1981ApJ...249...83G

THE ASTROPHYSICAL JOURNAL, 249:83–92, 1981 October 1
© 1981. The American Astronomical Society. All rights reserved. Printed in U.S.A.

SPECTROPHOTOMETRY OF TWO LUMINOUS VARIABLE STARS IN THE ANDROMEDA GALAXY[1]

J. S. GALLAGHER AND S. J. KENYON
Department of Astronomy, University of Illinois, Urbana
AND
E. K. HEGE
Steward Observatory, University of Arizona
Received 1981 March 6; accepted 1981 April 8

ABSTRACT

We present spectrophotometry of AF Andromedae and A-1 Andromedae, two S Doradus variables in M31. Emission lines of H Balmer, He I, Fe II, and [Fe II] dominate the spectra, and only Na D appears in absorption. The H Balmer flux ratios can be explained by case B recombination at $T \approx 10{,}000$ K and an Hβ luminosity of 500 $L_\odot$ with little circumstellar reddening. The optical continua may be fitted by reddened blackbodies ($E_{B-V} = 0.11$) at $T_{\rm color} \approx 10{,}000$ K. An analysis of the Fe II, [Fe II], and He I line strengths leads to a model in which a hot star ($T_* \gtrsim 25{,}000$ K) is surrounded by an extensive envelope ($R \approx 1$ AU, $N_e \approx 10^{10}$ cm^{-3}) with an implied mass loss rate of $\sim 10^{-5}$ $M_\odot$ yr^{-1}. This, the environments, and the ~ 10 times lower luminosity suggest that these stars are not necessarily produced by the same mechanism as η Carinae. The evolution of a massive star ($M \gtrsim 80$ $M_\odot$) to its core helium-burning phase ($M_{\rm He} \gtrsim 30$ $M_\odot$) may provide a model for the current status of A-1 And, while the position of AF And in an interarm region of M31 supports a binary interpretation.

Subject headings: galaxies: individual — stars: emission-line — stars: supergiant — stars: variable

I. INTRODUCTION

In a classic paper, Hubble and Sandage (1953) pointed out the variable nature and described the basic properties of the optically most luminous stars known to be in the major Local Group members M31 and M33. Long term, irregular variability is now recognized to be a general characteristic of extremely optically luminous stars, and these stars have been grouped together as the class of S Doradus variables (Kukarkin *et al.* 1974). Optical spectra are available for the majority of known Local Group S Doradus stars, and in most instances complex emission is present. This common spectroscopic characteristic is the basis for the belief that the S Doradus phenomenon is intimately associated with the presence of an extremely extended envelope surrounding a hot stellar surface. The presence of large amounts of circumstellar matter, however, obscures the hydrostatic stellar surface from direct optical observation, which complicates efforts to interpret the S Doradus stars, especially insofar as evolutionary status is concerned.

A possible clue to the conditions which produce an S Doradus star is provided by the morphological similarity between their optical spectra, which are rich in Fe II and [Fe II] emission, and the spectrum of η Carinae (Thackeray 1964, 1967; Bianchini and Rosino 1975; Humphreys 1975, 1978; Sharov, Esipov, and Lyutyj 1975). This qualitative parallel in spectroscopic characteristics leads to the suspicion that huge mass loss rates, perhaps associated with dramatic episodic events of the type seen in η Carinae during the 19th century (Gratton 1963) and inferred to have occurred in S Doradus itself (Wolf, Appenzeller, and Cassatella 1980), are at the root of these stars' peculiarities. The origin of very high mass loss rates, however, is also unclear, and models involving instabilities in the most massive stars (e.g., Davidson 1971; Humphreys and Davidson 1979, hereafter HD) or ejection of matter during binary star evolution on a dynamical time scale (Bath 1979; Tutukov and Yungel'son 1980) have been suggested.

Unfortunately, despite the increase in information about the spectra of S Doradus stars, little quantitative data other than broad-band optical photometry (which can be seriously effected by emission lines) and the pioneering infrared photometry of Humphreys and Warner (1978) are available for the stars in M31 and M33. As an additional step toward understanding these peculiar and important stars, we have obtained intermediate resolution spectrophotometry for two S Doradus stars in M31: AF And (Var 19, Hubble and Sandage 1953) and variable A-1 And (Rosino and Bianchini 1973). These data allow a first analysis of physical conditions within the stellar envelopes to be made and enable us to make a quantitative comparison with the well-studied case of η Carinae.

[1] Supported in part by the National Science Foundation through grants AST 79-09977, AST 78-20124, and AST 78-20123 to the University of Illinois at Champaign-Urbana.

