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DO ALL BARIUM STARS HAVE A WHITE DWARF COMPANION?

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ABSTRACT

International Ultraviolet Explorer short-wavelength, low-dispersion spectra were analyzed for four barium, two mild barium, and one R-type carbon star in order to test the hypothesis that the barium and related giants are produced by mass transfer from a companion now present as a white dwarf.

An earlier tentative identification of a white dwarf companion to the mild barium star ζ Cyg is confirmed. For the other stars, no ultraviolet excess attributable to a white dwarf is seen. Limits are set on the bolometric magnitude and age of a possible white dwarf companion.

Since the barium stars do not have obvious progenitors among main-sequence and subgiant stars, mass transfer must be presumed to occur when the mass-gaining star is already on the giant branch. This restriction, and the white dwarf's minimum age, $t_{\rm WD} > 8 \times 10^8$ yr, determined for several stars, effectively eliminates the hypothesis that mass transfer from an asymptotic giant branch star creates a barium star. Speculations are presented on alternative methods of producing a barium star in a binary system.

Subject headings: stars: Ba II — stars: binaries — stars: evolution — stars: white dwarfs

I. INTRODUCTION

The origin of the classical Ba II giants first isolated as a class of peculiar G and K giants by Bidelman and Keenan (1951) remains obscure. A Ba II giant's outstanding spectroscopic characteristics include an overabundance of carbon by a factor of 2–3 and an *s*-process overabundance of up to a factor of about 10 (Warner 1965; Tomkin and Lambert 1979, 1983). The typical Ba II giant has a luminosity $M_{\rm bol} \sim 0$, i.e., a luminosity class III. A few more luminous Ba II stars are known of which ζ Cap may be considered the prototype with $M_{\rm bol} \sim -3.7$ (Scalo 1976).

Other peculiar giants suggest themselves as relatives of the Ba II stars. The mild Ba II stars are giants in which modest *s*-process overabundances are unaccompanied by a carbon overabundance (Sneden, Lambert, and Pilachowski 1981). The warm carbon stars of types R0 to R4 have carbon abundances similar to those of the Ba II stars but lack the characteristic *s*-process enhancement (Greene *et al.* 1973; Dominy 1982). The CH subgiants lying between the main sequence and the giant branch show both the C and *s*-process overabundances and so are putative progenitors of the Ba II stars (Bond 1974; Luck and Bond 1982).

In this paper, we describe a search for white dwarf companions to a few of the nearest Ba II giants, mild Ba stars, and one R star. Our search with the low-dispersion, short-wavelength spectrograph of the *International Ultraviolet Explorer* (*IUE*) satellite was prompted by McClure, Fletcher, and Nemec's (1980) announcement that all the classical Ba II giants are spectroscopic binaries. Their radial velocity survey further suggested that the mild barium stars were not binaries. R-type stars and CH subgiants were not observed by McClure *et al.* As the discoverers recognized, a spectroscopic binary opens up a link to the theoretical studies of the evolution of intermediate-mass stars. For these stars, it is predicted that thermal pulses on the asymptotic giant branch (AGB) dredge up carbon and *s*-process elements (Iben 1975*a*, *b*; Truran and Iben 1977). The luminosity class III Ba II giants are demonstrably not intermediate-mass (3–8 $M_\odot$) stars on their AGB, but their companions may have been. In this scenario, preferred by McClure *et al.*, the original primary evolved to the AGB where it experienced thermal pulses that polluted its outer envelope with C and *s*-process elements. A portion of this envelope was dumped onto the secondary in the terminal phase of an AGB star that converts the giant to a planetary nebula with a central star that today should be a faint white dwarf. Our search for the predicted white dwarf is described here.

Mass transfer within a binary as the key to barium stars received a boost when Böhm-Vitense (1980) discovered white dwarf companions to ζ Cap, the prototype of the more luminous barium stars, and to the mild barium star ζ Cyg. Later, Schindler *et al.* (1982) identified a white dwarf accompanying a mild barium star 56 Peg (Warren and Williams 1970).

II. OBSERVATIONS

The contrast between a G or K giant and a white dwarf companion is greatest in the wavelength interval spanned by the short-wavelength, low-dispersion camera

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[1] Guest Observer with the *International Ultraviolet Explorer* satellite.

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TABLE 1

IUE OBSERVATIONS OF BARIUM AND OTHER PECULIAR RED GIANTS

Star	Class	*IUE*	Exp. Time (minutes)	Flux[a] f_{obs}
HR 2392	barium	SWP 8231	240	5.5×10^{-13}
HR 3123/12 Pup	barium	SWP 7321	222	1.2×10^{-12}
HR 4862	barium	SWP 15088	325	6.3×10^{-13}
HR 5058	barium	SWP 7320	240	4.2×10^{-13}
HR 5802/16 Ser	mild barium	SWP 13925	225	6.6×10^{-13}
HD 156074	R	SWP 15087	480	1.1×10^{-13}
HR 8115/ζ Cyg	mild barium	SWP 15090	290	7.4×10^{-12}

[a] The flux f_{obs} is the integrated flux across the interval from 1325 to 1625 Å. For ζ Cyg, the giant makes a contribution to f_{obs} (see Fig. 1).

on the *IUE* satellite. Exposures considered here are listed in Table 1. Images SWP 7320, 7321, and 8231 were obtained by Dr. E. Böhm-Vitense, and provided to us by the National Space Science Data Center.

With the exception of ζ Cyg, a very mild barium star, our search for white dwarf companions was fruitless. Our deeper exposure of ζ Cyg confirms an earlier tentative identification of a white dwarf (Böhm-Vitense 1980). In Figure 1 we show our spectra of ζ Cyg and HR 4862. Our spectra provide interesting upper limits on the luminosity of a white dwarf companion and, hence, constraints on the mass-transfer origin for barium stars.

