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A new assessment of the kinematic distance to the Pleiades: based on radial velocities and proper motions only

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Abstract. We present a new determination of the distance to the Pleiades using the moving-cluster method, allowing for inclusion of the effects of expansion and rotation of the cluster. While rotation appears neglegible, we find a slight expansion of the cluster with a maximum velocity of 0.15 km s^{-1} and a distance modulus of $(m - M)_0 = 5.50 \pm 0.13$ mag. This is larger but compatible with the new *Hipparcos* distance modulus of 5.40 ± 0.03 mag. On the other hand, various distance moduli for the Pleiades are found in the literature, many resulting from isochrone fitting. They scatter around a value of 5.63 mag. Our results are also compatible with these measurements, within the error bars.

Keywords. open clusters and associations: individual (Pleiades), stars: distances

1. Introduction

The distance to the Pleiades is a crucial rung of the cosmic distance ladder. In 1997, when the *Hipparcos* catalogue was published and a distance modulus of 5.37 ± 0.07 mag was found (van Leeuwen 1999), it was incompatible with the results from all previous determinations. This value could not be confirmed subsequently using a range of other methods either. These included, e.g., isochrone fitting, *Hubble Space Telescope (HST)* differential parallaxes, and the use of astrometric binaries. An overview and critical discussion of the various results can be found in van Leeuwen (2009). In the latter paper, van Leeuwen used his new reduction of the raw data from *Hipparcos* (van Leeuwen 2007) to find a distance modulus of 5.40 ± 0.03 mag. Taking a weighted average of the other methods, he found 5.63 ± 0.02 mag, in clear contradiction to the *Hipparcos* result. In the new *Hipparcos* reduction, the correlations in parallax between the bright stars in the central part of the Pleiades had been reduced considerably. Previously, it had been argued (see, e.g., Pinsonneault *et al.* 1998) that these correlations in the original *Hipparcos* parallaxes were responsible for a bias in the *Hipparcos* parallax of the Pleiades.

A purely kinematic approach to assess the Pleiades' parallax was adopted by Narayanan & Gould (1999), who used the gradient in the radial velocities of individual members and the mean proper motion of the cluster to obtain $(m - M)_0 = 5.58 \pm 0.18$ mag. Their approach is a simplified version of the rigorous solution that we present below. In addition, these authors could not make use of the Tycho-2 data, nor of the most recent determinations of radial velocities.

2. The moving-cluster method

Open star clusters are stellar aggregates where members share the same 3D space velocity. Measurements of proper motions and radial velocities of stars (or cluster member candidates) can be used to determine this motion, as well as cluster membership probabilities. This procedure is generally known as the moving-cluster method, and it also yields individual parallaxes of the cluster members, called secular parallaxes. These secular parallaxes are independent of both the *Hipparcos* trigonometric parallaxes and the photometric parallaxes. In our approach, we simultaneously solve for the unknown 3D space velocity and for the individual parallaxes of the members.

In the equatorial coordinate system, the well-known relation between the 3D Cartesian space-velocity components U, V, W and the observables $V_{\rm r}$, $\mu_{\alpha *}$ and μ_δ is given by

$$\left[\begin{array}{l} V_{{\rm r},j} \\ \kappa\, \mu_{\alpha *,i}/\varpi_i \\ \kappa\, \mu_{\delta,i}/\varpi_i \end{array}\right] = \left[\begin{array}{rrr} \cos\alpha_j \cos\delta_j & \sin\alpha_j \cos\delta_j & \sin\delta_j \\ -\sin\alpha_i & \cos\alpha_i & 0 \\ -\cos\alpha_i \sin\delta_i & -\sin\alpha_i \sin\delta_i & \cos\delta_i \end{array}\right] \times \left[\begin{array}{c} U \\ V \\ W \end{array}\right], \qquad (2.1)$$

where $\mu_{\alpha *} = \mu_\alpha \cos\delta$ and κ is the conversion factor from mas yr^{-1} to km s^{-1}. Eqs (2.1) contain as unknowns the three components of the space velocity U, V, W and the individual parallaxes ϖ_i of the $i^{\rm th}$ star. The equations are non-linear, so we linearize them and solve them iteratively using the weigthed least-squares technique.

