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FINAL REPORT: 13th Episode IUE Observing Program

Title: A STUDY OF THE STELLAR POPULATION IN SELECTED SO GALAXIES

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The goal of this program was to observe at least two SO galaxies with abnormal colors in the blue and clear optical signatures of dust and gas. The galaxies NGC 2217 and NGC 1808 were observed at least in one of the IUE cameras (1200-200 and 2000-3200 A) during the 13th episode, using the 4 US1 shifts assigned to this program.

The galaxy NGC 2217 had been found to be part of a subgroup of SO galaxies with external gas rotating in retrograde motion with respect to the stars. This galaxy is a face-on object with indications of large amount of gas, quite rare for a SO galaxy. We observed this object on three different occasions with IUE at different positions of the large aperture (spacecraft roll angle) with respect to the nuclear region. These exposures allowed us to take full advantage of the spatial resolution of IUE by mapping the nuclear and bulge region of this galaxy. We found that the data point to a marginally earlier stellar population toward the central region. The UV light as a whole is dominated by a late-type stellar population of principally G and K stars. The almost face-on view of this galaxy appears optically thick to UV light. It is conceivable that in analogy to our own Galaxy, the stellar populations weakly detected in NGC 2217, are mostly halo and late-type stars in the center with an increasing contribution of dust and early stellar populations (so far undetected) as we move outward along the faint spiral arms. This result is contrary to our initial expectation, since the counterrotating gas does not appear to be enhancing star formation in this galaxy.

Even more interesting were the observations of NGC 1808; galaxy which has been classified, with a handful of other objects, both as a starburst and Seyfert galaxy. This object is very similar, although more distant, to the well-known Seyfert and starburst galaxy NGC 1068, which presents an active galactic nucleus and episodes of recent starburst in the spiral arms detected as bright condensations. The UV spectrum of NGC 1808 exhibits 3 distinct non-stellar features which may be clusters of star formation. The inner cluster shows strong Mg II lines in absorption which are absent in the outer clusters. Strong extinction is evident in the nuclear regions of NGC1808 and we have argued that in the inner regions dust is heated and Mg is released from dust grains.

The results of these new observations have already been presented to several professional meetings either as posters (e.g., AAS meetings) or as contributed papers. A more comprehensive paper on the issue of stellar populations of a larger sample of SO galaxies is currently under preparation with several other investigators (e.g., M. Fanelli, NRC/GSFC).

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The White-Dwarf Companions of 56 Persei and HR 3643

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ABSTRACT. We have obtained low-dispersion *IUE* spectra of the stars 56 Persei (F4 V) and HR 3643 (F7 II), as part of a survey of late-type stars with a 1565 Å flux excess in the *TD-1* ultraviolet sky survey. The *IUE* spectrum of each star reveals the presence of a hot white-dwarf companion. We fit the Lyα profile and ultraviolet continuum using pure hydrogen models, but the distance of the primary star is also needed to uniquely constrain the white-dwarf parameters. We derive $T_{\rm eff}=16{,}420\pm420$ K, $\log g=8.46\pm0.2$ for the white dwarf companion to 56 Per, using the photometric distance of 30.1 ± 2.8 pc. The implied white-dwarf mass is $0.90\pm0.12\ M_\odot$, considerably above the median mass ($\sim0.6\ M_\odot$) of single white dwarfs. The parameters of the white dwarf in HR 3643 are not well constrained, mainly due to a large uncertainty in the distance. By assuming a reasonable range of gravity for the white dwarf ($7.3<\log g<9.0$), we derive $-1.4<M_V<0.6$ for the F7 II star, and $28{,}970<T_{\rm eff}<35{,}990$ K for the white dwarf. Prompted by our detection of a white-dwarf companion of a luminous F star, we have examined the *IUE* archives to assess the upper limits on possible white-dwarf companions to Cepheids. The detection of a Cepheid–white-dwarf binary would provide important insights concerning the most massive progenitors of white dwarfs. Only for the cases of α UMi and β Dor are existing *IUE* spectra of Cepheids sufficiently deep to rule out the presence of a white-dwarf companion.

1. INTRODUCTION

Fewer than 20 stars in the *Yale Bright Star Catalog* are known to have white-dwarf companions. This number almost certainly underestimates the true binary fraction, due to the observational difficulty of detecting white-dwarf companions of bright ($m_V\lesssim7$) stars. The white-dwarf companion can be spatially resolved in the classical nearby visual binaries, such as Procyon and Sirius, as well as in common-proper-motion systems such as HR 6094/CD $-38°10980$ (Oswalt et al. 1988). In unresolved systems, the white dwarf is generally too faint to be revealed by optical spectroscopy, but may be detected at shorter wavelengths, provided that the white dwarf is hotter than the primary star. Several white-dwarf companions of late-type stars have been serendipitously discovered using the *International Ultraviolet Observer (IUE)* satellite (e.g., Böhm-Vitense 1992, 1993), but there has been no systematic ultraviolet survey for such systems. The determination of the fraction of nondegenerate stars with white-dwarf companions would have several important astrophysical applications. As one example, the white-dwarf binary fraction might provide a significant correction to the single white-dwarf luminosity function, which can be used to estimate the star-formation history of the Galaxy (Wood 1992).

