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The distance to the Pleiades

Main sequence fitting in the near infrared

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Abstract. Hipparcos parallax measurements of stars in the Pleiades notoriously result in a cluster distance of 118 pc, which is approximately 10% shorter than the "classical" result obtained from earlier main sequence (MS) fitting studies. In an earlier paper we developed a purely empirical MS-fitting method in an attempt to address this problem. This work produced conflicting results for the Pleiades between the $(B-V)$ and $(V-I)$ colour indices, indicating that the cluster's photometric metallicity is substantially lower than its generally accepted spectroscopic metallicity of [Fe/H] $= -0.03$. We were able to reconcile the discrepancy by assuming [Fe/H] $= -0.4$, the appropriate metallicity indicated from $(B-V)/(V-I)$ colour–colour plots, and the distance moduli obtained from the two colour indices were in agreement with the Hipparcos result, within the 1σ errors.
With the release of the 2MASS All Sky Catalogue, we now apply our MS-fitting method to the Pleiades using the infrared colours in addition to the optical bands, in order to test the plausibility of our earlier result.
Using the full field dwarf sample and fitting in the $V/(V-K)$ and $K/(J-K)$ colour planes, we find that assuming a substantially subsolar metallicity does not produce distances in agreement with the $(B-V)$ and $(V-I)$ results. However the infrared plus $(V-I)$ distances are in mutual agreement when adopting the spectroscopic metallicity. By considering only the field dwarfs with $M_V \leq 6$, i.e. brighter than the magnitude where the Pleiades $(B-V)$ colours start to be anomalous (Stauffer et al. 2003, AJ, 126, 833), the infrared and optical colour indices all yield consistent distances using the spectroscopic [Fe/H]. The concordant distances thus obtained from the $V/(B-V)$, $V/(V-I)$, $V/(V-K)$ and $K/(J-K)$ planes yield a mean of 133.8 ± 3 pc, in excellent agreement with both the pre-Hipparcos MS-fitting results, and the most recent determinations from other methods.
We conclude that there are two distinct, and unrelated, issues affecting the Pleiades: 1) the Hipparcos parallax is in error by $\sim$10%, as previously claimed; 2) the $(B-V)$ colours of the lower MS are anomalous, and we caution against using the $(B-V)$ index for MS-fitting to the Pleiades and similarly young open clusters.

Key words. Galaxy: open clusters and associations: general – Galaxy: open clusters and associations: individual: Pleiades – stars: Hertzsprung-Russell (HR) and C-M diagrams – stars: distances

1. Introduction

The distance to the Pleiades has been controversial ever since the Hipparcos mission (Perryman & ESA 1997) measured parallaxes of individual stars in the cluster – the mean distance to the cluster determined from individual star parallaxes was found to be approximately 10% shorter than distances previously determined from main sequence (MS) fitting methods. Specifically, the parallax measurements yield a distance of 118.34 pc, corresponding to a distance modulus of $(m-M)_0 = 5.37$ (van Leeuwen 1999 and references therein), whereas MS-fitting generally yields $(m-M)_0 \approx 5.6$ (around 132 pc) or even longer (e.g. Mitchell & Johnson 1957; Crawford & Perry 1976; Mermilliod 1981; Nicolet 1981; Eggen 1986; Vandenberg & Poll 1989).

After the release of the Hipparcos results, several authors attempted to address this discrepancy using various methods based on semi-empirical MS-fitting techniques, and all found distance moduli in agreement with the earlier MS-fitting results (Pinsonneault et al. 1998; Soderblom et al. 1998; Stello & Nissen 2001). On the other hand Castellani et al. (2002), who used purely theoretical isochrones in their fits, were able to retrieve the Hipparcos parallax distance by assuming a substantially subsolar metallicity for the cluster. Concerns were raised that most of the distance determinations in the literature use methods which have some model dependence which may introduce unquantified systematic errors, hence in an earlier paper (Percival et al. 2003, hereafter PSK03) we developed a purely empirical MS-fitting method. This method employs a sample of 54 local field stars, all with precise Hipparcos parallaxes, and with homogeneous metallicity determinations on a scale consistent with that of the open clusters being studied. These field stars were used to construct a template MS which was fit to several open clusters, including the Hyades and the Pleiades (PSK03; Percival & Salaris 2003). Fitting in both the $(B-V)$ and $(V-I)_C$ colour planes[1], this method precisely reproduces the Hipparcos distance to the Hyades, yielding $(m-M)_0 = 3.33 \pm 0.06$. Applying the same method to the Pleiades, we found that the $(B-V)$ fits yield $(m-M)_0 = 5.76 \pm 0.06$ whilst $(V-I)$ gave $(m-M)_0 = 5.58 \pm 0.04$ (corresponding to 141.9 and 130.6 pc respectively). Not only are these results much longer than the Hipparcos parallax distance, they are also mutually inconsistent.

