# THE DISTANCE OF THE PLEIADES AND NEARBY CLUSTERS*

**J.-C. Mermilliod[1], C. Turon[2], N. Robichon[2], F. Arenou[2], Y. Lebreton[2]**

[1] Institut d'Astronomie, Université de Lausanne, Switzerland
[2] DASGAL/URA CNRS 335, Observatoire de Paris, 92 195 Meudon Cedex, France

ABSTRACT

We have determined the distance to nearby open clusters from the means of Hipparcos parallaxes recomputed from the intermediate data. The first result worth noticing is that Praesepe, Coma Ber, $\alpha$ Persei and Blanco 1 define the same main sequence in spite of their differences in metallicity. The second and more surprising result is that the Pleiades, and probably IC 2391 and 2602, define a sequence about 0.5 mag fainter than the previous one. The mean parallax of the Pleiades is 8.60 mas, corresponding to 116 pc. There is no way to reconcile the trigonometric and photometric distances of the Pleiades. These results contradict the commonly accepted interpretation of the metallicity effects. The results are the same for the UBV, uvby and Geneva photometric systems. The parameter responsible for these differences has not yet been identified, although they could be accounted for by a significant difference in the helium abundance. However there is presently no indication of a much higher helium abundance in nearby young clusters or associations. The present result could be linked to the so-called Hyades anomaly.

Key words: open cluster; Hipparcos; distance; chemical composition.

## 1. INTRODUCTION

The direct determination of the distance to nearby open clusters is of paramount importance because open clusters are cornerstones in metallicity determination and distance-scale calibration, while their ages are important to understand the characteristics of different populations and their evolution. Consequently open clusters have been widely used to define the Zero Age Main Sequence (ZAMS), loci of constant ages (empirical isochrones) and of constant chemical compositions in photometric diagrams.

So far, only indirect reasoning has been used to correct the distances obtained by the main sequence fitting procedure for metallicity effects. Turner (1979) estimated a distance modulus correction of 0.15 mag to account for the metallicity diference between the Hyades and Pleiades clusters. This correction is based on relations between metallicity estimators like $\delta(U-B)$ or $\delta m_1$ and absolute magnitude difference $\Delta M_V$. Such a distance modulus correction should be even larger between the Hyades and Coma Berenices clusters, because the difference in chemical composition is larger. Direct distances obtained by Hipparcos are therefore crucial to fix the distance of the nearby clusters independently of any *a priori* knowledge of their properties, age, metallicity and C, N, O abundances.

The results obtained from the analysis of Hipparcos parallaxes do not correspond to any expectation in this respect: the relative positions of the sequences of each cluster in the colour-magnitude diagram are not simply correlated with metallicity or any known parameter. Accumulated evidences do not permit to cast doubts on Hipparcos data, but show that the standard analysis methods, mainly focused on the effect of metallicity alone, were too naive.

## 2. MEAN PARALLAX DETERMINATION

Although the Hipparcos parallaxes are probably unbiased, the operation mode of the satellite induces correlations between the abscissae obtained on a given 'reference great circle'. This effect may be significant for stars within a few degrees of the sky, such as clusters (Arenou et al. 1997a). As a consequence, the straight average of the parallaxes of the cluster stars is not an optimal estimate of the mean cluster parallax, and moreover the standard error on this estimate would be clearly underestimated.

The proper way to obtain an optimal mean parallax is to use the Hipparcos intermediate astrometric data. The correlation between the abscissae of two stars on each reference great circle has been calibrated as a function of the abscissae difference allowing to obtain the full covariance matrix between all the observations for the given cluster. These observations together with their covariance matrix were then processed with a least-squares programme where either the mean parallax or proper motion or both have been considered as the same unknowns for the cluster, the other astrometric parameters of the stars remaining determined individually.

*Based on data from the ESA Hipparcos satellite.

van Leeuwen & Hansel Ruiz (1997) have independently investigated the distance of the Pleiades and incorporated more precise ground based proper motions determined from astrometric plates spending a large time interval. They basically obtained the same value of the mean parallax.

## 3. CLUSTER DISTANCES

The cluster stars chosen for the Hipparcos mission were selected according to the available membership criteria (proper motion, radial velocity and photometry). Known double stars were rejected from the sample. Hipparcos parallaxes and proper motions confirm the membership of the stars included in the initial sample.

The cluster mean parameters derived from the present analysis are displayed in Table 1. It gives the cluster designation, number of member stars used in the solution, mean parallax from Hipparcos, $\sigma$ on this parallax, the inferred distance in [pc], the effect on the distance of a change of 1 $\sigma$ on the mean parallax (+ 1 $\sigma_\pi$, − 1 $\sigma_\pi$), the distance modulus and again the effect in magnitude of a change of 1 $\sigma$ on the mean parallax (+ 1 $\sigma_\pi$, − 1 $\sigma_\pi$), the next three columns give the distance moduli, E(B-V), [Fe/H] from Lyngå's (1987) and ages from the recent literature. Part of the difference with Lyngå's moduli is due to the change of the Hyades distance ($m - M$ = 3.33) determined by Perryman et al. (1997), as presented by Brown et al. (1997) at this conference (Lyngå still used 3.01). But, even with this value of the Hyades distance, the distances of the three 'peculiar' clusters (Pleiades, IC 2391 and IC 2602) based on Hipparcos parallaxes are smaller than those deduced from Lyngå's compilation. The distance for $\alpha$ Persei is left unchanged.

