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Open clusters with Hipparcos*

I. Mean astrometric parameters

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Abstract. New memberships, mean parallaxes and proper motions of all 9 open clusters closer than 300 pc (except the Hyades) and 9 rich clusters between 300 and 500 pc have been computed using Hipparcos data. Precisions, ranging from 0.2 to 0.5 mas for parallaxes and 0.1 to 0.5 mas/yr for proper motions, are of great interest for calibrating photometric parallaxes as well as for kinematical studies. Careful investigations of possible biases have been performed and no evidence of significant systematic errors on the mean cluster parallaxes has been found. The distances and proper motions of 32 more distant clusters, which may be used statistically, are also indicated.

Key words: stars: distances – Galaxy: open clusters and associations: general

1. Introduction

Hipparcos observations of stars in nearby open clusters offer, for the first time, the possibility of determining accurate distances to these clusters without any assumption about their chemical composition or about stellar structure. The new distance modulus of the Hyades, 3.33 $\pm$ 0.01, derived by Perryman et al. (1998) is a first step in the determination of the distance scale in the universe. The high precision obtained represents an important improvement with respect to the results of decades of attempts to fix the zero point of the distance scale.

The position of the Zero Age Main Sequence (ZAMS) is sensitive to the exact chemical composition of the clusters and a difference of [Fe/H] = 0.15, corresponding to the metallicity difference between the Hyades and the Sun, results in a displacement of about 0.2 magnitude in absolute magnitude (M_V) according to several internal structure and atmosphere models. As the exact chemical composition of most clusters is not presently known with the required accuracy, the metallicity corrections to the distance moduli are not known with precision. Thanks to Hipparcos observations, it is possible to determine the absolute position of the main sequences of several open clusters independently of any preliminary knowledge of the chemical composition. According to the present data on chemical composition, no large discrepancies are found between the Hipparcos distance moduli of most of the cluster and the positions of their sequences in the HR diagram (Mermilliod et al. 1997a, Robichon et al. 1997), with the noticeable exception of the Pleiades. Because the Main-Sequence Fitting (MSF) method is still the basic tool in determining the distances of open clusters, the understanding of the Pleiades anomaly appears to be the first priority.

Pinsonneault et al. (1998) (herafter PSSKH) have tackled the problem with a grid of models adapted to the mass range of solar-type stars which are unevolved in nearby clusters, and chemical composition of these clusters. Their method determines the distance modulus and metallicity simultaneously from $(M_V, (B-V)_0)$ and $(M_V, (V-I)_0)$, using the fact that $(V-I)$ is much less sensitive to the metallicity than $(B-V)$. Good agreement is found for several clusters (Hyades, Praesepe, α Persei), i.e. the distances determined for the adopted metallicity correspond to those obtained from Hipparcos. Problems are found for the Pleiades (and Coma Ber cluster which only has $B-V$ colours). PSSKH attributed these discrepancies to 1 mas systematic errors in the Hipparcos Catalogue.

In fact, a more general view of the situation should be obtained from the analysis of additional nearby open clusters. For example, NGC 2516 which occupies the lowest position in the HR diagram with respect to Praesepe (even below that of the Pleiades) has a metallicity $[Fe/H] = -0.32$ (Jeffries et al. 1997), in good agreement with that required to adequately fit the ZAMS in the colour-magnitude diagram.

The results and detailed discussions presented in this paper are in keeping with preliminary results presented at the Venice'97 Symposium (Robichon et al. 1997). Since this Symposium, careful investigations of possible biases have been performed, but no evidence of any bias larger than few tenths of a milliarcsecond has been discovered. Discrepancies between the parallaxes of the Pleiades and Coma Ber with the ground-based values of Pinsonneault et al. still exists, and an attempt to explain them will be given in a following paper (Robichon et al.

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in prep.). This second paper will analyse the cluster sequences in the colour-magnitude diagram in the light of Hipparcos data. It will complete the analysis of the cluster sequences in several photometric systems presented in Mermilliod (1998) which exhibits a significant correlation between the cluster metallicities and their relative positions in the $(M_V,\ (B-V)_0)$ diagram when using the Hipparcos distance moduli.

The outline of the paper is the following. Sect. 2 depicts the two different methods adopted for selecting cluster members from the Hipparcos astrometric data, depending on whether or not they are closer than 500 pc and contain at least 8 members. With these sets of members, the mean astrometric parameters (π, $\mu_\alpha \cos\delta$, μ_δ) of 18 rich clusters closer than 500 parsecs, and 32 more distant and/or containing between 4 and 7 members, are computed and given in Sect. 3. The method used to compute these mean astrometric parameters is briefly described. It utilizes Hipparcos intermediate data which allow to take account of the star to star correlations. The rest of the paper reviews the possibility of systematic errors in the parameters both at large scale and small scale. The conclusion of this last part is that the mean astrometric parameters are statistically unbiased over the sky and that their formal errors are not severely underestimated.

2. Selection of cluster members

2.1. Pre-launch selection

The initial selection for inclusion of cluster stars in the Hipparcos Input Catalogue (HIC) (Turon et al. 1992) is described in detail in (Mermilliod & Turon 1989). It was based on the conditions of membership from proper motions and radial velocities when available, and the positions in the colour-magnitude diagram on the single star sequence to minimize the effects of potential companions. Further selections were applied during the mission simulations to remove those stars that could be affected by veiling glare of bright neighbouring stars. In the case of the Pleiades and Praesepe, stars from the outer region have been included in the sample to enlarge the total number of stars in these two clusters. As in any other field, the selection was also constrained by the satellite capabilities and was achieved through simulations.

The candidates in the Praesepe and Pleiades clusters were selected on the basis of proper motion, radial velocity and photometry analysed in Mermilliod et al. (1990) and Rosvick et al. (1992), with the same criteria, especially concerning the duplicity. These conditions are reflected in the fact that the sequences in the colour-magnitude diagrams of most clusters are quite narrow.

2.2. Final catalogue member selection

In this study, two different member selections have been applied to the open clusters in order to securely distinguish the members from the field stars based on their astrometric parameters (π, $\mu_\alpha \cos\delta$, μ_δ).

The mean astrometric parameters of clusters closer than 500 pc and containing at least 8 stars observed by Hipparcos can be derived with good accuracy. Because they are quite different from field star parallaxes and pro-per motions, a new and secure selection of members in the Hipparcos Catalogue can be performed, which replaces the pre-launch selected sample. This concerns all the clusters closer than 300 pc and 8 additional clusters closer than 500 pc.

For the other clusters, situated further than 500 pc or with a number of Hipparcos stars smaller than 8, the mean parallaxes and proper motions are small or not accurate enough and members are harder to separate from field stars on an astrometric basis. A selection based only on astrometrical criteria would accept non member stars and could then bias the computed mean parameters of the cluster. Nevertheless, even if the mean Hipparcos parallax is not so precise compared to distance modulus derived, for example, from a MSF, it is interesting to compute their mean astrometric parameters for at least two reasons. On the one hand, mean parallaxes of dozens of clusters allow statistical calibration of other distance indicators. On the other hand, the cluster mean proper motions can be very useful for galactic kinematic studies. For these clusters, only stars preselected in the Hipparcos Input Catalogue were taken into account. For the 110 clusters farther than 300 pc and with at least 2 Hipparcos stars, the mean astrometric parameters have also been derived.

No attempt has been made to find new nearby clusters in the Hipparcos Catalogue. Platais et al. (1998) made a survey of new open clusters and associations in the Hipparcos Catalogue. They found some possible new clusters which need to be confirmed by further analysis at fainter stars. These new objects are then not included in the present paper. The same goes for OB associations which are studied in detail using Hipparcos data in a comprehensive paper by de Zeeuw et al. 1999. The method used here to derive cluster mean astrometric parameters is not suited for the Hyades because its depth is not a negligible fraction of its distance at the Hipparcos precision. The Hyades properties were analysed in detail by Perryman et al. (1998) with the Hipparcos data.

The selections carried out in this paper rely on the assumption that all the cluster members have the same space velocity and, for the closest clusters, that they lie within a 10 parsec radius sphere centred on the cluster centre (which roughly corresponds to the tidal radius of an open cluster). One cluster, NGC 1977, has been rejected from the present study because the distribution of its members over the sky is not in good agreement with a bound cluster (in particular, no centre can be defined). These stars are rather part of a 80 pc long feature, connected with the Orion OB1 association (Tian et al. 1996). Another nearby object, Melotte 227, as well as most of the nearby Collinder groups (Cr 399, 359, 135 and 463) have been rejected since the astrometric data of the preselected stars do not show the characteristics of an open cluster, in particular in their spatial structure.

2.2.1. Members in the closest clusters

Although a visual examination of the vector-point and colour-magnitude diagrams can easily confirm the presence of an open cluster, an objective selection of members is always an issue.

