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The low-mass white dwarf companion to β Crateris

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ABSTRACT

We present *FUSE* H Lyman series spectroscopy of the hot white dwarf companion to the 4th magnitude A1 III star β Crt, which shows that it has an unusually low mass, $M_{\rm WD} = 0.43\,{\rm M}_\odot$, and has almost certainly evolved through binary interaction. This system could be a long-sought remnant of Algol-type evolution, although radial velocity measurements appear to show that the pair are not close. Instead, micro-variations in the proper motion of β Crt as measured by *Hipparcos* suggest that the period could be as high as $\sim$10 yr. However, a low-mass white dwarf in a system with a period $\gtrsim$3 yr is difficult to explain by conventional models for binary evolution. We speculate on alternative models for the evolution of this system which involve an eccentric binary or multiple components.

Key words: binaries: general – stars: individual: β Crt – white dwarfs – ultraviolet: stars.

1 INTRODUCTION

Sirius-like binaries contain a main sequence or evolved star (spectral type K or earlier) and a non-interacting white dwarf secondary. Until recently only a handful of such systems were known, such as the prototype Sirius, where the white dwarf Sirius B (1.03 $M_\odot$, Holberg et al. 1998) is in a wide visual orbit about the A0 V star Sirius A ($P \sim 50$ yr). Since then, through the *ROSAT* Wide Field Camera (WFC) and the *Extreme Ultraviolet Explorer* (*EUVE*) all-sky surveys of the early 1990s, more than 20 new Sirius-like systems have been discovered, with primaries as massive as spectral type B (Barstow et al. 1994; Burleigh, Barstow & Fleming 1997; Burleigh & Barstow 1998; Vennes, Christian & Thorstensen 1998, hereafter VCT98). None of these new systems are spatially resolved from the ground, although Barstow et al. (2001) have recently resolved a number in the far-ultraviolet (FUV) using the Wide Field Planetary Camera 2 (WFPC2) camera on *HST*.

Sirius-like binaries are of astrophysical interest because they can be used to investigate the relationship between the mass of a main-sequence star and its white dwarf progeny – the initial–final mass relation (Weidemann 1987). Assuming the pair have never interacted, the white dwarf must have evolved from an object more massive than the current primary. In addition, if the two components can be resolved and an astrometric mass determined for the degenerate star, these systems can potentially be used to investigate the theoretical white dwarf mass–radius relation, for which few data points currently exist (Vauclair et al. 1997; Provencal et al. 1998).

The first new Sirius-like system discovered by *ROSAT* was β Crt (HD 97277 = HR 4343, A1 III + WD, $V = 4.5$, Fleming et al. 1991). Unfortunately, published estimates of the effective temperature ($T_{\rm eff}$), surface gravity ($\log g$) and mass ($M_{\rm WD}$) of the white dwarf in this system are poorly constrained. Since it is unobservable at optical wavelengths, due to the overwhelming brightness of the A1 III companion, we cannot establish these parameters by the usual method of fitting a grid of model atmospheres to the optical H Balmer absorption line series. An unambiguous determination of $T_{\rm eff}$ and $\log g$ (and, hence, $M_{\rm WD}$) requires three or more spectral lines, but existing *IUE* FUV spectra of the white dwarf only cover the H Lyman α absorption line at 1216 Å. From a careful analysis of the profile of this line, Barstow et al. (1994) and VCT98 could only constrain the gravity of the white dwarf to be $\leq$8.3. Assuming both the white dwarf and the A1 giant lie at the *Hipparcos* distance estimate of $\sim$82 pc, VCT98 could further constrain the gravity $\log g$ to be $\leq$7.6. This would imply that the white dwarf has an unusually low mass, $M_{\rm WD} \leq 0.44\,{\rm M}_\odot$, too low for it to have evolved in isolation (e.g. Marsh, Dhillon & Duck 1995). The progenitor of such a low-mass degenerate must at some stage have interacted with another star, during which it lost mass and thus its evolution was accelerated. For example, the progenitor could lose its outer envelope without having reached the asymptotic giant branch or ever having ignited helium in its core (which requires a core mass of 0.49 $M_\odot$). Nelemans & Tauris (1998) even speculate that such low-mass degenerates might form when a solar-like star ascends the giant branch and captures a nearby giant planet (e.g. HD 89707). The subsequent spiral-in phase expels the envelope of the giant, leaving a low-mass helium-core white dwarf remnant.

Before we speculate on the possible origins of a low-mass white

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dwarf in the β Crt system, we need to be certain that the degenerate star and the A1 giant are actually physically related and do not merely form a chance alignment. If the gravity of the white dwarf was in reality nearer $\log g = 8$, then it would lie in front of the A giant and have a mass nearer the mean for such objects, $\sim 0.6\,M_{\odot}$. In that case, there would be no need to invoke binary evolution to explain its existence.

