FIRST STEPS TOWARD THE DETERMINATION OF THE ESCAPE VELOCITY IN THE SOLAR NEIGHBOURHOOD

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ABSTRACT

Hipparcos parallaxes and proper motions, combined with radial velocities from CORAVEL, allow the space velocities of several thousands of stars to be determined with unprecedented accuracy. A detailed analysis of the errors, taking into account the correlations between the astrometric parameters (positions, parallaxes and proper motions) for each star, is developed. The escape velocity is then estimated following the method first developed by Leonard & Tremaine (1990).

Key words: galactic kinematics; high-velocity stars; escape velocity.

1. INTRODUCTION

One way to derive the mass of the Galaxy is to use the escape velocity from the Galaxy at the solar position. Indeed, it is directly related to the gravitational potential, and hence to the mass of the Galaxy (Binney & Tremaine 1987). In 1990 Leonard & Tremaine developed a new statistical method based on a sample of stars with very high velocities, assuming that each object was still bound to the Galaxy.

The lists and catalogues of high proper motion or high velocity stars were carefully incorporated into the Hipparcos Catalogue up to the Hipparcos limiting magnitude ($Hp \approx 12.5$), while in the same time many efforts were made for measuring accurate radial velocities for a large fraction of these stars.

With this new data, the statistical method of Leonard & Tremaine (1990) is expected to give improved results.

2. THE SAMPLE

Our sample was built to include the largest possible number of the high-velocity stars contained in the Hipparcos Input Catalogue (hereafter HIC), in order to approach the escape velocity. A first list of stars with high tangential velocities was proposed in 1982; it was later completed in 1992 with all the stars contained in the HIC and having large tangential or radial velocities.

The stars belong to late spectral types (F to M) and include the known subdwarfs and high-velocity stars. The color-magnitude diagram obtained with the data of the Hipparcos Catalogue is shown on Figure 1.

The sample suffers from severals sampling biases, mainly in magnitude (reflecting the magnitude distribution of the Hipparcos Catalogue), and in spatial distribution over the sky (due to the limited availability of the Michigan Spectral Survey in 1982).

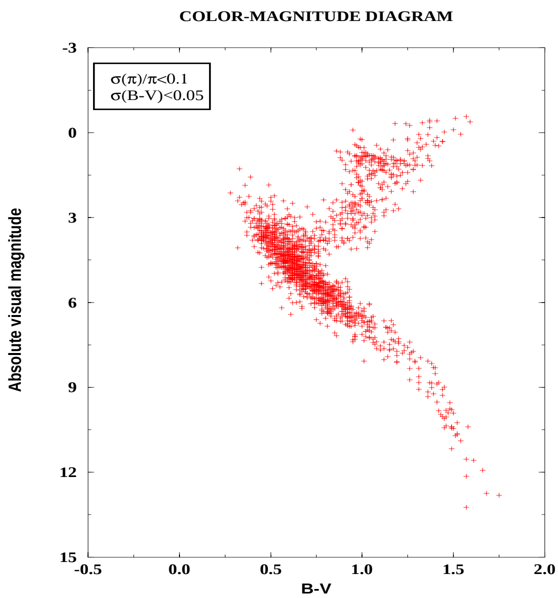

Figure 1. Color–magnitude diagram for stars of our sample with a relative error in parallax less than 0.1 and an absolute error in B-V less than 0.05.

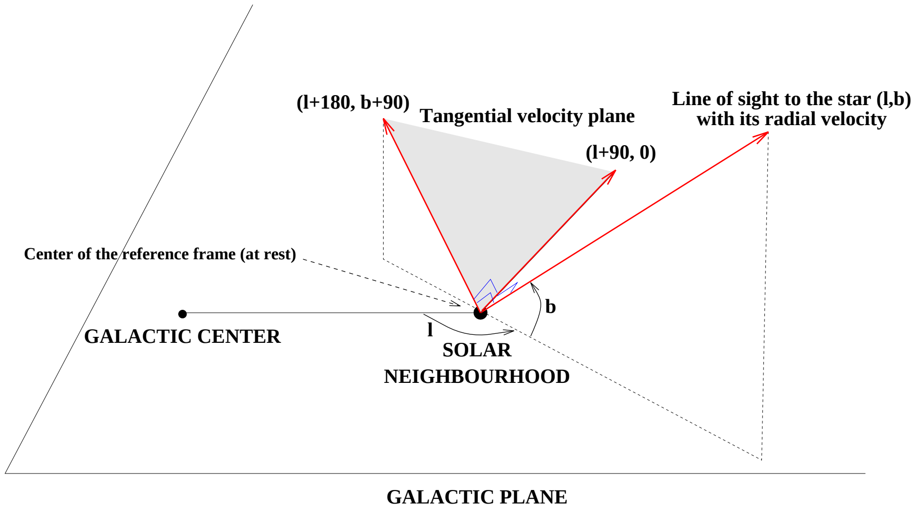

Figure 2. Galactic rest-frame used to define the radial (V_r), the tangential (V_{tg}) and the space velocity ($V_{\rm tot}$).

