A WHITE DWARF COMPANION TO THE B5 V STAR HR 2875 (γ PUPPIS)¹

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ABSTRACT

An extreme-ultraviolet source in the *EUVE* and *ROSAT* Wide Field Camera catalogs, also identified with a very soft *ROSAT* PSPC X-ray source, is coincident with the B5 V star HR 2875 (γ Pup). We present an analysis of PSPC and *EUVE* spectra revealing the presence of a hot white dwarf companion to HR 2875, which then constitute the first confirmed B star plus white dwarf system. The B star shows variable Si II, He I, and H I line profiles in high-dispersion spectra, possibly related to its binary nature, but our measurements limit the radial velocity semiamplitude of the B star to ≤ 2 km s⁻¹. We speculate that the white dwarf is most likely massive, and we propose some observational tests of the model.

Subject headings: binaries: general — stars: abundances — stars: individual (HR 2875) — ultraviolet: stars — white dwarfs

1. INTRODUCTION

The star HR 2875 (γ Pup, HD 59635, CD $-38^\circ 3400$) is a southern hemisphere luminous blue object recently detected at extreme-ultraviolet (EUV) wavelengths (*EUVE* J0729–388, 2RE J0729–384)⁵ and soft X-ray energy (IRXS J072905.9–384839).⁶ Hiltner, Garrison, & Schild (1969) classify HR 2875 as a B5 Vp star, which translates into a distance modulus of $m - M = 6.5$. This classification is in agreement with the recent *Hipparcos* parallax measurement, $\pi = 0''.0056 \pm 0''.0005$ ($d = 164$ – 196 pc). Hiltner et al. (1969) noted abnormally strong silicon lines in optical spectra.

Motch et al. (1997) report *ROSAT* PSPC observations that suggest but do not demonstrate the presence of a white dwarf companion to the B5 V star HR 2875. Berghöfer et al. (1997) also recognized that a few other B stars, besides HR 2875, associated with ultrasoft X-ray sources may, in fact, hide hot white dwarf companions (e.g., λ Cen and λ Sco). In the case of HR 2875, the progenitor of the white dwarf would have been a main-sequence star earlier than B5 ($M \geq 6 M_\odot$); some initial-mass–final-mass relations (M_f/M_i) applicable to such objects (Vassiliadis & Wood 1993; Wagenhuber & Weiss 1994; Blöcker 1995) would predict the presence of a high-mass white dwarf star ($M \geq 0.9 M_\odot$). A study of the HR 2875 system would, in fact, help constrain theoretical M_f/M_i relations and would provide useful insights to the evolution of early main-sequence stars.

Using EUV and soft X-ray observations of HR 2875, we propose to demonstrate the presence of a hot white dwarf companion to the B star, and, adopting a new estimate of the distance toward HR 2875, we constrain the white dwarf parameters. In § 2 we present new optical, ultraviolet, and soft X-ray observations of HR 2875 that show the likely presence of a white dwarf. In § 3 we show that the properties of the

white dwarf resemble in every aspect the properties of the EUV-selected population of white dwarf stars. We summarize in § 4, discuss the implications for stellar evolution, propose new observations to measure the surface gravity, and hence the mass, of the white dwarf, and determine the binary properties.

2. OBSERVATIONS

2.1. X-Ray

Berghöfer, Schmitt, & Cassinelli (1996) and Motch et al. (1997) report *ROSAT* PSPC observations of an ultrasoft X-ray source associated with the B5 V star HR 2875 between 1990 October 17 and 20 (separation = $5''.5$, well within the PSPC error circle). Figure 1 shows the analysis of the PSPC energy spectrum with blackbody models revealing a very soft source ($T[\text{eV}] = 15.6 \pm 3.7$) also characterized by a low neutral hydrogen column density in the line of sight ($n_{\text{H}} \approx 2 \times 10^{19}$ cm⁻²). Comparing this spectrum with a sample of PSPC spectra of hot white dwarf stars (Jordan et al. 1994), we conclude that the X-ray spectrum of HR 2875 definitely bears the signature of a hot, noninteracting white dwarf with, most probably, a hydrogen-rich (DA) atmosphere.

On the other hand, *ROSAT* observations of OB stars show that the spectral type B1 defines a dividing line for early-type star X-ray emission (Berghöfer et al. 1997). It is accepted that X-ray emission in early-type stars is produced by shocks in massive stellar winds. The ratio between bolometric and X-ray luminosity observed for HR 2875, $\log(L_X/L_{\text{bol}}) = -4.84$, exceeds the canonical value of $\log(L_X/L_{\text{bol}}) \sim -7$ for O stars. The X-ray emission from HR 2875 cannot be explained by shocks in the stellar wind; other X-ray-emitting mechanisms are not known for B stars.

