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The distance to the Pleiades from orbital solution of the double-lined eclipsing binary HD 23642⋆,⋆⋆

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Abstract. Combining precise B, V photometry and radial velocities, we have been able to derive a firm orbital solution and accurate physical parameters for the newly discovered eclipsing binary HD 23642 in the Pleiades open cluster. The resulting distance to the binary and therefore to the cluster is 132 ± 2 pc. This closely confirms the distance modulus obtained by classical main sequence fitting methods ($m - M = 5.60$ or 132 pc), moving cluster techniques and the astrometric orbit of Atlas. This is the first time the distance to a member of the Pleiades is derived by orbital solution of a double-lined eclipsing binary, and it is intended to contribute to the ongoing discussion about the discordant Hipparcos distance to the cluster.

Key words. stars: binaries: eclipsing – stars: distances – stars: fundamental parameters – stars: individual: HD 23642 – stars: HR and C-M diagrams – Galaxy: open clusters and associations: individual: Pleiades

1. Introduction

The distance to the Pleiades has been derived by main-sequence fitting methods several times over the years, and consistently found to cluster around $m - M = 5.60 \pm 0.04$ (e.g. Turner 1979; Meynet et al. 1993), corresponding to a distance of 132 (±2) pc. Values of $m - M = 5.52$ (127 pc) by Mitchell & Johnson (1957) and $m - M = 5.75$ (141 pc) by Eggen (1950) bracket the range of published distance moduli. Therefore, it came as a surprise the shorter distance of 116 ± 3.3 pc ($m-M = 5.33 \pm 0.06$) derived from the parallaxes of 54 Pleiades members when the results of the Hipparcos astrometric mission became available (van Leeuwen & Hansen Ruiz 1997). The ~0.3 mag difference has far reaching consequences in many areas of astrophysics, and it soon prompted extensive observational and theoretical work to account for it.

An anomalous abundance of helium was discussed as a possible explanation of the large difference between Hipparcos and ground-based photometric distances to the Pleiades (Mermilliod et al. 1997a). The required helium over-abundance ($Y = 0.37$) is however too large to be a feasible explanation according to Pinsonneault et al. (1998). A sub-solar metallicity could reconcile the distances, but the metallicity of the Pleiades has been measured several times and with different methods, which generally converged to a mean value of [Fe/H] = 0.00 ± 0.03 (e.g. Stauffer et al. 2003). Castellani et al. (2002) were able to obtain a good fit of the Pleiades main sequence with their theoretical isochrones (with updated physical inputs) and the Hipparcos distance, employing a sub-solar metallicity of [Fe/H] = −0.15. Working differentially with a sample of nearby G and K stars, Percival et al. (2003) presented a recalibration of photometric metallicity indexes and argued that they support a sub-solar metallicity of the Pleiades in spite of the spectroscopic evidences (e.g. Boesgaard & Friel 1990) for a solar one, therefore removing the difference between main-sequence fitting and Hipparcos distances. However, Stauffer et al. (2003) remarked about the anomalous blue colors of K stars in the Pleiades, that they ascribed to fast rotation and spotted surfaces as a consequence of the young age of the cluster.

Narayanan & Gould (1999) derived a distance modulus to the Pleiades of $m - M = 5.58$ (±0.18) using a variant of the moving cluster method, the gradient in the radial velocity of the cluster members in the direction of the proper motion of the cluster. Their techniques relies on the assumption that the velocity structure of the Pleiades is not significantly affected by rotation. Narayanan & Gould concluded that the errors in the Hipparcos parallaxes toward Pleiades are spatially correlated over angular scales of a few degrees, with an amplitude

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⋆ The photometric and spectroscopic observations discussed in this paper are electronically available from the web page http://ulisse.pd.astro.it/HD_23642/

⋆⋆ Based in part on spectra collected with the ELODIE spectrograph at the 1.93 m telescope of the Observatoire de Haute Provence (OHP), France.