The [Fe/H] values are from Cayrel de Strobel (1990) for Coma Ber, Pleiades, Praesepe and $\alpha$ Per, from Edvardsson et al. (1995) for Blanco 1 and from Lyngå (1987) for IC 2391 and IC 2602. No recent determination of the iron abundance in IC 2391 and IC 2602 has been found in the literature, nor in the new catalogue of Thévenin (1997).

## 4. NEW WORKING PARADIGM

It has been known for a long time, and confirmed by the results presented at this conference by Giusa Cayrel (Cayrel de Strobel et al. 1997), that the Hyades and Coma Ber clusters have different metallicities. This is displayed in Figure 1 which depicts a portion of the ($d$, $\Delta$) plane from the Geneva photometric system with the sequences of Hyades (filled squares) and Coma Berenices (open squares). $d$ and $\Delta$ are two reddening-free parameters defined by the linear combination of colour indices:

$$\begin{aligned} d &= (U - B_1) - 1.430\,(B_1 - B_2) \\ \Delta &= (U - B_2) - 0.832\,(B_2 - G) \end{aligned}$$

(Golay 1973, 1980). $d$ is a measure of the Balmer discontinuity. It has a good correlation with Strömgren $c_1$ parameter: $d = c_1 + 0.37$ in the spectral range covered by the Hyades (A0 - G8). The signification of $\Delta$ varies along the main sequence. In the domain of solar-type stars, it is sensitive to chemical composition. The effect of the different chemical composition between the Hyades and Coma Berenices is clearly apparent in Figure 1. This difference has also been well documented in the uvby$\beta$ system by Crawford & Strömgren (1966) who analysed in detail the various diagrams built on the uvby data. The same plane (Figure 2) for Praesepe (filled squares) and the Pleiades (open squares) shows about the same difference between the two sequences. The Hyades and Praesepe share the same sequence in this plane and the other nearby clusters discussed in this study follow the same trend as the Pleiades or Coma Berenices clusters.

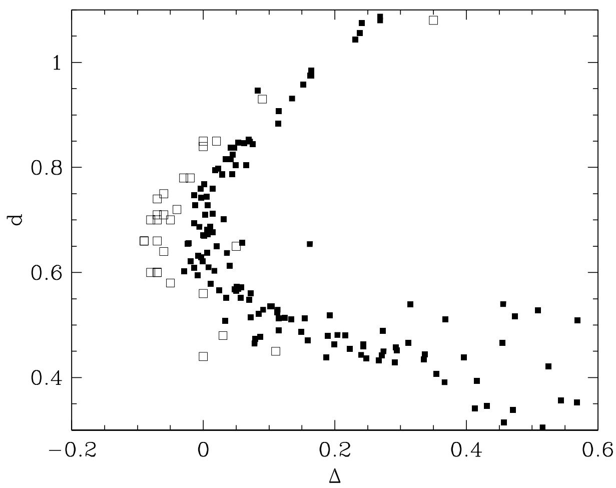


*Figure 1. Comparison of the sequences of the Hyades (filled squares) and Coma Ber (open squares) clusters. The difference is interpreted in terms of chemical composition: $\Delta$ increases with increasing metal content.*

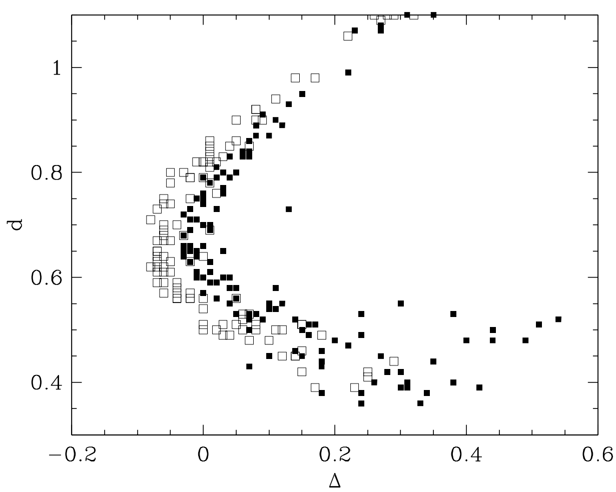


*Figure 2. Comparison of the sequences of the Praesepe (filled squares) and Pleiades (open squares) open clusters. The difference is interpreted in terms of chemical composition: $\Delta$ increases with increasing metal content.*