Table 1. Equatorial coordinates (J2000.0) from Lyngå (1987) and mean radial velocity of the cluster centres

Cluster name	α h m s	δ ° ′	V_R km s^{-1}	# of@ stars
Coma Ber	12 25 07	26 06.6	-0.1 ± 0.2	22$^{(1)}$
Pleiades	3 47 00	24 03.0	5.7 ± 0.5	78$^{(1)}$
IC 2391	8 40 14	-53 03.6	14.1 ± 0.2	15$^{(1)}$
IC 2602	10 43 12	-64 24.0	16.2 ± 0.3	18$^{(1)}$
Praesepe*	8 40 00	19 30.0	34.5 ± 0.0	104$^{(1)}$
NGC 2451	7 45 12	-37 58.2	28.9 ± 0.7	5$^{(2)}$
α Per	3 22 02	48 36.0	-0.2 ± 0.5	18$^{(1)}$
Blanco 1	0 04 24	-29 56.4	5.1 ± 0.2	28$^{(1)}$
NGC 6475	17 53 43	-34 48.6	-14.7 ± 0.2	40$^{(1)}$
NGC 7092	21 32 12	48 26.4	-5.4 ± 0.4	7$^{(1)}$
NGC 2232	6 26 24	-4 45.0	21.0 ± 0.6	4$^{(2)}$
IC 4756	18 38 58	-5 27.0	25.8 ± 0.2	13$^{(1)}$
NGC 2516	7 58 00	-60 48.0	22.7 ± 0.4	6$^{(2)}$
Trumpler 10	8 47 48	-42 29.4	25.0 ± 3.5	2$^{(2)}$
NGC 3532	11 06 24	-58 42.0	3.1 ± 2.5	3$^{(2)}$
Collinder 140	7 23 55	-32 12.0	19.9 ± 3.1	4$^{(2)}$
NGC 2547	8 10 48	-49 18.0	14.4 ± 1.2	5$^{(2)}$
NGC 2422	7 36 36	-14 30.0	29.4 ± 3.7	4$^{(2)}$

Source of the mean radial velocity:
$^{(1)}$ CORAVEL mean value of members selected from CORAVEL and photometric data;
$^{(2)}$ mean value from the WEB Catalogue (Duflot et al. 1995) of selected Hipparcos members.
* coordinates from Raboud & Mermilliod 1998.
the last column indicates the number of members used to compute the mean radial velocity.

The selection presented in this section is based on an iterative method, which converges after 2 or 3 iterations, namely when no more stars are rejected from the selection. This iterative procedure is primed with a set of well known members.

At each iteration, the cluster mean parallax and mean proper motion at the position of the centre are computed from Hipparcos intermediate data, according to the computation described in Sect. 3, using the members selected at the previous iteration. The computation also takes into account the cluster mean radial velocity to correct the perspective effect due to the different angular directions of the members compared to the cluster centre. The values of cluster centres are taken from Lyngå (1987) except for the Pleiades for which it is taken from Raboud & Mermilliod (1998) who derived a new centre of mass for the cluster. These cluster centres are fixed once for all and are not calculated from Hipparcos data since the number of Hipparcos stars in each cluster is generally not large enough to obtain new accurate cluster mass centres.

When available, radial velocities obtained with the CORAVEL radial-velocity scanner by Rosvick et al. (1992), Mermilliod et al. (1997b) and additional unpublished data have been used to compute cluster mean radial velocities V_{R0}.

Because the CORAVEL scanner is adapted to measure stars later than the spectral type F5 $(B-V>0.45)$ while Hipparcos measured the brightest and thus bluest part of the main sequence, there are few stars in common between the CORAVEL and HIPPARCOS samples for most of the clusters. Therefore, CORAVEL mean velocities have been computed from all observed known members (not only Hipparcos members), with the exclusion of binaries without a determination of orbital elements. When too few CORAVEL data were available, radial velocities from the WEB Catalogue (Duflot et al. 1995) of the Hipparcos stars selected in this paper were averaged. Fortunately, the value of the mean cluster radial velocities does not need to be so precise since only its projection at the position of each member is used. For example, an error of 1 km s^{-1} in the mean radial velocity would induce an error on the proper motion of a Pleiades member situated at 3 degrees from the cluster centre (6 pc) of about 0.1 mas/yr. Mean radial velocities and the number of stars and references of the sources (Coravel or the WEB Catalogue) used to compute them are given in Table 1.

Each star in the area of the cluster is submitted to a succession of selection tests described hereafter and taking into account its position, parallax, proper motion and photometry, their associated errors, and the mean radial velocity of the cluster.

Let $\mathbf{x}_i = (\pi_i, \mu_{\alpha i}\cos\delta_i, \mu_{\delta i})$ be the vector containing the Hipparcos parallax and proper motion of star i with $\mathbf{\Sigma}_i$ being the covariance matrix. Let $\mathbf{x_0} = (\pi_0, \mu_{\alpha 0}\cos\delta_0, \mu_{\delta 0})$ be the parallax and proper motion of the cluster centre corresponding to the mean velocity of the cluster with covariance matrix $\mathbf{\Sigma_0}$. Let $\mathbf{x_0}_i = (\pi_0, \mu_{\alpha 0_i}\cos\delta_i, \mu_{\delta 0 i})$ be the parallax and proper motion corresponding to the mean velocity of the cluster at the position of star i with covariance matrix $\mathbf{\Sigma_0}_i$. These are deduced from $\mathbf{x_0}$ and $\mathbf{\Sigma_0}$ and the mean radial velocity of the cluster V_{R0} by the following rotation:

$$\begin{aligned} \mu_{\alpha 0_i}\cos\delta_i &= \cos\Delta\alpha_i\mu_{\alpha 0}\cos\delta_0 \\ &\quad + \sin\delta_0\sin\Delta\alpha_i\mu_{\delta 0} \\ &\quad - \cos\delta_0\sin\Delta\alpha_i\frac{V_{R0}\pi_0}{4.74} \\ \mu_{\delta_{0i}} &= -\sin\delta_i\sin\Delta\alpha_i\mu_{\alpha_0}\cos\delta_0 \\ &\quad + (\cos\delta_i\cos\delta_0 + \sin\delta_i\sin\delta_0\cos\Delta\alpha_i)\mu_{\delta_0} \\ &\quad + (\cos\delta_i\sin\delta_0 - \sin\delta_i\cos\delta_0\cos\Delta\alpha_i)\frac{V_{R0}\pi_0}{4.74} \end{aligned} \quad (1)$$

where (α_i, δ_i) are the equatorial coordinates of star i, (α_0, δ_0) are the equatorial coordinates of the cluster centre and $\Delta\alpha_i = \alpha_i - \alpha_0$. Note that, since the cluster depth is neglected, all the members are assumed to share the same parallax π_0.

Assuming a Gaussian distribution of errors, the value $\chi^2 = (\mathbf{x}_i - \mathbf{x_0}_i)^{\mathbf{T}}(\mathbf{\Sigma}_i + \mathbf{\Sigma_0}_i)^{-1}(\mathbf{x}_i - \mathbf{x_0}_i)$ follows a Chi-square distribution with 3 degrees of freedom. Star i is considered as a cluster member if $\chi^2 < 14.16$ (corresponding to a 3σ Gaussian two-sided test).

If star i is considered as a cluster member at the previous iteration, i.e. if it is used for the calculation of $\mathbf{\Sigma_0}_i$, then $\mathbf{\Sigma}_i$ and $\mathbf{\Sigma_0}_i$ are correlated. Nevertheless this correlation is small and has been neglected because $\mathbf{\Sigma_0}_i$ is calculated with a sufficiently large number of stars (between 8 and 54).

A diagonal correlation matrix simulating the depth of the cluster and the internal velocity dispersion can be added to $\mathbf{\Sigma}_i$ and $\mathbf{\Sigma_0}_i$ but it is small compared to them. For example, using 2 pc as a typical cluster core radius and a velocity dispersion of 0.5 km s^{-1}, the member selection in each cluster remains unchanged.

To avoid any erroneous selection, stars with a standard error of the parallax larger than 3 mas or a standard error of the proper motion larger than 3 mas/yr have also been rejected. This concerns only 1 or 2 stars per cluster at the most.

To be sure that only real members are selected, and not stars from a possible moving group associated with the cluster, stars whose distance from the cluster centre, perpendicularly to the line of sight, is greater than 10 pc (corresponding to a typical open cluster tidal radius) have also been rejected.

Hipparcos double stars were rejected when their duplicity could damage or bias the mean proper-motion and parallax values, i.e. when the field H59 of the Hipparcos Catalogue was equal to C, G, O, V or X (see ESA 1997). G, X and V entries have abscissae on the Reference Great Circles (RGC) which reflect the combination of the proper motion of the system (depending of the mean cluster velocity) and the orbital motion of the system. C and O entries have a proper motion in the Hipparcos main Catalogue decoupled from the orbital motion because they were reduced with an appropriate algorithm taking into account more than the 5 astrometric parameters needed to describe the astrometry of a single star. The global cluster reduction (Sect. 3) doesn't take these supplementary parameters into account and thus, the astrometric parameters that are calculated for these stars could be biased by the orbital motions. Hipparcos double stars considered as cluster members and not used in the reduction are given in the appendix Table A1.

Once cluster members have been selected from their astrometric parameters, their membership is verified with the help of the $(V, B-V)$ colour-magnitude diagram (hereafter CMD). This test was positive for all clusters, except for NGC 6475 in which two stars (HIP 86802 and 88224) were rejected according to their discrepant positions in the CMD.

