HR2875: Spectroscopic discovery of the first B star+white dwarf binary

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ABSTRACT

We report the discovery, in an Extreme Ultraviolet Explorer (EUVE) short wavelength spectrum, of an unresolved hot white dwarf companion to the 5th-magnitude B5Vp star HR2875. This is the first time that a non-interacting white dwarf+B star binary has been discovered; previously, the the earliest type star known with a white dwarf companion was Sirius (A1V). Since the white dwarf must have evolved from a main sequence progenitor with a mass greater than that of a B5V star (≥6.0M⊙), this places a lower limit on the maximum mass for white dwarf progenitors, with important implications for our knowledge of the initial-final mass relation. Assuming a pure-hydrogen atmospheric composition, we constrain the temperature of the white dwarf to be between 39,000K and 49,000K. We also argue that this degenerate star is likely to have a mass significantly greater than the mean mass for white dwarf stars (≈0.55M⊙). Finally, we suggest that other bright B stars (e.g. θ Hya) detected in the extreme ultraviolet surveys of the ROSAT Wide Field Camera and EUVE may also be hiding hot white dwarf companions.

Key words: Stars: binaries – Stars: white dwarfs – Stars: early-type – Stars: individual: HR2875 – X-ray: stars.

1 INTRODUCTION

The extreme ultraviolet (EUV) surveys of the ROSAT Wide Field Camera (WFC, Pounds et al. 1993) and the Extreme Ultraviolet Explorer (EUVE, Bowyer et al. 1994) have found a substantial number of white dwarfs, in excess of 120. Most of these stars are isolated, but over 30 are now known to lie in binary systems (Burleigh 1997). In particular, nearly 20 unresolved pairs consisting of a hot white dwarf and a bright, normal star (spectral type K or earlier) have been found (e.g. Barstow et al. 1994, Vennes et al. 1995, Burleigh et al. 1997, Burleigh 1998). Prior to the two EUV surveys, these systems were all but unidentifiable, since the normal stellar companion completely swamps the optical flux coming from the white dwarf. In each case, however, the detection of EUV radiation with the spectral signature of a hot white dwarf gave a clue to the existence of the previously invisible, faint degenerate companion. Far-ultraviolet spectra taken with the International Ultraviolet Explorer satellite (IUE) were then used to confirm the identifications. This technique has proved excellent for finding these systems in all cases where the normal star is of spectral type ~A5 or later.

In fact, the earliest type star so far identified by this method to have an unresolved hot white dwarf companion is Beta Crateris (A2IV+WD, Fleming et al. 1991). Indeed, it took a very careful, detailed, analysis by Barstow et al. (1994) to finally confirm this discovery. Unfortunately, even at far-UV wavelengths, stars of spectral types early A, B or O will still completely dominate any emission from smaller, fainter companions, rendering them invisible even to IUE or HST. Overall, the earliest type star known with a white dwarf companion remains Sirius (A1V+DA).

The spectral type of the normal star in these binaries gives a lower limit to the mass of the white dwarf progenitor. The value of the maximum mass feasible for producing a white dwarf, and the form of the initial-final mass relationship (IMFR), are long-standing astrophysical problems (e.g. Weidemann 1977). Weidemann (1987) gives the upper limit as 8M⊙ in his semi-empirical IMFR. Recent observations of four white dwarfs in the young open cluster NGC 2516 (Jeffries 1997), however, imply that the upper mass limit for white dwarf progenitors is only 5–6M⊙. This value is actually in agreement with current stellar evolutionary models which include moderate core overshoot, but, clearly, any observations which can place limits on the maximum white dwarf progenitor mass have important implications for our theories and models of stellar evolution, the birth rate...
of neutron stars and the predicted rates of type II Galactic supernovae.

HR2875 (=HD59635, =y Pup) is one of a small number of bright (V≈5.41) B stars unexpectedly detected in the ROSAT and EUVE all sky surveys. Hiltner et al. (1969) classify it as B5Vp, noting that it is overabundant in Si, although in the Michigan Catalog of HD Stars (Houk 1982) it receives a B3V classification. In this paper we present an analysis of an EUVE spectrum of HD2875 which appears to reveal the presence of a previously hidden hot white dwarf. If this detection is real and the system is a true binary, then HD2875 is the earliest type star known with a white dwarf companion.

