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Evidence for a substellar secondary in the magnetic cataclysmic binary EF Eridani *

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Abstract. Low-state spectrophotometry of the short-period polar EF Eridani ($P_{\rm orb}$= 81 min) found the system at $V = 18.0$ with no trace of the companion (Wheatley and Ramsay 1998). We show that the lack of such spectral features implies that the companion to the white dwarf in EF Eri has a spectral type later than M9 and is either a transition object at the brink of hydrogen burning or a brown dwarf. The optical low state spectrum indicates a temperature of the white dwarf of $T_{\rm eff}$= 9500 ± 500 K. This is one of the coldest white dwarfs in cataclysmic variables, implying a cooling age $t_{\rm cool} \gtrsim 10^9$ yrs or accretional heating at a rate as given by gravitational radiation. The large age of the system excludes a warm brown dwarf as companion. EF Eri has either just passed through the period minimum of cataclysmic variable stars or has started mass transfer from an old brown dwarf secondary.

Key words: stars:low-mass, brown dwarfs – stars: evolution – stars: formation – cataclysmic variables – white dwarfs

1. Introduction

Cataclysmic binary stars (CVs) with short orbital periods ($P_{\rm orb} < 2$ h) lose angular momentum by gravitational radiation, causing these systems to shrink and their orbital periods to decrease. Mass loss ablates the secondary star until it drops below the minimum mass needed for hydrogen burning, becomes increasingly degenerate, and enters the regime of brown dwarfs. The associated change in the mass–radius relation of the secondary causes the orbital period $P_{\rm orb}$ to increase again. The abrupt cutoff in the period distribution of CVs locates the observed period minimum at 77 min (e.g. Kolb & Baraffe 1999). Short-period CVs with $P_{\rm orb} > 90$ min which approach the period minimum have observed secondaries with spectral types dM4–dM6. For $P_{\rm orb} < 90$ min, the secondary stars are expected to be of still later spectral type and have escaped detection so far (e.g. Beuermann et al. 1998). Some dwarf novae of the WZ Sge type are suspected to have passed the period minimum and to harbour a degenerate companion (Howell et al. 1995). V592 Her may be such a system (van Teeseling et al. 1999).

Direct observational proof of this evolutionary scenario is scarce so far. Spectroscopic detection of the secondaries in short-period dwarf novae is extremely difficult because the accretion disc and the white dwarf dominate the optical/near IR emission of the systems. The situation is more favourable in magnetic CVs which lack a disc. In these systems, accretion ceases at irregular instances and reveals the naked binary.

In this paper, we discuss low state observations of the 81-min magnetic CV EF Eri (Wheatley & Ramsay 1998) which allow us to set tight limits on the spectral flux and on the physical nature of the secondary.

2. Observations

Wheatley & Ramsay (1998) found EF Eri in a low state in February 1997 with V varying between 17.95 and 18.20. Besides photometry, they performed spectrophotometry on February 7 and 8 using the ESO 3.6-m telescope at La Silla/Chile equipped with the focal reducer spectrograph EFOSC 1 Accretion did not cease completely as is evidenced by Balmer line emission and weak cyclotron emission in the red/infrared part of the spectrum. Cyclotron emission was observed only during linear polarization phases 0.5–0.9 and was removed from the individual spectra using the difference spectrum between cyclotron maximum and the cyclotron free spectra as a template. In the two nights, the observations started at airmasses 1.1 and 1.2 and were carried on until airmasses 1.8 and 2.5, respectively. A slow flux decrease was observed with increasing airmass, probably caused by the deteriorating seeing at lower altitude. We adopted the flux level of the cyclotron-free spectra at the beginning of the observations (airmass < 1.27) and corrected this level to zero airmass. A nearby standard star of early spectral type was used to correct for the telluric O_2 and H_2O bands. This correction minimizes the excursions from a smooth continuum and causes the resulting spectrum to be artificially smooth at the centre of the A-band between 7600 and 7660Å. The resulting mean spectrum is shown in Fig. 1 as the upper solid line and the narrow uncertain section between 7600

