic Structure: solar motion.

1. INTRODUCTION

The kinematics of stars near the Sun has long been known to provide crucial information regarding both the structure and the evolution of the Milky Way. Karl Schwarzschild (1908) already interpreted the distribution of random velocities as forming a triaxial 'velocity ellipsoid', which Oort, B. Lindblad and Strömberg were able to relate to the large-scale structure of the disk. In the early 1950s Parenago (1950), Nancy Roman (1950, 1952) and others pointed out that stellar kinematics varies systematically with stellar type, in the sense that groups of stars that are on average younger have smaller velocity dispersions and larger mean Galactic rotation velocities than older stellar groups. Spitzer & Schwarzschild (1953), Barbanis & Woltjer (1967) and Wielen (1977) explained these correlations in terms of the diffusion of stars through phase space as the Galactic disk ages—for recent studies of these processes see Binney & Lacey (1988) and Jenkins (1992).

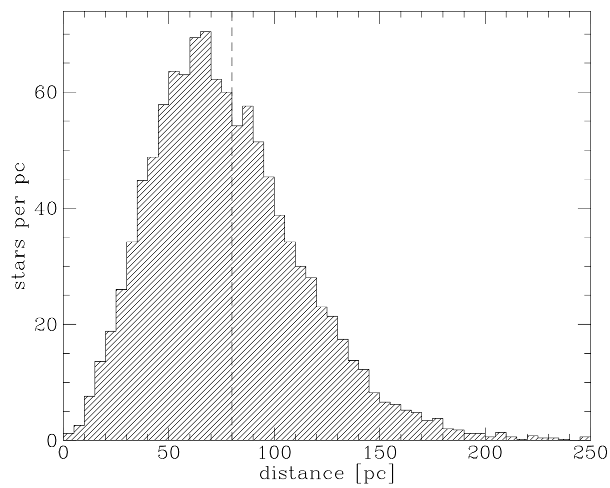

Figure 1. The distribution with respect to distance of the 5610 objects in the sample. 2384 of these have a distance > 80 pc.

The Hipparcos satellite provides an important opportunity to re-examine the fundamental data of solar-neighbourhood kinematics by providing the first all-sky catalogue of *absolute* parallaxes and proper motions. From the Hipparcos catalogue we can, moreover, extract samples of objects that are completely free of the kinematic biases that have plagued similar studies in the past. The present paper reports the analysis of one such kinematically unbiased sample. Other aspects are analysed by Murray et al (1997) and Houk et al. (1997).

2. THE SAMPLE

The sample is based on the first three volumes of the Michigan Spectral Catalogue (Houk & Cowley 1975, Houk 1978, Houk 1982), which provide two-dimensional MK classifications of stars in the Henry Draper Catalogue with declinations $\delta < -26°$. All stars of luminosity class IV-V and V were identified in

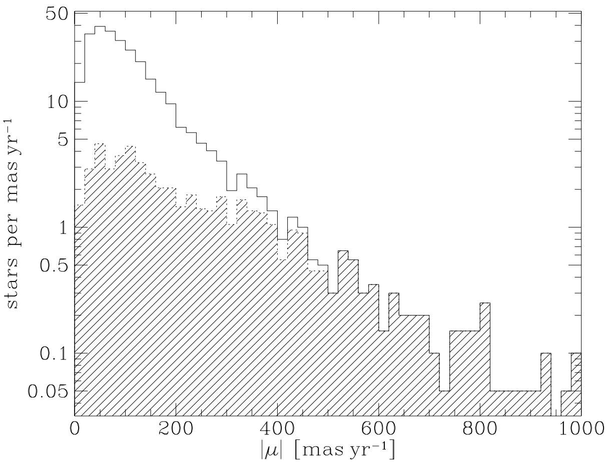

Figure 2. The distribution with respect to magnitude of proper motion of the 5610 stars in the sample (upper histogram) and of the 1072 sample stars for which radial velocities are available (shaded).

the Michigan Catalogue that were judged, from their apparent magnitudes and spectral classifications, to lie within 80 pc of the Sun. The great majority of these stars were brighter than $m = 10$ (see Figure 2 of Houk et al. 1997), and at $m = 9$ Hipparcos positions have a typical error of 1 mas. Hence Hipparcos could determine distances with negligible error for any programme star that actually lies within 80 pc.

