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IUE AND GROUND-BASED OBSERVATIONS OF THE HUBBLE-SANDAGE VARIABLES IN M31 AND M33

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ABSTRACT

Ultraviolet spectroscopy from the *IUE*, in combination with ground-based visual and infrared photometry, allows us to determine the energy distributions of the luminous blue variables, the Hubble-Sandage variables, in M31 and M33. The observed energy distributions, especially in the ultraviolet, show that these stars are suffering interstellar reddening. When corrected for interstellar extinction, the integrated energy distributions yield the total luminosities and blackbody temperatures of the stars. The resulting bolometric magnitudes and temperatures confirm that these peculiar stars are indeed very luminous, hot stars. They occupy the same regions of the M_{bol} versus temperature diagram as do η Car and P Cyg in our Galaxy and S Dor in the LMC.

Many of the Hubble-Sandage variables have excess infrared radiation which is attributed to free-free emission from their extended atmospheres. Rough mass loss estimates from the infrared excess yield rates of $10^{-5}\ M_{\odot}\ \text{yr}^{-1}$. The ultraviolet spectra of the H-S variables are also compared with similar spectra of η Car, P Cyg, and S Dor.

Subject headings: galaxies: individual — stars: mass loss — stars: supergiants — stars: variables — ultraviolet: spectra

I. INTRODUCTION

The Hubble-Sandage (H-S) variables are among the most luminous stars known. These blue variables are spectroscopically and photometrically similar to the highly luminous, peculiar stars η Car and P Cyg in our Galaxy and S Dor in the Large Magellanic Cloud. They are included in the class of stars termed *S Doradus variables* by Kukarkin *et al.* (1974). Five blue variables in M31 and M33 were the original H-S variables (Hubble and Sandage 1953): AF And (Var 19) in M31 and variables A, B, C, and 2 in M33. Other luminous, blue stars which resemble the original group are also included as H-S variables; Hubble Var 15 and Var A-1 (Rosino and Bianchini 1973) and AE And (Sandage and Tammann 1974) in M31 and Var 83 in M33 (van den Bergh, Herbst, and Kowal 1975).

These variable stars share common spectroscopic and photometric characteristics. They display irregular variability consisting of extended maximum and minimum phases, frequently lasting several years, and separated by relatively short transition phases. Their light curves may be found in Hubble and Sandage (1953) and Rosino and Bianchini (1973). The spectral characteristics of the H-S variables are discussed by Humphreys (1975, 1978). These variables display a strong, hot continuum extending into the ultraviolet, no apparent Balmer discontinuity, and strong emission lines of H, He I, Fe II, and [Fe II]. They show ultraviolet excess radiation, and some have infrared excesses (Humphreys and Warner 1978). In AF And, Var A-1, Var 83, and Var 2, the infrared excess may be due to free-free emission from extended atmospheres, while in Var A it is very likely caused by circumstellar dust.

Current models suggest that the H-S variables are hot, massive supergiants surrounded by circumstellar envelopes (Humphreys 1978; Gallagher, Kenyon, and Hege 1981; Wolf, Appenzeller, and Cassatella 1980). Their photometric behavior, combined with their low surface gravities, suggests that their atmospheres may be unstable in a manner similar to η Car (Davidson 1971). A better understanding of their evolutionary status and their role in massive star evolution requires information on their total luminosities and temperatures.

For this reason ultraviolet spectra were obtained with the *International Ultraviolet Explorer* (*IUE*) of the brightest H-S variables. The ultraviolet fluxes in combination with visual and infrared photometry allow us to determine their energy distributions, luminosities, and temperatures. The ultraviolet spectra can also be compared with possibly related objects like η Car, S Dor, and P Cyg. The observations and the resulting energy distributions are described in §§ II and III. The ultraviolet spectra are presented in § IV. In § V the importance of the Hubble-Sandage variables for the study of massive star evolution is discussed.

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TABLE 1

JOURNAL OF OBSERVATIONS WITH *IUE*

Star	α(1950)	δ(1950)	Image No.	Date	Exposure Time (min)
M31 AF And	$0^{\rm h}40^{\rm m}48\overset{\rm s}{.}6$	$+40°55'45\overset{''}{.}0$	LWR 11850	1981 Nov	420
			SWP 18689	1982 Nov	391
			LWR 14756	1982 Nov	316
M31 Var A-1	0 42 05.6	+41 14 13.8	LWR 11853	1981 Nov	430
M33 Var 83	1 31 21.7	+30 19 16.7	LWR 10956	1981 Jun	210
			LWR 10971	1981 Jun	390
			SWP 14342	1981 Jun	165
			LWR 11881	1981 Nov	340
			SWP 15359	1981 Nov	395
			SWP 18247	1982 Oct	380
			LWP 1718	1982 Nov	365
M33 Var 2	1 31 29.0	+30 23 16.5	LWR 10966	1981 Jun	240
			SWP 14355	1981 Jun	180
M33 Var B	1 31 00.0	+30 22 48.1	LWR 11861	1981 Nov	360

II. OBSERVATIONS

Although the H-S variables are blue and have ultraviolet excesses, they are typically 16–17 mag in the visual, and only the very brightest can be observed with the *IUE*. Only five of the H-S variables were bright enough and then only marginally. These stars were all brighter than $V = 17$ mag, and most were near $V \approx 16$ mag at the time of observation. Long (LWR = 1800–3255 Å and short (SWP = 1135–2085 Å) wavelength low-dispersion spectra were obtained of AF And in M31 and Var 83 and Var 2 in M33, but only long-wavelength spectra were observed for Var B in M33 and Var A-1 in M31. Because of their faintness these stars could not be seen with the acquisition telescope, and the spectra had to be acquired by blind offset from nearby stars which were typically $V \approx 12$–14 mag. The stars were all centered in the large *IUE* aperture, and there was no problem with possible contamination from nearby hot stars. The spectra were all stellar, which means that the effective aperture for possible contamination is actually a 10″ × 6″ area. Table 1 is a journal of the ultraviolet observations and includes the 1950 coordinates for these objects. The positions were measured from plates of M31 and M33 at Kitt Peak and ESO and are based on coordinates of SAO stars. The accuracy of these coordinates is 1″ from both the internal accuracy of the measurements and a comparison of the two independent determinations.

All of the 1981 *IUE* spectra were obtained at NASA Goddard Space Flight Center and were reduced according to standard procedures. Known reseau marks and hot pixels were removed from the spectra and patched over before any integrated fluxes were measured. The 1982 *IUE* spectra of Var 83 and AF And were recorded at the Villafranca Satellite Tracking Station of the European Space Agency. The geometrically and photometrically two-dimensional corrected images were converted to the format of the ESO two-dimensional data reduction system (IHAP) and analyzed in Garching.

Broad-band fluxes were measured from the calibrated ultraviolet spectra for three passbands: a short wavelength (SW), a long wavelength (LW), and one (MW) centered on the 2200 Å feature. The central wavelength and width of each passband are

	λ (μm)	$\Delta\lambda$ (μm)
SW	0.160	0.1225–0.1975
MW	0.220	0.2050–0.2350
LW	0.270	0.2350–0.3050

The corresponding fluxes for the five variables are in Table 2. Narrower passbands were not used because of the stars' faintness. Formal error estimates based on signal-to-noise ratios are unrealistically small. The real uncertainty can be estimated from comparison of the stars' spectra with the noise in the background spectra. This comparison suggests uncer-

TABLE 2

FLUXES FROM THE *IUE* OBSERVATIONS

		FLUX (10^{-19} W cm^{-2})		
STAR	DATE	SW (0.16 μm)	MW (0.22 μm)	LW (0.27 μm)
M31 AF And	1981 Nov	...	0.80	2.35
	1982 Nov	2.40	0.60	2.03
M31 Var A-1	1981 Nov	...	0.34	1.14
M33 Var 83	1981 Jun	5.10	1.41	3.50
	1981 Nov	4.84	1.24	3.51
	1982 Nov	2.93	1.29	3.99
M33 Var 2	1981 Jun	3.74	1.09	2.22
M33 Var B	1981 Nov	...	1.46	3.31

tainties of 10%–20% for the best spectra and about 30% for the worst cases.