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* Based in part on observations at the European Southern Observatory La Silla (Chile)

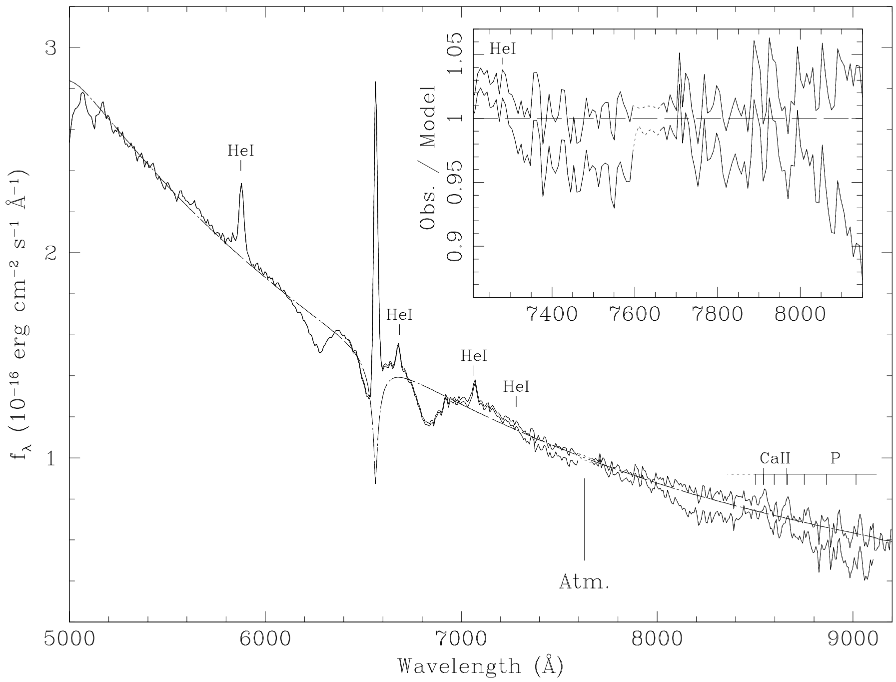

Fig. 1. Mean spectrum of EF Eri in the 1997 low state for orbital phases corrected for the remnant cyclotron emission (upper solid curve) along with the best-fit non-magnetic model spectrum for $T_{\rm eff} = 9500$ K (dot-dashed curve). The lower solid curve indicates the observed spectrum corrected for a 5% flux contribution at 7500Å by a dM9 companion star. The negative M-star features indicate that the companion must be fainter than this. The spectral region between 7600 and 7660Å is uncertain due to the correction for the atmospheric A-band (dashed section of the curves).

and 7660Å is shown as the dashed line. The pronounced dips at 6300, 6500, and 6800 Å are the σ^+, π, and σ^- Zeeman components of Hα. Zeeman tomography of the magnetic-field structure of EF Eri will be presented elsewhere.

3. Spectral analysis

We fit the continuum of the white dwarf at wavelengths $\lambda >$ 5300Å (excluding the Hα absorption and emission line region) with pure-hydrogen line-blanketed magnetic and non-magnetic model atmosphere spectra (Jordan 1992, Gänsicke et al. 1995). The best fit is achieved for a mean effective temperature of 9500 ± 500 K (dashed curve in Fig. 1). The observed spectral flux and the surface flux of the white dwarf for $T_{\rm eff} = 9500$ K gives an angular radius $R_1/d = (2.30 \pm 0.17) \times 10^{-12}$ radians. Using magnetic model atmospheres yields a temperature lower by 200 K and an identical angular radius. As in other polars, the remnant modulation of the blue continuum of 0.2 mag (Wheatley & Ramsay 1998) can be explained by a moderately hot spot of 15 000 K covering 6% of the cross section of the white dwarf. The model spectrum excellently fits the observed continuum between 5300 and 9000 Å with no evidence for a contribution by the companion.