The cluster members obtained by this selection process are listed (by HIP number) in the appendix Table A2. The number of selected members varies from 8 to 54.

2.2.2. Selection of members in more distant clusters

For the most distant clusters or for clusters with less than 8 members, the selection is more difficult. Because it is not possible to redefine a secure membership selection for these clusters, only the HIC preselected stars were taken into account and no attempt has been done to identify new members. Possible non-members were excluded using BDA, the open cluster database (Mermilliod 1995). An iterative procedure was then applied to compute the mean proper motion of the members and to reject stars with a proper motion discrepant by more than 3σ from the mean. The final mean astrometric parameters are then computed in the same way as for the nearby clusters (see Sect. 3 below). They may be useful mainly for statistical studies (e.g. Sect. 4.2.2).

3. Cluster mean astrometric parameters

3.1. Hipparcos intermediate data

The mean cluster parallax cannot be computed without caution from the Hipparcos observations. As was explained before the satellite launch, the estimation of the mean parallax or proper motion of a cluster observed by Hipparcos must take into account the observation mode of the satellite (Lindegren 1988). This is due to the fact that stars within a small area in the sky have frequently been observed in the same field of view of the satellite. Consequently, one may expect correlations between measurements done on stars separated by a few degrees, or with a separation being a multiple of the basic angle (58°) between the two fields of view.

The consequence is that, when averaging the parallaxes or proper motions for n stars, the improvement factor does not follow the expected $1/\sqrt{n}$ law and will not be asymptotically better than $\sqrt{\rho}$ if ρ is the mean positive correlation between data (Lindegren 1988). Ignoring these correlations would thus underestimate the formal error on the average parallax.

The proper way to take these correlations into account is to go one step back in the Hipparcos reduction and to work with the abscissae of stars on the Reference Great Circles (RGC), as observed by the satellite. Then, by calibrating the correlations between the RGC abscissae, the full covariance matrix $\mathbf{V}$ between observations allows to find the optimal astrometric parameters. The method, fully described in van Leeuwen & Evans (1998), has been used with minor differences only. The calibration of correlation coefficients has been done on each RGC, the reason being that significant variations may be found from one orbit to another (Arenou 1997). This has been done using the theoretical formulae of Lindegren (1988) to which harmonics were added through the use of cosine transform (Press et al. 1992). Another difference from van Leeuwen & Evans (1998) comes from the fact that the formal abscissae errors and correlations have been recalibrated as described in Arenou (1997) using the final Hipparcos data, the changes being at the level of few percent only.

The quantities of interest are the mean parallax π_0 and the mean proper motion $\mu_{\alpha 0}\cos\delta_0$, $\mu_{\delta 0}$ of each cluster centre and the position α_i, δ_i of each cluster member i. When computing the cluster mean parallax, one implicitly assumes that the dispersion in individual parallaxes is only due to the measurements errors. In fact, the depth of the cluster increases the error on the mean cluster parallaxes by few tenths of mas but should not bias it under the hypothesis that stars are symmetrically distributed.

In the Hipparcos intermediate data CD-ROM, the abscissae are not given but their residuals with respect to the main Hipparcos Catalogue astrometric parameters are given instead. The new residuals on the abscissae, $\delta\mathbf{a}$, with respect to the current iteration value of $(\alpha_i, \delta_i, \pi_0, \mu_{\alpha 0}\cos\delta_0, \mu_{\delta 0})$ are computed. The corrections to these parameters δp_k are then found by weighted least-squares, minimizing

$$\left(\delta\mathbf{a} - \sum_{k=1}^{5} \frac{\partial \mathbf{a}}{\partial p_k}\delta p_k\right)^T \mathbf{V}^{-1} \left(\delta\mathbf{a} - \sum_{k=1}^{5} \frac{\partial \mathbf{a}}{\partial p_k}\delta p_k\right).$$

Using the partial derivatives $\frac{\partial a_i}{\partial \mu_{\alpha i}\cos\delta_i}$, $\frac{\partial a_i}{\partial \mu_{\delta i}}$ of the star i given in the Hipparcos intermediate astrometric data annex, the partial derivatives of the abscissae with respect to the mean proper motion $(\mu_{\alpha 0}\cos\delta_0, \mu_{\delta 0})$ are thus computed using the linear equations 1 and the relations

$$\frac{\partial a_i}{\partial \pi_0} = \frac{\partial a_i}{\partial \pi_i}\frac{\partial \pi_i}{\partial \pi_0} + \frac{\partial a_i}{\partial \mu_{\alpha_i}\cos\delta_i}\frac{\partial \mu_{\alpha_i}\cos\delta_i}{\partial \pi_0} + \frac{\partial a_i}{\partial \mu_{\delta_i}}\frac{\partial \mu_{\delta_i}}{\partial \pi_0}$$

$$\frac{\partial a_i}{\partial \mu_{\alpha 0}\cos\delta_0} = \frac{\partial a_i}{\partial \mu_{\alpha_i}\cos\delta_i}\frac{\partial \mu_{\alpha_i}\cos\delta_i}{\partial \mu_{\alpha 0}\cos\delta_0} + \frac{\partial a_i}{\partial \mu_{\delta_i}}\frac{\partial \mu_{\delta_i}}{\partial \mu_{\alpha 0}\cos\delta_0}$$

$$\frac{\partial a_i}{\partial \mu_{\delta 0}} = \frac{\partial a_i}{\partial \mu_{\alpha_i}\cos\delta_i}\frac{\partial \mu_{\alpha i}\cos\delta_i}{\partial \mu_{\delta 0}} + \frac{\partial a_i}{\partial \mu_{\delta_i}}\frac{\partial \mu_{\delta_i}}{\partial \mu_{\delta_0}}$$

As part of the least-square procedure, the final covariance matrix between all the astrometric parameters is also computed.

3.2. Results

The mean astrometric parameters $(\pi, \mu_\alpha\cos\delta, \mu_\delta)$ and associated standard errors of clusters closer than 500 pc are given in Table 2. The unit weights errors are close to 1 but, in general, slightly smaller. This is possibly because the star to star correlations between abscissae on the RGCs have not been perfectly calibrated. However this also suggests that non members have not been erroneously included and that the cluster depth did not play a significant role.

The derived distance parameters (distances and distance moduli) given in Table 2 deserve some further comments. Since the transformation from parallax to distance or absolute magnitude is not linear, a small bias could be expected (see Brown et al. 1997). However, the relative error σ_π/π is small (between 2 and 20 percent) so the effect is negligible (between 0.04 percent and 4 percent).

Table 3 shows the derived kinematical parameters (U, V, W) of clusters. They are computed using a solar motion $(U_\odot, V_\odot, W_\odot) = (10.00, 5.25, 7.17)$ km s^{-1} (Dehnen & Binney 1998), with respect to the LSR.

Concerning the more distant clusters, the mean cluster parallaxes have been computed as described above, under the standard assumption that members of a given cluster share the common parallax and proper motion. This concerns 110 clusters more distant than 300 pc with at least 2 Hipparcos stars (among which 9 clusters described in Table 2). The parameters of 32 of these clusters containing at least 4 stars observed by Hipparcos are indicated Table 4. The parameters of the remaining clusters are not given here though part of them are included in the comparison of parallaxes between Hipparcos and groundbased determinations in Sect. 4.2.2.

Since the relative parallax error of these distant clusters is 40% on the average, their mean parallaxes are not useful individually, but rather for statistical studies. Compared to these parallaxes, the photometric parallaxes are far more precise. We could have derived the mean proper motion simultaneously with the parallax, but it was prefered to constrain the parallax to its photometric estimate and to compute the resulting mean proper motion (Table 4). In general, these proper motions are close to those obtained without adopting the photometric parallax, but this allows to gain one degree of freedom.

4. Systematic errors

4.1. Systematics in the Hipparcos Catalogue

For the Hipparcos mission, the question of systematic errors has always been a major issue; it should be remembered that, apart from the higher number of stars measured, one of the advantages of the Hipparcos data over the ground-based parallaxes is the uniformity of global astrometry observed by a single instrument. Therefore, during the data reduction special attention was paid in order to keep the systematics far below the random errors. A recent study (Makarov, 1998, priv. comm.) shows that systematic intra-revolution variations of the basic angle or of the star abscissae, of the order of 4 mas through the entire mission, would be needed in order to produce a 1 mas systematic error of the parallaxes in the Pleiades area. If this had occurred, it would have produced sizable distortions in other parts of the sky, and consequently a scatter in parallax measurements much greater than predicted by the formal errors.

The accuracy and formal precision of the Hipparcos data has been verified before the delivery of the data (Arenou et al., 1995, 1997, Lindegren 1995). Among the available external data of better or comparable precision, the comparisons used the best ground-based parallaxes, distant stars, distant clusters and Magellanic Cloud stars. In the two latter cases, it should be pointed out that these comparisons gave some insight into the property of the parallax errors at small angular scale, although the effect of astrometric correlations was taken into account only approximately. In all cases, it was shown that, over the whole catalogue, not only the zero-point was smaller than 0.1 mas, but also that the formal errors were not underestimated by more than $\approx 10\%$, this slight underestimation being possibly due to undetected binaries. In any case, this is far from the $\approx 60\%$ which would be needed for the brighter stars to have 1 mas systematic errors.

