THE ASTROPHYSICAL JOURNAL, **219**: 445–451, 1978 January 15

LUMINOUS VARIABLE STARS IN M31 AND M33

ROBERTA M. HUMPHREYS*
School of Physics and Astronomy, University of Minnesota
Received 1977 March 21; accepted 1977 July 15

ABSTRACT

Spectra and *UBVRI* photometry of eight luminous blue variables in M31 and M33 reveal the presence of both ultraviolet and infrared excess radiation. These supergiants, including four Hubble-Sandage variables, have spectra characterized by a strong ultraviolet continuum, no apparent Balmer discontinuity, and emission lines of H, He I, Fe II, and [Fe II]. They have very low surface gravities combined with large radiated fluxes. Their luminosities are typically near -10 mag (M_v) at maximum light. AF And in M31 was measured at 2 μ and is the most distant *single star* yet observed at long wavelengths. In addition, a red variable in M31 has been classified as an M supergiant with $M_v \sim -7.2$ mag at maximum.

The hot, very luminous supergiants are spectroscopically and photometrically similar to η Car and S Dor and related objects in our Galaxy and the LMC. Together they form a recognizable group of luminous blue stars in four separate galaxies in the Local Group.

Subject headings: galaxies: individual — stars: emission-line — stars: supergiants — stars: variables

I. INTRODUCTION

The original Hubble-Sandage (H-S) variables (Hubble and Sandage 1953) are a group of five luminous blue variables in M31 and M33: Var 19 (AF And) in M31 and variables A, B, C, and 2 in M33. Spectra of four of the H-S variables (excluding Var A, which is too faint now) plus AE And in M31 were described by the author in a recent paper (Humphreys 1975, Paper I). Their spectra all show a very strong, hot continuum in the ultraviolet and no Balmer discontinuity plus emission lines of H, He I, and Fe II and [Fe II]. These luminous stars are spectroscopically similar to stars like η Car in our own Galaxy and S Dor in the Large Magellanic Cloud and probably belong to the class of stars termed "S Doradus variables" by Kukarkin *et al.* (1974).

In this paper the spectra of three additional blue variables in M31 and M33 and a red variable in M31 are discussed. These luminous blue stars, Var 15 (Hubble 1929) and Var A-1 (Rosino and Bianchini 1973) in M31 and Var 83 in M33 (van den Bergh, Herbst, and Kowal 1975) resemble the H-S variables both spectroscopically and photometrically. The red star, Var 4 in Baade's M31 Field IV (Baade and Swope 1963), is an M supergiant. Additional spectra of AE And and the four H-S variables are also described, and changes in their spectra are noted.

The observations also include *UBVRI* photometry of the luminous blue variables and a 2 μm measurement of AF And (M31 Var 19). The discussion of the spectra and the photometric data suggests that these supergiants in M31 and M33 form a class of objects physically similar to the η Carina–like stars recognized in our Galaxy and the LMC.

II. THE OBSERVATIONS

The "gold" spectrograph with the three-stage RCA image tube was used on the 4 m telescope at the Kitt Peak National Observatory with the 600 g mm^{-1} grating (1st order blaze 4000 Å) to obtain the spectra at 79 Å mm^{-1} with a resolution of $\sim$4 Å. The spectra were automatically widened to 1.2 mm on nitrogen-baked IIa-O plates. Well-exposed spectra are obtained from about 3000 to 5500 Å, and a typical exposure time is 12 minutes for a star with B = 17th magnitude.

The *UBV* photometry was obtained with the "computer photometer" system on the KPNO 2.1 m telescope with an S-11 photocathode and standard filters, and the *VRI* observations were made with an RCA 31034 photomultiplier pulse-counting system on the UM–UCSD 1.5 m telescope at Mount Lemmon.

Since these blue variables are all intrinsically very luminous and have spectroscopic features common to η Car and other peculiar emission-line stars which have infrared excesses, it was thought worthwhile to look for long-wavelength radiation from these peculiar stars. An InSb system on the 1.5 m telescope was used for observations of AF And and AE And at K(2.2 μm). Only AF And was definitely detected at 2 μm.

All of the photometric data are summarized in Table 1, and the standard deviations from the standard star transformations are given at the head of each column. The errors for the program stars are about twice these values. The spectra are described in the next section.

* Visiting Astronomer, Kitt Peak National Observatory, supported by the National Science Foundation under contract NSF-C866.

