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Local stellar kinematics from RAVE data – I. Local standard of rest

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ABSTRACT

We analyse a sample of 82 850 stars from the RAdial Velocity Experiment (RAVE) survey, with well-determined velocities and stellar parameters, to isolate a sample of 18 026 high-probability thin-disc dwarfs within 600 pc of the Sun. We derive space motions for these stars, and deduce the solar space velocity with respect to the local standard of rest. The peculiar solar motion we derive is in excellent agreement in radial $U_{\odot}$ and vertical $W_{\odot}$ peculiar motions with other recent determinations. Our derived tangential peculiar velocity, $V_{\odot}$, agrees with very recent determinations, which favour values near 13 km s^{-1}, in disagreement with earlier studies. The derived values are not significantly dependent on the comparison sample chosen, or on the method of analysis. The local Galaxy seems very well dynamically relaxed, in a near symmetric potential.

Key words: Galaxy: kinematics and dynamics – solar neighbourhood – Galaxy: stellar content.

1 INTRODUCTION

The kinematics of stars near the Sun provide vital information regarding the structure and the evolution of the Galaxy. Since the observations are relative to the Sun, which is not stationary, the kinematical parameters we obtain need to be corrected accordingly to the local standard of rest (LSR), which is defined as the rest frame of a star at the location of the Sun that would be on a circular orbit in the gravitational potential of the Galaxy. This implies the determination of the solar peculiar velocity components relative to that standard, $U_{\odot}$, $V_{\odot}$ and $W_{\odot}$. These values are also of considerable intrinsic interest, as their determination as a function of the spatial distribution and kinematic properties of the comparison stellar sample is a test of the symmetry of the local Galactic potential as a function of, for example, velocity dispersion. One can test if thin disc slowly moving stars are, or are not, affected by a Galactic bar, among many other considerations. Uncertainty in the solar

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Table 1. Space velocity components of the Sun with respect to the LSR as given in the literature.

Reference	Source	$U_\odot$ (km s^{-1})	$V_\odot$ (km s^{-1})	$W_\odot$ (km s^{-1})
This study (2010)	RAVE DR3	8.50 ± 0.29	13.38 ± 0.43	6.49 ± 0.26
Bobylev & Bajkova (2010)	Masers	5.5 ± 2.2	11.0 ± 1.7	8.5 ± 1.2
Breddels et al. (2010)	RAVE DR2	12.0 ± 0.6	20.4 ± 0.5	7.8 ± 0.3
Schönrich et al. (2010)	*Hipparcos*	11.10 ± 0.72	12.24 ± 0.47	7.25 ± 0.36
Francis & Anderson (2009)	*Hipparcos*	7.5 ± 1.0	13.5 ± 0.3	6.8 ± 0.1
Veltz et al. (2008)	RAVE DR1	8.5 ± 0.3	–	11.1 ± 1.0
Bobylev & Bajkova (2007)	F and G dwarfs	8.7 ± 0.5	6.2 ± 2.2	7.2 ± 0.8
Piskunov et al. (2006)	Open clusters	9.44 ± 1.14	11.90 ± 0.72	7.20 ± 0.42
Mignard (2000)	K0−K5	9.88	14.19	7.76
Dehnen & Binney (1998)	*Hipparcos*, $d_{\rm max} = 100$ pc	10.00 ± 0.36	5.25 ± 0.62	7.17 ± 0.38
Binney et al. (1997)	Stars near South Celestial Pole	11 ± 0.6	5.3 ± 1.7	7.0 ± 0.6
Mihalas & Binney (1981)	Galactic Astronomy Second Edn.	9.2 ± 0.3	12.0	6.9 ± 0.2
Homann (1886)	Solar neighbourhood stars	17.4 ± 11.2	16.9 ± 10.9	3.6 ± 2.3