III. ANALYSIS

Our analysis utilizes the flux-calibrated spectra provided on magnetic tape from the Goddard Space Flight Center. With the exception of ζ Cyg, the spectra do not show an ultraviolet flux excess attributable to a white dwarf. For the extraction of an upper limit to the luminosity of a white dwarf companion, we decided to compare the observed flux in a broad bandpass with the flux predictions for a set of white dwarf model atmospheres. The chosen bandpass, which runs from 1325 to 1625 Å, avoids the chromospheric lines of O I at 1304 Å and He II at 1640 Å. In all stars except ζ Cyg, the giant's contribution to the spectrum is not

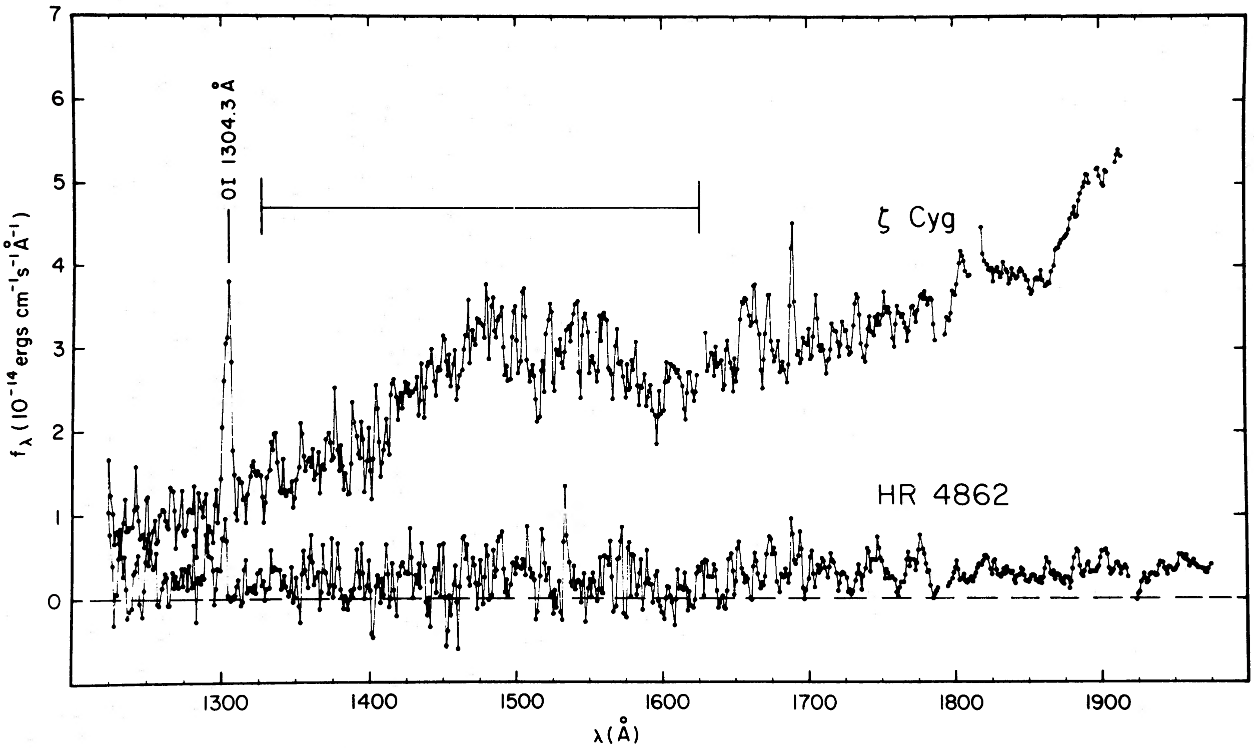

FIG. 1.—Spectra of ζ Cyg and HR 4862 (HD 111315) obtained during the same *IUE* shift. The white dwarf's flux in the spectrum of ζ Cyg is evident between 1400 and 1600 Å. The chromospheric O I triplet of multiplet UV 2 is evident in both spectra. The "UV" bandpass 1325–1625 Å used in the analysis has been indicated.

detectable at wavelengths shorter than about 1700 Å. No correction was made for chromospheric emission lines in the chosen bandpass because no certain identifications could be established on these noisy spectra. Since we use the observed flux without a correction for the contributions from the chromosphere of the giant star and the scattered light within the spectrograph, our fluxes are firm upper limits (Table 1) to a contribution from a white dwarf.

The conversion of these flux limits to a limit on the bolometric luminosity of a white dwarf requires predicted ultraviolet fluxes for white dwarfs of different effective temperature and a distance estimate for the barium star. Predicted fluxes were kindly supplied by Shipman (1982) for models with a pure hydrogen atmosphere (Shipman 1977; Shipman and Sass 1980). The models span the effective temperature range from 4000 to 16,000 K at a surface gravity $\log g = 8$. The atmospheric composition is not critical to our analysis. Since the giant is probably losing mass through a wind, a white dwarf would most probably accrete a thin hydrogen-rich skin around its carbon or helium core. The total flux estimates are based on a 0.75 $M_\odot$ white dwarf with a radius $R = 0.0103\ R_\odot$ taken from the mass-radius relation for white dwarfs with a carbon core (Hamada and Salpeter 1961). The adopted mass is the mean mass for nearby white dwarfs (Shipman and Sass 1980). The fraction of the total flux emitted in the selected ultraviolet bandpass is not very sensitive to the surface gravity, and, therefore, we may neglect the slight inconsistency between the surface gravity of the representative white dwarf ($\log g = 8.24$) and the $\log g = 8$ of the model atmosphere.

If the integrated flux for the ultraviolet bandpass is $f_{\rm uv}^{\rm obs}$ (in ergs cm^{-2} s^{-1}), the apparent bolometric magnitude of the white dwarf is

$$m_{\rm bol} = -11.49 - 2.51 \log (C f_{\rm uv}^{\rm obs}) ,$$

where the solar constant and bolometric magnitude are taken from Allen (1973), and the total-to-ultraviolet ratio from the model,

$$C = \sigma T_{\rm eff}^4 / f_{\rm uv}^{\rm model} ,$$

is computed from the predicted fluxes. Conversion of the apparent to an absolute bolometric magnitude requires an estimated distance.

