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On the nature of the Be star HR 7409 (7 Vul)

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ABSTRACT

HR 7409 (7 Vul) is a newly identified Be star, possibly part of the Gould Belt, and is the massive component of a 69-d spectroscopic binary. The binary parameters and properties of the Be star measured using high-dispersion spectra obtained at Ondřejov Observatory and at Rozhen Observatory imply the presence of a low-mass companion ($\approx$0.5–0.8 $M_\odot$). If the pair is relatively young ($<$50–80 Myr), then the companion is a K V star, but, following another, older evolutionary scenario, the companion is a horizontal branch star or possibly a white dwarf star. In the latter scenario, a past episode of mass transfer from an evolved star on to a less massive dwarf star would be responsible for the peculiar nature of the present-day, fast-rotating Be star.

Key words: stars: emission-line, Be – stars: individual: HR 7409.

1 INTRODUCTION

The B5 star HR 7409 (7 Vul, BD+19 4039, TD1 24807, HD 183537, HIC/HIP 95818) was noted for its broad helium lines and other unspecified spectroscopic peculiarities (Lesh 1968). The broad helium and magnesium line profiles show that HR 7409 has a high rotation velocity $v \sin i = 300 \pm 30\,\mathrm{km\,s^{-1}}$ (Wolff, Edwards & Preston 1982; Abt, Levato & Grosso 2002). Hill, Hilditch & Pfannenschmidt (1976) found it to be photometrically variable ($\Delta m \approx 0.1$ mag) but with an unknown period, although *Hipparcos* photometry only shows possible variations of 0.009 mag and an 'unsolved' periodicity of 0.59 d during the survey time line (Koen & Eyer 2002). Using the same data Molenda-Żakowicz (2002) measured variations of 0.013 mag with a period of 2.72 d. The ultraviolet (UV) spectrum obtained with the *TD-1* satellite (Jamar et al. 1976) shows a B5-type star intermediate to main sequence and supergiant (Cucchiaro et al. 1980). The UV photometric measurements obtained with the *Astronomical Netherlands Satellite* (*ANS*; Wesselius et al. 1982) are consistent with *TD-1* flux measurements (Thompson et al. 1978) and show the effect of interstellar reddening (Savage et al. 1985; Friedemann 1992) consistent with its proximity to the Galactic plane ($l = 55.2026$, $b = +1.1794$). The *ANS* photometry also shows evidence of variability.

HR 7409 originally figured among stars assembled as a likely open cluster around 4 and 5 Vul (Meyer 1903, 1905) and later known as Collinder 399 (Collinder 1931). After the Collinder 399 membership was reduced to six objects that excluded HR 7409 (Hall & Vanlandingham 1970), the increased precision of parallax and proper motion measurements (*Hipparcos*, Tycho, Tycho2) allowed Baumgardt (1998) and Dias, Lépine & Alessi (2001) to conclude that Collinder 399 is not a real cluster. In summary, HR 7409 is not part of a cluster, but it may belong to a local system or association referred to as the Gould Belt (Lesh 1968).

Plaskett et al. (1921) initially listed HR 7409 as a new spectroscopic binary but additional radial velocity measurements (Plaskett & Pearce 1931) contradicted their initial assessment. Plaskett et al. (1921) noted the 'nebulous' helium lines while broad hydrogen lines were also noted by Plaskett & Pearce (1931). Both observations were evidence of a high rotation velocity. A few additional radial velocity measurements that differ from these early measurements are available in the literature (Duflot, Figon & Meyssonnier 1995; Fehrenbach et al. 1996) underlining difficulties in measuring radial velocities in fast rotating B stars. On the other hand, Abt & Cardona (1984) did not consider HR 7409 to be in a binary.

Although HR 7409 was known to be peculiar, a detailed spectroscopic investigation of a possible link to the Be phenomenon is so far lacking. Slettebak (1976) examined the role played by rotation on the Be phenomenon (see the review by Porter & Rivinius 2003) and concluded that although Be stars are apparently rotating near critical velocity, other mechanisms are possibly responsible for episodes of mass loss. In fact, Frémat et al. (2005) found that the average rotation rate is 88 per cent of the critical velocity, while Cranmer (2005) concluded that Be stars are subcritical rotators.

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Table 1. HR 7409 (7 Vul).

Parameter	Value	Ref.[a]
	Hipparcos	
π (mas)	4.29 ± 0.76, 2.81 ± 0.48	1, 2
$\mu_\alpha \cos\delta$ ($\mathrm{mas\,yr^{-1}}$)	2.95 ± 0.46, 1.38 ± 0.43	1, 2
μ_δ ($\mathrm{mas\,yr^{-1}}$)	-16.89 ± 0.54, -15.84 ± 0.55	1, 2
	ANS photometry	
$m[155 \pm 15\,\mathrm{nm}]$ (mag)	4.261 ± 0.014	3
$m[180 \pm 15\,\mathrm{nm}]$ (mag)	4.472 ± 0.018	3
$m[220 \pm 20\,\mathrm{nm}]$ (mag)	4.928 ± 0.014	3
$m[250 \pm 15\,\mathrm{nm}]$ (mag)	5.116 ± 0.011	3
$m[330 \pm 10\,\mathrm{nm}]$ (mag)	5.537 ± 0.010	3
	Johnson photometry	
$U - B$ (mag)	-0.53 ± 0.02, -0.525 ± 0.063	4, 5
$B - V$ (mag)	-0.10 ± 0.01, -0.107 ± 0.012	4, 5
V (mag)	6.31 ± 0.02, 6.338 ± 0.028	4, 5
	2MASS photometry	
J (mag)	6.439 ± 0.026	6
H (mag)	6.505 ± 0.017	6
K (mag)	6.554 ± 0.024	6
	Colour excess	
$E(B - V)$ (mag)	0.06, 0.07, 0.09, 0.08	7, 8, 9, 10

