Astrometric Detection of a Low Mass Companion Orbiting the Star AB Doradus

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ABSTRACT

We report submilliarcsecond-precise astrometric measurements for the late-type star AB Doradus via a combination of VLBI (very long baseline interferometry) and Hipparcos satellite data. Our astrometric analysis results in the precise determination of the kinematics of this star, that reveals an orbital motion readily explained as caused by the gravitational interaction with a low-mass companion. From the portion of the reflex orbit covered by our data and using a revised mass of the primary star (0.76 $M_\odot$) derived from our new value of the parallax ($66.3 < \pi < 67.2$ milliarcseconds), we find the dynamical mass of the newly-discovered companion to be between 0.08 and 0.1131,7. If accurate photometric information can be obtained for the low-mass companion, our precise mass estimate could serve as an accurate calibration point for different theoretical evolutionary models of low-mass objects. This represents the first detection of a low-mass stellar companion using the VLBI technique, a technique which will become an important tool in future searches for planets and brown dwarfs orbiting other stars.

Subject headings: astrometry — techniques: interferometric — stars: individual (AB Doradus) ----- stars: kinematics --- stars: low-mass, brown dwarfs

1. INTRODUCTION

The recent discoveries of several possible planet or brown dwarf candidates using pulsar timing (Wolszczan & Frail 1992) or optical spectroscopy (Mayor & Queloz 1995; Marcy & Butler 1996) have yielded a spectacular advance in the search for low-mass stellar companions. However, pulsar timing and optical spectroscopy do not yield unambiguous estimates of the companion masses due to the undetermined orbital inclination. Moreover, alternate explanations may exist for the radial velocity variations (Gray 1997). Companion masses can be uniquely determined by astrometric measurements of the motions of stars in the plane of the sky, which provide a full set of orbital elements. Submilliarcsecond VLBI astrometry, using phase-referencing techniques (Lestrade et al. 1990), of weakly-emitting radio stars has reached precision better than one milliarcsecond, and should be a powerful tool for searching for very low-mass objects.

Since 1992 we have been monitoring, with milliarcsecond precision, the radio positions of a few Southern-Hemisphere radio stars with VLBI (Guirado et al. 1996). The main purpose of these astrometric observations is to contribute to the determination of the link between the celestial radio reference frame, defined by the VLBI positions of extragalactic radio sources, and the optical reference frame, defined by the positions of the stars observed by the European Space Agency's astrometric satellite Hipparcos (Lindegren & Kovalevsky 1995; Lestrade et al. 1995). One of the stars of this program is AB Doradus (= HD 36705 = HIP 25647, AB Dor hereafter), an active K0-star. Based on its high rotation rate (P_{rot} = 0.514 days, $v \sin i \sim 100 \pm 5$ kms), lithium abundance (Rucinski 1982; Vilhu et al. 1987), and membership in the Pleiades Moving Group (Innis et al. 1985), AB Dor is commonly accepted to be a young pre-main-sequence star coeval with the stars of the Pleiades (~70 Myr). AB Dor has an apparent physical companion, Rst 137B, a dM4e star, also a rapid rotator (Lim 1993) ($P_{rot} \leq 0.38$ days), separated by only 10 arcsec on the sky from AB Dor. The two stars are believed to be associated based on their common proper motions and common radial velocities (Innis et al. 1985; Innis et al. 1986).

In this Letter we describe the results of our astrometric analysis, which reveals an acceleration in the position of AB Dor that can be readily explained as caused by the gravitational interaction with a low-mass companion.

2. VLBI OBSERVATIONS AND DATA REDUCTION

We performed VLBI measurements of AH Dor at S.4 GHz at multiple epochs with an Australian array of radio telescopes (see Table 1). For each experiment. we interleaved observations of the strong background radio source PKS 0516-621 using, typically. a 2.50 sec duty cycle which consisted of 140 sec on AB Dor , 70 sec on 0516-621, and 20 sec slew time between each source. The data were correlated at the Mark 111A correlator of the US Naval Observatory in Washington, DC.