Of the several indicators of the absolute magnitude, we give highest weight to the Wilson-Bappu effect using the Ca II K line width. Wilson's (1976) catalog includes three of our stars: HR 5058 with $M_v = +1.5$, HR 5802 with $M_v = +1.6$, and ζ Cyg with $M_v = +1.1$. Both HR 5802 and ζ Cyg have a measured trigonometrical parallax of marginal significance (Hoffleit 1982) in rough agreement with the K line estimates. HR 5802 with $\pi = +0''.030 \pm 0.007$ or $M_v = 2.6 \pm 0.5$ and ζ Cyg with $\pi = 0''.021 \pm 0.007$ or $M_v = -0.2 \pm 0.8$. The parallax $\pi = +0''.006 \pm 0.012$ for HR 5058 allows a lower limit $M_v < 1.4$ which is just consistent with the K line magnitude. For a nearby binary (e.g., ζ Cyg), the dynamical parallax may rival the trigonometrical parallax. When the latter is derived from observations over a short interval, a systematic error may result. Our analysis of the ζ Cyg binary shows that the adopted K line M_v leads to a normal white dwarf (Fig. 2). This is evidence that the K line is normal for barium giants in a binary.

For the three remaining barium stars, neither the K line width nor the trigonometrical parallax is available. The null measurement $\pi = -0''.008 \pm 0.009$ for HR 3123 does suggest that this star is rather more luminous than either HR 5058 or HR 5802. The spectral classification supports this suggestion. Kemper (1975) exploited the Hα line width as a luminosity indicator. This technique appears to be valid in a statistical sense, but absolute magnitude estimates for individual stars are subject to a large uncertainty. For ζ Cyg, Kemper gives $M_v = +2.9$ which is surely too faint for a luminosity class III–IIIa star. Kemper's estimates for HR 2392 and HR 3123 are $M_v = +0.5$ and -2.6 respectively. Our M_v estimate for HR 4862 is obtained from the luminosity classification. The adopted M_v values are given in Table 2.

The estimate of M_v for HD 156074 ($m_v = 7.61$, $m_{\rm bol} = 7.18$) is the mean of two direct and two indirect methods (Table 3). The direct methods are the Wilson-

TABLE 2

THE LIMITING BOLOMETRIC MAGNITUDE AND AGE OF THE WHITE DWARF COMPANIONS

				GIANT		WHITE DWARF	
STAR	CLASS	SP. TYPE	V	M_v[a]	Source	$M_{\rm bol}$	Age (10^8 yr)
HR 2392	barium	K0 III: Ba 3	6.27	+0.5	Hα	>11.2	>5
HR 3123/12 Pup	barium	cK 2	5.10	−2.6	Hα	>9.0	>1
HR 4862	barium	G8 Ib–II	5.54	−2.5	Sp	>9.4	>1
HR 5058	barium	K0.5 III: Ba 3	5.09	+1.5	K	>12.2	>9
HR 5802/16 Ser	mild barium	K0 III: CN 1 Ba 0.7 Sr 2	5.26	+1.6	K	>11.8	>7
HD 156074	R		7.60	+1.0	K	>11.5	>6
HR 8115/ζ Cyg	mild barium	G8 + III–IIIa Ba 0.6	3.19	+1.1	K	11.5[b]	6

[a] The three sources of M_v are: K = Wilson-Bappu effect from Wilson (1976); Hα = Hα line width—see Kemper (1975); Sp = luminosity classification.

[b] Computed from $T_{\rm eff} \approx 12{,}000$ K and $R/R_\odot = 0.010$.

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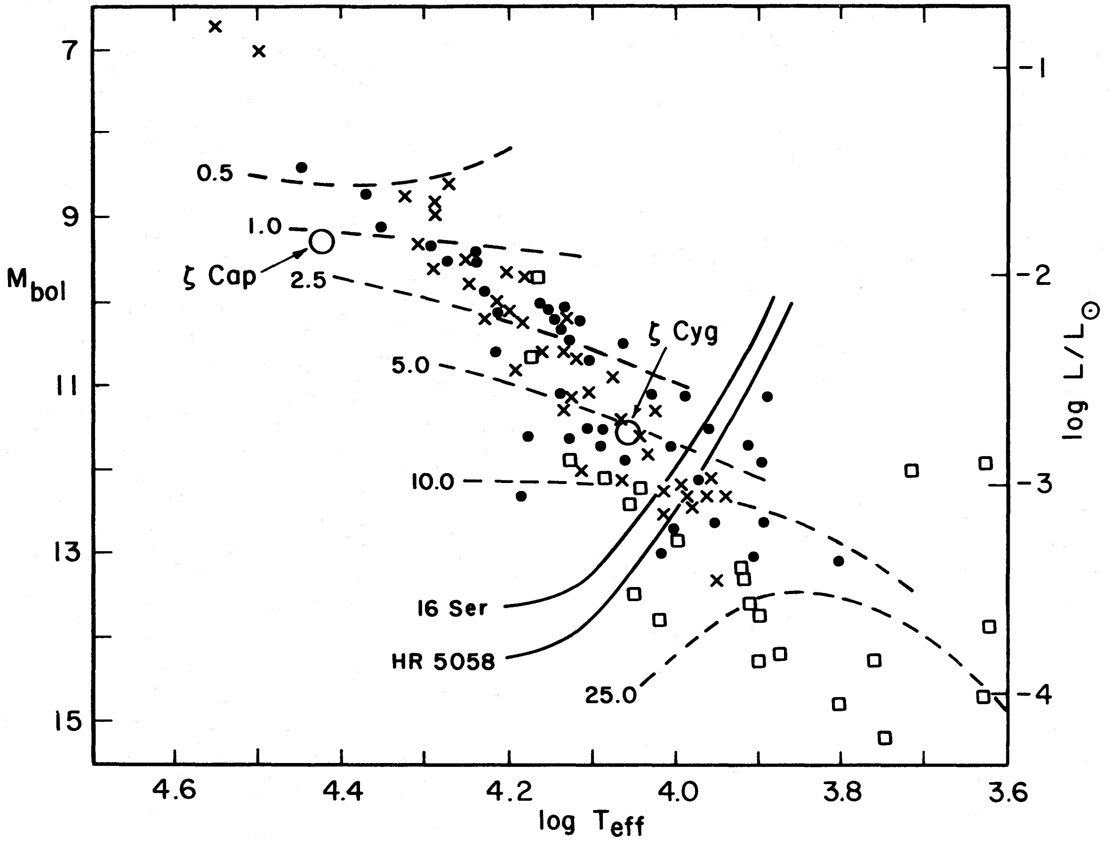

FIG. 2.—A Hertzsprung-Russell diagram adapted from Weidemann (1968). Nearby field white dwarfs are shown: spectral type DA with known distance (*filled circle*), spectral type DA with spectroscopic distance (*cross*), and white dwarfs of other spectral types (*open square*). Lines of constant cooling time for carbon-interior dwarfs, with $Y = 0.999$, $Z = 0.001$ outer layers, are represented by the broken lines and are labeled in units of 10^8 yr. The white dwarf companions to ζ Cap and ζ Cyg are identified (Sweeney 1976). The limiting M_{bol} versus log T_{eff} loci for white dwarf companions to HR 5058 (barium star) and HR 5802/16 Ser (mild barium star) are shown.

