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SPECTROSCOPY OF THE WINDS FROM HUBBLE-SANDAGE STARS IN M31 AND M33[1]

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ABSTRACT

We have secured intermediate resolution (1 Å) spectra of five Hubble-Sandage (H-S) stars in M31 (AE And, AF And, and Variable A-1) and M33 (Variables B and C). P Cygni profiles are present on all strong permitted lines, indicating photospheric outflow velocities of $\sim$100–300 km s^{-1} and mass-loss rates of 1–5 $\times$ 10^{-5} $M_\odot$ yr^{-1}. These dense, low-velocity winds are characteristic of optically thick flows driven by continuum radiation pressure, and can be produced, in principle, by either (1) very massive single stars evolving off the main sequence, or (2) massive binary stars undergoing an epoch of rapid mass exchange. We favor a very massive single star model for systems such as η Car and R127, since these objects are located in active star formation centers in Carina and the LMC, respectively. However, some H-S variables in M31 (e.g., AF And) lie well outside major star-forming centers, implying significantly longer main-sequence lifetimes than can be achieved by a very massive single star. This property, and the lack of evidence for enhanced nitrogen abundances in the winds of these systems, lead us to suggest that some H-S variables are in fact binary stars, and thus may not represent the special circumstances that produce luminous Wolf-Rayet stars.

Subject headings: galaxies: individual — stars: emission-line — stars: mass loss — stars: variables

I. INTRODUCTION

The Hubble-Sandage (H-S) subclass of S Dor variable stars was first identified in the Local Group spiral galaxies M31 and M33 (Duncan 1922; Wolf 1923; Hubble 1926, 1929). In a comprehensive photometric study, Hubble and Sandage (1953) established many of the salient features of these variables: high intrinsic luminosities; substantial optical variability over periods of years; and, in most instances, blue optical colors. They also described photographic spectra which showed the presence of H I and He I emission lines superposed on a strong continuum, and noted the likely presence of P Cygni profiles in some cases.

With the advent of improved detectors, low-resolution optical spectra obtained for most of the M31 and M33 H-S stars have confirmed the features described by Hubble and Sandage and provided an important link between H-S stars and objects such as η Car and S Dor (cf. Humphreys 1975, 1978; Gallagher, Kenyon, and Hege 1981 [hereafter GKH] and references therein). These have been supplemented in several cases by infrared photometry and *IUE* satellite ultraviolet spectroscopy (Humphreys and Warner 1978; Humphreys *et al.* 1984). All these data are consistent with H-S stars having high mass-loss rates which produce dense circumstellar envelopes that greatly modify the underlying properties of the luminous core objects (cf. Humphreys 1978; GKH; Humphreys *et al.* 1984). But despite the observational improvements, several facets of the H-S variables, including the mass-loss mechanism and their evolutionary status, remain poorly known (cf. Stothers and Chin 1983; Maeder 1983).

H-S stars continue to be of special interest, in part because of their potential roles as crucial evolutionary links between massive O–B stars and luminous Wolf-Rayet stars (Maeder 1983). Because H-S stars are extraordinarily luminous, they also may be important as standard-candle distance indicators in extragalactic astronomy (Hubble and Sandage 1953; Sandage 1983, 1984*a*, *b*). In both instances, the mass-loss process is a key to a proper understanding of the physical and observable characteristics of H-S variables, although mass loss has yet to be investigated in the classic M31 and M33 H-S stars. As a first step toward resolving this deficiency, we have used the Multiple Mirror Telescope (MMT) to obtain high-quality, intermediate-spectral-resolution observations of the H-S stars AE And, AF And, and variable A-1 in M31, and variables B and C in M33. These spectra allow accurate measurements of typical wind velocities and provide a basis for improved diagnostics of conditions in the circumstellar envelopes. While the MMT spectra and their physical interpretation are the primary subjects of this paper, we also touch briefly on comparisons between H-S stars and their possible galactic counterparts (such as η Car), and on the origins of the H-S phenomenon.

II. OBSERVATIONS

Spectroscopy of five H-S stars in M31 and M33 (AE And, AF And, variable A-1 in M31, and variables B and C in M33) was obtained in 1983 November 10/11 with the MMT spectrograph and the Big Blue II image tube. Simultaneous star and sky measurements were made through 12 apertures of 2″.5, and the objects were periodically beam-switched to minimize differences between the two halves of the Reticon array. In all instances, sky positions were separated from the objects by 32″ and were free of stars visible on the MMT acquisition television ($m_{\rm red} \geq 21$). The effects of the brightness gradient due to

