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θ Hya: spectroscopic identification of a second B star+white dwarf binary

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Abstract. We report the identification, in an Extreme Ultraviolet Explorer (EUVE) spectrum, of a hot white dwarf companion to the 3rd magnitude late-B star θ Hya (HR3665, HD79469). This is the second B star+white dwarf binary to be conclusively identified; Vennes et al. (1997), and Burleigh & Barstow (1998) had previously reported the spectroscopic discovery of a hot white dwarf companion to the B5V star y Pup (HR2875). Since these two degenerate stars must have evolved from main sequence progenitors more massive than their B star companions, they can be used to place observational lower limits on the maximum mass for white dwarf progenitors, and to investigate the upper end of the initial-final mass relation. Assuming a pure hydrogen composition, we constrain the temperature of the white dwarf companion to θ Hya to lie between 25,000K and 31,000K. We also predict that a third bright B star, 16 Dra (B9.5V), might also be hiding an unresolved hot white dwarf companion.

Key words: stars: white dwarfs – stars: binaries: general – stars: individual: θ Hya

1. Introduction

Prior to the extreme ultraviolet (EUV) surveys of the ROSAT Wide Field Camera (WFC, Pye et al. 1995) and NASA's Extreme Ultraviolet Explorer (EUVE, Bowyer et al. 1996), only a handful of binary systems consisting of a normal star (spectral type K5 or earlier) plus a degenerate white dwarf had been identified. Some of these systems, like the prototype Sirius (A1V+DA), are relatively nearby and wide enough that the white dwarf can be readily resolved from its bright companion. Most of these types of binary, however, are all but unidentifiable optically since the normal stellar companion completely swamps the flux coming from the white dwarf. The detection by ROSAT and EUVE of EUV radiation with the spectral signature of a hot white dwarf originating from apparently normal, bright main sequence stars, therefore, gave a clue to the existence of a previously unidentified population of Sirius-type binaries, and around 20 new systems have now been identified (e.g. Barstow et al. 1994, Burleigh et al. 1997, Burleigh 1998 and Vennes et al. 1998, hereafter V98). In each case, far-ultraviolet spectra taken with the International Ultraviolet Explorer (IUE) were used to confirm the identifications. This technique proved excellent for finding systems where the normal star is of spectral type ~A5 or later, since the hot white dwarf is actually the brighter component in this wavelength regime (~1200−~2000Å). Unfortunately, even at far-UV wavelengths, stars of spectral types early-A, B and O will completely dominate any emission from smaller, fainter, unresolved companions, rendering them invisible to IUE.

θ Hya (HR3665, HD79469) and y Pup (HR2875) are two bright B stars unexpectedly detected in the ROSAT and EUVE surveys. Their soft X-ray and EUV colours are similar to known hot white dwarfs, so it was suspected that, like several other bright normal stars in the EUV catalogues, they were hiding hot white dwarf companions. However, for these two systems it was, of course, not possible to use IUE or HST to make a positive identification, and instead we had to wait for EUVE's spectrometers to make a pointed observation of each star. y Pup was observed in 1996, and the formal discovery of its hot white dwarf companion was reported by Vennes et al. (1997), and Burleigh & Barstow (1998). θ Hya was observed by EUVE in February 1998 and the EUV continuum distinctive of a hot white dwarf was detected (Fig. 1). This spectrum is presented, analysed and discussed in this letter.

White dwarf companions to B stars are of significant importance since they must have evolved from massive progenitors, perhaps close to the maximum mass for white dwarf progenitor stars, and they are likely themselves to be much more massive than the mean for white dwarfs in general (0.57$M_{\odot}$, Finley et al. 1997). The value of the maximum mass feasible for producing a white dwarf is a long-standing astrophysical problem. Weidemann (1987) gives the upper limit as 8$M_{\odot}$ in his semi-empirical initial-final mass relation. Observationally, the limit is best set by the white dwarf companion to y Pup, which must have evolved from a progenitor more massive than B5 (6−6.5$M_{\odot}$).