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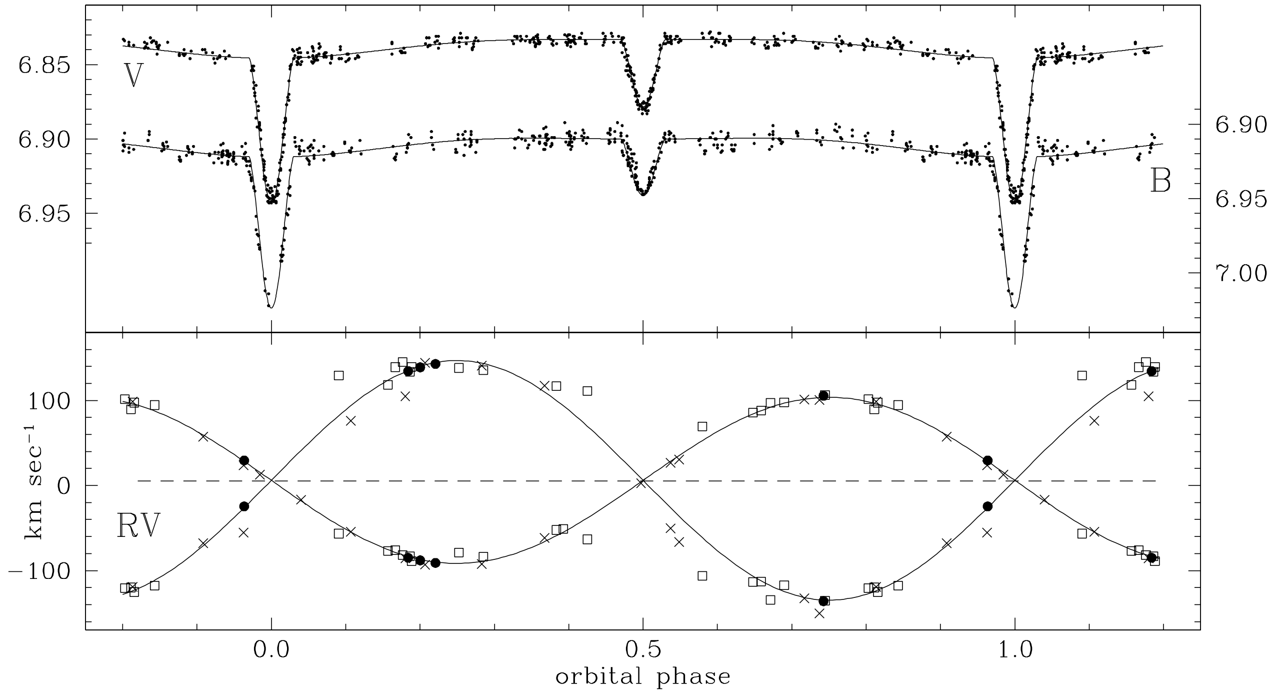

Fig. 1. Our photo-electric V (*top*) and B (*bottom*) observations of HD 23642 are phase plotted in the upper panel following the ephemeris of Table 2. The lower panel displays our radial velocities from Table 1 (filled circles) and those from Pearce (1957, squares) and Abt (1958, crosses). The curves over plot the orbital solution given in Table 2.

up to 2 mas. Almost simultaneously, however, van Leeuwen (1999) compared the results on 9 clusters and concluded instead that the Hipparcos parallaxes of the Pleiades were basically unaffected by systematics and that the distance modulus to the latter is $m - M = 5.37$ (±0.07). Makarov (2002) suggested that, while Hipparcos parallaxes are overall of excellent quality, those for the Pleiades suffered from data analysis procedures that could have introduced systematics when a rich and bright cluster was crossing one of the two Hipparcos fields of view while the other was essentially deprived of stars, as in the case of Pleiades. From intermediate Hipparcos data and under some assumptions, Makarov has recomputed the distance to the Pleiades as 129 ± 3 pc. van Leeuwen (private communication) is currently working on a further iteration on original Hipparcos reductions that should assess and quantify is any systematics affect the Pleiades data.

The question about the distance to the Pleiades has not yet been firmly solved, and to tackle it new, robust and independent approaches (as much geometric as possible) are required. A first one, advocated by Paczýnski (2003), combines astrometric and spectroscopic observations of Atlas (HD 23850), one of the brightest members of the Pleiades, which is an astrometric binary with a period of 291 day, a semi-major axis of 12.9 mas and 0.246 eccentricity. Pan et al. (2004) did not have the radial velocities, but they anyway derived the distance by combining the astrometric orbit with a mass-luminosity relation. They derived a distance of 135 ± 2 pc, which is in close agreement with the results of main-sequence fitting methods.

Another method involves double-lined eclipsing binaries (SB2 EB), which are the distance indicators now providing the most reliable distances to Magellanic Clouds and other galaxies in the Local Group. The recent discovery by Torres (2003) that HD 23642 in the Pleiades is an SB2 eclipsing binary (the only one so far known in the cluster) prompted us to use it to measure the distance to the Pleiades. In this *Letter* we present accurate new B and V photoelectric photometry and radial velocities of HD 23642, and use them to derive an orbital solution and infer the distance to the star, and therefore to the cluster.