2.2. Ultraviolet and Optical

EUV detection of the B star HR 2875 was reported in the *ROSAT* Wide Field Camera (WFC) all-sky survey and then in the *EUVE* all-sky survey; the *ROSAT* WFC observations occurred between 1990 October 13 and 23, while the *EUVE* observations occurred between 1992 October 23 and November 2. Table 1 summarizes the photometric EUV/soft X-ray measurements. *EUVE* spectroscopic observations of HR 2875 were obtained between 1996 April 5 and 14 for a total exposure of 113,000 s. The star was detected only in the short-wavelength spectrometer (SW). Because of the poor signal-to-noise ratio

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⁵ Pye et al. (1995); Bowyer et al. (1996).

⁶ Voges et al. (1997).

FIG. 1.—*ROSAT* PSPC energy distribution in the range 0.1–0.3 keV (41–124 Å). The spectrum is characteristic of a hot, noninteracting, white dwarf observed toward a low column density in the interstellar medium.

achieved during this observation, the spectrum was reconstructed with 5 Å bins. Finally, we obtained two high-dispersion *IUE* spectra of HR 2875 (LWP 29521 and SWP 52272) from the archives at Goddard Space Flight Center. We reconstructed the spectra with 2.5 Å wavelength bins; Figure 2 presents the ultraviolet energy distribution between 70 and 3250 Å.

We obtained a series of high-dispersion spectra of HR 2875 using the Coudé Auxiliary Telescope (CAT) and Hamilton echelle spectrograph at Lick Observatory on 1997 January 8–11, February 6 and 9, and March 12. We used a 2048 × 2048 CCD binned 2 × 2 with a dispersion of 0.054 Å pixel^{−1} at H α ; the spectral resolution is 7.5 km s^{−1}. The spectra were wavelength calibrated using Th-Ar comparison lamps. We observed HR 2875 at low air mass at the coudé focus of the 74 inch (1.9 m) telescope at Mount Stromlo Observatory (MSO) on 1997 April 24 and 25. We used the 32 inch (81 cm) camera and a 600 lines mm^{−1} grating resulting in a dispersion of 0.163 Å pixel^{−1} at H ϵ in the third order and 0.243 Å pixel^{−1} at H α in the second order. We established the wavelength scale using Cu-Ar comparison lamps. We obtained 300 s exposures of the high Balmer line series (H δ –H9, 3798–4132 Å) and H α spectral range (6324–6820 Å); we eliminated overlapping orders using BG12 and GG495 filters, respectively. The Lick and Stromlo images were bias subtracted and flat-fielded using a quartz lamp, and the spectra were extracted using standard NOAO's IRAF procedures.

3. A B5 V PLUS DA WHITE DWARF BINARY

3.1. The B Star

HR 2875 is classified as B5 V, corresponding to $T_{\text{eff}} \approx 15,000$ K, and $\log g \approx 4$. Figure 2 shows the ultraviolet (70–3200 Å) spectrum observed with *IUE* and *EUVE*; the medium-resolution *EUVE* spectrum confirms the presence of a white dwarf companion to the B star. Figure 3 shows high-

FIG. 2.—Ultraviolet spectrum of a composite B5 V star plus a hot white dwarf. EUV emission (80–150 Å) demonstrates the presence of a hot white dwarf companion to the B star HR 2875. The white dwarf is approximately 11 mag fainter in the optical range. The white dwarf EUV emission is compared with a representative model atmosphere ($T_{\text{eff}} = 40,000$ K, $\log g = 8.5$) scaled to a distance of 177 pc and theoretical white dwarf radius. The EUV spectral range is attenuated by a neutral hydrogen absorption in the local ISM ($n_{\text{H I}} = 3 \times 10^{19}$ cm^{−2}).

dispersion spectra of H α and the Si II $\lambda 3858$ triplet obtained at Mount Stromlo. Hiltner et al. (1969) noted strong optical Si II lines that appeared peculiar: the MSO high-dispersion optical spectra show narrow lines of the Si II $\lambda 3858$ triplet and Si II $\lambda 4130$ doublet in the H δ –H9 spectral range. Surprisingly, the shape of the Si II lines varies with time and, synchronized with H α emission, appeared to split during the April 24 observation. The lines appeared normal on April 25, and the equivalent width measurement of Si II $\lambda 4128.067$, $W = 157$ mÅ, translates into an abundance between $\log(\text{Si}/\text{H}) = -4.1$ ($\xi = 0$ km s^{−1}) and $\log(\text{Si}/\text{H}) = -4.8$ ($\xi = 6$ km s^{−1}) using Becker & Butler's (1990) non-LTE equivalent width calculations. Depending on the exact value of the microturbulence velocity, ξ , the Si abundance would be above or below the solar abundance [$\log(\text{Si}/\text{H}) = -4.5$], but it remains comparable to other silicon abundance measurements in B stars (see a compilation in Adelman, Robinson, & Wahlgren 1993). We note that Be stars are not known to show Si II emission lines.