1978ApJ...219..445H

TABLE 1

PHOTOMETRIC OBSERVATIONS*
(in magnitudes)

Star (σ)	V (0.01)	$U-B$ (0.01)	$B-V$ (0.01)	$V-R$ (0.04)	$V-I$ (0.04)	K (2.2 μm)
AF And.........	16.05	−0.85	0.11	0.43	0.74	14.79 ± 0.23
AE And.........	17.00	−0.81	0.10	0.34	0.62	
M31 Var A-1....	16.26	−0.54	0.41	0.54	0.71	
M31 Var 15.....	17.47	−0.49	0.44	0.66	0.84	
M33 Var 83.....	16.72	−0.93	0.05	0.22	...	
M33 Var B......	17.11	−0.82	0.01	0.93:	...	
M33 Var C......	17.17	−0.79	−0.05	...	...	
M33 Var 2......	18.17	−1.00	−0.17	0.46	...	

* Date of observation: *UBV* 1976 September 22; *VRI* 1976 October 18; *K* 1976 October 30.

TABLE 2

EMISSION AND ABSORPTION LINES OBSERVED

Approximate Wavelength (Å)	Possible Identification	Remark
	M31 Variable 15	
Emission lines:		
5315....	Fe II λ5317	blend
5270....	[Fe II] λ5273	
5235....	Fe II λ5235	
5195....	Fe II λ5198; [Fe II] λ5199	
5160....	[Fe II] λ5158	
5015....	Fe II λ5018; He I λ5015	possible blend
4922....	Fe II λ4924	blend He I λ4922
4861....	Hβ	
4730....	[Fe II] λ4728	weak
4582....	Fe II λ4583; Fe II λ4584	blend
4570....	Cr I λ4571; or Mg I λ4571	blend; uncertain identification
4555....	Fe II λ4556	
4550....	Fe II λ4549	
4471....	He I λ4471	weak
4360....	[Fe II] λ4359	
4350....	Fe II λ4352	
4340....	Hγ	
4230....	[Fe II] λ4232 Fe II λ4233	possible blend
4172....	Fe II λ4173	
4101....	Hδ	
3889....	He I λ3889	blend
Absorption lines:		
3968....	Ca II H λ3969	
3933....	Ca II K λ3934	
	M31 Variable A-1	
Emission lines:		
5333....	[Fe II] λ5334	
5315....	Fe II λ5317	blend
5295....	[Fe II] λ5296; [Fe II] λ5297	
5270....	[Fe II] λ5273	
5260....	[Fe II] λ5262	
5195....	Fe II λ5198; [Fe II] λ5199	
5170....	Fe II λ5169	
5160....	[Fe II] λ5158	
5016....	Fe II λ5018; He I λ5015	possible blend
4922....	Fe II λ4924	blend He I λ4922
4873....	[Fe II] λ4874	
4861....	Hβ	
4814....	[Fe II] λ4815	
4625....	Fe II λ4629	
4582....	Fe II λ4583; Fe II λ4584	
4555....	Fe II λ4556	
4518....	Fe II λ4515; Fe II λ4520; Fe II λ4522	blend of several lines
4471....	He I λ4471	
4452....	[Fe II] λ4452; [Fe II] λ4458	
4414....	[Fe II] λ4414; [Fe II] λ4416	strong, blend
4360....	[Fe II] λ4359	
4340....	Hγ	
4320....	[Fe II] λ4319.6; Fe II λ4319.7	
4305....	[Fe II] λ4306	
4285....	[Fe II] λ4287	
4275....	[Fe II] λ4277	
4244....	[Fe II] λ4245	blend
4101....	Hδ	
Absorption lines:		
3889....	He I λ3889	blend
3968....	Ca II H λ3969	
3933....	Ca II K λ3934	
	M33 Variable 83	
Emission lines:		
5270....	[Fe II] λ5273	
5260....	[Fe II] λ5262	
5170....	Fe II λ5169	
5155....	[Fe II] λ5158	
5015....	Fe II λ5018; He I λ5015	P Cygni profile, absorption blue side
4970....	[Fe II] λ4973	
4922....	Fe II λ4924	blend He I λ4922
4861....	Hβ	
4813....	[Fe II] λ4814	
4730....	[Fe II] λ4728	
4715....	He I λ4713; [Fe II] λ4716	
4580....	Fe II λ4583; Fe II λ4584	
4550....	Fe II λ4549	
4471....	He I λ4471	
4450....	[Fe II] λ4452	
4414....	[Fe II] λ4414; [Fe II] λ4416	strong, blend
4360....	Fe II λ4359	
4340....	Hγ	
4320....	[Fe II] λ4319.6; Fe II λ4319.7	
4305....	[Fe II] λ4306	
4290....	[Fe II] λ4287	
4275....	[Fe II] λ4277	
4245....	[Fe II] λ4245	
4101....	Hδ	
3970....	Hε	
3889....	He I λ3889; Hζ λ3889	blend
3187....	He I λ3187	