[a] References: 1 – Perryman et al. (1997); 2 – van Leeuwen (2007); 3 – Wesselius et al. (1982); 4 – Crawford, Barnes & Golson (1971); 5 – Mermilliod (2006); 6 – Skrutskie et al. (2006); 7 – Savage et al. (1985); 8 – Friedemann (1992); 9 – Neckel & Klare (1980); 10 – Guarinos (1992).

We present in Section 2 a series of Hα high-dispersion spectra showing that HR 7409 is a Be star in a single-lined spectroscopic binary. The Hα emission appears variable on a time-scale of years. We constrain the parameters of the Be star using the ultraviolet-to-optical spectral energy distribution (SED; Section 3.1) and Balmer line profiles (Section 3.2). Next, we measure the binary parameters (Section 4.1) and mass function of the companion (Section 4.2) while attempting to retrace the prior evolution of the system. We summarize and conclude in Section 5.

2 OBSERVATIONS

Table 1 lists astrometric and photometric measurements of HR 7409. The ultraviolet (*ANS*), optical (*UBV*) and infrared [Two Micron All Sky Survey (2MASS)] photometry and the *Hipparcos* parallax help to calculate the extinction-corrected absolute luminosity. The *ANS* magnitudes are converted to flux measurements using

$$\log f(\mathrm{W\,m^{-2}\,nm^{-1}}) = -0.4(m + 26.1).$$

We observed HR 7409 using the Coudé spectrograph attached to the 2-m telescope at Ondřejov Observatory (Šlechta & Škoda 2002). We obtained the spectroscopic series using the 830.77 lines $\mathrm{mm^{-1}}$ grating with a SITe 2030 × 800 CCD, with the slit width set at 0.7 arcsec, resulting in a spectral resolution of $R = 13\,000$ and a spectral range from 6254 to 6763 Å. We verified the stability of the wavelength scale by measuring the wavelength centroids of O I sky lines. The velocity scale remained stable within $1\,\mathrm{km\,s^{-1}}$. Table 2 presents our observation log.

We also obtained a series of spectra on UT 2010 November 15 using the Coudé spectrograph attached to the 2-m telescope at Rozhen National Astronomical Observatory (Bulgaria). We used the 632 lines $\mathrm{mm^{-1}}$ grating with a SITe 1024 × 1024 CCD. We set the slit width at 0.83 arcsec resulting in a spectral resolution of $R =$ 31 000, 20 000, 17 000 and 16 000 at four tilt angles centred on Hα, Hβ, Hγ and Hδ, respectively.

All spectra were wavelength calibrated with a ThAr comparison arc spectra obtained shortly after each exposure. The telluric features in the Hα spectra were removed using a fast-rotating B star template (HR 7880). The data were reduced using standard IRAF procedures.

The first spectrum obtained on 2007 May 23 revealed a fast-rotating star with a Hα emission core typical of Be stars. Spectra obtained in the following months and years show the emission component decreasing in strength. The Ondřejov spectra also show the rotationally broadened lines He I λ6678, Si II $\lambda\lambda$6347.109, 6371.371 and Ne I λ6402.246.

Table 2. Observation log.

UT date	UT start	t_{exp} (s)	UT date	UT start	t_{exp} (s)	UT date	UT start	t_{exp} (s)	UT date	UT start	t_{exp} (s)
2007-05-23	22:27:44	1800	2007-07-25	20:13:33	2722	2009-04-13	01:58:08	2200	2010-04-28	02:05:12	900
2007-07-04	23:11:43	3083	2007-07-26	20:28:09	1800	2009-07-30	22:22:44	1200	2010-04-28	02:20:50	900
2007-07-06	20:31:48	1200	2007-07-27	23:47:42	3209	2009-07-30	22:43:52	1200	2010-06-26	00:02:11	1200
2007-07-07	01:08:58	1203	2007-08-05	00:12:08	2799	2009-07-31	20:40:23	1180	2010-06-29	20:49:26	600
2007-07-08	01:08:57	1200	2007-08-06	00:19:45	3000	2009-08-02	02:11:07	900	2010-06-29	21:07:20	600
2007-07-13	23:17:35	1200	2007-08-06	20:35:40	1200	2009-08-30	19:49:42	1800	2010-08-20	19:29:20	600
2007-07-14	02:10:38	800	2007-08-12	21:33:52	3200	2009-08-30	23:09:56	1800	2010-08-20	19:40:03	600
2007-07-14	20:38:12	2270	2007-10-13	17:28:29	3100	2009-09-21	20:18:39	1800	2010-08-21	19:44:16	600
2007-07-15	00:51:18	1426	2007-10-13	20:41:59	3200	2009-09-23	18:05:36	1200	2010-08-21	19:55:02	600
2007-07-15	01:18:16	1528	2007-10-15	17:32:02	301	2009-09-23	22:03:55	1200	2010-08-22	19:55:24	600
2007-07-15	01:46:26	1207	2007-10-15	17:38:08	2506	2009-09-23	22:26:49	1200	2010-08-22	20:06:25	600
2007-07-15	21:19:03	3000	2007-10-15	20:33:06	2900	2009-10-09	18:13:24	1800	2010-09-21	19:26:24	600
2007-07-15	22:12:23	3000	2007-10-16	18:27:36	2200	2009-10-09	20:52:25	1800	2010-09-22	19:10:45	600
2007-07-16	00:41:30	3000	2008-07-02	00:59:40	900	2010-04-24	02:16:39	1200	2010-09-23	18:48:06	900
2007-07-16	01:34:34	2700	2008-08-28	00:26:07	600	2010-04-24	02:37:23	1200	2010-09-24	18:46:04	900
2007-07-22	21:14:23	3684	2008-10-13	18:22:53	600	2010-04-25	02:45:10	900	2010-09-30	18:34:54	900
2007-07-22	23:29:54	4309	2008-10-13	18:36:29	2200	2010-04-26	02:37:15	900	2010-10-13	18:58:08	600