kinematic parameters can have profound implications for Galactic structural analyses (cf. e.g. McMillan & Binney 2010) and may be affected systematically in turn by presumptions about larger scale Galactic stellar populations (cf. e.g. Schönrich, Binney & Dehnen 2010). There have been several very recent determinations of the solar peculiar velocity, including some using RAdial Velocity Experiment (RAVE; Steinmetz et al. 2006, see also Section 2) data as we use here (e.g. Pasetto, Grebel & Bienaymé 2010). A summarized list of recent determinations of the space velocity components of the Sun appearing in the literature is given in Table 1, while Francis & Anderson (2009) provide an even longer list of references. Given the astrophysical significance of systematic sample- and method-dependent effects in the determination, we consider here a further determination of the solar space velocity, using a complementary technique.

The determination of the solar space motion relative to a LSR is a long-standing challenge. The robust determination of the systematic motion of some stellar population relative to some agreed LSR would itself be of considerable interest. Hence many studies have been carried out since that of Homann (1886) to estimate these parameters. However, there is still uncertainty about the numerical values of the solar velocity components, relative to local thin-disc stars, especially for the $V_\odot$ component, due to the complexity involved in compensating for the velocity 'lag' of sample stars. The difference between the results of different researchers originates from different data as well as different procedures used. The very different results derived by Dehnen & Binney (1998) and Schönrich et al. (2010), both of whom who used the *Hipparcos* data, are an illustration of the continuing model-dependence of the result.

The radial ($U_\odot$) and vertical ($W_\odot$) components of the solar motion, as a function of the relevant stellar population, can be obtained in principle by direct analysis of the mean heliocentric velocities of solar neighbourhood stars, subject to appropriate sample selection. As one can see in Table 1, the various determinations are in tolerable agreement. However, the determination of the component in the direction of Galactic rotation ($V_\odot$) is complicated by systematics: the mean lag, i.e. asymmetric drift $V_{\rm a}$, with respect to the LSR which depends on the velocity dispersion (σ) of the stellar sample in question. An extensive discussion of the radial Jeans' equation on which analysis of the asymmetric drift is based, including its derivation, relevant approximations and applications, can be found in Gilmore, Wyse & Kuijken (1989). At its simplest, a single population asymmetric drift/Jeans' analysis assumes a linear relation between (suitable values of) the asymmetric drift $V_{\rm a}$ of any stellar sample and its squared radial velocity dispersion $\sigma_{\rm R}^2$ (Strömberg 1946). Formal least-squares straight line fits intercept the $V_{\rm a}$ axis at some negative value, typically in the range −20 to $-5\,{\rm km\,s^{-1}}$. This $V_{\rm a}$ intercept determines the solar velocity $V_\odot$ using the equation $\bar{V}_{\rm s} = V_{\rm a} + V_\odot$. $\bar{V}_{\rm s}$ is the negative mean heliocentric azimuthal velocity of any stellar sample. The value $V_\odot = 5.25 \pm 0.62\,{\rm km\,s^{-1}}$ of Dehnen & Binney (1998, hereafter DB98) is typical of the smaller values deduced recently from this procedure.

However, four other recent studies argue for larger values of $V_\odot$ than that of DB98. Piskunov et al. (2006) determined a value different from that of DB98 by about $7\,{\rm km\,s^{-1}}$ in the V component of the solar motion, when determined with respect to open clusters in the solar neighbourhood. Binney (2010) fitted distribution function models to two sets of velocity distributions and obtained a difference of about $6\,{\rm km\,s^{-1}}$ compared to the value of DB98. This higher value of $V_\odot$ has been confirmed by Reid et al. (2009) and Rygl et al. (2010) in their works related to radio frequency astrometry of masers in regions of massive star formation (though see McMillan & Binney 2010, for a different analysis). Schönrich et al. (2010) applied a particular chemodynamical model of the Galaxy to DB98's data and determined a value for the $V_\odot$ solar velocity component consistent with recent high values. The key factor in the Schönrich et al. (2010) analysis, and of others, is the relevant range of radial velocity dispersions $\sigma_{\rm R}^2$ which is used in the Jeans' analysis. Schönrich et al. (2010) showed that for $\sigma_{\rm R}^2 \geq 600$ (km s^{-1})^2 the *Hipparcos* data define a straight line, whereas for $\sigma_{\rm R}^2 \leq 400$ (km s^{-1})^2 they deviate from such a simple fit. If one omits stars with low dispersions, and extrapolates the linear fit for stars with high dispersion to zero, the linear fit for stars with high dispersions, one confirms the low value of DB98. Actually, this is the procedure used by DB98, who also ignored stars with low velocity dispersion due to their probable lack of dynamical equilibrium. While it is true that low velocity dispersion stars are likely to be most affected by the effects of dissolving star clusters and the non-axisymmetric gravitational potential of spiral arms, one does need to consider carefully the offset character of the relation between $V_{\rm a}$ and $\sigma_{\rm R}^2$ at low velocity dispersions to avoid bias.