Bappu K line magnitude ($M_v = +0.9 \pm 1.3$) found by Gordon (1968) and the assignment of $M_{bol} = +0.8$ by Eggen (1971, 1972) based on the assumed membership of this star in the Wolf 630 moving group (Eggen 1969). The two indirect methods include the use of the derived mean absolute magnitudes for the classical early R stars and a spectroscopic determination of surface gravity. For $\langle M_v \rangle = 0.44 \pm 0.29$ (Vandervort 1958; Gordon 1968; Scalo 1976), a distance modulus $m_v - \langle M_v \rangle = 7.2$ is derived. Baumert (1974) finds the mean absolute magnitude in the narrow 1.04 μm photometric band to be -0.8 ± 1.0 for nonvariable R0–R4 stars. With $I(104) = 6.09$ for HD 156074 (Baumert 1972), a distance modulus of 6.9 is found. Greene *et al.* (1973) find that for HD 156074 $T_{eff} = 4750$ from a calibration of $V - r$ and broadband photometry with effective temperature and log $g = 2.05$ from the ionization equilibrium of iron. From these values, $M_{bol} = -0.6$ is obtained for an assumed mass of $1.2\ \mathcal{M}_\odot$. We adopt $M_v = +1.0$.

TABLE 3

THE ABSOLUTE VISUAL MAGNITUDE OF HD 156074

Method	$m - M$	M_v
K line width	6.71	$+0.9 \pm 1.3$
Wolf 630 membership	6.4	+1.0
$\langle M_v \rangle = +0.44 \pm 0.29$	7.17	+0.44
$\langle M_{1.04\,\mu m} \rangle = -0.8 \pm 1.0$	6.89	+0.72
$T_{eff} = 4750$, log $g = 2.05$, $\mathcal{M} = 1.2\ \mathcal{M}_\odot$	7.75	−0.14
Adopted	...	+1.0

In all cases, the distance is the major source of uncertainty in setting an upper limit to the bolometric magnitude of a possible white dwarf companion. Adjustments to the adopted M_v result in a parallel adjustment to the limiting M_{bol} of the white dwarf. The M_v values in Table 2 have not been corrected for interstellar or circumstellar reddening. Reddening also reduces the flux f_{uv}^{obs}. If the visual absorption is A_v, the net correction to M_{bol} of the white dwarf is approximately $2A_v$. With the mean galactic absorption $A_v = 1.9$ mag kpc^{-1} (Allen 1973), the M_{bol} corrections are just 0.2 mag for HR 5058 and HR 5802 which provide the tightest constraint on the white dwarf's

$M_{\rm bol}$. The R stars appear to show an infrared excess (Mendoza 1968; Mendoza and Johnson 1965) which may be indicative of circumstellar dust and, hence, of a nonnegligible ultraviolet circumstellar opacity.

Since we have no *a priori* information on the white dwarf's effective temperature, our analysis converts the observed $f_{\rm uv}^{\rm obs}$ to a locus in the plane $M_{\rm bol}$ *versus* $T_{\rm eff}$, defining the maximum luminosity of a white dwarf companion (see Fig. 2). On the Hertzsprung-Russell diagram (Fig. 2), we include field white dwarfs for which Weidemann (1968) provides the basic data.

The predicted cooling times would not appear to be a significant source of uncertainty affecting our lower limits to the white dwarf's age. If the surface composition $Y = 0.98$ and $Z = 0.02$ is preferred, the age limits are increased by about 0.2 Gyr for the three highest age limits. Sweeney's (1976) calculations differ only slightly from earlier ones; e.g., Koester's (1972) calculations would decrease the three limits by about 0.2 Gyr. The major theoretical uncertainties impact cooling time estimates for the coolest white dwarfs with ages in excess of about 2 Gyr. Currently, our best limits are near 1 Gyr and, thus, are little affected by these uncertainties.

The white dwarfs accompanying ζ Cap and ζ Cyg are identified; $M_{\rm bol}$ and $T_{\rm eff}$ for this pair are taken from Böhm-Vitense (1980) and this paper respectively. For ζ Cyg, we estimate $T_{\rm eff} = 12{,}000$ K, but the predicted spectrum is not an especially good fit to the observed spectrum. We attribute this to the omission from the model atmosphere calculations of the ionization edges and lines provided by the metals. The possibility remains that the ultraviolet excess is a feature of the giant's chromospheric spectrum and not the signature of a white dwarf. Figure 2 does not include 56 Peg B because, with the effective temperature and radius derived by Schindler *et al.* (1982), its bolometric magnitude, $M_{\rm bol} = +4.4$, places it far above the white dwarf sequence. In the Appendix, we suggest that the ultraviolet excess is provided by an accretion disk around a white dwarf.

Sample loci defining the maximum allowed luminosity of a white dwarf companion are shown; we list in Table 2 limiting values of $M_{\rm bol}$ and the cooling time corresponding to the locus at the midpoint in the distribution of field white dwarfs. Loci of constant cooling time for white dwarfs with a carbon interior and a surface composition $Y = 0.999$ and $Z = 0.001$ are taken from Sweeney (1976). (In rare cases, the white dwarf could be present but eclipsed by the giant during the observation.)