We estimate the maximum possible contribution by the unseen companion, using the calibration of the surface brightness of late type main sequence stars in the prominent λ7500/7165Å TiO/VO band (Beuermann 1999, and paper in preparation). This calibration is based on the ZAMS stellar model radii of Baraffe et al. (1998), parameterized by Beuermann et al. (1999). Fig. 2 shows the derived surface fluxes F_λ of the late-type dwarfs Gl644C = VB8 (M7), Gl752B = VB10 (M8), and LHS2065 (M9). We denote the difference between the surface fluxes at 7500Å and 7165Å as $F_{\rm TiO}$ and have calibrated this quantity as a function of the spectral type for the range dM0–dM9. Gl 644C, Gl752B, and LHS2065 have $F_{\rm TiO} = 6.7 \times 10^4$, 3.0×10^4, and 1.2×10^4 ergs cm^{-2}s^{-1}Å^{-1}, respectively, very close to the mean $F_{\rm TiO}$ values of dM7, dM8, and dM9 dwarfs. For the present purpose, we include the very cool dwarf 2MASS1439+19 of spectral type L1 (Kirkpatrick et al. 1999) for which we estimate $F_{\rm TiO} \simeq 0.4 \times 10^4$ ergs cm^{-2}s^{-1}Å^{-1}. The observed flux of the companion which corresponds to $F_{\rm TiO}$ is denoted $f_{\rm TiO}$.

We subtract test fractions of the spectra of these stars from the observed spectrum and judge the acceptable contribution by eye. The lower solid curve in Fig. 1 shows the effect of an assumed contribution of LHS2065 which amounts to 5% of the observed flux at 7500Å. The resulting wavy structure is due to the subtracted M-star and clearly indicates that the contribution by the companion must be smaller than this. The insert shows the region around 7500 Å in more detail, now depicted as a flux ratio relative to the model spectrum. The signature of the M-star is clearly visible in the subtracted spectrum. We adopt the 5% flux contribution at 7500 Å as a strict upper limit to the flux contributed by the companion which corresponds to upper limits on $f_{\rm TiO}$ of 4.5, 3.9, 3.5 and 2.3×10^{-18} ergs cm^{-2}s^{-1}Å^{-1} for spectral types M7, M8, M9, and L1, respectively.

4. Companion mass

We now derive mass limits for the companion in EF Eri as functions of its spectral type and an assumed white dwarf mass M_1. Its radius R_1 and the distance d to EF Eri are related by

$$R_1/d = (f_\lambda/F_\lambda)^{1/2}_{\rm wd} \tag{1}$$

where f_λ and F_λ are the observed continuum flux and the model surface flux of the white dwarf with $T_{\rm eff} = 9500$ K, respectively,

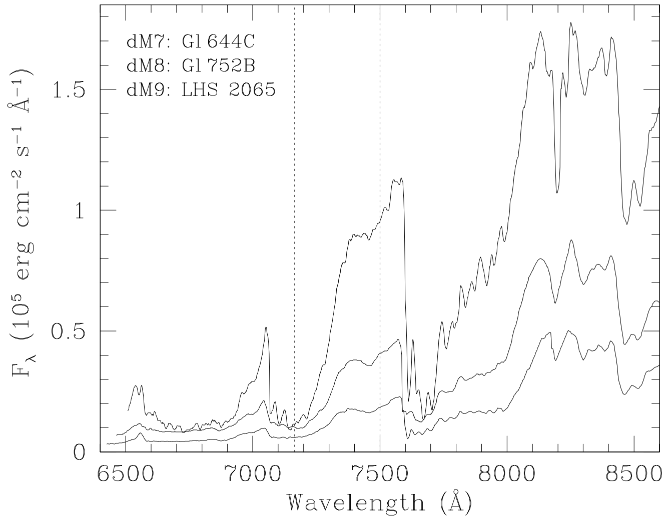

Fig. 2. Surface fluxes F_λ of representative late type dwarfs of spectral types dM7 (Gl644C), dM8 (Gl752B), and dM9 (LHS 2065). The vertical dashed lines indicate the wavelengths at which the quantity $F_{\rm TiO}$ is measured (from Beuermann 1999).