The advent of FUV spectroscopy from 900 to 1200 Å with the *Far Ultraviolet Spectroscopic Explorer* (*FUSE*) satellite, covering the entire H Lyman series, now provides us with a first opportunity to determine precisely the fundamental parameters of the white dwarf, β Crt B. In this paper we show that it does indeed have an unusually low mass, and has almost certainly evolved through binary interaction.

2 OBSERVATIONS AND DATA REDUCTION

2.1 *FUSE*

FUSE was launched from Cape Canaveral on 1999 June 24, and is designed to make high-resolution spectroscopic observations in the FUV regime (905–1187 Å), in particular covering the H Lyman series from Lyβ at 1026 Å to the Lyman limit at 912 Å. The instrument consists of four co-aligned prime focus telescopes and Rowland spectrographs with microchannel plate detectors. Two of the telescope channels use Al:LiF coatings for optimum reflectivity between 1000 and 1087 Å, and the other two channels use SiC coatings for optimized throughput between 905 and 1105 Å. Each channel is further subdivided into two non-continuous segments (they are split by a few angstrom). For a detailed overview of the *FUSE* mission and instruments, see Moos et al. (2000).

β Crt was observed by *FUSE* for a total of 8037 s on 2000 May 29. Two separate exposures were made, each of 4018.55 s. At that stage of the mission, *FUSE* was experiencing unexpectedly large changes in the alignment of the optics during each orbit as a result of thermal motion. In particular, small rotations in the mirror made it difficult to keep the four independent optical paths within the instrument co-aligned, sometimes resulting in misalignments large enough for targets to drift out of the aperture in one or more channels (for a full discussion of the on-orbit performance of *FUSE*, see Sahnow et al. 2000). The β Crt observations were therefore made using the low-resolution aperture (LWRS: $30 \times 30\,\mathrm{arcsec}^2$) in order to minimize these problems, but none the less the flux calibration and wavelength calibration of different segments of the spectrum were not originally altogether satisfactory. Re-extraction of the data with version 1.8.7 of the CALFUSE pipeline, released to the community in late 2000, resulted in a marked improvement in the flux calibration for each segment, although small differences were still noticeable. Consequently, we have scaled the flux level of each extracted segment to that of the LiF 1a segment, since the LiF 1 channel is used for guiding and is therefore controlled. Even after re-extraction and re-calibration with the most recently available wavelength calibration files, differences in the wavelength calibration of different segments of the spectrum were clearly noticeable. Again, each extracted segment was therefore shifted with respect to the calibration for the LiF 1 channel. Even so, the absolute wavelength calibration for LiF 1 is not necessarily reliable, and thus any line velocities should be treated with caution.

The two exposures for each segment were co-added, and then each segment was merged to form one continuous spectrum. Regions of low signal-to-noise ratio and/or poorly calibrated data were rejected at this stage. The merged spectra were then re-binned to 0.1 Å for the purpose of fitting the H Lyman lines to determine the temperature and gravity of the star, although the measured resolution is somewhat better; $R \approx 18000$–24000, depending on the wavelength region.

2.2 *EUVE*

EUVE observed β Crt for $\sim$110 000 s in 1998 February. Continuum flux from the white dwarf was detected in both the short wavelength (SW, 70–190 Å) and medium wavlength (MW, 140–350 Å) spectrometers. Note that the A1 III primary contributes no flux at these wavelengths. We have extracted these data from the *EUVE* GO-processed event data using standard IRAF procedures. Our reduction techniques are described in more detail in earlier work (e.g. Barstow et al. 1997a).

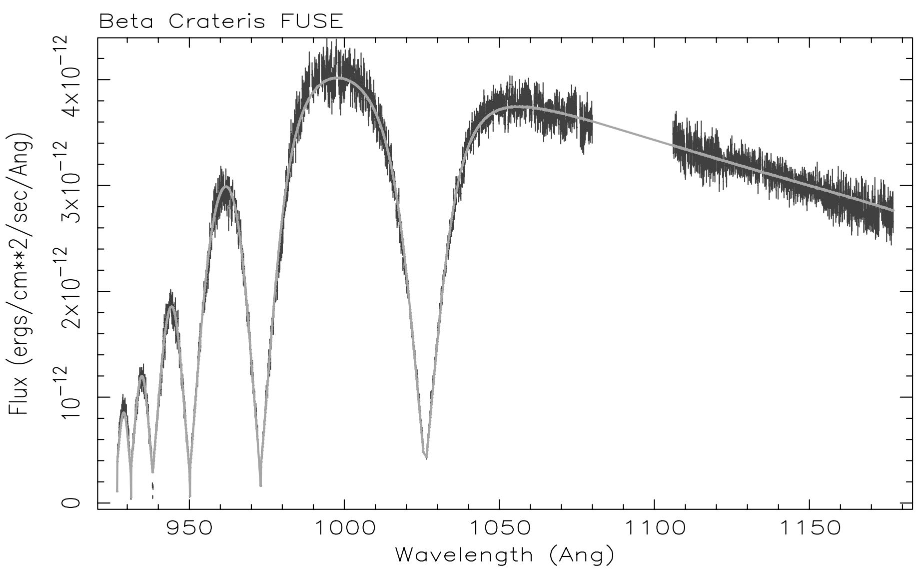

Figure 1. FUSE spectrum of the white dwarf companion to Beta Crateris, together with a model for $T_{\mathrm{eff}} = 35885$ K and $\log g = 7.198$.

