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A purely geometric distance to the binary star Atlas, a member of the Pleiades*

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Abstract. We present radial velocity and new interferometric measurements of the double star Atlas, which permit, with the addition of published interferometric data, to precisely derive the orbital parameters of the binary system and the masses of the components. The derived semi-major axis, compared with its measured angular size, allows to determine a distance to Atlas of 132 ± 4 pc in a purely geometrical way. Under the assumption that the location of Atlas is representative of the average distance of the cluster, we confirm the distance value generally obtained through main sequence fitting, in contradiction with the early Hipparcos result (118.3 ± 3.5 pc).

Key words. stars: individual: Atlas – stars: distances – stars: fundamental parameters – Galaxy: open clusters and associations: individual: Pleiades

1. Introduction

The distance of the Pleiades has been under debate ever since the publication of Hipparcos parallaxes (ESA 1997). Hipparcos data allowed to precisely calibrate and compare the positions of open cluster main sequences with those obtained using the usual main sequence fitting technique, and resulted in a mismatch in the case of at least two clusters (Pleiades and Coma Ber), the most severe being that of the Pleiades (Pinsonneault et al. 1998). Hipparcos locates the Pleiades at 118.3 ± 3.5 pc (van Leeuwen 1999), about 10% nearer than usually quoted results (132 ± 4 pc, see e.g. Meynet et al. 1993), that is about 14 pc nearer, or $\sim$0.3 mag brighter in distance modulus, or $\sim$1 mas larger in parallax.

Various explanations have been proposed to solve the problem: large helium abundance (Mermilliod et al. 1997), metal deficiency (Grenon 2000), problem in Hipparcos parallaxes (Makarov 2002). None of them brought scientific consensus.

The elements in the balance are not minor ones, as pointed out by Paczyński (2003). On one side, stellar evolution theory and photometric calibrations are at stake, or, on the other side, problems appear when averaging parallaxes in order to reach sub milliarcsecond accuracy from Hipparcos data. The problem must be solved, especially in the perspective of the future Gaia mission, which will acquire astrometric data with the same principle as Hipparcos. Thus, identifying the source of the problem is worth the effort. It is perhaps relevant to note here that the Pleiades lie near the ecliptic, where the number of great circles abscissae used for astrometry is especially small.

Fortunately, there exists several other ways to determine distances with no or little model dependencies.

This paper presents radial velocity (hereafter RV) measurements of the interferometric binary Atlas, which permit to derive the distance of Atlas from purely geometric arguments. This star was first discovered to be a binary by Bartholdi (1975) from occultation by the Moon. More recent interferometric measurements by Pan et al. (2004) yielded well constrained orbital parameters which lead to a distance of 135 ± 2 pc, but only when combined with a mass-luminosity relation, making the result model dependant. On the contrary, our RV data makes our work completely model free.

Another star allowed an independent measurement of the distance to the Pleiades. Using Hipparcos epoch photometry, Torres (2003) discovered that the spectroscopic binary

* Based on observations made with the ELODIE echelle spectrograph mounted on the 1.93-m telescope at the Observatoire de Haute-Provence (CNRS), with the FEROS echelle spectrograph mounted on the 2.2-m telescope at ESO-La Silla Observatory (programme No. 072.D-0235B), with the CORALIE echelle spectrograph mounted on the 1.2-m Euler Swiss telescope at ESO-La Silla Observatory, with the Naval Prototype Optical Interferometer (US Naval Observatory) and with the Mark III stellar interferometer at Mt Wilson.

Table 1. New astrometric measurements taken at the Mark III (BJD < 2 450 000) and NPOI (BJD > 2 450 000) interferometers. BJD means Barycentric Julian Day. Column 2 gives the number of visibilities, while the last three columns give the axes and orientation of the error ellipse.