and R_1/d is as quoted above. Correspondingly, the ratio of the (upper limit to the) observed flux $f_{\rm TiO}$ and the surface flux $F_{\rm TiO}$ of the companion in the $\lambda 7500/7165$Å band is given by

$$R_2/d = (f_{\rm TiO}/F_{\rm TiO})^{1/2}_{\rm sec}. \qquad (2)$$

Finally, Roche geometry implies

$$R_2 = 1.628 \times 10^{10} (M_2/M_\odot)^{1/3} P_{\rm h}^{2/3} f(q) \qquad {\rm cm} \qquad (3)$$

where $P_{\rm h}$ is the orbital period in hours, $f(q)$ is a function of the mass ratio $q = M_1/M_2$ which varies between 0.98 and 1.01 for q between 3 and 30, and M_1 and M_2 are the masses of the white dwarf and the companion, respectively. Eqs. (1) – (3) define (an upper limit to) the companion mass M_2 as a function of the unknown mass of the white dwarf and the spectral type of the companion, represented by R_1 and $F_{\rm TiO}$, respectively,

$$M_2 = \left(\frac{R_1}{f(q)\,1.628 \times 10^{10}{\rm cm}}\right)^3 \left(\frac{d}{R_1}\right)^3_{\rm wd} \left(\frac{f_{\rm TiO}}{F_{\rm TiO}}\right)^{3/2}_{\rm sec} \frac{1}{P_{\rm h}^2}. \qquad (4)$$

We use radii of white dwarfs with $T_{\rm eff} = 9500$ K and an envelope consisting of $10^{-4} M_\odot$ of hydrogen and $10^{-2} M_\odot$ of helium (D. Koester, private communication). Carbon white dwarfs of 1.0, 0.8, and 0.6 $M_\odot$ have R_1 = 0.57, 0.73, and 0.91×10^9 cm, respectively. An $0.4\,M_\odot$ helium white dwarf has $R_1 = 1.17 \times 10^9$ cm. In order to obtain upper limits to M_2, we employ the 1-σ upper limit to d/R_1 as given above and the upper limits to $f_{\rm TiO}$. Table 1 lists the resulting strict upper limits to M_2 for four values of M_1 and the assumed spectral types of the companion. Some insight into the systematics of the M_2-variation may be gained from noting that for low-mass white dwarfs with $R_1 \propto M_1^{-1/3}$, one obtains $M_2 \propto M_1^{-1} F_{\rm TiO}^{-3/2}$, i.e. the allowed mass of the companion is lowest for a massive white dwarf and an early spectral type of the companion. For brown dwarfs, M_2 is limited by the assumed spectral type and the age rather than by Eq. (4).

Table 1. Parameters of EF Eri for companions of spectral type dM7 to L1 and for a white dwarf with $T_{\rm eff} = 9500$ K and a mass between 0.4 and $1.0\,M_\odot$. M_2 is from Eq. (4) and $\dot M_{\rm hi}$ is in units of $10^{-11} M_\odot$ yr^{-1}. Acceptable M_1 – spectral type combinations are shown in boldface.

M_1 $M_\odot$	R_1 10^9 cm	d pc	$\dot M_{\rm hi}$	Spectral Type	R_2 10^9cm	M_2 $M_\odot$	Notes
0.4	1.17	165	25	M7	4.5	< 0.012	1,2,5
				M8	6.3	< 0.032	1,2,5
				M9	9.3	< 0.104	1
				L1	13.2	< 0.302	1,3
0.6	0.91	128	7.7	M7	3.5	< 0.006	2,5
				M8	4.9	< 0.015	2,5
				M9	7.2	< 0.049	2,5
				L1	10.2	< 0.142	**3**
				$\gtrsim$L4			**4**
0.8	0.73	103	2.9	M7	2.8	< 0.003	2,5
				M8	3.9	< 0.008	2,5
				M9	5.8	< 0.025	2,5
				L1	8.2	< 0.073	2,3,5
				$\gtrsim$L4			**4**
1.0	0.57	80	1.1	M7	2.2	< 0.002	2,5
				M8	3.1	< 0.004	2,5
				M9	4.5	< 0.012	2,5
				L1	6.4	< 0.035	2,5
				$\gtrsim$L4			**4**