The linearized equations take the form

$$\left[\begin{array}{l} \Delta V_{{\rm r},j,0} \\ \kappa\, \Delta\mu_{\alpha *,i}/\varpi_{i,0} \\ \kappa\, \Delta\mu_{\delta,i}/\varpi_{i,0} \end{array}\right] = \left[\begin{array}{cccc} a_{11,j} & a_{12,j} & a_{13,j} & a_{14,j} \\ a_{21,i} & a_{22,i} & a_{23,i} & a_{24,i} \\ a_{31,i} & a_{32,i} & a_{33,i} & a_{34,i} \end{array}\right] \times \left[\begin{array}{c} \Delta U \\ \Delta V \\ \Delta W \\ \Delta\varpi_i \end{array}\right], \qquad (2.2)$$

where $a_{kl,m}$ are the partial derivatives of the observables with respect to the unknowns for the $m^{\rm th}$ star and $\varpi_{i,0}$ is the approximate value of the parallax. With n_i measured radial velocities and n_j measured proper motions we have $(n_j + 2n_i)$ equations for $(n_i + 3)$ unknowns. Eqs (2.2) are weighted with the weights taken from the published rms errors for the radial velocities and proper motions (see Section 3).

The normal matrix associated with Eqs (2.2) takes a very simple form,

$$\left(\begin{array}{cc} A & B \\ B^{\rm T} & D \end{array}\right),$$

where A is a symmetric 3×3 matrix, D an $n_i \times n_i$ diagonal matrix, and B a $3 \times n_i$ matrix, a system which is easy to solve.

Eqs (2.1) and (2.2) describe the motion of a cluster simply as constant in space. We also checked if the cluster is expanding and exhibits a common bulk rotation. For expansion and rotation we use the *ansatz*

$$v_{\rm exp}(|\vec{r}|) = P \times |\vec{r}| + Q \times |\vec{r}|^2 \qquad \vec{v}_{\rm rot}(\vec{r}) = \vec{\omega} \times \vec{r}, \qquad (2.3)$$

where $\vec{r}$ is the radius vector from the cluster center to the individual star. This introduces two unknowns of expansion (P and Q) and three unknowns of rotation $(\omega_x, \omega_y, \omega_z)$.

3. Data

We used the Pleiades space motion given in van Leeuwen (2009) to derive preliminary kinematic and photometric membership probabilities of stars from the PPMX catalog using the moving-cluster method, as described in Röser *et al.* (2011). Although the van Leeuwen space motion is consistent with a Pleiades' distance modulus of 5.40 mag, this suffices to obtain initial membership determinations for the stars with measured radial velocities and proper motions, but has no implications for the final result. Eqs (2.2) allow

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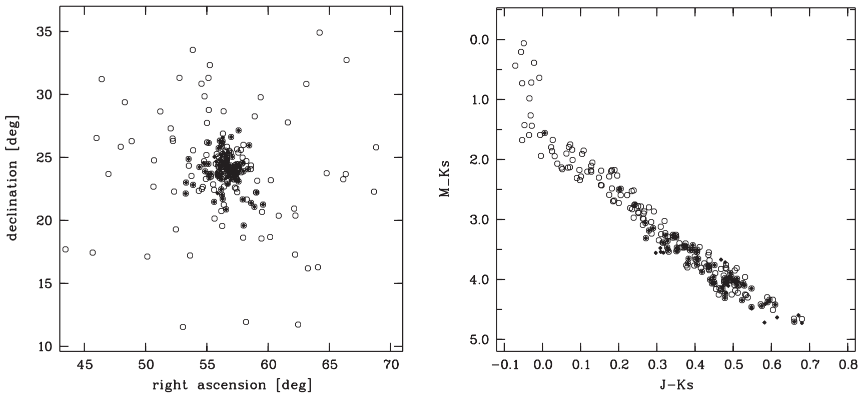

Figure 1. Distribution of the selected radial velocity (diamonds) and proper motion (circles) stars. (left) Distribution on the sky. (right) M_{K_s} versus $(J - K_s)$ color–magnitude diagram.

us to use the stars' measured radial velocities even if their proper motions are either not available or have poor accuracy. *Vice versa*, the same holds if only proper motions have been measured.