However, the statement of PSSKH that small-scale systematic errors may be present in Hipparcos data is not unjustified. Indeed, in a given cluster, the afore mentioned correlations between abscissae may be considered as a small error shared by the stars within a few square degrees. These errors, probably randomly distributed over the sky, may thus be regarded as systematics at small-scale. However, the method outlined in Sect. 3.1 takes these correlations into account during the computation of the mean parallax and its associated precision. Then the question is whether the mean cluster distances and their formal errors appear statistically biased. The following sections will answer in the negative using comparisons with previous determinations of cluster parallaxes and with the help of ad hoc simulations.

Table 2. Cluster mean astrometric parameters.

Cluster	NS	uwe	π	$\mu_\alpha \cos\delta$	μ_δ	d (pc)	$(M-m)_0$
name	NA	NR	σ_π	$\sigma_{\mu_\alpha \cos\delta}$	σ_{μ_δ}		
			$\rho_\pi^{\mu_\alpha \cos\delta}$	$\rho_\pi^{\mu_\delta}$	$\rho_{\mu_\alpha \cos\delta}^{\mu_\delta}$		
Coma Ber	**30**	0.97	**11.49**	**-11.38**	**-9.05**	$87.0^{+1.6}_{-1.6}$	$4.70^{+0.04}_{-0.04}$
	1563	15	0.21	0.23	0.12		
			-0.13	0.06	-0.12		
Pleiades	**54**	0.98	**8.46**	**19.15**	**-45.72**	$118.2^{+3.2}_{-3.0}$	$5.36^{+0.06}_{-0.06}$
	2158	25	0.22	0.23	0.18		
			-0.16	-0.07	0.21		
IC 2391	**11**	0.94	**6.85**	**-25.06**	**22.73**	$146.0^{+4.8}_{-4.5}$	$5.82^{+0.07}_{-0.07}$
	807	4	0.22	0.25	0.22		
			0.05	0.07	0.22		
IC 2602	**23**	0.93	**6.58**	**-17.31**	**11.05**	$152.0^{+3.8}_{-3.6}$	$5.91^{+0.05}_{-0.05}$
	1766	13	0.16	0.16	0.15		
			0.08	0.10	0.21		
Praesepe	**26**	1.03	**5.54**	**-36.24**	**-12.88**	$180.5^{+10.7}_{-9.6}$	$6.28^{+0.13}_{-0.12}$
	1126	6	0.31	0.35	0.24		
			-0.22	-0.11	-0.15		
NGC 2451	**12**	0.92	**5.31**	**-22.14**	**15.15**	$188.7^{+7.0}_{-6.5}$	$6.38^{+0.08}_{-0.08}$
	908	7	0.19	0.16	0.19		
			0.03	0.03	-0.03		
α **Per**	**46**	0.94	**5.25**	**22.93**	**-25.56**	$190.5^{+7.2}_{-6.7}$	$6.40^{+0.08}_{-0.08}$
	2198	12	0.19	0.15	0.17		
			0.14	-0.01	0.37		
Blanco 1	**13**	0.96	**3.81**	**19.15**	**3.21**	$262.5^{+34.3}_{-27.2}$	$7.10^{+0.27}_{-0.24}$
	798	10	0.44	0.50	0.27		
			0.26	0.05	-0.21		
NGC 6475	**22**	0.82	**3.57**	**2.59**	**-4.98**	$280.1^{+25.7}_{-21.7}$	$7.24^{+0.19}_{-0.18}$
	772	3	0.30	0.34	0.21		
			-0.10	0.04	-0.12		
NGC 7092	**8**	0.92	**3.22**	**-7.79**	**-19.70**	$310.6^{+30.7}_{-25.7}$	$7.46^{+0.20}_{-0.19}$
	589	1	0.29	0.29	0.25		
			-0.07	0.03	-0.18		
NGC 2232	**10**	0.91	**3.08**	**-4.67**	**-3.08**	$324.7^{+41.6}_{-33.1}$	$7.56^{+0.26}_{-0.23}$
	497	2	0.35	0.30	0.26		
			-0.07	0.03	0.05		
IC 4756	**9**	0.99	**3.03**	**-0.52**	**-5.83**	$330.0^{+59.1}_{-43.5}$	$7.59^{+0.36}_{-0.31}$
	522	1	0.46	0.40	0.33		
			0.07	0.10	0.00		
NGC 2516	**14**	0.92	**2.89**	**-4.04**	**10.95**	$346.0^{+27.1}_{-23.4}$	$7.70^{+0.16}_{-0.15}$
	947	4	0.21	0.22	0.20		
			0.10	0.05	-0.13		
Trumpler 10	**9**	0.97	**2.74**	**-13.29**	**7.32**	$365.0^{+43.2}_{-34.9}$	$7.81^{+0.24}_{-0.22}$
	702	2	0.29	0.25	0.24		
			0.04	0.06	0.03		
NGC 3532	**8**	0.92	**2.47**	**-10.84**	**5.26**	$404.9^{+75.9}_{-55.2}$	$8.04^{+0.37}_{-0.32}$
	552	5	0.39	0.38	0.37		
			-0.01	0.06	0.42		
Collinder 140	**11**	0.97	**2.44**	**-8.52**	**4.60**	$409.8^{+55.3}_{-43.5}$	$8.06^{+0.27}_{-0.24}$
	911	2	0.29	0.22	0.28		
			0.06	0.09	0.07		
NGC 2547	**11**	0.95	**2.31**	**-9.28**	**4.41**	$432.9^{+62.1}_{-48.3}$	$8.18^{+0.29}_{-0.26}$
	824	3	0.29	0.31	0.24		
			0.10	0.15	0.06		
NGC 2422	**9**	0.97	**2.01**	**-7.09**	**1.90**	$497.5^{+135.4}_{-87.7}$	$8.48^{+0.52}_{-0.42}$
	591	1	0.43	0.35	0.28		
			-0.13	-0.04	0.43		

π and σ_π are in mas, $\mu_\alpha \cos\delta$, μ_δ, $\sigma_{\mu_\alpha \cos\delta}$ and σ_{μ_δ} are in mas/yr.
The notations have the following meaning:
NS: number of Hipparcos stars used for the calculation,
NA: number of accepted abscissae,
NR: number of rejected abscissae,
uwe: unit-weight error.

Table 3. Cluster mean derived kinematical parameters. The velocity takes the solar motion (10.00,5.25,7.17) $\mathrm{km\,s^{-1}}$ into account, but not the rotation of the LSR

Cluster	l	b	U	σ_U	V	σ_V	W	σ_W	ρ_π^U	ρ_π^V	ρ_π^W	ρ_U^V	ρ_U^W	ρ_V^W
name	degree		$\mathrm{km\,s^{-1}}$						percent					
Coma Ber	221.28	84.03	7.82	0.09	-0.31	0.12	6.62	0.25	29	84	4	48	-16	-10
Pleiades	166.62	-23.57	3.65	0.45	-19.12	0.69	-5.85	0.35	9	98	75	-5	60	64
IC 2391	270.36	-6.89	-12.92	0.75	-8.33	0.25	1.18	0.24	98	-5	64	-6	64	2
IC 2602	289.63	-4.89	1.56	0.37	-15.01	0.30	6.88	0.12	93	41	-10	17	-10	13
Praesepe	206.07	32.34	-32.43	0.88	-14.99	0.44	-2.02	1.51	98	90	99	82	99	88
NGC 2451	252.40	-6.75	-18.74	0.80	-14.43	0.73	-6.79	0.44	94	-40	92	-15	90	-20
α Per	146.96	-7.12	-5.32	0.69	-20.53	0.96	-0.70	0.35	80	96	85	61	77	77
Blanco 1	14.95	-79.30	-11.68	2.51	-1.78	0.90	-2.35	0.54	98	87	91	90	92	85
NGC 6475	355.84	-4.49	-5.36	0.20	2.37	0.44	2.04	0.71	33	72	80	25	32	42
NGC 7092	92.46	-2.28	38.37	2.55	0.50	0.42	-6.05	1.31	-99	-14	94	14	-93	-13
NGC 2232	214.33	-7.73	-5.67	0.57	-6.66	0.48	-4.13	1.05	-32	9	90	31	-25	8
IC 4756	36.38	5.25	35.99	0.91	13.83	1.16	6.16	0.78	-93	92	64	-97	-58	52
NGC 2516	273.86	-15.89	-7.43	1.42	-18.48	0.42	3.30	0.36	97	31	-36	29	-32	-2
Trumpler 10	262.82	0.63	-17.25	2.65	-16.62	4.97	-2.48	1.16	96	-6	93	17	88	-10
NGC 3532	289.64	1.43	-10.92	3.56	-4.84	2.66	8.32	0.83	96	46	-16	24	-9	-11
Collinder 140	245.20	-7.85	-11.79	2.65	-4.91	4.59	-6.10	1.54	59	-20	84	64	83	26
NGC 2547	264.60	-8.55	-8.90	2.24	-5.58	1.26	-6.15	1.62	97	-34	92	-30	92	-24
NGC 2422	230.98	3.13	-18.26	3.14	-10.50	3.25	-3.65	2.71	66	-46	94	34	57	-49

4.2. Comparison with previous determinations

The first checking of the mean parallaxes comes from comparison with previous determinations. The first part of this section mainly deals with the 7 closest clusters, which have a formal error on the Hipparcos distance modulus smaller than 0.1 magnitude and can thus be compared individually with other determinations. The second part analyses statistically the parallaxes of the clusters more distant than 300 parsecs.