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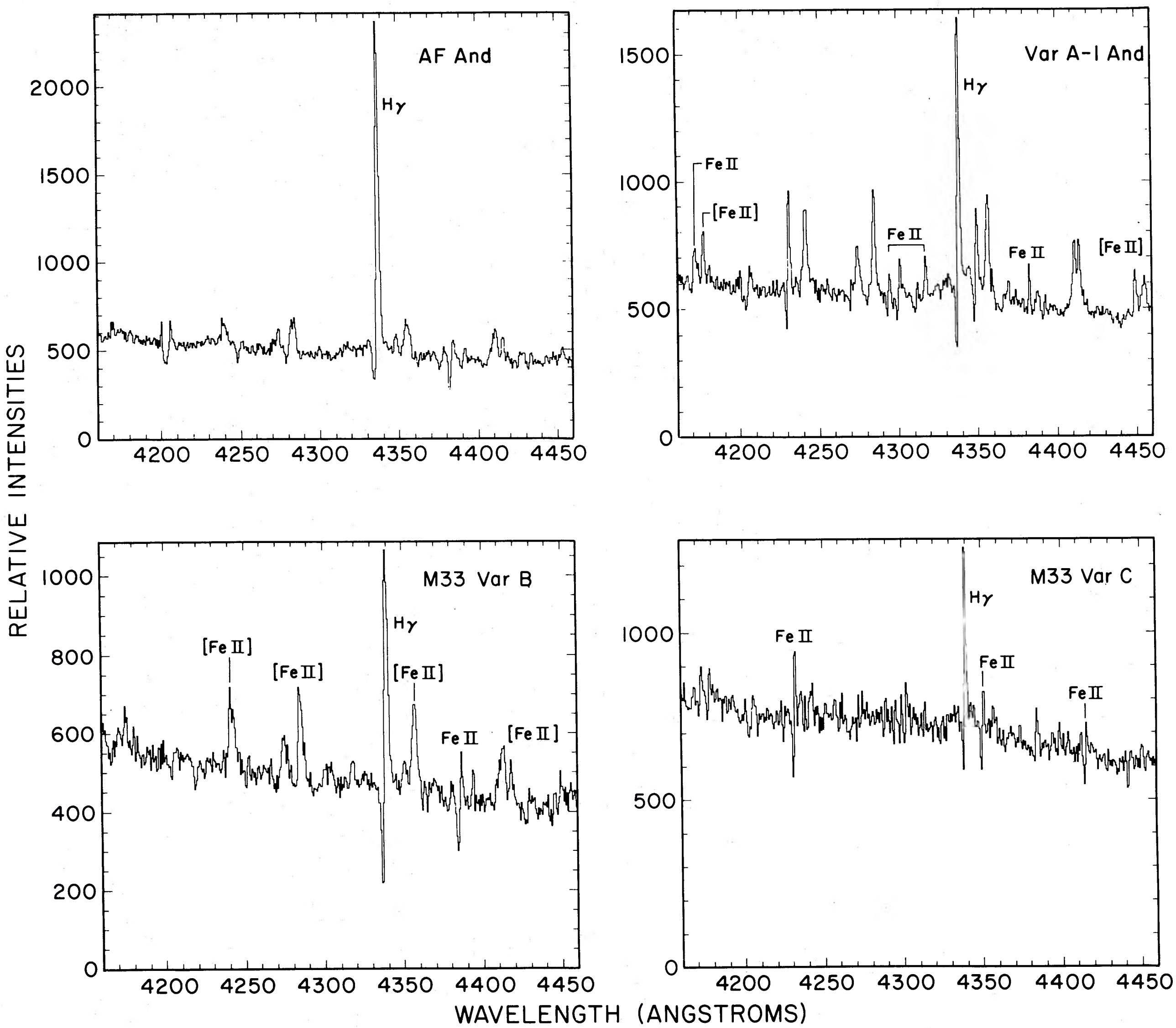

FIG. 1.—Optical spectra of four H-S stars over $\lambda\lambda$4160–4450. P Cygni absorption components are visible on Hγ and a few Fe II lines.

the underlying galaxy are also negligible based on surface photometry by Burgess (1976: M31) and Guidoni, Messi, and Natali (1981: M33), since the H-S stars are all quite bright relative to the background. A spectrum of an He-Ar lamp was secured immediately before and after each observation of a program star, and thus nearly all the distortion in the wavelength scale introduced by the image tube has been removed. The resulting spectra provide $\sim$1 Å ($\sim$65 km s^{-1}) resolution over $\lambda\lambda$4100–5050; however, since the apertures were small, and light cirrus clouds were visible throughout the night, no attempt was made to flux-calibrate the spectra.

Our spectra are displayed in Figures 1–4, while identifications and equivalent widths of various emission and absorption lines are listed in Tables 1–3. As with previous spectra of these objects, most of the emission can be attributed to Fe II or [Fe II], although Hβ is usually the strongest emission feature.

TABLE 1

HYDROGEN AND HELIUM EMISSION LINE EQUIVALENT WIDTHS[a]

Emission Line	AE And	AF And	M31 Var A-1	M33 Var B	M33 Var C
Hβ	11.3	16.9	6.9	8.2	2.4
Hγ	6.3	8.4	3.1	4.0	2.0
He I λ4388	...	<1.0	...	<1.0	...
He I λ4471	...	4.1	...	3.5	...
He I λ4713	...	2.1	...	2.3	...
He I λ4921	...	<1.0	...	<1.0	...

[a] Equivalent widths are measured in Å.