All of the available visual and infrared photometry is summarized in Table 3. The 1976 and 1977 observations are from Humphreys (1978) and Humphreys and Warner (1978). Additional *UBVR* photometry was measured in 1980, 1981, and 1982 August with the Mark I "computer photometer" on the KPNO 2.1 m telescope and in 1982 October with the pulse-counting photometer on the UM-UCSD 1.5 m on Mount Lemmon. Both visual photometers are aperture chopping instruments with simultaneous sky measurements. To map the background contribution, different sky positions were measured around each star. The *JHK* observations were made with the indium-antimonide system on the Mount Palomar 5 m in 1980 October. The standard beam-switching observing procedures for infrared photometry were used.

III. THE SPECTRAL ENERGY DISTRIBUTIONS

Fluxes ranging from the ultraviolet to 2.2 μm are now available for five of the H-S variables, and it is possible to

TABLE 3

SUMMARY OF VISUAL AND INFRARED PHOTOMETRY

Star	Date	V (mag)	$U-B$ (mag)	$B-V$ (mag)	$V-R$ (mag)	$V-I$ (mag)	$V-J$ (mag)	$V-H$ (mag)	$V-K$ (mag)
M31 AE And....	1976 Sep	17.00	−0.81	+0.10	+0.34	+0.62	…	…	…
	1977 Oct	17.33	−0.78	+0.06	+0.24	…	…	…	…
	1980 Nov	17.94	…	+0.08	+0.41	…	…	+0.91	+0.82
	1981 Dec	17.79	−0.85	0.00	+0.47	…	…	…	…
	1982 Aug	17.57	−0.95	+0.08	+0.41	…	…	…	…
	1982 Oct	17.39	−0.96	+0.05	…	…	…	…	…
M31 Var 15	1976 Sep	17.47	−0.49	+0.44	+0.66	+0.84	…	…	…
	1977 Oct	17.69	−0.57	+0.36	+0.63	…	…	…	…
	1980 Nov	17.32	…	…	+0.74	…	+1.41	+1.59	+1.96
	1981 Dec	17.27	−0.49	+0.43	+0.80	…	…	…	…
	1982 Aug	17.01	−0.35	+0.48	+0.71	…	…	…	…
	1982 Oct	17.35	−0.27	+0.33	+0.95	…	…	…	…
M31 AF And....	1976 Sep	16.05	−0.85	+0.11	+0.43	+0.74	…	…	…
	1977 Oct	16.11	−0.82	+0.18	+0.35	…	…	…	+1.3
	1980 Nov	16.42	…	−0.01	+0.26	…	+0.74	+1.07	+1.33
	1981 Dec	16.52	−0.92	+0.13	+0.37	…	…	…	…
	1982 Aug	16.40	−0.90	+0.18	+0.41	…	…	…	…
	1982 Oct	16.35	−0.91	+0.20	+0.49	…	…	…	…
M31 Var A-1	1976 Sep	16.26	−0.54	+0.41	+0.54	+0.71	…	…	…
	1977 Oct	16.25	−0.49	+0.40	+0.58	…	…	…	+1.8
	1980 Nov	16.59	…	+0.39	+0.50	…	+1.13	+1.36	+1.47
	1981 Dec	16.75	−0.65	+0.42	+0.50	…	…	…	…
	1982 Aug	16.39	−0.71	+0.40	+0.51	…	…	…	…
	1982 Oct	16.60	−1.12:	+0.35	+0.95:	…	…	…	…
M33 Var B	1976 Sep	17.11	−0.82	+0.01	+0.93	…	…	…	…
	1977 Oct	17.31	−1.02	−0.11	+0.05	…	…	…	…
	1981 Dec	16.14	−0.75	+0.22	+0.37	…	…	…	…
	1982 Aug	16.30	−0.39	+0.14	+0.34	…	…	…	…
	1982 Oct	15.63	−0.51	+0.31	+0.53	…	…	…	…
M33 Var 2	1976 Sep	18.17	−1.00	−0.17	+0.46	…	…	…	…
	1977 Oct	18.10	−1.03	−0.19	+0.42	…	…	…	…
	1980 Nov	16.36	…	+0.22	+0.41	…	+0.59	+0.89	+1.07
	1981 Dec	17.29	−0.93	+0.05	+0.43	…	…	…	…
	1982 Aug	17.43	−0.85	+0.15	+0.45	…	…	…	…
	1982 Oct	17.63	−1.00:	+0.01:	+0.51:	…	…	…	…
M33 Var 83	1976 Sep	16.72	−0.93	+0.05	+0.22	…	…	…	…
	1977 Oct	16.63	−0.87	0.00	+0.30	…	…	…	+2.5
	1980 Nov	16.51	…	+0.10	+0.34	…	+0.27	+0.45	+0.68
	1981 Dec	16.16	−0.90	+0.05	+0.37	…	…	…	…
	1982 Aug	15.67	−0.90	+0.18	+0.35	…	…	…	…
	1982 Oct	15.43	−0.83	+0.20	+0.24	…	…	…	…
M33 Var A	1977 Oct	18.55	+0.05	+0.84	+1.25	…	…	…	+4.8
	1980 Nov	18.45	…	+1.05	+1.10	…	+2.31	+3.26	+4.43
	1981 Dec	18.43	…	+1.24:	+1.14	…	…	…	…
	1982 Aug	18.09	+0.11	+0.88	+1.03	…	…	…	…
M33 Var C	1976 Sep	17.17	−0.79	−0.05	…	…	…	…	…
	1977 Oct	16.98	−0.76	0.00	+0.10	…	…	…	…
	1980 Nov	17.21	…	−0.01	+0.08	…	…	…	…
	1981 Dec	17.23	−0.77	+0.10	…	…	…	…	…
	1982 Aug	17.15	−0.43	+0.09	+0.29	…	…	…	…
	1982 Oct	16.48	−0.59	+0.09	+0.52	…	…	…	…

NOTE.—The errors in the visual photometry for most of these stars are 0.02–0.05 mag, and for the infrared photometry they are typically 0.10 mag.

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TABLE 4

SUMMARY OF LUMINOSITIES AND TEMPERATURES FOR THE HUBBLE-SANDAGE VARIABLES

Star	V (mag)	Date	A_v (mag)	V_0 (mag)	M_v (mag)	$M_{\rm bol}$ (mag)	$T_{\rm BB}$ (K)	$M_{V\rm max}$ (mag)	$\dot{M}$ ($10^{-5}\ M_\odot\ \rm yr^{-1}$)
M31 AF And[a]	16.35	1982 Oct	1.05	15.30	−8.8	−10.9	25000	−9.9	4.8
Var A-1[a]	16.59	1980 Nov	1.3	15.3	−8.8	−10.6 to −11.3	25000–30000	−10.9	1.5
AE And	17.79	1981 Dec	0.70	17.09	−7.0	−8.3	15000	−10.2	...
Var 15	17.27	1981 Dec	1.05	16.22	−7.9	−8.4	8300	−8.9	...
			1.70	15.57	−8.5	−9.5	12400	−9.6	...
M33 Var 83	16.16	1981 Dec	0.9–1.10	15.16	−8.7	−11.7	37000	...	3.0
	15.43	1982 Oct	0.9–1.10	14.43	−9.5	−11.4	25000	−9.5	3.0
Var 2	16.36	1980 Nov	0.77–0.97	15.49	−8.4	−10.8	27400	−9.0	3.6
Var B	16.14	1981 Dec	0.55–0.75	15.49	−8.4	−10.3	22900	−9.8	...
Var A	18.45	1980 Nov	2.53–2.73[b]	15.82	−8.1	...	...	...	...
			0.82–1.02[c]	...	...	...	...	−9.5	...
Var C	17.2	1980/1981	0.70–0.90	16.4	−7.5	...	...	−8.9	...