3 DATA ANALYSIS

3.1 Temperature, gravity and mass from *FUSE*

We have matched the *FUSE* spectrum with a grid of non-local thermodynamic equilibrium (NLTE) model atmospheres, assuming a pure-H composition, calculated using the TLUSTY code (e.g. Lanz & Hubeny 1995). The grid spans from 20 000 to 100 000 K in $T_{\rm eff}$ and from 6.5 to 9.75 in $\log g$. We fitted five H Lyman absorption lines shortwards of and including Lyβ, and the continuum redward from Lyβ to ≈1180 Å. Geocoronal emission lines in the cores of Lyβ and Lyγ were ignored in the fit, as were regions around narrow interstellar medium (ISM) absorption lines such as O I at 1039.2 and 988.7 Å. A model was included in the fit to account for the narrow H I ISM absorption lines seen in the core of each H photospheric line. Although this is necessary in order to correctly model the broad photospheric absorption lines, the H I ISM absorption lines are saturated and cannot be used to determine the column density. Instead, we have estimated the H I column density of β Crt from the *EUVE* spectrum, see below.

A best-fitting model was found by fitting our combination of photospheric and ISM models within the program XSPEC, in a manner similar to fitting the H Balmer series in optical spectra (e.g. Marsh et al. 1997). We find the best-fitting parameters to be $T_{\rm eff} =$ 35885 K (formal 1σ errors 35810–35940 K) and $\log g = 7.198$ (7.190–7.209, see also Table 1). The model fit is shown in Fig. 1. Confidence contours for this fit are shown in Fig. 2. We note that slight variations on this fitting (e.g. adding or ignoring a few extra data points at the short-wavelength end) can produce slightly different results with very similar reduced chi-squared values (χ^2_r), but the best-fitting parameters always lie within the ranges $35750 < T_{\rm eff} < 35950$ K and $7.17 < \log g < 7.21$. Inclusion of higher-order H lines results in much poorer fits ($\chi^2_r > 2.0$), although the surface gravity is slightly reduced as a consequence. This is not altogether surprising since the higher-order lines are more contaminated by ISM absorption than the stronger, lower-order lines. On the other hand, inclusion of the continuum longwards of Lyβ is important, since this includes some of the redward wing of this line and the measured gravity is found to be higher by ~0.05 dex without these data.

Extending the best-fitting model into the optical region, we estimate the magnitude of the white dwarf at $V = 13.4 \pm 0.2$. Of course, this is dependent on the error in the *FUSE* flux calibration, which we have assumed to be ~10–15 per cent (note that the likely error in the flux calibration is much greater than the formal errors on the best-fitting $T_{\rm eff}$ and $\log g$). If $V = 13.2$, we estimate the absolute magnitude $M_v = 8.19$ and $d = 101$ pc, compared to the *Hipparcos* distance estimate to the primary of 77–87 pc. We do not regard this difference as significant given the uncertainties in the *FUSE* calibration.

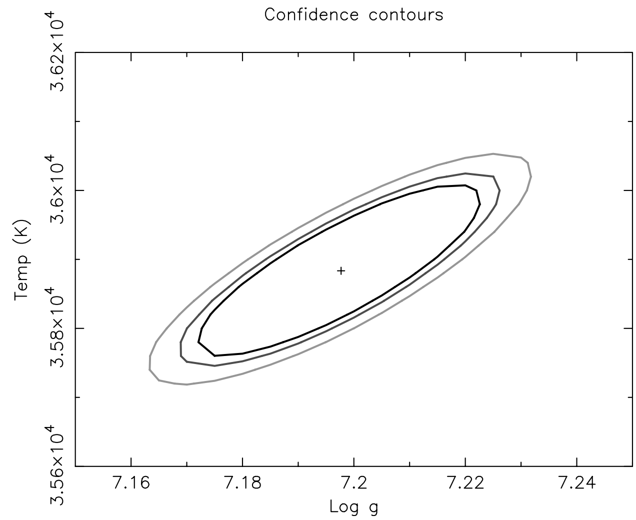

Figure 2. Confidence contours for the spectral fit to the FUSE data, at 66, 90 and 99 per cent in the ($\log g$, $T_{\rm eff}$) plane.