For the astrometric analysis we followed the phase-referencing VLBI technique described by Lestrade et al. (1990) and used the software SPRINT, developed by one of us (JFL). We outline briefly this analysis: first, we used the most accurate parameters to model the geometry of the interferometric array (reference source coordinates, antenna positions, and Earth orientation parameters were obtained from the International Earth Rotation Service: 1995 IERS Annual Report), and the propagation media in order to produce theoretical estimates of the visibility phase that were subtracted from the observed ones; second, we interpolated the residual quasar phases (observed minus theoretical values) to the times of the star observations and subtracted them from the star fringe phases to form the differential residual fringe phase; and third, we carried out the Fourier transform of the resulting visibilities. This provided us a phase-referenced map of the star whose coordinates are referred to the PKS 0516 621 position. The relative position of the star is then found by measuring the coordinates of the brightness peak on the phase-referenced map. Extensive error analysis at each observational epoch has been carried out to determine the uncertainties of the relative coordinates due to errors inherent to the propagation media, the reference source radio structure, and the geometry of the interferometry array. These uncertainties, ranging from 0.3 to 1.7 milliarcseconds (mas), were 5-to-7 times larger than the errors due 10 the signal-to-noise ratio of our VLBI data. The resulting positions and standard deviations are shown in 'I'able 2.

3. ORBIT DETERMINATION

The measured VLBI coordinates of AB Dor (Table 2), referred to the IERS radio reference frame through the coordinates of PKS 0516-621, have been used to derive the star's proper motion, parallax, and position at a reference epoch (1993.00) via a weighted-least-squares fit. In our first analyses, the root-mean-square (rms) of the postfit residuals was about five-fold higher than that of the other southern stars included in our program (Guirado et al. 1996), indicating that proper motion and parallax alone did not suffice to account for the trajectory of AB Dor on the sky. The systematic signature, both in right ascension and declination, of the postfit residual positions of AB Dor led us to consider that the excursions were produced by the gravitational effect of a companion other than Rst 137B in orbit around AB Dor.

In order to enlarge our observational time-span. we augmented the number of data points by using positions of AB Dor measured by the Hipparcos satellite at several epochs over the mission lifetime (1990.2 - 1993.3), during a time interval not covered by the VLBI data. In the final Hipparcos solution (ESA 1997), aligned with the IERS reference frame (Kovalevsky et al. 1997), as are the VLBI data, the motion of the photocenter of AB Dor was found to be non- linear, corroborating the signature apparent in the VLBI residuals and showing that the star was an astrometric double. There were 55 individual data points for this star that were combined to obtain independent position estimates at five different epochs during the Hipparcos mission (see Table 2). The standard deviations of these estimates are of about 1.5 mas in right ascension and 0.S mas in declination. **We note that the latter standard deviations also account for the uncertainty of the alignment between the radio and optical reference frames.**

To determine the orbital elements of the reflex motion of AB Dor, we combined both VLBI and Hipparcos data sets to estimate simultaneously the parameters that describe the system via a weighted least-squares analysis based on the Thiele-Innes method (Green 1985). These parameters include the five astrometric parameters and the seven orbital elements. 'The astrometric parameters are the two position coordinates, the two proper motion components, and the parallax of the mass center of the system (central star and low-mass companion). The orbital elements are the period (P), semimajor axis ($a_1=$ a x M_c x $(M_1+M_c)^{-1}$, with a the semimajor axis of the relative orbit, M_1 the mass of AB Dor, and M_c the mass of the low-mass companion), eccentricity (e), inclination (i), argument of the periastron (ω), position angle of the node (Ω), and epoch of periastron passage (T_o). This simultaneous fit has the advantage that any sinusoidal behaviour of the data is not absorbed by proper motion and parallax effects (Black & Scargle 1982). The result of this fit showed that our joint VLB1 + Hipparcos data set did not cover a full orbit, and orbits with periods longer than seven years fit the data equally well.

To investigate the possible orbits for AB Dor consistent with the data, we used the Thiele-Innes method to treat the non-linear actuations of the elliptic motion. This method has the advantage to separate between the three non-linear orbital parameters (F', e, and T_o) and the four linear Thiele-Innes coefficients that are the combinations of a, i, ω, and Ω. Consequently, the dimension of the parameter space to be searched is reduced from seven to three. Practically. we made multiple weighted-least-squares fits, each fit had fixed values for the three non-linear orbital elements while we solved for the four Thiele-Innes coefficients and the five astrometric parameters. We sampled a wide range of the parameter space: $6.5 < P < 27.5$ years by steps of 5 days; $1990.0 < T_o < 1990.0 + P$ by steps of 20 days; $0 < e < 1$ by steps of 0.005. We selected as plausible solutions those whose χ^2-difference with the minimum χ^2 was less than 15% of the latter value (0.9-1 mas). The resulting ranges of the astrometric parameters and orbital elements are given in Table 3. For each plausible orbit, we used Kepler's third law ($M_c^3/(M_1 + M_c)^2 = a_1^3/P^2$) to estimate the mass M_c of the unseen companion, AB Dor C . For this analysis, we used our new, more accurate, value of the parallax (see Table 3) to scale the mass of the central star AH Dor given by Vilhu et al. (1987) to $0.76 \pm 0.02\,M_\odot$. We found that the mass of AB Dor C was constrained to the range $0.08 - 0.11\,M_\odot$. This tight constraint on the mass for AB Dor C could not be obtained from either the VLBI or Hipparcos data sets alone. An orbit corresponding to a mass of AB Dor C near the center of the mass interval is displayed in Fig. 1. We are continuing to obtain more VLBI data to make the range of the mass estimate narrower.