3 PROPERTIES OF THE Be STAR

We analysed the SED and line profiles using a grid ($T_{\rm eff} \geq 15\,000$ K) of line-blanketed spectra in non-local thermodynamic equilibrium (non-LTE 'BSTAR' grid; Lanz & Hubeny 2007). We supplemented this grid with models ($T_{\rm eff} \leq 15\,000$ K) from a grid of spectra in LTE (Castelli & Kurucz 2003). We selected spectra with solar abundances from both model grids. However, the effect of gravitational darkening and geometric distortion on parameter measurements of fast-rotating B stars such as HR 7409 is sizeable. Frémat et al. (2005) and Lovekin, Deupree & Short (2006) investigated the effect of near critical equatorial rotation velocity on mean effective temperature and surface gravity measurements. The magnitude of the effect depends on the projection angle as well as the fraction of the critical velocity attained ($v/v_{\rm c}$), and may amount to an underestimation of the temperature by 10 per cent and surface gravity by 0.2 dex.

We estimated the mean stellar parameters by (1) fitting the infrared to ultraviolet SED, and (2) fitting the Balmer line series from Hα to Hδ.

3.1 Spectral energy distribution

The SED is affected by extinction in the interstellar medium. The colour-excess measurements range from $E(B-V) = 0.06$ to 0.09 mag (Table 1), i.e. $A_V = 0.19$–0.28 mag assuming $R_V = 3.1$. The two lowest measurements ($E(B-V) = 0.06$–0.07) were obtained by modelling the 2200 Å bump in the five-channel *ANS* ultraviolet photometry. The two highest measurements ($E(B-V) = 0.08$–0.09) were obtained assuming $(B-V)_0 = -0.18$ mag for a B5 V-type star. HR 7409 lies toward the Vulpecula Rift, an extinction wall associated with the Vulpecula molecular cloud and rising at a distance of 0.3 kpc (Fresneau & Monier 1999), and in a region of colour excess $E(B-V) \approx 0.1$–0.5.

We fitted the SED with model spectra assuming $\log g = 3.75$ and variable temperature and extinction. The SED comprises 11 data points (Table 1) with equal weights assigned to them. We employed the parametrized extinction curves ($R_V = 3.1$) from Cardelli, Clayton & Mathis (1989). A minimum effective temperature $T_{\rm eff} \gtrsim 12\,900$ K is obtained by setting $E(B-V) = 0$. Allowing the temperature to increase to 14 000, 15 000 and 16 000 K, we found that the best-fitting $E(B-V)$ increased to 0.053, 0.087 and 0.117, respectively. Varying the temperature and the colour excess simultaneously the best-fitting parameters are

$$T_{\rm eff} = 14\,400 \pm 800\,{\rm K}, \quad E(B-V) = 0.069 \pm 0.030.$$

The LTE and non-LTE models at 15 000 K delivered consistent solutions for the colour excess, $E(B-V) = 0.089$ and 0.087, respectively. Fig. 1 shows the infrared to ultraviolet SED of HR 7409 using the non-LTE model fit at the lower edge of the non-LTE grid (15 000 K).

The extinction-corrected V magnitude is $V_0 = 6.10 \pm 0.10$. Therefore, adopting the revised *Hipparcos* parallax of van Leeuwen (2007), the distance modulus is

$$m - M = 5 \log d - 5 = 7.76^{+0.41}_{-0.34},$$

and the de-reddened absolute V magnitude is $M_V = -1.66^{+0.44}_{-0.51}$, somewhat brighter than for a normal B4 V star ($M_V = -1.2$). Lamers et al. (1997) found that absolute visual magnitudes of O and B stars based on *Hipparcos* parallaxes correlate with rotation velocity and may be up to 1.5 mag brighter than inferred from the apparent spectral types.