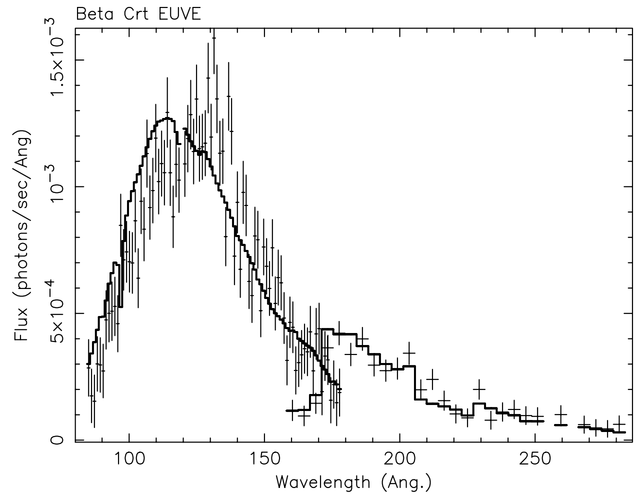

Figure 3. *EUVE* spectrum of the white dwarf companion to Beta Crateris, together with a model fit incorporating radiatively levitated quantities of C, N, O and Si. See text for details.

3.2 Heavy element opacity and ISM columns from *EUVE*

We attempted to match the *EUVE* spectrum with the same grid of NLTE model atmospheres as used for the *FUSE* data, again assuming a pure-H composition, together with an ISM model, in order to constrain the interstellar column densities of $N_{\rm H\,I}$, $N_{\rm He\,I}$ and $N_{\rm He\,II}$. The white dwarf temperature and gravity were fixed within the 90 per cent limits determined from fitting the *FUSE* data, and the $N_{\rm H\,I}/N_{\rm He\,I}$ and $N_{\rm He\,I}/N_{\rm He\,II}$ ISM ratios were fixed according to the mean ionization fractions in the local ISM determined by Barstow et al. (1997a). Unfortunately, a good fit could not be satisfactorily obtained. The pure-H model predicts a factor of ~2 more flux below ~120 Å than is seen in the *EUVE* data. Therefore, an additional source of opacity is needed.

Incorporating a homogeneous mixture of H + He into the model provided a reasonable match to the data for log(H/He) = 4.2($\chi^2_r =$ 2.8). A better match ($\chi^2_r < 2.0$) was obtained using a stratified LTE H + He model atmosphere (Koester 1991), which would suggest the atmosphere of the white dwarf consists of a thin H layer overlying a much thicker He envelope. However, it is more likely that the additional opacity is provided by a mixture of elements heavier than He, supported within the white dwarf against gravitational settling by radiation pressure. A similarity can be drawn here with the white dwarf RE J0720+318. Burleigh, Barstow & Dobbie (1997) demonstrated that the *EUVE* spectrum of this object could be matched with a stratified H + He model atmosphere, suggesting it has a thin surface H layer, but Dobbie et al. (1999) later demonstrated that a sophisticated model incorporating a mixture of radiatively levitated heavy elements provided a more realistic and convincing description of the atmospheric structure and composition of RE J0720+318.

A satisfactory match ($\chi_r^2 < 2.0$) to the *EUVE* spectrum of β Crt B was obtained with a fully line-blanketed NLTE model incorporating a homogeneous mixture of those heavy elements expected to provide most of the opacity in this temperature regime – C, N, O and Si (Fig. 3). The abundances for these elements were taken from the predictions of Chayer et al. (1995), which were calculated in the context of an equilibrium radiative levitation theory: C/H $= 4.98 \times 10^{-6}$, N/H $= 2.47 \times 10^{-6}$, O/H $= 8.99 \times 10^{-7}$, Si/H $= 3.37 \times 10^{-6}$. Again, the white dwarf temperature and gravity were fixed within the 90 per cent limits determined from fitting the *FUSE* data, and the $N_{\mathrm{H\,I}}/N_{\mathrm{He\,I}}$ and $N_{\mathrm{He\,I}}/N_{\mathrm{He\,II}}$ ISM ratios were fixed according to the mean ionization fractions in the local ISM determined by Barstow et al. (1997a).

3.3 A search for variability in the *EUVE* light curve

The hot white dwarf GD394 is variable in the EUV with a period of 1.150 ± 0.003 d (Dupuis et al. 2000). The white dwarf companion to V471 Tauri is also variable in the EUV with a period of 555 s. (Jensen et al. 1996; Dupuis et al. 1997). In both cases the variability is probably due to an accretion 'spot' of heavy elements such as Si on the stellar surface. The 'spot' appears dark at EUV wavelengths due to absorption of emergent flux. We have examined the *EUVE* Deep Survey Lexan/B (67–178 Å) detector light curve of β Crt B for variability with periods ranging from 500 s to 3 d, but find no significant evidence for such behaviour.