IV. BARIUM STARS AND BINARIES

McClure, Fletcher, and Nemec's (1980) radial velocity study of classical barium and mild barium stars and of a control sample of similar giants of normal composition provided two results: (i) the classical barium stars, which were defined by McClure *et al.* to belong to Warner's (1965) classes Ba 2 to 5, all belong to binary systems; (ii) the mild barium stars, as defined by Warner's class Ba 1, do not appear to have a physical companion. McClure (1982) discusses an expanded survey of classical barium stars, finding that 17 of the 20 stars show velocity variations indicative of orbital motion. This survey answers recent objections (Culver and Ianna 1980) to the earlier conclusion. McClure *et al.* noted that "it is not unreasonable to conclude that Ba II stars are all binaries with low-mass secondaries consisting of degenerate objects." While the statistics of the radial velocity variations seem consistent with the identification of Ba II stars with binary systems, *no* evidence was provided to support the assertion that the secondaries are degenerate objects. That assertion was rooted in the idea that mass transfer of nuclear processed material from a more massive star leads to the conversion of a normal companion to a barium star with the mass-losing star now present as a white dwarf or a neutron star. Furthermore, Griffin (1982) notes that mild barium stars "mostly seem to be binaries" according to his continuing investigations of the radial velocities of giants. We shall generally merge the mild and classical barium stars and speak of "barium stars."[2]

White dwarf companions have been found for ζ Cap, ζ Cyg, and 56 Peg. Zeta Cap is an accredited barium star. Zeta Cyg and 56 Peg are labeled "mild" barium stars. Brown, Tomkin, and Lambert (1983) found a Zr enhancement of 0.4 dex for ζ Cyg as a result of a comparison of Zr I and Ti I lines. Sneden, Lambert, and Pilachowski (1981) reported a lower *s*-process overabundance. Identification of 56 Peg as a mild barium star was proposed by Warren and Williams (1970) from narrow-band photometric measurements of the Ba II 6142 Å line. Strömgren four-color photometry (Pilachowski 1978) further suggests that it is a mild barium star. Our one reservation about this appellation arises because Warren (1970) also identified ϵ Peg as a mild barium star, but Hyland and Mould's (1974) spectroscopic abundance analysis failed to confirm this identification. When judged by the narrowband Ba index, ϵ Peg has a higher Ba overabundance than 56 Peg. Until a spectroscopic analysis is available, we tentatively accept 56 Peg as a mild barium star. Although these three stars may be cases where mass transfer from a companion has led to a barium star, alternative rôles for the companion cannot be excluded. There remains the possibility that the white dwarf is just an innocent bystander.

Primitive clues to the origin of barium stars are provided by combining our search for white dwarfs with McClure's (1982) radial velocity survey. Orbital elements are available now for seven Ba II binaries. The

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[2] One speculation challenging the implicit assumption that the radial velocity variations are solely the result of orbital motions might be noted. Is it possible for the He-core flash in a *single* star to produce a barium star and to stimulate and maintain for about 10^8 years low-amplitude, long-period, nonradial pulsations that might be mistaken for orbital motion?

mean mass function is small: $\langle f(\mathcal{M})\rangle = 0.025$. The true $\langle f(\mathcal{M})\rangle$ is certainly even smaller because the current sample must be biased toward the shorter period and large-amplitude systems. With a Ba II star's mass $\mathcal{M} \sim 1.5\ \mathcal{M}_\odot$, $\langle f(\mathcal{M})\rangle$ provides a mass ratio $\alpha \sim 0.4$, and α is likely to decline as more systems are analyzed. Although the sample is small, the Ba II binaries do seem to show a remarkable deficiency of systems with $\alpha \sim 1$, which are a feature of many types of binaries. For example, Abt and Levy (1976) examined a sample of solar-type stars for companions reporting a fair fraction to have $\alpha \sim 1$. Trimble (1978), who compiled a distribution function for α from 900 spectroscopic binaries, found a bimodal function with a sharp peak near $\alpha \sim 0.95$, a deep minimum at $\alpha \sim 0.7$, and a second, broader peak at $\alpha \sim 0.25$. Mass ratio and the separation of the two stars show a rough correlation with the separation being largest for the small mass ratio systems.

The apparent lack of $\alpha \sim 1$ systems among the barium stars requires either that unevolved systems with $\alpha \sim 1$ do not produce barium stars or that these systems are converted to lower mass ratio binaries by mass loss or transfer before a barium star is created. We are uncomfortable with the former explanation because the $\alpha \sim 1$ systems generally have a smaller separation between components and, hence, might be expected to provide a larger "interaction" between the stars and so an enhanced probability of producing a barium star. Exploration of the latter explanation leads to some interesting conclusions.

Mass transfer is perhaps the most obvious "interaction" leading to the production of a barium star. We follow the development of a binary consisting of main-sequence stars A and B with $\mathcal{M}_{\rm A} = \mathcal{M}_{\rm B} + \Delta\mathcal{M}$, where $\Delta\mathcal{M} \lesssim 0.2\mathcal{M}_{\rm A}$ according to the shape of the $\alpha \sim 1$ peak in Trimble's (1978) distribution function. Star A evolves through He-core burning without *s*-process enhancements at the surface. On the AGB, thermal pulses occur, and freshly synthesized *s*-process (and other) elements are dredged to the surface, but this star is too luminous to be called a classical barium star; it is probably a carbon star. Severe mass loss ensues with a partial transfer to the unsuspecting companion. The primary survives as a white dwarf. Our assumption is that the atmosphere of the mass-gaining star *immediately* reflects the *s*-process overabundances. If, instead, the *s*-processed material were buried beneath a sheath of normal composition, the abundance anomalies would not be revealed until the companion became a red giant with a deep convective envelope. In the mass-losing red-giant companion to the future barium star, the *s*-process elements are probably enhanced throughout the envelope. The deeper layers which may be transferred last surely contain the highest enhancements. Direct transfer of mass to below the mass-gaining star's outer layers is improbable. Accretion of a layer of normal composition to hide the transferred mass seems unlikely. In short, our assumption is quite plausible. If the mass lost by the primary is that contained within its deep convective envelope, the mass ratio can be reduced from $\alpha \sim 1$ to $\alpha \sim 0.3$.

