Spectroscopic confirmation of a white dwarf companion to the B star 16 Dra

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Abstract. Using an Extreme Ultraviolet Explorer (EUVE) spectrum, we confirm the identification of a white dwarf companion to the B9.5V star 16 Dra (HD150100), and constrain its surface temperature to lie between 29,000 K and 35,000 K. This is the third B star + white dwarf non-interacting Sirius-type binary to be confirmed, after y Pup (HR2875, HD59635) and θ Hya (HR3665, HD79469). 16 Dra and its white dwarf companion are members of a larger resolved proper motion system including the B9V star 17 Dra A (HD150117). The white dwarf must have evolved from a progenitor more massive than this star, $M_{MS} \approx 3.7 M_{\odot}$. White dwarf companions to B stars are important since they set an observational limit on the maximum mass for white dwarf progenitors, and can potentially be used to investigate the high mass ends of the initial-final mass relation and the white dwarf mass-radius relation.

Key words: stars: individual: 16 Dra – stars: binaries: general – stars: white dwarfs

1. Introduction

Unresolved Sirius-type binary systems consisting of a white dwarf and a main sequence star (spectral type B−K) are difficult to identify optically, since the bright main sequence companion completely swamps the degenerate star's flux. However, through the ROSAT Wide Field Camera (WFC, Pounds et al. 1993) and Extreme Ultraviolet Explorer (EUVE, Bowyer et al. 1994) surveys, EUV radiation with the spectral signature of a hot white dwarf has been detected originating from apparently inactive main sequence stars, giving a clue to the existence of a previously unidentified population of Sirius-type binaries. Over 20 new systems have now been identified (e.g. Barstow et al. 1994, Burleigh et al. 1997, Vennes et al. 1998). For companions of spectral type ∼A5 or later, far-ultraviolet spectra obtained with the International Ultraviolet Explorer (IUE) have been used to confirm the identifications, since the white dwarf is actually the brighter component at these wavelengths. Unfortunately, stars of spectral types O, B and early A will still dominate any emission from a white dwarf in the far-UV regime, and IUE or HST

cannot be used to identify any putative degenerate companions to these objects.

Two bright B stars, θ Hya (HR3665) and y Pup (HR2875), were unexpectedly detected in the ROSAT and EUVE surveys. Since their soft X-ray and EUV colours were similar to many known hot white dwarfs, it was suspected that they too were hiding hot white dwarf companions. Fortunately, both EUV sources were bright enough to be observed by EUVE's spectrometers. y Pup was observed by EUVE in 1996, θ Hya in 1998, and the formal discovery of these Sirius-type systems was subsequently reported by Vennes et al. (1997, y Pup), Burleigh & Barstow (1998, y Pup), and Burleigh & Barstow (1999, θ Hya).

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. They are also likely to be significantly more massive than the mean for white dwarf stars in general ($\approx 0.57 M_{\odot}$, Bergeron et al. 1992). The value of the maximum mass for a white dwarf progenitor star, and hence the minimum mass for producing a Type II supernova through core collapse in a single star, is a long-standing astrophysical problem. Weidemann (1987) gives the limit as $\sim 8 M_{\odot}$ in his semi-empirical initial-final mass relation. Observationally, this limit is best set by the white dwarf companion to y Pup (HR2875). Echelle spectroscopy of this object by Vennes (2000) has recently revealed that this system comprises two main sequence B stars (B3.5V+B6V) in an eccentric ≈ 15 day orbit, with the white dwarf forming a third, wider component. The white dwarf must then have evolved from a star more massive than B3.5V, $\sim 5.5 M_{\odot}$ (Vennes 2000). We also note that Berghöfer et al. (2000) have recently suggested that the spectroscopic companion to the B1.5IV star λ Sco might be a hot ultramassive white dwarf ($1.25 M_{\odot} < M_{WD} < 1.4 M_{\odot}$), based on an excess of EUV and soft X-ray radiation detected in ROSAT and EUVE photometric observations. If the existence of a white dwarf in this system was confirmed it would obviously set the lower limit on the maximum mass for white dwarf progenitors at a value near Weidemann's semi-empirical $\sim 8 M_{\odot}$ limit, although unfortunately λ Sco is a close binary ($P = 5.959$ days) and mass transfer may have taken place at some stage.