3.4 A search for heavy element lines in the FUSE spectrum

Given the detection of a source of opacity in the *EUVE* spectrum of β Crt B, we have searched the *FUSE* data for absorption lines due to elements heavier than He. No such features could be identified, other than low-ionization ISM lines e.g. O I, C II, C III, N I, N II, N III and Ar I.

We can, though, place limits on the photospheric abundances of C, N, O and Si in the *FUSE* wavelength range (these are the elements in our best-fitting model to the *EUVE* data). Spectra were computed from the previous best-fitting pure-H model to the *FUSE* data using the program SYNSPEC and incorporating C, N, O and Si at the abundances predicted by Chayer et al. (1995, table 3), and compared to the data. Calculations were also carried out for 0.1, 0.01, 0.001, 0.0005 and 0.0002 times these abundances, maintaining the relative fractions of each element as constant and identical to the predicted ratios. No O lines are visible within the *FUSE* range at the Chayer et al. (1995) predicted abundance. We estimate the limiting abundances for C, N and Si in this range at a few $\times 10^{-9}$/H. We note that the presence of C, N, O and Si at these abundances would have little effect on our determination of the effective temperature and surface gravity (Barstow, Hubeny & Holberg 1998).

Table 1. Physical parameters of the white dwarf companion to β Crt, from *FUSE* and *EUVE* spectroscopy

T_{eff}	35 885 K (90 per cent error: 35810–35940 K)
$\log g$	7.198 (90 per cent error: 7.190–7.209)
Mass	$0.43\,\mathrm{M}_{\odot}$
Radius	$0.027\,\mathrm{R}_{\odot}$
V	13.4 ± 0.2
M_v	8.19
$N_{\mathrm{H\,I}}$	$9.25 \pm 0.25 \times 10^{18}$ atoms cm^{-2}
$N_{\mathrm{He\,I}}$	1.0×10^{18} atoms cm^{-2}
$N_{\mathrm{He\,II}}$	0.4×10^{18} atoms cm^{-2}

4 DISCUSSION

4.1 The white dwarf mass

FUSE spectroscopy of the H Lyman series of the hot white dwarf companion to β Crt constrains its effective temperature to $T_{\mathrm{eff}} \approx 35\,900$ K and surface gravity $\log g \approx 7.20$. Combining these measurements with the evolutionary models of Bloecker (1995) and Dreibe et al. (1998) for He- and CO-core white dwarfs, we find $M_{\mathrm{WD}} = 0.43\,\mathrm{M}_{\odot}$, confirming it does indeed possess an unusually low mass, although it lies on the boundary between their He- and CO-core models with a cooling age $\sim 10^6$ yr. This result suggests that it must have evolved through binary interaction, during which the white dwarf progenitor lost mass and its evolution was accelerated.

4.2 Heavy element abundances

Model fits to the *EUVE* spectrum of β Crt B require an additional source of atmospheric opacity, other than simply assuming a pure-H composition. Although a satisfactory fit could be achieved with a stratified model which assumes a thin surface H layer overlying a thicker He envelope, a good fit could also be achieved with a sophisticated NLTE model incorporating trace abundances of radiatively levitated C, N, O and Si.

We note that it was previously believed that the photospheres of white dwarfs below $T_{\mathrm{eff}} \approx 40\,000$ K were essentially pure H in composition. In fact, at the low surface gravity of β Crt B it is possible for these relatively high heavy element abundances to be levitated radiatively within the atmosphere at a temperature as low as $T_{\mathrm{eff}} \approx 36\,000$ K, supplying the opacity seen in the *EUVE* spectrum (see table 2 of Barstow et al. 1997a).

Comparisons can be drawn with the apparently isolated white dwarf GD394 and the white dwarf secondary in the V471 Tauri binary system. Both stars are in a similar temperature regime to β Crt B and show strong evidence for heavy elements in their atmospheres, but in contrast to β Crt B they have much higher surface gravities (e.g. for V471 Tauri $\log g \approx 8.3$, Barstow et al. 1997b) and the heavy elements are probably being accreted rather than simply levitated and maintained by radiation pressure. For example, GD394 possesses an unusually high Si abundance for a $T_{\mathrm{eff}} \approx 39\,000$ K white dwarf (Dupuis et al. 2000). Most likely, for this object, the material is being episodically accreted, either from the ISM or from an unseen low-mass companion. The white dwarf secondary in the V471 Tauri system has $T_{\mathrm{eff}} \approx 32\,000$ K (Barstow et al. 1997b), and the indications are that this object is also actively accreting Si, in this case from its close, active K2 V companion (Sion et al. 1998).

The lack of any variability in the EUV light curve of β Crt B argues against accretion as the source of the heavy elements in the atmosphere of β Crt B, since these atmospheric contaminants do not appear to be concentrated at any particular surface 'spot', unlike GD394 (Dupuis et al. 1997), V471 Tau (Jensen et al. 1986) and RE J0720−318 (Dobbie et al. 1999). β Crt B is, therefore, one of the coolest DA white dwarfs to possess radiatively levitated heavy elements in its photosphere.