2 DETECTION OF EUV RADIATION FROM HR2875 IN THE ROSAT WFC AND EUVE SURVEYS

The ROSAT WFC EUV and X-ray all-sky surveys were conducted between July 1990 and January 1991; the mission and instruments are described elsewhere (Trümper 1992, Sims et al. 1990). HR2875 (HD59635, y Pup), catalogued as B5Vp by SIMBAD, is associated in the WFC Bright Source Catalogue (Pounds et al. 1993) with the source RE J0729−388. The count rates given in the revised 2RE Catalogue (Pye et al. 1995), which was constructed using improved methods for source detection, background screening, etc., are 61±14 counts/ksec in the S1 filter and 108±16 counts/ksec in S2 (see also Table 1). The same source was also detected in the Extreme Ultraviolet Explorer (EUVE) all-sky survey, which was carried out between July 1992 and January 1993; the count rates given in Table 1 are taken from the revised Second EUVE Source Catalog (B bowyer et al. 1996). Finally, the EUVE source is coincident with a ROSAT PSPC soft X-ray detection, although it is only seen in the lower (soft) and upper (hard) bands, while only one (rather unusual) white dwarf has ever been detected in this energy range (KPD0005+5106, Fleming et al. 1993). The X-ray/EUV colours and count rate ratios (S2/S1≈2) for HR2875 are also very similar to many of the hot white dwarfs detected by ROSAT and EUVE, a point emphasised by Motch et al. (1997), who discounted HR2875 as a new massive X-ray binary but also suspected that it might be hiding a non-accreting white dwarf. Burleigh et al. (1997) suggested, therefore, that HR2875, like almost 20 other stars in the EUVE catalogues, may be hiding a hot white dwarf companion.

3 EUVE POINTED OBSERVATION AND DATA REDUCTION

HR2875 was observed by EUVE in dither mode during April 1996. Two separate observations were made (GO458 & GO459, PI: R.S. Polidan), of ≈85,000 and ≈65,000 secs respectively, which became publicly available one year later. We have extracted the spectra from the images ourselves, using standard IRAF procedures. Our general reduction techniques are described in earlier work (e.g. Barstow et al. 1997).

The target was not detected in either the medium wavelength (140–380Å) or long wavelength (280–760Å) spectrometers, and the signal/noise of the data in the short wavelength spectrometer (70–190Å) in both observations was very poor. Consequently, we have co-added the two short wavelength spectra to improve the signal/noise for the subsequent analysis. This pointed observation, shown in Figure 1, reveals a weak continuum, with a peak flux of ∼1.5–2.0×10⁻¹³ ergs cm⁻² sec⁻¹ Å⁻¹, characteristic of the many hot white dwarfs observed by EUVE with this spectrometer, and, in addition, there is no evidence for strong emission features. This would appear to rule out a hot wind as the source of the EUV and soft X-ray emission, as we
might have expected to see emission lines from high ionisation species of e.g. iron. Similarly, we can also eliminate the possibility that this might be an RS CVn binary such as $\chi$ Uma (Schrijver et al. 1995), or that HR2875 might be hiding an active late-type companion, such as in the B8V+K2IV binary Algol (Stern et al. 1995). In both those systems, high ionisation features of e.g. iron, oxygen, nickel and calcium are seen in EUVE short wavelength spectra.

4 ANALYSIS

Since we suspected that the EUV continuum detected by the short wavelength spectrometer is being produced by a hot white dwarf, we decided to try to match this spectrum (together with the ROSAT WFC S1, S2 and PSPC broad band fluxes) with a grid of white dwarf+ISM model atmospheres, in order to constrain the possible atmospheric parameters (temperature and surface gravity) of the degenerate star and the interstellar column densities of HI, HeI and HeII. Unfortunately, there are no spectral features (e.g. H absorption lines) in this region of the spectrum to give us an unambiguous determination of $T$ and log $g$. However, by making a range of assumptions to reduce the number of free parameters in our models, we can place constraints on e.g. the white dwarf’s temperature.

Firstly, we assume that the white dwarf has a pure-hydrogen atmosphere. This is a reasonable assumption to make, since Barstow et al. (1993) first showed that for $T_{\text{eff}} < 40,000$ K hot white dwarfs have essentially pure-H atmospheres. We can then fit a range of models, each fixed at a value of the surface gravity log $g$. Before we can do this, however, we need to know the normalisation parameter of each model, which is equivalent to $(\text{Radius WD}/\text{Distance})^2$. We can use the Hipparcos parallax (5.86 ± 0.51 milli-arcsecs., ESA 1997) to calculate the distance to the system (170$^{+17}_{-13}$ parsecs), and the Hamada-Salpeter zero-temperature mass-radius relation to give us the radius of the white dwarf corresponding to each value of the surface gravity (see Table 2).

We can also reduce the number of unknown free parameters in the ISM model. From EUVE spectroscopy, Barstow et al. (1997) measured the line-of-sight interstellar column densities of HI, HeI and HeII to a number of hot white dwarfs. They found that the mean H ionisation fraction in the local ISM was 0.35±0.1, and the mean He ionisation fraction was 0.27±0.04. From these estimates, and assuming a cosmic H/He abundance, we can place constraints on the column density ratios in our model, leaving us with just two free parameters - temperature and the HI column density.