White dwarfs in Sirius-type binaries can also be used to investigate the relationship between the mass of a main sequence
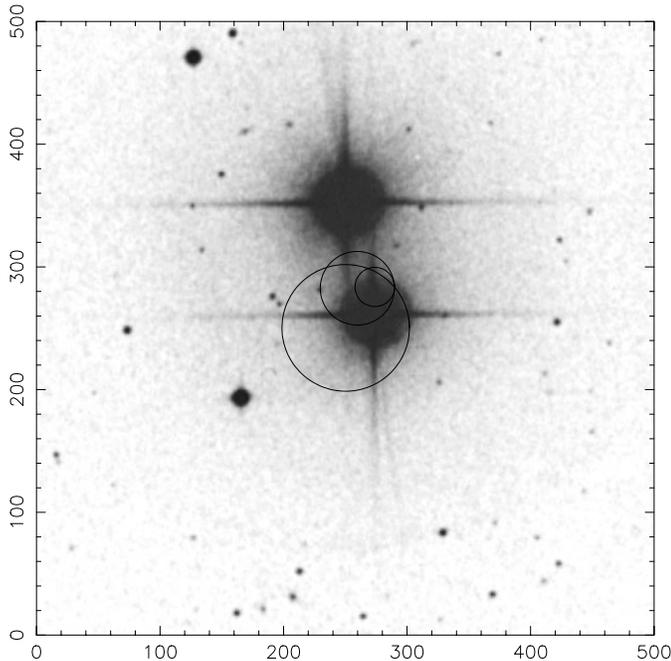
Fig. 1. Optical image of the 16 Dra system from the Digitized Sky Survey. The field is 8×8 arcmin. The lower of the bright stars is 16 Dra. The upper bright star is the 17 Dra A/B pair, unresolved here but in fact separated by 3.2 arcsec. The circles denote, in decreasing order of size, the ROSAT WFC, EUVE and ROSAT PSPC source error boxes.

star and its white dwarf progeny, the initial-final mass relation. In particular, white dwarf + B star binaries can be used to investigate the upper end of this relation. Likewise, if the two components can eventually be resolved and an astrometric mass determined for the white dwarf, these systems can potentially be used to investigate the high mass end of the theoretical white dwarf mass-radius relation, for which few observational data points currently exist (Vauclair et al. 1997, Provencal et al. 1998).

In addition to y Pup and θ Hya, another B star was also detected in the ROSAT WFC and EUVE surveys, 16 Dra (HD150100, B9.5V). In this paper we present an EUVE spectrum of 16 Dra, which proves that it too has a hot white dwarf companion.

2. The 16 Dra system

16 Dra (HR6184, HD150100, ADS10129C) is a V=5.51 B9.5V star in a visual triple system with two other early-type stars, 17 Dra A (HR6185, HD150117, ADS10129A, B9V, V=5.08) and 17 Dra B (HR6186, HD150118, ADS10129B, A1V, V=6.58). The Hipparcos Catalogue (Perryman et al. 1997) gives the separation of 17 Dra A&B as just 3.208 arcsec; 17 Dra A and 16 Dra are then separated by 90.17 arcsec (Fig. 1). The Hipparcos parallax for 16 Dra is 8.16±0.55 mas, corresponding to a distance of 122.5 pc (114.8−131.4 pc), and the parallax for 17 Dra A is similar, 8.22±0.60 mas, corresponding to a distance of 121.6 pc (113.4−131.2 pc). No solution is given for 17 Dra B. The proper motions of 16 Dra and 17 Dra A are also very similar: for 16

Dra μ_α=−12.9±0.6 mas/yr and μ_δ=28.7±0.6 mas/yr; for 17 Dra A μ_α=−12.3±0.6 mas/yr and μ_δ=27.4±0.6 mas/yr. All three stars are therefore almost certainly related. In that case, any white dwarf in the system must have descended from a progenitor more massive than the earliest-type star extant, B9V (17 Dra A).