BJD −2 400 000	No. of visib.	ρ (mas)	θ (deg)	$\sigma_{\rm maj}$ (mas)	$\sigma_{\rm min}$ (mas)	φ (deg)
47 833.8408	12	15.08	161.16	0.70	0.11	101.6
48 532.8198	58	6.53	359.22	0.47	0.10	97.7
48 561.8206	74	10.24	331.61	0.44	0.11	86.6
48 940.8405	58	8.26	184.50	0.40	0.11	88.9
48 941.8267	82	8.58	182.32	0.36	0.11	93.0
50 787.8002	418	13.60	147.06	0.47	0.12	178.0
50 788.7864	240	13.23	145.38	0.53	0.13	8.5
51 813.7875	644	4.43	267.23	0.48	0.12	0.3
51 815.7963	644	4.28	262.75	0.49	0.12	180.6
51 835.7755	368	5.64	203.45	0.48	0.12	168.5
51 877.7793	184	13.01	167.71	0.48	0.12	169.8
51 879.7881	184	12.83	167.07	0.41	0.13	171.7

HD 23642 (HIP 17704) is also eclipsing. Munari et al. (2004) obtained photometric and additional RV observations and derived a distance of 132 ± 2 pc, perfectly compatible with the result of the main sequence fitting technique, even though the error bar looks rather optimistic. This method is almost model-free, but not entirely since the effective temperatures of the components were determined through comparison with synthetic spectra.

In addition, Soderblom et al. recently announced (AAS meeting) a distance of 135 ± 3 pc on the basis of new parallax measurements made with the HST on three stars.

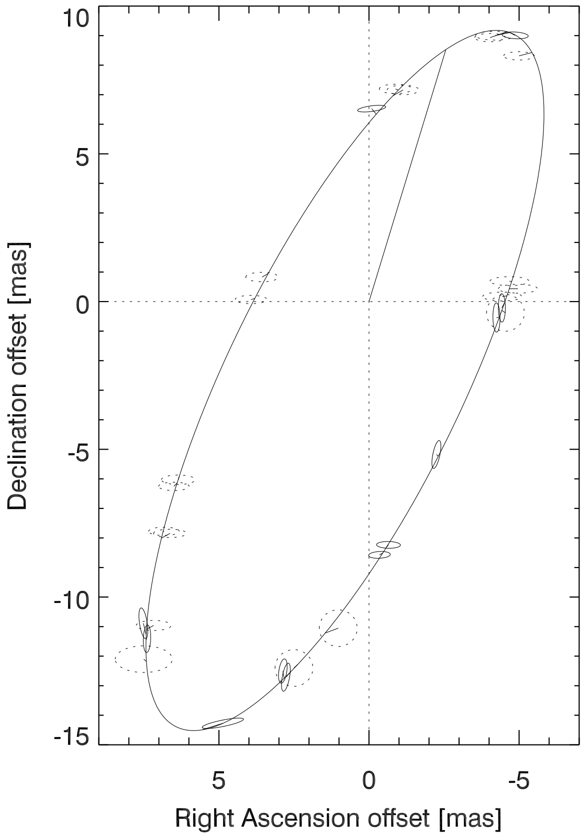

Fig. 1. Astrometric orbit with published data from Pan et al. (2004) (dotted error ellipses) and new data from C. Hummel (full lines; see Table 1). The ellipses indicate the errors on each axis, while the full straight line denotes the periastron.

2. Observations and data reduction

2.1. Additional interferometric observations

Atlas was observed by CH between 1989 and 1992 with the Mark III interferometer, and in 1997 and 2000 with the Navy Prototype Optical Interferometer (NPOI). The journal of these astrometric observations is given in Table 1. The reduction and calibration of the data followed the procedures described by Hummel et al. (1998). Although these data are less numerous than those published by Pan et al. (2004) on the basis of observations with the Mark III stellar interferometer and with the Palomar Testbed Interferometer (PTI), those collected with the NPOI have the advantage of being free from any ambiguity on the orientation of the orbit, because NPOI measures closure phases. The precision is comparable with that reported by Pan et al. (2004), so we could merge both samples together and obtain an improved estimate of orbital parameters (see Table 4 below), using the OYSTER code. The observations and fitted orbit are shown in Fig. 1.