[a] See the text for more discussion of these stars' temperatures and luminosities.

[b] A_v includes circumstellar component.

[c] A_v interstellar only.

discuss their energy distributions and a determination of their bolometric luminosities and temperatures. However, the observations must first be corrected for interstellar extinction, both foreground and internal reddening. These stars are in young stellar associations in the spiral arms of M31 and M33, and it is very likely that they suffer some reddening due to dust inside their galaxies. Indeed their observed energy distributions show that these stars are suffering some reddening.

Because of their peculiar emission-line spectra, we cannot use the observed multicolor photometry to estimate their reddening. An alternative method is available from the neutral hydrogen maps, which provide a means of estimating the visual extinction along the line of sight. Knapp, Kerr, and Rose (1973) and Savage and Jenkins (1972) have shown that the column density of neutral hydrogen in our Galaxy is proportional to $E_{B-V}(n_{\rm H\,I} = 5.6 \times 10^{21} E_{B-V})$. The $n_{\rm H\,I}$ is then determined along the line of sight to each star from the H I maps published by Roberts (1966) for M31 and by Wright, Warner, and Baldwin (1972) for M33. The corresponding visual extinction, A_v, is found from the above relationship assuming that the ratio of total to selective extinction is 3. We do not know the exact location of the stars with respect to the neutral hydrogen along the line of sight, and it is rather unlikely that all of the extinction estimated from the H I column density should be applied; consequently, we have assumed that on the average the stars experience only half the extinction from the neutral hydrogen. We also know that the minimum A_v due to foreground reddening is 0.4 mag in front of M31 (van den Bergh 1968) and 0.1–0.3 mag in front of M33 (van den Bergh 1968; Humphreys 1980; Sandage 1983; Massey and Hutchings 1984). The adopted A_v is then defined as the foreground A_v and half that from the neutral hydrogen column density. This information is included in Table 4, together with the visual magnitude closest to the time of the ultraviolet observations and the resulting absolute visual luminosity from the adopted true distance moduli of 24.1 mag (van den Bergh 1977) and 23.9 mag (Humphreys 1980) for M31 and M33, respectively.

The broad-band energy distributions from the ultraviolet to 2.2 μm are shown in Figures 1 through 6 for the five H-S variables with *IUE* observations. The visual and infrared photometry closest to the time of the ultraviolet data are used for the energy distributions. This presents a small problem for some of the stars which were varying, because it was not always possible to have nearly simultaneous observations, but the colors of most of the stars show only small fluctuations even though the visual magnitude may be varying somewhat. Only one complete set of infrared photometry (*JHK*) is presently available for most of the stars, and these same infrared colors were assumed to be applicable to visual photometry obtained later. The original observations together with the data corrected for the visual extinction defined above

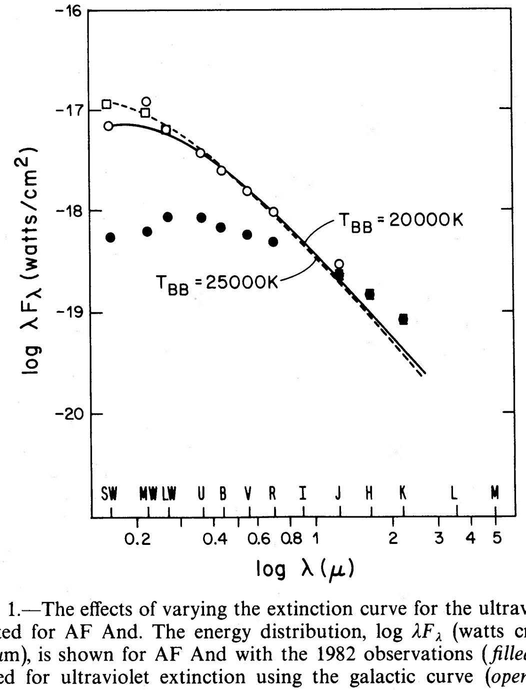

FIG. 1.—The effects of varying the extinction curve for the ultraviolet are illustrated for AF And. The energy distribution, log λF_λ (watts cm^{-2}) vs. log λ (μm), is shown for AF And with the 1982 observations (*filled circles*) corrected for ultraviolet extinction using the galactic curve (*open circles*) and the curve for the LMC (*squares*). The extinction curves for the two galaxies give significantly different results only for wavelengths shorter than about 2500 Å. The 2200 Å feature can be better fitted with a blackbody when the LMC extinction curve is used.

are shown in the plots of the energy distributions, Figures 1 to 9, for the H-S variables.

The effects of varying the ultraviolet extinction curve are illustrated in Figure 1 for AF And. The original observations are shown corrected using both the galactic (Nandy *et al.* 1975) and the LMC (Nandy *et al.* 1980) ultraviolet extinction curves with the adopted visual extinction. It is clear that the galactic extinction curve overcorrects the flux in the 2200 Å feature. This is the case for all of the H-S variables in both M31 and M33. On the average the 2200 Å feature from hot stars in the LMC is somewhat lower, and when the UV extinction curve for the LMC is used, the "excess" at 2200 Å is largely eliminated for most of the H-S variables. Use of the LMC extinction curve also results in higher temperature blackbody fits to the observations and consequently higher luminosities.

It may seem premature to draw conclusions about the ultraviolet interstellar extinction in M31 and M33 on the basis of these marginal data, because the 2200 Å region has low sensitivity with the *IUE* detector, and the calibration at these low flux levels is uncertain. However, Massey and Hutchings (1984) have also found that the LMC ultraviolet extinction curve is more appropriate for their *IUE* observations of the luminous Wolf-Rayet stars in M33. For these reasons we have decided to adopt the LMC extinction curve for the H-S variables in M31 and M33.

We have also investigated the effects of varying the adopted extinction on the blackbody temperatures and luminosities. It is obvious from the observations that all of the stars require some correction for interstellar extinction. Figures 3 and 4*a* for Var A-1 in M31 and Var 83 in M33, respectively, show the observations corrected for the minimum, or foreground, reddening, the medium or adopted value defined above, and the maximum value from the neutral hydrogen column density. A blackbody curve fit to these stars' observations when corrected for the minimum extinction can usually be matched reasonably well with the ultraviolet photometry, but gives a poor fit at the red and infrared wavelengths, often with a very large infrared excess, which is unrealistic. (Evidence for free-free emission from some of the H-S variables is discussed below.) For most of the H-S variables the maximum extinction also gives a much poorer blackbody fit to the observations, often resulting in a very large depression of the visual, red, and infrared photometry below the blackbody curve as for Var 83, for example. Thus it seems that our adopted extinction based on the foreground reddening plus the average extinction from the neutral hydrogen column density is reasonable for most of the stars.

We have fitted the unreddened observations with simple blackbody curves. Our energy distributions based on broadband photometry and our low ultraviolet fluxes very likely do not warrant more extensive modeling. In addition, their low surface gravities and lack of a Balmer discontinuity in their blue spectra suggest that the H-S variables are more like blackbodies than normal stars of similar temperatures. The unreddened distributions with the adopted blackbody curves were integrated from 0.09 to 2.2 μm to determine the total flux of the star and consequently its total luminosity. The blackbody temperatures and the luminosities (M_{bol}) determined in this way are also included in Table 4. Further discussion of the choice of the appropriate temperature for each individual star is given below. Additional evidence for the extinction and temperature selection for AF And and Var A-1 discussed below can be obtained from the Zanstra method and the Hβ line strengths for these stars from Gallagher, Kenyon, and Hege (1981).

