Precise Stellar Radial Velocities
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Radial Velocities Without Spectroscopy

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Abstract. We discuss non-spectroscopic (astrometric) ways to determine radial velocities and their potentials in future astrometric missions. Radial-velocity accuracies are presented, based on Hipparcos parallax and proper motion data for several open clusters.

1. Introduction

Accuracies in space astrometry now permit accurate determination of stellar radial velocity without using spectroscopy or invoking the Doppler principle. Already Hipparcos data permit accuracies of 100 m s^{-1} in some cases, while future space astrometry missions will enable such determinations for a broad range of stars.

Fundamental radial-velocity standards have hitherto been limited to solar-system objects, in particular asteroids, whose space motions can be derived with very high accuracy without the use of spectroscopic data. Astrometric techniques are now extending the realm of such geometrically determined radial velocities to many nearby stars.

2. Methods

Three methods have been identified by which radial velocities without spectroscopy, or astrometric radial velocities, can be determined (Lindegren et al. 1999). The methods are described below and illustrated in Figure 1.

Changing annual parallax: Among astrometric measures for radial-velocity determination, the most direct is the secular change in trigonometric parallax (π) due to the radial displacement of a star. Although this requires extremely accurate measurements over years or decades, it should become feasible with planned space missions, aiming at microarcsecond (μas) parallax accuracy. For example, for Barnard's star (π = 549 mas, $v_r = -110$ km s^{-1}), the expected parallax change is 34 μas yr^{-1}.

Changing proper motion: Assuming that a star moves uniformly through space, its radial velocity can also be derived from the gradual change in its proper motion (which varies, due to the changing perspective, along the stellar path). For astrometric missions now being planned, this method could yield radial velocities to a few 100 m s^{-1} for several nearby high-velocity stars (Table 1).

Changing angular extent: A third astrometric method which has already been applied to Hipparcos data, uses the gradual change of the angular extent

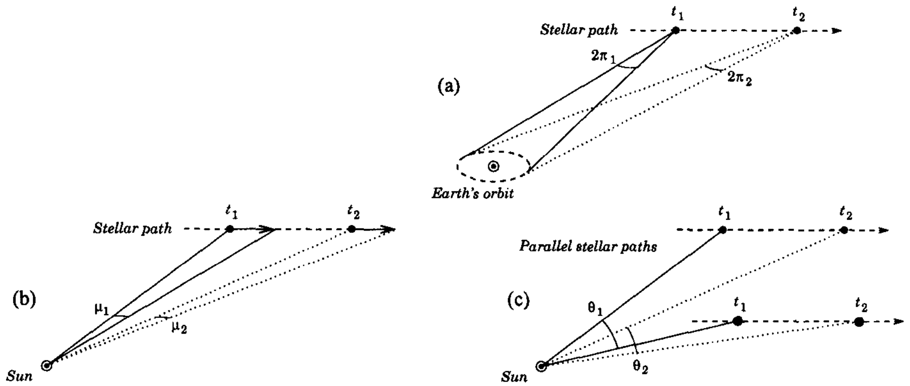

Figure 1. Schematic illustrations of the three methods showing the motion of stars from time t_1 to t_2, and the corresponding change in (a) parallax, (b) proper motion, and (c) angular extent.

of a moving star cluster. Since all cluster stars share the same [average] space velocity vector, the cluster's apparent size changes as it moves in the radial direction. This relative change in size (revealed by the proper-motion vectors towards the cluster convergent point) equals the relative change in distance. Since the individual stellar distances are known from parallaxes, their radial velocities follow. Predicted accuracies for some clusters are shown in Table 2.

3. The Hyades Open Cluster

Applying the method of changing angular extent to Hipparcos data, radial velocities have been derived for many stars in the Hyades open cluster (Dravins et al. 1997, Madsen et al. 1999). Candidate stars for the study of the Hyades were selected based on the final membership assigned by Perryman et al. (1998).

Table 1. Predicted accuracy ϵ_{v_r} of the astrometric radial velocity deduced from changing proper motion for some well-known nearby stars. Case A: a 5 yr mission yielding standard error 1 μas yr^{-1}; Case B: combination of two such measurements separated by 50 yr.

Star	ϵ_{v_r} [km s^{-1}] Case A	Case B
Barnard's star	0.13	0.01
α Cen C (Proxima)	0.25	0.01
Kapteyn's star	0.34	0.01
61 Cyg	0.50	0.02
Luyten's star	0.77	0.03
Groombridge 1830	0.98	0.04
van Maanen 2	1.1	0.04