Hipparcos measured the parallaxes and proper motions of the 6840 programme stars and showed that only 3091 of these stars actually lie within 80 pc—errors in photometric distance moduli resulted in roughly half the programme stars lying beyond the 80 pc cutoff (Murray et al. 1997). All but two of the 5612 stars that have distances accurate to better than 20 per cent belong to luminosity class V. In this study we analyse the kinematics of these 5610 class V stars. Figure 1 shows the distribution of their distances.

3. RADIAL VELOCITIES

For many studies it is of the greatest importance to have space velocities rather than merely the two components of a star's velocity on the sky. For this reason it was early on hoped that the Hipparcos mission would be accompanied by an international programme to determine the radial velocities of stars in the Hipparcos catalogue and we await with interest the publication of the results of the two survey programmes with the Coravel spectrometers (Mayor et al. 1997). For this work we were able to find a radial velocity for only one in five of our stars in either the Hipparcos Input Catalogue (Turon et al. 1993) or the catalogues of Barbier-Brossat et al. (1994) and Duflot et al. (1995) that are available in the CDS archive in Strasbourg. Figure 2 shows the distribution over proper motion μ of both stars in our sample (upper histogram) and the 1072 stars with radial velocities (shaded histogram). Clearly the probability that a randomly chosen star has a radial velocity increases strongly with its proper motion because high-proper motion stars are preferentially put on radial-velocity programmes. In the absence of precise knowledge of how stars with radial velocities have been selected, it is dangerous to employ *any* radial velocities in a study such as this. Thus, we feel obliged to discard the radial velocities that we do have and to work with proper motions alone. The unsatisfactoriness of this state of affairs cannot be too strongly emphasized.

4. THE SOLAR MOTION

Let the direction to the kth star be given by the unit vector $\hat{\boldsymbol{r}}_k$ and let the distance and proper motion of this star be denoted by d_k and $\boldsymbol{\mu}_k$, respectively. Then $\boldsymbol{\mu}_k$ is related to the space velocities $\boldsymbol{v}_k$ and $\boldsymbol{v}_\odot$ of the kth star and the Sun by:

$$d_k \boldsymbol{\mu}_k = \boldsymbol{A}_k \cdot (\boldsymbol{v}_k - \boldsymbol{v}_\odot) \tag{1}$$

where the matrix $\boldsymbol{A}_k \equiv \boldsymbol{I} - \hat{\boldsymbol{r}}_k \otimes \hat{\boldsymbol{r}}_k$ projects velocities onto the plane of the sky. The solar velocity relative to any given group of stars is defined to be the value of $\boldsymbol{v}_\odot$ that minimizes:

$$S^2 \equiv \left\langle \left| \boldsymbol{A} \cdot \boldsymbol{v} \right|^2 \right\rangle = \left\langle \left| d\boldsymbol{\mu} + \boldsymbol{A} \cdot \boldsymbol{v}_\odot \right|^2 \right\rangle \tag{2}$$

where $\langle\,\rangle$ denotes sample average. Indeed, in this frame we have $\langle \boldsymbol{A} \cdot \boldsymbol{v} \rangle = 0$, i.e. the stars have zero mean velocity. The solar motion in this frame and its variance[1] can be estimated as:

$$\boldsymbol{v}_\odot = -\langle \boldsymbol{A} \rangle^{-1} \cdot \langle d\boldsymbol{\mu} \rangle \tag{3}$$

$$\boldsymbol{V}(\boldsymbol{v}_\odot) = N^{-1} \langle \boldsymbol{A} \rangle^{-1} S^2 \tag{4}$$

where S^2 (Equation 2) is evaluated at $\boldsymbol{v}_\odot$ from (3). The variance of S^2 is estimated as:

$$V(S^2) = N^{-1} \left(\left\langle \left| d\boldsymbol{\mu} + \boldsymbol{A} \cdot \boldsymbol{v}_\odot \right|^4 \right\rangle - \left\langle \left| d\boldsymbol{\mu} + \boldsymbol{A} \cdot \boldsymbol{v}_\odot \right|^2 \right\rangle^2 \right) \tag{5}$$

again using $\boldsymbol{v}_\odot$ from (3).