An important breakthrough in the detection of white-dwarf binaries was provided by the *ROSAT*/WFC and *EUVE* all-sky surveys, with the discovery (thus far) of ten A–K stars with white-dwarf companions (Barstow et al. 1994; Vennes et al. 1995). But the EUV surveys suffer from three important selection effects that limit their utility for the derivation of the white-dwarf binary fraction. First, the EUV surveys are sensitive only to DA white dwarfs with $T_{\rm eff}\gtrsim24{,}000$ K. Second, the EUV flux is strongly attenuated by the local interstellar medium, resulting in an asymmetric distribution of detected sources (Warwick et al. 1993). Third, the EUV flux can be strongly suppressed by the presence of trace absorbers (helium or metals) in the white-dwarf photosphere. The presence of trace absorbers is believed to be the main reason why the number of white dwarfs discovered in the *ROSAT* survey is only about one-tenth that predicted in pre-flight models (Fleming et al. 1993).

An all-sky *ultraviolet* (~1400 Å) survey of late-type stars for white-dwarf companions would suffer minimal selection effects due to ultraviolet extinction or to the presence of trace photospheric absorbers, and could reveal the presence of DA and non-DA white-dwarf companions as cool as $\sim10{,}000$ K.

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

TABLE 1
Stellar Parameters

HR	Name	HD	Spec	V	$B-V$	d (pc)
1379	56 Per	27786	F4 V	5.76	0.40	30.1 ± 2.8
3643		78791	F7 II	4.48	0.61	60–300

Unfortunately, sensitive ultraviolet imaging experiments such as FAUST (Bowyer et al. 1995) or the Ultraviolet Imaging Telescope (UIT, Stecher et al. 1992) have covered only a small fraction of the sky. In 1971, the S2/68 ultraviolet sky survey telescope on the *TD-1* satellite did survey the entire sky at 1565 Å (Thompson et al. 1978), but only to a limiting sensitivity of about 10^{-12} erg cm^{-2} s^{-1} Å^{-1}, and using a large 11′ by 18′ entrance slot that presented severe problems with source confusion. Nevertheless, the utility of the *TD-1* catalog for the detection of hidden white-dwarf binaries was recently demonstrated for the case of HR 1608 (K0 IV, V=5.4). The 1565 Å flux for HR 1608 listed by Thompson et al. is $1.1\pm0.1\times10^{-12}$ erg cm^{-2} s^{-1} Å^{-1}, which is far above what is expected for a K0 IV star. However, HR 1608 was not observed with *IUE* until after its detection as an EUV source in the *ROSAT* WFC catalog (Landsman et al. 1993). The *IUE* spectrum clearly shows the presence of a white-dwarf companion, and verifies the accuracy of the *TD-1* flux.

We are currently using *IUE* to observe late-type stars with a UV excess at 1565 Å recorded in the *TD-1* catalog. In this paper, we report the detection of white-dwarf companions to the V=5.8, F4 V star 56 Persei (=HR 1379, HD 27786) and the V=4.5, F7 II star HR 3643 (=HD 78791). The detection of a white-dwarf companion to a luminous F star is particularly interesting, since such a system implies a massive (>2 $M_\odot$) progenitor for the white dwarf. In the case of HR 3643, however, we find that the constraints that can be placed on the white-dwarf progenitor are limited by the difficulty of determining the distance, mass, and age of the nonvariable bright giant primary. These difficulties prompted us to consider the feasibility of detecting white-dwarf companions to Cepheids, where the distance, mass, and age can be derived to much better precision. Therefore, in Sec. 4, we report on a search of the *IUE* archives for white-dwarf companions of the nearest Cepheids.

A complete analysis of our *IUE* sample of late-type stars will be reported in a subsequent paper.

TABLE 2
IUE Observing Log

Star	Year	Day	Image	Exp (s)	Aperture	Comment
56 Per	94	286	LWP 29387	90	L	
	94	286	LWP 29388	30	L	
	94	283	SWP 52365	900	L	Negative fluxes
	94	286	SWP 52391	2700	S	Negative fluxes
	94	286	SWP 52392	2400	L	
	94	286	SWP 52393	1800	L	
HR 3643	94	318	LWP 29509	3360	L	Multiple
	94	309	SWP 52733	900	L	
	94	318	SWP 52797	3600	L	

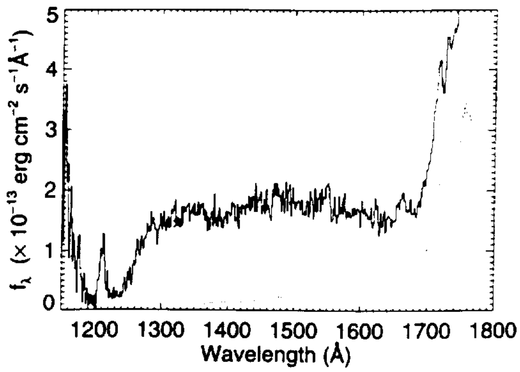

FIG. 1—The co-added *IUE* spectrum of 56 Per (solid line). Geocoronal Lyα emission has been removed as described in the text, and the observed Lyα emission is chromospheric. The dotted line shows our adopted template spectrum of Procyon, scaled down by a factor of 142.

2. OBSERVATIONS

Table 1 lists the parameters of the two F-star targets. Neither star has a parallax measurement, and our source for the distances given in Table 1 will be discussed in detail in the text. As pointed out by Landsman et al. (1993), knowledge of the distance of the primary is essential for constraining the white-dwarf parameters, since low-dispersion *IUE* spectra cannot be used to constrain both $T_{\rm eff}$ and log g in the white dwarf. The Strömgren photometry used in the discussion of the distance determinations is taken from Hauck and Mermilliod (1990).