![Figure 1. EUVE short wavelength spectrum of HR2875, binned to the resolution of the instrument, \(\approx 0.5\AA\). (Note that this spectrum was further binned by a factor 8 during the analysis). Also shown is a pure hydrogen white dwarf + ISM model for \(T_{\text{eff}} = 43,400\) K, \(N_{\text{HI}} = 2.1 \times 10^{19}\) atoms cm\(^{-2}\), \(N_{\text{HeI}} = 2.4 \times 10^{18}\) atoms cm\(^{-2}\), and \(N_{\text{HeII}} = 8.9 \times 10^{17}\) atoms cm\(^{-2}\).](image-url)

Table 2. Hamada-Salpeter zero-temperature mass-radius relation

| log $g$ | $M_{\text{WD}}$ | $R_{\text{WD}}$ | $R_{\text{WD}}$ | $(R_{\text{WD}}/D)^2$ |
|--------|----------------|----------------|----------------|---------------------|
| 7.5    | 0.50           | 0.017          | 11.832         | 5.089 \times 10^{-24} |
| 8.0    | 0.55           | 0.013          | 9.048          | 2.975 \times 10^{-24} |
| 8.5    | 0.83           | 0.009          | 6.264          | 1.426 \times 10^{-24} |
| 9.0    | 1.18           | 0.006          | 4.176          | 0.634 \times 10^{-24} |

Table 3. White dwarf atmospheric parameters and interstellar column densities

| log $g$ | $T_{\text{eff}}$ (K) & 90% range | $N_{\text{HI}} \times 10^{19}$ & 90% range | $N_{\text{HeI}}$ | $N_{\text{HeII}}$ |
|--------|---------------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| 7.5    | 40,500 (39,200–41,700) | 2.8 (2.3–3.3) | 3.1 | 1.2 |
| 8.0    | 41,000 (40,100–42,300) | 2.4 (2.0–2.9) | 2.7 | 1.0 |
| 8.5    | 43,400 (41,900–45,200) | 2.1 (1.7–2.6) | 2.4 | 0.9 |
| 9.0    | 46,800 (45,500–48,400) | 1.9 (1.5–2.3) | 2.1 | 0.8 |
The model fits at a range of surface gravities from log $g=7.5-9.0$ are summarized in Table 3.

5 DISCUSSION

We have discovered an unresolved hot white dwarf companion to the 5th magnitude B star HR2875 (y Pup). This is the first time a hot white dwarf + B star binary has been detected, and it has important implications for our understanding of white dwarf and stellar evolution, since a white dwarf companion to such an early-type star must have evolved from a very massive progenitor, close to the upper limit for white dwarf formation. According to Lang (1992) a B5V star has a mass of 5.9M$_\odot$ (or 6.5M$_\odot$ according to Allen, 1973), and if the spectral type is as early as B3V (as classified in the Michigan Catalog of HD Stars, Houk 1982) then it will of course have a slightly higher mass. This is $\geq 5-6M_\odot$ upper mass limit for white dwarf progenitors of Jeffries (1997), but still significantly less than the 8M$_\odot$ upper limit from Weidemann (1987).

Since it must have evolved from such a massive progenitor, it is likely that this white dwarf also has a higher mass than the mean for these degenerates (0.58+0.078M$_\odot$, Marsh et al. 1997). We can use the theoretical initial-final mass relation between main sequence stars and white dwarfs to calculate the mass of the white dwarf if its progenitor was only slightly more massive than HR2875:

$$M_{WD} = A \exp(B \times M_{MS})$$

where $A=0.49462 M_\odot$ and $B=0.09468 M_\odot^{-1}$. For $M_{MS}=6.5M_\odot$, we find $M_{WD}=0.91M_\odot$. This would suggest the surface gravity of the white dwarf log $g=8.5$. In the log $g=8.5$ model, $T_{eff}=43,400$K and the white dwarf has a V magnitude =16.4 (calculated from the model flux at 5500Å).

HR2875 is not known to display radial velocity variations, and Hipparcos found no evidence for micro-variations in its proper motion across the sky to suggest that this might be a relatively short period binary system (P<few years, ESA 1997). However, it is clearly important to study this system further, and if radial velocity variations are detected then the binary parameters and the white dwarf’s mass can be constrained, with important implications for our knowledge of the initial-final mass relation. Additionally, further study of the B star primary might reveal evidence for past interaction. Could the over-abundance of Si detected in this object by Hiltner et al. (1969) be due to accretion from the wind of the evolved giant progenitor to the white dwarf, as in the WD+K2V binary RE J0357+28 (Jeffries, Burleigh and Robb 1996)?

Are there more early-type star+hot white dwarf binaries in the ROSAT and EUVE catalogues awaiting discovery? From its ROSAT WFC EUV and PSPC soft X-ray count rates and colours (S1=52±7 counts/ksec, S2=148±12 counts/ksec, PSPC=124±24 counts/ksec - all in the lower band), we strongly suspect that the 4th magnitude star θ Hya (B9.5V, =HR3665, =RE J0914+02) also hides a hot white dwarf companion, and indeed EUVE is scheduled to observe this star spectroscopically in March 1998. Other B stars detected in the EUV surveys may also have non-interacting degenerate companions, e.g. ADS10129C (B9.5V, =HD150100, =RE J1636+52) which also has EUV and soft X-ray count rates very similar to known hot white dwarfs (ROSAT WFC S1=12±4 counts/ksec, S2=46±11 counts/ksec, PSPC=72±15 counts/ksec - again, all in the lower band). Unfortunately these objects are probably too faint to be detected by the EUVE spectrometers.

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Note added in proof After this paper had been submitted for publication, we learned of a similar study by Vennes et al. (1997, ApJ, 491, L85). Their conclusions about the properties of the white dwarf are in agreement with ours.

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