The location of the MS in a colour–magnitude diagram (CMD) is, of course, dependent on metallicity and hence MS-fitting methods rely on matching the metallicity of the template MS to that of the cluster. In PSK03 we used the generally accepted spectroscopic metallicity for the Pleiades in our "standard" fits, specifically [Fe/H] = -0.03 ± 0.06 (this value, plus error bar is taken from the catalogue of Gratton 2000 and is based on the HRS determination of Boesgaard & Friel 1990). Since the $(B-V)$ and $(V-I)$ colour indices have different sensitivities to metallicity, the discrepancy found between the $(B-V)$ and $(V-I)$ MS-fitting results suggests that the spectroscopic metallicity is not the appropriate one to use when applying MS-fitting to the Pleiades. Assuming that both the $(B-V)$ and $(V-I)$ colours are normal for some metallicity, PSK03 used colour-colour diagrams to demonstrate that the photometric metallicity of the Pleiades is consistent with [Fe/H] = -0.4, and hence argued that this is the appropriate metallicity to use for MS-fits to the cluster. Repeating the MS-fits using this lower metallicity, PSK03 found that consistent distances were obtained between the two colour planes. Furthermore, the concordant distances derived at this assumed metallicity are much shorter than those obtained from the solar abundance fits, and are thus consistent with the Hipparcos parallax distance (see PSK03 for full details, and summary in Sect. 3.3, Table 1). Hence, in PSK03 we concluded that our analysis did not support any mismatch between the MS-fitting and Hipparcos distances for the Pleiades and that the widely discussed discrepancy is just an artifact due to the cluster's $(B-V)$ and $(V-I)$ colours (and hence, photometric metallicity), which are inconsistent with the spectroscopic metallicity.

However, the three most recent studies of the Pleiades, which use alternative distance determination methods, once again find long distances in general agreement with the earlier MS-fitting results. Pan et al. (2004) examined data for Atlas (the second brightest star in the Pleiades), a wide binary which is resolved using optical interferometry. Combining orbital data with an assumed mass-luminosity relation, they determine a distance of $133 < D < 137$ pc, with a firm lower bound of $D > 127$ pc. The results are slightly model-dependent, since the masses of the two components must be taken from model isochrones – however a 10% uncertainty on the mass only leads to a 3% uncertainty on the final derived distance, due to the precision of the orbital parameters. Meanwhile, Munari et al. (2004) studied the eclipsing binary HD 23642. From extensive new observations in Johnson B and V (to obtain light curves) and high resolution spectra (yielding radial velocities) they modelled the system and found a distance of 132 ± 2 pc. These results are also slightly model dependent as the temperature of the primary star must be determined independently – this is done by comparing photometry in many different systems (from the literature) to synthetic spectra. Most recently, Soderblom et al. (2004) have measured trigonometric parallaxes for three G and K dwarfs in the Pleiades, using the Fine Guidance Sensors on HST. Their net parallax result of 7.43 ± 0.17 milliarcsec, corresponding to a distance of 135 ± 3 pc, is in excellent agreement with both Pan et al. (2004) and Munari et al. (2004).

Hence the problem of the Pleiades distance discrepancy still exists – whilst empirical MS-fitting using the $(B-V)$ and $(V-I)$ colours now yields a distance in agreement with the Hipparcos one (by assuming the photometric metallicity rather than the spectroscopic one), other methods continue to find distances in agreement with the earlier, pre-Hipparcos, results.

It should be pointed out at this stage however that there is a known problem with the Pleiades, which may or may not be related to the distance discrepancies (we hope to clarify this point later). This is that the lower main sequence stars (the K dwarfs) fall well below the position expected for a solar metallicity system in the $V/(B-V)$ colour–magnitude diagram. Hence these stars are either underluminous, or have $(B-V)$ colours which are too blue for their (spectroscopic) metallicity. As discussed in detail by Stauffer et al. (2003) (hereafter S03), this fact has been known for many years, but has largely been ignored, and certainly not explained. S03 present new spectroscopic observations of several Pleiades K dwarfs and, by comparison with similar observations of K dwarfs in Praesepe, they show that the unusual blue colours in the Pleiades arise from anomalous spectral energy distributions (SEDs) – at least for the two Pleiades K dwarfs that they study. This anomaly, which S03 ascribe to rapid stellar rotation and "spottedness", causes the Pleiades stars to be approximately 10% brighter in the B-band than their Praesepe counterparts, whilst the V-band flux is unaffected. These spectroscopic measurements indicate that the $(B-V)$ colours of the Pleiades K dwarfs should be about 0.1 mag bluer in $(B-V)$ than the "standard" solar sequence, in agreement with the broadband observations.

Comparison of the shape of the MS for the two clusters shows that in the $V/(B-V)$ CMD the two sequences start to diverge at $M_V \approx 6.0$, in the sense that the Pleiades MS becomes increasingly bluer (or fainter) than the Praesepe MS towards fainter magnitudes (see S03, their Fig. 4). Crucially, this divergence occurs right in the middle of the magnitude range of the field dwarfs used in our empirical MS-fitting work, which have $5.4 \leq M_V \leq 7.0$. However, similar comparisons in the $V/(V-I)$ and $V/(V-K)$ planes show that the two sequences have identical shapes in the full magnitude range of our field dwarfs. This fact is very important for our study, as it implies that only the $(B-V)$ index is affected by an anomaly, and that

[1] Note that throughout this paper $(V-I)$ always refers to $(V-I)_C$, i.e. photometry in the Cousins system. Some cluster data used here has been converted from other photometric systems, as detailed in PSK03.