The *IUE* images used in this study are listed in Table 2. The standard IUESIPS processing was used with the exception of the following three steps. The fluxes were corrected for the long-term degradation of the sensitivity of the SWP camera using a linear extrapolation of the tabulation of Bohlin and Grillmair (1988). The white-dwarf-based absolute calibration was taken from Finley (1993, private communication). The diffuse geocoronal and interplanetary Lyα emission was removed using the spatial information perpendicular to the dispersion in the *IUE* line-by-line image (Landsman and Simon 1993).

The large-aperture spectra of each target were added together, after weighting by the exposure time. The gross flux of the small-aperture image SWP 52391 is negative at wavelengths less than 1400 Å, indicating that the pedestal level for this image is below that of the Intensity Transfer Function (ITF) used to linearize *IUE* fluxes. The photometry of this image should be considered uncertain due to the extrapolation of the ITF to negative flux values (De La Peña 1994, private communication), and thus it was not used for the co-added spectra. The problem with negative gross fluxes also occurred to a lesser extent with the image SWP 52365, but this image was already given low weight due to its short exposure time.

3. RESULTS

3.1 56 Per

The co-added SWP spectrum of 56 Per is shown in Fig. 1. Also shown for comparison is a spectrum of Procyon (F5 IV-V) scaled by a factor of 142, in agreement with the dif-

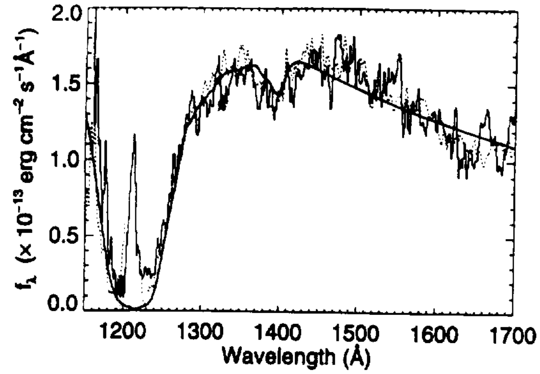

FIG. 2—The co-added *IUE* spectrum of 56 Per after subtraction of the template star (solid line). The thick solid line shows our best-fit model assuming $\log g=8.5$. The dotted line shows the spectrum of the white dwarf G148-7 (SWP 28185) scaled by a factor of 1.45.

ference of the V magnitudes. This scaling of Procyon provides an excellent match to the LWP (2000–3200 Å) spectrum of 56 Per. The F-star flux drops rapidly shortward of the Si II ionization edge at 1680 Å , and the presence of a hot companion in 56 Per is indicated by the persistent hot continuum toward shorter wavelengths. The broad Lyα absorption profile shows that the hot companion is, in fact, a white dwarf. Weak stellar Lyα emission from the F star is detected in the core of the white-dwarf Lyα profile. The weak broad-absorption feature at 1400 Å indicates the presence of a quasi-molecular Lyman alpha H-H satellite, commonly seen in warm (8000 - 17,000 K) DA white dwarfs (e.g., Bergeron et al. 1995b).

56 Per is a visual binary (ADS 3188) with a $V\sim8.7$ variable star located 4.″3 from the primary. The visible companion is too luminous to be the white dwarf seen in the *IUE* spectra, and therefore 56 Per must be (at least) a triple system. Our large (10″ by 20″) aperture *IUE* observations do not, by themselves, exclude the possibility that the white dwarf is associated with the visible companion rather than the F-star primary. This is because the orientation of the large aperture (P.A.$=143°$) was such that the visible companion was located predominantly in the direction of the dispersion. However, the ratio of the flux at 1300 Å (primarily due to the white dwarf) to the flux at 1700 Å (primarily due to the F star) is approximately equal for both the small (3″ circle) and large aperture spectra. Thus the white dwarf must be located within about 1″ from the F star.

Figure 2 shows the spectrum of 56 Per after subtraction of a spectrum of the template star, Procyon. Also shown is a spectrum (SWP 28185) of the white-dwarf G 148-7, scaled by a factor of 1.45. The G 148-7 spectrum provides an excellent fit to the 56 Per white-dwarf spectrum, including the region of the Lyα satellite at 1400 Å. From simultaneous fitting of the Balmer line profiles, Bergeron et al. (1995a) derived $T_{\rm eff}=15480$ K, and $\log g=7.97$ for G 148-7. However, the similarity of the ultraviolet spectra does *not* imply that the white dwarfs have the same temperature and gravity (Bergeron et al. 1995b). Thus we follow Landsman et al. (1993), and tabulate models for a grid of ($T_{\rm eff}$, $\log g$) values consistent with the *IUE* spectrum of 56 Per (Table 3). The models are computed as in Bergeron et al. (1995b), with the

TABLE 3
White-Dwarf Model Fits

	$\log g$	T_{eff} (K)	R^2/D^2	$M/M_\odot$	M_V	d (pc)
56 Per	7.50	14520	9.08×10^{-23}	0.435	10.61	43
	8.00	15460	6.50×10^{-23}	0.615	11.20	36
	8.50	16515	4.63×10^{-23}	0.931	11.88	30
	9.00	17620	3.56×10^{-23}	1.198	12.72	22
HR 3643	7.00	26900	1.32×10^{-23}	0.262	8.55	176
	7.50	28970	9.81×10^{-24}	0.431	9.23	139
	8.00	31130	7.62×10^{-24}	0.652	9.87	109
	8.50	33250	6.23×10^{-24}	0.952	10.58	82
	9.00	35990	5.20×10^{-24}	1.188	11.46	56