*Table 1. New cluster distances.*

| Cluster | N | $\bar{\pi}$ [mas] | $\sigma_{\bar{\pi}}$ [mas] | d [pc] | – [pc] | + [pc] | m–M [mag] | – [mag] | + [mag] | m–M [mag] Lyngå | E(B–V) [mag] Lyngå | [Fe/H] [dex] | Age [Myr] | Ref |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Coma Ber | 26 | 11.34 | 0.22 | 88.2 | 1.7 | 1.7 | 4.73 | 0.04 | 0.04 | 4.49 | 0.00 | –0.065 | 455 | 1 |
| Pleiades | 51 | 8.60 | 0.24 | 116.3 | 3.2 | 3.3 | 5.33 | 0.06 | 0.06 | 5.61 | 0.04 | +0.026 | 100 | 2 |
| IC2602 | 13 | 6.81 | 0.22 | 146.8 | 4.6 | 4.9 | 5.83 | 0.07 | 0.07 | 6.02 | 0.04 | –0.200 | 30 | 3 |
| IC2391 | 7 | 6.78 | 0.25 | 147.5 | 5.2 | 5.6 | 5.84 | 0.08 | 0.08 | 5.96 | 0.01 | –0.040 | 30 | 3 |
| Praesepe | 24 | 5.65 | 0.31 | 177.0 | 9.2 | 10.3 | 6.24 | 0.12 | 0.12 | 5.99 | 0.00 | +0.095 | 830 | 1 |
| $\alpha$ Per | 32 | 5.43 | 0.22 | 184.2 | 7.2 | 7.8 | 6.33 | 0.09 | 0.09 | 6.36 | 0.09 | +0.061 | 50 | 2 |
| Blanco 1 | 11 | 3.96 | 0.48 | 252.5 | 27.3 | 34.8 | 7.01 | 0.25 | 0.28 | 6.97 | 0.02 | +0.230 | 100 | 4 |

References for the ages: (1) Lyngå (1987), (2) Meynet et al. (1993), (3) Stauffer et al. (1997), (4) this work.

In view of the differences noticed in the $(d, \Delta)$ planes, it is interesting to look at the relative positions of the main sequences in the colour-magnitude diagrams $(M_V, (B_2 - V_1)_o)$ in the Geneva photometry. This system has been chosen because it provides homogeneous magnitudes and colours from one source (Rufener 1989), which is not the case for the other systems. We find the following situation:

- Coma Berenices sequence well matches that of Praesepe (or Hyades) in spite of the mentioned difference in chemical composition (Figure 3). The same is true for the $\alpha$ Persei and Blanco 1 clusters;
- the Pleiades defines a main sequence different from that of Praesepe or Coma Ber (Figure 4). This difference is large (about 0.5 mag) and very surprising due to the similarity of the behaviour of the Pleiades and Coma Berenices clusters in the $(d, \Delta)$ diagram. The two young southern open clusters IC 2391 and IC 2602 seem to follow the same trend as the Pleiades. Results from a poster displayed at this conference by Robichon et al. (1997) show that the sequences of other clusters, and especially that of NGC 2516, are also located well below the Hyades-Praesepe sequence;
- the difference is also observed between the Pleiades and $\alpha$ Persei clusters which are often associated as young clusters to compare their properties to those of the older pair formed by the Hyades and Praesepe.

The analysis of the three clusters, Praesepe, Coma Berenices and Pleiades is sufficient to describe the whole problem: Praesepe and Coma Berenices are different in the $(d, \Delta)$ diagram but define the same zero age main sequence, while the Pleiades and Coma Berenices clusters are very similar in the $(d, \Delta)$ diagram, but strongly differ in the colour-magnitude diagram. The difference between the position of Praesepe and the Pleiades (0.5 mag) is larger than determined on the basis of the difference in chemical composition alone. Turner (1979) obtained a ZAMS correction of 0.15 mag from the observed $(U - B)$ excess of 0.03 mag. Furthermore, such an effect is not observed between Praesepe and Coma Ber, although the difference in chemical composition is commonly considered to be larger. Therefore, it can safely be argued that, contrary to the expectation, the differences in chemical composition, as measured by the parameter $\Delta$ or the iron abundance [Fe/H], do not explain the observed relative positions of the main sequences of the nearby open clusters. Cayrel de Strobel et al. (1997) have shown, from high-resolution spectra, that the metallicities of these clusters were not so different from that of the Sun, with the exception of the Hyades cluster.

The estimate of chemical composition is a difficult question and it is now evident that the photometric and spectroscopic approaches may produce differing results, which is not surprising because the measured features are different. For example, from a photometric point of view the Hyades and Praesepe are very similar, while in a recent analysis of high dispersion spectra, Praesepe appears to be more solar in iron abundance (Cayrel de Strobel et al. 1997). Blanco 1 offers a second example: Eggen (1970) claimed that this cluster shows a moderate metal deficiency, while a value of [Fe/H] $= +0.23$ was obtained by Edvardsson et al. (1995) from a high dispersion spectroscopic analysis, which makes Blanco 1 even more metal rich than the Hyades. This is at odds with the observed $(U - B)$ excess: the metal deficiency is confirmed by the behaviour of Blanco 1 in the photometric diagrams of the uvby and Geneva systems.