III. THE INDIVIDUAL STARS

Hubble Var 15 and Var A-1, first described by Rosino and Bianchini (1973), and Var 83 in M33 (van den Bergh, Herbst, and Kowal 1975) were observed for the first time on this program in 1976 August. These three variables all have spectra characterized by Fe II and [Fe II] emission lines plus hydrogen and helium emission, and like the H-S variables they have a very strong ultraviolet continuum and no evident Balmer discontinuity. A more complete description is given below, and Table 2 lists the emission and absorption lines identified in these three variables. The spectra are shown in Figure 1 (Plate 19) together with AE And which is spectroscopically very similar to η Car.

The spectra of AE And and the H-S variables—AF And (M31 Var 19) and Var B, Var C, and Var 2 in M33—were described in detail in Paper I. Since these stars are variable, they were observed again in 1976 to look for any spectroscopic changes. Their spectra are also described briefly below and any changes are noted, although only Var C and possibly Var 2 showed any significant variations.

M31 Var 15.—The most prominent features are the Fe II and [Fe II] emission lines, although there are not as many as in AE And or η Car. In addition to the Balmer series there is weak emission at λ4471 and λ3889 due to He I. There is also an emission line near 4570 Å which may be due to either Cr I or Mg I, although the identification is uncertain. The Ca II H and K lines are the only absorption lines present.

M31 Var A-1.—Bianchini and Rosino (1975) have recently described the spectrum of this blue variable from Hγ to 6000 Å. The spectrogram reproduced in Figure 1 is at a higher dispersion and extends much farther into the ultraviolet, revealing the strong hot continuum. This spectrum is very similar to the one published by Bianchini and Rosino, although a few of the Fe II and [Fe II] emission lines they observed are missing. The emission feature near 4640 Å which they identified with N II and O II is also not present, although there is a weak emission line near 4630 Å attributed to Fe II. It is very likely that the spectrum is variable.

In this spectrum the Fe II and [Fe II] emission lines are prominent, although not as sharp as in AE And, presumably owing to greater turbulence in the extended atmosphere of Var A-1. He I is identified at λ4771 and a weak λ3889. Ca II H and K are the only absorption lines.

M33 Var 83.—Again the Fe II and [Fe II] emission spectrum is dominant. The hydrogen lines Hβ, Hγ, Hδ, and Hϵ are present in emission plus He I at λ4471, λ3889, and probably at λ3187. No absorption lines are obvious.

M31 Var 4 in Baade's Field IV.—This red variable is an M supergiant and has been classified M1 I by comparison with the M supergiant standards μ Cep and BU Gem in our Galaxy. Since the star is so red the exposure time was two hours, and consequently, shortward of 4300 Å, the spectrum is badly contaminated by night-sky emission. However, from about 4300 Å to 5400 Å, the late-type star's spectrum is well exposed and compares very well with the M supergiant standards.

AE And.—There are no obvious changes in the spectrum since 1974.

AF And.—The hydrogen lines are not as strong as in the 1974 spectrogram; otherwise there are no other apparent variations in the spectrum.

M33 Var B.—He I λ4471 emission is new in this spectrum, although there are no other changes in the emission spectrum. A broad absorption feature from $\sim$4630 to 4650 Å which was observed before is easier to see in this spectrum. It is possibly due to a blend of O II ($\lambda\lambda$4649, 4642, 4639) and C III ($\lambda\lambda$4647, 4650, 4651).

M33 Var C.—This spectrum shows significant changes since 1974. The hydrogen emission lines are weaker, and the He I emission lines at λ3889 and λ4713 are much weaker, although λ4471, also weaker, is still easily seen. The [Fe II] emission at λ4414 and Fe II λ5018 are both absent.