ML2/$\alpha=0.6$ parametrization of the mixing-length theory, and the Lyα quasi-molecular satellite profiles of Allard et al. (1994). The white-dwarf mass is derived from the temperature and gravity using the white-dwarf cooling models of Wood (1995) for a pure carbon composition, with thick hydrogen and helium layers. Note that the model with $T_{\rm eff}=15{,}460$ K, $\log g=8.0$ provides a very close match to the parameters derived optically for G 148-7 by Bergeron et al. (1995a), and illustrates the internal consistency of the model parameters derived from *IUE* and optical spectroscopy.

A determination of the stellar distance is required to further constrain the white-dwarf parameters. The Strömgren absolute-magnitude calibration of Nissen (1988), as implemented in the FORTRAN program of Napiwotzki et al. (1993), gives $M_V=3.37$, and thus a distance of 30.1 pc to 56 Per. This absolute magnitude is in excellent agreement with the value of $M_V=3.3$, tabulated by Corbally and Garrison (1984) for an F4 V star. An error of one spectral type at F4 V corresponds to a difference of 0.2 in M_V, or a difference of 2.8 pc in the distance estimate. Interpolating a distance of 30.1 ± 2.8 pc in the grid in Table 3, gives $T_{\rm eff}=16{,}420\pm420$ K and $\log g=8.46\pm0.2$ for the white dwarf, and an implied mass of $0.90\pm0.12\ M_\odot$.

The mass distribution for single white dwarfs has a median value of $\sim0.6\ M_\odot$, with a sparsely populated high-mass tail extending to $\sim1.0\ M_\odot$ (Bergeron et al. 1995b; Bragaglia et al. 1995). According to current estimates of the initial-mass–final-mass relation (IMFMR), this high mass tail has its origin in progenitor stars with $M\gtrsim2.5\ M_\odot$, with the remnant mass increasing smoothly with the progenitor mass above this threshold (Weidemann 1987; Bragaglia et al. 1995). Most functional forms of the IMFMR require a mass greater than 5 $M_\odot$ for the progenitor of a 0.9 $M_\odot$ white dwarf (cf. Fig. 23 in Wood 1992). If the white-dwarf progenitor mass were this large, it would place a strong upper limit on the lifetime of the 56 Per system. The pre-WD lifetime of a 5 $M_\odot$ star is about 110 Myr (Schaller et al. 1992), and the time required for a 0.9 $M_\odot$ white dwarf to cool to $T_{\rm eff}=16{,}400$ K is 320 Myr (Wood 1995), so that the total lifetime of the system must be less than about 430 Myr. Such a short lifetime seems implausible for 56 Per, since it is not identified with a young cluster or supercluster. Unfortunately, since the F star in 56 Per is located near the main sequence, its Strömgren photometry is consistent with any evolutionary

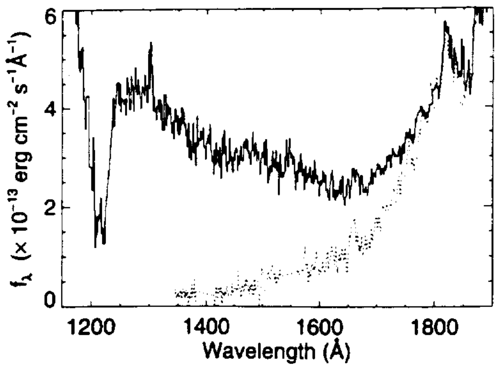

FIG. 3—The co-added *IUE* spectra of HR 3643 (solid line), after dereddening with $E(B-V)=0.04$. The geocoronal Lyα emission has been removed as described in the text. The dotted line shows our template spectrum of υ Peg (SWP 40364), multiplied by the ratio (1.1) of the dereddened V magnitudes.

age up to about 2 Gyr, according to the solar metallicity isochrones of Bertelli et al. (1994).

The SIMBAD data base gives four radial-velocity references for 56 Per, with the average velocity falling between -31.2 and -35.4 km s^{-1}. The radial velocity is marked as variable in an early (1923) study, but no orbit has been determined. Since 56 Per appears to have a large mass ratio ($\sim 1.4\ M_\odot$ for the F4 V star, and $\sim 0.9\ M_\odot$ for the white dwarf), the low velocity amplitude indicates either a low orbital inclination, or, more likely, a long-period orbit. Further radial-velocity studies on 56 Per are clearly warranted.

3.2 HR 3643

Figure 3 shows the co-added *IUE* spectrum of HR 3643, along with the spectrum of the template star υ Peg (F8 IV, $B-V=0.60$). The HR 3643 spectrum has been dereddened by $E(B-V)=0.04$. This reddening value, and our use of υ Peg as a template star, are discussed further below. The spectrum of HR 3643 shows a steeper rise of the UV continuum and a narrower Lyα absorption profile than does the 56 Per spectrum, indicating a higher temperature white dwarf. The very steep flux rise shortward of Lyα may indicate some contribution by long-wavelength scattered light. The spectrum shows strong O I λ 1305 and possible C IV λ 1550 emission, but no other chromospheric line (including Lyα) is clearly detected.