The results shown by Figures 3 and 4 for the Geneva photometric system are confirmed in the UBV and uvby systems. The same clusters (Coma Berenices, $\alpha$ Persei, Blanco 1) match the sequence of Praesepe, while the difference of the Pleiades is also quite striking. The main difference between the Pleiades and the other clusters is really on the magnitude: the diagrams $(M_V,\ d)$ (Figure 5) and $(M_V,\ \Delta)$ (Figure 6) for Praesepe (filled squares) and the Pleiades (open squares) clearly show that all the sequences are displaced vertically. Evolutionary effects should be taken into account in the appreciation of the upper main sequence relative positions. Similar conclusions are obtained by examination of the $(M_V, \beta)$ diagram (Figure 7).

The comparison of the cluster pairs formed by $\alpha$ Persei and Coma Ber (Figure 8), $\alpha$ Persei and the Pleiades (Figure 9) show that $\alpha$ Per is very similar to Coma Ber but differs from the Pleiades.

Another presentation at this conference (de Zeeuw et al. 1997) demonstrated that the distances to the associations defining the Gould Belt are reduced by about 10 per cent. Therefore the effect found for the Pleiades, IC 2391 and 2602 is not a unique example.

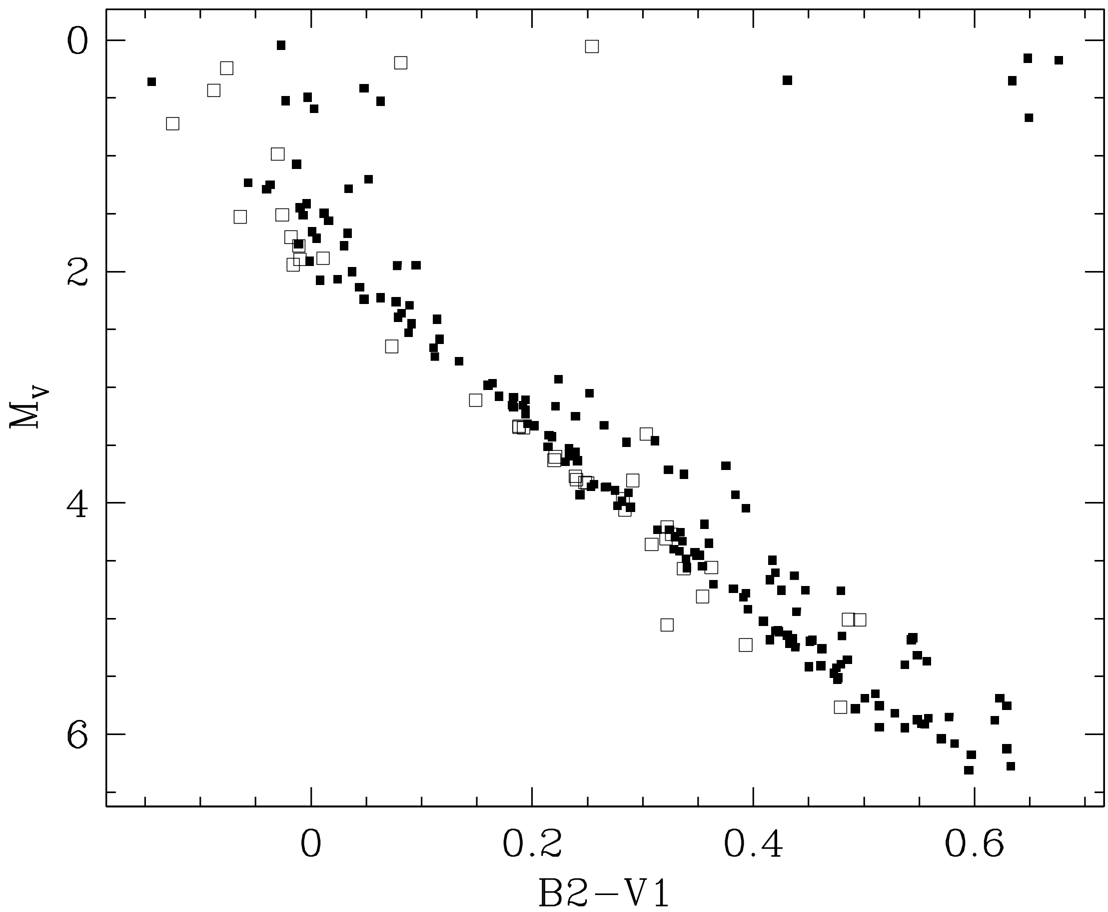


*Figure 3. Comparison of the sequences of Praesepe (filled squares) and Coma Ber (open squares) clusters. The distance is derived directly from Hipparcos parallaxes. The agreement of the sequences is very good in the unevolved part, in the range 0.2 < $B_2 - V_1$ < 0.4.*

If the photometric distances to these associations are primarily based on that to the Pleiades, the smaller distance is then expected. If their distances are more independent of that of the Pleiades, it offers another example of the same difference. In both cases, it adds credibility to the Pleiades' new parallax.