MS-fitting using $(V - I)$ and $(V - K)$ should give reliable (and consistent) results using the spectroscopic [Fe/H] for the cluster. We note here that when applying a MS-fitting method, for a fixed metallicity, the bluer (or more subluminous) the cluster MS, the longer the derived distance will be – hence the PSK03 results for $(B-V)$ and $(V-I)$, at [Fe/H] = −0.03, are consistent with the observations of S03.

With the release of the 2MASS All Sky Catalogue, we are now able to test our empirical MS-fitting method using the infrared colours in addition to the optical bands. We now know (from S03) that MS-fitting using $(B - V)$ colours may give spurious results for the Pleiades, therefore it is important to apply the method using the $(V - K)$ colours to see whether they yield a distance which is consistent with the $(V-I)$ result, since both indices appear to be unaffected by any colour anomalies in the magnitude range of interest. Also, if concordant distances are obtained, we vitally need to know whether they are consistent with the Hipparcos parallax distance, or the longer distance determined from other methods. The 2MASS data also allows us to utilise the $(J - K)$ colours. Whilst we have no specific information on the SEDs of the Pleiades K dwarfs in this part of the spectrum, the $(J-K)$ index should be much less sensitive to differences in metallicity than either $(V-I)$ or $(V-K)$, and is also much less affected by extinction. Using the $K/(J - K)$ CMD also ensures that the photometry is completely homogeneous between cluster and field stars and thereby minimizes systematic errors. Using $(J-K)$ and $(V-K)$ colour indices in addition to $(V-I)$ helps to constrain the cluster metallicity (and reddening) since the sensitivities are different for each colour index and consistent distances must be obtained from all the colour planes used if the results are valid. This should enable us to determine once and for all whether the discrepancy between the MS-fitting distance and the Hipparcos parallax distance for the Pleiades is real.

As in PSK03, the method can be tested on the Hyades since fits using the $(V - K)$ and $(J - K)$ must also be able to reproduce the Hipparcos distance modulus for the cluster. We can also use M 67 as a comparison cluster for the Pleiades since it has a similar spectroscopic metallicity ([Fe/H] = 0.02 ± 0.06 according to Gratton 2000), its $(B - V)/(V - I)$ colour–colour plot is consistent with solar metallicity field dwarfs (PSK03) and its distance is not disputed (see Sect. 3.2).

The layout of the rest of the paper is as follows: Sect. 2 lists the sources of data used in this work; Sect. 3 gives a brief overview of the empirical MS-fitting method, and presents the results of its application to the Hyades, M 67 and the Pleiades, and Sect. 4 contains a discussion of the results and some general conclusions.

2. Data sources

The empirical MS-fitting method used here is described in detail in PSK03, to which we refer the interested reader. In outline, the method utilizes a sample of 54 local unevolved (MS) field stars, with metallicities in the range $-0.4 \leq$ [Fe/H] $\leq$ 0.3 for which PSK03 obtained new $BV(RI)_C$ photoelectric photometry. All the stars in the sample have Hipparcos parallax measurements with errors less than 12%, Hipparcos catalogue entries were also carefully checked to avoid the inclusion of any binaries, and metallicities were determined from their Strömgren indices. JHK data were extracted from the 2MASS all-sky point source catalogue[2] using a star-by-star coordinate search. Combining the 2MASS magnitudes with the parallax data yields the absolute magnitudes, M_J, M_H and M_K, which are then corrected for Lutz-Kelker bias, as described in PSK03. We note here the 2MASS JHK data have already been retrieved and utilized by Sarajedini et al. (2004) in a MS-fitting study of several open clusters, and appear in their Table 2.

2MASS data for the Hyades were retrieved for all stars listed in Perryman et al. (1998) as single, definite cluster members, again using a coordinate search. Data for the Pleiades were obtained in a similar manner, individual MS stars having been identified from the Mermilliod's WEBDA database[3] (and see PSK03) and known binaries removed (Bouvier et al. 1997; Raboud & Mermilliod 1998). For M 67, the single star sequence was taken from Table 5 of Sandquist (2004), individual stars and their coordinates were then identified by cross-correlating with the data of Montgomery et al. (1993).

Since the field star and cluster data from 2MASS are all in the same photometric system, for which the K filter used is actually K_S (K short), no photometry conversions were necessary.

3. MS-fitting using 2MASS colours

Before MS-fitting can be performed, the [Fe/H] dependence of the colour index used must be determined so that the field star template can be matched to the metallicity of the cluster – here we use $(V - K)$ and $(J - K)$. This procedure is fully described in PSK03, where it was applied to $(B-V)$ and $(V-I)$, and it is also utilized by Sarajedini et al. (2004) to determine the metallicity dependence of $(V - K)$. Firstly, the slope of the relevant portion of the MS is estimated using the Hyades MS as a guide, then using this slope, each field star is "shifted" along this vector to an absolute magnitude of $M_V = 6.0$. The colour of each star at $M_V = 6.0$ (i.e. $(V - K)_{M_V=6.0}$) is then plotted against [Fe/H] to determine the metallicity dependence of the colour index (see top panel of Fig. 1). Using this procedure we find $\Delta(V - K)/\Delta$[Fe/H] = 0.190, in complete agreement with Sarajedini et al. (2004), who find $\Delta(V - K)/\Delta$[Fe/H] = 0.185.