No evidence for radial-velocity variations has been found for HR 3643, which, in fact, has occasionally been adopted as a radial-velocity standard (e.g., Layden 1994). Houk and Cowley (1975) give a spectral type of F7 II for HR 3643 and quote an unpublished type of F8 II from Garrison and Hagen. SIMBAD gives a best spectral type of F6 II-III from deVaucouleurs (1957), while the *Yale Bright Star Catalog* (Hoffleit and Warren 1991) gives a spectral type of F9 II. The bright-giant classification of HR 3643 thus seems secure, and provides a crude estimate of the absolute magnitude. Corbally and Garrison (1984) tabulate $M_V=-2.0$ for a F7 II star. To estimate the possible range, we assume that HR 3643 is brighter than a F7 III star ($M_V=0.6$) and fainter than the F7 Ib-II low-amplitude Cepheid, α UMi, which has $M_V=-2.94$ (Fernie et al. 1995). These absolute magnitudes are used to derive the crude HR 3643 distance estimate of 60–300 pc given in Table 1.

We are unable to determine a more refined distance to HR 3643 due to the relative rarity of F bright giants at known distances. For example, the Strömgren F-star absolute-magnitude calibrations of Crawford (1975) or Nissen (1988) specifically exclude luminosity class II stars with the Strömgren parameters of HR 3643 ($\beta=2.625$ and $\delta c_1=0.26$). On the other hand, the Strömgren F supergiant standards used by Gray (1991) or Arellano Ferro and Parrao (1990) all appear to be more luminous than HR 3643. Eggen (1989) classified HR 3643 as an old disk giant and on that basis derived an absolute magnitude $M_V=+1.4$. The kinematics of HR 3643 do place it just outside the region of young disk stars (see Fig. 3 in Eggen). However, several pieces of evidence suggest that HR 3643 is instead an intermediate mass star ($\sim 2-5\ M_\odot$) with a higher intrinsic luminosity. First, the rotational velocity ($\upsilon \sin i=53$ km s^{-1}) of HR 3643 is much larger than typically found for old disk giants. Second, the linewidths of the Ca H and K profiles of HR 3643 are extremely broad, indicating a high stellar luminosity from the Wilson-Bappu relation. From Fig. 2 in Dravins (1981), after a crude correction for the rotational velocity, we estimate a Ca K linewidth of log $W=2.3$ km s^{-1}, which is typical of a type Ib supergiant (Wilson 1976). Additional evidence for a large intrinsic luminosity comes from the *IUE* emission-line spectrum. Figure 3 shows that O I λ1305 emission is present, but that C II λ1335 and C IV λ1548 are either absent or marginally detected. The presence of strong O I emission with weak or absent C II and C IV is characteristic of stars on the luminous side of the chromosphere- transition region dividing line (Linsky and Haisch 1979). We measure an O I flux in HR 3643 of 3.9×10^{-13} erg cm^{-2} s^{-1}, and derive a normalized emission-line flux of f(O I)/l_{bol} = 9×10^{-7}, which is typical of the values seen in Cepheid stars (Schmidt and Parsons 1982). (HR 3643 is almost certainly not a Cepheid, since no radial-velocity variations have been found, and Fernie, 1976, reports no evidence for photometric variability.)

A large distance to HR 3643 is also indicated by the evidence for non-negligible reddening. The reddening derived from the Strömgren F-star calibration of Crawford (1975) is $E(b-y)=0.029$, while the supergiant F-star calibration of Gray gives $E(b-y)=0.043$. Bersier (1995) derived $E(B-V)=0.071$ toward HR 3643 on the basis of Geneva photometry. We adopt $E(B-V)\sim E(b-y)/0.73=0.04$ from the Crawford F-star calibration. The implied hydrogen column density is then N(H I) $\sim 2\times 10^{20}$ cm^{-2}, assuming a dust to gas ratio of N(H I)/$E(B-V)=5.2\times 10^{21}$ cm^{-2} mag^{-1} (Shull and Van Steenberg 1985). This large hydrogen column density would explain the nondetection of the HR 3643 white dwarf in the *ROSAT WFC* and *EUVE* surveys (Pye et al. 1995; Bowyer et al. 1996), and is also consistent with our failure to detect any stellar Lyα emission from the F star in the core of the white-dwarf Lyα absorption profile (Landsman and Simon 1993).

Figure 4 shows that the LWP spectrum of HR 3643 is well matched by a spectrum (LWP 14389) of υ Peg (F8 IV, V $=4.40$, $B-V=0.60$), multiplied by the ratio (1.1) of the

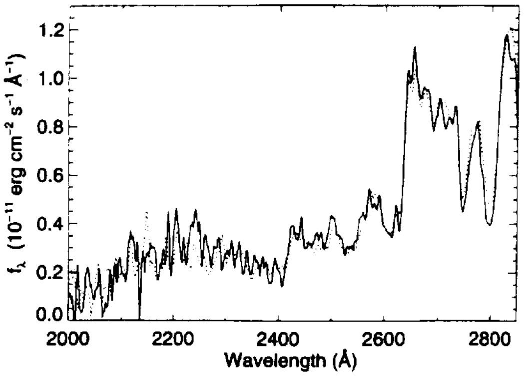

FIG. 4—The long-wavelength spectrum (LWP 29509) of HR 3643, dereddened with $E(B-V)=0.04$. A model white-dwarf spectrum (derived from fitting the short wavelengths of the SWP spectrum) has been subtracted. The dotted line shows the spectrum of υ Peg after scaling by the ratio (1.1) of the dereddened V magnitudes.