We checked the sensitivity of our solution to a different choice of epochs of the Hipparcos positions by repeating the astrometric analyses with Hipparcos positions at epochs other than those shown in Table 2; the new results do not change significantly the ranges given in Table 3. Regarding the astrometric parameters, the proper motion in right ascension and declination found in our analysis are consistent with long-term optical values (White et al. 1988) to within twice the standard deviation of the optical estimates. **Also, our new parallax coincides with previously reported values at the limit of the quoted uncertainties (Innis et al. 1986). Finally, we note that our estimates given in Table 3 might be affected by a possible inconsistency between the two different data types, VLBI and Hipparcos. Since there is no overlapping between the portions of the orbit sampled by each data type, it is difficult to estimate the effect of such an inconsistency. However, this effect is unlikely to be significant given the high precision of the alignment between the radio and optical reference frames (Kovalevsky et al. 1997).**

4. ALTERNATE EXPLANATIONS

Some alternate explanations for the shifts in positions of AB Dor, such as stellar pulsation or surface activity, can be ruled out because the smallest semimajor axis for the possible orbits investigated is ~20 mas, equivalent to about 60 stellar radii. The gravitational interaction of AB Dor with Rst 137B can be also ruled out, as we calculate the wobble produced by Rst 137B on AB Dor to have an amplitude of $\sim 3''$ and ~2000 yr period, given the common parallax and the mass for both stars (for this estimate, we scaled the mass of Rst 137B given by Vilhu et al. (1987) to 0.21 $M_\odot$). Most of this orbital motion appears as a linear position drift during the short (compared with the 2000 yr period) time-span of our observations and it is absorbed by the proper motion estimate. The corresponding acceleration, about 0.03 mas/yr^2, produces a shift less than 0..5 mas in our 6-year data span and, therefore, is not detectable in our present measurements. However, the gravitational interaction with Rst 137B will become significant after a few more years of observation and we plan to include this effect in future astrometric analyses.

5. DISCUSSION

With a mass between 0.0S and 0.11 $M_\odot$, AB Dor C is **one of the few low mass objects near the hydrogen burning limit whose mass has been determined dynamically** (Henry & McCarthy 1993). AB Dor C offers a rare opportunity to combine a precise mass determination with photometric and/or spectral information for a young low-mass object. in particular, a suitable photometric calibration would locate this object in a mass-luminosity diagram and would **add a new precise point to the data given by Henry

& McCarthy (1993) for calibration of the low end of the main sequence (D'Antona & Mazitelli 1985; Burrows et al. 1993; Barrafe et al. 1996). ^{*K}

An approximate expected magnitude for AB Dor C can be calculated from our mass estimate and assumed age ($\sim$70 Myr, assuming that AB Dor and AB Dor C are coeval) by using theoretical evolutionary tracks for very low mass stars and brown dwarfs. The model X of Burrows et al. (1993) yields a luminosity for AB Dor C of $\log(L/L_{\odot}) \sim -2.5$, and an effective temperature of $\sim$3000 K. Taking the bolometric corrections derived for other very low mass stars in the Pleiades (Hamilton & Stauffer 1993), and using our parallax determination, we can estimate the expected apparent magnitudes of AB Dor C to be $m_v \sim 16$ and $m_K \sim 9$. The magnitude difference between AB Dor (m_V=6.95) and its dark companion, along with their separation, ranging from 0$''$.2 to 0$''$.7, makes the direct detection of AB Dor C unlikely with ground-based telescopes and very near the limits of the HST's WFPC2 capabilities (Schroeder & Golimowski 1996). The contrast of the sources is more favorable for detection at near-infrared wavelengths (m_K=6 and 9 for AB Dor and AB Dor C, respectively), but the spatial resolution of ground-based southern hemisphere infrared devices is still too coarse. The NICMOS camera that has now been deployed on HST in 1997 appears to be the best way to get photometric information of AB Dor C.