2.2. Spectroscopic observations

Echelle spectra of Atlas were obtained using above all the ELODIE spectrograph attached to the 1.93 m telescope at Observatoire de Haute-Provence, France, but also with the CORALIE spectrograph attached to the Swiss Euler 1.2 m telescope at ESO La Silla, Chile, and with the FEROS spectrograph attached to the 2.2 m telescope at ESO La Silla. Almost all observations were gathered during the 2003−2004 season, though a few archive spectra taken with ELODIE date as far back as 1995. All spectra were taken without simultaneous ThAr calibration, either in star mode only, or in star+sky mode. Until the end of February 2004, observations were made within time normally allocated to other programmes, thanks to the good will of some observers. From the 27th of February to the 29th of March 2004, spectra were taken at OHP within officially allocated time in service mode. The exposure times were typically 10−15 min, resulting in a *S/N* ratio varying from ∼120 in the worst atmospheric conditions to more than 400 in the best ones.

The ELODIE and CORALIE spectra were reduced and normalized to continuum using IRAF, with the method described by Erspamer & North (2002). The FEROS spectra were reduced using the standard reduction pipeline provided by ESO in the MIDAS context. Then, a more careful continuum normalization was performed in the immediate vicinity of the few lines which appeared useful for RV determination.

The journal of the observations is given in Table 2. Since spectra with $S/N <\sim 200$ proved to be of little help because of the shallowness of the lines (<0.1), only the best exposed ones are listed here.

Table 2. Journal of the specroscopic observations. Epochs are given in Barycentric Julian Day. Key to the observers: yd = Y. Debernardi; cv = C. Vuissoz; fg = F. Galland; mg = M. Groenewegen; rm = R. Monier; pn = P. North; rds = R. da Silva; bp = B. Pernier; pg = P. Girard.

Date	BJD −2 400 000	Instr.	Expos. time (s)	*S/N*	Obs.
1995.11.08	50 030.4725	ELODIE	361	342	?
2001.08.04	52 126.6265	ELODIE	268	198	yd
2003.09.14	52 897.6390	ELODIE	450	419	cv
2003.11.05	52 949.5254	ELODIE	600	294	fg
2003.11.14	52 958.4601	ELODIE	600	291	bp
2003.11.17	52 961.4405	ELODIE	600	381	bp
2003.12.11	52 985.6503	CORALIE	900	223	mg
2004.01.05	53 010.2836	ELODIE	600	351	rm
2004.01.10	53 015.3717	ELODIE	600	324	rm
2004.02.02	53 038.3266	ELODIE	300	314	fg
2004.02.27	53 063.2736	ELODIE	900	279	fg
2004.02.29	53 065.2571	ELODIE	900	218	fg
2004.03.02	53 067.2649	ELODIE	600	316	rds
2004.03.03	53 068.2741	ELODIE	600	303	rds
2004.03.05	53 070.4947	FEROS	250	315	pn
2004.03.06	53 071.4943	FEROS	250	313	pn
2004.03.07	53 072.2627	ELODIE	600	246	rds
2004.03.07	53 072.4966	FEROS	250	312	pn
2004.03.10	53 075.2677	ELODIE	600	296	pg
2004.03.11	53 076.2775	ELODIE	600	332	pg
2004.03.14	53 079.2716	ELODIE	900	440	pg
2004.03.15	53 080.2739	ELODIE	900	460	pg
2004.03.27	53 092.3056	ELODIE	900	270	fg
2004.03.28	53 093.3090	ELODIE	900	340	fg

Table 3. Lines used in this work for radial velocity estimations.