2. Observations

We observed HD 23642 in B and V (standard Johnson filters) from a private observatory near Cembra (Trento), Italy. The instrument was a 28 cm Schmidt-Cassegrain telescope equipped with an Optec SSP5 photometer. It proved already to be a very accurate and reliable instrument (cf. Siviero et al. 2004) perfectly suited to deal with the low amplitude of HD 23642 eclipses (~0.1 mag). HD 23568 (HIP 17664, $V_T = 6.824 \pm 0.011$, $B_T = 6.842 \pm 0.015$, spectrum B9.5V) was chosen as comparison star and HD 23763 (HIP 17791, $V_T = 6.963 \pm 0.011$, $B_T = 7.109 \pm 0.016$, spectrum A1V) as a check star. Following the Bessell (2000) transformations between Tycho and Johnson photometric systems, we adopted $V = 6.830$ and $B = 6.851$ for the comparison star. The comparison star was measured against the check star at least once every observing run, and found constant with standard deviations of 0.005 mag in V and 0.006 mag in B, confirming the Hipparcos photometric results. In all, 492 measurements in V, and 432 in B were collected of HD 23642 between Aug. 19, 2003 and Feb. 16, 2004. All the observations were corrected for atmospheric extinction and instrumental color equations (via calibration on Landolt's equatorial fields), and the instrumental differential magnitudes were transformed into the standard Johnson UBV system. The variable, comparison and check stars are similar in spectral type, lie very close on the sky (15 arcmin) and

Table 1. Heliocentric radial velocities of HD 23642. The S/N is evaluated around 5500 Å.

date 2004	UT	HJD (+2453000)	S/N	RV_1 (km s^{-1})	RV_2 (km s^{-1})
Feb 3	21.8689	39.41273	152	−85.0±0.5	+134.5±0.5
Feb 3	22.8489	39.45356	118	−88.0±0.5	+139.0±0.5
Feb 4	0.0949	39.50548	84	−91.0±0.5	+143.0±1.0
Feb 7	17.9842	43.25049	106	+105.5±1.5	−136.0±1.0
Feb 10	18.0764	46.25318	121	+29.5±0.5	−24.5±1.0

were always observed at zenith distances <60°, which argues for a high consistency of our photometry.

High resolution spectra of HD 23642 were obtained at five distinct epochs with the ELODIE echelle spectrograph at the 1.93 m telescope of the Haute-Provence Observatory (Baranne et al. 1996). ELODIE covers the spectral range 3900–6800 Å in a single exposure as 67 orders at a mean resolving power of 42 000. Optimal extraction and wavelength calibration were performed with the on-line automatic reduction pipeline. Radial velocities for the two components are reported in Table 1. They were measured by both classical cross-correlation against suitable A-type templates and by the Least-Square Deconvolution method of Donati et al. (1997). The errors given in Table 1 reflect the scatter of the measurements obtained with the two methods run with different parameters.

3. The temperature of the primary and the reddening

One parameter, the temperature of the primary (T_1), cannot be directly modeled in SB2 EB analysis and must be determined independently. In the case of HD 23642, the spectral classification reported in literature is too sparse, ranging from B9 to A1. To determine T_1 we then turned to photometry and searched the literature and the General Catalogue of Photometric Data (GCPD, Mermilliod et al. 1997b) for observations of HD 23642. Data were found in the Walraven *VBLUW*, Strömgren *ubvy*, *WBVR*, Geneva, DDO, Vilnius, Johnson *UBVRI*, Tycho, 2MASS and ASN 74 photometric systems (Crawford & Perry 1976; Kornilov et al. 1991; Morel & Magnenat 1978; Persinger & Castelaz 1990; van Leeuwen et al. 1986; Wesselius et al. 1982, GCPD). Using the relevant parameters for these systems as censed in the Asiago Database on Photometric Systems (Moro & Munari 2000; Fiorucci & Munari 2003), they were applied to the extensive synthetic spectral atlas of Munari et al. (2004). A total of 2310 synthetic spectra of the binary were retrieved from it considering all possible combinations of 7 different temperatures for the primary ($9000 \leq T_2 \leq 10\,500$ K), 10 for the secondary ($6750 \leq T_2 \leq 9000$ K), 3 values for the gravity ($\log g$ = 4.0, 4.5, 5.0) and 11 for the reddening ($0.00 \leq E_{B-V} \leq 0.10$). The [Fe/H] = 0.00 ± 0.02 metallicity of the Pleiades reported by Stauffer et al. (2003) was adopted, as well as the standard $R_V = A_V/E_{B-V} = 3.1$ reddening law (Fitzpatrick 1999) that was found to be valid for the Pleiades by Guthrie (1987). A minimum distance method was then applied to observed and computed colors in each photometric system, which provided pretty consistent results among them. The weight averaged means for the temperature of the primary and the reddening were well constrained to $T_1 = 9671 \pm 46$ K and $E_{B-V} = 0.012 \pm 0.004$. Less constrained were the temperature of the fainter secondary ($T_2 = 8023 \pm 544$ K) and the surface gravity of the primary ($\log g_1 = 4.17 \pm 0.13$), while the gravity of the secondary gave no measurable signal.

Table 2. Orbital solution for HD 23642 (over plotted to observed data in Fig. 1). Formal errors of the solution are given. †: derived from analysis of multi-band photometry and fixed.