When the best fit blackbody curve is placed through the ultraviolet and visual observations for some of the H-S variables, it is readily apparent that their infrared fluxes lie somewhat above the blackbody curves. It is very likely that these stars have some excess infrared radiation due to free-free emission from their extended atmospheres. The low-resolution *IUE* spectra are inadequate to comment on evidence for mass loss from the line profiles. However, a rough mass loss ($\dot{M}$) estimate can be determined from the $J-K$ color excess due to free-free emission from Hyland's (1979) empirical calibration of $E_{\mathrm{ff}}(J-K)$ versus $\dot{M}/V_{\infty}$, where V_{∞} is the terminal velocity. The adopted intrinsic $J-K$ colors are from Johnson (1966) using the best fit blackbody temperature from the energy distributions to approximate the true stellar temperature. Because we cannot measure V_{∞} directly for these stars, we adopted the value for P Cyg of 300 km s^{-1} from Barlow and Cohen (1977). This assumption is reasonable because the H-S variables are spectroscopically and photometrically similar to P Cyg (see § V). R81 in the LMC, another member of this class of variables, has a V_{∞} of 250 km s^{-1} (Wolf *et al.* 1981). The resulting mass loss rates are given in Table 4 and, for all the stars, are around 10^{-5} $M_{\odot}$ yr^{-1}, which is comparable to the mass loss rates for the other luminous variables P Cyg, R81, R71, and S Dor. Although these rates are quite reasonable, they must be considered preliminary until higher resolution ultraviolet spectra become available.

The energy distributions for the individual stars are discussed below.

M31: AF And.—An LWR spectrum was obtained with *IUE* in 1981 November, and in 1982 October/November, both SWP and LWR observations were successfully made. The latter observations are used for the energy distribution in Figure 2.

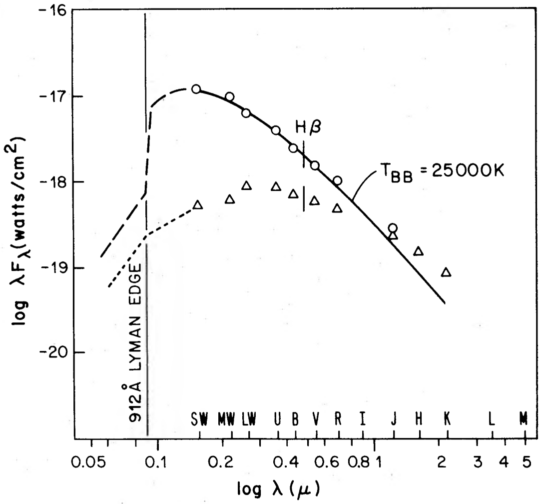

FIG. 2.—The energy distribution, log λF_{λ} (watts cm^{-2}) vs. log λ (μm), for AF And with the 1982 observations (*triangles*). When corrected for the adopted extinction (*circles*) using the LMC curve, a 25,000 K blackbody gives a good fit to the data, with a small excess in the infrared. The Lyman discontinuity has been estimated from the Hβ emission-line intensity (see text).

It is fortunate that there is nearly simultaneous visual photometry from 1982 August and October, although it is necessary to use the infrared colors from the 1980 observations. A 25,000 K blackbody gives a good fit to the ultraviolet and visual data; however, the infrared flux is significantly above any blackbody fit to the short-wavelength observations. The same is true with the 1980 and 1981 observations. This infrared excess radiation, attributed to free-free emission in the star's extended atmosphere, corresponds to a mass loss rate of $4.8 \times 10^{-5}\ M_{\odot}\ \mathrm{yr}^{-1}$.

Another indicator of the appropriate temperature of AF And is the strength of the Lyman discontinuity. These stars have weak Balmer discontinuities, so emission-line intensities should not be affected much by underlying absorption. Therefore, we have used the Hβ equivalent width for the Zanstra estimate of the ionizing continuum ($\lambda < 912$ Å). For such an estimate one supposes that the Hβ flux indicates the rate of hydrogen recombinations in the gas ionized by the star, and therefore the rate at which the star radiates ionizing photons.

Figure 2 illustrates the results of the Zanstra estimate for AF And. For simplicity, the blackbody fits are continued almost to the Lyman threshold (912 Å), and the ionizing continua are taken to have the same slopes that the ultraviolet blackbody curves would have. A moderately large Lyman discontinuity is found for the 25,000 K blackbody fit. This is probably reasonable or even a little large for this temperature. The appropriate temperature for AF And is probably 20,000–25,000 K. A much higher temperature is definitely ruled out, and a lower temperature would have too small a Lyman discontinuity to be plausible. Using Panagia's (1973) compilation of parameters, we would estimate $T_{\mathrm{eff}} \sim 24{,}000$ K for AF And on the basis of the Hβ equivalent width alone. The luminosity is -10.90 mag for 25,000 K.

Var A-1.—Only "long-wavelength" (LWR) observations from *IUE* are available for Var A-1, and its energy distribution is shown in Figure 3 with three different estimates of the visual extinction. The visual photometry from 1981 December was obtained only 1 month after the ultraviolet spectrum. The observations for Var A-1 corrected for minimum reddening ($A_v = 0.4$ mag) cannot be fitted with a blackbody curve. The medium ($A_v = 1.05$ mag) and maximum ($A_v = 2.70$ mag) extinction estimates from the neutral hydrogen column density correspond to blackbody temperatures of 20,000 K and 37,000 K, respectively. The 37,000 K blackbody fit entails a very strong Lyman discontinuity (see Fig. 3), too strong to be plausible for such a high temperature. (This statement is based on available models for main-sequence continua [Auer and Mihalas 1972; Panagia 1973] plus the qualitative fact that lower surface gravity implies a reduced Lyman discontinuity.) The 20,000 K fit has only a small Lyman discontinuity, which is also implausible for such a *low* temperature. Thus, an intermediate temperature, around 25,000–30,000 K, is most likely. This corresponds to an intermediate extinction around $A_v = 1.3$ mag and a luminosity of -10.6 to -11.3 mag for Var A-1. The effective temperature for Var A-1 based on Panagia's parameters is also about 25,000 K, from the Hβ equivalent width alone, independent of reddening.

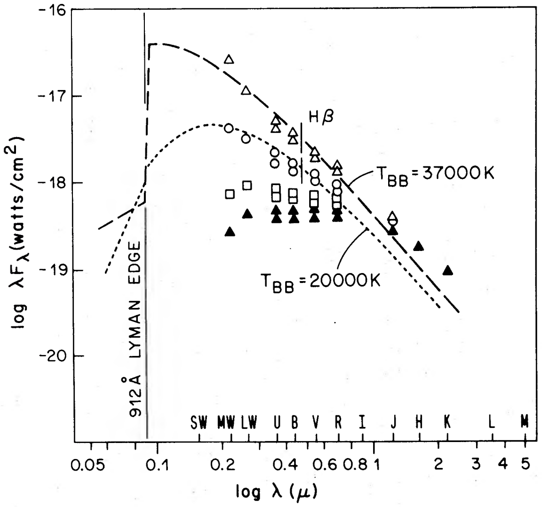

FIG. 3.—The energy distribution, log λF_{λ} (watts cm^{-2}) vs. log λ (μm), for Var A-1 with the 1980 and 1981 (*filled triangles*) observations corrected for three different estimates of the visual extinction (see text). The Lyman discontinuity has been estimated from the Hβ emission-line intensity (see text).

With a 25,000 K blackbody fit to the ultraviolet and visual observations, Var A-1 has a small excess in the infrared. A mass loss rate of 1.5×10^{-5} is derived from this free-free emission in the infrared.

M33: Var 83.—This star seems to be the hottest in the group at this time. It is also now the visually brightest; consequently, it has the largest number of *IUE* observations. It is worth noting that Var 83 has been slowly getting brighter over the past 6 yr, and it is now (1982 October) the brightest it has ever been observed ($V = 15.4$ mag). Both LWR and SWP observations of Var 83 were obtained in 1981 June and November and in 1982 October/November. During this time the star brightened in the visual by nearly a magnitude. This makes it possible to compare the star's temperature and total luminosity as it brightens.

The energy distributions are shown in Figures 4*a* and 4*b* for the 1981 November and 1982 November observations, respectively. The 1981 visual photometry was obtained only 1 month after the ultraviolet observations, but the infrared data are from the previous year.