M33 Var 2.—This is a much better exposure than the 1974 spectrogram. The hydrogen lines appear to be stronger, and He I λ4471 and λ3889 are also present. There are additional emission lines at λ5018 Fe II, λ5005 Fe II and [Fe II], and λ4294 Fe II plus two emission lines near 3750 Å which are difficult to identify. They might both be due to Fe II. A broad absorption feature from $\sim$4280 to 4300 Å might be a G band, since the 1974 spectrogram showed several absorption lines suggesting spectral type A or F.

IV. DISCUSSION

The spectra of the eight blue variables which have now been observed in M31 and M33 are very similar. They all have a strong ultraviolet continuum, no apparent Balmer discontinuity, and emission lines of H, He I, Fe II, and [Fe II]. In general they are spectroscopically like the most luminous hot variables recognized in the Galaxy and the LMC—stars like η Car, MWC 349, S Dor, and HDE 269006. Their membership in M31 and M33 of course confirms their high luminosity.

Since *UBVRI* photometry is available for most of these eight stars, color-color diagrams have been prepared for $(U - B)_0$ versus $(B - V)_0$ and $(V - I)_0$ versus $(B - V)_0$. It is first necessary to attempt to correct the observed colors for interstellar extinction; the extinction between us and M31 and M33, and if possible, any extinction in front of these stars inside the galaxies. Van den Bergh (1968) has suggested that A_v is 0.4 mag and 0.3 mag in front of M31 and M33, respectively. Another way of estimating the visual absorption which should account for some of the extinction in M31 and M33 is determined from the neutral hydrogen along the line of sight. Knapp, Kerr, and Rose (1973) and Savage and Jenkins (1972) have shown that $n_{\rm H\,I}$, the column density, is proportional to $E_{B-V}(n_{\rm H\,I} = 5.16 \times 10^{21} E_{B-V})$. 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

TABLE 3

ESTIMATES OF THE VISUAL ABSORPTION AND THE INTRINSIC COLORS

Star	A_v (Galaxy) (mag)	A_v ($n_{\rm H\,I}$) (mag)	$(U-B)_0$	$(B-V)_0$	$(V-R)_0$	$(V-I)_0$	$(V-K)_0$
AF And.........	0.4	1.3	−0.94	−0.02	+0.33	0.53	0.90
			−1.16	−0.32	+0.09	0.04	0.06
AE And.........	0.4	0.6	−0.90	−0.03	+0.24	0.41	
			−0.96	−0.11	+0.17	0.28	
M31 Var A-1....	0.4	1.3	−0.63	+0.28	+0.44	0.50	
			−0.85	−0.02	+0.20	0.01	
M31 Var 15.....	0.4	1.3	−0.58	+0.31	+0.56	0.63	
			−0.80	+0.01	+0.32	0.01	
M33 Var 83.....	0.3	1.6	−1.00	−0.05	+0.38	...	
			−1.30	−0.47	+0.04		
M33 Var B......	0.3	0.9	−0.89	−0.10	...	...	
			−1.03	−0.30			
M33 Var C......	0.3	1.2	−0.86	−0.15	...	...	
			−1.07	−0.45			
M33 Var 2......	0.3	1.35	−1.07	−0.27	+0.14	...	
			−1.32	−0.62	−0.14		