Table 2 presents our radial velocity measurements probing timescales of hours, days, and months. The average radial velocity is $\langle v_{\text{rad}} \rangle = 24.9$ km s^{−1} with a standard deviation of only 1.4 km s^{−1} ($n = 18$). The value is in remarkable agreement with Campbell & Moore (1928) who measured $\langle v_{\text{rad}} \rangle = +26.0$ km s^{−1}, $\sigma(v_{\text{rad}}) = 6.3$ km s^{−1}. Therefore, the system shows no measurable radial velocity variations. On the other hand, the B star clearly displays variable line profiles on a timescale of

TABLE 1
EUV AND SOFT X-RAY MEASUREMENTS OF HR 2875

<i>EUVE</i> ^a		<i>ROSAT</i> WFC ^b		<i>ROSAT</i> PSPC ^c	
Survey 100 Å	DS 100 Å	S1	S2	PSPC	HRI
0.094 ± 0.012	0.199 ± 0.016	0.061 ± 0.014	0.108 ± 0.016	0.50 ± 0.05	−1.00 ± 0.02

^a *EUVE* all-sky survey observations in the Lexan bandpass (Survey 100 Å) and Guest Observer pointed observation using Deep Survey instrument and the Lexan bandpass (DS 100 Å).

^b *ROSAT* WFC all-sky survey observations at 90 (S1) and 160 (S2) Å.

^c *ROSAT* PSPC hardness ratio defined as $HRI = (B - A)/(B + A)$, where A is the count rate between 0.11 and 0.41 keV and B is the count rate between 0.52 and 2.01 keV.

FIG. 3.—Coudé spectra of the B star HR 2875 showing emission reversals occurring on 1997 April 24 in the cores of H α , He I λ 6678.15 (*bottom*), and the Si II λ 3858 triplet lines (*top*). We divided the H α spectra obtained on April 24 with the spectrum obtained on April 25 and plotted the resulting emission features.

1 day, which may be linked to the presence of a white dwarf companion. We note that Buscombe & Morris (1958) report large radial velocity variations in four measurements (extrema: -5 and $+40$ km s $^{-1}$); their data may have been affected by variations in the line shape (Fig. 3), which, until now, were unnoticed. Future observations should be aimed at establishing a periodicity for these variations.

3.2. The White Dwarf

Because the B star dominates the optical and far-ultraviolet (FUV) spectral range, we must then determine the solid angle subtended by the white dwarf, assuming a distance and a radius for the compact object. Fortunately, the distance to the B star is known (164–196 pc), and the white dwarf radius is strictly a function of age and stellar mass, which are easily converted into effective temperature and surface gravity measurements adopting the evolutionary mass-radius relations of Wood (1995):

$$R_{WD} = f(\text{Age}, M) = f(T_{\text{eff}}, g). \quad (1)$$

Figure 4 shows an analysis of the *ROSAT*/*EUVE* data in the $(T_{\text{eff}}, \log g, \log n_{\text{HI}})$ parameter space, where n_{HI} is the neutral hydrogen column density in the local interstellar medium (ISM), adopting pure hydrogen model atmospheres. Likelihood contours at 66% (1 σ), 90%, and 99% are projected in the $(T_{\text{eff}}, \log g)$ and $(T_{\text{eff}}, \log n_{\text{HI}})$ planes. Assuming a surface gravity in the range $7.0 \leq \log g \leq 9.5$, the photometric data alone constrain well the white dwarf parameters:

$$\begin{aligned} T_{\text{eff}} &= 34.0\text{--}52.5 \times 10^3 \text{ K}, \\ n_{\text{HI}} &= 0.8\text{--}4.0 \times 10^{19} \text{ cm}^{-2}. \end{aligned} \quad (2)$$