P (d)	2.46113400	±	0.00000034
$T_\circ$ (HJD)	2452903.5981	±	0.0013
$a\,(R_\odot)$	11.956	±	0.030
V_γ (km sec^{-1})	5.17	±	0.24
$q = \frac{m_2}{m_1}$	0.6966	±	0.0034
$i\,(°)$	78.10	±	0.21
e	0.0	±	0.002
T_1 (K)	9671†		
T_2 (K)	7500	±	61
Ω_1	7.323	±	0.111
Ω_2	6.703	±	0.096
$R_1\,(R_\odot)$	1.81	±	0.030
$R_2\,(R_\odot)$	1.50	±	0.026
$M_1\,(M_\odot)$	2.24	±	0.017
$M_2\,(M_\odot)$	1.56	±	0.014
$M_{bol,1}$	1.26	±	0.042
$M_{bol,2}$	2.77	±	0.052
$M_{bol,tot}$	1.02	±	0.035
$\log g_1$ (cgs)	4.27	±	0.015
$\log g_2$ (cgs)	4.28	±	0.016
distance (pc)	131.9	±	2.1

The value of the reddening is perfectly confirmed by the equivalent width of the interstellar NaI D lines. We measured them on our high resolution spectra and found *EW*(NaI 5890 Å) = 0.035 ± 0.001 Å that corresponds to E_{B-V} = 0.011 adopting the Munari & Zwitter (1997) calibration. White et al. (2001) has derived a closely similar equivalent width (0.036 ± 0.003 Å) from a single, higher resolution spectrum.

4. Orbital solution and distance to the Pleiades

To augment the number and phase coverage of the radial velocities, in the orbital solution we also considered the measurements by Pearce (1957) and Abt (1958). The adopted average relative weights are 10, 2, 1.5 for ours, Pearce and Abt data, respectively.

The orbital solution of HD 23642 has been obtained with version WD98K93d of the Wilson-Devinney code (Wilson & Devinney 1971) as modified by Milone et al. (1992) to include Kurucz's model atmospheres to approximate the surface fluxes of the two stars. The computations have been run within `Mode-2` program option. Limb darkening coefficients have been taken from van Hamme (1993) interpolated for the metallicity, temperature and gravity appropriate for the components of HD 23642. A linear law for limb darkening and single reflection (i.e. only the inverse square law illumination) were considered. The bolometric albedos were set to 1.0 and tests on the lightcurve confirmed the choice. Finally, a gravity brightening exponent β = 1.0 has been adopted consistent with the radiative nature of the atmospheres in HD 23642. The effects on the orbital solution of the adopted limb darkening coefficients and law, bolometric albedos, single reflection scenario and gravity brightening exponent are essentially negligible. Their cumulative impact on the final distance to HD 23642 does not exceed ∼1 pc. The orbital solution is given in Table 2 and over plotted to the data in Fig. 1. The parameters in common with the radial-velocities-only solution of Torres (2003) are very similar.

The two stars are well within their Roche lobes and not distorted. The orbit appears relaxed to stationary conditions. In fact, the eccentricity is null within a small uncertainty and the rotational velocity of the two components, as measured on the high resolution spectra (37 ± 1 for the primary and 31 ± 2 km s^{-1} for the secondary), is that expected for the rotation period to be synchronous with the orbital period.

The barycentric radial velocity of HD 23642, V_γ = 5.17 ± 0.24 km s^{-1}, is coincident with the mean radial velocity of the Pleiades within the velocity dispersion of its members. They are $RV_{\rm cluster}$ = 5.19 km s^{-1} and σ_{RV} = 0.70 km s^{-1} according to Smith & Struve (1944), or $RV_{\rm cluster}$ = 5.74 ± 0.07 km s^{-1} and $\sigma_{\rm RV}$ = 0.69 ± 0.05 km s^{-1} following Narayanan & Gould (1999).

The distance to HD 23642 resulting from our orbital solution is 132 ± 2 pc (cf. Table 2). This result does not depend on the measured reddening for HD 23642. Rising it to E_{B-V} = 0.035 average reddening for cluster members (e.g. Crawford & Perry 1976), would require an increase to 9910 ± 145 K for the primary to fit observed colors (the larger error indicates a much poorer χ^2 fit to literature photometry compared to E_{B-V} = 0.012). The larger intrinsic brightness compensates for the extra $\Delta A_{\rm V}$ = 0.07 mag extinction and the resulting distance is 130.6 ± 3.7 pc. Even if the distance to HD 23642 derived in this paper concerns just one cluster member, nevertheless it is in excellent agreement with the results from the main-sequence fitting, moving cluster method and astrometric orbit of Atlas. These results agree so well that the issue of the distance to the Pleiades seems now addressed, and finally over.

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