We have shown that VLBI phase-referencing, enhanced in this case with Hipparcos positions, is one of the most powerful techniques for searching for very low-mass companions orbiting stars. Significant improvement of the precision of this technique is potentially possible. Even with a similar precision to that achieved for AB Dor, the application of this technique to nearby (< 5 pc) M-dwarfs could be extraordinary effective for detecting substellar companions with masses as low as 1 Jupiter mass and orbital periods less than five years (Lestrade et al. 1996).

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REFERENCES

Arenou, F ., 1996, in *De1 'utilisation des données Hipparcos*, edited by M. Froeschlé and F. Mignard, Observatoire de la Côte d'Azur, p. 31

Barrafe, I,., et al., 1996, ApJ, 446, 1,35

Black, D.C, and Scargle, J.I)., 1982, ApJ, 263, 854

Burrows, A., et al., 1993, ApJ, 406, 15S

Collier-Cameron A., et al., 1988, MNRAS, 231, 131

ESA, 1997, The Hipparcos and Tycho Catalogues, ESA S1'-1200

D'An tona, F., and Mazitelli, I., 1985, ApJ, 345, 939

Feissel, M. & Essaïfi, N. (eels.) 1996, IERS Annual Report for 1995 (Observatoire de Paris, Paris)

Green, R. M., 1985, Spherical Astronomy, Cambridge University Press (Cambridge)

Gray, D. F., 1997, Nature 385, 795

Guirado, J.C. et al., 1996, in *Radio Emission from the Stars and the Sun*, edited by A.R. Taylor and J .M. Paredes, ASP Conf. Ser. Vol. 6 (ASP, San Francisco), p. 134

Hamilton, D. and Stauffer, J. R., 1993, AJ, 105, 1S55

Henry, T. J., and McCarthy, W., 1993, AJ, 106, 773

Innis, J.L., et al.. 1985, Proc. Astron. Sot. Aus., 6, 156

Innis, J.I.., Thompson, K., and Coates, 1). W., 19S6, MNRAS, 223, 183

Kovalevsky, J., et al., 1995, A&A, 304, 34

Kovalevsky, J. et al., 1997, A&A, in press

Lestrade, J.-F., et al., 1990, AJ, 99, 1663

Lestrade, J.-F. et al., 1995, A&A, 304, 182

Lestrade, J.-F., et al., 1996, JGR, 101, E6, 14837

Lim, J. 1993, ApJ, 405, L33

Lindegren, L. & Kovalevsky, J., 1995, A&A, 304, 1S9

Lindegren, L., et al., 1992, A&A, 258, 1S

Marcy, G.W. & Butler, R. P., 1996, ApJ, 464, L147

Mayor, M. & Queloz, D., 1995, Nature, 378, 355

Rebolo, R., Zapatero-Osorio, M. R., and Martin, E. L., 1995, Nature, 377, 129

Rogers, A.E.E. et al., 1983, Science, 219, 51

Rucinski, S. M., 19S2, MNRAS, 215, 591

Stauffer, J. R., Hamilton, D., and Probst, R. G., 1994, AJ, 108, 155

Schroeder, D. J., and Golimowski, D. A., 1996, PASP, 108, 510

Vilhu, O., Gustafsson, B., and Edvardsson, B., 1987, ApJ, 320, 850

White, G. L., et al., 1988, PASP, 100, 825

Wolszczan, A., and Frail, D. A., 1992, Nature, 355, 145

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FIGURE CAPTION

Figure 1. An orbit for the reflex motion of AB Dor corresponding to a companion mass of 0.094 $M_\odot$. Plots show right ascension (a) and declination (b) of AB Dor for the observation epochs after subtracting proper motion and parallax effects: the five earliest epochs correspond to Hipparcos data; the continuous line corresponds to the least -squares fitted reflex orbital motion of AB Dor. The apparent orbit is shown in plot (c), also with proper motion and parallax effects subtracted.