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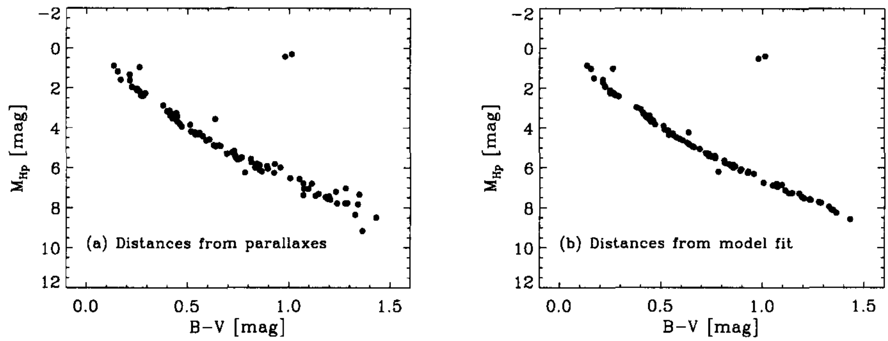

Figure 2. (a) HR diagram for the Hyades cluster using the original Hipparcos parallaxes for calculating the absolute magnitudes. (b) HR diagram for the same sample of Hyades stars, using the improved parallaxes obtained from the maximum likelihood solution with 136 stars included. Known binary stars are not plotted. Note the improved definition of the main sequence in (b).

From this sample a rejection procedure successively removed stars, leaving only the most likely cluster members. First we applied the maximum-likelihood method to estimate the velocity vector $\mathbf{V} = (v_x, v_y, v_z)$, the internal velocity dispersion σ_v, and the parallaxes of the individual stars. We then calculated the discrepancy measure g_i for each star as an indication of membership probability, and removed the star with the highest g_i in order to get a 'cleaner' sample. The rejection procedure must stop before the estimated velocity dispersion becomes negative. The radial velocity accuracy varies little between samples of between 170 to 136 stars, and any solution in this range appears equally valid.

Monte Carlo simulations show that the estimated parameters have no significant bias, except σ_v, which is systematically underestimated due to the rejection of stars with velocities deviating from the cluster mean. Additional model parameters describing rotation and shear of the cluster can be included. However, in the case of the Hyades, such systematic velocity patterns appear to be insignificant. The accuracy of the radial component of the Hyades space velocity, as determined from the Hipparcos data alone, is 0.32 km s^{-1}.

4. The Hertzsprung-Russell Diagram

The estimated Hyades parallaxes obtained from the maximum-likelihood fitting have standard errors that are a factor three better than the Hipparcos parallaxes. This improvement results from combining the parallax data with kinematic distances derived from the proper motions and the common space motion. The improvement is confirmed by simulations. As a by-product we can use the improved parallaxes to draw an HR diagram with a much better defined main sequence than with the original Hipparcos parallaxes. Figure 2a shows the original HR diagram, and Figure 2b that with the improved parallaxes. In both cases the sample was from the solution with 136 stars included, but with all known

Table 2. Accuracy ϵ_{v_r} of the astrometric radial velocity for some nearby clusters. Case A: predicted for a space astrometry mission with proper motion accuracy 1 mas yr^{-1}; Case B: 1 μas yr^{-1}. An internal velocity dispersion of $\sigma_v = 0.25$ km s^{-1} is assumed in both cases. The last column gives the accuracies actually obtained from Hipparcos data.

Cluster	ϵ_{v_r} [km s^{-1}]		
	Case A	Case B	Hipparcos
Hyades	0.19	0.14	0.32
Ursa Major	0.11	0.10	0.09
Perseus	0.63	0.18	8.3
Coma Berenices	0.84	0.43	1.9
Pleiades	1.1	0.43	5.2
Praesepe	3.1	0.98	75

binaries removed in the plots. In Figure 2b, the cluster stars lie practically on a line, which is a confirmation of the parallax improvement, and thus of our model as a whole, including the reliability of the astrometric radial velocities.

5. Other Clusters

Astrometric radial velocities have been derived for other nearby clusters as well, using Hipparcos data. Typical standard errors ϵ_{v_r} of the estimated astrometric radial velocities are presented in Table 2 (last column). They are obtained from the best subsamples, which is why Ursa Major has a higher standard error ϵ_{v_r} predicted in both case A and case B than the actual result from Hipparcos. Other differences between predicted and actual accuracies are due to the limited number of cluster stars included in the Hipparcos Catalogue.

6. Conclusions

We have presented three methods by which radial velocities without spectroscopy can be calculated from pure geometry, and have shown that for one of the methods we can achieve a accuracy, with currently available astrometric data, that is astrophysically interesting. The comparison with spectroscopic radial velocities is discussed by Dravins et al. (1998) at this Colloquium.

Discussion

Hajian: I just wanted to mention an excellent paper by Gatewood & Russell where they (in 1974!) measured the change in proper motion of the white dwarf van Maanen 2.

Scarfe: Absolute velocities in clusters like the Hyades will permit the measurement of color-dependent systematic behaviour in radial-velocity measurements, and differences between instruments that are color-dependent.

Dravins: Yes, indeed. For many of the Hyades stars with astrometric radial-velocity determinations, we have recently also obtained ELODIE spectra at Haute-Provence. One of the program aims is to improve the understanding of how the apparent radial-velocity changes with spectral type.

References

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