KINEMATICS AND M_V CALIBRATION OF K & M DWARF STARS USING HIPPARCOS DATA

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ABSTRACT

We present a new determination of the luminosities and kinematics of lower main sequence stars in the spectroscopically selected sample of Vyssotsky, covering spectral types from K3 to M5, using Hipparcos parallaxes and proper motions. The stars separate into two kinematically distinct components, which we label 'young' and 'old' disk. The young component has velocity dispersion (30, 17, 12) km s^{-1} in the UVW directions respectively, asymmetric drift of 8 km s^{-1}, a marginally significant vertex deviation of 10 deg ±3 deg, and absolute magnitude $M_V = 10.48$ at color $(R-I)_{\rm Kron} = 1.0$ mag. The old component has velocity dispersions (56, 34, 31) km s^{-1}, asymmetric drift 28 km/s, and absolute magnitude 0.6 mag fainter at the same color. The slope and intrinsic width of the magnitude calibration of each component are also determined. All results are in agreement with previous determinations using ground-based data, but the errors are considerably smaller.

The analysis is also used to investigate the possible presence of residual systematic discrepancies of the model with Hipparcos observations. There is some indication of a possible underestimate of the parallax errors, but the sample used here is too small for a positive determination.

Key words: celestial mechanics; stellar dynamics; stars, late-type; maximum likelihood.

1. INTRODUCTION

We present an analysis of the Hipparcos parallaxes and proper motions for the Vyssotsky sample of 895 K and M dwarfs, with photoelectric BVRI photometry by Weis & Upgren (1995). This analysis follows closely that of ground-based data for the same sample by Ratnatunga & Upgren (1997), where a detailed description of the Vyssotsky catalogue and of our method can be found. Hipparcos parallaxes and proper motions for 849 stars in the Vyssotsky sample were provided to A.R.U. under the Hipparcos proposal 191.

The analysis excludes both known spectroscopic binaries and those stars flagged as potential binaries in the Hipparcos solution (flag H59 set, or flag H61 set to S). Stars with multiple components separated by less than 5 arcsec were also excluded because of potential problems with the ground-based photometry. In total, we consider 577 stars, 345 of which have an observed radial velocity as well. As these K and M dwarfs are all within about 50 pc, we neglect interstellar absorption and assume that the density distribution is constant within this volume.

The essence of the maximum likelihood procedure used here (and in Ratnatunga & Upgren 1997) is to define a model of the stellar population under examination, and vary its parameters so as to optimize the probability of its observed realization, the actual data. Conditional probabilities are used to overcome possible systematic incompleteness in the sample, following Casertano et al. (1990).

The population of K and M dwarfs is described as a sum of components, each defined by its kinematics, a trivariate velocity ellipsoid plus the asymmetric drift, and its luminosity calibration, represented by a linear color-absolute magnitude relation with a cosmic dispersion assumed to be Gaussian. We also solve for the U and W motion of the Sun, while the V motion is inferred by assuming the asymmetric drift found for each component to be proportional to σ_R^2. Additional parameters tested for are a vertex deviation for each component and systematic properties of the parallax observations and error estimates.

2. RESULTS

The population of K and M dwarfs identified by Vyssotsky is successfully modeled by two separate components with distinct kinematics and luminosity properties. The bright, low-velocity dispersion component represents the 'young' disk population, while the faint, high-velocity component represents an 'old' disk population, probably akin to the thick disk. For both components, the absolute magnitude can be expressed as a linear function of color (see Figure 1) in the range $0.35 < (R-I)_{\rm Kron} < 1.30$ mag, with a modest cosmic dispersion of few tenths of a magnitude. The cosmic dispersion is also well constrained by the fit.

The parameters of the young component are:

$$M_V = (10.48 \pm 0.04) + (5.76 \pm 0.08)(R - I - 1)$$

$$\sigma_{md} = 0.21 \pm 0.02\,\mathrm{mag}$$

$$(\sigma_R, \sigma_\phi, \sigma_z) = (30.2{\pm}1.8, 17.3{\pm}0.9, 11.9{\pm}0.7)\ \mathrm{km\ s^{-1}}$$

$$v_a = 8.2 \pm 1.2\ \ \mathrm{km\ s^{-1}}\ ,$$

where M_V is the absolute magnitude, σ_{md} the cosmic (magnitude) dispersion, $(\sigma_R, \sigma_\phi, \sigma_z)$ the principal components of the velocity dispersion, and v_a the asymmetric drift. This component shows a small vertex deviation of 9.7 ± 3.4 degrees. This is probably a sign that the component has yet to relax kinematically, and thus additional evidence of its relative youth.