When working with the $(J - K)$ colour index we will be using the $K/(J-K)$ CMD and hence the procedure is modified to find the $(J-K)$ colour at $M_K = 4.0$ (this roughly corresponds to $M_V = 6.0$ for the field star sample in that it falls near the middle of the range of magnitudes for the sample). The precise metallicity dependence of $(J - K)$ is harder to determine since the colour range of the field star sample is very small and the resultant $(J-K)_{M_K=4.0}$ vs. [Fe/H] plot is dominated by intrinsic scatter. In fact, the total colour range of the field dwarf sample, at their observed colours, is only 0.25 in $(J-K)$ compared with 0.91 in $(V - K)$.

A formal fit to the field star data yields a metallicity dependence of $\Delta(J - K)/\Delta$[Fe/H] = 0.078 although most of this dependence comes from the stars with [Fe/H] < 0.0 (see bottom

[2] Hosted by `http://irsa.ipac.caltech.edu/`

[3] `http://obswww.unige.ch/webda/webda.html`

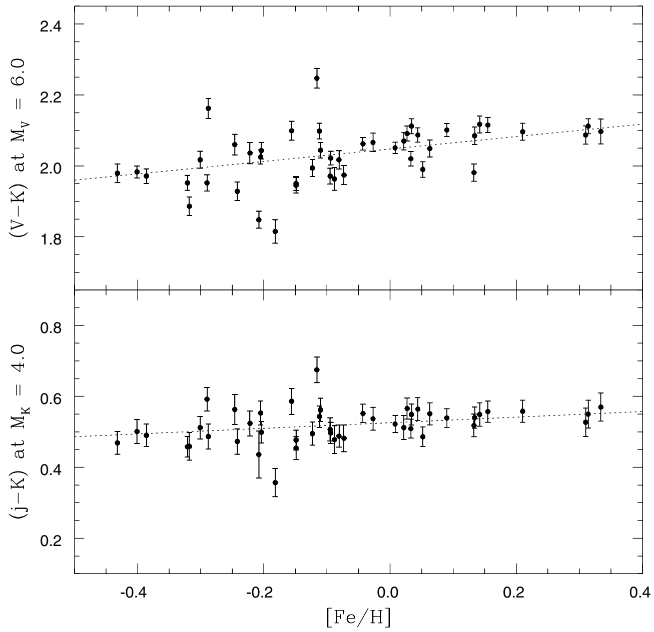

Fig. 1. Metallicity dependence in $(V-K)$ and $(J-K)$. Top panel – best fit relationship for the $(V-K)$ data, $\Delta(V-K)/\Delta$[Fe/H] = 0.19; bottom panel – best fit single slope to the $(J-K)$ data, $\Delta(J-K)/\Delta$[Fe/H] = 0.078. Note that the metallicity dependence is negligible for [Fe/H] $\geq$ 0.0

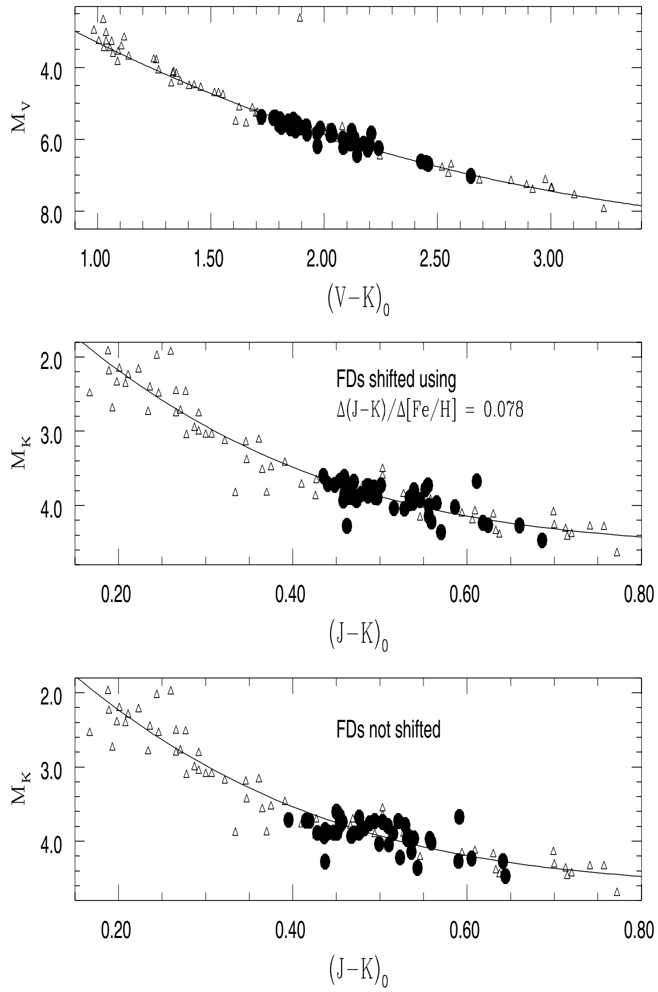

Fig. 2. Fits to the Hyades MS. All 3 plots show the Hyades single star data (open triangles) and polynomial fit to the MS line, both shifted in magnitude by the best-fit distance modulus, and the field star data at their absolute magnitudes (filled circles). Top panel – $V/(V-K)$ CMD, using best-fit distance modulus of $(m-M)_0$ = 3.33; middle and bottom panels – $K(J-K)$ CMDs, showing shifted and unshifted field stars using best-fit distance moduli of $(m-M)_0$ = 3.40 and $(m-M)_0$ = 3.35 respectively.