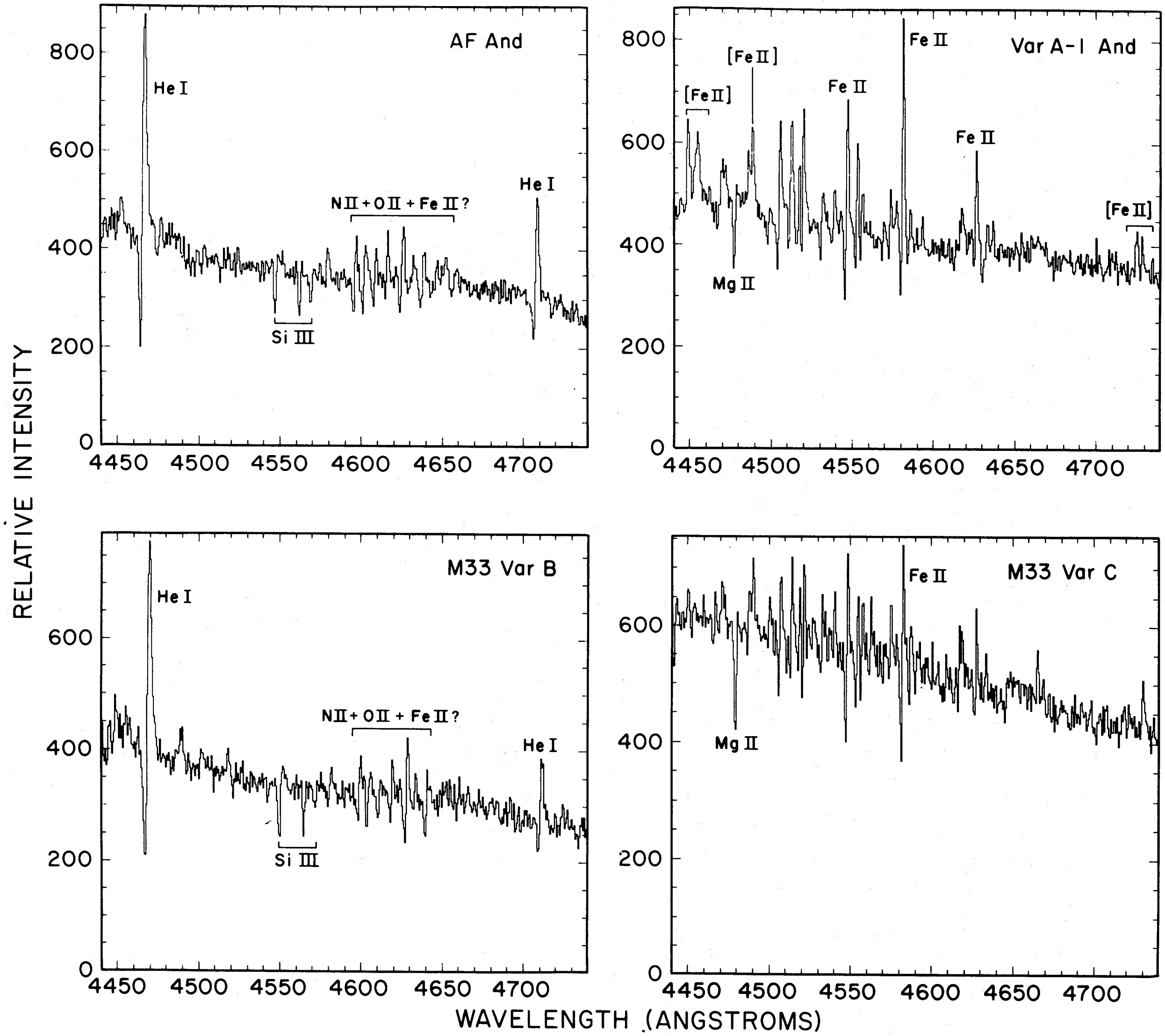

FIG. 2.—As in Fig. 1, but for λλ4450–4740. Both AF And and M33 Var B show evidence for Si III absorption, while Mg II absorption is prominent in M31 Var A-1 and M33 Var C.

The Hβ line is composed of a strong emission peak, a narrow absorption component, and broad (~500 km s^{-1}) wings. This structure is similar to that observed in P Cygni and some Be stars, in which the broad wings are a result of electron scattering in an expanding atmosphere (cf. Poeckert and Marlborough 1979; Bernat and Lambert 1978). P Cygni absorption components are quite obviously present on a number of the more prominent emission lines, and indicate photospheric outflow velocities of ~200 km s^{-1} (Var A-1 and Var C) or ~350 km s^{-1} (AF And and Var B). In general, the emission-line profiles of M31 Var A-1 and M33 Var C appear somewhat narrower than those of AF And and M33 Var B, while the [Fe II] lines are definitely narrower than the H I and Fe II lines in each object. These spectra show significant variations since those of GKH and Humphreys (1975, 1978), and we therefore discuss each separately.

AF And.—AF And has evolved dramatically since GKH, as Hβ and Hγ are ~50% stronger relative to the continuum. The He I lines appear to be much stronger as well, although Fe II and [Fe II] are somewhat weaker. A few absorption lines are present in Figure 2, and are most likely due to Si III (λλ4552, 4568, 4575). This transition is sensitive to dilution of the radiation field in early B stars (Underhill 1970), and since λ4575 is fairly strong, we classify the absorption spectrum as B1–2 Ia–Ib. This implies a temperature of ~28,000 K (e.g., Code *et al.* 1976), which agrees with the temperature indicated by *IUE* observations discussed by Humphreys *et al.* (1984; $T \approx 25{,}000$ K) and by the presence of strong He I emission ($T > 25{,}000$ K;

TABLE 2

HYDROGEN AND HELIUM ABSORPTION LINE EQUIVALENT WIDTHS[a]

Emission Line	AF And	Var A-1	Var B	Var C
Hβ	<1.0	1.2	2.0	0.4
Hγ	2.5	0.7	1.6	1.1
He I λ4388	<1.0	...	<1.0	...
He I λ4471	2.9	...	3.1	...
He I λ4713	0.6	...	<1.0	...
He I λ4921	1.1	...	<1.0	...

[a] Equivalent widths are measured in Å.