The faint, high-velocity dispersion component represents an 'old' disk population, with parameters:

$$M_V = (11.08 \pm 0.02) + (6.79 \pm 0.06)(R - I - 1)$$

$$\sigma_{md} = 0.27 \pm 0.03\,\mathrm{mag}$$

$$(\sigma_R, \sigma_\phi, \sigma_z) = (56.1{\pm}3.9, 34.2{\pm}2.5, 31.2{\pm}2.5)\ \mathrm{km\ s^{-1}}$$

$$v_a = 28.3 \pm 3.8\ \mathrm{km\ s^{-1}}\ .$$

This component is 0.60 mag fainter than the younger component at the reference color $(R-I)_{\rm Kron} =$ 1.0 mag, has a somewhat steeper slope of the magnitude-color relation, and has a velocity dispersion typical of the Sandage & Fouts (1987) thick disk, corresponding to a typical metallicity [Fe/H] ~ -0.7 (Bell 1996).

The motion of the local standard of rest (LSR) is determined by assuming that the two components have zero mean motion relative to the LSR in the U and W directions, and that the asymmetric drift is proportional to the square of the radial velocity dispersions. With these assumptions, we find the peculiar motion of the Sun relative to the LSR as follows:

$$(U_\odot, V_\odot, W_\odot) = (9.5{\pm}1.5, 7.3{\pm}2.5, 6.8{\pm}0.7)\ \ \mathrm{km\ s^{-1}}.$$

All errors quoted are standard deviations determined by the fitting procedure; they have been shown by Monte Carlo simulations to be internally consistent (Ratnatunga & Casertano 1991). However, the error estimates are purely internal to the assumed model; a change in the descriptions of the components can result in different parameters.

We have also attempted fits with a third independent component. These fits converge to a third component with velocity dispersions slightly different from the young disk. At this stage the third component does not appear to improve the description of the Galaxy, and therefore we have chosen not to include it in our results.

3. SYSTEMATIC PROPERTIES OF THE HIPPARCOS DATA

One of the features of the maximum likelihood method, as applied here, is that it is possible to carry out consistency tests for the data themselves. Of course, the validity of these tests depends on the validity of the model used; any inconsistency found could represent a limitation in either the model or the data. Yet this approach can provide a type of data verification that would not be available otherwise, and that has proven useful in the past. For example, Ratnatunga & Upgren (1997), using exclusively ground-based astrometric measurements for a sample similar to the current one, were able to identify a mean zero-point shift of 3 ± 1.3 mas for the parallax scale, and a mean 20 per cent underestimate for the internal parallax errors in the Yale Parallax catalogue (van Altena et al. 1995).

The same test carried out on the Hipparcos data finds no zero-point error in the parallaxes, within our uncertainty of 0.5 mas. However, we do find some evidence for an average underestimate of $40{\pm}14$ per cent in the parallax errors quoted in the Hipparcos Catalogue for the stars in our sample. Specifically, we have carried out our maximum likelihood optimization under the assumption that the parallax errors were larger than the catalogue values by a constant factor r_σ. The result of the optimization is that $r_\sigma = 1.40 \pm 0.14$. The quality of the fit with this additional parameter is improved with a formal 96 per cent significance. None of the other fitted parameters is changed significantly; the values reported in the previous section are for the fit that includes r_σ.

We emphasize that it would be premature to interpret this result to indicate that the Hipparcos parallax errors are really underestimated by this amount. First, other methods mentioned in Volume 3, Chapter 20 of the Hipparcos Catalogue (ESA 1997) appear to indicate that the parallax errors are properly estimated, at least for very distant stars. Second, the sample tested by us is a very small fraction of the full catalogue, and the effect is of marginal significance—less than 3σ. Third, and more important, deviations from our simple model could well give a false indication of underestimated parallax errors, and remain otherwise undetected in our small sample; such deviations could include a non-Gaussian cosmic dispersion in luminosity at a given color, undetected photometric binaries, and other kinematic and luminosity components.