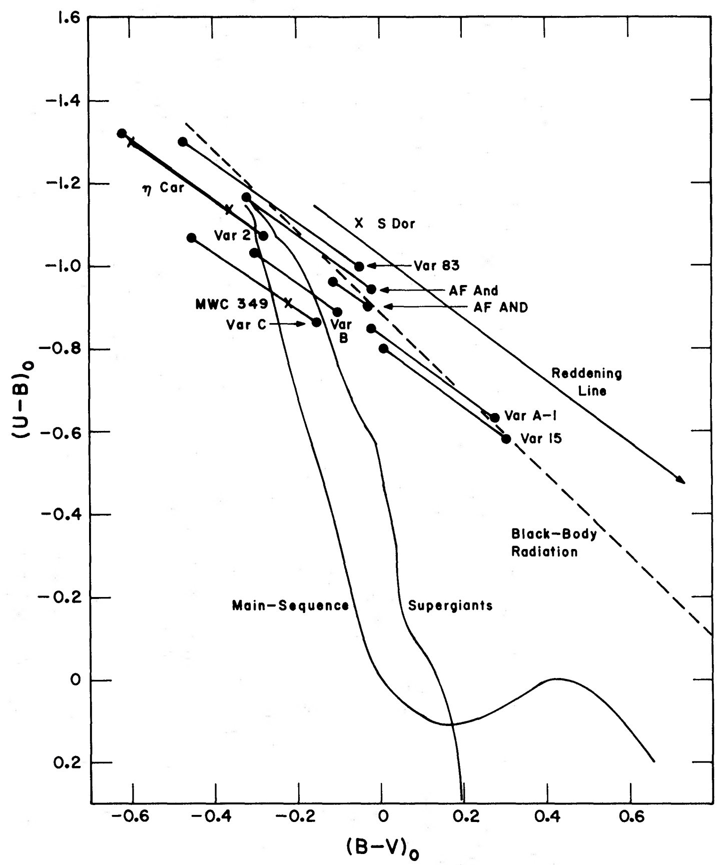

FIG. 2.—The $(U-B)_0$ versus $(B-V)_0$ diagram for eight blue variables plus η Car, MWC 349, and S Dor. The M31 and M33 stars are shown as lines representing the range of intrinsic colors they would have for the upper and lower values for their interstellar reddening. Eta Car is also shown as a line for two different determinations of the intrinsic colors. All of these stars have ultraviolet excesses and lie near the blackbody radiation line.

M33, and the corresponding color excess is found from the above relationship.

The color excesses determined from the absorption in front of the galaxies and from the neutral hydrogen are treated as lower and upper limits, respectively, for these stars. The unreddened colors are given in Table 3 for both methods of determining the extinction, and in the two-color diagrams each star is plotted as a line showing the range of intrinsic colors it might have for the two extremes of reddening.

The galactic stars η Car and MWC 349 and S Dor in the LMC are also shown on the color-color diagrams for comparison, since they are also very luminous variables and spectroscopically similar to the blue variables in M31 and M33. The photometry for η Car comes from Feinstein (1967) and Gehrz *et al.* (1973) and has been corrected for $E_{B-V} = 1.2$ mag (Pagel 1969). Another determination of the intrinsic colors of η Car based on the continuum published by Rodgers and Searle (1967) corrects for the contributions of the strong emission lines to the colors. Both values are shown on the two-color diagrams. Photometry by Allen (1973) and Lee (1970) were used for MWC 349 with $A_v \sim 9.1$ mag (Allen 1974), and for S Dor recent photometry is available by Humphreys (1976) and Allen and Glass (1976). The visual absorption for S Dor was estimated to be 0.57 mag from a nearby B supergiant, although this is probably an underestimate.

Figure 2 shows the upper part of the standard $(U - B)_0$ versus $(B - V)_0$ diagrams for the main sequence and the supergiants. The line for blackbody radiation and the reddening line are also shown. All of the stars lie either above the standard curves or on the uppermost part. It is significant that η Car, S Dor, AF And, AE And, Var 15, Var A-1, and Var 83 all lie either on or very near to the blackbody radiation line. This is as expected from their spectra, which lack a Balmer discontinuity. The colors show that these stars are very low surface gravity objects which more closely resemble blackbodies than ordinary stars. Sharov, Esipov, and Lyutyj (1975) have recently reported *UBV* colors for AF And, AE And, and Var A-1 in M31, and they also note the similarity to S Dor.

The $(V - I)_0$ versus $(B - V)_0$ diagram for supergiants is shown in Figure 3, and the four stars with accurate *I* magnitudes—AF And, AE And, Var A-1, and Var 15—are plotted. AF And and AE And lie in the same region as η Car, S Dor, and MWC 349—above the normal line for supergiants which shows that they also have excess radiation in the infrared as well as the ultraviolet. On this diagram, Var A-1 and Var 15 have colors more like A- or F-type supergiants, although they also have ultraviolet excesses.

AF And is the only star in this group which has been detected at longer wavelengths to date. On the $(V - K)_0$ versus $(B - V)_0$ diagram (Fig. 4), AF And