Here we use a new sample of stars and a different methodology to re-estimate the $U_\odot$, $V_\odot$ and $W_\odot$ solar velocity components. (1) We use RAVE data extending to larger distances than the *Hipparcos* sample. (2) We applied the following constraints to obtain a sample of main-sequence stars: (i) we selected stars with surface gravity

$4 < \log g < 5$; (ii) we omitted stars with $(J - H)_0 < 0.05$ and $(J - H)_0 > 0.55$ to avoid the blue horizontal branch and possible red giant stars; (iii) we excluded stars with space velocity errors larger than $25\,\mathrm{km\,s^{-1}}$ and (iv) we separated stars into populations (see Section 5), and we used the thin-disc population which is not contaminated by thick disc/halo as a preferred sample in our work. The last constraint is especially important in estimating $V_{\odot}$, because it excludes thick-disc and halo stars which have relatively large asymmetric drift. Thus, it limits the range of V velocity component, which in turn minimizes possible astrophysical large-scale dynamical asymmetry effects.

The RAVE survey is described in Section 2, the data are presented in Section 3, Sections 4 and 5 are devoted to kinematics and population analysis, respectively. The results are given in Section 6 and finally a discussion is presented in Section 7.

2 RAVE

The RAVE (Steinmetz et al. 2006) is a spectroscopic survey aiming to measure radial velocities and stellar atmospheric parameters, temperature, metallicity, surface gravity, of up to one million stars using the 6 degree Field (6dF) multi-object spectrograph on the 1.2 m UK Schmidt Telescope of the Australian Astronomical Observatory. The RAVE programme started in 2003, obtaining medium resolution spectra in the Ca-triplet region (8410–8795 Å) for Southern hemisphere stars in the magnitude range $9 < I_{\mathrm{DENIS}} < 13$. The scientific goals of RAVE include analysing the chemical and dynamical evolution of the Galaxy, using both dwarfs and giants observed locally. The main-sequence stars occupy a region extending to a distance of a few hundred parsecs, whereas giants extend up to a few kpc. RAVE was designed to avoid high reddening in the Galactic plane and contamination from the bulge, i.e. $|b| > 5^{\circ}$ and $l < 315^{\circ}$ constraints are applied when selecting programme stars.

RAVE is a precursor of the spectroscopic part of the cornerstone mission *Gaia* of the European Space Agency. The wavelength range for RAVE spectra was chosen to match that of the *Gaia* Radial Velocity Spectrometer (Munari 2003; Katz et al. 2004; Wilkinson et al. 2005), i.e. around the Ca II IR triplet. This wavelength range also includes lines from elements such as Fe, Ca, Si, Mg and Ti which can be used to estimate [α/Fe] in addition to overall metallicity (see Steinmetz et al. 2006, for a more detailed description of the goals of RAVE).

