Astron. Astrophys. 341, L71–L74 (1999)

ASTRONOMY AND ASTROPHYSICS

LETTER

Letter to the Editor

Hipparcos distance calibrations for 9 open clusters*

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Received 16 November 1998 / Accepted 27 November 1998

Abstract. Parallaxes have been determined for 9 nearby open clusters in order to derive a composite, age resolved, HR diagram. An age-luminosity relation was found to exist for main-sequence stars. A suggested 1 mas error in the Hipparcos parallax for the Pleiades, to explain the difference with the ground-based photometric distance estimate, seems unlikely: 5 other young open clusters examined (IC 2602, IC 2391, α Per, NGC 2451 and Blanco 1) all share the Pleiades main sequence locus in the HR diagram. The 3 older open clusters (Coma Ber, Praesepe and NGC 6475) were found displaced towards brighter magnitudes. These trends are more pronounced than predicted by theoretical stellar evolution models, and affect distance, metallicity and possibly also age determinations for open- and globular clusters through the use of theoretical isochrones.

Key words: stars: distances – stars: evolution – stars: Hertzsprung–Russel (HR) and C-M diagrams – Galaxy: open clusters and associations: general

1. Introduction

With reliable trigonometric distances available, open clusters become a very powerful tool for testing theories of stellar structure and evolution: the homogeneity in age and chemical composition of the member stars provide the empirical isochrones which are to be emulated by theoretical stellar evolution models in both the position of, and the population density along, the track. These models provide the only tool for estimating cluster ages, and their reliability is therefore of crucial importance in astrophysics. Since the publication of the Hipparcos data the issue of open cluster parallax determinations has been confusing rather than aiding astronomy: while the Hyades (Perryman et al., 1998) and Praesepe clusters were found close to the expected parallax values, the Pleiades parallax put it considerably (10 to 15 percent) closer to the Sun than expected (van Leeuwen and Hansen-Ruiz, 1997, Mermilliod et al., 1997 (Merm97)). Differences found were more than could be accommodated in currently available stellar evolution models or through abundance variations. This led to speculations that there could be local errors at a level of 1 mas (milli-arcsecond) in the Hipparcos parallaxes (Pinsonneault et al., 1998), though Merm97 had reported earlier that other young open clusters show the same sub-luminous characteristics as the Pleiades. It has been known for a long time (Lindegren, 1992) that some correlations (up to a level of 0.10 to 0.15, van Leeuwen, 1999) exist in the Hipparcos parallaxes for stars with separations of less than 1°, but these can only explain small scale error correlations at a level of 0.1 mas.

The current study was set up to:

- verify the methods used to determine cluster distances from the Hipparcos data,
- treat systematically all clusters within an estimated parallax of at least 4 mas by exactly the same determination methods,
- examine the composite HR diagram that results from these determinations,
- examine the likelihood of local “discrepancies” in the Hipparcos parallaxes as a result of correlations between astrometric parameters (described in van Leeuwen, 1999).

Sect. 2 summarizes briefly the combined abscissae method used for deriving cluster parallaxes, and is followed by a summary of the astrometric parameter determinations for the 9 selected clusters. In Sect. 4 the composite HR diagram for the clusters is presented, followed by a brief discussion of the results.

2. Determining cluster parallaxes and proper motions from Hipparcos data

The combined abscissae method used to determine the parallax and proper motion of an open cluster from the Hipparcos data has been presented by van Leeuwen (1997) and van Leeuwen and Evans, 1998 (VLE98). It combines the intermediate astrometric data (abscissa residuals, ESA, 1997) for single cluster members, and accounts for correlations between measurements obtained on the same great circle. The degrees of freedom are reduced with respect to the sum of the individual star solutions, which makes the astrometric-parameter estimates more robust. Correlations between position and parallax determina-

* Based on observations obtained with the Hipparcos satellite

** *Current address:* Institute of Astronomy, Madingley Road, Cambridge, UK tions (pointed out by Pinsonneault as a possible explanation for the larger than expected parallax for the Pleiades) are much smaller in the combined solution, which also provides, through its variance (column 10 in Table 1), a parameter that indicates whether the modelling assumptions (a shared proper motion and parallax) were justified.