4.2.1. The closest clusters

Previous cluster distance determinations were mainly derived from the MSF technique. With the exception of the Hyades, where ground-based trigonometric parallaxes are in excellent agreement with the Hipparcos ones (see Perryman et al. 1998), and the series of papers by Gatewood et al. (1990), Gatewood & Kiewiet de Jonge (1994) and Gatewood (1995) (see below), practically no direct determination of distance exists in the literature.

Distance moduli of the 18 clusters derived from the Hipparcos mean parallaxes are compared in Table 5 to those determined by Lyngå (1987), Dambis (1999), Loktin & Matkin (1994) and Pinsonneault et al. (1998). Lyngå's values, though outdated, are given for comparison, since Lyngå's catalogue of open cluster parameters has long been the catalogue of reference. These values are the result of a compilation and do not present any homogeneity. On the contrary, Loktin & Matkin (330 clusters) and Dambis (202 clusters) catalogues are quite homogeneous. Because the Hipparcos mean distance modulus of the Hyades is 3.33 $\pm$ 0.1 (Perryman et al. 1998), the distance moduli of Loktin & Matkin (1994), which are based on a value of 3.42, are probably systematically overestimated by about 0.1 mag.

Focusing on the 7 nearest clusters for which the Hipparcos distance modulus errors are smaller than 0.1 magnitude (and excluding NGC 2451 for the reasons given below), the following remarks can be done:

- Coma Ber and α Per distance moduli are larger for Hipparcos than for the other references. Concerning α Per, it should be noticed that the difference between Hipparcos and PSSKH, 0.17 magnitude, is nearly twice as small as the difference between PSSKH and Dambis, 0.30 magnitude.
- The Pleiades distance modulus is smaller for Hipparcos, but the difference between Dambis and Hipparcos, 0.11 magnitude, is in the order of the difference between PSSKH and Dambis, 0.13 magnitude.
- IC 2391 and 2602 are approximatively at the same distance for Dambis, Loktin & Matkin and Hipparcos, but the Hipparcos value is between the two others which are discrepant by 0.35 magnitude (0.25 if Loktin & Matkin are corrected from the distance modulus of the Hyades).

No systematic differences are, thus, noticeable between Hipparcos distance moduli and ground-based ones in the sense that there is no general trend of the Hipparcos distance moduli to be different from all the MSF distance moduli from all the cited references. On the contrary, the difference between Hipparcos and any of these references is of the same order, 0.2 magnitude, than that between two of these external references. This behaviour tends to show that the formal errors of distance moduli derived from the MSF technique are underestimated. This is not so surprising since MSF distance moduli depend on the theoretical (or empirical) sequence used, the metallicity and the reddening chosen and the relations used to transform ($T_{\rm eff}$, $M_{\rm bol}$) into observable quantities. For example, an error of 0.1 dex in the metallicity will lead to a variation of the distance modulus

Table 4. Mean parameters for all clusters with more than 4 Hipparcos members (#) and more distant than 500 pc or with less than 8 Hipparcos members. The proper motions have been computed constraining the photometric distance estimate $\pi_{\rm P}$. This estimate is indicated with its reference: D for Dambis, L for Loktin & Matkin, G for Lyngå, in decreasing order of preference. The units are mas for the parallaxes, mas/yr for proper motions; the correlation coefficient (%) between $\mu_{\alpha\cos\delta}$ and μ_δ is indicated in the last column.

Name	#	π mas	$\pi_{\rm P}$ mas	$\mu_\alpha\cos\delta$ mas/yr	μ_δ mas/yr	ρ %
Cr 121	13	1.80±.24	1.58D	-3.88±.16	4.35±.19	19
Cr 132	8	1.54±.33	2.43G	-3.57±.24	4.16±.31	14
IC 1805	4	1.80±.78	0.52D	-1.14±.71	-2.29±.62	-32
IC 2944	4	0.56±.43	0.48D	-5.61±.38	0.98±.37	11
NGC 0457	4	1.55±.58	0.41D	-1.49±.40	-1.98±.36	-39
NGC 0869	4	1.01±.48	0.54D	-0.79±.38	-1.44±.33	-25
NGC 0884	5	0.93±.51	0.50D	-0.77±.42	-1.87±.35	-31
NGC 1647	4	1.09±.80	2.42D	-0.56±.94	-0.14±.77	71
NGC 2244	6	1.37±.56	0.70D	-0.59±.46	0.55±.38	-12
NGC 2264	6	2.86±.63	1.39D	-0.40±.64	-4.05±.44	27
NGC 2281	4	0.82±.73	1.89L	-2.84±.82	-7.51±.54	17
NGC 2287	8	1.91±.52	1.53L	-4.29±.43	0.04±.44	1
NGC 2467	5	1.79±.65	0.79D	-3.19±.35	1.92±.46	-5
NGC 2527	4	1.51±.95	1.65L	-6.27±.49	8.14±.69	11
NGC 2548	5	1.51±.79	1.51L	-0.63±.67	0.92±.63	-25
NGC 3114	6	1.14±.36	1.05D	-7.77±.39	4.15±.31	-9
NGC 3228	4	1.39±.50	1.89L	-15.28±.43	0.40±.37	-9
NGC 3766	4	1.36±.63	0.59D	-7.28±.54	1.19±.52	28
NGC 4755	5	0.52±.40	0.53D	-4.69±.33	-1.47±.30	36
NGC 5662	5	1.94±.62	1.39D	-5.70±.56	-7.58±.55	-5
NGC 6025	4	0.76±.55	1.79D	-3.63±.47	-2.87±.53	-28
NGC 6087	4	1.30±.61	1.23D	-1.60±.62	-1.43±.56	-10
NGC 6124	4	2.71±.86	2.15L	-1.21±.96	-1.92±.71	-31
NGC 6231	6	-0.62±.48	0.71D	0.04±.47	-1.94±.34	-18
NGC 6405	4	1.69±.52	2.19D	-1.47±.58	-6.78±.36	-28
NGC 6530	4	1.31±.80	0.79D	1.26±.86	-2.04±.55	-54
NGC 6633	4	2.70±.70	2.61L	-0.09±.60	-0.39±.51	7
NGC 6882	4	2.38±.44	1.68G	2.60±.28	-9.81±.27	-26
NGC 7063	4	2.21±.81	1.31L	0.43±.52	-4.24±.56	-20
NGC 7243	4	0.43±.61	1.30D	1.72±.48	-2.41±.52	9
Stock 02	5	2.90±.60	3.30G	15.97±.75	-13.56±.54	-42
Tr 37	6	1.03±.38	1.23D	-3.75±.35	-3.48±.33	23

of the order of 0.1 magnitude when using Johnson B,V photometry. And an error of 0.01 magnitude in the reddening will produce an error of about 0.05 magnitude in $m-M$.

Noticing these discrepancies between the MSF distance moduli, it would be prudent to consider the Hipparcos data as a good test of the accuracy of MSF, when the exact chemical composition of the clusters is not known, and would possibly be a way to give constraints on this composition. A review of the consequences of Hipparcos distance moduli on the MSF technique will be given in the second paper (Robichon et al. in prep.).

NGC 2451 presents the most discrepant values. The nature of this cluster was already discussed by Röser & Bastian (1994) and more recently by Platais et al. (1996), Baumgardt 1998 and Carrier et al. (1998). According to Röser & Bastian NGC 2451 can be divided into two different entities. The closest one, at about 220 pc, has a well defined sequence in the colour-magnitude diagram but presents a large scatter in proper motion as taken from the PPM catalogue and looks more like a moving group than like an open cluster. The most distant entity, situated at about 400 pc, seems to form an open cluster. Platais et al. (1996) definitively found two clusters NGC 2451-a and NGC 2451-b at 190 and 400 pc utilizing CCD photometry, while Carrier et al. (1998) confirmed the existence of these two clusters at 198 and 358 pc from Geneva photometry and the Hipparcos data. Baumgardt (1998) also found NGC 2451-a at 190 pc from Hipparcos data and supported the existence of NGC 2451-b in Hipparcos and ACT data. Using Hipparcos data alone, NGC 2451-a (π=5.30 mas) exhibits a distinct clump in the vector-point diagram and a well defined peak in parallax, and has then all the characteristics of an open cluster. Another peak in the parallax distribution at 2.5 mas, corresponding probably to NGC 2451-b, connected with a concentration in the vector point diagram near ($\mu_\alpha\cos\delta$, μ_δ)=(-9, 5) is noticeable. But it is difficult to distinguish from the field star distribution because both parallax and proper motion are close to those of field stars.