Species	λ_0 [Å]	Remark
Mg II	4481.2	
Si II	6347.1	Telluric lines present
Si II	6371.4	Telluric lines present

3. Analysis of spectra and orbit determination

Since the lines of the components are wide and always blended, we have used the KOREL code by Hadrava (1995) for spectral disentangling and RV determination. Even with this tool, the task was a delicate one because of the very small number of suitable lines and because of their shallowness. Unfortunately, the Balmer lines could not be used because of their larger width compared with the relatively small RV amplitude. The lines we used are listed in Table 3. The cleanest is that of Mg II. The two Si II lines are appropriate as well, but suffer from contamination by telluric lines which, although not very deep, do hamper convergence if they are not corrected for. In order to suppress these telluric lines, we used the high resolution spectrum of telluric lines provided by Hinkle et al. (2000) together with their visible atlas of the Arcturus spectrum. This spectrum was convolved with a Gaussian instrumental profile corresponding to the resolving power of ELODIE $R = 42\,000$; since CORALIE and FEROS have only slightly better resolving powers ($R = 50\,000$ and 48 000 respectively), the same convolved telluric spectrum

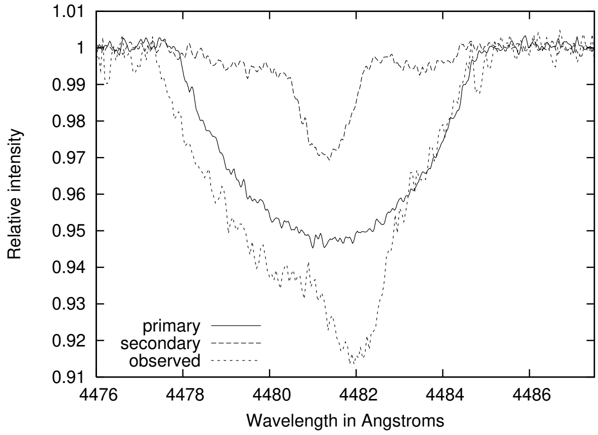

Fig. 2. Disentangled lines of Mg II centered on the systemic velocity. Full line: primary; broken line: secondary. Dotted line: spectrum observed in 1995 near quadrature, at phase $\phi \sim 0.1$.

Table 4. Astrometric and spectroscopic orbital parameters adjusted with the OYSTER and KOREL codes respectively. A simultaneous fit of astrometric and RV data yields essentially the same results. The errors on the spectroscopic parameters are those obtained through the jackknife method alone, but the error on d includes the small uncertainty on a''.

Parameter	Value	Parameter	Value
Period [d]	290.984 ± 0.079	K_1 ($\mathrm{km\,s^{-1}}$)	26.55 ± 1.41
T_0 [BJD]	$2\,450\,583.0 \pm 1.9$	K_2 ($\mathrm{km\,s^{-1}}$)	36.89 ± 0.22
e	0.2385 ± 0.0063	q	0.720 ± 0.036
i (deg)	107.87 ± 0.49	a (AU)	1.73 ± 0.04
ω (deg)	151.9 ± 2.2	M_1 ($M_\odot$)	4.74 ± 0.25
Ω (deg)	154.0 ± 0.7	M_2 ($M_\odot$)	3.42 ± 0.25
a'' (mas)	13.08 ± 0.12	d (pc)	132 ± 4

proved useful for them as well. Since airmass and humidity varies from one spectrum to the next, the correction had to be adjusted visually for each spectrum by scaling the telluric line intensities (see North et al. 1994, for details), mainly on lines lying on the continuum. This procedure proved quite satisfactory, thanks to the fact that the relative depths of the telluric lines remain the same in a given spectrum even though their absolute depths change from one spectrum to the other.

Fortunately, most orbital parameters are known from interferometry, especially T_0, e, i and ω, so these quantities could be fixed while running KOREL, leaving only the RV amplitude K_1 and the mass ratio q as adjustable parameters.