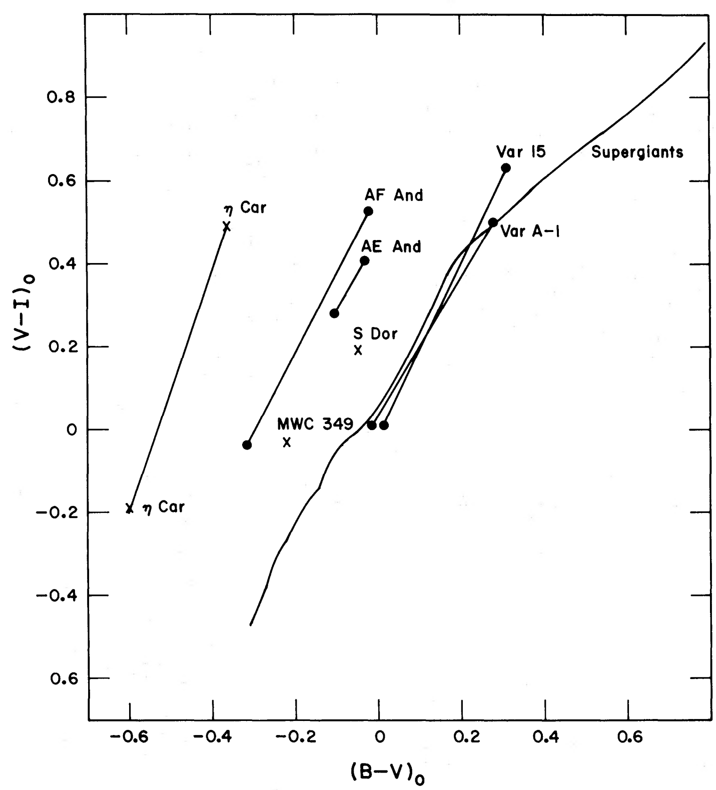

FIG. 3.—The $(V - I)_0$ versus $(B - V)_0$ diagram for AE And, AF And, M31 Var 15, and M31 Var A-1. AE And and AF And lie in the same region as S Dor and MWC 349, above the line for unreddened supergiants.

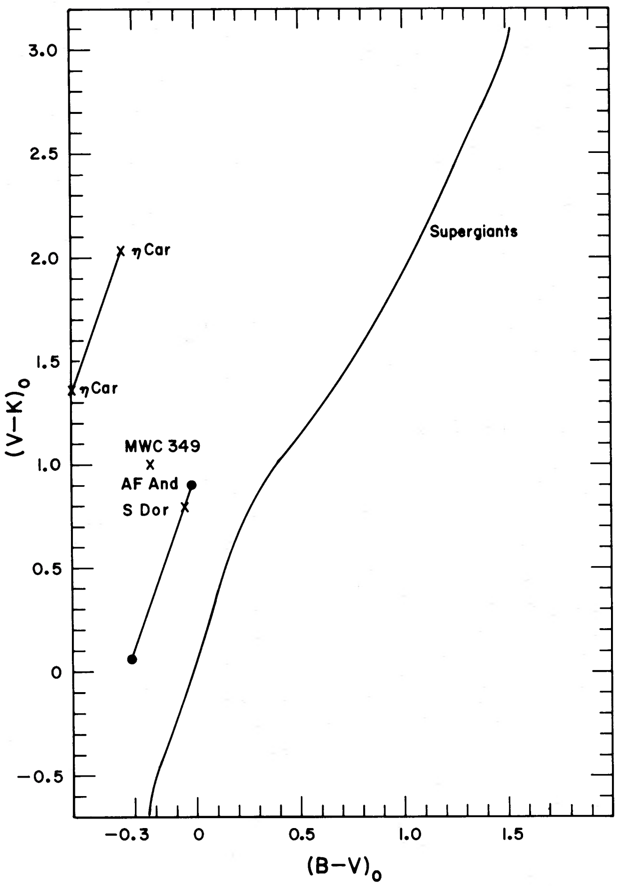

FIG. 4.—The $(V-K)_0$ versus $(B-V)_0$ diagram for AF And. This star has excess radiation at 2 μm similar to S Dor and MWC 349.

lies very close to S Dor and MWC 349, again demonstrating its similarity to these stars and the presence of an infrared excess. Eta Car lies significantly above these stars due to its extensive dust shell. The long-wavelength energy distribution for MWC 349 also reveals a circumstellar dust shell, while for S Dor the infrared radiation more closely resembles free-free emission. AF And may also have a dust shell, but more likely its extended atmosphere produces free-free emission in addition to the normal blackbody radiation.

Since the visual absorptions have already been estimated, it is also possible to determine the absolute visual magnitudes of these luminous variables both at the time of observation and at maximum light. The results are given in Table 4, and the apparent visual magnitude for each star has been corrected for the visual absorption by using the two estimates in Table 3. When the maximum magnitude is photographic, it is corrected by the observed $B-V$ color to determine V(max). Unreddened distance moduli 24.1 mag and 24.5 mag have been adopted for M31 and M33, respectively, to derive the absolute luminosities.