The minimum value of S^2 is a measure of the velocity dispersion of the group. In fact, in the frame defined by Equation 3:

$$S^2 = \left\langle |\boldsymbol{v}|^2 \right\rangle - \left\langle (\boldsymbol{v} \cdot \hat{\boldsymbol{r}})^2 \right\rangle \tag{6}$$

so if the direction of the line of sight, $\hat{\boldsymbol{r}}_k$, did not vary significantly from star to star, S^2 would be the mean-square random velocity of the stars less the mean-square velocity parallel to $\hat{\boldsymbol{r}}_k$. Consider the case in which the velocity ellipsoid of the stars is aligned with the frame in which the x axis points towards the Galactic centre, the y axis points in the direction of Galactic rotation and the z axis points towards the north Galactic pole. Then at the centre of our field, $(\boldsymbol{v} \cdot \hat{\boldsymbol{r}})^2$ has an expectation value of

[1]The contribution of uncertainties in distance and proper motion of the individual stars in the sample is neglible compared to the Poisson noise due to the finite sample size.

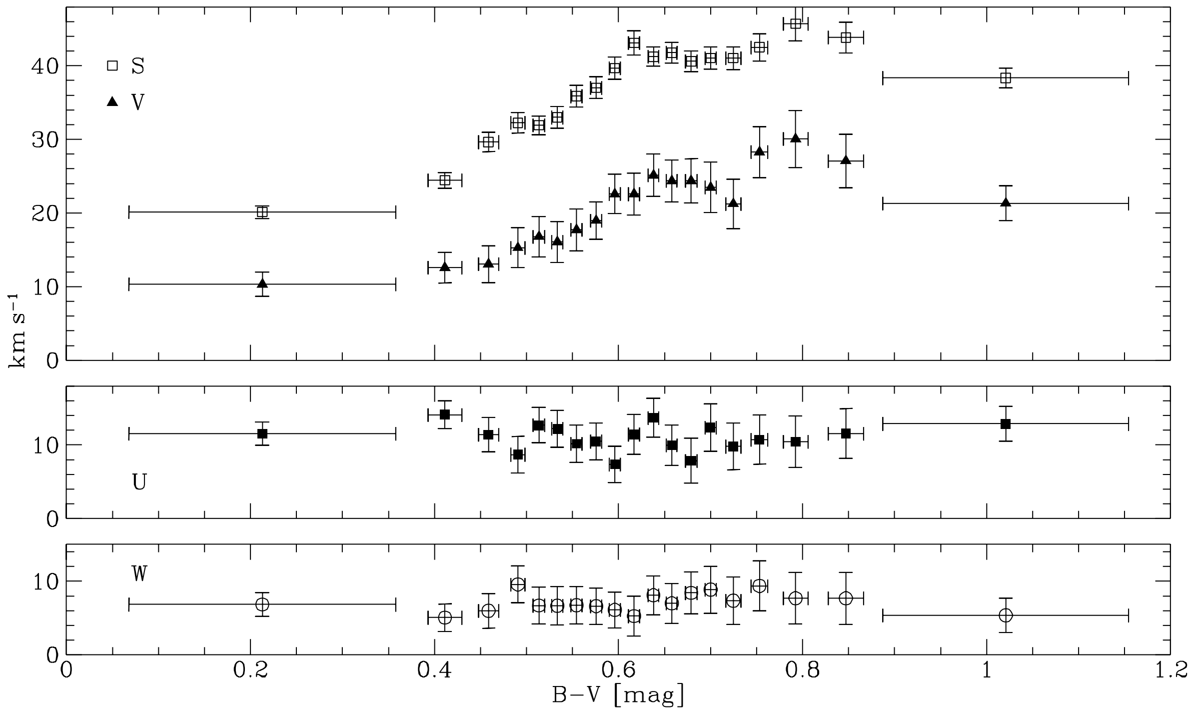

Figure 3. The variation with colour B–V of the components of solar motion U, V, W and of the dispersion S.

$0.23\,\sigma_x^2 + 0.55\,\sigma_y^2 + 0.21\,\sigma_z^2$, where σ_i^2 is the mean-square component of random velocity along the ith axis. Substituting this into Equation 6 we have:

$$S^2 = 0.77\,\sigma_x^2 + 0.45\,\sigma_y^2 + 0.79\,\sigma_z^2 \qquad (7)$$

Since our field has finite extent and the velocity ellipsoid is probably not perfectly aligned with the x, y, z frame, S^2 will in reality be a slightly different linear combination of velocity moments. But Equation 7 gives a useful idea of what S^2 is measuring.