Pleiades, Praesepe and Coma trigonometric parallaxes were obtained from the ground by Gatewood et al. (1990), Gatewood & Kiewiet de Jonge 1994) and Gatewood (1995). In Praesepe, the mean parallax from Gatewood (1994) is 5.21 ± 0.8 mas in good agreement with Hipparcos and MSF values of Loktin & Matkin (1994) and Pinsonneault et al. (1998). For the Pleiades, Gatewood et al. (1990) obtained a mean value of 6.6 ± 0.8 mas, using 5 cluster members. This value is noticeably smaller than both Hipparcos and MSF values. On the contrary their Coma parallax (Gatewood et al. 1995), 13.53 ± 0.54 mas, is much larger. These discrepancies may be due to the fact that, although the internal accuracy of parallaxes are of the order of 1 mas, the zero point, fixed by 4 field stars for the Pleiades, 6 for Praesepe and 8 for Coma, may be uncertain. There is only one field star in common with their list, AO 1143 (=HIP 60233). It has a parallax of 2.3 ± 0.6 in Gatewood et al. (1995) and of 4.27 ± 0.92 mas in the Hipparcos Catalogue.

Van Leeuwen & Evans (1998) also calculated the mean astrometric parameters of the Pleiades and Praesepe as an example of the use of Hipparcos intermediate astrometric data. Their method is very similar to the one presented in this paper as mentioned in Sect. 3.1. The final obtained values (van Leeuwen 1999), are also close to the ones calculated in this paper. This is not unexpected since the same abscissae have been used in both cases. However different sets of members and slight differences in the abscissae formal errors and correlations account for the observed differences in the results.

O'Dell et al. (1994), used the apparent star diameters to derive the distances of the Pleiades and α Per. They obtained a distance of 132±10 pc for the Pleiades and 187±11 pc for α Per. The value of α Per agrees closely with the Hipparcos value while the distance of the Pleiades is in agreement with Hipparcos within the error bars. The method makes a statistical use of $V\sin i$ of cluster members associated with their rotational

Table 5. Hipparcos compared to previous determinations of cluster distance moduli and redennings.

Cluster name	$(m-M)_0$ Hipparcos	$(m-M)_0$ Lyngå	$E(B-V)$ Lyngå	$(m-M)_0$ Dambis	$E(B-V)$ Dambis	$(m-M)_0$ Loktin & Matkin	$E(B-V)$ Loktin & Matkin	$(m-M)_0$ Pinsonneault et al.
Coma Ber	$4.70^{+0.04}_{-0.04}$	4.49	0.00			4.60	0.01	4.54±0.04 *
Pleiades	$5.36^{+0.06}_{-0.06}$	5.48	0.04	5.47±0.05	0.040	5.50	0.04	5.60±0.04
IC 2391	$5.82^{+0.07}_{-0.07}$	5.92	0.01	5.74±0.07	0.004	6.07	0.01	
IC 2602	$5.91^{+0.05}_{-0.05}$	5.89	0.04	5.68±0.05	0.038	6.07	0.05	
Praesepe	$6.28^{+0.13}_{-0.12}$	5.99	0.00			6.26	0.02	6.16±0.05
NGC 2451	$6.38^{+0.08}_{-0.08}$	7.49	0.04			6.92	0.04	
α Per	$6.40^{+0.08}_{-0.08}$	6.07	0.09v	5.94±0.05	0.099	6.15	0.09	6.23±0.06
Blanco 1	$7.10^{+0.27}_{-0.24}$	6.90	0.02					
NGC 6475	$7.24^{+0.19}_{-0.18}$	6.89	0.06					
NGC 7092	$7.46^{+0.20}_{-0.19}$	7.33	0.02			7.71	0.01	
NGC 2232	$7.56^{+0.26}_{-0.23}$	7.80	0.01	7.90±0.05	0.021	7.50	0.03	
IC 4756	$7.59^{+0.36}_{-0.31}$	7.94	0.20v			8.41	0.20	
NGC 2516	$7.70^{+0.16}_{-0.15}$	8.07	0.13	7.85±0.05	0.111	7.86	0.10	
Trumpler 10	$7.81^{+0.24}_{-0.22}$	8.09	0.06	7.80±0.05	0.035	7.64	0.02	
NGC 3532	$8.04^{+0.37}_{-0.32}$	8.40	0.04			8.23	0.04	
Collinder 140	$8.06^{+0.27}_{-0.24}$	7.39	0.04	7.71±0.05	0.026	7.70	0.04	
NGC 2547	$8.18^{+0.29}_{-0.26}$	8.20	0.05	7.90±0.10	0.054	8.16	0.04	
NGC 2422	$8.48^{+0.52}_{-0.42}$	8.37	0.08	8.13±0.05	0.088	8.15	0.07	

* based only on the sequence in the $(M_V, B-V)$ diagram. v: variable redenning.

periods and their angular diameters. Unfortunately, as too few direct angular star diameters are available for Pleiades members, a calibration of the diameters as a function of V and $B-V$ from Hendry et al. (1993) was used. As for the MSF method, these distances are thus not directly obtained but, once again, they depend on calibrations which can be biased by several other parameters like chemical composition or age.

Recently, Chen & Zhao (1997) and Narayanan & Gould (1999) used purely geometrical methods to derive the distance of the Pleiades. Both methods are based on the hypothesis that members share the same space velocity within a small random velocity dispersion of a few km s^{-1}.

Chen & Zhao (1997) used proper motions and radial velocities of members to derive the distance and the spatial velocity of the cluster with a global maximum likelihood procedure. They obtained a distance of 135.56±0.72 pc. The tiny error bar seems dubious. In addition, they used the proper motions of Hertzsprung (1947) which are only relative. The zero point of the proper motions is not given. From their resulting space velocity, the components of the proper motions ($\mu_\alpha \cos\delta$,μ_δ) can be estimated to be (21.50, -33.04). The component in declination is quite different from the Hipparcos mean proper motion of the cluster. Moreover, the differences between Hertzsprung's proper motions and the ACT catalogue proper motions (Urban et al. 1998) show very significant dependencies with magnitudes and coordinates. This suggests biases in the Herstzsprung catalogue of the order of few mas/yr. No discussion on proper-motion biases, neither on the discrepant value of the mean proper motion, is given by Chen & Zhao (1997).

Narayanan & Gould (1999) used the gradient of radial velocities to derive a Pleiades mean distance of 130.7±11.1 pc, in agreement with Hipparcos within the error bars. Their set of 154 individual radial velocities is a compilation of CORAVEL measurements taken from the same references as those of Sect. 2. They used a mean proper motion of $(\mu_\alpha \cos\delta, \mu_\delta) = (19.79, -45.39)$ computed as an average of 65 Hipparcos members. They explained the difference with the Hipparcos mean parallax by small scale correlations between individual Hipparcos parallaxes, greater than those described above. However, following their arguments, if the mean Hipparcos parallax is biased, then the mean proper motion could also be biased. The fact that Narayanan & Gould use an average of the Hipparcos proper motions could be a problem since a variation of 1 mas/yr in μ_δ, for instance, modifies the mean distance by about 2.5 pc.

In order to analyse the radial-velocity gradient method, a new selection of radial velocity members was done. All the members with a CORAVEL radial velocity were considered. The spectroscopic binaries were rejected when they had no orbital solution as well as all stars with less than 3 measurements (and which thus could also be non detected spectral binaries). 133 stars were selected on this basis. Their mean distance is 133.8±9.3 pc using the radial-velocity gradient method and the mean values of the centre, mean radial velocity and proper motion indicated in Tables 1 and 2 respectively. This distance confirms the result of Narayanan & Gould (1999). However some doubts can be casted upon the assumption that all the members share the same space velocity and are at the same distance. Adopting the same notations as Narayanan & Gould (1999), let

$V_{r,i}$ be the observed radial velocity of a member i, $\mathbf{n_i}$ the unit vector pointing in its line of sight and V_r, $\boldsymbol{\mu}$ and $\mathbf{n}$ the mean radial velocity, mean proper motion and direction of the cluster center. Fig. 2 of Narayanan & Gould (1999) shows the difference between $V_{r,i} - V_r(\mathbf{n}.\mathbf{n_i})$ versus $\boldsymbol{\mu}.\mathbf{n_i}$. The slope of the linear regression of these points gives directly the distance of the cluster. The most weighty points are then those with the most extreme values of the proper-motion projection on the line of sight, i.e. the most distant members from the cluster centre parallel to the proper motion direction. The cluster distance derived selecting only the 27 stars satisfying $|\boldsymbol{\mu}.\mathbf{n_i}| > 7$ is 145±11 pc while it is 100±16 pc when using the 106 other members. This behaviour is quite puzzling. If the CORAVEL data are free from any bias, this could indicate that the spatial structure of the cluster is not symmetrical or that the member velocity dispersion is not uniform, due to tidal distortion by the galactic potential for example. Nevertheless, investigations need to be carried out and would probably be the subject of a further paper.

Summarizing this paragraph leads to two distance estimates for the Pleiades. The Hipparcos one around 120 pc (this paper and van Leeuwen 1999) and a group of other values around 130 pc (PSSKH, O'Dell et al. 1994, Chen & Zhao 1997, and Narayanan & Gould 1999), part of them being compatible with the Hipparcos result within the error bars.