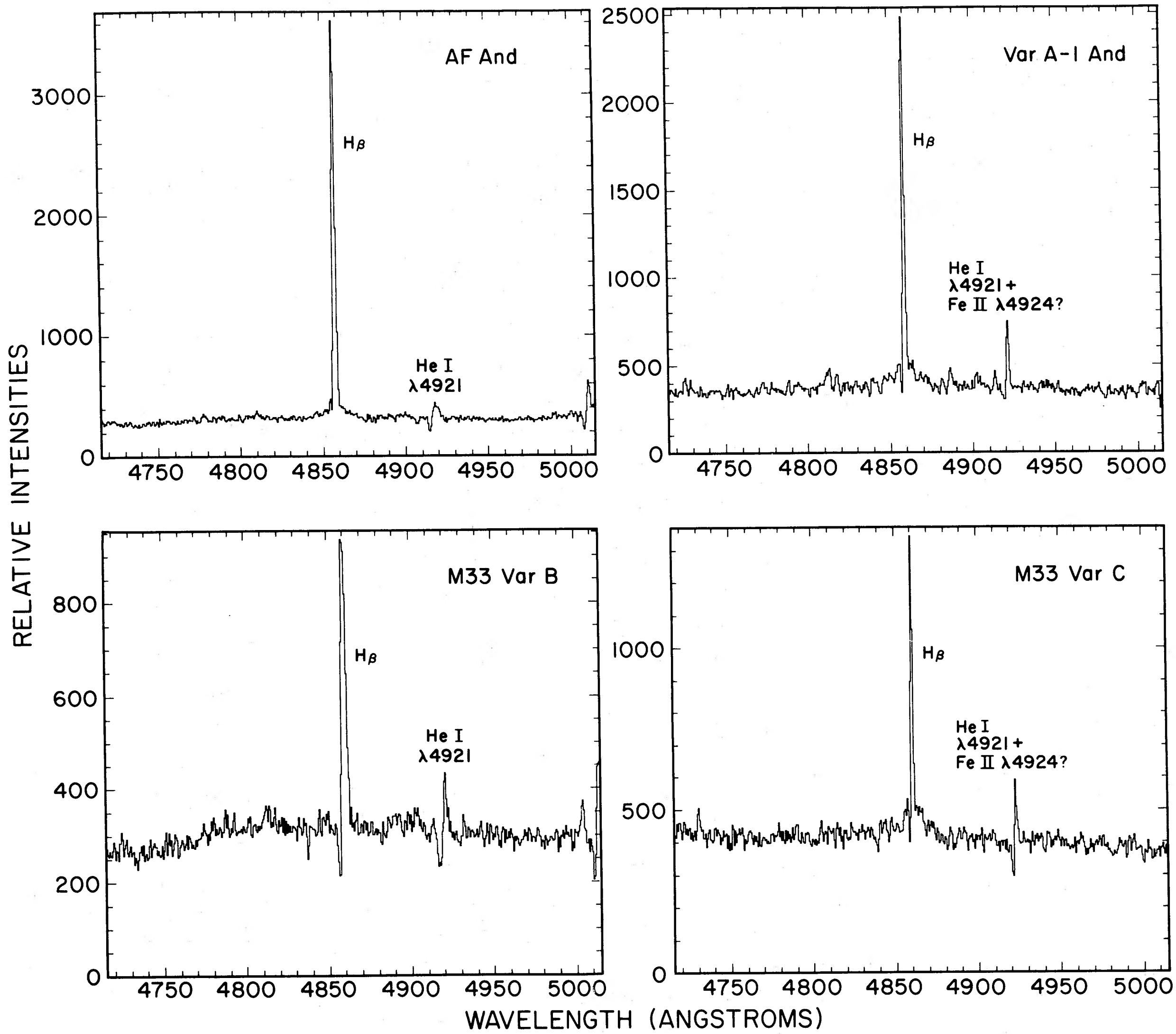

FIG. 3.—As in Fig. 1, but for $\lambda\lambda$4710–5010. Prominent P Cygni profiles are visible on Hβ, He I, and Fe II lines.

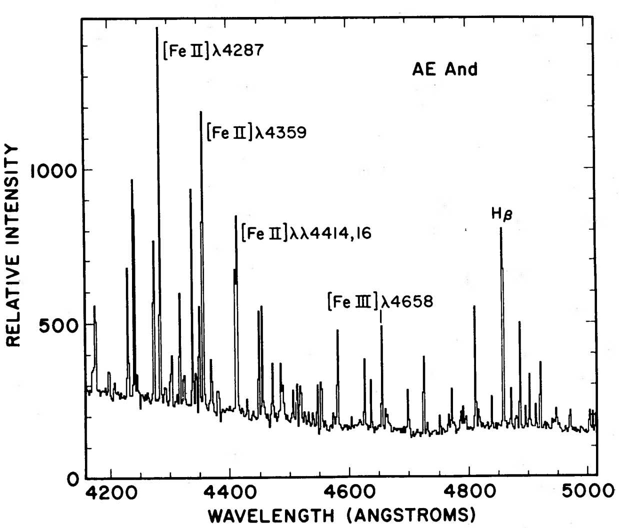

FIG. 4.—Optical spectrum for the H-S variable AE And. A few of the more prominent emission lines have been labeled; most of the remaining lines are due to Fe II or [Fe II].

Kaler 1978). It therefore appears that AF And has increased in temperature since GKH, when we adopted $T_* \approx$ 10,000–12,000 K.

Var A-1.—This system appears to have evolved considerably over the past 4 yr, as Hβ is a factor of $\sim$2 weaker in equivalent width. There is no evidence for He I emission, while the Fe II and [Fe II] lines may be unchanged or perhaps somewhat weaker than in 1979. Fairly strong He I lines had been reported by Bianchini and Rosino (1975), and thus Var A-1 has evolved toward lower effective temperatures (cf. Humphreys *et al.* 1984). The strong absorption line at 4477 Å may be identified as Mg II λ4481, which is usually observed in middle-B or later type stars. Since Si III absorption and He I emission lines are not seen in Var A-1, this star must have a comparatively cool stellar photosphere ($T_* \approx$ 10,000 K, or comparable to that adopted in GKH).

Var B.—This M33 variable resembles AF And in having intense H I and He I emission lines with strong blueshifted absorption components. The lines identified in Tables 1 and 2 agree favorably with Humphreys' (1975, 1978) description, although we find no trace of G band absorption. The two fairly