The non-detection of C, N and Si lines in the FUV of the *FUSE* spectrum at even a fraction of the Chayer et al. (1995) predicted abundances suggests that the white dwarf atmosphere is either stratified, with these heavy elements lying below the FUV line-forming region or, alternatively, that there is an different source of heavy element opacity, e.g. Fe. Unfortunately, since the A giant dominates the white dwarf flux above $\sim$1300 Å it will always be impossible to search for evidence of heavy elements at longer UV wavelengths with e.g. *HST*/STIS-echelle, and our best hope of finding any heavy element absorption lines remains high-resolution, high signal-to-noise *FUSE* observations.

4.3 The association of the white dwarf and β Crt

Before considering any evolutionary history for the β Crt system we must, of course, be convinced that the A1 giant and the white dwarf do indeed form a physical pair. Noting that Barstow et al. (2001) failed to resolve the two stars with *HST*/WFPC2, then their maximum separation is just 0.08 arcsec. Fleming et al. (1996) gives the space density of soft X-ray bright white dwarfs as $\sim 1 \times 10^{-5}\,\mathrm{pc}^{-3}$. Assuming a distance of $\sim$100 pc for the white dwarf (as estimated from its magnitude in Section 3.1), we calculate that the chance of a hot white dwarf randomly falling within any area of the sky with diameter 0.08 arcsec is $\sim 1 \times 10^{-11}$. We therefore regard the chance alignment of β Crt and the white dwarf as highly unlikely. We emphasize that although our model fit to the spectrum of the white dwarf *FUSE* results in a distance estimate slightly larger than the *Hipparcos* distance of 77–87 pc to the A1 giant, we do not regard the difference as significant due to the uncertainties in the *FUSE* flux calibration.

4.4 The binary period

Sporadic measurements of the radial velocity of β Crt B early in the 20th Century by Campbell & Moore (1928) seemed to indicate that it is variable, with a full amplitude $\sim 20\,\mathrm{km\,s^{-1}}$. This led Fleming et al. (1991) to speculate on a possible orbital period <20.1 d. Smalley et al. (1997) rejected this period, but a re-analysis of Campbell & Moore's data still showed that the binary period could be $\lesssim$160 d. However, Smalley et al.'s (1997) own radial velocity measurements, and those of Duemmler et al. (1997) and VCT98, contradict Campbell & Moore's data. These studies indicate that the orbital period of β Crt is more likely to be measured in years, if indeed the velocity is varying at all. For example, Smalley et al. (1997) observed practically no orbital motion between 1994 March and 1995 January, giving a full amplitude $K = 1.9 \pm 1.3\,\mathrm{km\,s^{-1}}$. In contrast, Duemmler et al. (1997) found that the radial velocity they measured in 1997 May was different by more than $8\,\mathrm{km\,s^{-1}}$ from those measured by Smalley et al. (1997) 2–3 yr earlier. Duemmler et al. (1997) could not derive a period from these data, but both groups are in agreement that the velocity is stable over periods of days to a year.

Additional velocity measurements by Grenier et al. (1999) obtained in the early 1990s also appear to show variation. For example, in 1990 January they measured the velocity at $+7.4 \pm 0.5\,\mathrm{km\,s^{-1}}$, but a year later (1991 March) it had apparently dropped to $+2.5 \pm 0.6\,\mathrm{km\,s^{-1}}$. By 1993 March the radial velocity was back at $+6.6 \pm 0.4\,\mathrm{km\,s^{-1}}$.

If all of these measurements and their errors are believable, and Duemmler et al. (1997) in particular carefully consider the errors in their data, then it is plausible that the radial velocity is slowly varying between observations taken a few years apart.

On the other hand, VCT98 monitored β Crt for over 15 months from 1995 December to 1997 March, covering the period between the Smalley et al. (1997) and Duemmler et al. (1997) observations, and saw no obvious velocity variations during this time. They concluded that there are only slight deviations from a systemic velocity of $\gamma = +8.6 \pm 1.6\,\mathrm{km\,s^{-1}}$, limiting the velocity amplitude $K < 1.6\,\mathrm{km\,s^{-1}}$.

Clearly, then, the β Crt system deserves regular monitoring in order to confirm firstly whether there are any long-term radial velocity variations due to orbital motion at all and, if there are, then to determine categorically the binary period and the velocity amplitude.

Perhaps a better indication of the binary period arises from microvariability in the proper motion of β Crt as measured by *Hipparcos*. These data indicate that any binary period is probably $\sim$10 yr. This would be consistent with the failure of Barstow et al. (2001) to resolve the system in the FUV with *HST* and WFPC2, limiting the separation to < 0.08 arcsec and placing an upper limit on the binary period of $\sim$9.5 yr, assuming a favourable geometry. From this diverse evidence we conclude that the β Crt system is not a close binary, unless the system is being viewed at a very unfavourable geometry (i.e. face-on). Further, it is plausible that the period is of order years, and that it may be as high as $\sim$10 yr.