Figure 4*a* shows the energy distribution of Var 83 with three different extinction corrections. The minimum value, due to foreground extinction alone ($A_v = 0.1$–0.3 mag), is obviously inappropriate and results in a large excess at the red and infrared wavelengths. In contrast the maximum extinction from the neutral hydrogen column density is obviously extreme and results in a depression of the long-wavelength data. The adopted extinction of 0.9–1.10 mag can be reasonably fitted by a 37,000 K blackbody with a small infrared excess, most likely the result of free-free emission. The corresponding mass loss rate is $3 \times 10^{-5}\ M_{\odot}\ \mathrm{yr}^{-1}$.

The 1982 observations show a significant change in the fluxes for both ultraviolet passbands. The short-wavelength (0.16 μm) flux decreased, while the star brightened at the longer wavelength (0.27 μm). The energy distribution clearly shows a shift in the peak flux to longer wavelengths, and a 25,000 K blackbody gives a good fit to the 1982 data. As the star brightened in the visual, its temperature decreased significantly by nearly 30%; however, the total luminosity of Var 83 remained essentially the same; the bolometric

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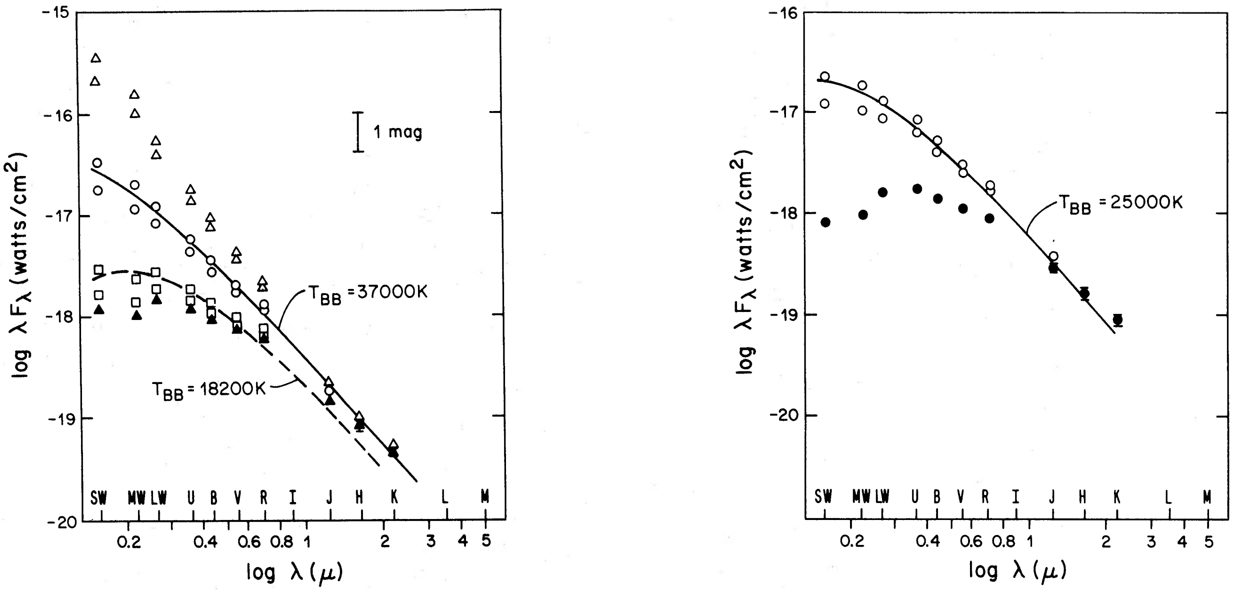

FIG. 4*a*

FIG. 4*b*

FIG. 4.—(*a*) The energy distribution, log λF_λ (watts cm^{-2}) vs. log λ (μm), for Var 83 with the 1981 November observations (*filled triangles*) corrected for three different values of the visual extinction (see text). The data corrected for the moderate adopted extinction can be fitted reasonably well with a 37,000 K blackbody. (*b*) Same as Fig. 4*a* for Var 83 with the 1982 November observations (*filled circles*). Comparison with Fig. 4*a* illustrates the shift in the peak flux to longer wavelengths as Var 83 brightened.

magnitudes are −11.7 mag and −11.4 mag in 1981 and 1982, respectively.

Var 2.—Both LWR and SWP spectra were obtained with *IUE* in 1981 June, but Var 2 decreased in visual brightness by nearly 1 mag between 1980 November and 1981 December. Figure 5 shows the energy distribution with the 1980 visual photometry. The ultraviolet data, taken in 1981 June, fit quite well with the 1980 visual and infrared data with a blackbody temperature of 27,400 K. The 1981 December photometry is too low to fit the ultraviolet data; therefore, it is suspected that most of the decline in brightness occurred between 1981 June and December. Indeed, if Var 2 had been as dim in June as the December observations indicate, it could not have been observed with *IUE*.

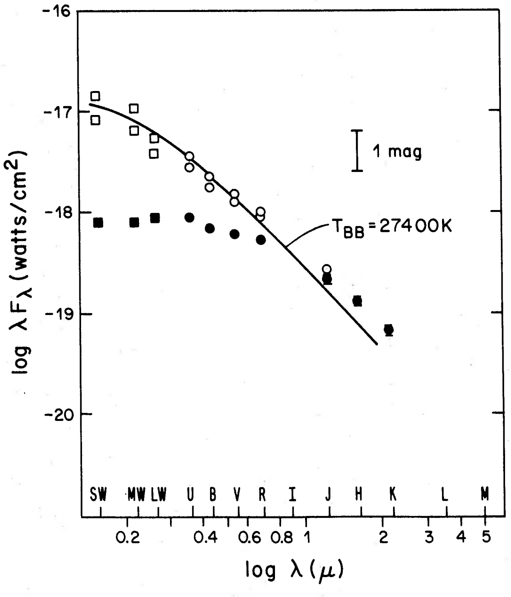

FIG. 5.—The energy distribution, log λF_λ (watts cm^{-2}) vs. log λ (μm), for the ultraviolet data (*squares*) and the 1980 (*circles*) visual and infrared observations of Var 2. When corrected for the adopted extinction (*open symbols*) a 27,400 K blackbody gives a good fit to the 1980 photometry and the ultraviolet data.

The infrared excess yields a mass loss rate of about 3.6×10^{-5} $M_\odot$ yr^{-1}.

Var B.—Only the LWR spectrum is available from *IUE*, and no infrared observations were made of Var B in 1980. With this limited wavelength coverage only a rough temperature estimate can be obtained; however, the available photometry definitely indicates a hot blackbody. A 22,900 K blackbody gives a good fit to the data in Figure 6.

The remaining four H-S variables were too faint at the time for observation with *IUE*. However, for the purpose of completeness it is possible to make some estimate of the temperature and luminosity of AE And and Var 15 in M31 from the visual and infrared photometry. Var C in M33 has been omitted from the discussion in this paper because of its limited wavelength coverage; only visual photometry is available. Var A is the most unique and, potentially, the most interesting of the H-S variables. It is the only one which apparently has a circumstellar dust shell. Its peculiar energy distribution is discussed here, but because of its very high reddening, it is not possible to determine the temperature and luminosity without further long-wavelength observations.