TABLE 3

METALLIC LINES IN AE And

Identification	Wavelength (λ)	Multiplet	Equivalent Width (Å)
Fe II	4233.2	27	2.3
[Fe II]	4244.0, 4244.8	21F	7.4
[Fe II]	4276.8	21F	5.5
[Fe II]	4287.4	7F	10.6
[Fe II]	4305.9	21F	1.7
[Fe II]	4319.7	21F	3.5
[Ni II]	4326.2	3F	1.2
[Fe II]	4346.9	21F	1.6
[Fe II]	4352.8	21F	3.8
[Fe II]	4359.3	7F	11.5
[Fe II]	4372.4	21F	1.7
[Fe II]	4382.8	6F	1.5
Fe II	4385.4	27	<1.0
[Fe II]	4413.8	6F	5.5
[Fe II]	4416.3	7F	6.0
[Fe II]	4452.1	7F	4.0
[Fe II]	4458.0	6F	3.5
[Fe II]	4474.9	7F	1.7
[Fe II]	4488.8	6F	1.6
Fe II	4491.4	37	blend
[Fe II]	4492.6	6F	1.0
Fe II	4508.3	38	blend
[Fe II]	4509.6	6F	1.5
Fe II	4515.3	37	2.0
Fe II	4520.2	37	1.4
Fe II	4522.6	38	<1.0
Fe II	4549.5	38	2.2
Fe II	4555.9	37	2.9
Fe II	4576.3	38	<1.0
Fe II	4583.8	38	3.7
Fe II	4629.3	37	2.1
[Fe II]	4639.7	4F	2.2
[Fe III]	4658.1	3F	4.6
[Fe III]	4701.6	3F	2.6
[Fe II]	4728.1	4F	4.6
[Fe III]	4754.8	3F	<1.0
[Fe III]	4769.6	3F	<1.0
[Fe II]	4774.7	20F	1.3
...	4790.0	...	<1.0
...	4794.1	...	<1.0
[Fe II]	4798.3	4F	<1.0
[Fe II]	4814.6	20F	5.0
...	4820.1	...	<1.0
...	4841.4	...	1.2
[Fe II]	4874.5	20F	1.7
[Fe II]	4889.6	4F	4.6
[Fe II]	4898.6	−F	<1.0
[Fe II]	4905.4	20F	2.0
...	4915.9	...	<1.0
Fe II	4923.9	42	3.5
[Fe II]	4947.4	20F	<1.0
[Fe II]	4950.7	20F	<1.0
[Fe II]	4973.4	20F	<1.0
[Fe II]	5005.5	20F	1.5
[Fe III]	5011.3	1F	<1.0

strong absorption lines shown in Figure 2 are due to Si III and are indicative of a B-type supergiantlike spectrum. The absence of Si III λ4575 suggests that Var B is either somewhat hotter or somewhat cooler than AF And (Yamashita, Nariai, and Norimoto 1978). Given the overall strength of the He I lines relative to Hβ, we favor a B0 Ia–Ib spectral type for the photosphere. Thus Var B is the hottest of the systems in this study, and we adopt a temperature of $T_* \approx 30{,}000$ K in our subsequent analysis. This is comparable to the $T_* \approx 25{,}000$ K derived from *IUE* spectra by Humphreys *et al.* (1984).

Var C.—This system has the poorest emission-line spectrum of our sample, but P Cygni absorption components are still visible on the stronger lines. As with Var A-1, no He I lines are identified on our spectrum, while Fe II and [Fe II] are fairly prominent. Humphreys (1975, 1978) had noted λ4471 emission on her plates, and since the star appeared unusually bright on the MMT TV guider, we suspect Var C has evolved to a lower temperature and a higher visual luminosity since the 1970s (cf. Humphreys *et al.* 1984). This is confirmed by the identification of the rather strong Mg II λ4481 absorption on the spectrum shown in Figure 2. As noted above, Mg II is strongest in A-type stars; the strength of this line in Var C suggests it may be marginally cooler than Var A-1 (i.e., $T_* \lesssim 10{,}000$ K).

AE And.—The spectrum of AE And is significantly different from those discussed previously and has much in common with spectra of η Car. Both Hβ and Hγ are prominent emission lines, and lines of singly ionized metals (especially [Fe II]) are also quite strong. Satisfactory line identifications could not be obtained for five emission lines listed in Table 3. Two of these have been observed in symbiotic stars ($\lambda\lambda$4790, 4819), while another has been detected in a few planetary nebulae (λ4915). There is a hint of evolution in AE And, since Humphreys (1975, 1978) noted a strong absoption line at 4647 Å (O II?) which does not appear on our spectrum. Since P Cygni absorption components are not associated with any of the strong emission lines, we may safely conclude that any wind in AE And has a velocity less than $\sim$50 km s^{-1}, which suggests the mass-loss rate is comparatively low.

III. DISCUSSION

a) *Mass-Loss Rates*

Now that we have measured expansion velocities for a sample of typical H-S stars, previous estimates of mass-loss rates can be placed on a firmer basis. Mass-loss rates are usually assumed to depend linearly on the flow velocity in the stellar wind at large distances, which we denote by v_∞. Since the He I lines are formed close to the stellar core (GKH), our measurements of P Cygni profiles may not be indicative of material in the outer regions of the wind. Indeed, lower excitation [Fe II] lines are nearly unresolved on our spectra, suggesting that the wind may decelerate through the envelope, and that $v_\infty \leq 100$ km s^{-1}. In hot stars, v_∞ is usually readily estimated from ultraviolet resonance lines, but these lines will probably lead us to considerably overestimate v_∞ in H-S stars if deceleration occurs. AE And has no P Cygni profiles, but there is a radial velocity difference of $\sim$25 km s^{-1} between the hydrogen Balmer and the metalic emission lines that may reflect a low expansion velocity.

GKH in their equation (2) derive mass-loss rates from Hβ luminosities for AF And and M31 Var A-1, which are $\sim 5 \times 10^{-5}$ $M_\odot$ yr^{-1} for $v_\infty = 100$ km s^{-1}. Humphreys *et al.* (1984) utilize the infrared $J-K$ color excess to deduce somewhat lower mass-loss rates of $3 \pm 2 \times 10^{-5}$ $M_\odot$ yr^{-1} for a typical H-S star. Although stellar mass-loss rates of 1–5×10^{-5} $M_\odot$ yr^{-1} are large, they are not extraordinary, and indeed similar mass-loss rates are found in other types of extremely luminous stars (Cassinelli 1979; Abbott, Bieging, and Churchwell 1981). We therefore conclude that the mass-loss *rates* alone do not distinguish H-S stars from "normal" extremely luminous supergiants. Rather, the key factor is the abnormally high density of the wind, which is a direct result of the combined effects of large mass-loss rates and low wind velocities. The situation is probably further complicated by nonsteady mass-loss rates or flow velocities, which are certainly typical of S Dor stars as a class and are a major factor in producing optical variability (cf. Stahl and Wolf 1982; Wolf and Stahl 1982; Stahl *et al.* 1983).