3. Detection of EUV radiation from 16 Dra 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). 16 Dra is associated with the WFC source RE J1636+525, and was later also detected in the EUVE all-sky survey (conducted between July 1992 and January 1993). This source is also coincident with a ROSAT Position Sensitive Proportional Counter (PSPC) soft X-ray detection. The count rates from all three instruments and associated filters 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 First EUVE Source Catalog (Bowyer et al. 1994). The source is not included in the revised Second EUVE Source Catalog (Bowyer et al. 1996, see discussion below). The PSPC count rate was obtained from the on-line ROSAT All Sky Survey Bright Source Catalogue source browser, maintained by the Max-Planck-Institute in Germany (Voges et al. 1999)[1].

Fig. 1 shows an optical image of the 16 Dra field from the Digitized Sky Survey[2], including the nearby pair 17 Dra A/B. Also shown are the ROSAT WFC, EUVE and PSPC source error boxes. Clearly, no obvious optical counterpart is visible or resolved within the intersection of these three boxes, other than 16 Dra itself.

The EUV and soft X-ray colours are similar to known hot white dwarfs, and the EUV radiation is too strong for it to be the result of UV leakage through the WFC filters, although in the EUVE source catalogs (e.g. Bowyer et al. 1994) it is flagged as such (and, indeed, omitted from the second EUVE source catalog as a result, Bowyer et al. 1996). Far-UV leakage is a known problem for EUVE, but the effect is almost negligible in the WFC, especially for a late B star like 16 Dra. Assuming a temperature of 10,000 K, we estimate the far-UV leakage contribution to the WFC S2 flux at just 3×10^{-5} counts/sec, compared with the ≈0.05 counts/sec detected. Add the fact that the EUV detection is also coincident with a PSPC soft X-ray detection, and it can be safely assumed that it is real.

16 Dra is only detected 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). Most active stars are also hard X-ray sources, and indeed Berghöfer et al. (1996) found only three of the B stars detected by the ROSAT PSPC were not hard X-ray sources. Interestingly, these
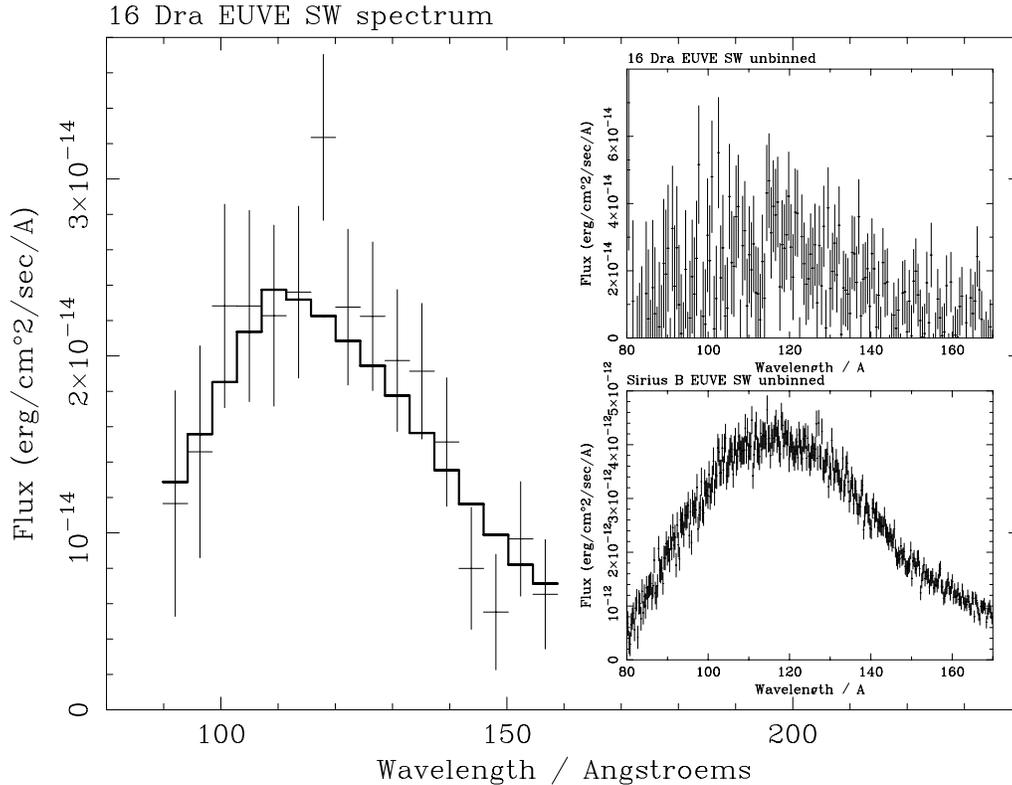
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[1] http://www.rosat.mpe-garching.mpg.de/cats/src-browser/
[2] http://ledas-www.star.le.ac.uk/DSSimage/