M31: AE And.—This blue variable has photometric data from the visual through the infrared. The 1980, 1981, and 1982 visual observations are all shown in Figure 7 with the 1980 infrared photometry. The observed energy distribution is fitted reasonably well by a 15,000 K blackbody. It is possible that a higher temperature blackbody could be drawn through

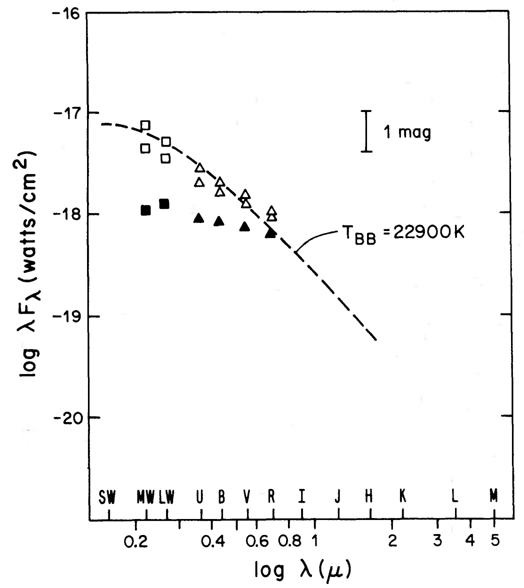

FIG. 6

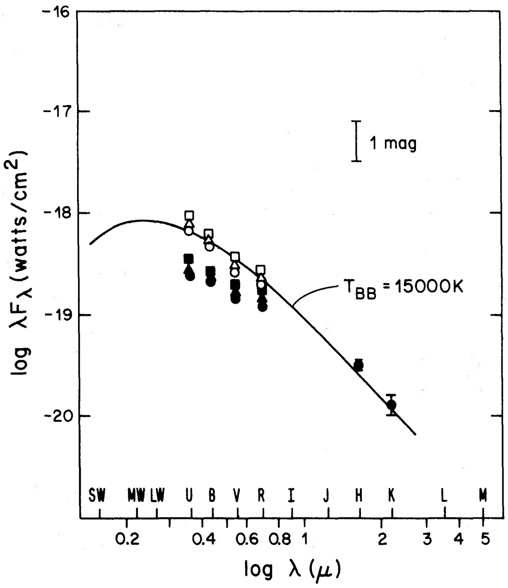

FIG. 7

FIG. 6.—The energy distributions, log λF_λ (watts cm^{-2}) vs. log λ (μm), for the 1981 observations of Var B. A 22,900 K blackbody is shown fitted to the limited visual and ultraviolet photometry corrected for the adopted extinction.

FIG. 7.—The energy distribution, log λF_λ (watts cm^{-2}) vs. log λ (μm), for AE And. The 1980 (*circles*), 1981 (*triangles*), and 1982 (*squares*) visual photometry is all shown. There are no ultraviolet observations. When corrected for the adopted extinction (*open circles*) the data are fitted reasonably well with a 15,000 K blackbody.

the visible points, with the infrared partially attributed to free-free emission. Obviously, ultraviolet data are needed for a more accurate determination of the temperature of AE And.

Var 15.—This star appears to be the coolest of the H-S variables. The energy distribution in Figure 8 is best fit by a blackbody of 8300 K. Even with the maximum visual extinction from the H I data applied, a relatively low temperature is still indicated, 12,400 K. Since a low temperature is unusual for this group of stars, the 1976 and 1977 observations were also examined, and they also suggest a temperature near 8000 K.

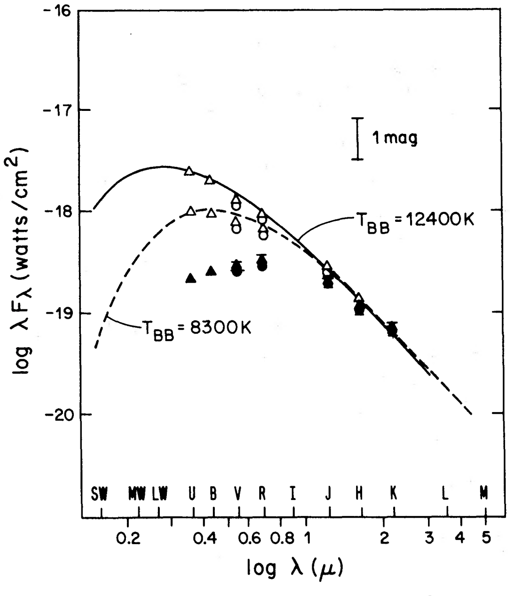

FIG. 8.—The energy distribution, log λF_λ (watts cm^{-2}) vs. log λ (μm), for Var 15 showing the 1980 (*circles*) and 1981 (*triangles*) observations. A 8300 K blackbody is fitted through the observations corrected for the adopted extinction (*open symbols*), and a 12,400 K blackbody for the same observations with maximum extinction.

M33: Var A.—This peculiar star is the most interesting member of the H-S group. It may very well be an extragalactic η Car. Its light curve (Hubble and Sandage 1953; Rosino and Bianchini 1973) is quite similar to η Car. In late 1950, Var A reached maximum brightness ($M_{pg} \approx 15.7$ mag) with a color index of +0.33 mag. After a very rapid decline followed by a secondary peak, the color index had reddened to +1.5, and the star had dimmed to $M_{pg} \approx 19$ mag. It has remained faint ever since (see Table 3). Humphreys and Warner (1978) found that Var A has a large infrared excess with a $V-K$ of 4.8 mag. Var A's photometric behavior plus its infrared radiation suggests the ejection of one or more shells in 1950–1953, followed by the formation of circumstellar dust.

Figure 9 shows its energy distribution. Clearly the infrared flux is increasing with wavelength and is highly suggestive of circumstellar dust. The observations corrected for interstellar extinction determined as for the other variables are shown, and it is obvious that Var A may have additional reddening, perhaps due to circumstellar dust. To test this idea a value for circumstellar extinction is estimated. Assuming dust formed after Var A reached maximum, much of the presently observed red color may be attributed to circumstellar dust. The color index at maximum, transformed to $B-V$, is assumed to be due to the star plus some interstellar reddening, and the extinction from circumstellar dust is defined as

$$(E_{B-V})_{\rm CS} = (B-V)_{\rm now} - (B-V)_{\rm max} .$$

A $B-V$ of 1.01 mag is adopted from the observations in Table 3, and the excess attributed to circumstellar dust is 0.57 mag. Assuming the same ratio of total to selective

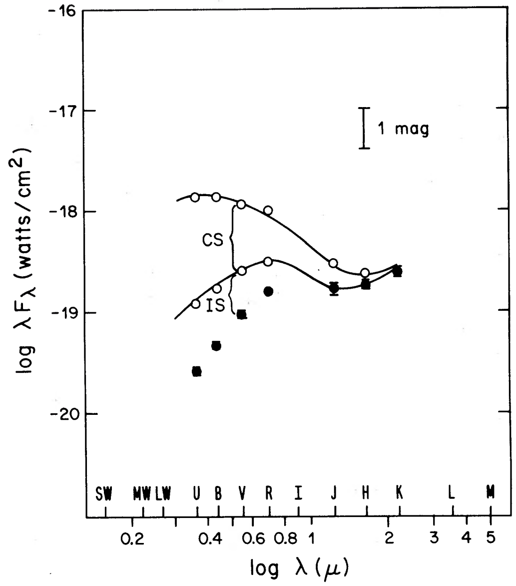

FIG. 9.—The energy distribution, log λF_λ (watts cm^{-2}) vs. log λ (μm), for Var A with the 1980 observations (*filled circles*). The data are shown (*open circles*) when corrected for interstellar extinction and for possible circumstellar extinction (see text).

extinction (R) as for interstellar dust yields $(A_v)_{CS}$ of 1.71 mag. The value of R may be larger than 3 for the circumstellar dust, but it is at present unknown. This then gives a total reddening of 2.73 mag $[(A_v)_{IS} + (A_v)_{CS}]$. The energy distribution corrected for this total reddening is also shown in Figure 9. These results are of course all very preliminary, but it is very interesting that with a correction for circumstellar reddening, Var A is still brightening at K (2.2 μm). Certainly, longer wavelength observations, especially at 10 μm, are needed.

IV. THE ULTRAVIOLET SPECTRA OF THE HUBBLE-SANDAGE VARIABLES

Several of the brightest members of the "S Doradus" class of variables have been observed previously with *IUE*. Wolf, Appenzeller, and Cassatella (1980), Wolf, Appenzeller, and Stahl, (1981), and Wolf *et al.* (1981) have discussed the ultraviolet spectra of S Dor, R71, and R81 in the LMC. Cassatella *et al.* (1979), Luud and Sapar (1980), and Lamers, de Groot, and Cassatella (1983) have described the ultraviolet spectrum of P Cyg, and Cassatella, Giangrande, and Viotti (1979) and Viotti *et al.* (1981) have briefly commented on the spectrum of η Car.