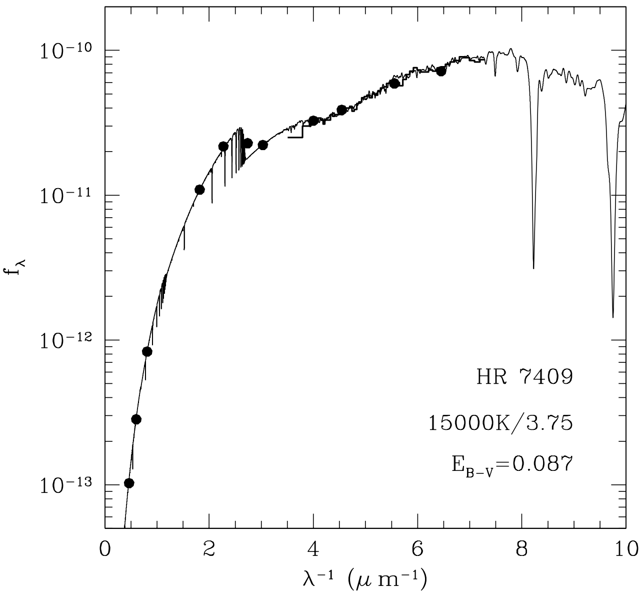

Figure 1. SED built using from left to right (full circles) 2MASS K, H and J, optical V, B and U and *ANS* 330, 250, 220, 180 and 155 nm photometric data points. The near- to far-UV spectrum is also covered with *TD-1* spectrophotometry (thick line). The observed distribution is compared to a model spectrum at $T_{\rm eff} = 15\,000$ K, $\log g = 3.75$ and solar metallicity (thin line) attenuated by interstellar extinction in the line of sight ($E(B-V) = 0.087$).

3.2 Line profile analysis: Balmer lines

Fig. 2 shows Hα spectra obtained 3.4 yr apart and illustrating extreme ranges in observed line profiles. Fig. 3 shows the evolution of the line equivalent width (EW) during that period. The EW was

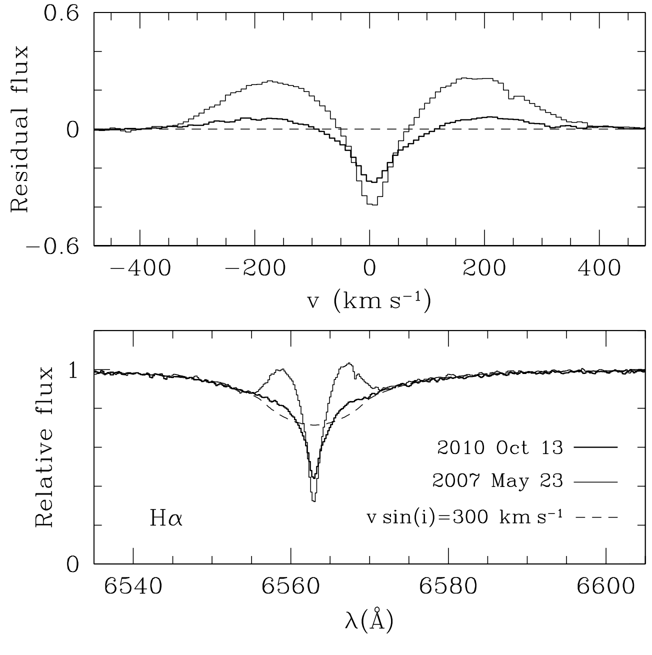

Figure 2. Bottom: optical spectra obtained at two epoches separated by ~1239 d (thick and thin lines) compared to a model at $T_{\rm eff} = 15\,000$ K and $v \sin i = 300\,{\rm km\,s^{-1}}$ (dashed line). The Hα line profile shows broad photospheric line wings, and variable disc emission/absorption. Top: the flux residual shows the emission and absorption components typical of a rotating disc with negligible radial motion.

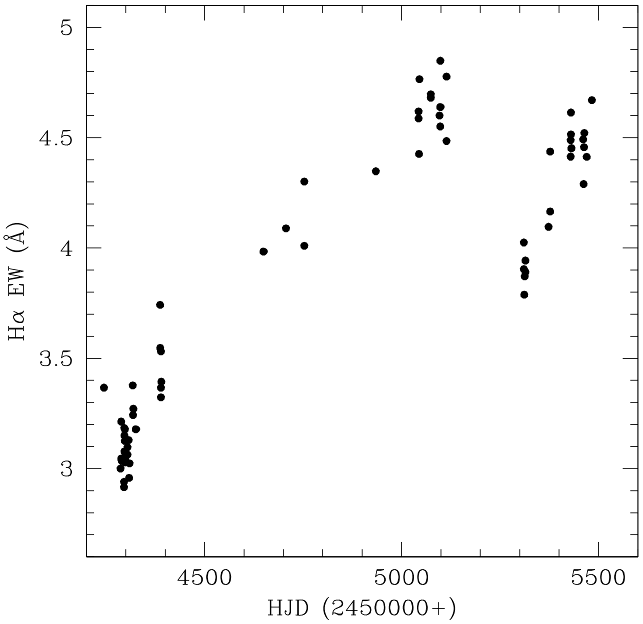

Figure 3. EW of the Hα line profile measured within a window of ±25 Å. The broad-line wings are blended with an emission component shown in Fig. 2; the emission decreases with time resulting in increasing EW measurements.