3. CALCULATION OF VELOCITIES AND THEIR ERRORS

3.1. Data

Positions, parallaxes and proper motions are those measured by Hipparcos (ESA 1997).

Most of the radial velocities V_R used in this study (73 per cent of the final sample) were obtained with the 1.54-m Danish telescope at La Silla (Chile) in the scope of an ESO key-program, for the southern hemisphere (Mayor et al. 1998, in prep.) and with the Geneva observatory 1-m telescope at the Observatoire de Haute-Provence (OHP, France) for the northern part (Udry et al. 1999, in prep.); other radial velocities were taken in the catalogue of Barbier-Brossat et al. (1994) (16 per cent) and in the compilation 'Wilson-Evans-Batten' from Duflot et al. (1995) (6 per cent).

Our final sample contains 5307 stars, all with radial velocities and Hipparcos astrometric data.

3.2. Radial, Tangential and Space Velocity

Following Leonard & Tremaine (1990), we define the radial velocity V_r and the tangential velocity V_{tg} of each star in a Galactic reference frame centred on the Sun, but at rest with respect to the Galaxy (see Figure 2). We use a circular velocity of 220 km s^{-1} and the solar motion is taken from Delhaye (1965) ($U = +9$ km s^{-1}, $V = +12$ km s^{-1}, $W = +7$ km s^{-1}; U being positive toward the galactic center).

In the Galaxy's rest frame we have:

$$V_{\rm tot} = \sqrt{V_r^2 + V_{tg}^2}$$

The radial velocities 'at rest' V_r depend only on the usual radial velocities V_R measured from the Sun, and not on the tangential velocities; their errors are therefore smaller than those on space velocity $V_{\rm tot}$. The escape velocity estimated as the upper limit of the radial velocities only should therefore be rather reliable.

3.3. Propagation of Errors

The goal of this section is to estimate the uncertainties on each type of velocities (radial, tangential and space) from those of the primary data: the astrometric data and the radial velocities. Errors on positions, parallaxes and proper motions from Hipparcos are given; radial velocities are given with errors.

However, a new aspect comes from the results of Hipparcos. Indeed, Hipparcos measurements of positions, parallaxes and proper motions are not independent but correlated and we have to take it into account in the equations in order to estimate the final errors as the variables change.

So, from the six parameters a_k (positions, proper motions, parallax and radial velocity) with error σ_{a_k} and associated correlation matrix $[A]$ we calculate new parameters b_k (velocities), their errors σ_{b_k} as well as the associated correlation matrix $[B]$, and the transformation from the a_k to the b_k is performed through the equations: $b_k = f_k(a_k)$.

The method is as follows:

- the covariance matrix $[A_v]$ is deduced from the correlation matrix $[A]$:

$$A_v(i,j) = \sigma_{a_i}\ \sigma_{a_j}\ A(i,j)$$

- the Jacobian matrix $[J]$ is calculated from the equations f_k:

Table 1. Estimates of the escape velocity from each type of velocity for our stars and those of Leonard & Tremaine (1990).

		Hipparcos		LEONARD & TREMAINE			
	k_r	Ve km s^{-1}	Confidence interval km s^{-1}	Ve km s^{-1}	Confidence interval km s^{-1}		
		44 stars used		15 stars used			
RADIAL	1.0	424	417 – 443	460	436 – 522		
VELOCITY	2.0	438	432 – 469	494	450 – 587		
$V_{\rm cut} \geq 250$ km s^{-1}	3.0	461	434 – 503	535	471 – 660		
	k_t	Ve km s^{-1}	Confidence interval km s^{-1}	Ve km s^{-1}	Confidence interval	Ve km s^{-1}	Confidence interval
		10 stars used		33 stars used			
		$\sigma_{V_{tg}} \leq 50$ km s^{-1}		$\sigma_{V_{tg}} = 25$ km s^{-1}		$\sigma_{V_{tg}} = 50$ km s^{-1}	
TANGENTIAL	0.5	373	367 – 400	423	398 – 455	366	329 – 407
VELOCITY	1.5	379	367 – 424	462	428 – 505	406	360 – 461
$V_{\rm cut} \geq 300$ km s^{-1}	2.5	388	367 – 453	499	457 – 555	446	390 – 515
	k	Ve km s^{-1}	Confidence interval km s^{-1}	Ve km s^{-1}	Confidence interval	Ve km s^{-1}	Confidence interval
		12 stars used		26 stars used			
		$\sigma_{V_{\rm tot}} \leq 50$ km s^{-1}		$\sigma_{V_{tot}} = 25$ km s^{-1}		$\sigma_{V_{tot}} = 50$ km s^{-1}	
TOTAL SPACE	0.0	440	434 – 461	452	428 – 480	397	360 – 435
VELOCITY	1.0	458	436 – 507	490	460 – 530	439	391 – 493
$V_{\rm cut} \geq 350$ km s^{-1}	2.0	490	450 – 567	526	487 – 583	479	422 – 550

$$J(i,j) = \frac{\partial b_i}{\partial a_j} = \frac{\partial f_i(a_i)}{\partial a_j}$$