Fig. 2. EUVE short wavelength spectrum of 16 Dra, shown together with a pure-H white dwarf + ISM model (solid line) for $\log g = 8.5$, $T_{\mathrm{eff}} = 31,900\mathrm{K}$, $N_{\mathrm{HI}} = 8.2 \times 10^{18}$ atoms cm^{-2}, $N_{\mathrm{HeI}} = 9 \times 10^{17}$ atoms cm^{-2}, and $N_{\mathrm{HeII}} = 3 \times 10^{17}$ atoms cm^{-2}. Inset (upper): the same data, displayed at the instrument resolution of ≈ 0.5Å. Inset (lower): EUVE short wavelength spectrum of Sirius B, for comparison.

Table 1. X-ray and EUV count rates (counts/ksec) and size of source error box (radius in arcsec). The EUVE source error box is a nominal 30 arcsec, since no value is given in Bowyer et al. (1994). The ROSAT WFC error includes the formal 90% error and a quadratically added 30 arcsec error to account for systematics in the aspect solution.

		WFC			PSPC			EUVE		
ROSAT No.	Name	error box	S1	S2	error box	0.1–0.4 keV	0.4–2.4 keV	error box	100 Å	200 Å
RE J1636+525	16 Dra	51.6	12±4	46±11	16	72±15	0.0	30	32±4	0.0

are y Pup, θ Hya (both of which have confirmed white dwarf companions) and 16 Dra. Therefore, Burleigh & Barstow (1999) confidently predicted that 16 Dra might also be hiding a hot white dwarf companion, and using the ROSAT count rates demonstrated that it probably had a surface temperature between 25,000−37,000 K.

4. EUVE pointed observation and data reduction

16 Dra was observed twice by EUVE in dither mode, firstly for ≈220,000 sec between 1999 February 28th and 1999 March 7th, and then for ≈230,000 sec between 1999 June 27th and 1999 July 6th, giving a total exposure time of 453,985.5 sec. We have extracted the spectra from the detector images using standard IRAF procedures. Our general reduction techniques are described in earlier work (e.g. Barstow et al. 1997).

The target was only detected, weakly, in the short (70−190Å) wavelength spectrometer. To improve the sig-

nal/noise ratio, we combined the two observations before extracting this spectrum, and then binned the data by a factor 32. The resultant spectrum is shown in Fig. 2. The flux distribution is similar in shape to the familiar EUV continuum expected from hot white dwarfs in this spectral region (Fig. 2, inset). No emission lines are visible in the raw data (Fig. 2, inset), despite the apparent excess of flux at ∼120Å in the binned spectrum.