panel of Fig. 1). Fitting the subsolar and supersolar metallicity ranges separately we find $\Delta(J-K)/\Delta$[Fe/H] = 0.086 for [Fe/H] < 0.0, whilst $\Delta(J-K)/\Delta$[Fe/H] is virtually negligible for [Fe/H] > 0.0. We note here that this difference in metallicity dependence for the two metallicity regimes is in qualitative agreement with the theoretical isochrones of Girardi et al. (2000)[4] and Pietrinferni et al. (2004)[5]. However, the errors on these fits are of the same order of magnitude as the slopes, due to the relatively large scatter in the colours and, in fact, tests using the Hyades show that the metallicity dependence in $(J-K)$ is actually consistent with zero (see Sect. 3.1).

3.1. The Hyades

The Hyades fiducials were determined by fitting a polynomial (cubic) to all the available single star data, reddening was assumed to be zero and the metallicity was taken to be [Fe/H] = 0.13 ± 0.06 (cluster metallicities are taken from Gratton 2000, as explained in PSK03). Shifting the field star sample to [Fe/H] = 0.13 and fitting to the cluster fiducial in the $V/(V-K)$ plane gives a best-fit distance modulus of $(m-M)_0 = 3.33 \pm 0.04$, where the 1σ error accounts for photometry errors for the field stars, errors on magnitudes due to their parallax errors, and error due to the cluster metallicity, all added in quadrature.

In the $K/(J-K)$ plane, applying the maximum possible metallicity dependence ($\Delta(J-K)/\Delta$[Fe/H] = 0.078) to the field stars yields a best-fit distance modulus of $(m-M)_0 = 3.40 \pm 0.04$ which is marginally inconsistent with the Hipparcos parallax result of $(m-M)_0 = 3.33 \pm 0.01$. Since the mean metallicity of the field star sample is [Fe/H] ≈ -0.07 and the Hyades is at [Fe/H] = +0.13 (i.e. near the top end of the range of metallicities for the field stars), a relatively small error in the estimation of the metallicity dependence can become significant when the field stars are shifted. Hence it appears that the estimate of $\Delta(J-K)/\Delta$[Fe/H] = 0.078 is slightly too high. Repeating the MS-fit assuming no metallicity dependence in $(J-K)$ (i.e. $\Delta(J-K)/\Delta$[Fe/H] = 0.0) results in a best-fit distance modulus of $(m-M)_0 = 3.35 \pm 0.04$ (random errors only), in complete agreement with the Hipparcos result. The uncertainty on the level of metallicity dependence in the $(J-K)$ index induces a systematic error of ~0.06 mag on the Hyades distance modulus since the colours of the stars are being "shifted" on average 0.2 dex in metallicity, with an uncertainty of 0.078 in $\Delta(J-K)/\Delta$[Fe/H], and the slope of the MS in the $K/(J-K)$ CMD is approximately 4.

[4] Available at `http://pleiadi.pd.astro.it/`

[5] Available at `http://www.te.astro.it/BASTI/index.php`

It is important to realise however that the assumed level of metallicity dependence makes negligible difference to the MS-fitting results for the Pleiades. This is because the metallicity of the Pleiades is very close to the mean of the field star sample (we assume $[\mathrm{Fe/H}]_{\mathrm{Pleiades}} = -0.03 \pm 0.06$ in our standard fits). When building the MS template, individual field stars are being shifted both ways in the CMD, i.e. from lower to higher and from higher to lower metallicity, to match the metallicity of the cluster. Since the mean metallicity of the field stars is well matched to the cluster metallicity, most of the effects of the uncertainty on the metallicity dependence cancel out in this process (see Sect. 3.3).

3.2. M 67

Fiducials for M 67 were determined in the same way as for the Hyades, by fitting a polynomial to all the available single star data. The cluster metallicity was taken to be [Fe/H] = +0.02 ± 0.06 (Gratton 2000) and a reddening value of $E(B-V) = 0.04$ was taken from Twarog et al. (1997). Relative extinctions and reddenings were calculated according to Cardelli et al. (1989), so that $A_K = 0.114A_V$, $E(V-K) = 2.75E(B-V)$ and $E(J-K) = 0.52E(B-V)$. After correcting the cluster fiducial for extinction and reddening, and shifting the field stars to the cluster metallicity, the best-fit distance modulus in the $V/(V-K)$ plane was found to be $(m-M)_0 = 9.65 \pm 0.06$. We note that this is in complete agreement with the results of Sarajedini et al. (2004) who find $(m-M)_V = 9.74 \pm 0.06$ (corresponding to $(m-M)_0 = 9.62$, with $E(B-V) = 0.04$) from a $(V-K)$ MS-fit of our field dwarf sample to the M 67 data of Montgomery et al. (1993). In the $K/(J-K)$ plane the best-fit is $(m-M)_0 = 9.63 \pm 0.06$ if the stars are shifted using $\Delta(J-K)/\Delta[\mathrm{Fe/H}] = 0.078$, or $(m-M)_0 = 9.61 \pm 0.06$ if no metallicity dependence is assumed. The quoted 1σ errors are as for the Hyades, but now also include the effect of an assumed uncertainty of 0.02 mag in $E(B-V)$. These results are in complete agreement with the results of MS-fitting using optical CMDs – Percival & Salaris (2003) find $(m-M)_0 = 9.60 \pm 0.09$ whilst Sandquist (2004) finds 9.60 ± 0.03.