b) The Mass-Loss Process

The physical mechanism which drives mass from very luminous evolved stars has yet to be unambiguously identified. While stellar pulsations have long been suspected to be involved in the S Dor stars (Stothers and Chin 1983; Maeder 1983), a good circumstantial case can be made for radiation pressure as the primary destabilizing agent. The Eddington limit defines the maximum luminosity that a hot star of mass M can attain in a static configuration. For higher luminosities, theoretical models show that mass loss will occur via an optically thick stellar wind (e.g., Zytkow 1972, 1973; Bath 1978; Ruggles and Bath 1979). The classic Eddington limit is in fact quite conservative, and for an appropriate mean opacity $\bar{\kappa}$ in a stellar atmosphere, the limiting luminosity is:

$$L_{\max} \approx 4 \times 10^4 (M/M_\odot)(\kappa_{es}/\bar{\kappa}) L_\odot ,$$

where κ_{es} is the Thomson electron-scattering opacity. As Humphreys and Davidson (1984) have pointed out, any process that causes a hot star to become more distended results in cooling of matter toward hydrogen recombination and thus a substantial increase in $\bar{\kappa}$. This is likely to have a major impact on the stability of atmospheres in stars with $L \approx L_{\max}$, which is almost certainly the case for H-S stars with $L \approx 10^6 L_\odot$.

The models for stars with $L > L_{\max}$ suggest that the resulting optically thick stellar winds will be somwhat different from the more nearly optically thin winds of O–B stars. Most of the acceleration occurs at large optical depths beneath the apparent photosphere, and the wind then coasts out to its eventual terminal velocity. For high mass-loss rates from very luminous stars, Zytkow's (1973) models show that the maximum mass-loss rates are obtained for $v_\infty \rightarrow 0$; models with luminosities and mass-loss rates similar to those of H-S stars have $v_\infty \approx$ 1–$2v_{esc}$ (the escape velocity from the photosphere). It is also interesting to note that for $v_\infty = 100$ km s^{-1} and $L = 10^6 L_\odot$, the mass-loss rate inferred from the momentum of the radiation field (L/c) is 1–$2 \times 10^{-4} M_\odot$ yr^{-1}, or ~ 10 times the observed rate of 1–$5 \times 10^{-5} M_\odot$ yr^{-1}. Thus the momentum is largely carried by the radiation field, and we may safely conclude that H-S stars are not in an extremely unstable state (this is precisely the opposite situation from what occurs in a typical slow classical nova, where L/c is roughly comparable to, or perhaps slighly less than, $\dot{M}v_\infty$; cf. Ruggles and Bath 1979).

A simple test of the basic wind model is possible if we assume that our P Cygni profiles provide some measure of the escape velocity at the photosphere, e.g., $v_{\rm P\,Cygni} = kv_{esc}$. The photospheric luminosity is $L = 4\pi R_{phot}^2 \sigma T^4 \propto R_{phot}^2 T^4$, and substituting for R_{phot} in terms of the escape velocity, we have $L \propto T^4 M^2 v_{esc}^{-4}$ or $L \propto T^4 M^2 v_{\rm P\,Cygni}^{-4}$. If the bolometric luminosity of a given S Dor star remains roughly constant, then we expect $v_{\rm P\,Cygni}$ to be roughly proportional to the photospheric temperature as the visual luminosity of the star varies. Alternatively, taking H-S stars as a group with similar values of L and M, we should see a correlation of $v_{\rm P\,Cygni}$ with $T_{\rm eff}$. From our spectra, we find that M33 Var B and AF And have high P Cygni velocities of ~ 350 km s^{-1}, and on the basis of optical spectra and UV energy distributions have temperatures of $\sim 30{,}000$ K (Humphreys *et al.* 1984). The cooler stars M31 Var A-1 and M33 Var C have lower velocities of ~ 150–200 km s^{-1} from their P Cygni profiles, and AE And probably has both the densest, coolest shell and the lowest expansion velocity. This qualitative agreement supports the wind model, and suggests that the gross velocity structure of the wind [i.e., $v(R)/v_\infty$ where R is the distance from the central source] is relatively independent of the photospheric temperature. Crucial tests will involve tracking the energy distributions and wind velocities of individual H-S stars as they vary with time.

c) Evolutionary Notes

The most common model for H-S variables is a massive ($M \approx 60$–$100\ M_\odot$) single star undergoing a period of enhanced mass loss (cf. Humphreys and Davidson 1984, and references therein). It then follows that H-S stars may represent an evolutionary link between luminous O–B stars and Wolf-Rayet stars, and that during this phase the hydrogen-rich envelope is lost, possibly by catastrophic events as in η Car (Humphreys and Davidson 1979). This view certainly receives support from the properties of η Car: it is located in a major region of active star formation (i.e., the Carina OB1 association; Humphreys 1978) and has the enhanced nitrogen abundances expected for a star in this post–main-sequence evolutionary transition phase (Davidson, Walborn, and Gull 1982). A parallel case can be made for R127, an LMC S Dor variable with characteristics intermediate between Of and WN spectral classes (Stahl *et al.* 1983). Like η Car, R127 is located in an area of recent star formation within the envelope of the 30 Dor nebula. Thus both the intrinsic properties and locations in large star-forming centers of these two stars (as well as AG Car) are consistent with evolution into luminous Wolf-Rayet stars, which also tend to be directly associated with major centers of recent star formation (cf. van der Hucht *et al.* 1981; Massey and Conti 1983; Garmany 1984).

These attributes (enhanced nitrogen abundances and location in star-forming centers), however, do not apply to most of the classical H-S stars. For example, in Figure 2, we see that N II does not dominate the $\lambda\lambda 4600$–4650 region in AF And and M33 Var B as in R127 (Stahl *et al.* 1983), and that O II absorption is probably also present. Thus there is no strong case for an enhancement in the nitrogen abundance in these two stars. M31 Var A-1 and M33 Var B perhaps provide the best cases for location in active star-forming areas, but neither star is situated in a region like Carina. M31 Var A-1 lines on the periphery of Hodge's (1981) OB association 42, and is outside of major H II regions (Pellat *et al.* 1978). Var B is similarly located at the edge of the Humphreys and Sandage (1980) OB association 142, while other H-S stars are even more remote from centers of star formation (e.g., AF And; cf. also Table 10 of Humphreys and Sandage).