## 5. WHAT IS THE GOVERNING FACTOR?

The colour indices used as temperature indicator, namely $B - V$, $B_2 - V_1$ and $b - y$ are not very sensitive to small differences in metallicity around the solar value due to compensation of blanketing between the filters $B_2$ and $V_1$ on the one hand and b and y on the other. Therefore the use of a single zero main sequence is probably appropriate for many open clusters. However the apparent magnitude is sensitive, at least in the case of the Pleiades and of the Gould Belt associations, to an unknown factor which makes them appear fainter for their distance. Comparisons of the apparent V magnitudes of Pleiades stars between the three photometric systems (Geneva, UBV and uvby) show a rather good agreement within ± 0.02 mag and, as a systematic error of 0.5 mag in the zero point is excluded, there is no reason to suspect the measured magnitudes.

The main factor could be the helium abundance. Models computed by Y. Lebreton (Figure 10) show that the large difference could be explained by an enrichment in helium for the Pleiades. The existence of a larger helium abundance in the Gould Belt associations could find some support in the observations by Nissen (1976) and Peterson & Shipman (1973) who found that helium abundance in Sco-Cen, Lac OB1 and Ori OB1 is larger than that in NGC 2264, h & $\chi$ Persei or Cep OB3. The values found in the literature for the Pleiades (Klochkova & Panchuk 1986) is probably not reliable because of the large differences between these values and those published by Wolff & Hasley (1985) for clusters in common. However the change in abundance needed to reproduce the 0.5 mag effect observed in the colour-magnitude diagram is too large to be acceptable.

Abundances of C, N, O elements could also play a role. Differences have been found by Alexander (1986) in the $C_2$ molecule measured in the Hyades and Coma Berenices. However, the problem is more complex, because in the case of the Hyades and Coma Berenices clusters we have to understand why they share the same main sequence. Therefore any difference in element- or molecule abundances worsens the problem instead of solving it.

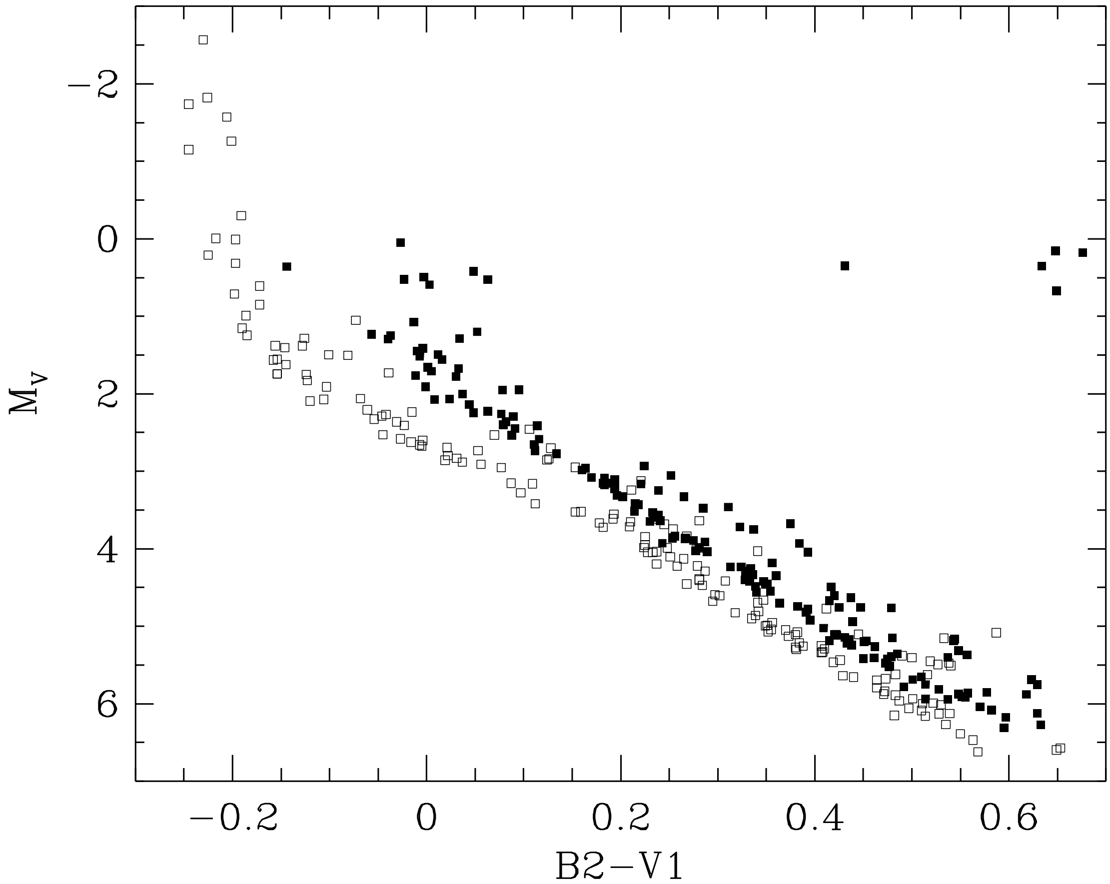


*Figure 4. Comparison of the sequences of the Praesepe (filled squares) and Pleiades (open squares) clusters. For $B_2 - V_1 > 0.20$, the difference is roughly constant and reaches 0.5 mag. The scatter observed in both sequences is mainly due to the presence of binary stars (Mermilliod et al. 1992, 1994).*