Before applying our method, we have corrected the observed proper motions for galactic rotation using Feast & Whitelock's (1997) values for Oort's constants. In the solution for $\boldsymbol{v}_\odot$ (Equation 3) we have excluded outlying stars by an iterative process: at each solution we excluded any star that would have contributed to S^2 more than κ^2 times the previously obtained value of S^2, where κ ranged from 2.5 to 4. The results obtained prove to be only weakly sensitive to the value of κ. Below we cite results for $\kappa = 4$, when 12 stars of 5610 are excluded against an expected number of 0.35 for a Gaussian distribution of contributions to S^2.

Figure 3 shows the values of S and the components $U \equiv \boldsymbol{v}_\odot \cdot \hat{\boldsymbol{x}}$, $V \equiv \boldsymbol{v}_\odot \cdot \hat{\boldsymbol{y}}$ and $W \equiv \boldsymbol{v}_\odot \cdot \hat{\boldsymbol{z}}$ of the solar motion for our stars when they are grouped by $B - V$ colour. U and W do not vary significantly between groups, while both V and S increase systematically from early to late spectral types. The points for S display very beautifully Parenago's discontinuity: around $B - V \simeq 0.62$ there is an abrupt change in gradient from a strongly positive value to about zero (Parenago 1950). The same discontinuity is visible, though less clearly, in the data for V. Parenago's discontinuity is thought to arise from the fact that the mean age of stars decreases as one moves blueward of the discontinuity, while it is independent of colour redward of the discontinuity: scattering processes cause the random velocities of stars to increase steadily with age (e.g. Jenkins 1992). Hence velocity dispersion reflects age, and decreases as one moves blueward from the discontinuity through ever younger stellar groups, while remaining constant with mean age redward of the discontinuity. The discontinuity itself should occur at the colour for which the main-sequence lifetime of a star equals the age of the Galactic disk. However, since stars change colour during their life on the main sequence, detailed modelling of stellar populations is necessary, to infer the age of the stellar disk from this datum.

5. THE SUN'S VELOCITY W.R.T. THE LSR

Figure 4 is a plot of U, V and W versus S^2. This clearly shows the linear dependence of V on S^2 that is predicted by Strömberg's asymmetric drift equation (e.g. Equation 4-34 of Binney & Tremaine 1987). That is, V increases systematically with S^2 because the larger a stellar group's velocity dispersion is, the more slowly it rotates about the Galactic centre and the faster the Sun moves with respect to its lagging frame. The velocity (U_0, V_0, W_0) of the Sun with respect to the local standard of rest (the velocity of the closed orbit in the plane that passes through the location of the Sun) may be read off from Figure 4 by extrapolating any trends of U, V and W with S^2