All of these stars are in the Galaxy or the LMC and are therefore sufficiently bright to be observed with the *IUE* high-dispersion camera. Most of the previous work, mentioned above, is primarily concerned with an analysis of the line profiles and a determination of the mass loss rates. There has been no previous attempt to compare the energy distributions and the main spectral features in the ultraviolet region as derived from the low-dispersion data. Therefore, we have also obtained low-dispersion spectra of η Car, P Cyg, and S Dor for a comparative discussion with our ultraviolet spectra of the H-S variables, for which only a few features can be recognized due to the low signal-to-noise ratio. The combined *IUE* short- and long-wavelength spectra of η Car, P Cyg, and S Dor are shown in Figure 10*a*, with the principal line identifications from the above references. The ultraviolet spectra of AF And and Var 83 in M33 from two different times are shown in Figure 10*b*.

The observed energy distributions of P Cyg and η Car are strongly affected by interstellar reddening, and both stars showed a marked 2200 Å depression. Both the short- and long-wavelength spectra of η Car show strong features, many in absorption, which are blends of metallic lines and are difficult to disentangle at low dispersion. The spectrum of η Car shows a strong Mg II doublet at 2793 and 2803 Å, a very broad absorption centered at 2600 Å due mainly to Fe II multiplet 1, and a sharp drop below 2415 Å, attributed to a combination of absorption by Fe II multiplet 2 and extinction by the 2200 Å feature. In the short-wavelength spectrum, C IV is not as prominent as three strong absorption features centered at 1565, 1620, and 1700 Å, to which the main contributors are probably low-ionization ions of Fe, Mg, Ni, and Al.

In P Cyg, the absorption lines in the 2000–3000 Å region are not as prominent as in η Car; only the Mg II doublet and the Fe II multiplet 1 are readily apparent. The same is true for S Dor, where only Mg II is strong, and the fainter lines have been identified with Fe II by Wolf, Appenzeller, and Cassatella (1980). The same authors show that in the short-wavelength range, C IV at 1500 Å is the strongest feature.

The change in the slope of the continuum of Var 83 between 1981 June and 1982 November, discussed in the previous section, is easily recognized in the ultraviolet spectra shown in Figure 10*b*. However, only a few spectral features can be definitely identified. At short wavelengths, Si II + S II at 1260 Å, Si II + O I at 1303 Å, and C II at 1335 Å are probably present and are mainly interstellar in origin. Si IV 1394–1403 Å and C IV 1550 Å are not clearly identified. At long wavelengths three absorption features are seen centered at approximately 2400 Å (Fe II, 2), 2600 Å (Fe II, 1), and 2800 Å (Mg II). In this respect, the spectrum of Var 83 is more like that of η Car than S Dor. In AF And we cannot clearly identify any features.

V. DISCUSSION: THE HUBBLE-SANDAGE VARIABLES AND MASSIVE STAR EVOLUTION

The *IUE* data presented in this paper confirm the high luminosities and high temperatures suspected from the earlier visual spectra and photometry of the H-S variables. Their bolometric luminosities and absolute visual luminosities corresponding to the time of the ultraviolet observations are summarized in Table 4 together with the blackbody temperatures from their energy distributions; M_v ranges from -7.0 to -9.5 mag and M_{bol} from -8 to ~ -11.7 mag. The brightest magnitudes recorded in the literature (see Humphreys 1978 for references and the data) are used to derive the visual luminosities at "maximum light," which range from -9.0 mag to perhaps as bright as -11 mag. Of course some of these stars may not have been observed at their maximum brightness, and it is unfortunate that we do not know their corresponding bolometric luminosities.

The positions of the H-S variables on the M_{bol} versus temperature H-R diagram are shown in Figure 11 using the bolometric luminosities and blackbody temperatures in Table 4. This H-R diagram from Humphreys (1983) is a

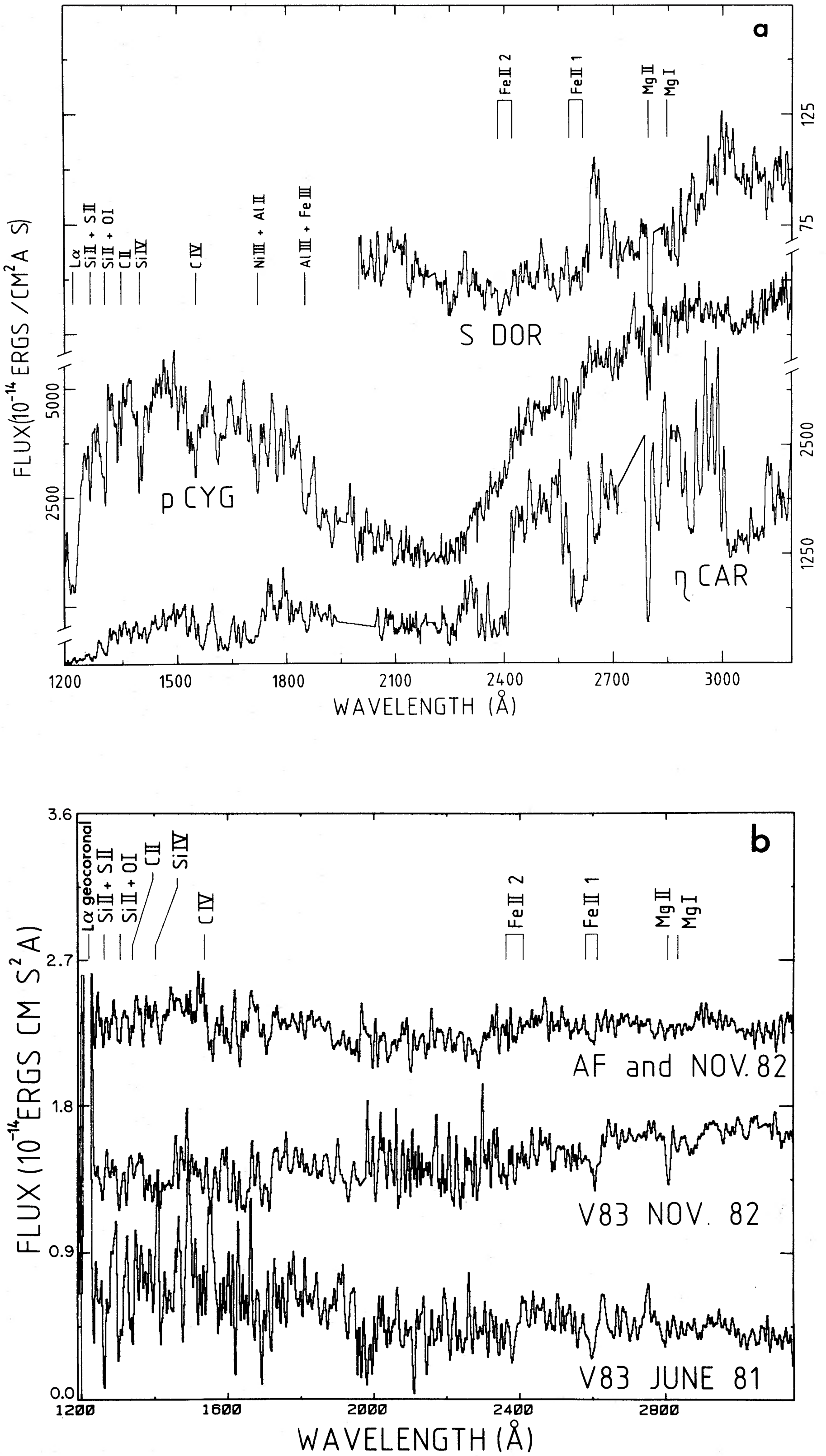

FIG. 10.—(*a*) The combined short- and long-wavelength ultraviolet spectra (1200–3000 Å) of P Cyg and η Car in the Galaxy and of S Dor in the Large Magellanic Cloud (LWR only). The flux scale is indicated on the left for P Cyg and on the right for η Car and S Dor. (*b*) The observed ultraviolet spectra of Var 83 in M33 obtained at two different dates and of AF And in M31. The 1982 spectrum of Var 83 has been shifted upward by one unit, and that of AF And by two units. These spectra have a poor signal-to-noise ratio in the 1950–2350 Å interval because of the low sensitivity in the *IUE* camera in that wavelength range.