Restricting the surface gravity to a range corresponding to a

TABLE 2
LICK AND STROMLO RADIAL VELOCITY
MEASUREMENTS

HJD 2,450,000+	v (km s $^{-1}$)	Lines Measured
456.8639	...	Emission cores
456.8764	...	Emission cores
456.8884	...	Emission cores
457.8663	+26.3	H α
457.8783	+27.2	H α
457.9283	+26.6	H α
458.9146	+24.1	H α
458.9284	+24.1	H α
459.8189	+23.6	H α
459.8871	+23.9	H α
459.9531	+25.1	H α
485.7201	...	Emission cores
485.7530	...	Emission cores
485.7785	...	Emission cores
485.8027	...	Emission cores
485.8242	...	Emission cores
488.7189	+25.1	H α
488.7415	+25.0	H α
488.7642	+25.0	H α
488.7867	+26.3	H α
488.8100	+26.7	H α
519.6968	+22.5	H α
519.7140	+22.9	H α
519.7365	+22.9	H α
562.8771	...	Emission cores
562.8884	...	Emission cores
562.9098	...	Emission cores
562.9611	...	Emission cores
563.8671	+26.0	H γ –H8, Si II
563.9104	+25.0	H α

massive white dwarf, i.e., $9.0 \leq \log g \leq 9.5$, we then find that

$$\begin{aligned} T_{\text{eff}} &= 42.0\text{--}52.5 \times 10^3 \text{ K}, \\ n_{\text{HI}} &= 0.8\text{--}3.0 \times 10^{19} \text{ cm}^{-2}. \end{aligned} \quad (3)$$

FIG. 4.—Model atmosphere analysis of the *EUVE* photometric and spectroscopic data and *ROSAT* WFC photometric data in the $(T_{\text{eff}}, g, n_{\text{HI}})$ parameter space (*bottom*). Solutions to the photometric (*dashed lines*) and spectroscopic (*solid lines*) analyses are shown with 66%, 90%, and 99% confidence contours in the $(T_{\text{eff}}, \log g)$ plane (*bottom right*) and in the $(T_{\text{eff}}, \log n_{\text{HI}})$ plane (*bottom left*). The models are assumed pure in hydrogen and are normalized to a distance of 177 pc and theoretical white dwarf radii (Wood 1995). The best model atmosphere fit is presented with the *EUVE* spectrum (*top*).

The assumption of a pure hydrogen composition for the atmosphere of the white dwarf is debatable, considering the relatively high effective temperature range deduced for the star. Recent *ROSAT* soft X-ray and EUV measurements (see Wolff, Jordan, & Koester 1996; Barstow et al. 1993) confirm the prevalence of trace heavy elements among DA white dwarfs with $T_{\text{eff}} \geq 40,000$ K. The low signal-to-noise ratio achieved during the EUV spectroscopic observation does not allow us to ascertain the presence of heavy elements in the atmosphere of the white dwarf (Fig. 3).

Figure 4 also shows an analysis of the *EUVE* spectroscopic data. The range of solutions obtained is consistent with the analysis of photometric data:

$$\begin{aligned} T_{\text{eff}} &= 34.5\text{--}52.0 \times 10^3 \text{ K}, \\ n_{\text{H I}} &= 1.8\text{--}5.0 \times 10^{19} \text{ cm}^{-2}, \end{aligned} \quad (4)$$

again assuming that $7.0 \leq \log g \leq 9.5$. Fixing the surface gravity at $\log g = 8.0$ and $\log g = 9.0$, the effective temperature is in the ranges

$$\begin{aligned} T_{\text{eff}} &= 37.0\text{--}40.0 \times 10^3 \text{ K} (M_{\text{WD}} \approx 0.7 M_{\odot}), \\ T_{\text{eff}} &= 42.5\text{--}46.5 \times 10^3 \text{ K} (M_{\text{WD}} \approx 1.2 M_{\odot}), \end{aligned} \quad (5)$$

respectively. Following the same procedure, the *ROSAT* PSPC spectrum corresponds to almost identical effective temperature ranges:

$$\begin{aligned} T_{\text{eff}} &= 37.5\text{--}43.0 \times 10^3 \text{ K} (M_{\text{WD}} \approx 0.7 M_{\odot}), \\ T_{\text{eff}} &= 41.8\text{--}47.0 \times 10^3 \text{ K} (M_{\text{WD}} \approx 1.2 M_{\odot}). \end{aligned} \quad (6)$$

The H I column density in the local ISM is limited to $n_{\text{H I}} \leq 5.6 \times 10^{19} \text{ cm}^{-2}$ ($\log g = 8$ models) and $n_{\text{H I}} \leq 3.4 \times 10^{19} \text{ cm}^{-2}$ ($\log g = 9$ models), in agreement with the EUV data. These ranges of effective temperatures, for either masses, are generally characterized by a low heavy element abundance (Z) in white dwarf atmospheres. However, should the white dwarf possess a mass in excess of $1.2 M_{\odot}$ and resemble the massive DA white dwarf GD 50 ($T_{\text{eff}} = 43,000$ K, $\log g = 9.2$; Vennes et al. 1997), it may then share also its large helium

abundance ($Y = 2.4 \times 10^{-4}$; Vennes, Bowyer, & Dupuis 1996). So far, the spectroscopic properties of GD 50 appear unique among hot white dwarf stars, but they may also be a common characteristic of massive white dwarfs.