If the mass difference $\Delta\mathcal{M}$ exceeds a critical size, the mass-gaining companion may be on the main sequence just prior to mass transfer. On the reasonable assumption that the additional mass does not lead to a nearly instantaneous transition to the giant branch, the absence of barium main-sequence and subgiant stars provides a limit to $\Delta\mathcal{M}$. In short, we require that the companion have evolved to the base of the first red-giant branch prior to mass transfer. Then, the maximum cooling time available to the white dwarf is the time spent by the barium giant in ascending the giant branch and burning He in its core. This requirement translates into a stiff one on the mass ratio α. Our estimates are based upon published model sequences of low-mass stars (Iben 1965, 1967*a*, *b*; Faulkner and Cannon 1973; Sweigart and Gross 1976). For $\mathcal{M}_{\rm A} \sim 2.25\ \mathcal{M}_\odot$, $\Delta\mathcal{M} \lesssim 0.18\ \mathcal{M}_\odot$, or $\mathcal{M}_{\rm A} \gtrsim \mathcal{M}_{\rm B} \gtrsim 2.07\ \mathcal{M}_\odot$ is required ($\alpha \gtrsim 0.93$) and the cooling time is $t_{\rm WD} \lesssim 0.2$ Gyr; i.e., the white dwarf must be detectable. At $\mathcal{M}_{\rm A} \sim 1.25\ \mathcal{M}_\odot$, we find $\Delta\mathcal{M} \lesssim 0.02\ \mathcal{M}_\odot$ and $t_{\rm WD} \lesssim 0.7$ Gyr. Although this time is just compatible with the limits set by HR 5058 and 16 Ser, the required mass ratio $\alpha \gtrsim 0.98$ is exceedingly restrictive. In short, mass transfer ought to produce barium subgiants and main-sequence stars.[3] The subgiant CH stars (Bond 1974) have a chemical composition (Sneden and Bond 1976; Luck and Bond 1982) that identifies them as possible progenitors of the barium stars, but, as Luck and Bond (1982) stress, the confinement of the peculiar subgiants to a spectral type near G0 is difficult to explain with the binary hypothesis. An origin in terms of a drastic internal mixing seems more probable. Kollatschny (1980) reported a factor of 5 enhancement for barium and other *s*-process elements in the dwarf ϵ Indi. Confirmation of these anomalies is awaited with interest. Our conclusion is that the general lack of barium subgiants and main-sequence stars is a severe obstacle to the acceptance of mass transfer of *s*-process–enhanced material as the origin of the barium giant stars. Our arguments are strengthened when the unevolved binary has $\alpha \sim 0.3$.

The lack of the low-luminosity barium stars is most readily explained if the *s*-process enhancements are induced within a star as a result of conditions arising from its membership in a binary system. Our speculation focusses on the He-core flash in low-mass stars. This flash is a violent event that may result in processing and mixing (Cole and Deupree 1980; Deupree and Cole 1981*a*, *b*). The effect of a companion may be to produce the conditions needed to dredge *s*-processed material to the surface. The tidal forces would appear to be

[3] It might be argued that transfer of the processed material is more effective if the mass-receiving star is a giant of large radius. On the other hand, dwarfs lack the deep convective envelope of the giants and so would be unable to dilute the processed material and very large abundance anomalies might be expected from small amounts of transferred material. (The dwarf carbon star G77-61 may fit this description [Dahn *et al.* 1977].)

insignificant. A more likely possibility is that the distribution of angular momentum is affected. Calculations suggest that a rapidly spinning core may facilitate mixing out to the surface during the core flash (Mengel and Gross 1976). Primaries with a mass $\mathscr{M} \gtrsim 2.25\ \mathscr{M}_\odot$ do not experience a He-core flash but instead ignite He quiescently and so do not become barium stars. If the primary is a low-mass star, we might expect it to evolve to a barium star accompanied by a main-sequence star. In a few cases, the companion should also be evolved. Unless mass is lost at the core flash, these binary systems should have a mass ratio similar to that of the initial binary; i.e., this scheme does not transform a $\alpha \sim 1$ unevolved binary to a $\alpha \sim 0.3$ binary with a barium star. Furthermore, a main-sequence companion in an $\alpha \sim 1$ binary should be detectable on *IUE* spectra. Binaries with low mass ratios would result if the secondary experiences the He-core flash after the primary has ejected substantial mass and become a white dwarf. This requirement sets a loose constraint on the initial mass difference $\Delta\mathscr{M} = \mathscr{M}_A - \mathscr{M}_B$. Perhaps, the key issue to explain is why the secondary, not the primary, becomes the barium star in binaries with an initial mass ratio $\alpha \sim 1$. Our tentative assertion that the primary does not evolve to a barium star is based on the apparent absence of $\alpha \sim 1$ binaries with a barium star. It may be that large-scale mass transfer within the binary converts the secondary to a star with a non-standard structure that subsequently experiences an abnormal core flash and a conversion to a barium star. Perhaps, the key lies in the formation of the binary with the secondary acquiring a substantially different distribution of angular momentum in spite of the modest mass difference. Alternatively, the majority of the barium stars evolve from the binary systems with low mass ratios.

An alternative scenario incorporating mass transfer deserves a mention. Accreting white dwarfs are attracting attention as a site for the *s*-process (Fujimoto and Sugimoto 1979; Iben 1981). Mass ejection from the white dwarf following a shell flash could convert a companion to a barium star. The attractive features of this scenario are several:

1. In order to provide an adequate accretion rate, the companion must surely be a giant. Main-sequence stars lose mass too slowly to trigger shell flashes in the white dwarf. This requirement explains the absence of barium main-sequence stars and subgiants.

2. This model can produce massive barium stars (e.g., ζ Cap). Earlier models relying on the He-core flash in the barium star itself are constrained to produce barium stars with $\mathscr{M} \lesssim 2\ \mathscr{M}_\odot$. Since the mass loss rates from giants increase with luminosity, production of massive barium stars is more likely.

3. The association of barium stars with low-α binaries is a direct result of the model. In the earlier alternative, where the induced abnormal He-core flash produces a barium star, it is difficult to explain the absence of $\alpha \sim 1$ binaries and, also, to understand the occurrence of normal giants in $\alpha \sim 1$ short-period systems. This difficulty is removed with the prerequisite that the white dwarf initiate the *s*-processing.