It will be especially worthwhile to apply our method to the sample of stars of spectral class A and B in the Hipparcos Catalogue. This constitutes a more homogeneous sample, and intrinsically small parallaxes of these stars better lend themselves to a systematic study of the parallax error. If confirmed, a 40 per cent underestimate of the parallax error could lead to errors of 0.1–0.2 mag in the distance estimates for stars with parallax errors of 5–10 per cent.

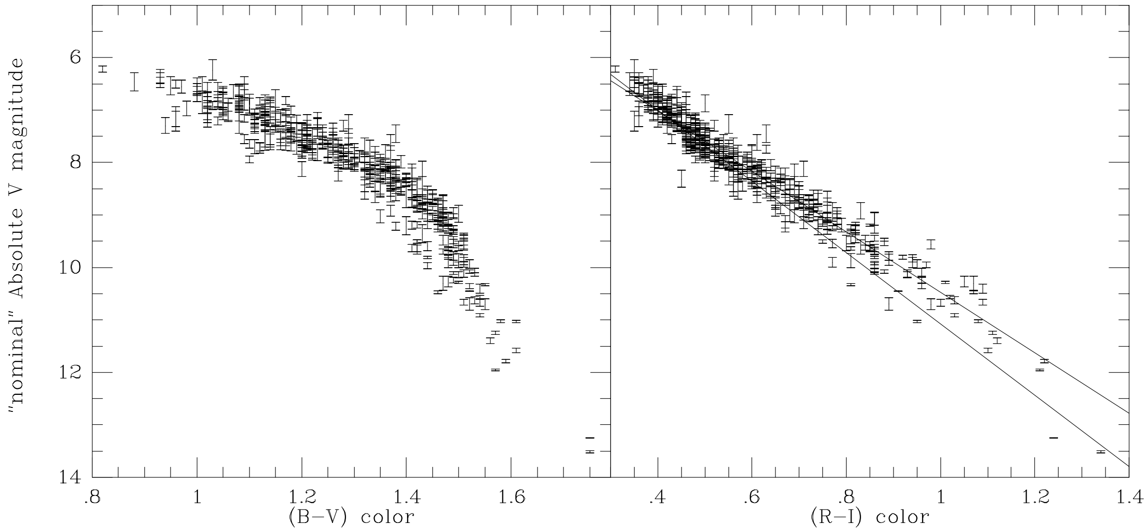

Figure 1. The 'nominal' absolute magnitude derived from the 'best' Hipparcos parallaxes, those with fractional error <10 per cent, against both $(B-V)$ and $(R-I)_{\mathrm{Kron}}$ color. We use primarily the $(R-I)_{\mathrm{Kron}}$ color because its relation to absolute magnitude is very close to linear in this range.

4. IMPLICATIONS FOR THE DISTANCE SCALE

In principle, the subdwarf luminosity scale can be used to determine the distance to globular clusters, and thus obtain information on their age and the global distance scale, by main-sequence fitting. This method has been recently used by Reid (1997) and Gratton et al. (1997) to determine the distance to low- and intermediate-metallicity globular clusters, respectively.

If, as the kinematics indicate, our old component is indeed representative of the thick disk, with average metallicity [Fe/H] ~ -0.7, then the main sequence we derive should be a very good match to that of 47 Tucanae, with a metallicity of -0.73 (Hesser et al. 1987; Gratton et al. 1997). Using the Hesser et al. (1987) photometry, the apparent magnitude of the main sequence of 47 Tucanae is $V = 21.15 \pm 0.02$ mag at $(B-V) = 1.1$ mag. Rather than transforming our luminosity calibration to Johnson BV, we obtained a luminosity calibration directly in terms of B and V for the blue part of our sample ($B-V < 1.3$ mag), and derived an absolute magnitude for the old component of $M_V = 7.40 \pm 0.05$ mag at that color, resulting in a distance modulus of 13.75 ± 0.05 mag. This would place the horizontal branch of 47 Tucanae at $M_V = 0.35 \pm 0.05$ mag, significantly brighter than the usually accepted value of 0.6 mag.

However, because of the method used in our work, it is possible that the effective metallicity corresponding to our luminosity calibration could be somewhat higher, up to -0.5 dex; this would imply a luminosity calibration at the metallicity of 47 Tucanae fainter by about 0.1–0.2 mag. If this were the case, the estimated distance modulus for 47 Tucanae would be 13.6 ± 0.15 mag, and the horizontal branch would have $M_V = 0.5 \pm 0.15$ mag, close to the canonical value. Obviously, the effect of the uncertainty in the metallicity of our sample is very significant at this level.

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