4.2.2. Statistical properties of distant cluster mean parallaxes

The MSF method may be used efficiently for distant (e.g. > 300 pc) clusters, since in this case, for a given absolute magnitude error, the photometric parallax error becomes far smaller than the Hipparcos parallax error. Even a systematic absolute magnitude shift would only produce a slight asymmetry on the distribution of differences between Hipparcos and MSF parallaxes; this may be seen when Hipparcos is compared to Loktin & Matkin (1994) distance moduli, in Arenou & Luri (1999).

Since these distant clusters are much more concentrated on the sky than the nearby clusters, the effect of angular correlations should also be more obvious. If systematic errors were present in the Hipparcos mean cluster parallaxes, then they would show up as either a systematic offset when cluster parallaxes are compared to photometric parallaxes, or as a scatter not accounted for in the formal errors. On the contrary, the errors on the normalized parallax differences appear normally distributed, the Gaussian (0,1) null hypothesis being compatible with the observations.

A further piece of evidence that the RGC correlations (and consequently the formal error on the mean cluster parallaxes) seem to have been correctly taken into account is shown Table 6, where the mean parallaxes are compared with those deduced from Dambis (1999). This reference was chosen because the formal error of the photometric parallaxes is indicated. Therefore, the statistical properties of mean cluster parallaxes may be safely studied.

For the 66 clusters more distant than 300 pc, with at least two members and a Dambis distance modulus, the normalized differences between Hipparcos and Dambis parallaxes have been calculated. Then, the mean formal error $\langle\sigma_\pi\rangle$ and the unit-weight error (RMS error of the normalized differences) in several groups of clusters containing the same number of Hipparcos stars, have been computed (Table 6). If systematic errors were present, the RMS error should increase with the number of stars in each cluster (since the mean formal error $\langle\sigma_\pi\rangle$ decreases). No such trend has been found and the random errors are mainly responsible of the departure from the expected value (equal to 1 if the formal parallax errors are realistic). The average unit-weight error, 1.15, is not that bad since the membership in these distant clusters is not firmly determined. There is then no room for 1 mas systematic error or in only very few clusters.

Table 6. RMS normalized differences between cluster parallaxes and Dambis photometric parallaxes as a function of number of Hipparcos stars in each cluster.

# of members	# of clusters	$\langle\sigma_\pi\rangle$ (mas)	RMS
2	28	1.03	1.00
3	11	0.80	1.25
4	12	0.60	1.26
5	4	0.55	0.98
6	6	0.48	1.57
≥ 9	5	0.29	0.99

The estimation of the formal error of the mean parallax based on distant clusters seems statistically realistic. There is then no reason to suspect the presence of a problem on closer clusters, because the error on the parallax is independent from the parallax itself (Arenou et al. 1995). Concerning the Pleiades, this suggests that the formal parallax error has been correctly estimated. The Pleiades could of course be at 4σ from the true parallax, but this is improbable, except if this is one special case where the small-scale correlations have been severely underestimated.

No reason however has been found, which could justify this hypothesis. For instance, one way of testing the way the small-scale correlations were taken into account is to study the variations of astrometric parameters with the angular distance between stars. Pleiades stars have been grouped in six bins of nine stars with increasing distances from the centre and the mean astrometric parameters for each bin are given in Table 7. All values are compatible with the adopted mean values, and no significant trend appears for π or $\mu_\alpha \cos\delta$. Concerning μ_δ, the last bin (containing the 9 farthest stars from the cluster centre) is at 3.2 σ from the cluster mean value. If these 9 stars were rejected, the new mean values of the astrometric parameters remain compatible with the adopted values, but the last bin would then be at more than 2σ in $\mu_{\alpha\cos\delta}$ and 4σ in μ_δ.

No definitive explanation has been found to explain this behaviour. However, if we add to this problem what has yet been noticed about the radial velocities, and if the effect on parallaxes shown by Narayanan & Gould is not interpreted as systematics, there are indications that the spatial and/or kinematical distributions of the Pleiades are not as regular as expected. This is possibly an explanation to the so-called Pleiades anomaly.

Table 7. Mean astrometric parameters on subsamples of the Pleiades (6 bins of 9 stars) selected by increasing distances from the cluster centre. The average angular distance $\langle d \rangle$ from the cluster centre is indicated

bin #	$\langle d \rangle$ $^\circ$	π mas	$\mu_{\alpha\cos\delta}$ mas/yr	μ_δ mas/yr
1	0.35	8.30 ± 0.46	19.73 ± 0.43	-44.87 ± 0.32
2	0.67	9.07 ± 0.42	18.59 ± 0.42	-45.05 ± 0.32
3	1.31	8.89 ± 0.45	19.35 ± 0.46	-45.59 ± 0.36
4	1.96	7.37 ± 0.58	18.97 ± 0.59	-45.58 ± 0.45
5	2.84	8.65 ± 0.49	18.53 ± 0.51	-45.45 ± 0.41
6	4.24	8.17 ± 0.43	19.98 ± 0.51	-46.94 ± 0.38
all	1.90	8.46 ± 0.22	19.15 ± 0.23	-45.72 ± 0.18

Table 8. Errors on mean Hipparcos cluster parallax (mas) as a function of the cluster average $\rho^{\pi}_{\alpha\cos\delta}$.

$\langle \rho^{\pi}_{\alpha\cos\delta} \rangle$	$\langle \pi_{\rm Hip} - \pi_{\rm Dambis} \rangle$
-0.34	-0.34 ± 0.32
-0.20	-0.53 ± 0.21
-0.10	0.10 ± 0.32
-0.04	-0.29 ± 0.30
0.03	0.17 ± 0.18
0.11	-0.04 ± 0.23
0.32	0.29 ± 0.31

4.3. The effect of $\rho^{\pi}_{\alpha\cos\delta}$

According to PSSKH, systematic errors, on the order of 1 mas and thus far greater than the mean random error, are present in the Hipparcos Catalogue. They would be due to the existing correlations between right ascension and parallax for stars within a small angular region. PSSKH have shown that there is a trend in π vs $\rho^{\pi}_{\alpha\cos\delta}$ for the Pleiades, where the most luminous stars near the cluster centre, and with the highest $\rho^{\pi}_{\alpha\cos\delta}$, are those which raise the average parallax above that expected from MSF. In view of their results, PSSKH cautioned the users of Hipparcos data for the stars with high $\rho^{\pi}_{\alpha\cos\delta}$.

This section shows that, on the contrary, no bias on the parallax can be attributed to $\rho^{\pi}_{\alpha\cos\delta}$ neither on large scale nor on small scale.

4.3.1. Behaviour over the whole sky

Using the whole Hipparcos Catalogue, stars more distant than 500 pc according to their $uvby\beta$ photometry have been selected. Taking into account this selection bias as described in Arenou et al. (1995), Sect. 4, the zero-point of Hipparcos parallaxes is found to be -0.09 ± 0.14 mas for 74 stars with $\rho^{\pi}_{\alpha\cos\delta} > 0.3$, with an unit-weight error of parallax 0.94 ± 0.10, whereas the same computation with no restriction on $\rho^{\pi}_{\alpha\cos\delta}$ gives -0.05 ± 0.05 mas. Thus high $\rho^{\pi}_{\alpha\cos\delta}$ do not seem to play a special role on the parallax of individual stars.

However, this does not exclude possible effects at small angular scales. For this purpose, the mean parallaxes for distant clusters have been compared to their photometric counterpart. Using the 66 clusters more distant than 300 pc, the average difference between cluster parallaxes, (Hipparcos − Dambis), is indicated Table 8 in 7 quantiles of 9–10 clusters according to the average $\rho^{\pi}_{\alpha\cos\delta}$. Although some significant departures from 0 are present when individual stars are used (Arenou & Luri 1999), the correlation $\rho^{\pi}_{\alpha\cos\delta}$ does not seem to influence the mean cluster parallaxes. There is only one significant bin, at $\rho^{\pi}_{\alpha\cos\delta} \approx -0.2$, which is mainly due to one cluster, NGC 6231, where all stars have a negative parallax. The Pleiades being in the last bin, a 1 mas error due to $\rho^{\pi}_{\alpha\cos\delta}$ would be improbable.

4.3.2. Small scale effect: the Pleiades

PSSKH found a slope of 3.04 ± 1.36 mas when computing a linear regression between $\rho^{\pi}_{\alpha\cos\delta}$ and π of their Pleiades members. For the members determined in this study, a slope of 1.95 ± 0.99 mas has been obtained. PSSKH interpreted this slope as the signature of an Hipparcos systematic error. It should however be remembered that a correlation is not always a causality. In the present case, the slope comes partially from the fact that the members in the central part of the cluster share the same RGCs. This implies that the individual values of the parallax are correlated. This also implies that the $\rho^{\pi}_{\alpha\cos\delta}$ values are similar since the distribution of time on the parallactic ellipses are nearly the same. Due to the scanning law of the satellite in this area, the correlations are all around 0.3. But there are no reason for believing that an unbiased value of the mean parallax can be derived using $\rho^{\pi}_{\alpha\cos\delta} = 0$. Two kinds of Monte-Carlo simulations have been done in order to assess these points.