The spatial locations of many H-S stars are therefore rather surprising if we think of these variables in terms of the 60–100 $M_\odot$ stars that must become luminous Wolf-Rayet stars. A related facet of this problem is the apparent scarcity of H-S stars relative to Wolf-Rayet stars. For example, in the LMC Wolf-Rayet stars outnumber S Dor stars by 20:1, and a similar situation probably prevails in M33. If about one-half of all Wolf-Rayet stars pass through an S Dor phase, then the lifetime of the S Dor phase must be only $\sim 10\%$ of the Wolf-Rayet lifetime. Since Wolf-Rayet stars clearly are in a post–main-sequence evolutionary phase, this implies a lifetime for an H-S or S Dor star of $\lesssim 10^5$ yr. With our current estimates of mass-loss rates, $< 10\ M_\odot$ is driven off during this time interval, which is not enough to make a catastrophic difference to a very massive star (Dearborn, Tinsley, and Schramm 1978; Tutukov and Yungel'son 1983).

How do we resolve this apparent quandary? There are several possibilities:

1. The classical H-S variables may be in interlude phases of low mass-loss rates, which accounts for their optical variability. During major outbursts, they, like η Car, may become dust-shrouded and thus optically dim. As a result, both the numbers and mass-loss rates of stars in an H-S phase are underestimated by surveys based on optical luminosities. The strange behavior of M33 Var A is consistent with this possibility (Hubble and Sandage 1953; Humphreys *et al.* 1984).

2. H-S variables may exist within the major star-forming centers of M31, M33, and the LMC, but have not been recognized due to crowding and high nebular background-light levels. The core of 30 Dor would be a particularly good place to test this possibility.

3. The basic model may be incorrect. If the H-S stars result from a radiation pressure instability, then they might be produced by either binaries or massive single stars (Bath 1979). Due to selection effects, we could tend to miss the single-star candidates and yet find binary systems with extreme mass-loss rates, which have the potential for being older and thus more isolated from star-forming centers than extremely massive single stars.

d) The Binary Alternative

Binary models for H-S stars have not gained wide acceptance, in part because η Car fulfills so many of the expected properties for a single-star model (cf. Humphreys and Davidson 1984). Yet we have seen that many of the Local Group S Dor and H-S stars do not follow the spatial pattern expected for extremely massive Wolf-Rayet star progenitors, nor do they have the prodigious mass-loss rates of η Car. On the other hand, there have been suggestions (Webbink 1979*a*) that P Cyg may owe its peculiar properties to binary-driven mass loss. In view of the possibility that there may be more than one physical channel which can lead to stars having the properties of H-S variables, in this section we briefly review the case for a binary model.

Two facts assure us that binary evolution will play a role in the evolution of massive stars: (1) About one-third of all O stars are likely to be binaries, and a large fraction of these have short orbital periods which will inevitably lead to interactions as the binary components evolve (Garmany, Conti, and Massey 1980). (2) We see the end products of binary evolution, such as X-ray binaries containing luminous stars (Tutukov, Yungel'son, and Kraitcheva 1974; de Loore *et al.* 1974; van den Heuvel 1980; de Loore 1982) and peculiar objects such as SS 433 and binary pulsars. The evolutionary connection between massive O-type binaries and these end products, however, is not certain, but could include objects with the properties of H-S stars.

The distinguishing features of binary evolution are mass exchange between members of the system and mass loss from the system as a whole, both of which are driven by the increasing size of the stars as they evolve (cf. Webbink 1979*b*). This can lead to an extra source of luminosity in the system due to mass accretion, and possibly result in a binary embedded in a common envelope (Paczyński 1971, 1976). Bath (1979) has presented a basic model which shows that accretion onto main-sequence stars at very high rates, $\sim 10^{-2}\ M_\odot\ \mathrm{yr}^{-1}$, will yield H-S variables with the supra-Eddington luminosities needed to drive mass loss at large rates. Under these conditions, a common envelope will develop around the system which will further obscure the underlying binary (Paczyński 1976) and will aid the driving of mass loss at appropriate rates for H-S stars (Tutukov and Yungel'son 1979, 1980). A schematic model for such a binary system is shown in Figure 5.

The advantage of a binary model is to reduce the total mass of the initial system needed to make a H-S star to $\leq 50\ M_\odot$. Thus the binary H-S star may have a source more prevalent than the requisite type of single star (the $\sim$15–25 $M_\odot$ stars in an H-S binary are individually at least 10 times more common than 60–100 $M_\odot$ stars), which makes it easier to account for the presence of H-S variables outside sites of major star formation. Since a star of 20 $M_\odot$ can yield $M_{\mathrm{bol}} = -10$ at an Eddington critical-accretion luminosity, the binary will also have a longer main-sequence lifetime by perhaps several million years before the H-S phase is reached, as compared with a massive single star. This will also help resolve the H-S spatial-distribution problem.

If H-S variables are in some instances binaries, then much of their radiated power will originate in an accretion disk (cf. Bath 1979; Fig. 5 above). For accretion rates slightly below the Eddington critical limit, maximum disk temperatures of 30,000–40,000 K are reached for a $\sim$15 $M_\odot$ central star, when $M_V = -7$ and $B-V \approx -0.2$ (Kenyon 1985). Such a disk produces a characteristic flat spectrum, with an ultraviolet color temperature of $\sim$30,000–40,000 K and an optical color temperature of $\sim$10,000 K, in reasonable agreement with the observations (cf. Humphreys *et al.* 1984; GKH). Small increases in the accretion rate (i.e., slightly above the Eddington limit) result in an expansion of the disk at roughly constant bolometric luminosity, thereby lowering the effective temperature and raising the visual luminosity (Bath 1979). Model calculations suggest that 2.5 mag excursions in the visual brightness are possible under these conditions, which are comparable to the variations experienced by most H-S stars (cf. Hubble and Sandage 1953). While a detailed comparison of disk models and observations must await more sensitive ultraviolet detectors, this qualitative agreement lends further support to a binary interpretation for some H-S stars.