By limiting the data set to spectra with $S/N \geq 200$, and with starting values of K_1 between 10 and 60 $\mathrm{km\,s^{-1}}$ and of q between 0.3 and 1.0, we found good convergence towards the values given in Table 4. The disentangled spectra are shown in Fig. 2 for the Mg II line. One clearly sees that the primary rotates much faster than the secondary, the line exhibiting a typical rotational profile. The $v \sin i$ values are respectively about 240 and 60 $\mathrm{km\,s^{-1}}$. The RV curves computed by the KOREL code are shown in Fig. 3; the points are obtained by cross-correlating the individual spectra with the disentangled spectra. The error estimate on the fitted orbital parameters is not straightforward, since the disentangling method used in

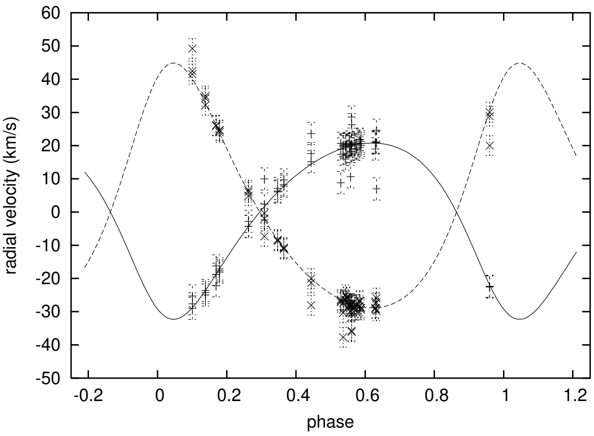

Fig. 3. Radial velocity curves given by the KOREL code. All orbital parameters were fixed at their astrometric values, except K_1 and q. There are three radial velocity estimates per epoch, one per line, even though the RV curves were constrained simultaneously by all three lines. Note that the systemic velocity is arbitrarily set to zero because the KOREL code cannot determine it.

the KOREL code does not give it in a natural way. Therefore, we had recourse to the jackknife method (Efron & Tibshirani 1993), which consists in removing each spectrum in turn from the whole set of data, and run KOREL with the remaining 23 spectra. One obtains slightly different values of the fitted parameters, and their variance multiplied by the number of spectra gives the final error estimate (e.g., Ilijić 2003).

Since KOREL gives individual RV values, we mixed the latter with the astrometric data of Pan et al. (2004) and ours to fit simultaneously all orbital parameters. This is in principle a more elegant method than to fit separately the spectroscopic data and the astrometric ones. However, in our case one has to bear in mind that the individual RV values are not mutually independent stricto sensu, because they result from a cross-correlation between each individual spectrum and the components' disentangled spectra. Since the latter are built on the same data, there is some circularity which tends to reduce the O−C residuals. In addition, the spectroscopic orbit is not independent from tbe astrometric one, since the latter was used to constrain most orbital parameters. Nevertheless, such a consistency check is reassuring in that it provides the same result as when combining the separate astrometric and spectroscopic solutions.

4. Distance of Atlas and conclusions

The orbital parameters obtained above yield a final distance of $d = 132 \pm 4$ pc which confirms the "traditional" distance obtained through the main sequence fitting technique. Thus the result obtained by Pan et al. (2004) is fully confirmed, and there is no need for any revision of the stellar evolution models, or assumed helium content of the Pleiades members, or to postulate a non-solar metallicity.

Our result has the advantage of relying exclusively on *empirical* data, without the least recourse to any model. The only assumption we made is that of no intrinsic spectral variability of the components of Atlas, an assumption which is well justified a posteriori for the Mg II line at least, but which will be examined further in a more complete forthcoming paper.

It is worth mentioning that our result is completely coherent with the distance of the recently discovered eclipsing binary HD 23642 (Munari et al. 2004), within the errors and within the expected depth of the Pleiades cluster. Thus, there are now two objects for which a more or less direct distance estimate puts the Pleiades at about 130−135 pc, which is clearly different from the Hipparcos estimate published by van Leeuwen (1999). It appears increasingly urgent to understand what went wrong with that estimate, a difficult task which is in progress (van Leeuwen 2004).

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