3 DATA

The data used in this study are a working version of what will become RAVE's third data release (DR3; Siebert et al., in preparation). DR3 will consist of 82 850 stars, each with equatorial and Galactic coordinates, radial velocity, metallicity, surface temperature and surface gravity. We also note the two existing data releases, i.e. DR1 (Steinmetz et al. 2006), DR2 (Zwitter et al. 2008). Proper motions were compiled from several catalogues: *Tycho-2*, Supercosmos Sky Survey, Catalog of Positions and Proper Motions on the ICRS (PPMXL) and USNO CCD Astrograph Catalog 2 (UCAC-2). Proper motion accuracy decreases in this order, therefore, if proper motions were available from all catalogues, *Tycho-2*'s value was used. If *Tycho-2* did not provide proper motions, then the values were taken from the Supercosmos Sky Survey, etc. Photometric data are based on optical and near-IR (NIR) systems. The magnitudes of stars were obtained by matching RAVE DR3 with *Tycho-2*, USNO-B, DENIS and Two Micron All Sky Survey (2MASS) catalogues. The analysis here uses stars in RAVE DR3 with 2MASS catalogue photometry.

3.1 Main-sequence stars and distance determination

We applied two constraints to obtain a main-sequence sample: we selected stars with surface gravities $4 < \log g < 5$, and we excluded stars with $(J - H)_0 < 0.05$ and $(J - H)_0 > 0.55$. The second constraint is especially effective in reducing the contamination due to blue horizontal branch and possible red giant stars. Thus, the sample was reduced to 21 310 stars. The $(J - H)_0$– $(H - K_s)_0$ two colour diagram of the parent sample (Fig. 1a) has a bimodal distribution, confirming the presence of K and M giants in addition to the F–M dwarfs, whereas the sample obtained after applying the two constraints cited, shown in Fig. 1(b), has only one mode indicating a pure main-sequence sample.

Contrary to the *Hipparcos* catalogue, parallaxes are not available for stars observed in the RAVE survey, but not existing in the *Hipparcos* survey. Hence, the distances of the main-sequence stars were calculated using another procedure. We applied the main sequence colour–luminosity relation of Bilir et al. (2008), which, as described in that reference, is valid in the absolute magnitude range $0 < M_J < 6$. The errors of the distances were estimated combining the internal errors of the coefficients of Bilir et al. (2008) equation and the errors of the 2MASS colour indices.

As most of the stars in the sample are at distances larger than 100 pc, their colours and magnitudes will be affected by interstellar reddening. Hence, distance determination is carried out simultaneously with dereddening of the sample stars. As the first step in

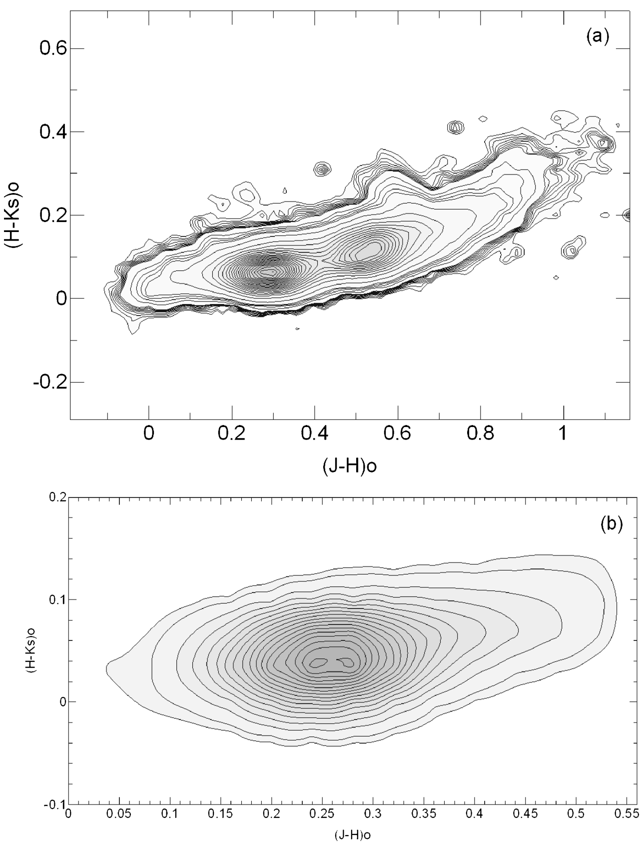

Figure 1. Two colour diagrams for two samples of RAVE DR3 stars: (a) for the original sample (main-sequence stars and giants); (b) for main-sequence stars only.