TABLE 1 **Phase-referenced VLBI** observations of **AB** Dor

Epoch	Antennas[1]	Recording mode[2]	Integration time (hours)	SNR[4]
25 Apr 92 (1992.23)	T,H,P	MkIII A	2.7	13
6 Sep 92 (1992.68)	T,H,P	MkIII A	2.9	25
14 Feb 93 (1993.12)	T,H	MkIII B	2.7	10
24 Oct 94 (1994.81)	T,H,P	MkIII B	7.7	15
21 Feb 95 (1995.14)	T,H	MkIII B	1.7	8
24 Feb 96 (1996.15)	T,H	MkIII A	3.8	90
15 May 96 (1996.37)	T,H	MkIII A	2.1	25

[1] The symbols correspond to the following Australian antennas: T, 70 m NASA DSN antenna at Tidbinbilla; H, 26 m antenna of Mount Pleasant Observatory at Hobart; P, 64 m ATNF antenna at Parkes.

[2] We used the Mark III system (Rogers et al. 1983) to record twenty-eight 2 MHz adjacent channels covering 8402.99--8458.99 MHz (mode A) or fourteen 2 MHz adjacent channels covering 8402.99–8430.99 MHz (mode B). Right-hand circular polarization (IEEE convention) was recorded.

[3] Total integration time resulting from the coherent addition of the VLBI data by using the phase-reference mapping technique.

[4] Signal-to-noise ratio of the AB Dor detections.

TABLE 2 J2000 estimates of the position of AB Dor[1]

Epoch	Technique	α	δ
1990.3s88	Hipparcos	$5^{h}\,28^{m}\,44^{s}.77474 \pm 0^{s}.00026$	$-65^{\circ}\,26'\,56''.2416 \pm 0''.0007$
1990.5640	Hipparcos	$5^{h}\,28^{m}\,44^{s}.78652 \pm 0^{s}.00025$	$-65^{\circ}\,26'\,56''.2272 \pm 0''.0007$
1991.0490	Hipparcos	$5^{h}\,28^{m}\,44^{s}.77578 \pm 0^{s}.00024$	$-65^{\circ}\,26'\,56''.2615 \pm 0''.0007$
1991.5330	Hipparcos	$5^{h}\,28^{m}\,44^{s}.78942 \pm 0^{s}.00025$	$-65^{\circ}\,26'\,56''.0757 \pm 0''.0008$
1992.0180	Hipparcos	$5^{h}\,28^{m}\,44^{s}.78202$ ± 0?0002-1	$-65^{\circ}\,26'\,56''.1160 \pm 0''.0009$
1992.2.329	VLBI	$5^{h}\,28^{m}\,44^{s}.77687$ ± 0?00019	$-65^{\circ}\,26'\,56''.0049 \pm 0''.0007$
1992.6S49	VLB1	$5^{h}\,28^{m}\,44^{s}.80124$ ± 0?0001S	$-65^{\circ}\,26'\,55''.9395 \pm 0''.0006$
1993.1233	VLB1	$5^{h}\,28^{m}\,44^{s}.78492 \pm 0^{s}.00024$	$-65^{\circ}\,26'\,55''.9137 \pm 0''.0008$
1994.8137	VLBI	$5^{h}\,28^{m}\,44^{s}.81768 \pm 0^{s}.00019$	$-65^{\circ}\,26'\,55''.6866 \pm 0''.0005$
1995.1425	VLBI	$5^{h}\,28^{m}\,44^{s}.80247$ ± 0?00027	$-65^{\circ}\,26'\,55''.6248 \pm 0''.0011$
1996.1507	VLBI	$5^{h}\,28^{m}\,44^{s}.81137 \pm 0^{s}.00013$	$-65^{\circ}\,26'\,55''.4852 \pm 0''.0003$
1996.3607	VLBI	5^{h}28’” $44^{s}.81776 \pm 0^{s}.00018$	$-65^{\circ}\,26'\,55''.3785 \pm 0''.0010$

[1] VLB1 positions of AB Dor were determined with reference to the IERS coordinates of the background radio source PKS 0516-621 ($\alpha=5^{h}\,16^{m}\,44^{s}.926178, \delta=-62^{\circ}\,7'\,5''.38930$)