The only stars other than white dwarfs whose photospheric EUV radiation has been detected by the ROSAT WFC and EUVE are the bright early 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 by EUVE in the short and medium wavelength spectrometers from e.g. high ionisation features of iron. Similarly, strong narrow emission features of e.g. oxygen, nickel and calcium are commonly seen
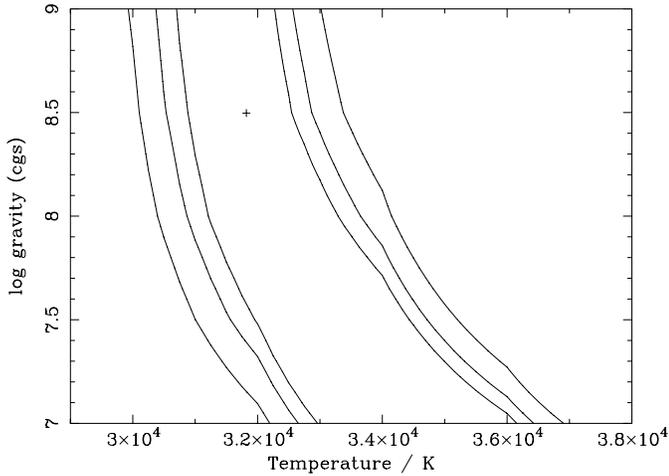
Fig. 3. Confidence contours for the spectral fit to the EUVE data, at 66%, 90% and 99% in the ($T_{\rm eff}$, log g) plane.

Table 2. Hamada-Salpeter zero-temperature mass-radius relation. 16 Dra is assumed to lie at a distance of 122.5 pc.

log g	$M_{\rm WD}$ $(M_\odot)$	$R_{\rm WD}$ $(R_\odot)$	$R_{\rm WD}$ $(\times 10^8 \rm cm)$	$(R_{\rm WD}/D)^2$
7.5	0.30	0.017	11.832	9.929×10^{-24}
8.0	0.55	0.013	9.048	5.806×10^{-24}
8.5	0.83	0.009	6.264	2.783×10^{-24}
9.0	1.18	0.006	4.176	1.237×10^{-24}

in EUV spectra of active stars and RS CVn systems. Since no such features are visible in this spectrum of 16 Dra, we can categorically rule out a hot wind or unresolved active late-type companion to 16 Dra as an alternative source for the EUV radiation.

5. Analysis of the hot white dwarf's EUV spectrum

We have matched the EUV spectrum of 16 Dra with a grid of hot white dwarf + ISM model atmospheres, in order to constrain the 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 $T_{\rm eff}$ 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 white dwarf's physical parameters. Our method is similar to that used in the analysis of y Pup (Burleigh & Barstow 1998) and θ Hya (Burleigh & Barstow 1999).

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 $T_{\rm eff} < 40,000$K hot DA white dwarfs have an essentially pure-H atmospheric composition. We can then fit a range of models, each fixed at a discrete value of the surface gravity log g. However, before we can do this we need to know the normalisation parameter of each
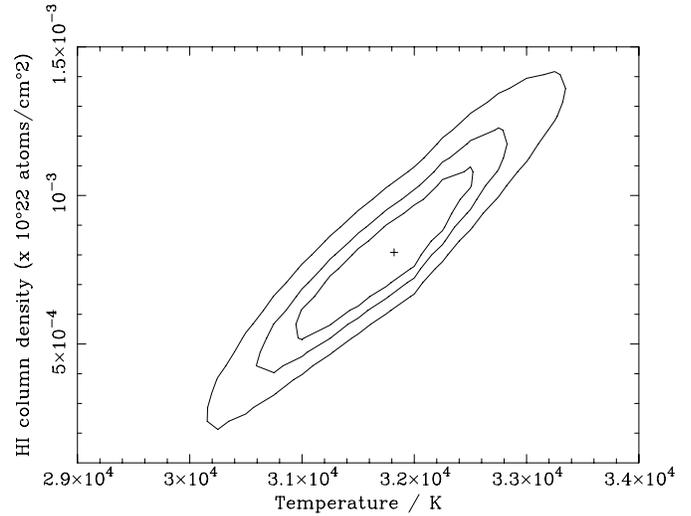

Fig. 4. Confidence contours for the spectral fit to the EUVE data, at 66%, 90% and 99% in the (log g, $N_{\rm HI}$) plane.

model, which is equivalent to $(R_{\rm WD}/D)^2$. For this, we can use the Hipparcos parallax to give us the distance, and the Hamada & Salpeter (1961) 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 fraction was 0.27±0.04. From these estimates, and assuming a cosmic H/He abundance, we calculate the ratio $N_{\rm HI}/N_{\rm HeI}$ in the local ISM=8.9 and $N_{\rm HeI}/N_{\rm HeII} = 2.7$. 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 agreement with those of Burleigh & Barstow (1999), who modelled the ROSAT EUV and soft X-ray photometric data for 16 Dra on the assumption that the source was indeed an unresolved white dwarf.