an iterative process, we assume the original $(J - H)$ and $(H - K_s)$ colour indices are dereddened, and evaluate the M_J absolute magnitudes of the sample stars by means of the colour–luminosity relation of Bilir et al. (2008). Combination of the apparent and absolute magnitudes for the J band gives the distance d of a star. We used the maps of Schlegel, Finkbeiner & Davis (1998) and evaluated the colour excess $E_\infty(B - V)$ for each sample star. The relation between the total and selective absorptions in the UBV system, i.e.

$$A_\infty(b) = 3.1 E_\infty(B - V) \tag{1}$$

gives $A_\infty(b)$ which can be used in evaluating $A_d(b)$ using Bahcall & Soneira (1980) procedure:

$$A_{\rm d}(b) = A_\infty(b)\left[1 - \exp\left(\frac{-|d\ \sin(b)|}{H}\right)\right], \tag{2}$$

where b and d are the Galactic latitude and distance of the star, respectively. H is the scaleheight for the interstellar dust which is adopted as 125 pc (Marshall et al. 2006), and $A_\infty(b)$ and $A_{\rm d}(b)$ are the total absorptions for the model and for the distance to the star, respectively. Then, the colour excess at the distance of the star, $E_{\rm d}(B - V)$, can be evaluated using a specific form of equation (1):

$$A_{\rm d}(b) = 3.1 E_{\rm d}(B - V). \tag{3}$$

That value was used in Fiorucci & Munari (2003) equations to obtain the total absorptions for the J, H and $K_{\rm s}$ bands, i.e. $A_J = 0.887 \times E(B - V)$, $A_H = 0.565 \times E(B - V)$ and $A_{K_{\rm s}} = 0.382 \times E(B - V)$, which were used in Pogson's equation ($m_i - M_i = 5 \log d - 5 + A_i$; here i denotes a specific band) to evaluate distances. Contrary to the assumption above, the original $(J - H)$ and $(H - K_{\rm s})$ colour indices are not dereddened. Hence, the application of the equations (1) to (3) is iterated until the distance d and colour index $E_{\rm d}(B - V)$ approach constant values.

Our resulting distribution of $E(B - V)$ reddening for our 21 310 RAVE main-sequence stars in the X–Y Galactic plane is given in Fig. 2. To analyse the reddening in the solar neighbourhood more accurately, we divided the stars into three subsamples according to their Galactic latitude: Fig. 2(a) shows the stars with $|b| \leq 30°$, in Fig. 2(b) the stars with $30° < |b| \leq 60°$ are shown, whereas Fig. 2(c) gives the stars with $|b| > 60°$. The first feature of the reddening distribution is the complex structure of the reddening in the first two panels. The local bubble, i.e. the region within 0.1-kpc distance from the Sun, is not affected by the reddening effect of the interstellar dust, whereas $E(B - V)$ can be as high as 0.35 mag

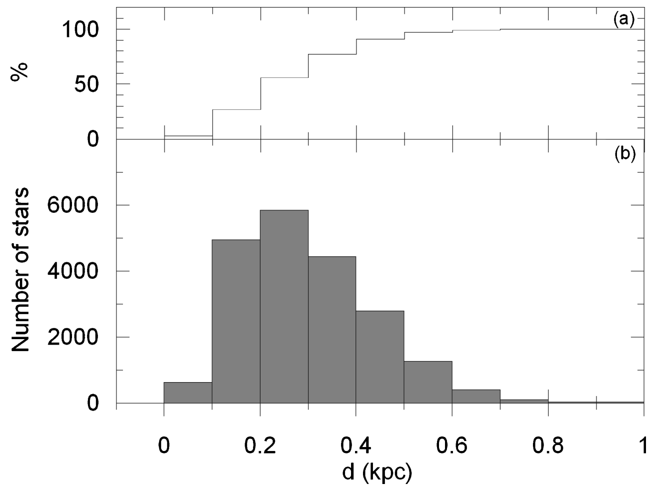

Figure 3. Cumulative (panel a) and frequency (panel b) distributions of distances of main-sequence stars.