## 6. THE HYADES ANOMALY

The results from the analysis of Hipparcos data and the problem raised by the distance to the Pleiades are probably related to the so-called Hyades anomaly described by Crawford & Strömgren (1966). In the ($c_1$, $b-y$) plane, the sequence of unevolved Hyades stars deviates from the ZAMS sequence of field stars with the same overall metal abundance as the Hyades. After a thorough discussion of the anomaly, Strömgren et al. (1982) have suggested that it is due to a helium abundance difference. However, a combination of high resolution spectroscopy by Cayrel de Strobel et al. (1997) and new models adapted to the Hyades chemical composition discussed at this conference by Lebreton et al. (1997) shows that the helium abundance of the Hyades is $Y = 0.26 \pm 0.02$, and close to the solar one. This confirms earlier conclusion reached by Dobson (1990).

Alexander (1986) has shown that four parameters are needed to understand the colours of G dwarfs. Further insight has been provided by Nissen (1988) who observed unevolved F-type stars in 7 open clusters. He estimated photometric values of [Fe/H] from $\delta m_o$ and the value of $\delta c_o$ for each cluster. He corrected the absolute magnitude $M_V$ by the factor $f\ \delta c_o$, $f$ being defined by Crawford (1975, 1979). As stated by Nissen, 'the $\delta c_o$ anomaly of a cluster leads to an inconsistency in connection with the determination of its distance'. The resulting distance moduli are rather different from those obtained by standard main sequence fitting procedure. If the distance moduli of his Table 6 are adjusted to the Hipparcos Hyades – Praesepe distances, that of the Pleiades becomes close to the direct Hipparcos determination. This correction is admittedly crude and it would be necessary to redo the calibration with the latest values, but at least the order of magnitude of the effect has the right size. However the corrected moduli for $\alpha$ Persei and Coma Berenices are in bad agreement with those deduced from Hipparcos parallaxes.

Furthermore, in Nissen's (1988) Figure 9, the clusters that define the same zero age main sequence (Hyades, Praesepe, Coma Ber and $\alpha$ Persei) are on the same line defined by $\delta c_o = 0.25$ [Fe/H]. The Pleiades and NGC 2516 are clearly outside. Both clusters are well below the Hyades main sequence as shown in this contribution for the Pleiades and by Robichon et al. (1997) for NGC 2516.

Recently, Joner & Taylor (1995) have obtained new uvby$\beta$ data and found that Praesepe does not share the Hyades anomaly and is undistinguishable from Coma Berenices in that regard.

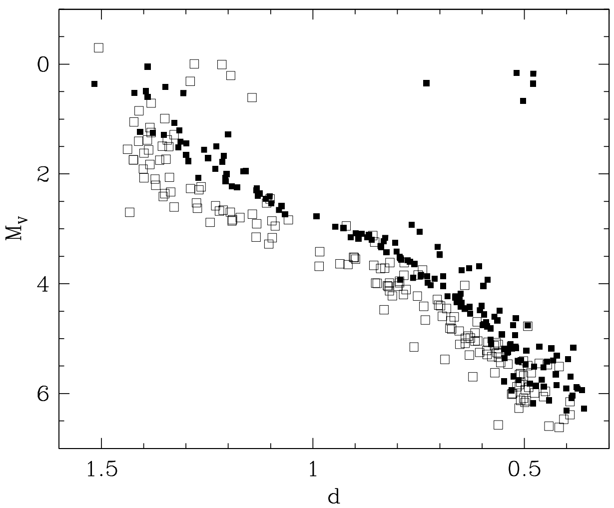


*Figure 5. Comparison of the sequences of the Praesepe (filled squares) and Pleiades (open squares) clusters. This plane is equivalent to ($M_V, c_1$).*

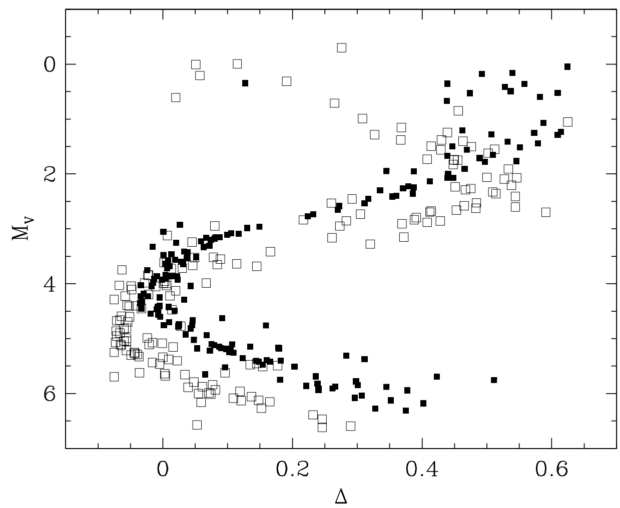


*Figure 6. Comparison of the sequences of the Praesepe (filled squares) and Pleiades (open squares) clusters. The all sequence of the Pleiades is displaced vertically.*

## 7. DISCUSSION

In the present situation, no simple correlation can be deduced from the available data. When clusters are taken by pairs of similar or different chemical composition, all situations arise:

- clusters with similar behaviour in the ($d$, $\Delta$) plane either define the same main sequence in the colour-magnitude diagram, as shown by the pair Coma Ber – $\alpha$ Persei, or define sequences that differ by 0.5 mag on the absolute magnitude axis, as shown by the pairs $\alpha$ Persei – Pleiades or Coma Ber – Pleiades;
- conversely, clusters with different behaviour in the ($d, \Delta$) plane, like Praesepe and Coma Ber, or Praesepe and Blanco 1, define closely the same main sequence.