6. Discussion

We have analysed the weak EUVE spectrum of the B9.5V star 16 Dra, and confirm that there is an unresolved hot white dwarf in the field.

Fig. 1 clearly shows that the white dwarf is not resolved from 16 Dra in the Digitized Sky Survey image, and their angular separation can be no more than ≈30 arcsec. However, if the white dwarf lies at the same distance as 16 Dra and its proper motion companions 17 Dra A & B, and is related to them, then it must have evolved from a progenitor more massive than the earliest extant star in the system, 17 Dra A (B9V). Thus this degenerate has the second most massive progenitor among known white

Table 3. WD parameters and interstellar column densities.

log g	T_{eff} (K)	90% range	N_{HI} $\times 10^{19}$	90% range $\times 10^{19}$	N_{HeI} $\times 10^{18}$	N_{HeII} $\times 10^{17}$
7.5	29,300	(28,100−30,400)	1.0	(0.4−1.5)	1.1	4.1
8.0	30,100	(28,900−31,200)	0.9	(0.4−1.4)	1.0	3.7
8.5	31,900	(30,500−33,000)	0.8	(0.4−1.2)	0.9	3.4
9.0	34,200	(32,800−35,400)	0.7	(0.3−1.1)	0.8	3.0

Table 4. The earliest-type stars known to have white dwarf companions

Name	Alt. name	Sp. Type	M_{MS} ($M_\odot$)	Period	Distance (pc) (Hipparcos)	M_{WD} ($M_\odot$)	Reference
λ Sco*	HR6527	B1.5IV	$\sim$9	5.959 days	180−265	1.25−1.4	Berghöfer et al. (2000)
y Pup	HR2875	B3.5V+B6V	5.5		157−187	>0.91	Burleigh & Barstow (1998) Vennes et al. (2000)
16 Dra†	HD150100	B9V	3.7		115−131	>0.69	this paper
θ Hya††	HR3665	B9.5V	3.4	$\gtrsim$10 yrs	38−41	>0.68	Burleigh & Barstow (1999)
Sirius B‡		A0V	3.25	$\approx$50 yrs	2.637±0.011	1.034±0.026	Holberg et al. (1998)
Beta Crt.††		A1III	2.9	$\gtrsim$10 yrs	77−87	0.44	Vennes et al. (1998)

Main sequence masses from Allen (1973).

$\star$ Suggested, not confirmed. Note that the Hipparcos distance estimate is inconsistent with the photometric distance ($\sim$ 140pc). An alternative explanation is that the system consists of two B stars.

† The spectral type of 16 Dra is in fact B9.5V. Its proper motion companion 17 Dra A is B9V, and thus any white dwarf in the system must have evolved from a progenitor more massive than this. See text for futher discussion.

†† Micro-variability in the proper motions of these stars as measured by Hipparcos indicate binary periods $\gtrsim$10 yrs.