Notes: (1) $M_1 = 0.4\,M_\odot$ excluded by high temperature of hard X-ray spectrum; (2) brown dwarf with M_2 and assumed spectral type excluded at age $t > t_{\rm cool}$ (see text) (Baraffe et al. 1998); (3) spectral type indicates a transition object with $M_2 \sim 0.075\,M_\odot$; (4) spectral type implies a brown dwarf companion; (5) M_2 may not be able to supply $\dot M_{\rm hi}$ if driven by gravitational radiation only (Kolb & Baraffe 1999).

5. Accretion rate

Before its recent low state, EF Eri was known as a roughly steady X-ray source for two decades. The integrated high-state orbital mean X-ray and cyclotron flux is $f_{\rm hi} = 3 \times 10^{-10}$ ergs cm^{-2}s^{-1} (Beuermann et al. 1987, 1991). The soft X-ray flux, still quite uncertain in the EINSTEIN observations (Beuermann et al. 1987), is more accurately defined in the ROSAT data (Beuermann et al. 1991). The integrated luminosity is $L_{\rm hi} \simeq 2.6 \times 10^{32} (d/100\,{\rm pc})^2$ ergs s^{-1}, where we have accounted for the different geometry factors of the individual radiation components following Beuermann et al. (1987). The corresponding distance-dependent high-state accretion rate

$$\dot M_{\rm hi} = L_{\rm hi} R_{\rm wd}/(G M_{\rm wd}) \qquad (5)$$

is probably accurate to better than a factor of two (Table 1). We expect that $\dot M_{\rm hi} > \langle \dot M \rangle$, the long-term mean mass transfer rate which is about $3 \times 10^{-11} M_\odot$yr^{-1} for short-period CVs with low-mass main sequence donors (Kolb & Baraffe 1999, their Fig. 1). For $M_1 \geq 0.8\,M_\odot$, $\dot M_{\rm hi}$ and even more so $\langle \dot M \rangle$ fall below $3 \times 10^{-11} M_\odot$yr^{-1}, suggesting a substellar companion. For lower M_1, the derived value of $\dot M_{\rm hi}$ permits a stellar or a substellar companion.

6. Discussion and Conclusion

Table 1 lists the limits on M_2 obtained from Eq. (4) for an assumed white dwarf mass and spectral type of the companion. We have included a line for brown-dwarf companions with spectral type $\gtrsim$ L4 for which Eq. (4) is no longer applicable.

Several authors have argued in favour of a rather massive white dwarf in EF Eri. Beuermann et al. (1987) find $M_1 > 0.56\,M_\odot$, Wu et al. (1995) $M_1 \simeq 0.57\,M_\odot$, and Cropper et al. (1999) $M_1 \simeq 0.80\,M_\odot$, all using the observed bremsstrahlung temperature. The observed mass function (Mukai & Charles 1985) suggests $M_1 \gtrsim 0.8\,M_\odot$. Hence, $M_1 \gtrsim 0.6\,M_\odot$ and the companion is substellar or later than M9 (Note 1 in Table 1).

Stars just above the limit for hydrogen burning, $M_{\rm min} \simeq 0.075\,M_\odot$, with solar composition and an age > 2 Gyr reach a stable effective temperature of ~ 2000 K (Baraffe et al. 1998). Their nominal spectral type would be ∼M9/L0, while objects of slightly lower mass rapidly fade to still lower temperatures. The details are still uncertain because the definition of the M-star/L-dwarf transition is a spectroscopic one and the conversion to mass is not straightforward (Baraffe et al. 1998, Kirkpatrick et al. 1999, Reid et al. 1999).