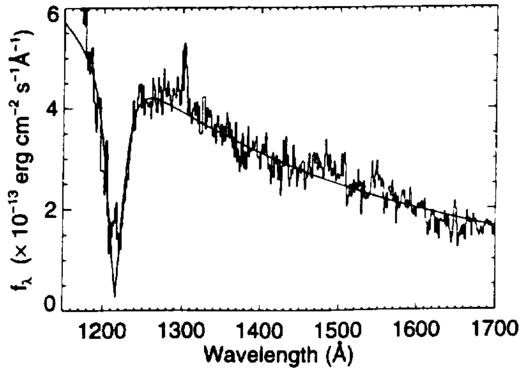

FIG. 5—The spectrum of HR 3643 after subtraction of 0.7 times the spectrum of the template star, υ Peg. The thick, solid line shows a best-fit white-dwarf model, assuming $\log g=8.0$.

dereddened V magnitudes. Among the late-F stars with well-exposed SWP and LWP spectra in the *IUE* archives, υ Peg provides the best fit[2] to the LWP spectrum of HR 3643. However, υ Peg is not an ideal template star because it is considerably less luminous than HR 3643, and exhibits intense C II and C IV chromospheric emission (Simon and Drake 1989). In fact, Fig. 3 shows that the SWP spectrum of υ Peg overcorrects for the contribution of the F star near 1850 Å. Therefore, to create the HR 3643 white-dwarf spectrum shown in Fig. 5, we scaled the υ Peg spectrum by a factor (0.7) chosen to yield a smooth continuum following the subtraction. We then fit white-dwarf models to the spectrum shortward of 1700 Å. However, we would have derived very similar white-dwarf parameters if we had fit only to wavelengths <1500 Å, where the contribution of the F star is negligible.

Table 3 displays a grid of white-dwarf models consistent with the HR 3643 white-dwarf spectrum, and Fig. 5 shows a model spectrum for the case of $\log g=8.0$. The distance estimate for HR 3643 given in Table 1 is too uncertain to provide any further constraint on the white-dwarf parameters. Instead, the absolute magnitude for the F star can be constrained by assuming a reasonable range of surface gravity for the white dwarf. The observed surface gravities for isolated white dwarfs range between $7.3<\log g<9.0$ (Bergeron et al. 1992). From Table 2, this surface-gravity constraint implies a distance to HR 3643 of $56<d<150$ pc, and an absolute magnitude of the F star of $-1.4<M_V<0.6$. Should the distance to HR 3643 turn out to be greater than $\sim$150 pc, then the possibility must be considered that the white dwarf is not physically associated with HR 3643. However, the spatial separation of the two stars must be less than about 2″, since the line-by-line *IUE* spectra do not show a spatial shift between the regions of the spectrum dominated by the white dwarf and the F star. Given this close proximity, and the broad overlap in the estimated distances of the F star and the white dwarf, we consider a physical association to be highly probable.

HR 3643 may be the most massive star known to have a white-dwarf companion, and thus is an important object for the study of the massive progenitors of white dwarfs. However, further analysis of this system will require a better distance determination, for example, from the results of the *Hipparcos* satellite. Another important observation will be to obtain *high*-dispersion Lyα observations, which, unlike the case with the low-dispersion *IUE* Lyα profile, can be used to constrain both the gravity and temperature of the white dwarf (Landsman et al. 1995).

4. WHITE-DWARF COMPANIONS TO CEPHEIDS

The mass of the white-dwarf progenitor in a noninteracting binary must have been larger than that of the remaining nondegenerate star. Thus, in principle, binary systems can provide constraints on the upper mass, M_u, of a star that can leave a white-dwarf remnant, and on the initial-mass–final-mass relation (IMFMR) that accounts for the total mass loss during stellar evolution. The detection of a close white-dwarf companion to a main-sequence B star is not possible using ultraviolet spectroscopy[3]. Thus, our empirical knowledge of M_u and the IMFMR is based mainly on observations of young open clusters (Weidemann 1990), where the white-dwarf progenitors must have been more massive than the turn-off mass of the cluster. In particular, the detection of massive white dwarfs in the young cluster NGC 2516 shows that stars with masses up to $8(^{+3}_{-2})$ $M_\odot$ can leave white-dwarf remnants (Reimers and Koester 1982).

After a main-sequence B star evolves into a cool supergiant, the detection of a hot white-dwarf companion becomes feasible in the ultraviolet. In the case of HR 3643, the main-sequence progenitor of the F bright giant (with $T_{\rm eff}=6000$ K and $M_V=-0.4\pm1$) was probably a late-B star of mass 2–4 $M_\odot$, according to the evolutionary tracks of Schaller et al. (1992). However, the case of HR 3643 also illustrates the difficulty in obtaining accurate values of the distance, mass,

[2] Note that the *IUE* spectrum of HD 160365, adopted as the F6 III standard star in the *IUE* Spectral Atlas (Wu et al. 1983) cannot be used as a F-star template, because HD 160365 itself has a hot white-dwarf companion (Böhm-Vitense 1992).

[3] In principle, hot white-dwarf companions to B stars could be detected with *EUV* spectroscopy, but no such systems are yet known. Also, white-dwarf companions to B stars may have been detected in interacting systems such as Be stars (e.g. Haberl 1995).