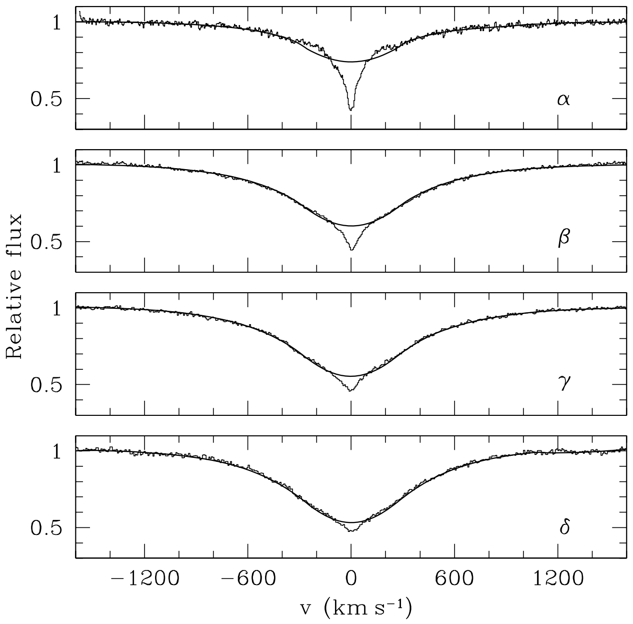

Figure 4. Spectra of the Balmer line series (Hα to Hδ) obtained at Rozhen and best model fit at $T_{\rm eff} = 15\,600$ K, $\log g = 3.75$ and $v \sin i = 300\,{\rm km\,s^{-1}}$.

measured using a ±25 Å window; the weakening of the emission wings over time results into deeper absorption and larger EW. HR 7409 was caught during a declining phase. Because disc variability may occur on time-scales of years (Clark, Tarasov & Panko 2003) or decades (Hubert 2007), continuing monitoring should assist us in capturing the next activity episode. The absence of central emission, but, instead, the broad shoulder and narrow line core suggest the onset of a 'shell' phase (see Steele, Negueruela & Clark 1999).

Next, we fitted the Balmer line spectra observed at Rozhen Observatory using the 'BSTAR' model grid with He/H = 0.1. The model line profiles were convolved with a rotational broadening function with $v \sin i = 300\,{\rm km\,s^{-1}}$ and limb darkening coefficient $\mu = 0.4$ (see Cranmer 2005). As discussed earlier, we neglected the effect of gravity darkening. Both model and spectra are normalized at $\pm 1500\,{\rm km\,s^{-1}}$ and we excluded the line cores ($\pm 400\,{\rm km\,s^{-1}}$) from the fit. Fig. 4 shows the best model fit to the Balmer line series (Hα to Hδ):

$$T_{\rm eff} = 15\,600 \pm 200\,{\rm K}, \quad \log g = 3.75 \pm 0.02.$$

Parameter estimations based on the Balmer line wings and on the SED are both possibly affected by the fast rotation of the star. The small statistical errors in the measurements based on the line profiles are almost certainly underestimating the true errors and do not encompass systematic effects. Although the apparent parameters are estimated conservatively as

$$T_{\rm eff} = 15\,500 \pm 1000\,{\rm K}, \quad \log g = 3.75 \pm 0.13,$$

and are marginally consistent with the published spectral type B5 V, the true spectral type is possibly earlier than this by at least one subtype. We propose the classification B4–5 III–IVe. Molenda-Żakowicz (2002) measured $T_{\rm eff} = 14\,930$ and $\log g = 3.52$ using *ubvy* data, in agreement with our results. Following the isochrones of Schaller et al. (1992) for $Z = 0.02$ models in the ($T_{\rm eff}$, $\log g$) plane as well as the ($T_{\rm eff}$, M_V) plane, HR 7409 is a $5.5 \pm 0.5\,{\rm M}_\odot$ star with an age of ≈50–80 Myr old nearing the end of its main-sequence life. The estimated age ignores, at this stage, the possibility of past binary interaction.

4 BINARY PARAMETERS AND NATURE OF THE COMPANION

We measured radial velocities using narrow Hα line core showing, as suspected in earlier investigations, that HR 7409 resides in a binary (Table 3). The velocities were obtained by fitting Voigt profiles to the central 10 pixels and we applied the heliocentric velocity correction. The Hβ, Hγ and Hδ velocities measured at Rozhen at a single epoch differ from the Hα velocity by up to $\approx 20\,{\rm km\,s^{-1}}$. The zero-point of the velocity scale appears uncertain although all measurements obtained with Hα are internally consistent. Fig. 5 shows the periodogram and Hα radial velocity measurements phased on the orbital period. The velocity residual is $1.3\,{\rm km\,s^{-1}}$ and is commensurate with the expected velocity accuracy. In the following we identify the Be star with the subscript 'A' and the unseen companion with 'B'.

4.1 Binary parameters

We fitted the Hα radial velocity measurements and simultaneously constrained the systemic velocity $\gamma_{\rm A} \equiv \gamma({\rm H}\alpha)$, the velocity semi-amplitude $K_{\rm A} \equiv K({\rm H}\alpha)$, the eccentricity e and the angle of passage of star A at T_0 (passage at periastron). Table 4 lists the best-fitting orbital parameters.