The luminous barium star ζ Cap with an attendant white dwarf is possibly a case where the *s*-processing was performed on the white dwarf. The Nb abundance of ζ Cap hints at a recent production of *s*-process nuclei. Over a wide range in neutron density, the *s*-process chain bypasses ^{93}Nb, the sole stable nucleus of Nb, and ^{93}Nb is produced from unstable ^{93}Zr after cessation of *s*-processing. In a comprehensive analysis, Tech (1971) reported that the Nb enhancement was rather lower than that of adjacent elements. After a correction for the dilution by the envelope of unprocessed material, the Nb/*Y* ratio in the *s*-processed material is Nb/*Y* ~ 0.01 (see Tomkin and Lambert 1983 for a description of the correction procedure). The predicted ratio after complete decay of ^{93}Zr is Nb/*Y* ~ 0.2. The half-life of ^{93}Zr for low temperatures ($T \lesssim 2 \times 10^8$ K) is $\tau_{1/2} \sim 1.5 \times 10^6$ yr. The observed low Nb/*Y* ratio suggests that *s*-processing occurred quite recently. Technetium is the traditional monitor of recent and continuing *s*-processing. The upper limit on the Tc abundance in ζ Cap (Boesgaard and Fesen 1974) slightly exceeds the predicted abundance at the *s*-process site, and, hence, Tc cannot confirm the suggestion that *s*-processing has recently ceased. If the stellar wind provides a quasi-steady accretion rate, shell flashes on the white dwarf will occur repetitively. This scenario makes it a little easier to accept the low Nb/*Y* ratio and attendant conclusion.

One of the several potential problems must be mentioned. If the white dwarf experiences He shell flashes for an extended period, it will be heated, and, then, the model cannot be reconciled with the non-detection of white dwarf companions to HR 5058 and 16 Ser. Prior to the onset of accretion, the white dwarf will probably be cold. If mass transfer is a brief episode (e.g., a burst initiated by the He-core flash in the giant), nuclear energy generation on the white dwarf may be short-lived with little heating of the white dwarf.

The label "barium stars" covers such a wide range of objects, from luminous stars like ζ Cap through the classical giant Ba II and mild barium stars to the subgiant CH stars, that more than one origin may be suspected. Mass transfer may be the key to stars like ζ Cap. A He-core flash inducing extensive mixing seems more probable for the subgiant CH stars.

V. CONCLUDING REMARKS

Our series of *IUE* observations challenges the hypothesis that *all* barium stars are created by mass transfer when a companion evolves to the planetary nebula phase following contamination of its outer envelope with *s*-process elements and carbon through thermal pulses on the AGB. The hypothesis remains an attractive possibility for the luminous barium stars such as ζ Cap which has a white dwarf companion.

Additional observational tests are required to resolve critical questions such as: Are all barium stars of all types members of binary systems? Is the companion an evolved degenerate star or a main-sequence star? Are there normal giants with white dwarf companions?

An expanded radial velocity survey should define the proportion of barium and mild barium stars, R stars, CH subgiants, and normal giants that have a physical companion. The survey may also reveal systematic differences in the orbits of the different groups of barium stars. McClure, Fletcher, and Nemec's (1980) apparently premature announcement that mild barium stars do not have companions may possibly indicate that they belong to long-period systems.

A deeper ultraviolet survey for white dwarf companions must await the Space Telescope. There remains a few bright and nearby mild barium stars to which the *IUE* satellite should be exposed; for example, ϵ Aql (spectral type K1 III, CN 0.5, Ba 0.2, Keenan and Pitts 1980) is a single-lined spectroscopic binary (Griffin 1982) with $m_v = 4.0$ and $M_v = +1.2$ according to Wilson (1976) so that the limiting bolometric magnitude of a white dwarf companion is about 1 mag fainter than the limit set for HR 5058 and HR 5802. Omicron Vir, a proven mild barium star (Sneden, Lambert, and Pilachowski 1981), with $m_v - M_v = 2.8$ is another attractive target. If white dwarf companions are not found with the Space Telescope, the mass transfer idea will be in very severe trouble.

The barium stars may be binary systems in which the *s*-processing and carbon enrichment are induced by the companion. The companion may be a lower mass main-sequence star whose detection presents a stiff challenge. The large luminosity difference between the giant and its companion would seem to preclude detection of the companion's line spectrum even in spectra of a high signal-to-noise ratio. Spatial resolution of the giant and cool companion could be attempted with the Space Telescope. The problem is similar to that to be encountered in searches for planets around nearby stars. The angular separation between two stars in a circular orbit is

$$\phi(\text{arcsec}) \approx P^{2/3}(\mathscr{M}_1 + \mathscr{M}_2)^{1/3}/d\ ,$$

where the period is P(yr), the masses are $\mathscr{M}_1$ and $\mathscr{M}_2$ (in $\mathscr{M}_\odot$), and the distance d(pc). For $P = 4$ yr, $\mathscr{M}_1 + \mathscr{M}_2 = 2\ \mathscr{M}_\odot$ at $d = 50$ pc (e.g., HR 5058 and 16 Ser) and the angular separation is $\phi \sim 0''.06$. Thanks to the large luminosity difference between the stars, such a binary will be a unresolvable by the Space Telescope, but astrometric observations may show the orbital motion of the barium star. In rare cases, favorable combinations of long period and small distance may allow a partial resolution of the two stars. It seems most likely that the identity of the companion as a main-sequence star will be established indirectly when ultraviolet photometry of spectroscopy shows that it is not a white dwarf.

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APPENDIX

56 PEGASI—AN ACCRETION DISK?

The white dwarf companions of ζ Cap and ζ Cyg are representative of their class (see Fig. 2). 56 Peg B is a remarkable white dwarf. Schindler *et al.*'s (1982) derived parameters are $T_{\text{eff}} = 32{,}000 \pm 4000$ K and a radius $r_{\text{WD}} = (2.7 \pm 1.0) \times 10^9$ cm, which correspond to $M_{\text{bol}} = +4.4$ with a range $3.4 < M_{\text{bol}} < 6.0$ provided by appropriate temperature and radius limits. Although these M_{bol} estimates should be increased by $2.5 \log \pi = 1.2$ mag because Schindler *et al.*'s derivation of r_{WD} from the observed flux is in error, 56 Peg B remains a very luminous white dwarf. This fact led to a reconsideration of an accretion disk around a white dwarf as the principal source of the ultraviolet excess. Schindler *et al.*, who rejected the accretion disk hypothesis, apparently failed to recognize that 56 Peg B was a remarkably luminous white dwarf. However, Simon, Linsky, and Stencel (1982) do classify the secondary as sd0.