3.3. The Pleiades

The Pleiades fiducials were determined in the same way as for the Hyades, by fitting a polynomial to all the single star data. As in PSK03, reddenings for individual stars were taken from Breger (1986) (for those with no listing an average of $E(B-V) = 0.04$ was used) and Gratton's metallicity of $[\mathrm{Fe/H}] = -0.03 \pm 0.06$ was assumed in the standard fits. Applying reddening and extinction corrections as before and shifting the field stars to the cluster metallicity, the best-fit distance modulus in $V/(V-K)$ is $(m-M)_0 = 5.67 \pm 0.06$, where the 1σ error includes an uncertainty of 0.02 mag in $E(B-V)$, as for M 67. In the $K/(J-K)$ plane, the best-fit yields $(m-M)_0 = 5.61 \pm 0.05$ – it is important to note that in this plane, the results are the same, to within 0.01 mag, whether or not a metallicity dependence is assumed in $(J-K)$.

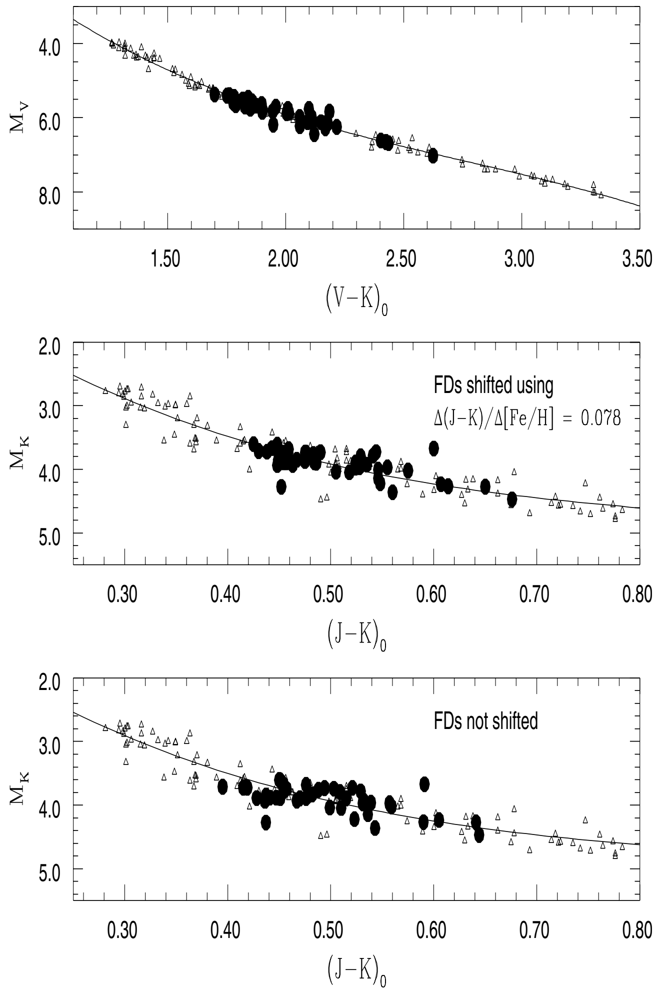

Fig. 3. Fits to dereddened and extinction corrected M 67 MS – symbols as for Fig. 2. Top panel – $V/(V-K)$ CMD, using best-fit distance modulus of $(m-M)_0 = 9.65$; middle and bottom panels – $K(J-K)$ CMD, showing shifted and unshifted field stars, using best-fit distance moduli of $(m-M)_0 = 9.63$ and 9.61, respectively.

In response to the findings of S03, we returned to the $(B-V)$ data and tested the effect of imposing a cut at $M_V = 6.0$, the point at which the $V/(B-V)$ MS appears to diverge from the "standard" sequence. Using only field stars with $M_V < 6.0$ in the fit, the best-fit distance modulus is $(m-M)_0 = 5.67 \pm 0.06$, a reduction of 0.09 mag compared to the result from the full sample (PSK03). Significantly, imposing the same cut in the $V/(V-I)$, $V/(V-K)$ and $K/(J-K)$ planes produces the same results as those obtained from the full sample.

We recall here that PSK03 found that by assuming $[\mathrm{Fe/H}]_{\mathrm{Pleiades}} = -0.4$, the $V/(B-V)$ and $V/(V-I)$ CMDs yielded distance moduli in agreement with the Hipparcos parallax result (specifically, $(m-M)_0 = 5.46$ and 5.39 respectively, using the full field dwarf sample). In order to test the plausibility of this cluster abundance, we performed the $V/(V-K)$ and $K/(J-K)$ fits again, this time using [Fe/H] = −0.4, keeping the same reddening as for the standard fits. The $V/(V-K)$ fit yields $(m-M)_0 = 5.53 \pm 0.06$ whilst the $K/(J-K)$ fits yield $(m-M)_0 = 5.49 \pm 0.05$ for $\Delta(J-K)/\Delta[\mathrm{Fe/H}] = 0.078$ and $(m-M)_0 = 5.61 \pm 0.05$ when no metallicity dependence