4.5 A post-Algol system?

Low-mass ($M \lesssim 0.5\,\mathrm{M_\odot}$), helium-core white dwarfs cannot be made by standard single star evolution since the main sequence lifetime of their progenitor stars is longer than the Hubble time. The usual scenario for making such white dwarfs involves a phase of mass transfer between stars in a binary system. In this picture the expansion of the white dwarf progenitor, as it evolves up the giant branch, causes it to fill its Roche lobe while the core mass remains low. Mass transfer to the secondary star (in this case β Crt A) then exposes the low-mass, helium core.

The β Crt system could, therefore, be a long-sought remnant of Algol-type evolution. In an Algol-type binary, a cool F-K III-IV secondary star fills its Roche lobe and transfers mass to a hot B-A V primary. These systems were a puzzle to astronomers because the less massive secondary is more evolved than its companion. This paradox was resolved when it was realized that the current secondary was originally the more massive star, and that the current configuration of the binary was the result of extensive mass transfer, resulting in a reversal of the mass ratio of the system. A remnant of such an Algol-type binary would then consist of an early-type intermediate-mass star with a low-mass white dwarf companion. Although Algols are the most numerous of known eclipsing binaries, their post-mass transfer counterparts have eluded discovery because the white dwarfs are overwhelmed at optical wavelengths by their bright companions. β Crt could be the first confirmed post-Algol system.

If β Crt is indeed a remnant Algol-type binary, we would expect the orbital period to be $\lesssim$ tens of days. Of course, as discussed above, the period is currently unknown. It is possible that the system appears face-on to us, so that it shows little or no radial velocity variation, even if the period was short. If, on the other hand, the period is $\gtrsim$ years, then this would start to cause problems for standard models of binary evolution.

4.6 Alternative evolutionary scenarios

As discussed in Section 4.4 above, there is evidence to suggest that the orbital period is in fact relatively long, perhaps as high as $\sim$10 yr. Unfortunately, it is difficult to explain the existence of such a system with standard binary evolution models. For example, the Roche lobe radius of the white dwarf progenitor in, say, a 7-yr orbit is $\gtrsim 260\,R_\odot$. The only stars with radii this large have masses $\gtrsim 10\,M_\odot$, and are on the giant branch with helium core masses much larger than $0.4\,M_\odot$. In fact, the largest radius at which a star of any mass has a helium core of $0.4\,M_\odot$ is about $100\,R_\odot$, for a $0.8\,M_\odot$ star almost at the tip of the giant branch (Webbink 1985). More massive stars create helium cores of $0.4\,M_\odot$ much earlier in their evolution, and hence at smaller radii. Stars with masses greater than about $4\,M_\odot$ reach core masses of $0.4\,M_\odot$ on the main sequence. Therefore, it seems clear that the white dwarf progenitor must have been less massive than $4\,M_\odot$. However, the large Roche radius of this progenitor star leaves the standard scenario facing a number of severe difficulties in explaining the existence of a low mass white dwarf in a system with an orbital period as high as $\sim$10 yr. Nuclear-driven, conservative, stable mass transfer from the white dwarf progenitor to the secondary while the progenitor was on the giant branch could increase the orbital period of the system (Webbink, Rappaport & Savonije 1983; Ritter 1999), but it is not possible to increase the orbital period beyond $\sim$3 yr for a helium-core white dwarf of $0.4\,M_\odot$. Therefore, the possible $\sim$10 yr orbital period of β Crt, or indeed any orbital period significantly longer than $\sim$3 yr, remains a puzzle in the context of conventional models of binary evolution.

We now consider a number of other evolutionary possibilities.

(a) *Unstable mass transfer.* If the initial binary system had an extreme mass ratio, or if the white dwarf progenitor had a deep convective envelope when mass transfer was initiated, the mass transfer could have become unstable and occur on the thermal or dynamical time-scale of the mass donor. Under these circumstances, the analytic and semi-analytic models break down, and it is difficult to determine the outcome of such a situation. It is possible that the white dwarf progenitor could be driven far out of equilibrium, allowing it to continue to fill its Roche lobe as the mass ratio reverses and the orbit expands to the observed period. Calculations of thermal time-scale mass transfer (Schenker 2001), in which the donor star is out of thermal equilibrium, suggest that the system behaves differently for a short time. However, it returns to a stable mass transfer configuration on the giant branch reasonably quickly. On the other hand, dynamical instability of the donor star is usually assumed to lead to common envelope (CE) evolution. While CE evolution is a viable mechanism for the production of low mass white dwarfs it is also associated with a decrease in the orbital period, as the orbital angular momentum is reduced in driving off the envelope. Therefore, we conclude that it is unlikely that a period of unstable mass transfer or non-equilibrium evolution of the white dwarf progenitor alone could produce the low-mass white dwarf in β Crt.