The ultraviolet excess, which is detectable from 1250 Å to about 2000 Å where it blends with the K giant's spectrum, is just fitted by the $f_\lambda \propto \lambda^{-7/3}$ prediction for an optically thick accretion disk (Lynden-Bell 1969). Standard expressions (Bath, Pringle, and Whelan 1980) give the mass-transfer rate through the disk onto the white dwarf as

$$\begin{aligned}\dot{\mathscr{M}}_{\text{disk}} &\sim 7 \times 10^{-18} L_{\text{disk}}\ , \quad (\text{g s}^{-1}) \\ &\sim 2 \times 10^{-10} \quad (\mathscr{M}_\odot\ \text{yr}^{-1})\end{aligned}$$

for the 56 Peg disk.

The X-radiation is assigned to the boundary layer between the disk and the white dwarf (see also Schindler *et al.* 1982 who make the same assignment). Observations of cataclysmic and related variables imply that current theoretical understanding of the boundary layer is incomplete (Ferland *et al.* 1982). A key issue is the size of the hot region on the white dwarf. This determines the temperature and, hence, the shape of the X-ray spectrum. Nonetheless, Pringle's (1977) calculations show that a mass transfer rate within a factor 3 of $\mathcal{M} \sim 2 \times 10^{-10}$ $\mathcal{M}_\odot$ yr^{-1} provides a boundary layer with luminosity of between 2×10^{28} and 5×10^{31} ergs s^{-1} at a temperature from 0.6 to 2×10^5 K. At this mass transfer rate, the X-ray luminosity is very sensitive to the assumed mass of the white dwarf. Schindler *et al.* (1982) independently estimated that $\dot{\mathcal{M}} \sim 1 \times 10^{-10}$ $\mathcal{M}_\odot$ yr^{-1} was necessary to provide the X-ray flux. Note that a rate $\mathcal{M}_{\text{disk}} \sim 10^{-10}$ $\mathcal{M}_\odot$ yr^{-1} explains both the UV excess and the X-ray luminosity. The observed soft X-ray luminosity corrected for absorption by neutral gas is about 3×10^{31} ergs s^{-1} (Schindler *et al.*). The agreement is satisfactory.

Since the white dwarf's accretion radius is of rather modest size, the K giant which supplies mass to the disk through its stellar wind must, if the wind is spherically symmetric, lose mass at a much higher rate. Following Schindler *et al.* (1982), the mass from the K giant $\dot{\mathcal{M}}_{\text{K}}$ and $\dot{\mathcal{M}}_{\text{disk}}$ are related through the equation

$$\frac{\dot{\mathcal{M}}_{\text{K}}}{\dot{\mathcal{M}}_{\text{disk}}} \sim \frac{4a^2}{r_a^2} ,$$

where a is the separation between the two stars and $r_a = 2GM_{\text{WD}}/V_{\text{rel}}^2$ where r_a is the accretion radius of the white dwarf and V_{rel} is the relative velocity between the wind and the white dwarf. Then,

$$\frac{\dot{\mathcal{M}}_{\text{K}}}{\dot{\mathcal{M}}_{\text{disk}}} \sim 4a_{13}^2 V_{50}^2 ,$$

where $a_{13} = a/10^{13}$ cm and $V_{50} = V_{\text{rel}}/50$ km s^{-1}. The orbit of 56 Peg is unknown. Schindler *et al.* estimate $a_{13} \sim 1$–5 for the barium star systems observed by McClure, Fletcher, and Nemec (1980). The relative velocity is, perhaps, in the range $1 \lesssim V_{50} \lesssim 2$. These uncertainties correspond to range from 4 to 400 in the $\dot{\mathcal{M}}_{\text{K}}/\dot{\mathcal{M}}_{\text{disk}}$ ratio, i.e., $\dot{\mathcal{M}}_{\text{K}} \sim 8 \times 10^{-10}$ to 8×10^{-8} $\mathcal{M}_\odot$ yr^{-1}. These estimates are within the range of derived mass loss rates for K giants (Cassinelli 1979).

Our arguments indicate that, contrary to the assertion of Schindler *et al.* (1982), the ultraviolet excess may plausibly be identified with the accretion disk rather than with a white dwarf. Schindler *et al.* considered three other arguments for rejecting the accretion disk in favor of the white dwarf. The first argument centered on the shape of the ultraviolet excess, but the wavelength dependence is fitted by either a hot blackbody (i.e., a white dwarf photosphere) or an accretion disk. Higher quality spectra and a more certain isolation of the ultraviolet excess from the giant's continuum and emission lines should distinguish between these alternatives. The presence of the Lyα line in absorption also cannot be used to distinguish the two sources. Cooler gas above the accretion disk will provide a Lyα absorption line (see, for example, the strong line seen in the spectrum of V603 Aql, an old nova with an accretion disk—Ferland *et al.* 1982). Higher resolution observations should serve to distinguish between stellar and disk absorption lines. Third, Keplerian motions in the disk may lead to very broad emission lines. Schindler *et al.* note that a high-resolution spectrum shows that the lines are narrow (FWHM ~ 110 km s^{-1}). This observation is not a fatal objection to the accretion disk hypothesis; the disk may be viewed nearly face-on or the ionized gas may be external to the disk and a nonparticipant in the Keplerian motions of the disk.

Our preference for the accretion disk rather than the white dwarf as the source of the ultraviolet excess does not call into question Schindler *et al.*'s discovery of a white dwarf companion to 56 Peg. Indeed, if accretion disks around white dwarf companions are common and similar to the 56 Peg example, detection of the fainter white dwarfs is facilitated by the presence of the brighter accretion disk.

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