Adopting $M = 5.5\,{\rm M}_\odot$ and $R = 5.2\,R_\odot$, i.e. $\log g = 3.75$, the critical velocity is $v_{\rm c} = 367\,{\rm km\,s^{-1}}$ (assuming $R = R_{\rm polar}$; see Cranmer 2005). Therefore, the measured rotation velocity limits the inclination to $\sin i \gtrsim 0.83$, or $i \gtrsim 56^\circ$.

Table 3. Radial velocity (Hα core).

HJD (245 0000+)	$v_{\mathrm{H}\alpha}$ (km s^{-1})	HJD (245 0000+)	$v_{\mathrm{H}\alpha}$ (km s^{-1})	HJD (245 0000+)	$v_{\mathrm{H}\alpha}$ (km s^{-1})	HJD (245 0000+)	$v_{\mathrm{H}\alpha}$ (km s^{-1})
4244.44879	−20.2	4307.36287	−25.8	4934.59438	−25.8	5314.59285	−8.8
4286.48853	−13.4	4308.36767	−25.1	5043.44372	−11.7	5314.60371	−7.9
4288.36662	−15.3	4309.51439	−22.3	5043.45840	−11.9	5373.51247	−8.4
4288.55912	−15.7	4317.52888	−17.1	5044.37252	−12.5	5377.37525	−8.0
4289.55911	−15.0	4318.53531	−15.6	5045.60056	−12.3	5377.38768	−7.6
4295.48184	−18.9	4319.36927	−16.0	5074.33998	−23.0	5429.31932	−17.2
4295.59970	−19.6	4325.42111	−10.3	5074.47902	−23.6	5429.32676	−15.8
4296.37736	−20.3	4387.24668	−17.1	5096.35883	−5.9	5430.32966	−16.4
4296.54824	−19.1	4387.38162	−17.1	5098.26284	−5.8	5430.33713	−14.7
4296.56756	−19.1	4389.23280	−16.2	5098.42833	−4.5	5431.33735	−14.6
4296.58526	−19.4	4389.24980	−15.6	5098.44423	−3.2	5431.34500	−15.2
4297.40996	−20.8	4389.37358	−15.7	5114.27061	−13.0	5461.31562	−12.8
4297.44700	−20.7	4390.28230	−13.3	5114.38103	−12.4	5462.30469	−15.8
4297.55055	−21.7	4649.55082	−24.5	5310.60225	−7.4	5463.29063	−13.9
4297.58567	−21.6	4706.52511	−15.0	5310.61665	−6.6	5464.28915	−11.4
4304.41070	−23.7	4753.26994	−4.1	5311.62039	−8.4	5470.28099	−14.8
4304.50842	−24.2	4753.28864	−5.5	5312.61496	−8.8	5483.29445	−23.7

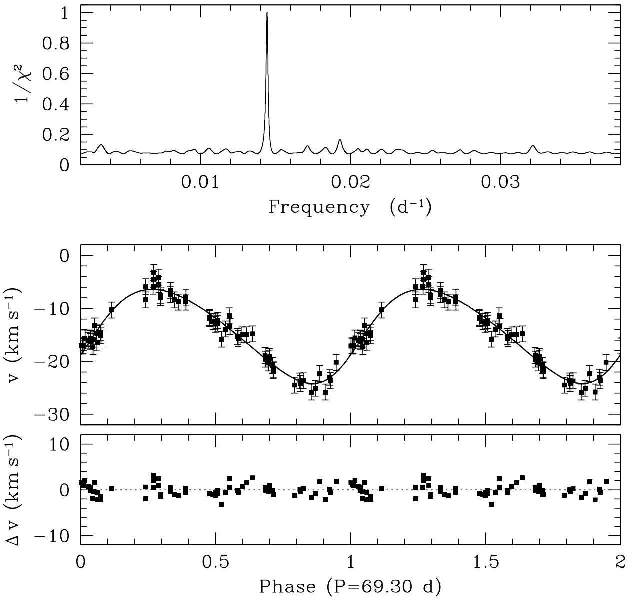

Figure 5. Top: periodogram of the Hα line velocity measurements. Middle: the velocity variations are well matched by an eccentric orbit of 69 d. Bottom: velocity residuals of only 1.3 km s^{-1}.

4.2 Nature of the companion and evolutionary scenarios

We may now constrain the nature of the binary companion by calculating the mass function:

$$f(M_\mathrm{B}) = \frac{PK_\mathrm{A}^3}{2\pi G}(1-e^2)^{3/2} = (4.9 \pm 0.7) \times 10^{-3}\,\mathrm{M}_\odot,$$

and solving iteratively for the secondary mass M_B:

$$M_\mathrm{B} = f(M_\mathrm{B})\frac{(1+q)^2}{\sin^3 i},$$

where $q = M_\mathrm{A}/M_\mathrm{B}$. The orbit and the Be star rotation are almost certainly coplanar. Adopting $\sin i = 0.83$ for the inclination of the Be star rotation plane, i.e. assuming subcritical rotation velocity, and adopting $M_\mathrm{A} = 5.5 \pm 0.5\,\mathrm{M}_\odot$, we find $M_\mathrm{B} = 0.62$–$0.77\,\mathrm{M}_\odot$ and $q = 7.8$–8.1. A lower limit on the secondary mass is set by assuming $\sin i = 1$ resulting in $M_\mathrm{B} = 0.50$–$0.63\,\mathrm{M}_\odot$, or $q = 9.5$–10. In summary, the secondary star has a mass within the range $M_\mathrm{B} = 0.50$–$0.77\,\mathrm{M}_\odot$ for a binary mass ratio $q = 7.8$–10. The semimajor axis is $a = 130 \pm 5\,\mathrm{R}_\odot$ or 0.60 ± 0.02 au.