Similar methods have been developed by F. Arenou and N. Robichon in Paris, and earlier results were in some cases discrepant. This was in particular the case for Praesepe, where VLE98 presented a parallax 5.04 mas, while Merm97 gave 5.65 mas (the value now agreed is 5.32 ± 0.37). In a joint effort with N. Robichon, discrepancies between the two implementations were all sorted out and explained as due to minor implementation mistakes. The results presented in the present paper have been derived with the corrected implementation, and are essentially the same as would be obtained from the same selection of stars by the implementation of Arenou and Robichon.

3. Parallaxes and proper motions for 9 open clusters

The catalogue of open-cluster parameters by Lyngå (1987) contains 12 clusters for which the distance given is less than 250 pc. At this distance, a cluster with stellar density like the Pleiades will still cover an area of about 4 degrees diameter on the sky (some 12 square degrees), making it likely to find at least of the order of 5 to 10 members amongst the Hipparcos stars. Given an average parallax accuracy of 1.2 mas, this would provide an estimated formal error for the mean cluster parallax of 0.3 to 0.4 mas, on a parallax of 4 mas or more. Thus, the 250 pc limit corresponds roughly with the 10 percent accuracy level for the expected cluster parallax, or, when expressed in distance modulus, a formal error of at most 0.2 magnitudes. The estimated accuracies for the distances in the Lyngå catalogue are about ± 10 per cent, originating from pre-Hipparcos Hyades distance calibrations and subsequent main sequence fits.

Of the 12 selected clusters, the Hyades has been extensively studied by Perryman et al. (1998) and Madsen (1999). Due to its extent on the sky, its study requires special methods which are not provided for in the reduction software used for the more distant clusters. A re-examination of the Hyades is therefore not included. Of the remaining 11 clusters, two were clearly shown to be spurious: Upgren 1 (C1232+365) and Collinder 399 (C1923+200). The cluster parameters and selection criteria for the remaining 9 clusters are presented in Table 1.

In obtaining selections of cluster members it was noted that for most clusters an additional proper motion dispersion had to be included (see column 9 in Table 1), which was in most cases larger than could be expected from internal dynamics. However, in the combined solution there was in all but two cases (Pleiades and Praesepe) no trace left from this internal dispersion: the unit weight standard error of each solution was very close to the expected value of 1.00. The additional dispersion was therefore more likely due to correlations within the astrometric parameter solutions of the individual stars. In the Pleiades an internal proper motion dispersion at a level of 0.8 to 1.0 mas per year has been observed from ground-based differential proper motions (van Leeuwen, 1994), while in Praesepe the selection of members could be affected by a halo of escaped members as has been observed for the Hyades by Perryman et al. (1998). The fact that in most solutions the standard error was below one is an indication that on average the correlations of the abscissa residuals may have been slightly overestimated, which would mean that the formal errors on the mean astrometric cluster parameters are slightly overestimated. It should also be noted that, though included here, α Per clearly showed not to be dynamically bound as a cluster, and therefore should not be considered to be equally homogeneous in age and chemical composition as the real clusters included.