TABLE 4
Limits on White Dwarf Companions to Cepheids

HD	Name	$<V>$	$<B>-<V>$	$E(B-V)$	d (pc)	SWP	Time (min)	Flux[a]	T_{eff}(K) 0.6 $M_\odot$	T_{eff}(K) 1.0 $M_\odot$	Note
8890	α UMi	1.98	0.60	0.00	97	28557	65	<1.29	<14370	<16840	
17463	SU Cas	5.97	0.70	0.29	265	16480	40	···	···	···	1
29260	SZ Tau	6.53	0.84	0.29	450	24985	120	<0.79	<64400	···	3
37350	β Dor	3.73	0.81	0.04	340	28452	400	<0.36	<19080	<23550	
45412	RT Aur	5.45	0.59	0.05	430	7188	70	<1.14	<28850	<43400	
52973	ζ Gem	3.92	0.80	0.02	390	17939	180	<0.43	<20310	<25320	
68808	AH Vel	5.69	0.58	0.07	500	21379	120	<1.03	<27800	<40140	
108968	BG Cru	5.49	0.61	0.05	410	···	···	···	···	···	2
161592	X Sgr	4.55	0.74	0.20	330	6216	60	<1.38	<41000	<84950	
164975	W Sgr	4.67	0.75	0.11	410	15303	29	···	···	···	1
176155	FF Aql	5.37	0.76	0.22	360	10085	160	<0.73	<35850	<67860	
180583	V473 Lyr	6.18	0.63	0.03	365	8317	16	<1.83	<28660	<42780	
187929	η Aql	3.90	0.79	0.15	270	5701	48	···	···	···	1
201078	DT Cyg	5.77	0.54	0.04	400	···	···	···	···	···	2
213306	δ Cep	3.95	0.66	0.09	250	28556	300	<1.10	<23650	<30480	

Notes to TABLE 4

[a]$\times 10^{-14}$ erg cm^{-2} s^{-1} Å^{-1}.

Note.—(1) Hot main-sequence companion present, (2) No SWP observations exist, (3) No T_{eff} constraint possible for 1 $M_\odot$ model.

and age of nonvariable bright giants or supergiants. For example, Gray (1991) found that the scatter in absolute magnitude for nonvariable F supergiants was too large to allow a useful calibration with Strömgren photometry. Some of this scatter is due to the fact that the helium-burning evolutionary tracks of intermediate-mass stars can overlap, so that a single photometric box or MK spectral type does not correspond to a unique mass.

In contrast, the discovery of a Cepheid with a white-dwarf companion would provide particularly useful constraints on M_u and the IMFMR. The minimum mass for a Cepheid is 3–4 $M_\odot$, so the white-dwarf progenitor must be at least this massive. More importantly, the Cepheid pulsations can be used to estimate the distance and age of the system. Comparison of the white-dwarf cooling age with the evolutionary age of the Cepheid would then provide a relatively precise estimate of the mass of the white-dwarf progenitor (cf. Evans 1994). The time for a white dwarf to cool to 15,000 K is 540 Myr for a 1.0 $M_\odot$ remnant, and 210 Myr for 0.6 $M_\odot$ remnant (Wood 1995). On the other hand, the hydrogen-burning lifetime of a 4 $M_\odot$ star (the progenitor of a low-mass Cepheid) is about 165 Myr (Schaller et al. 1992). Thus, if a Cepheid originally had a more massive companion, then the white-dwarf remnant of the companion, if it exists, should still be detectable by deep ultraviolet spectroscopy.

What percentage of Cepheids should have white-dwarf companions? The original mass ratio, $q=M_2/M_1$ for such a system must be greater than about 0.5, since the primary, M_1 must be less massive than M_u ($\sim 8 M_\odot$), and the secondary, M_2, must be more massive than the minimum Cepheid mass ($\sim$4 $M_\odot$). The system must also have a long-period orbit (>1 year) so that each star can evolve to a supergiant without interacting with its companion. Abt et al. 1990 found that B stars in long-period orbits did *not* favor mass ratios near unity, and instead were distributed as a power law toward lower masses. However, it is plausible that at least some Cepheid-white-dwarf binaries exist, since, out of 20 Cepheids with well-determined orbits, Evans (1995) found four with secondary masses between 4 and 5.5 $M_\odot$. Such systems could eventually evolve into a Cepheid- white-dwarf binary, if the current secondary eventually evolves into a Cepheid, and the current Cepheid leaves a white-dwarf remnant.

No white-dwarf companion to a Cepheid has yet been found, despite the fact that numerous Cepheids have been observed with *IUE*. For example, Evans (1992) has conducted a magnitude-limited survey to eighth mag of 76 Cepheids with the long-wavelength camera on *IUE*, while Evans (1995) has obtained deep short-wavelength images of 20 Cepheids with well-determined orbits. However, because her surveys were designed to detect main-sequence companions, they concentrated on longer wavelengths (and shorter exposure times) than is optimal for a white-dwarf search. Therefore, we have examined the archival *IUE* data set for the nearest Cepheids in order to assess the current limits on white-dwarf companions.

Table 4 lists the 15 Cepheids within 500 pc, as tabulated in the catalog of Fernie et al. (1995). (EW Sct has been omitted from the list due to its very large reddening, $E(B-V)=1.1$.) For each star, we extracted the image with the longest SWP exposure. We used NEWSIPS processed data (Nichols et al. 1994) whenever it was available. Two of the Cepheids in Table 4 (BG Cru and DT Cyg) have not been observed with the SWP camera. Another three Cepheids (W Sgr, SU Cas, and η Aql) have hot (>9000 K) main-sequence companions (Evans 1992) which swamp any potential signal from a white dwarf in the *IUE*-wavelength range.