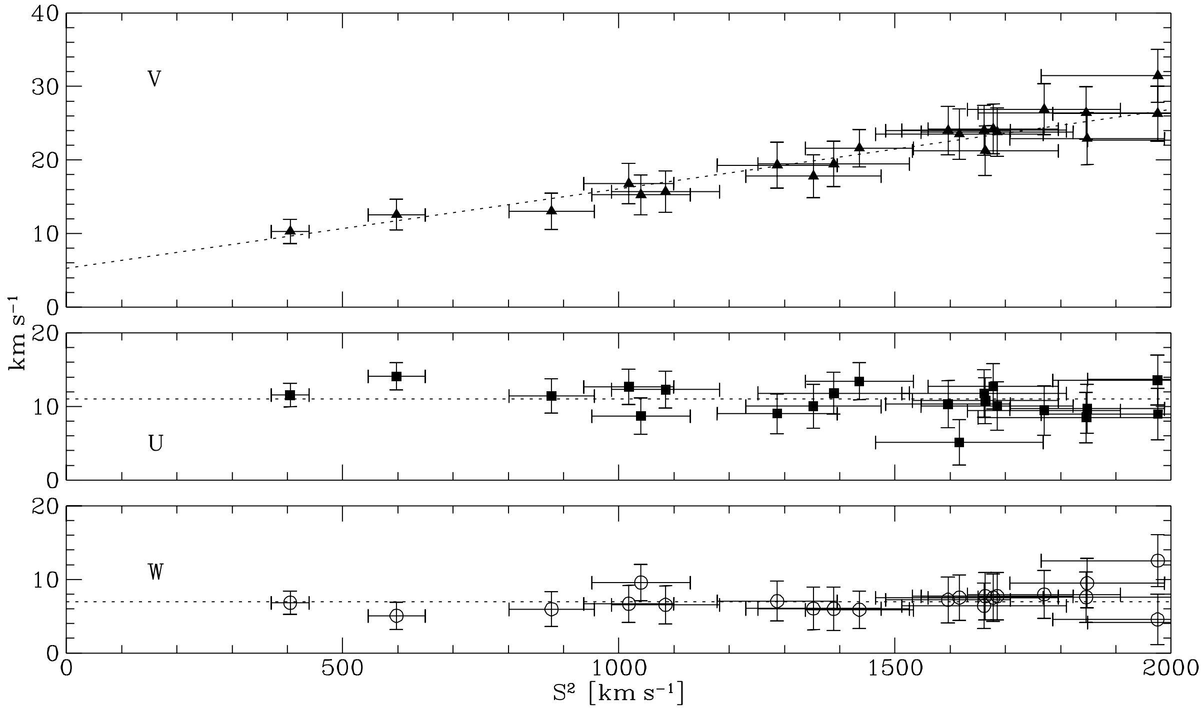

Figure 4. The dependence of U, V, W on S^2. The dotted lines correspond to the linear relation fitted (V) or the mean values (U and W).

back to $S = 0$. We find:

$$\begin{array}{rl} U_0 = & 11.0 \pm 0.6 \ \ \mathrm{km\,s^{-1}} \\ V_0 = & 5.3 \pm 1.7 \ \ \mathrm{km\,s^{-1}} \\ W_0 = & 7.0 \pm 0.6 \ \ \mathrm{km\,s^{-1}} \end{array} \qquad (8)$$

The quoted errors on U_0 and W_0 are smaller than that on V_0, because we have assumed that U and W are independent of $B - V$ such that no binning in colour was made. The signs of the components are such that the Sun is moving towards the Galactic centre, towards the North Galactic pole and currently lies inside the guiding centre of its epicyclic orbit.

The solar velocity (Equation 8) relative to the LSR may be compared with the classical value of Delhaye (1965) that is used in many studies: $(U_0, V_0, W_0) = (9, 12, 7)$ km s^{-1}. Clearly our value W_0 does not differ significantly from Delhaye's. Our values of U_0 and V_0 differ from Delhaye's values by 3σ and 4σ, respectively. Delhaye's result may have been affected by biases towards high proper motions in the catalogues he employed—such biases tend to exaggerate V_0. Several more recent determinations have, like us, derived smaller values of V_0 (Mayor 1974, Gómez & Mennessier 1977, Delhaye 1982, Oblak 1983, Bienaymé & Sechaud 1997).

6. CONCLUSIONS

We have used proper motions and parallaxes from the Hipparcos satellite to study the kinematics of a kinematically unbiased sample of main-sequence stars that lie south of declination $\delta = -26°$. When the stars are grouped by $B-V$, the random velocities within each group increase linearly from $B - V \simeq 0.4$ to $B - V \simeq 0.62$ and then are essentially independent of $B - V$ redward of $B - V \simeq 0.62$. Thus these data display very cleanly the classical Parenago discontinuity, which arises because the random velocities of stars increase steadily with time.

The values U and W of the solar motion relative to stars of different colours show no significant trends. Our mean value of W is in good agreement with earlier determinations of the Sun's velocity with respect to the Local Standard of Rest, while our mean value of U is marginally larger than Delhaye's (1965) mean value. Our values of V increase linearly with the mean-square random velocities S^2 of the groups, just as Strömberg's asymmetric drift equation predicts. Extrapolating the dependence of V upon S to $S = 0$ we derive a value of the Sun's tangential velocity with respect to the LSR, $V_0 = 5.2 \pm 1.7$ km s^{-1} that is smaller than Delhaye's classical (1965) value but in better agreement with several recent studies.

Our analysis is based on the very small subset of Hipparcos Catalogue to which we had privileged early access. When the catalogue is published in mid 1997 it will be possible to perform a much more satisfactory analysis. In particular, with all-sky coverage it will be possible to determine the shape and, possibly, the orientation of the velocity ellipsoid. We expect to report the results of such an analysis in the near future.

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