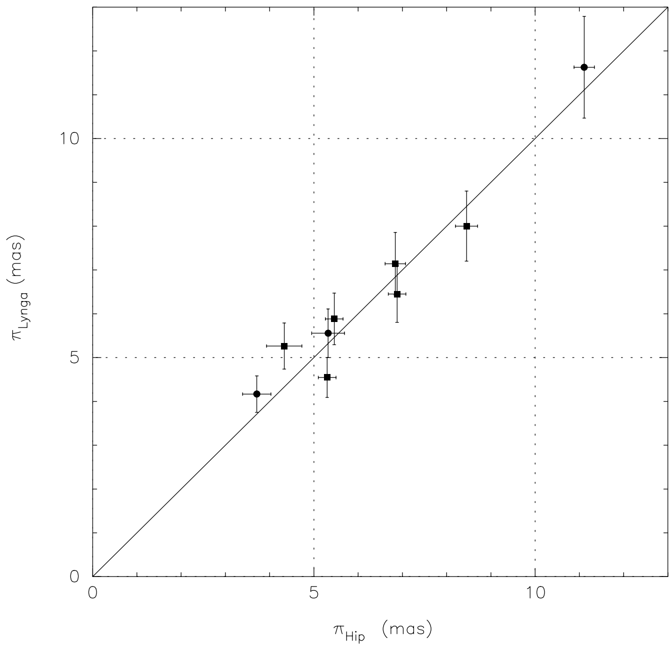

Fig. 1. Comparison between Hipparcos and estimated ground-based parallaxes for 9 nearby open clusters. Errors for the ground-based parallaxes were estimated at 10 percent.

A comparison between the distance estimates as given by Lyngå (1987) and as obtained from the Hipparcos data shows an overall good agreement, as can be seen in Fig. 1, where it should be noted that more recent estimates of the Pleiades distance have in general put the cluster at 130 rather than 125 pc (Pinsonneault et al., 1998 and references therein).

4. The composite HR diagram

The Hipparcos mission photometry (ESA, 1997, van Leeuwen et al., 1997) was used in the composite (reddening corrected) HR diagram for the 9 clusters, thus avoiding influences from photometric system transformations. Fig. 2 shows the composite diagram, resolved both according to cluster and according to age (where for comparison also data on the Hyades cluster has been included). In this diagram the Pleiades main sequence coincides with the main sequences of 5 other clusters, all of which have estimated ages similar to the Pleiades. Three older clusters appear to be brighter for the early F and A type stars, and co-

Table 1. Hipparcos astrometric paramaters for open clusters

Cluster alias	α δ	R	Dist.(pc) log(age)	Fe/H E_{B-V}	π $\sigma\pi$	$\mu_{\alpha*}$ $\sigma\mu_{\alpha*}$	μ_δ $\sigma\mu_\delta$	disp_μ	uwsd stars	Absc rej.	$\rho^{\pi}_{\mu\alpha*}$ $\rho^{\pi}_{\mu\delta}$	$\rho^{\mu\alpha*}_{\mu\delta}$	M − m σ(M − m)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
C1222+263	186°0	6°0	86	−0.03	11.11	−11.21	−9.16	0.8	0.99	1311	−0.112	−0.116	4.77
Coma Ber	26°0		8.60	0.00	0.23	0.26	0.15		25	1	0.049		0.05
C0344+239	56°5	5°0	125	0.11	8.45	19.14	−45.25	1.9	1.04	2224	−0.149	0.124	5.37
Pleiades	24°1		7.89	0.05	0.25	0.25	0.19		55	4	−0.132		0.07
C1041−641	161°0	2°5	155	−0.20	6.88	−17.40	10.85	1.8	0.92	1344	0.084	0.170	5.81
IC 2602	−64°4		7.00	0.03	0.20	0.20	0.18		17	5	0.055		0.06
C0838−528	130°0	2°5	140	−0.04	6.84	−24.98	22.58	1.7	0.98	880	0.041	0.240	5.82
IC 2391	−53°1		7.56	0.03	0.23	0.26	0.23		12	1	0.100		0.07
C0318+484	52°5	5°0	170	0.10	5.46	22.47	−25.99	1.8	0.98	2299	0.124	0.324	6.31
α Per	49°0		7.70	0.09	0.20	0.16	0.17		48	5	−0.031		0.08
C0837+201	130°0	2°7	180	0.07	5.32	−35.66	−12.70	1.9	1.05	1036	−0.213	−0.095	6.37
Praesepe	19°7		8.82	0.00	0.37	0.41	0.28		24	2	−0.156		0.15
C0743−378	116°4	3°0	220	−0.45	5.30	−21.81	15.19	1.8	0.96	915	0.028	−0.047	6.38
NGC 2451	−37°9		7.56	0.04	0.20	0.17	0.19		12	5	0.051		0.08
C0001−302	1°1	2°5	190	0.03	4.33	20.06	3.44	1.5	0.94	689	0.108	−0.334	6.82
Blanco 1	−29°9		7.70	0.09	0.40	0.49	0.25		11	2	−0.190		0.20
C1750−348	268°3	1°5	240		3.71	2.64	−4.87	1.0	0.82	565	−0.131	−0.132	7.15
NGC 6475	−34°8		8.35	0.03	0.32	0.35	0.22		17	0	0.022		0.19