2. The main sequence star θ Hya

θ Hya is a V=3.88 high proper motion star; *Hipparcos* measures the proper motion components as 112.57±1.41 and −306.07±1.20 milli-arcsecs. per year. θ Hya was originally

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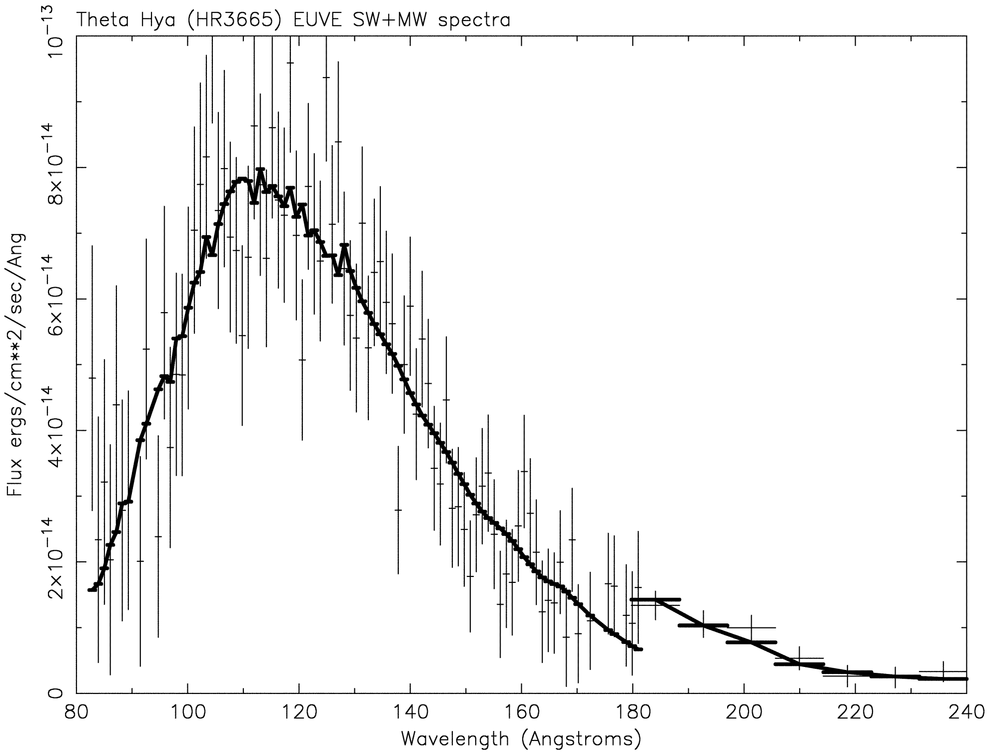

Fig. 1. EUVE short wavelength spectrum of θ Hya. Also shown is a pure hydrogen white dwarf + ISM model for log g =8.5, T_{eff} =28,500K, N_{HI}=6.6×10^{18}atoms cm^2, N_{HeI}=7.4×10^{17}atoms cm^2, and N_{HeII}=2.8×10^{17}atoms cm^2.

Table 1. X-ray and EUV count rates (counts/ksec)

		WFC		PSPC		EUVE			
ROSAT No.	Name	S1	S2	(0.1-0.4keV)	(0.4-2.4keV)	100Å	200Å	400Å	600Å
RE J0914+023	θ Hya	52±7	148±12	124±24	0.0	122±15	0.0	0.0	0.0

classified as a λ Boo chemically peculiar star, although from ultraviolet spectroscopy Faraggiani et al. (1990) later concluded that θ Hya was not in fact chemically peculiar, a finding backed up by Leone & Catanzaro (1998). Their derived abundances from high resolution optical spectroscopy are almost coincident with expected main sequence abundances. The *SIMBAD* database, Morgan et al. (1953) and Cowley et al. (1969) give the spectral type as B9.5V. V98 note that it is a fast rotator (v$_{rot}$sin i∼100 km s^{-1}), and that the detection of HeI at 4471Å also suggests a B star classification.

3. Detection of EUV radiation from θ Hya in the ROSAT WFC and EUVE surveys

The ROSAT EUV and X-ray all-sky surveys were conducted between July 1990 and January 1991; the mission and instruments are described elsewhere (e.g. Trümper 1992, Sims et al. 1990). θ Hya is associated with the relatively bright WFC source RE J0914+023. The same EUV source was later detected in the EUVE all-sky survey (conducted between July 1992 and January 1993). This source is also coincident with a ROSAT PSPC soft X-ray detection. The count rates from all three instruments are given in Table 1. The WFC count rates are taken from the revised 2RE Catalogue (Pye et al. 1995), which was constructed using improved methods for source detection and background screening. The EUVE count rates are taken from the revised Second EUVE Source Catalog (Bowyer et al. 1996). The PSPC count rate was obtained via the World Wide Web from the online ROSAT All Sky Survey Bright Source Catalogue maintained by the Max Planck Institute in Germany (Voges et al. 1996) [1].