We have so far relied mainly on one parameter, the metallicity, as measured by the ratio [Fe/H] or several photometric parameters, and assumed that the abundances of H and He were more or less similar. Now, we perhaps need to determine not only [Fe/H] but also the helium abundance. Even if the variations of these abundances are not correlated, it could happen that their effect sometimes cancels, namely if $\Delta Y \ / \ \Delta Z \sim 5$. This would explain why no difference is observed between Praesepe and Coma Ber or Blanco 1.

The Pleiades anomaly could be a peculiarity of the Local Association described by Eggen (1983a, 1983b) in which he included the Pleiades, IC 2602 and NGC 2516, three clusters affected by the Pleiades syndrome, and of the Gould Belt. If the link between the observed differences and the membership to the Local Association or the Gould Belt is correct and explains the effect shown by Hipparcos data, thus one could hope that the distances determined by the ZAMS fitting method for other clusters is safe. It will be however difficult to prove the validity of this assumption because no direct estimates of other distances can be obtained. Furthermore it cannot be excluded that similar anomalies also exist elsewhere in the solar vicinity.

The first question is thus to determine if the Pleiades anomaly is an isolated case or a frequent one. The answer is obviously not straightforward. The second question is whether there could be a 1.5 mas error in the parallax of the Pleiades: although errors in Hipparcos data cannot be precluded, various checks have been done about the parallax zero-point and the systematic error was found to be negligible on the average (Arenou et al. 1997b).

In another domain, the low detection rates of X-ray sources in Praesepe in comparison to the rates observed in the Hyades (Randich & Schmitt 1995) is another fact revealed by space observations of nearby clusters that challenges the present understanding of our visible Universe.

## 8. CONCLUSION

The analysis of Hipparcos parallaxes for nearby clusters have produced a complex result which challenges the common ideas and practice. On the one hand, Praesepe, Coma Berenices, $\alpha$ Persei and Blanco 1 define a common main sequence, and, on the other hand, the Pleiades, together with IC 2391 and IC 2602, defines another sequence about 0.5 mag fainter. No factor explaining this situation has yet been found. Metallicity effects alone can be probably ruled out. Differences in the abundances of helium and/or C, N, O elements could explain the observations. However the effect is not of the order of a few hundredths of magnitude: it reaches half a magnitude.

The displacement of the Pleiades sequence is not due to change in colour indices or parameters because the global effect is the same in several diagrams involving

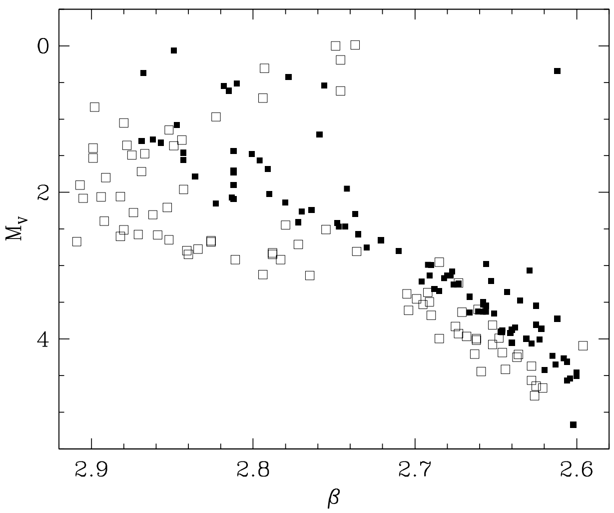


*Figure 7. Comparison of the sequences of the Praesepe (filled squares) and Pleiades (open squares) clusters. The same difference in the reference sequences is also apparent.*

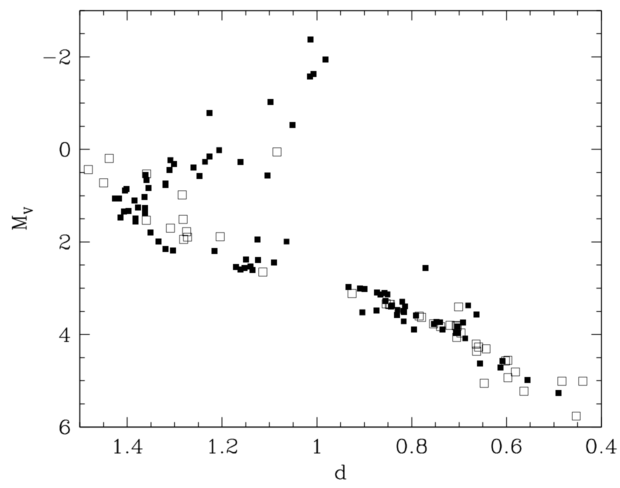


*Figure 8. Comparison of the sequences of $\alpha$ Per (filled squares) and Coma Ber (open squares) clusters. This diagram offers an example of a good agreement of the main sequences of both clusters.*

various parameters ($B_2 - V_1$, $d$, $\Delta$, $\beta$) which have different sensitivities to metallicity effects. Most of the effect is observed on the V magnitude. At a given $B - V$ value, a Pleiades star appears to be 0.5 mag fainter than a Coma Berenices or Praesepe star.