We cross-matched the membership list with the list of stars with measured radial velocities in Mermilliod *et al.* (2009). This is a homogeneous set of measurements observed with the Coravel instrument. Mermilliod *et al.* (2009) published measurements of 275 stars in the Pleiades region with spectral types from F to K. This new data set is based on improved reductions and supersedes the data published before 2000 by the same authors. After cross-matching with our members and excluding binaries, we were left with 87 *bona fide* single-star members. The rms errors of the measured radial velocities vary between 0.3 and 0.7 km s^{-1} and peak at 0.35 km s^{-1}.

The proper motions were taken from the PPMX catalog (Röser *et al.* 2008). All proper motion stars are included in the Tycho-2 catalog; the individual proper motions in the PPMX catalog were improved by including observations from CMC14. Note that we did not use the *Hipparcos* proper motions themselves to avoid any possible correlations. As for the radial velocities, we removed suspected binaries and, eventually, selected 203 stars in the least-squares adjustment. The rms errors of the proper motions vary between 0.6 and 2.2 mas yr^{-1} and peak at 1.3 mas yr^{-1}.

The distribution of all selected stars in right ascension and declination, as well as in the M_{K_s} versus $(J - K_s)$ color–magnitude diagram is shown in Fig. 1.

4. Results and discussion

We simultaneously solved Eqs (2.2) for $(n_i + 3)$, respectively $(n_i + 8)$ unknowns. Of order four iterations were needed for convergence (better than 1% for all unknowns). For the 'classic' moving-cluster solution (neglecting expansion and rotation), we find a mean cluster distance modulus of $(m - M)_0 = 5.64 \pm 0.13$ mag. Although Narayanan & Gould (1999) used a simplified method, and probably less accurate data, their result agrees remarkably well with ours.

The solution of Eqs (2.2) including rotation and expansion yields that (i) rotation is irrelevant and (ii) the expansion parameters are $P = +0.0438 \pm 0.0134$ km s^{-1} pc^{-1} and $Q = -0.0033 \pm 0.0008$ km s^{-1} pc^{-2}. The maximum expansion speed is 0.15 km s^{-1} at 6.6 pc from the cluster center and drops to zero at 13.2 pc. For this case, we find a mean cluster distance modulus of $(m - M)_0 = 5.50 \pm 0.13$ mag.

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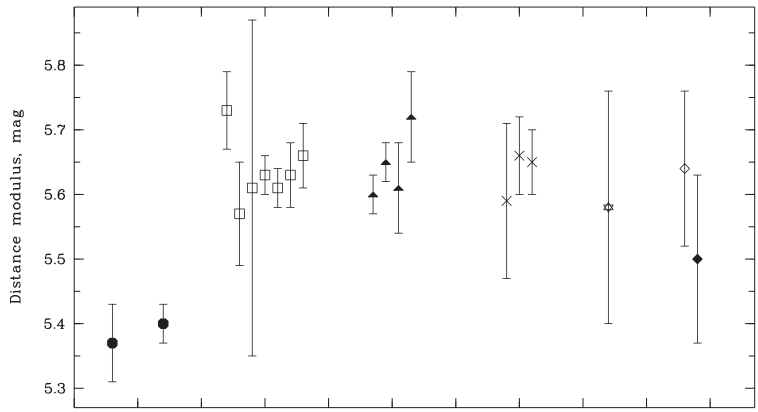

Figure 2. Summary of the Pleiades' distance moduli. Symbols (from left): *Hipparcos* = filled circles, isochrone fitting = open squares, binary stars = filled triangles, differential *(HST)* parallaxes = crosses. The Narayanan & Gould (1999) value (based on the moving-cluster method) is shown as an open asterisk. Our result, neglecting expansion, is shown as an open diamond, while with cluster expansion it is represented by the filled diamond.

In Fig. 2 we present a summary of results for the Pleiades distance modulus obtained based on different methods over the past 20 years. All methods employed so far to determine the Pleiades' parallax yielded larger distance moduli than the value based on the new *Hipparcos* reduction (van Leeuwen 2007). However, in many cases the error bars are so large that the *Hipparcos* result is not outright rejected. This controversy can only be resolved if new, independent measurements of *absolute* trigonometric parallaxes become available, either based on the VLBI project presented by Melis (this volume) or at the time of the first, preliminary trigonometric parallaxes from *Gaia*. This preliminary catalog (L+28) is expected 28 months after launch, as announced by Mignard at this IAU General Assembly.

Acknowledgements

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