First, using the assumed mean Hipparcos parallax and proper motion (given in Table 2) of the Pleiades, simulated abscissae have been generated, using the complete covariance matrix of these observations for the cluster. For each star, an astrometric solution has been performed. For each simulated Pleiades, the $\rho^{\pi}_{\alpha\cos\delta}$ and π of each star member and a mean value of π derived from the intermediate data are computed. The mean slope between $\rho^{\pi}_{\alpha\cos\delta}$ and π over the simulations spread from -3.9 mas to 2.9 mas with a mean value -0.12 ± 0.14 mas. The mean value of the mean parallaxes is 8.45 ± 0.25 mas. Keeping only the simulated Pleiades with a slope greater than 2 (less than 10% of the simulations), the mean parallax is 8.55 ± 0.13 mas. This fully demonstrates that the weight of the stars with a large $\rho^{\pi}_{\alpha\cos\delta}$ do not bias the mean parallax value.

Secondly, the $\rho^{\pi}_{\alpha\cos\delta}$ correlation appears for a star if the repartition of Hipparcos Reference Great Circles for this star is asymmetrical with regard to the position of the Sun (see chapter 3.2 of the Hipparcos Catalogue 1997). In the case of Pleiades stars, the RGCs are splitted into two groups of 2.5 months over the year, due to the scanning law of the satellite. The first group is centred on mid February and contains twice as many RGCs as the second group which is centred on mid August. To reduce the $\rho^{\pi}_{\alpha\cos\delta}$ values, new reductions computing both individual and mean cluster astrometric parameters were carried out, while rejecting randomly half of the RGCs of the first group. As expected, the $\rho^{\pi}_{\alpha\cos\delta}$ values became equal to zero on the average

(-0.01 ± 0.02), but the mean parallax still remains quite the same on the average (8.40 ± 0.12 mas), the slope between individual $\rho^{\pi}_{\alpha\cos\delta}$ and π remaining positive.

One can conclude, from these two groups of simulations, that the mean values of the cluster parallax do not depend on the correlations $\rho^{\pi}_{\alpha\cos\delta}$.

4.4. Other possible effects

4.4.1. Bad RGCs

For a normal RGC the individual precision on a star abscissa residual is 3 mas on average, the mean value being 0. If for some reason bad RGCs had a large weight, the mean parallax could be biased. For example, in the Pleiades, the mean parallaxes derived when removing all the abscissae of the RGC 221 or 1519 are, respectively, 8.24±0.23 and 8.56±0.23. These are the extreme cases, for which a convergence of factors are responsible: the large number of stars observed on these RGCs, the high value of the partial derivative $\frac{\partial a}{\partial \pi}$, the high parallactic factors at the time of observation and the good accuracy of the abscissae. The influence of the other RGCs is, in most cases, smaller than 0.05 mas. Anyway, except perhaps RGC 674, which has a lot of outliers, there is no indication that any particular RGC should be removed. And the mean astrometric parameters remain the same when discarding RGC 674.

4.4.2. Binarity

The possibility that systematic errors could originate from undetected binarity has also been checked for the Pleiades case. Apart from binary stars flagged as such by Hipparcos, and rejected in the solutions given in the previous section, a solution has also been performed where all the ground-based (spectroscopic or visual) binaries (20 stars) were rejected. The resulting average parallax (8.50±0.26) is not significantly different from the adopted solution.

In fact, excluding the rare cases where the period of the binary is about one year, no parallax bias due to unknown binarity is expected. To assess this point, a simple test has been done: using the stars given in the orbital solutions of the Hipparcos DMSA/O annex, and computing a single star solution instead does not change significantly their parallax estimate. Since the binarity of these stars was known, undetected binaries (which implies a much smaller astrometric perturbation) are thus less likely to produce a significant effect on the parallax.

5. Conclusions

Open clusters have been used for a long time to calibrate the main sequence in the Hertzsprung-Russell diagram as a function of age and chemical composition and define one of the first steps in the distance scaling of the Universe via photometric parallaxes.

The Hipparcos Catalogue allows, for the first time, to determine, without any physical assumption, the distances of the nearest open clusters presented here, and the locations of the cluster sequences in the HR diagram, which will be studied in detail in a further paper.

A new selection of members, based on Hipparcos main Catalogue data, in the 9 clusters closer than 300 pc (except the Hyades) and in 9 rich clusters between 300 and 500 pc, has been carried out. To these nearby clusters, a selection of 32 more distant clusters with at least 4 Hipparcos stars has also been added.

New mean astrometric parameters have been computed using Hipparcos intermediate data, taking account of the star to star correlations. The precisions are better than 0.5 mas for parallaxes and 0.5 mas/yr for proper motions. For the most distant clusters the relative precision of the mean parallax is not as good but they may be used for statistical purposes. Proper motions, computed using the photometric parallaxes, may also be useful e.g. for the kinematical study of young stars.

Extensive tests have been applied, on distant clusters as well as on the Pleiades, which show that no obvious systematic errors seem to be present in the obtained results, and that the computed precisions are representative of the true external errors. This should allow in turn to improve the MSF distance moduli and to obtain reliable estimates of their external errors.

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Appendix A: hipparcos cluster members

The appendix lists the Hipparcos stars selected as members in the nearby clusters. Table A1 contains the members seen as multiple by Hipparcos and not used in the mean parameter calculation (H59 = C, O, G, V or X), while Table A2 gives the numbers of single Hipparcos stars used.

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Table A1. Hipparcos cluster members flagged as multiple stars in HIP and not used for the calculation of the cluster mean astrometric parameters

Cluster name	H59	Hipparcos number			Cluster name	H59	Hipparcos number		
Coma Ber	C	60525			NGC 6475	C	87218	87567	
Pleiades	C	17572	17923			V	87063		
	O	17694	17847		NGC 7092	C	106262		
	G	18559				G	106170	106409	
IC 2391	C	42216	42715		NGC 2232	X	30076		
IC 2602	C	52116	52171	52815		C	30535		
		53330			NGC 2516	C	38416	38416	38966
	O	52419					39195	39562	
	X	51794	43044		Trumpler 10	C	43085	43087	43680
Praesepe	C	42497					43688		
	G	42542			NGC 3532	C	54184	54809	
NGC 2451	C	37322			NGC 2547	C	39479		
α Per	C	16244							

Table A2. Hipparcos cluster members used for the calculation of the cluster mean astrometric parameters

Cluster name	Hipparcos number									
Coma Ber	59364	59399	59527	59833	59957	60025	60063	60066	60087	60123
	60206	60266	60293	60304	60347	60351	60406	60458	60490	60582
	60611	60649	60697	60746	60797	61071	61074	61147	61295	61402
Pleiades	16217	16407	16423	16635	16639	16753	16979	17000	17020	17034
	17043	17044	17091	17125	17225	17245	17289	17316	17317	17325
	17401	17481	17489	17497	17499	17511	17527	17531	17547	17552
	17573	17579	17583	17588	17608	17625	17664	17692	17702	17704
	17729	17776	17791	17851	17862	17892	17900	17999	18050	18091
	18154	18431	18544	18955						
IC 2391	42274	42374	42400	42450	42459	42504	42535	42702	42714	42726
	43195									
IC 2602	50102	50612	51131	51203	51300	51576	52059	52132	52160	52221
	52261	52293	52328	52370	52502	52678	52701	52736	52867	53016
	53913	53992	54168							
Praesepe	41788	42106	42133	42164	42201	42247	42319	42327	42436	42485
	42516	42518	42523	42549	42556	42578	42673	42705	42766	42952
	42966	42974	42993	43050	43086	43199				
NGC 2451	36653	37297	37450	37557	37623	37666	37697	37752	37829	37838
	37982	38268								
α Per	14697	14853	14949	14980	15040	15160	15259	15363	15388	15404
	15420	15444	15499	15505	15531	15556	15654	15770	15819	15863
	15878	15898	15911	15988	16011	16036	16047	16079	16118	16137
	16147	16210	16318	16340	16403	16426	16430	16455	16470	16574
	16625	16782	16826	16880	16966	16995				
Blanco 1	163	212	232	257	328	349	389	395	477	512
	585	653	77							
NGC 6475	87102	87134	87230	87240	87360	87460	87472	87516	87529	87560
	87580	87616	87624	87656	87671	87686	87698	87722	87785	87798
	87844	88247								
NGC 7092	105658	105659	105955	106270	106293	106297	106329	106848		
NGC 2232	30197	30356	30595	30660	30700	30758	30761	30772	30789	31101
IC 4756	90958	90990	91171	91299	91312	91437	91513	91870	91909	
NGC 2516	38226	38310	38433	38536	38739	38759	38783	38906	38994	39070
	39073	39386	39438	39879						
Trumpler 10	42477	42939	43055	43182	43209	43240	43285	43326	43450	
NGC 3532	54147	54177	54197	54237	54266	54294	54306	54337		
Collinder 140	35432	35641	35700	35761	35795	35822	35855	35905	36038	36045
	36217									
NGC 2547	39679	39759	39988	40011	40016	40024	40059	40336	40353	40385
	40427									
NGC 2422	36717	36773	36967	36981	37015	37018	37037	37047	37119	

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