We examined each image for evidence of a broad Lyα absorption, but found no white-dwarf candidates. Several of the deepest images show a very steep rising flux shortward of Lyα, which is a signature of long-wavelength scattered light. We removed this scattered light by subtracting a constant level of *IUE* flux units so that the signal below Lyα (where the *IUE* sensitivity rapidly decreases) goes to zero. We compute an upper limit to the flux in a 50 Å bandpass centered at 1345 Å , by adding the residual mean flux in this bandpass to the 1 sigma flux variations within the bandpass. This wavelength is chosen as optimal for a white-dwarf search, because the contribution from the Cepheid at 1345 Å is expected to be small, and the contribution of the white dwarf will not be strongly affected by a possible broad Lyα absorption.

We then used white-dwarf atmosphere models to determine the temperatures of a 0.6 $M_\odot$ and a 1.0 $M_\odot$ white-dwarf consistent with the flux upper limits, using the distances and reddenings tabulated in Table 4. Although the white-dwarf mass function peaks near 0.6 $M_\odot$ (Bragaglia et al. 1995), the 1.0 $M_\odot$ model may be more appropriate for the remnant of a massive ($>3M_\odot$) progenitor. The reddening of the model UV flux was determined from $E(B-V)$ using the parametrization of Cardelli et al. (1989). The white-dwarf radii, needed to determine the flux scaling at the Cepheid distance, were computed from the mass and temperature using the cooling models of Wood (1995).

According to Table 4, the upper limit on the 1345 Å flux from α UMi (Polaris) implies that a 0.6 $M_\odot$ white-dwarf companion must be cooler than 14,370 K, and a 1.0 $M_\odot$ companion must be cooler than 16,840 K. The corresponding white-dwarf cooling ages are, respectively, 240 Myr and 400 Myr. As noted above, these cooling ages are longer than the lifetime of the Cepheid, so that a white-dwarf companion of α UMi is ruled out by the *IUE* observations. Since α UMi is a well-known astrometric and spectroscopic binary, its companion is thus likely to be an F star (Evans 1988, 1995). A white-dwarf companion can probably also be ruled out for β Dor, for which the upper limit in Table 4 of $T_{eff} < 19{,}080$ K for a 0.6 $M_\odot$ white dwarf implies a cooling age greater than 90 Myr. The absolute magnitude of β Dor is -4.08 (Fernie et al. 1995), corresponding to an evolutionary mass of about 7 $M_\odot$ and a lifetime of less than 60 Myr, according to the evolutionary tracks of Becker et al. (1977). The use of evolutionary tracks with larger convective core overshoot would give a smaller mass and somewhat longer lifetime for β Dor (cf. Evans 1995), but are still unable to accommodate a white-dwarf cooling age greater than 90 Myr.

For the remaining Cepheids listed in Table 4, the existing *IUE* data allow for the possibility of a white dwarf cooler than the upper limit on T_{eff}, but still young enough to be consistent with the Cepheid evolutionary age. Deeper ultraviolet observations of these Cepheids are needed to reveal or rule out the presence of a white-dwarf companion.

5. SUMMARY

We have detected white-dwarf companions to the F4 V star, 56 Per, and the F7 II star, HR 3643, using *IUE* spectroscopy. We derive $T_{\rm eff}=16{,}420\pm420$ K and $\log g = 8.46\pm0.2$ for the white-dwarf companion to 56 Per, using the photometric distance of 30.1 ± 2.8 pc. The implied white-dwarf mass is 0.90 ± 0.12 $M_\odot$. 56 Per is a known wide (4$''$.3) binary, but a small-aperture *IUE* spectrum is used to show that the white dwarf is a close companion of the F star, and thus that 56 Per is a triple system.

The parameters of the white dwarf in HR 3643 are not well constrained, mainly due to a large uncertainty in the distance of the primary. By assuming a reasonable range of gravity, ($7.3< \log g<9.0$), for the white dwarf, we derive $-1.4<M_V<0.6$ for the F7 II star, and $28{,}970<T_{\rm eff} <35{,}990$ K for the white dwarf.

Neither star has a parallax measurement, and the results from *Hipparcos* will provide important physical constraints. For 56 Per, an accurate parallax is needed to confirm the high white-dwarf mass implied by the photometric distance. In the case of HR 3643, a parallax is needed because photometric and spectroscopic distances lack sufficient precision to provide a useful constraint on the white-dwarf parameters.

Prompted by our detection of a white-dwarf companion to a F7 II star, we study the feasibility for the ultraviolet detection of white-dwarf companions to Cepheids. The detection of a Cepheid white-dwarf binary would provide important insights into the most massive progenitors of white dwarfs. The Cepheid distance can be used along with ultraviolet spectroscopy to determine the temperature and gravity of the white dwarf. The progenitor of the white dwarf must have been more massive than the existing Cepheid ($>3M_\odot$), and the evolutionary age of the Cepheid would allow a fairly precise mass estimate for the progenitor. From consideration of the evolutionary times, we show the white dwarf remnant of a Cepheid companion, if it exists, should still be hot ($>$ 15,000 K), and detectable by ultraviolet spectroscopy. Only for the cases of α UMi and β Dor, are existing *IUE* spectra sufficiently deep to rule out the presence of a white-dwarf companion.

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