Although the absolute magnitude depends on the size of the extinction correction, the maximum visual luminosities are typically −9 mag to −10 mag with M31 Var A-1 and M33 Var B possibly as bright as −11 mag at maximum. Thackeray (1974) gives −9.4 mag M_v(max) for S Dor and suggests that η Car was −8 to −10 (V) prior to its outburst. Thus the blue variables in M31 and M33 are again comparable to the most luminous stars known in our Galaxy and the LMC.

An absolute magnitude can also be estimated for the M supergiant in M31. Although no photoelectric photometry is available, the magnitude range and color (B = 19.6–20.7, $B-V$ = 2.25) of Var 4 published by Baade and Swope (1963) are used to yield 17.35 for V(max). Baade's Field IV is in a spiral arm in the outermost part of M31 and is outside the boundaries of Roberts's (1966) H I map of that galaxy; however, the more recent neutral hydrogen observations by Davies and Gottesman (1970) include Field IV. Their $n_{\rm H\,I}$ map yields A_v ~0.3 mag in the direction of Var 4. This result is very close to van den Bergh's estimate of 0.4 mag in front of M31, and this latter value has been used for the reddening. The absolute visual magnitude is then −7.2 mag for the red variable in M31. This luminosity is comparable to the most luminous known M supergiants in the Milky Way and the LMC (Humphreys 1970, 1974).

TABLE 4

THE ABSOLUTE VISUAL MAGNITUDES

Star	V (obs)	V_0 (obs)	M_v (obs)	V (max)	Ref.	V_0 (max)	M_v (max)
AF And..............	16.05	15.7–14.8	−8.8 to −9.7	15.5	4	15.1–14.2	−9.0 to −9.9
				15.2	1	14.8–13.9	−9.3 to −10.2
AE And..............	17.00	16.6–16.4	−7.9 to −8.1	16.1	3	15.7–15.5	−8.4 to −8.6
				14.6	2	14.2–14.0	−9.9 to −10.1
M31 Var A-1.........	16.26	15.9–15.0	−8.6 to −9.5	14.5	3	14.1–13.2	−10.0 to −10.9
M31 Var 15..........	17.47	17.1–16.2	−7.4 to −8.3	16.2	5	15.8–14.9	−8.3 to −9.2
M33 Var 83..........	16.72	16.4–15.1	−8.2 to −9.5	15.8	6	15.5–14.2	−9.0 to −10.3
M33 Var B...........	17.11	16.8–16.2	−7.8 to −8.4	14.7	5	14.4–13.8	−10.1 to −10.7
M33 Var C...........	17.17	16.9–16.0	−7.7 to −8.6	15.5	4	15.2–14.3	−9.3 to −10.2
M33 Var 2...........	18.17	17.9–16.8	−6.7 to −7.8	15.8	4	15.5–14.5	−9.0 to −10.0

References: (1) Luyten 1927; (2) Luyten 1928; (3) Sharov 1973; (4) Hubble and Sandage 1953; (5) Rosino and Bianchini 1973; (6) van den Bergh, Herbst, and Kowal 1975.

Var 4 is only representative of the stellar population in a small region in an outer spiral arm of M31. More luminous red supergiants may be present in M31 since there is no complete survey for red stars in that galaxy.

V. CONCLUDING REMARKS

The eight blue variables, four in M31 and four in M33, together with η Car, S Dor, and related objects in the Milky Way and the LMC form a recognizable group of hot, very luminous stars. The above discussion clearly demonstrates that they have large radiated fluxes combined with very low surface gravities, suggesting that their atmospheres are not very stable. In discussing η Car, Davidson (1971) remarked that if the temperature were only slightly reduced, the radiation pressure would overwhelm gravity in the outer layers. With these conditions in mind, we feel that these luminous blue stars in M31 and M33 may undergo η Carina–like outbursts. Therefore, it is very worthwhile to continue monitoring these variable stars.

Var A in M33 which is now about 20th magnitude may be an example of one of these stars which has had such an outburst. The light curve for this star (Hubble and Sandage 1953; Rosino and Bianchini 1973) closely resembles the available information on the maximum and decline of η Car. The only spectrum, obtained near maximum light, showed F supergiant–like characteristics, similar to those of η Car in 1896, and probably formed in the expanding shell. In addition, the color index was about +0.3 mag at maximum but had reddened to 1.5 mag at minimum. This reddening is probably due to the formation of a dust shell as occurred in η Car. M33 Var A is therefore a very good candidate for infrared observations.