‡ Holberg et al. (1998) use an initial-final mass relation to estimate the progenitor mass of Sirius B as 6−7$M_\odot$.
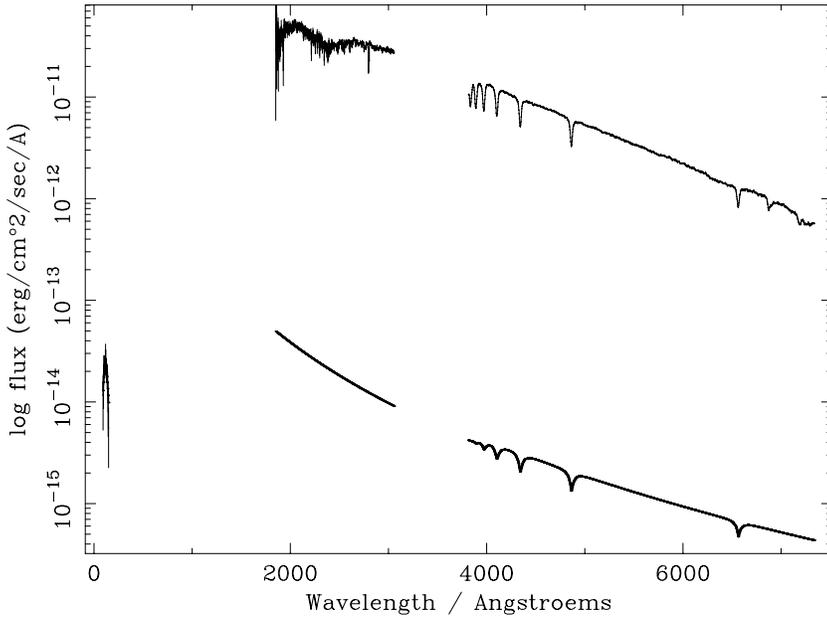

Fig. 5. Left to right: EUV, UV and optical spectra of 16 Dra, shown together with a white dwarf model for $T_{\mathrm{eff}} = 31,900$K and log $g = 8.5$. The B9.5V star clearly dominates the UV and optical flux, and the white dwarf is only detectable in the EUV. The UV spectrum was extracted from the IUE final archive (LWP18244). The optical spectrum was obtained on 1997 March 17 at the Russain Academy of Sciences' Special Astrophysical Observatory's 6m telescope, located in the Karachaevo-Cherkesia region of southern Russia.

dwarfs. Table 4 lists the earliest type stars known to have white dwarf companions, including all three B star + white dwarf binaries and Sirius.

EUVE spectra provide us with little information with which to constrain a white dwarf's surface gravity, and hence its mass, but we can use a theoretical initial-final mass relation between main sequence stars and white dwarfs, e.g. that of Wood (1992),

to estimate the mass of the white dwarf if the progenitor was slightly more massive than a B9V star: $M_{\mathrm{WD}} = A\,exp\,(B \times M_{\mathrm{MS}})$, where $A = 0.49M_\odot$ and $B = 0.094M_\odot^{-1}$.

For $M_{\mathrm{MS}} = 3.7M_\odot$, we find $M_{\mathrm{WD}} = 0.69M_\odot$. This would suggest the surface gravity of the white dwarf log $g > 8.0$ and, therefore, its surface temperature most likely lies between $\approx 29,000$K and $\approx 35,000$K.

Finally, we note that if this white dwarf can be resolved from 16 Dra, then an optical spectrum may potentially be obtained (e.g. with HST/STIS) from which its temperature and gravity can be tightly constrained. The mass can then be estimated, and this binary could be used to investigate the initial-final mass relation and to test the high mass end of the mass-radius relation.

Appendix: HD93847 - another B star + white dwarf binary in the ROSAT WFC catalogue?

A fourth B star, HD93847 (B9, V=7.46) was detected in the WFC survey, with a count rate of 9 ± 4 counts/ksec in the S1 filter and 18 ± 5 counts/ksec in the S2 filter. Since the S2/S1 count rate ratio is similar to known hot white dwarfs, it would be reasonable to suggest that perhaps this B star is also hiding a degenerate companion. The detected flux is highly unlikely to be due to far-UV leakage: we estimate this contribution as only 6×10^{-6} counts/sec. Unfortunately, this weak WFC source was not detected by the ROSAT PSPC or by EUVE, and thus it is not clear whether the detection is real. With a combined S1+S2 detection significance of only 5.8σ it is in the regime where a few spurious detections are expected (see Pye et al. 1995). Alternatively, the B star may be hiding an unresolved active late-type companion that flared in the EUV waveband. We are therefore unwilling to claim that this source is due to another hidden white dwarf.

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