Explanations per column: 1: identifier and name; 2: RA, Dec (ICRS); 3: field radius; 4 and 5: data from Lyngå (1987); 6, 7 and 8: Combined solution, astrometric parameters and their formal errors; 9: internal proper motion dispersion used in selecting members (mas/yr); 10: unit weight standard deviation and the number of stars in the solution; 11: total number used, and number of rejected, abscissae; 12 and 13: correlation parameters for combined solution;, 14: distance modulus and formal error.

incide with the average brightness of solar neighbourhood stars in the same colour region. Thus, it appears that the subluminous characteristic of the Pleiades stars is a general age-related feature rather than a local discrepancy in the Hipparcos parallaxes as was suggested by Pinsonneault et al. (1998). Such local discrepancies can also be excluded on grounds of various statistical tests on the Hipparcos parallaxes (van Leeuwen, 1999).

Soderblom et al. (1998) addressed the issue of age relation through comparing the luminosities of chromospherically active (assumed to be young) stars with inactive (assumed to be old) stars, but concluded that they could not find any of these young stars in the region where the Pleiades stars are found. However, the age estimate from a homogeneous group of stars contained in an open cluster should be much more reliable than the inference that certain types of activity can only be associated with young stars. There are some differences between known young stars with chromospheric activity in open clusters and some of the field stars of similar type, most noticeably in the relation between X-ray activity, rotational velocities and the amplitudes of the photometric variations (see Micela et al., 1985).

The conclusion by Pinsonneault et al. (1998) and by Soderblom et al. (1998) that one has to assume that the Hipparcos parallax for the Pleiades is unreliable, and affected by local problems in the Hipparcos parallax determinations can be rejected on the basis of statistical arguments derived from the Hipparcos data (van Leeuwen, 1999). In addition, to consider that 5 other young clusters would be affected in a similar way, while three older clusters are not affected at all seems unlikely. Of all 9 clusters, it is Praesepe that has the poorest coverage (shown by the correlation coefficients in the combined solution), but fits the expected position quite well.

5. Conclusions

The results shown by Fig. 2 are not in agreement with the predictions from theoretical models of stellar evolution. However, the general trends are very similar, only more pronounced in the observations: an increase in brightness already on the main sequence seems to start earlier than expected. From an observational point of view, one of the conclusions has to be that distance estimates for young star clusters have been over estimated. Among such estimates are distance determinations to the LMC and to OB associations. De Zeeuw et al. (1999) find for OB associations (spread over much larger parts of the sky than most open clusters) also distances which are generally less than what had been expected from ground-based observations.

What the consequences may be for absolute age estimates obtained from theoretical isochrones is far beyond the scope of this note. However, an unresolved difference between observations and theory as presented here inevitably introduces a degree