As with y Pup (RE J0729−388), the EUV and soft X-ray colours and count rate ratios are similar to known hot white dwarfs. The EUV radiation is too strong for it to be the result of UV leakage into the detectors (see the discussion in Burleigh & Barstow 1998). θ Hya is also only seen in the soft 0.1−0.4 kev PSPC band; only one (rather unusual) white dwarf has ever been detected at higher energies (KPD0005+5105, Fleming et al. 1993), while most active stars are also hard X-ray sources. Indeed, in a survey to find OB-type stars in the ROSAT X-ray catalogue by Berghöfer et al. (1996), only three of the detected B stars are not hard X-ray sources: y Pup (confirmed B5V+white dwarf), θ Hya and 16 Dra (B9.5V, see later). Therefore, Burleigh et al. (1997) and V98 suggested that θ Hya, like y Pup and nearly twenty other bright, apparently normal stars in the EUV catalogues, might be hiding a hot white dwarf companion.

[1] http://www.rosat.mpe-garching.mpg.de/survey/rass-bsc/cat.html

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

log g	M_{WD} $M_\odot$	R_{WD} $R_\odot$	R_{WD} $\times 10^6$m	$(R_{WD}/D)^2$ *where D=39.5pc*
7.5	0.30	0.017	11.832	9.4243×10^{-23}
8.0	0.55	0.013	9.048	5.5111×10^{-23}
8.5	0.83	0.009	6.264	2.6414×10^{-23}
9.0	1.18	0.006	4.176	1.1740×10^{-23}

Table 3. WD parameters and interstellar column densities

log g	T_{eff} (K) & 90% range	N_{HI} $\times10^{18}$ & 90% range	N_{HeI} $\times10^{17}$	N_{HeII} $\times10^{17}$
7.5	25,800 (25,500−26,200)	2.7 (1.1−4.9)	3.1	1.1
8.0	26,800 (26,400−27,100)	4.6 (3.2−6.3)	5.2	1.9
8.5	28,500 (28,200−28,900)	6.6 (5.3−7.9)	7.4	2.8
9.0	30,800 (30,400−31,200)	8.0 (7.0−9.1)	9.0	3.3

4. EUVE pointed observation and data reduction

θ Hya was observed by EUVE in dither mode in four separate observations in 1998 February/March for a total exposure time of ≈210,000 secs. We have extracted the spectra from the images ourselves using standard IRAF procedures. Our general reduction techniques have been described in earlier work (e.g. Barstow et al. 1997).

The target was detected in both the short (70−190Å) and medium (140−380Å) wavelength spectrometers (albeit weakly), but not the long wavelength (280−760Å) spectrometer. To improve the signal/noise, we have co-added the four separate observations, binned the short wavelength data by a factor four, and the medium wavelength data by a factor 16. The resultant spectrum, shown in Fig. 1, reveals the now familiar EUV continuum expected from a hot white dwarf in this spectral region.

The only stars other than white dwarfs whose photospheric EUV radiation has been detected by the ROSAT WFC and EUVE are the bright B giants β CMa (B1II−III, Cassinelli et al. 1996) and ϵ CMa (B2II, Cohen et al. 1996). The photospheric continuum of ϵ CMa is visible down to ∼300Å, although no continuum flux from β CMa is visible below the HeI edge at 504Å. Both stars also have strong EUV and X-ray emitting winds, and in ϵ CMa emission lines are seen in the short and medium wavelength spectrometers from e.g. high ionisation species of iron. Similarly, strong narrow emission features of e.g. oxygen, nickel and calcium are commonly seen in EUV spectra of active stars and RS CVn systems. Since no such features are visible in the θ Hya EUVE spectrum, we can categorically rule out a hot wind or a hidden active late-type companion to θ Hya as an alternative source of the EUV radiation.

5. Analysis of the hot white dwarf

We have attempted to match the EUV spectrum of θ Hya with a grid of hot 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 in this wavelength region to give us an unambiguous determination of T_{eff} 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 some of the the white dwarf's physical parameters. Our method is similar to that used in the analysis of the white dwarf companion to y Pup (Burleigh & Barstow 1998).