- then the new covariance matrix $[B_v]$ associated to the parameters b_k is:

  $$B_v = J A_v J^t$$

  Errors on the parameters b_k are the diagonal terms of this matrix;

- the new correlation matrix $[B]$ is deduced from the old one:

  $$B(i,j) = \frac{B_v(i,j)}{\sigma_{b_i} \sigma_{b_j}}$$

For each star the radial, tangential and space velocities with their errors are thus calculated. The errors on both solar motion and circular velocity are not taken into account.

4. STATISTICAL METHOD

For the estimation of the escape velocity we use a method similar to that of Leonard & Tremaine (1990). Assuming that all stars are bound to the Galaxy, the escape velocity Ve is estimated as the upper limit of the velocity distributions (space, tangential and radial). We are interested only in the tail of the distribution. The statistical method is used only with the velocities larger than a cutoff velocity $V_{\rm cut}$.

The tail of the velocity distribution is approximated by a simple analytical normalised function of the form:

$$\alpha (V_e - V)^k$$

Such an equation is written independently for the radial velocities V_r, tangential velocities $V_{\rm tg}$ and space velocities $V_{\rm tot}$ (as defined in the above rest frame), each with corresponding coefficients α et k (k being fixed, with several trial values).

These distributions are convolved with a normal error distribution law, for $V_{\rm tot}$ and $V_{\rm tg}$. The errors on V_r are small and no convolution has been applied.

A likelihood function can then be defined and the corresponding escape velocity is taken as the median of this likelihood function. A 90 per cent confidence interval is determined.

5. RESULTS

The values for $V_{\rm cut}$ are taken at 250 km s^{-1}, 300 km s^{-1} and 350 km s^{-1} for radial, tangential and space velocities respectively. Only stars with errors smaller than 50 km s^{-1} are kept. The three samples then reduce to 44 stars (V_r), 10 stars ($V_{\rm tg}$) and 12 stars ($V_{\rm tot}$).

Results are presented in Table 1 and Figure 3. In Table 1 we give our own values and those of Leonard & Tremaine (1990): our values are slightly smaller for V_r and $V_{\rm tg}$ and comparable for $V_{\rm tot}$. The main reason is that their 'fastest' stars are not included in the Hipparcos Catalogue, because they are too faint; while the method is extremely sensitive to the fastest objects of the sample. Our confidence intervals are smaller, thanks to the higher accuracy of our data and to the larger number of stars with radial velocities.

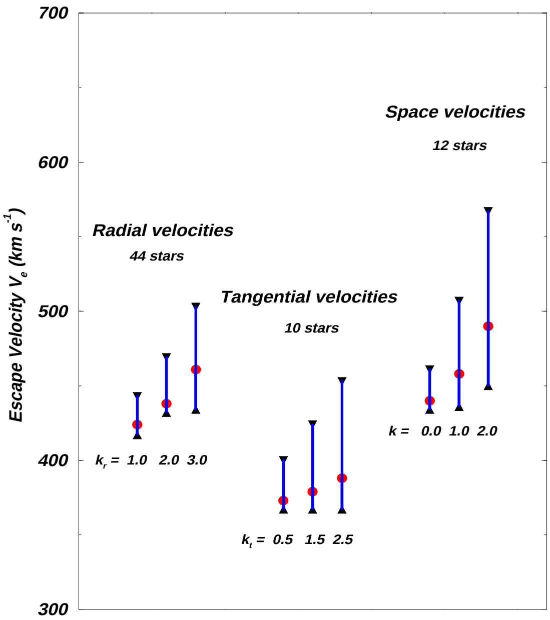

Figure 3. Graphic representation of our results.

This first result, based only on Hipparcos stars, gives therefore a lower limit of the escape velocity, and should not be considered as final. We will include fainter non-Hipparcos stars calibrated with respect to Hipparcos objects.

6. CONCLUSION

A first estimate of the escape velocity was deduced from a sample of over 5000 high-velocity Hipparcos stars. The value is below 500 km s^{-1} and within a 90 per cent confidence interval of [400 km s^{-1}, 550 km s^{-1}]. This value is smaller than previous results obtained by Leonard & Tremaine (1990). However, the lack of the fastest stars known (too faint for Hipparcos) leads to a lower limit. Fainter stars will be included in the future.

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