Table 4. Orbital parameters.

Parameter	Value
P	69.30 ± 0.07 d
T_0	HJD 245 4248.1 ± 2.7
$\gamma(\mathrm{H}\alpha)$	-14.8 ± 0.2 km s^{-1}
$K(\mathrm{H}\alpha)$	8.9 ± 0.4 km s^{-1}
ω	247° ± 16°
e	0.161 ± 0.035

The mass of the companion is typical of M1 to K1 main-sequence stars, but also of the bulk of white dwarf stars (Shipman 1979). If the companion is a main-sequence star, then the system is relatively young (young scenario: 50–80 Myr; Schaller et al. 1992) and with a total systemic mass of 5.5–$6.8\,\mathrm{M}_\odot$. If the companion is a white dwarf then the current orbital separation necessarily implies past interaction and we must investigate plausible evolutionary scenarios (old scenario; see Willems & Kolb 2004). The outcome of the old scenario is not necessarily a white dwarf plus main-sequence binary, but the evolved component of the system may also be caught at shorter-lived, intermediary stages.

The mass-accreting component of a close binary may acquire sufficient angular momentum to reach critical rotation velocity (Packet 1981). Although it was originally proposed that Be stars are subjected to ongoing accretion (Křìž & Harmanec 1975), the properties of Be stars rather suggest that many, but not all, are exhibiting the effect of past rather than current accretion events, more specifically a case B mass transfer events while the evolving star climbed the giant branch (Waters et al. 1989; Pols et al. 1991; van Bever & Vanbeveren 1997). Indeed, Waters, Cote & Pols (1991) find evidence that the Be binary HR 2142 holds a white dwarf or He star secondary, and Gies et al. (1998) show that the companion to the Be star ϕ Per (Poeckert 1981) is an extreme horizontal branch (EHB) star. HR 7409 shares a number of characteristics with the Be star 4 Her (Koubský et al. 1997). Both stars are fast rotating and reside in long-period binaries. Moreover, their mass functions imply the presence of a low-mass companion. However, our interpretation of the phenomenon involves past interaction and mass transfer rather than on-going accretion as proposed by Koubský et al. (1997).

Population syntheses (see e.g. Raguzova 2001; Willems & Kolb 2004) aim at predicting the binary period and final-mass distributions. Willems & Kolb (2004) described a likely scenario (labelled number '2') for the formation of the present-day binary HR 7409: a $5.5 + 3.5\,\mathrm{M}_{\odot}$ pair in a close 5-d binary is expected to experience its first Roche lobe overflow (RLOF) event after the primary crosses the Hertzsprung gap and climbs the giant branch ($t \approx 80\,\mathrm{Myr}$). The process quickly results in a reversal of the mass ratio (from $q = 1.6$ to 0.12). With the cessation of mass transfer, the binary enters an extended quiet period while the evolved star, labelled a 'naked' helium star, sits on the horizontal branch (HB) for $\approx$20 Myr. After exhaustion of the helium fuel, the binary enters a second RLOF episode and becomes a detached white dwarf plus B star binary with a final period of 93 d. This scenario is not only applicable to the formation of Be stars but also to any fast-rotating B stars. Gies et al. (2008) found that the fast-rotating B star Regulus is a 40-d binary with a likely white dwarf companion. Rappaport, Podsiadlowski & Horev (2009) reconstructed the past history of this system and concluded that the Regulus system will likely evolve into an AM CVn system.

HR 7409 appears to be a less massive version of scenario number 2 described by Willems & Kolb (2004). Assuming conservative mass transfer throughout the evolution we may assume initial masses of $M_{1,0} = 3.4$ ($t_{\mathrm{MS}} = 250\,\mathrm{Myr}$; Schaller et al. 1992) and $M_{2,0} = 2.7\,\mathrm{M}_{\odot}$ for the original primary and secondary and an orbital period of several days. In this scenario, $\approx 2.8\,\mathrm{M}_{\odot}$ are transferred from the original primary to the secondary leaving a fast-rotating $\approx 5.5\,\mathrm{M}_{\odot}$ star with an evolved $\approx 0.6\,\mathrm{M}_{\odot}$ He star or white dwarf companion. Considering that the present-day Be star exhibits evidence of a wind, an accreting white dwarf would emit copious X-rays as in the case of γ Cas (Harmanec et al. 2000) or HD 161103 and SAO 49725 (Lopes de Oliveira et al. 2006). However, HR 7409 is not an X-ray source (Berghoefer, Schmitt & Cassinelli 1996), leaving us with the possibility that the unseen companion is a He star with a shallower potential well.