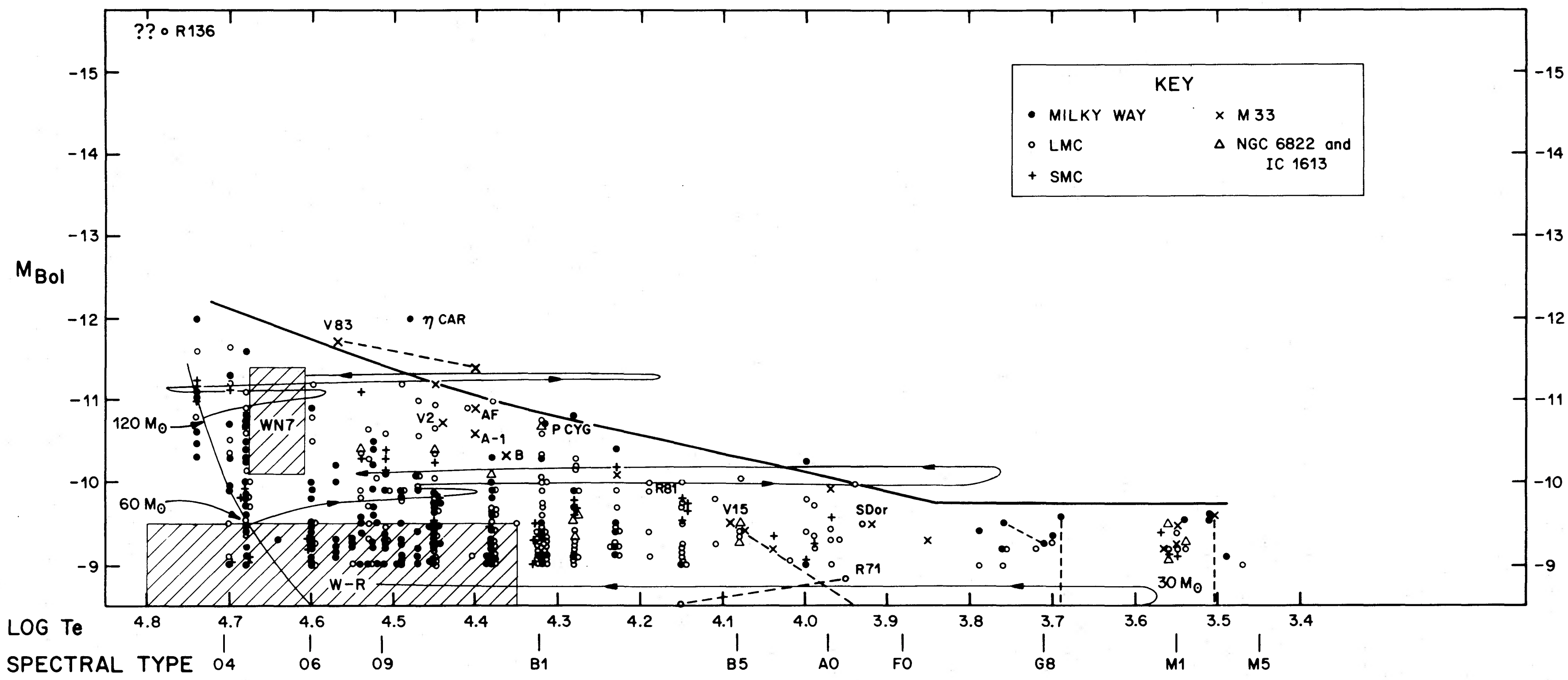

FIG. 11.—The H-R diagram, $M_{\rm bol}$ vs. temperature, for the most luminous stars ($M_{\rm bol} \leq -9.0$ mag) in six Local Group galaxies. The positions of the H-S variables are marked with X's and by name. Their temperatures ($T_{\rm BB}$) and luminosities are from Table 4.

composite for the brightest stars in six Local Group galaxies. Only stars brighter than $M_{\rm bol} = -9.0$ mag are shown, and the evolutionary tracks for massive stars are from Maeder (1983). It is clear from their positions on the H-R diagram that the H-S variables are among the most luminous stars known. Var 83 lies on or near the empirically determined upper luminosity boundary for normal supergiants. It is in the same general region of the diagram where η Car is also found, while AF And, Var A-1, Var 2, and Var B have luminosities and temperatures similar to P Cyg. Only AE And and Var 15 have relatively low luminosities compared with the other H-S variables. Both are presently very faint, perhaps near minimum light, and neither has ultraviolet observations. When ultraviolet data are available, higher temperatures might be indicated. Actually these two stars are rather similar to S Dor and R71 in the LMC (Appenzeller and Wolf 1981), which have luminosities between -8.5 and -9.5 mag and temperatures of 9000–14,000 K.

These observations are consistent with the interpretation that the Hubble-Sandage variables are single, very massive stars. On the basis of their positions on the H-R diagram and their observed instability, they are probably past the core-hydrogen–burning stage. An alternative model proposed by Bath (1979) suggests that stars like η Car and the H-S variables are actually accretion disks around moderately massive stars in binary systems. Unfortunately, the accretion disk model can neither be confirmed nor disproved observationally, although there is no evidence that the bright stars η Car and P Cyg are binaries. Bath's model does imply somewhat lower temperatures than are indicated for η Car and most of the H-S variables. His suggestion is perhaps more appealing for the extreme object, the proposed supermassive star, R136a in the LMC (Savage *et al.* 1983).

Because of their irregular variability and probable high mass loss rates, we may surmise that the H-S variables have reached the point in their evolution when the expected pulsational instabilities in the core (Schwarzschild and Härm 1959; Appenzeller 1970) and high radiation pressure at the surface are responsible for rapid mass loss. Stothers and Chin (1983) have investigated possible mechanisms for their irregular variability. They also conclude that the H-S variables are evolved very massive stars which lie near the Eddington limit of radiative stability and are experiencing recurrent outbursts of near catastrophic mass loss. The exact origin of the instability is not known but very likely occurs in the outer stellar layers or the dense circumstellar shell. Our observations of Var 83 which show it remaining nearly constant in luminosity as it cooled and brightened visually support their model calculations for a massive outflow from the surface of an evolved supergiant. Recent models by Maeder (1983) show that as very massive stars evolve to cooler temperatures, they encounter an instability limit where the turbulent acceleration equals the acceleration due to gravity, the de Jager limit (de Jager 1980). When the star reaches this limit, it must lose mass at an enhanced rate. The models show that although very massive stars near this limit may have significant changes in surface temperature on short time scales, they evolve essentially at constant luminosity. This corresponds to the observations of S Dor and R71 by Appenzeller and Wolf (1981) and Var 83 discussed in this paper. In the case of η Car, and presumably Var A, the mass loss is very likely sporadic and very rapid (Humphreys and Davidson 1979) and has resulted in the formation of an extensive dust shell.

Of the five H-S variables with ultraviolet observations, only Var 83 approaches the high luminosity of η Car ($M_{\rm bol} \approx -12$ mag), but of course most of them have only been observed for about 60 yr, and the information on maximum brightness is necessarily incomplete. Nevertheless, P Cyg, S Dor, R71, and the H-S variables appear to be less extreme examples of the η Car phenomenon. It is possible that all stars above some initial mass, say more than 60–80 $M_\odot$, pass through an η Car/P Cyg stage, during which they must shed a large amount of matter.

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