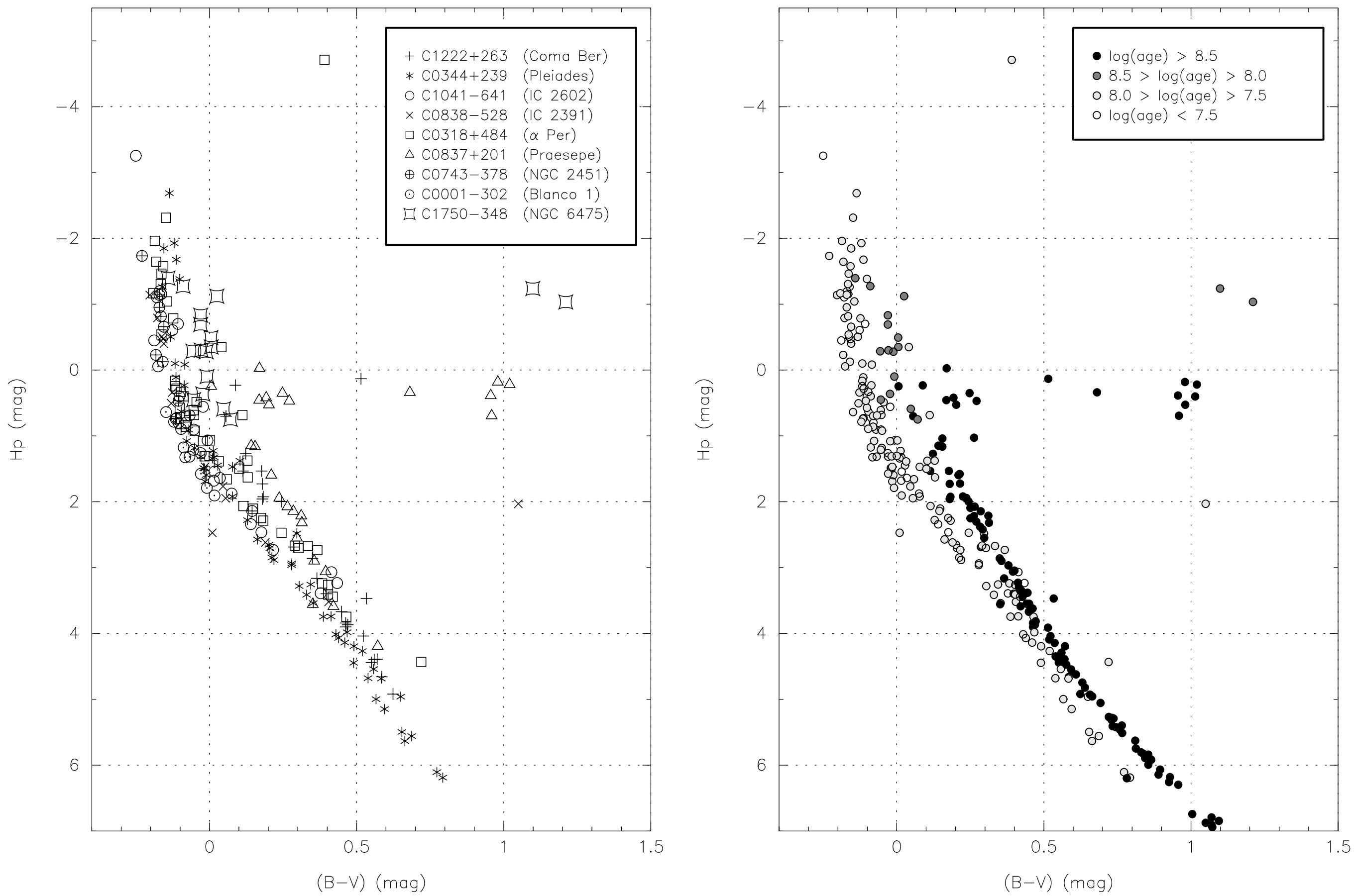

Fig. 2. The composite HR diagram for 9 open clusters. Left: showing the individual clusters; right: when split up in age groups (and including the Hyades as determined by Madsen, 1999).

of uncertainty in any such estimates. Differential age estimates as used in the present paper are unlikely to be affected.

Acknowledgements. I am indebted to Noel Robichon for helping to sort out the discrepancies between his and my implementation of the decorrelating of the abscissa data, Søren Madsen for making the Hyades parallaxes available, and to Michael Perryman who stimulated me into writing this note. Dafydd W. Evans, Margaret Penston and Jan Lub read earlier versions and provided useful comments.

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