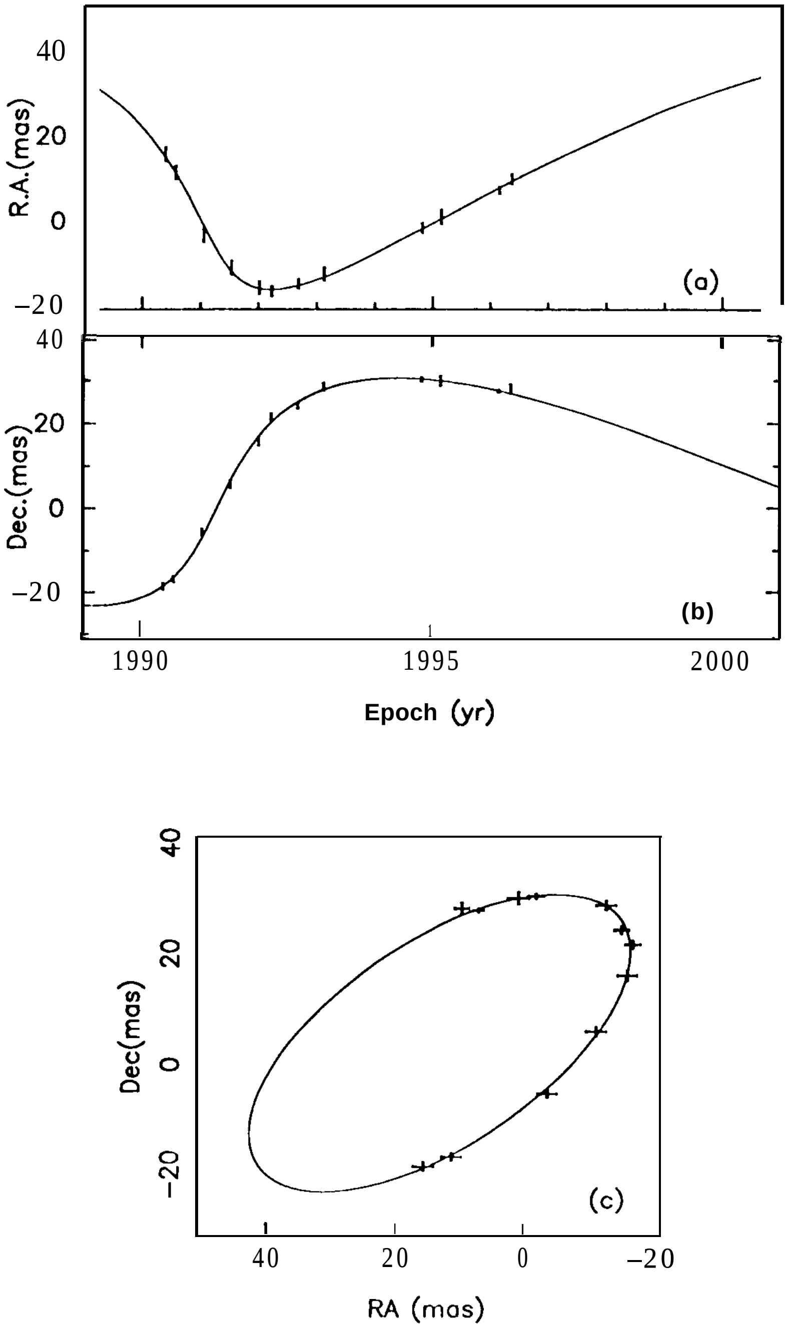
TABLE 3 **J2000.0 astrometric[1] and** orbital parameters of AB Dor

α^2:	$5^h\ 28^m\ 44\overset{s}{.}7948$	–	$44\overset{s}{.}7969$
δ^2:	$-65^\circ\,26'\,55''\!.933$	–	$55''\!.914$
μ_α:	$0\overset{s}{.}0074$	–	$0\overset{s}{.}0083\,\mathrm{yr}^{-1}$
μ_δ:	$0''\!.130$	–	$0''\!.145\,\mathrm{yr}^{-1}$
π:	$0''\!.0663$	–	$0''\!.0672$
P:	6..5	–	27.5 yr
al:	$0''\!.021$	–	$0''\!.075$
e:	0.28	–	0.78
i:	59°	–	71°
ω:	77°	–	127°
Ω:	127°	–	142”
TO:	1991.5	–	1992.2
M_c^3:	0.08	–	$0.11\ M_\odot$

[1] The astrometric parameters correspond to the mass center of the system AB Dor/AB Dor C.

[2] The reference epoch is 1993.00.

[3] Mass range obtained from the period and semimajor axis of each plausible orbit via Kepler's third law The mass adopted for the central star AB Dor was 0.76 M


40
20
0
−20
R.A.(mas)
(a)
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20
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1990
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Epoch (yr)
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RA (mas)