IV. CONCLUSIONS

1. We have measured P Cygni profile-expansion velocities in four H-S stars which lie in the range of 150–350 km s^{-1}. From the widths of the [Fe II] lines which originate in outer regions of the circumstellar envelope, we suspect that the stellar wind velocities at infinity are somewhat lower than the P Cygni values, with 100 km s^{-1} being typical. AE And does not show P Cygni profiles and has a low expansion velocity of ≤ 50 km s^{-1}.

2. Using our estimate of the terminal wind velocity in combination with previous derivations of mass-loss rates, we find that the stellar winds in H-S stars are carrying off $1\text{–}5 \times 10^{-5}\ M_\odot\ \mathrm{yr}^{-1}$. These are not extraordinary mass-loss rates for stars of this luminosity, and thus the mass-loss *rate* cannot be the sole cause of the H-S phenomenon.

3. The dense winds in H-S stars originate from a combination of substantial rates of mass loss and low wind velocities. We interpret these characteristics in terms of winds that are driven by continuum radiation pressure. Such winds can be produced, in principle, by either very massive single stars or by massive binary stars which are experiencing an epoch of rapid

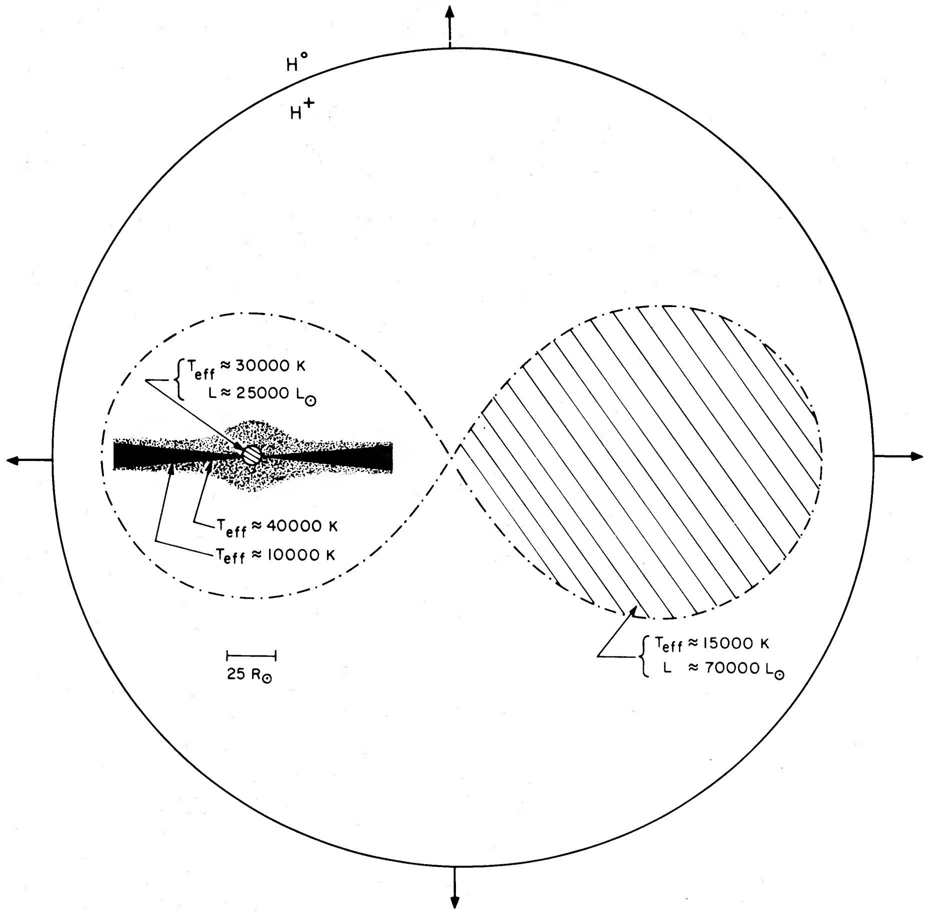

FIG. 5.—Schematic representation of a binary H-S star surrounded by an extended H II region ($R_{H\,II} \approx 1$ AU). Effective temperatures and luminosities for the two stars are as indicated. The lobe-filling component on the right loses material through the L_1 point, resulting in the formation of a massive accretion disk (*dark region*) surrounding the secondary star. The disk luminosity approaches $5 \times 10^5\ L_\odot$ for the accretion rates considered in the text, and therefore dominates the light output from the binary as a whole. Radiation pressure within the disk may cause the disk to "puff up," as indicated in the dotted region. Should the accretion rate through the L_1 point exceed the Eddington limit ($\sim 10^{-2}\ M_\odot\ \mathrm{yr}^{-1}$), the disk expands to engulf the system and form a common-envelope binary.

mass exchange. Thus S Dor and H-S spectral characteristics may occur in more than one physical class of star.

4. Since H-S stars are rare, we conclude that they are probably short-lived ($t_{\text{H-S}} \leq 10^5$ yr). Then unless the mean mass-loss rates during the H-S phase greatly exceed currently observed values, the H-S phase cannot have catastrophic evolutionary consequences for very massive stars. The H-S variables, however, may indicate stars in very interesting evolutionary states, and therefore deserve further study. In particular, it would be worthwhile to explore whether evolutionary links exist between H-S stars and unstable luminous supergiants of the ρ Cas type (cf. Morgan *et al.* 1981).

5. The lack of evidence for enhanced nitrogen abundances in the stellar winds and locations of the M31 and M33 H-S stars included in our study outside major star-forming sites stand in constrast to the galactic prototype η Car and to luminous Wolf-Rayet stars. These properties lead us to question whether all S Dor variables are single, very massive stars in a pre–Wolf-Rayet evolutionary phase, and to suggest that models based on massive binary stars have advantages in explaining the overall characteristics of the majority of M31 and M33 H-S stars.

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