The available photometric and spectroscopic data for this group of luminous, blue variables demonstrate that similar physical processes are occurring in the extended atmospheres of the most luminous and presumably most massive stars in four different galaxies in our Local Group.

It is a pleasure to thank members of the staff of Kitt Peak National Observatory for making these observations possible. I am especially grateful to Jim DeVeny, Doug Tody, and Dr. Tom Kinman for their assistance. I am also grateful to Robert Hubbard for his observing assistance at Mount Lemmon and to Jeff Puschell and Dr. Steve O'Dell for kindly taking time to obtain the 2 μm observation of AF And. This research was supported by the National Science Foundation.

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ROBERTA M. HUMPHREYS: Astronomy Department, University of Minnesota, 116 Church St. S.E., Minneapolis, MN 55455

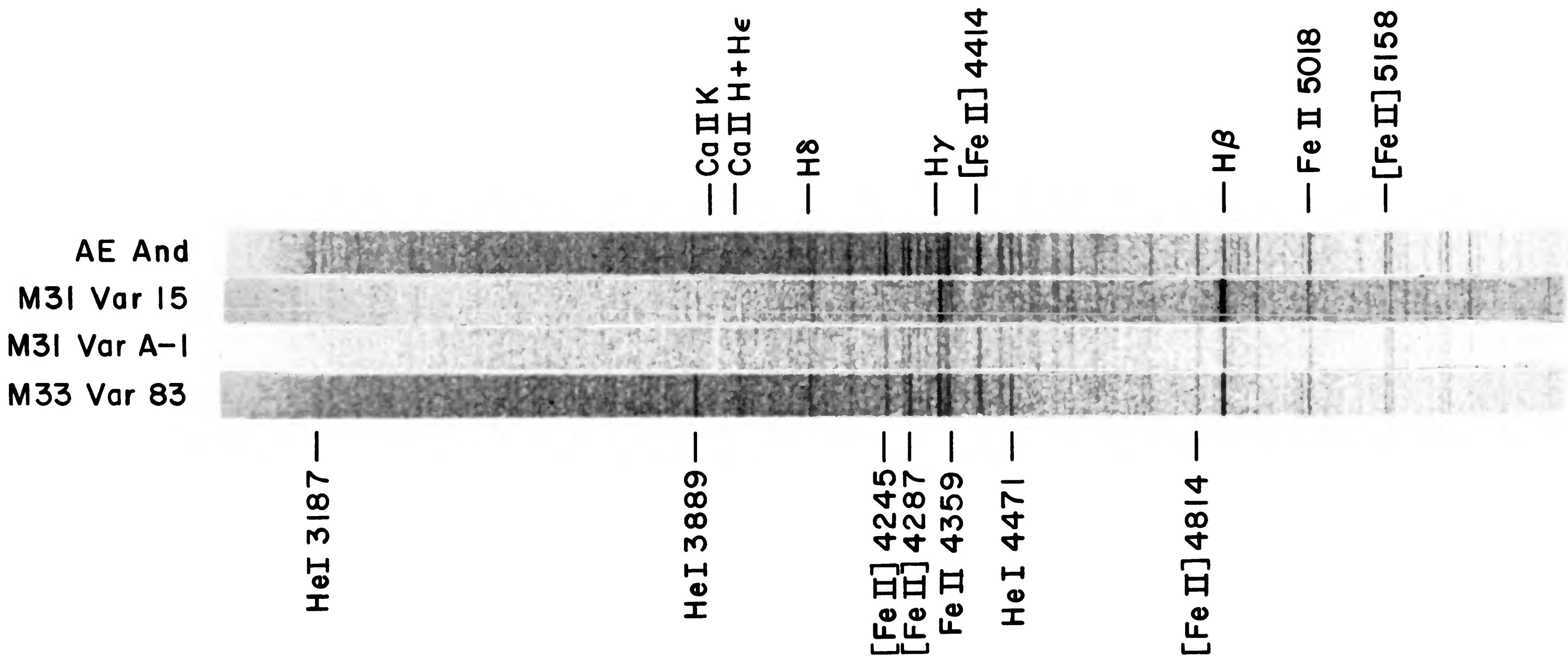

FIG. 1.—The spectra (79 Å mm^{-1}) of the variables AE And, M31 Var 15, M31 Var A-1, and M33 Var 83. The emission lines of hydrogen, helium, and some of the strongest lines of Fe II and [Fe II] are identified.

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