Having been striped of its hydrogen envelope, the naked He star may join other HB stars with $M_V \approx 0.5$ and contribute up to 15 per cent of the composite optical flux, or resemble a hot subdwarf on the EHB with absolute V magnitude $\approx$4 (see Heber 2009) and would contribute less than 1 per cent of the composite flux. Further examination of the high-dispersion spectra may offer clues to the nature of the companion.

4.3 Line profile analysis: He I λ6678.15

Fig. 6 shows co-added He I λ6678 spectra phased with the orbital period. In order to increase the signal-to-noise ratio and search for weak spectral lines tracing the orbit of the companion we regrouped the spectra in four bins and adjusted the velocity scale to the Be star rest frame. The He I λ6678 line shows a broad redshifted emission and its overall shape varies over time. A weak absorption feature ($\approx$30 mÅ) marked with vertical lines is moving in opposite directions to the Be star [$v(0.0\text{–}0.2, 0.2\text{–}0.4, 0.45\text{–}0.65, 0.75\text{–}1.0) \approx -15, -85, -45, 45\,\mathrm{km\,s^{-1}}$] and may belong to a subluminous B-type companion. The full amplitude of the motion, after correcting for orbital smearing in the co-added spectra, is $K \approx 140\,\mathrm{km\,s^{-1}}$ and would imply a mass ratio $\approx$8 for the companion in agreement with the mass function (Section 4.2).

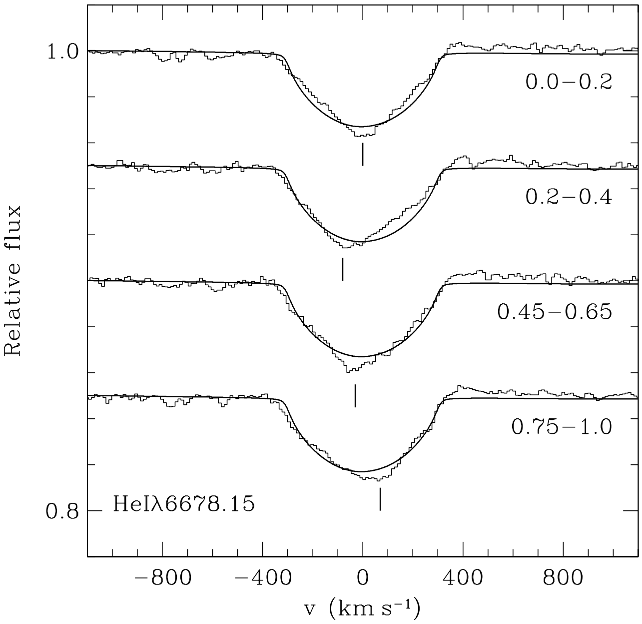

Figure 6. Co-added He I λ6678 spectra phased with the orbital period. The velocity scale is set in the Be star rest frame. The line asymmetry varies with the orbital phase. The spectra labelled 0.2–0.4, 0.45–0.65 and 0.75–1.0 are shifted down by 0.05, 0.10 and 0.15, respectively.

A confirmation of the detection of a secondary star may be secured with optical or ultraviolet echelle spectroscopy at high dispersion and very high signal-to-noise ratio.

5 SUMMARY AND CONCLUSIONS

Table 5 lists some stellar properties. We found that the Be star HR 7409 forms a 69.3-d binary with a low-mass companion. Although, we cannot exclude a low-mass main-sequence star, the companion is most likely a hot subluminous star. An evolutionary scenario involving an episode of conservative mass transfer also offers a natural explanation for the fast rotation of the Be star. Using the distance, systemic velocity and proper-motion measurements (d, v_r, μ_α and μ_δ) we confirm the peculiar kinematics of the Be star which imply that HR 7409 belongs to a group of runaway B stars (Hoogerwerf, de Bruijne & de Zeeuw 2001). Instead, we propose that its prior evolution and 'rejuvenation' suggests more evolved kinematical properties such as those of white dwarf stars that show a lag in the Galactic V component of $-40\,\mathrm{km\,s^{-1}}$ (Sion et al. 1988).

A relatively old age for the system would imply that it is not part of the Gould Belt. The main-sequence lifetime of the evolved star is estimated at 250 Myr for an initial mass of $3.4\,\mathrm{M}_{\odot}$ (see Section 4.2), but increasing the progenitor mass above $5\,\mathrm{M}_{\odot}$ ($t_{\mathrm{MS}} \lesssim 90\,\mathrm{Myr}$) would bring the system age closer to the estimated age of the Gould Belt (30–60 Myr; see Bekki 2009, and references therein). Detailed

Table 5. Kinematics, distance, masses and spectral types.

Parameter	Value
(U, V, W)	$(6^{+5}_{-3}, -42^{+2}_{-4}, -9^{+3}_{-4})\,\mathrm{km\,s^{-1}}$
d	356^{+75}_{-51} pc
$M_{\mathrm{A}}, M_{\mathrm{B}}$	$5.5 \pm 0.5, 0.50\text{–}0.77\,\mathrm{M}_{\odot}$
Types	B4–5 III–IVe plus (EHB, HB, K V or WD)

evolutionary models for this particular system should help elucidate the age problem.

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