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_{eff}<40,000K hot white dwarfs have an essentially pure-H atmospheric composition. We can then fit a range of models, each fixed at a value of the surface gravity *log g*. However, before we can do this we need to know the normalisation parameter of each model, which is equivalent to $(\mathrm{Radius}_{WD}/\mathrm{Distance})^2$. We can use the *Hipparcos* parallax of 4.34±0.97 milli-arcsecs., translating to a distance of 39.5±1.5 parsecs, together with 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 calculate the ratio N_{HI}/N_{HeI} in the local ISM=8.9, and N_{HeI}/N_{HeII}=2.7. We can then fix these column density ratios in our model, leaving us with just two free parameters - temperature and the HI column density.

The model fits at a range of surface gravities from log g =7.5−9.0 are summarized in Table 3. Note that our range of fitted temperatures is in broad agreement with those of V98, who modelled the EUV and soft X-ray photometric data for θ Hya on the assumption that the source was indeed a hot white dwarf.

6. Discussion

We have analysed the EUVE spectrum of the B9.5V star θ Hya which confirms that it has a hot white dwarf companion, and constrains the degenerate star's temperature to lie between ≈25,500K and ≈31,000K. This is the second B star+hot white dwarf binary to be spectroscopically identified, following y Pup (HR2875), a B5 main sequence star. The white dwarf in the θ Hya system must have evolved from a progenitor more massive than B9.5V (≈3.4$M_\odot$).

Although EUVE spectra provide us with little information with which to constrain a white dwarf's surface gravity, and hence its mass, we can use a theoretical initial-final mass relation between main sequence stars and white dwarfs, e.g. that of Wood (1992), to calculate the mass of a white dwarf if the progenitor was only slightly more massive than θ Hya:

$$M_{WD} = \mathrm{A}\exp(\mathrm{B} \times M_{MS})$$
where $\mathrm{A} = 0.49 M_\odot$ and $\mathrm{B} = 0.094 M_\odot^{-1}$.

For M_{MS}=3.4M$_\odot$, we find M_{WD}=0.68M$_\odot$. This would suggest the surface gravity of the white dwarf log g>8.0.

Data from *Hipparcos* indicates possible micro-variations in the proper motion of θ Hya across the sky, suggesting that the binary period may be ~10 years or more. Indeed, V98 measured marginal variations in the B star's radial velocity. Clearly, more measurements at regular intervals in future years might help to pin down the binary period.

7. A third B star+white dwarf binary in the EUV catalogues?

EUVE has now spectroscopically identified two B star+hot white dwarf binaries from the EUV all-sky surveys. As mentioned previously in Sect. 3, in a survey of X-ray detections of OB stars, Berghöfer et al. (1996) found just three B stars which were soft X-ray sources only: y Pup and θ Hya, which have hot white dwarf companions responsible for the EUV and soft X-ray emissions, and 16 Dra (B9.5V, =HD150100, =ADS10129C, V=5.53).

16 Dra is one member of a bright resolved triple system (with HD150118, A1V, and HD150117, B9V). Hipparcos parallaxes confirm all three stars lie at the same distance, ≈120 parsecs. 16 Dra is also a WFC and EUVE source (RE J1636+528), and it is so similar to y Pup and θ Hya that we predict it also has a hot white dwarf companion, most likely unresolved. Unfortunately, it is a much fainter EUV source than either y Pup or θ Hya, and would require a significant exposure time to be detected by EUVE's spectrometers (~400−500 ksecs).

However, we can estimate the approximate temperature of this white dwarf, and the neutral hydrogen column density to 16 Dra, using the ROSAT photometric data points: WFC S1 count rate =12±4 c/ksec, S2=46±11 c/ksec, and PSPC soft band count rate =72±15 c/ksec. We adopt a similar method to the analysis of θ Hya described earlier, using the Hamada-Salpeter zero-temperature mass-radius relation and the Hipparcos parallax to constrain the normalisation (equivalent to $(R_{WD}/D)^2$). Although we cannot constrain the value of the surface gravity using this method, we find that the white dwarf's temperature is likely to be between 25,000−37,000K, and the neutral hydrogen column density $N_{HI} < 4\times10^{19}$ atoms cm^{-2}.

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