4. SUMMARY

In summary, we find that a hot DA white dwarf with atmospheric parameters representative of the EUV-selected population of white dwarf stars (Vennes et al. 1997) provides an excellent interpretation of the EUV and soft X-ray observations of the B star HR 2875. The atmospheric parameters (T_{eff} , g , Y , Z) remain uncertain; additional EUV soft X-ray observations are needed to characterize the white dwarf fully. The B star itself is peculiar, showing variable H I, He I, and Si II line profiles with unknown periodicity, and it is now found to hide a white dwarf companion. The proximity of the B star and the white dwarf ($\leq 5''$), source of the EUV/soft X-ray emission, rules out a chance alignment and imposes a physical association.

The association of a white dwarf with a B5 V star extends the mass of main-sequence stars known to evolve through the asymptotic giant branch to at least $6 M_{\odot}$. It is usually believed such objects could be as massive as $8 M_{\odot}$. Nomoto (1984) extended this range to 8–11 $M_{\odot}$ main-sequence stars, possible progenitors of massive O-Ne-Mg white dwarfs. It is therefore critical to determine the surface gravity, and hence the mass, of the white dwarf in HR 2875. Such a measurement will be possible with the spectrometers on board the *Advanced X-Ray Astrophysics Facility* (AXAF) using the extreme sensitivity of the soft X-ray continuum of hot DA white dwarfs to surface gravity (Vennes 1992).

The peculiarity of the B star will be investigated further at MSO, with the particular aim of determining strict periodicity for the line variations. Emission features in the B-star spectrum raise the possibility of interaction, irradiation or mass exchange, between the binary components.

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REFERENCES

- Adelman, S. J., Robinson, R. D., & Wahlgren, G. M. 1993, *PASP*, 105, 327
 Barstow, M. A., et al. 1993, *MNRAS*, 264, 16
 Becker, S. R., & Butler, K. 1990, *A&AS*, 84, 95
 Berghöfer, T. W., Schmitt, J. H. M. M., & Cassinelli, J. P. 1996, *A&AS*, 118, 481
 Berghöfer, T. W., Schmitt, J. H. M. M., Danner, R., & Cassinelli, J. P. 1997, *A&A*, 322, 167
 Blöcker, T. 1995, *A&A*, 297, 727
 Bowyer, S., Lampton, M., Lewis, J., Wu, X., Jelinsky, P., & Malina, R. F. 1996, *ApJS*, 102, 129
 Buscombe, W., & Morris, P. M. 1958, *MNRAS*, 118, 609
 Campbell, W. W., & Moore, J. H. 1928, *Pub. Lick Obs.*, 16, 113
 Hiltner, W. A., Garrison, R. F., & Schild, R. E. 1969, *ApJ*, 157, 313
 Jordan, S., Wolff, B., Koester, D., & Napiwotzki, R. 1994, *A&A*, 290, 834
 Motch, C., Haberl, F., Dennerl, K., Pakull, M., & Janot-Pacheco, E. 1997, *A&A*, 323, 853
 Nomoto, K. 1984, *ApJ*, 277, 791
 Pye, J. P., et al. 1995, *MNRAS*, 274, 1165
 Vassiliadis, E., & Wood, P. R. 1993, *ApJ*, 413, 641
 Vennes, S. 1992, *ApJ*, 390, 590
 Vennes, S., Bowyer, S., & Dupuis, J. 1996, *ApJ*, 461, L103
 Vennes, S., Thejll, P., Génova-Galván, R., & Dupuis, J. 1997, *ApJ*, 480, 714
 Voges, W., et al. 1997, *A&A*, in press
 Wagenhuber, J., & Weiss, A. 1994, *A&A*, 290, 807
 Wolff, B., Jordan, S., & Koester, D. 1996, *A&A*, 307, 149
 Wood, M. A. 1995, in *White Dwarfs*, ed. D. Koester & K. Werner (Berlin: Springer), 41