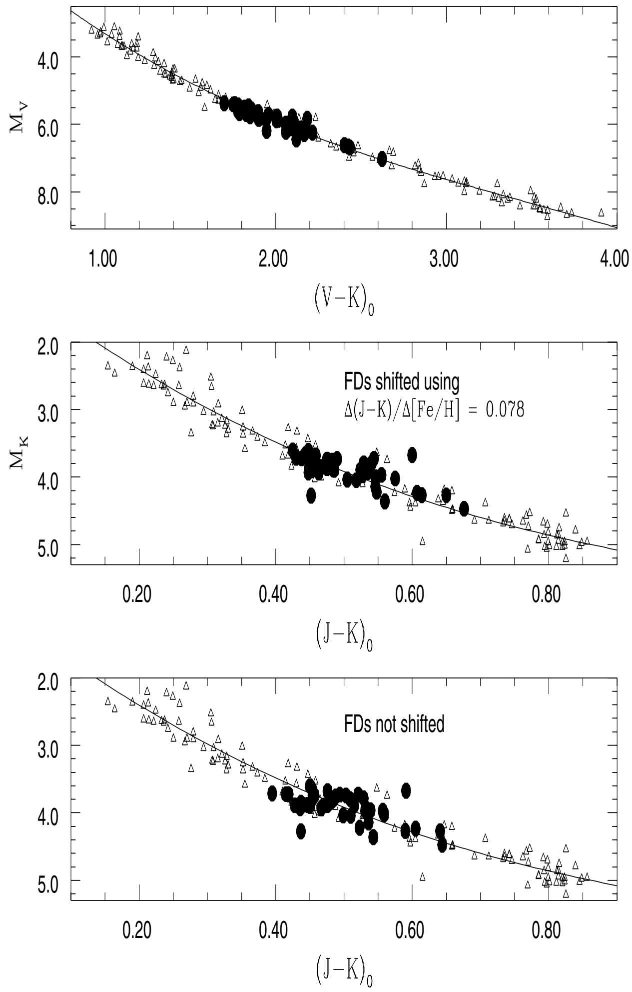

Fig. 4. Fits to dereddened and extinction corrected Pleiades MS – symbols as for Fig. 2. Top panel – $V/(V-K)$ CMD, using best-fit distance modulus of $(m-M)_0 = 5.67$; middle and bottom panels – $K(J-K)$ CMD, shifted and unshifted field stars respectively, both using best-fit distance modulus of $(m-M)_0 = 5.61$.

is assumed (i.e. the same result as for $[\mathrm{Fe/H}]_{\mathrm{Pleiades}} = -0.03$). Imposing a cut at $M_V = 6.0$, as before, has exactly the same effect on the results as for the $[\mathrm{Fe/H}] = -0.03$ fits, i.e. the $V/(B-V)$ distance modulus is reduced by 0.09 mag, to $(m-M)_0 = 5.37$, whilst the results from the other colour indices remain unchanged.

All these results are summarised in Table 1.

4. Discussion and conclusions

4.1. Summary of results

If we accept that the K dwarfs in the Pleiades really are too blue in $(B-V)$ for their spectroscopic metallicity, as indicated by S03, then we should not expect the $(B-V)$ and $(V-I)$ MS-fitting results to be the same if the full MS is used (i.e going fainter than $M_V = 6.0$). In fact, we should treat with caution any models which claim to find concordant distances in these two planes, since the colours of the lower MS (the K dwarfs) are obviously anomalous for any value of [Fe/H], whether solar or otherwise.

Excluding the $(B-V)$ results using the whole field dwarf sample, the distance moduli obtained from the "standard" fits in all the other colour planes (i.e. $V/(V-I)$, $V/(V-K)$ and $K/(J-K)$) are in agreement with each other within their 1σ errors – and all are discrepant by at least 3σ with the Hipparcos result. The average of the $(V-I)$, $(V-K)$ and $(J-K)$ fits is $(m-M)_0 = 5.62 \pm 0.05$, corresponding to 133.1 ± 3 pc. Imposing a cut at $M_V = 6.0$ and including the $(B-V)$ results, the average of the fits in all four colour planes is $(m-M)_0 = 5.63 \pm 0.04$, or 133.8 pc.

Assuming $[\mathrm{Fe/H}]_{\mathrm{Pleiades}} = -0.4$ (as we did in PSK03), whilst bringing the $(B-V)$ and $(V-I)$ results into agreement with the Hipparcos parallax distance, does not yield consistent results in $(V-K)$ and $(J-K)$. The $V/(V-K)$ distance modulus is still discrepant with the Hipparcos one at the 2σ level, whilst the $(J-K)$ result is slightly more ambiguous because of the uncertainty on the metallicity dependence for this colour index. However, even using the maximum dependence, the result of $(m-M)_0 = 5.49 \pm 0.05$ is still discrepant by more than 1σ from the Hipparcos distance modulus.