Another important result of this study is the low effective temperature of the white dwarf in EF Eri. With $T_{\rm eff} \simeq 9500$ K it is the coldest of all white dwarfs in CVs which have a reliably determined temperature (Gänsicke 1999). This low temperature implies a cooling age of $t_{\rm cool} = 9 \times 10^8 - 2 \times 10^9$ yrs for $M_1 = 0.6 - 1.0\,M_\odot$, respectively (Wood 1995). The companion must be older than $t_{\rm cool}$ and, hence, can not be a warm brown dwarf. This excludes all combinations of a spectral type M7–L1 and $M_2 < 0.06\,M_\odot$ (Note 2 in Table 1). For definiteness, we identify a spectral type L1 with a transition object of mass $M_2 \sim 0.075\,M_\odot$ and a spectral type $\gtrsim$ L4 with a brown dwarf (Notes 3 and 4 in Table 1). Acceptable companion objects are those which have only a boldface entry **4** in the Notes column of Table 1 (brown dwarfs). Acceptable is also the sole entry **3** (transition object) for $M_1 = 0.6\,M_\odot$, but marginally so because a companion of $\sim 0.075\,M_\odot$ is possibly not able to supply $\dot{M}_{\rm hi} = 8 \times 10^{-11}\,M_\odot{\rm yr}^{-1}$(Note 5). We conclude that the companion is either a transition object or a brown dwarf.

The true age of the white dwarf must exceed $t_{\rm cool}$ because the temperatures of accreting white dwarfs are kept above those of field white dwarfs of the same age by compressional heating of their envelopes (Sion 1995, Warner 1995, Gänsicke et al. 1999). If entirely due to accretion, $T_{\rm eff} = 9500$ K requires a mean accretion rate not exceeding that expected from gravitational radiation, $\langle \dot{M} \rangle \lesssim 3 \times 10^{-11}\,{\rm ergs\,cm^{-2}s^{-1}}$ (Gänsicke 1999), lending further support to a rather high white dwarf mass and a substellar companion.

The substellar nature of the companion is supported also by considerations of the evolutionary state of EF Eri. One of the main results of the theory of CV evolution is the recognition that a period bounce occurs when $M_2 \simeq 0.06\,M_\odot$ and the secondary becomes increasingly degenerate. The orbital period of EF Eri is 4 min longer than the observed minimum period $P_{\rm min} \simeq 77$ min and still further above the theoretical value of 67 min (Kolb & Baraffe 1999). If EF Eri evolved from longer periods, it is now either approaching the minimum or has already passed it. At 4 min above the *calculated* period minimum the donor mass/temperature would be either $0.08\,M_\odot$/2500 K or $0.05\,M_\odot$/1500 K, while at a calculated period of 81 min these numbers would be $0.10\,M_\odot$/2900 K and $0.035\,M_\odot$/1000 K (Kolb & Baraffe 1999). Since a spectral type L implies $T_{\rm eff} \lesssim 2000$ K, we conclude that EF Eri has passed $P_{\rm min}$. If it formed with a brown dwarf secondary of age > 1 Gyr, the companion would have $T_{\rm eff} \lesssim 2000$ K at $P_{\rm orb} = 81$ min, too (Kolb & Baraffe 1999). In both cases the companion is substellar with $M_2 \lesssim 0.06\,M_\odot$.

The reason for the discrepancy between calculated and observed $P_{\rm min}$ is not yet understood. Possible explanations include (i) the presence of an additional mechanism of angular momentum loss and (ii) a mechanism which causes CVs with stellar secondaries to become unobservable before they reach $P_{\rm min}$. As the most likely value of the companion mass is $< 0.06 M_\odot$ and EF Eri is still a bright X-ray source our result argues against the second explanation.

EF Eri is a key object for our understanding of CV evolution. Obtaining a trigonometric parallax would allow to determine accurate values of the mass, luminosity, and accretion rate of the white dwarf. Infrared spectrophotometry will allow to detect the companion ($M_{\rm K} < 12$ for companions as late as L8) against the veiling flux of the white dwarf ($M_{\rm K} \simeq 12.5$).

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