This result questions the simple main-sequence fitting method used so far to determine the distance of open clusters, and the predominent role of metallicity to explain the relative position of the ZAMS of different clusters. In addition to the metal and helium abundances, another parameter appears necessary to explain the behaviour of the Pleiades with respect to the other nearby clusters. Alexander (1986) and Nissen (1988) have already suggested that a fourth parameter was needed to describe solar-type stars.

In addition to the dramatic difference between the Pleiades and Praesepe, one should also remember the similarity of Coma Berenices and Praesepe, although the Coma Ber cluster was at the origin of the Hyades anomaly, and consequently the difference between the Pleiades and Coma Berenices, although they have a similar value of $\delta c_o$, according to Nissen (1988). No simple correlation is found when comparing the nearby open clusters by pairs: the behaviour in the colour-magnitude diagram is not related to any obvious differences in various photometric planes.

It is also interesting to consider the associations defining the Gould Belt. It has been shown in this conference that their direct distances are about 10 per cent smaller than their photometric distances. This result reinforces the reality of the new value of the Pleiades parallax.

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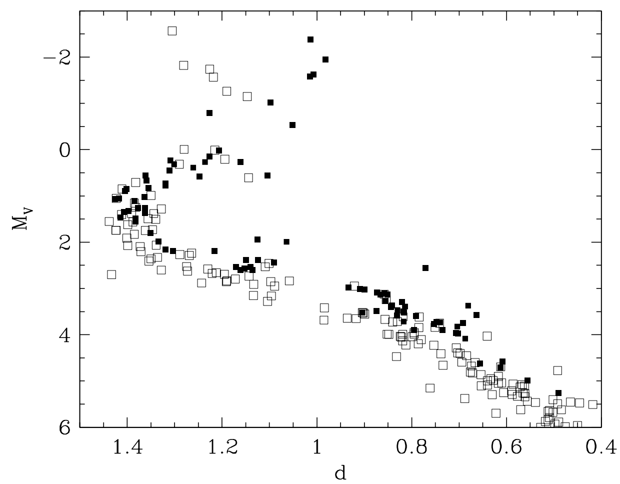


*Figure 9. Comparison of the sequences of the $\alpha$ Per (filled squares) and Pleiades (open squares) clusters. The Pleiades are located below the sequence of $\alpha$ Per.*

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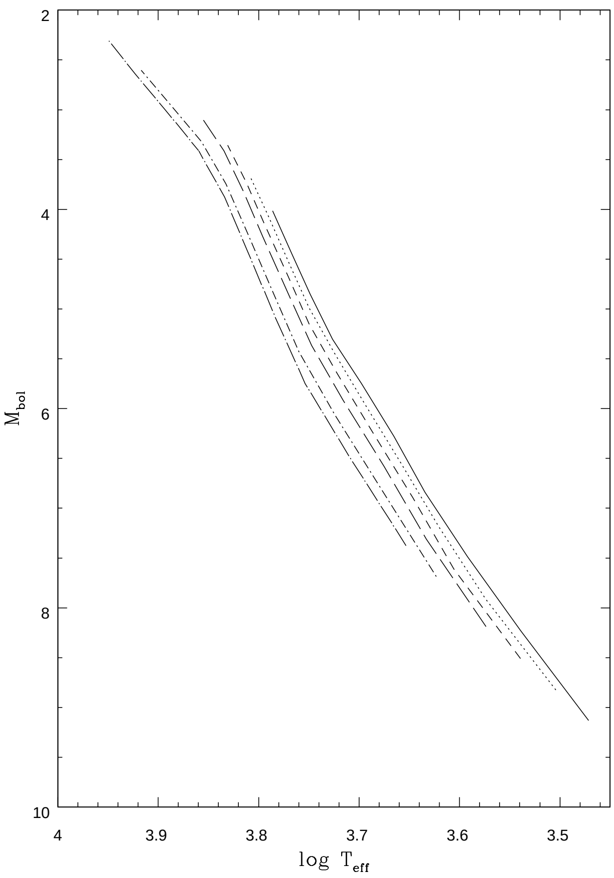


*Figure 10. The position of the ZAMS for various values of the helium abundance. From top to bottom: (Z,Y) = (0.020, 0.18), (0.020, 0.23), (0.020, 0.28), (0.020, 0.33), (0.015, 0.38), (0.015, 0.43).*


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