(b) *Period evolution after mass transfer ceases.* A long period system could be explained by allowing the orbital period to increase after the white dwarf has been formed. In general, a binary system can increase its period if mass is lost from the system with a relatively low specific angular momentum. The obvious physical example of such mass loss would be the presence of an intense stellar wind from one or both of the stars in β Crt. However the mass loss would have to be extreme: we could envisage a system in which β Crt A was initially much more massive. Some B stars are known to have significant winds, and the mass lost through such a wind could be lost from the binary system. The observed mass loss rates for B stars (10^{-5}–$10^{-7}\,M_\odot\,yr^{-1}$, Lamers 1981) are such that it would take $\sim 10^7$ yr to turn a 25-$M_\odot$ B star into a 4-$M_\odot$ A star. Even if this extreme mass reduction was allowed within the main sequence life of such a star the cooling age of the white dwarf is only $\sim 10^6$ yr, an order of magnitude shorter than the required mass loss time-scale. So it would seem that the large magnitude of the period increase and the short time-scale on which it needs to act combine to make the period increase solution very unlikely.

(c) *A multiple system.* It is possible that β Crt is in fact a triple system, with β Crt A orbiting a short period binary containing the white dwarf β Crt B and another star. In this case the evolution of the shorter period binary system resulted in the creation of the low mass white dwarf. The progenitor of the white dwarf must have been more massive than β Crt A, which is assumed to be unaffected by the evolution of the smaller binary system. Hence the age of the system is set by the age of the A1 giant β Crt A. In addition, the white dwarf has a cooling age of $\sim 10^6$ yr, which means that the progenitor has to be only slightly more massive than A1 III. Since the companion to the white dwarf is currently unseen, its mass must be less than $\sim 0.8\,M_\odot$. In order to produce a white dwarf mass of $0.4\,M_\odot$, a $3.5\,M_\odot$ star must have filled its Roche lobe with a radius of about 10^{12} cm. From these constraints on the masses of the two binary components and the Roche lobe radius, we calculate that such a system would have an orbital period of about 6 h. It would be interesting to measure the radial velocity of the white dwarf itself to see if it varies between the two *FUSE* exposures, but the lack of any narrow heavy element lines, the infilling of the H lines with geocoronal emission and/or interstellar absorption, and the poor wavelength calibration precludes any such measurement with these data.

(d) *An eccentric binary system.* Another possibility involves an eccentric binary system, in which mass transfer from the primary occurred in bursts at periastron. If the binary system had an eccentricity of $\sim$0.5 and a period $\sim$10 yr, then the Roche lobe radius of β Crt B at periastron is consistent with the radius of a giant that has a core mass of $0.4\,M_\odot$. Hence it is possible that the β Crt system was formed from a binary system consisting of two stars of similar mass ($\sim 2\,M_\odot$) in a wide, eccentric orbit. The more massive of these stars began evolving up the giant branch. Only when its core mass was greater than about $0.25\,M_\odot$ did the star fill its Roche lobe and begin transferring mass (conservatively) to the lower mass star. Since the system had an eccentric orbit, mass transfer only occurred at periastron. This changed the eccentricity of the orbit (Matese & Whitmore 1983), but clearly the final system must have had parameters which meant that the Roche lobe radius was $\sim 100\,R_\odot$ and the orbital period was of $\sim$10 yr.

5 CONCLUSION

FUSE spectroscopy of the hot white dwarf companion to β Crt shows that it has an unusually low mass ($M_{WD} = 0.43\,M_\odot$) and has almost certainly evolved through binary interaction. Thus, the system could be a long-sought remnant of Algol-type evolution. However, radial velocity measurements appear to indicate that the pair are not close. If the velocity is essentially static then we could of course be viewing the system at an unfavourable geometry (i.e. face-on). Alternatively, the binary is relatively wide. If the variations between radial velocity measurements made by Grenier et al. (1999) in the early 1990s, Smalley et al. (1997) in 1994/95, and Duemmler et al. (1997) in 1997 May are to be believed, then the period could be of order years. Failure to resolve the pair with *HST*/WFPC2 places an upper limit on the period of $\lesssim$9.5 yr, assuming a favourable geometry. Perhaps more importantly, microvariations in the proper motion of β Crt B as measured by *Hipparcos* suggest a binary period $\sim$10 yr. But any binary period $\gtrsim$3 yr poses a problem for standard models of binary interaction. The most likely evolutionary history of the β Crt system which could result in a low mass white dwarf in a $\sim$10 yr orbit with an A1 giant is one which involves either a multiple system or an eccentric binary orbit. Clearly, though, the orbital period urgently needs to be determined before we can distinguish between these possible evolutionary scenarios.

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