In summary, each of the four CMDs used here has a different slope on the MS and a different sensitivity to the effects of reddening and metallicity. We can find no combination of [Fe/H] and $E(B-V)$ which produces distance moduli which are consistent across all four colour planes simultaneously when the full magnitude range of our field dwarf sample is used. However, imposing a cut at $M_V = 6.0$ brings all the distance moduli into agreement when assuming the generally accepted metallicity of $[\mathrm{Fe/H}] = -0.03$, and average reddening of $E(B-V) = 0.04$. Furthermore, the average of the best-fit distance moduli yields a Pleiades distance of 133.8 ± 3 pc, in complete agreement with the results obtained from binaries in the cluster (Pan et al. 2004; Munari et al. 2004) and the most recent parallax determination from HST (Soderblom et al. 2004).

4.2. Some caveats

When applying the MS-fitting method to any cluster to derive its distance, using the local field stars as a template, we are assuming that we are comparing like with like – practically, this is the only sensible assumption we can make. The Pleiades is known to be anomalous in several respects – we know it is very young (~100 Myr) and has fast rotating stars, which may be affecting the $(B-V)$ colours, whilst the field stars have unknown ages but are likely to be much older (typically a few Gyr).

Spectroscopic metallicity determinations rely on some assumptions, one of which is a temperature scale. The spectroscopic determination used here (and generally regarded as the most reliable one) is from Boesgaard & Friel (1990), who used the temperature scale of Boehm-Vitense (1981). This temperature scale is based on $(B-V)$ colours – i.e. from an observed colour, a temperature is inferred. Boesgaard & Friel determined temperatures for the Pleiades stars using $(B-V)$, Strömgren $b-y$ and Hβ photometry, all essentially in the same (blue) portion of the optical spectrum, as detailed in Boesgaard et al. (1988). They themselves noted that the $(R-I)$ data was also examined for use in determining the temperatures but go on to say

Table 1. Summary of MS-fitting results for the Pleiades.

CMD	$(m-M)_0$ at [Fe/H] = −0.03	$(m-M)_0$ at [Fe/H] = −0.4
$V/(B-V)$ (full sample)	5.76 ± 0.06	5.46 ± 0.06
$V/(B-V)$ ($M_V < 6.0$ only)	5.67 ± 0.06	5.37 ± 0.06
$V/(V-I)$	5.58 ± 0.04	5.39 ± 0.04
$V/(V-K)$	5.67 ± 0.06	5.53 ± 0.06
$K/(J-K)$ (with [Fe/H] dependence)	5.61 ± 0.05	5.49 ± 0.05
$K/(J-K)$ (no [Fe/H] dependence)	5.61 ± 0.05	5.61 ± 0.05
Hipparcos result (van Leeuwen 1999)	5.37 ± 0.07	

that it was "rejected on the basis that all calibrations gave consistently lower temperatures than those obtained using the three other indices". We remark that this is consistent with the observation that the late-type MS stars in the Pleiades have $(B-V)$ colours which are anomalously blue when compared to indices in other parts of the spectrum, in that a bluer colour indicates a higher temperature.

The problem of determining which colour index yields the most appropriate temperature is not just confined to the Pleiades. In a study of photospheric abundances in active binaries, Morel et al. (2004) state that there is a tendency for the $(V-R)$ and $(V-I)$ indices to yield systematically lower temperatures than $(B-V)$. As was the case for the Pleiades, Morel et al. (2004) regard the $(V-R)$ and $(V-I)$ colour temperatures as being "spuriously low". On the other hand, in a study of the effect of chromospheric activity on the mean colour of late-type stars, Amado (2003) find evidence for a blue excess in both the $(U-B)$ and $(B-V)$ indices for active stars when compared with quiescent ones of the same spectral type. In fact, Amado (2003) cautions against the use of the $(B-V)$ index when determining fundamental parameters (e.g. temperature) for late-type active (i.e. young) stars and suggests that near-infrared colours should be better temperature indicators for these stars. It is beyond the scope of this work to predict what effect this may have on the derived spectroscopic metallicity for the Pleiades and other young clusters, but it should be borne in mind when assuming a metallicity for MS-fitting.

Reddening estimates are also generally determined from a star's colours, assuming that they are normal for their particular spectral type. Most of the Breger (1986) reddenings for the Pleiades stars are derived from broadband $(B-V)$ or Strömgren $b-y$ indices, both of which are in the potentially anomalous part of the spectrum. If the B flux is too strong for the late-type (lower MS) stars, and hence the colours too blue at a fixed spectral type, this would seem to indicate that the derived reddenings would be under-estimated. This would only serve to make the Pleiades problem worse in that assuming a higher reddening would yield an even longer distance. However the referee has pointed out that the Pleiades reddening (and metallicity) measurements are in fact heavily weighted towards stars of early spectral types (mostly B, A and F), and so the canonical reddening and metallicity values may not be greatly affected by the anomaly displayed by the K dwarfs.

4.3. Main conclusion

We conclude that there are two distinct, and unrelated, issues pertaining to the determination of the Pleiades distance:

- We believe that the Hipparcos parallax distance to the Pleiades really is too short by approximately 10%, as initially suspected.
- The $(B-V)$ colours of the lower MS (the K dwarfs) are anomalously blue and we caution against their use for MS-fitting to the Pleiades and other young open clusters.

More detailed spectroscopic study is urgently needed to determine the true [Fe/H] for the Pleiades – bearing in mind that spectroscopic metallicity determinations have to assume some temperature scale, any anomalies must be accounted for (or at least qualitatively assessed) in this process.

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