at larger distances. As expected, high-latitude stars (Fig. 2c) have smaller reddening values. The second feature is that one cannot ignore the interstellar reddening even when using NIR bands.

The distribution of distances (Fig. 3) shows that 80 per cent of the sample stars have almost a normal distribution within the distance interval $0 \leq d \leq 0.4$ kpc, whereas the overall distribution which extends up to 1 kpc is skewed, with a median of 0.276 kpc. However, 97 per cent of the sample stars are within $d = 0.6$ kpc.

The position of the sample stars in the rectangular coordinate system relative to the Sun is given in Fig. 4. The projected shapes both on the Galactic (X, Y) plane, and on the vertical (X, Z) plane of the sample show asymmetrical distributions. The median coordinates ($X = 60$, $Y = -107$, $Z = -108$ pc) of the sample stars confirm this appearance. The inhomogeneous structure is due to the incomplete observations of the RAVE project and that the programme stars were selected from the Southern Galactic hemisphere.

4 KINEMATICS

We combined the distances estimated in Section 3 with RAVE kinematics and the available proper motions, applying the (standard) algorithms and the transformation matrices of Johnson & Soderblom (1987) to obtain their Galactic space velocity components (U, V, W).

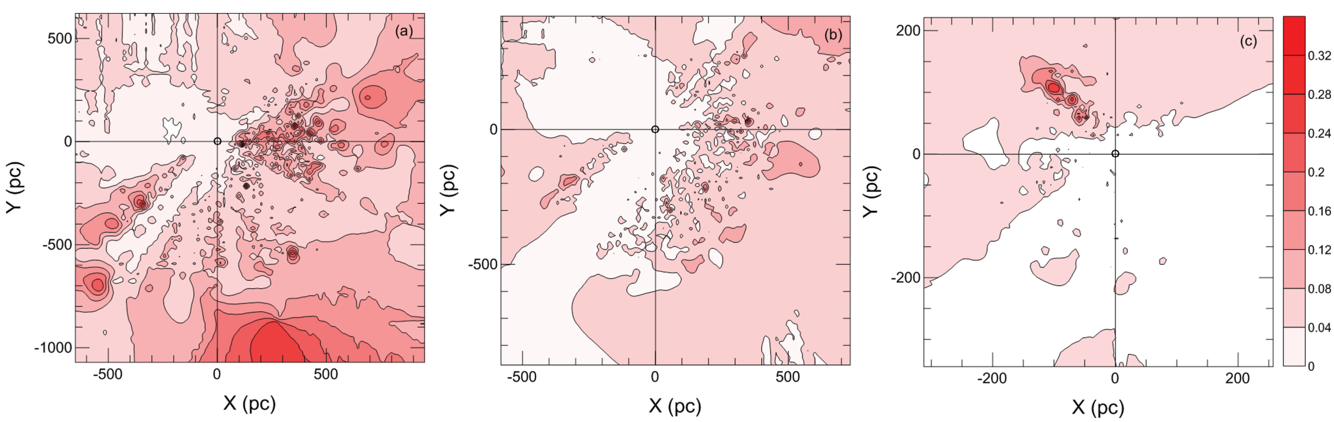

Figure 2. $E(B - V)$ reddening map in the solar neighbourhood for our RAVE main-sequence sample: (a) stars with $|b| \leq 30°$; (b) stars with $30° < |b| \leq 60°$ and (c) stars with $|b| > 60°$.