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1981ApJ...249...83G

II. OBSERVATIONS

Spectrophotometry of AF And and A-1 And was obtained in 1979 October 14 and 15, with the Steward Observatory 2.3 m telescope. For these measurements the intensified Reticon scanner was used in a red-sensitive mode in which Varo image intensifiers were utilized both for the initial detection and subsequent amplification of dispersed light from the Cassegrain spectrograph (Hege, Cromwell, and Woolf 1979). All data were taken in a star-sky chopping mode in which the object was in each 3″ aperture for one-half of the ~45 minute observing time. In both instances the sky positions were free from stars visible on the 2.3 m telescope acquisition television ($m_{\rm red} \sim 20$), and the effects of the brightness gradient due to the underlying galaxy are negligible based on the M31 photometry by Burgess (1976). The resulting spectra provide useful information over approximately $\lambda\lambda$4500–7300 with a FWHM resolution of ~12 Å.

The flux scale is based on observations of Oke (1974) standards, but since the apertures were small and the seeing mediocre and variable, the relative fluxes are better determined than the absolute fluxes. An external check on total magnitude was therefore obtained from photographic photometry with the Prairie Observatory 1 m reflector on 1979 October 20 and 22 (AF And) and on December 9 (A-1 And). For AF And we were able to take advantage of the Hubble and Sandage (1953) standard sequence to measure $m_{\rm pv} = 16.0$ and CI = 0.0 using a Cuffy iris photometer. This can be compared with $V = 16.05$ and $B - V = 0.11$ found by Humphreys (1978) in 1976 September and with $V = 16.6$ estimated by integrating the Reticon data over a V band pass. The magnitude of ~16 for A-1 And is based only on an eye estimate, but also suggests the Reticon data underestimate the total flux, perhaps by somewhat less than for AF And. Absolute fluxes have therefore been increased by factors of 1.7 and 1.5 over the Reticon data calibrations for AF and A-1 And, respectively.

Spectra for the two stars are shown in Figures 1 and 2; the increasing noise toward the blue is due both to grating efficiency and declining sensitivity of the first stage Varo image intensifier. The wavelength scale has been approximately corrected for distortions introduced by the intensifiers, although modest residual errors remain, and we were therefore able to obtain good line identifications,

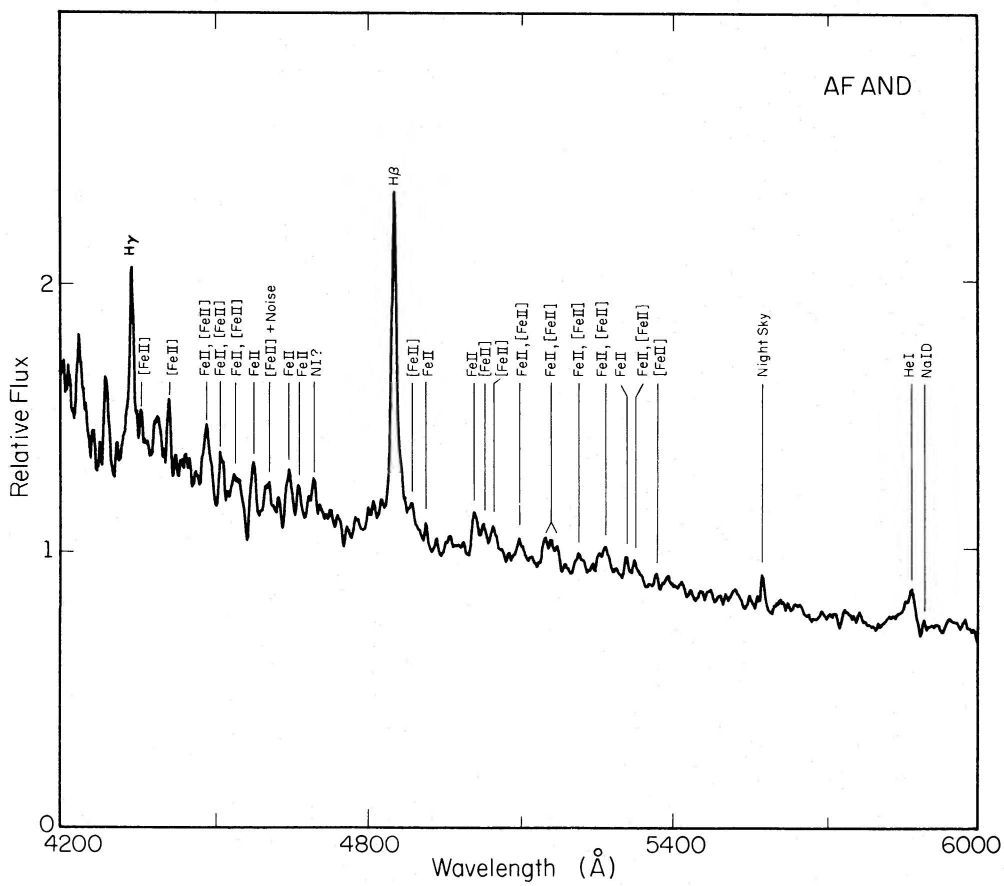

FIG. 1*a*

FIG. 1.—Spectrum of AF Andromedae obtained with the intensified Reticon spectrophotometer on the Steward Observatory 2.3 m telescope. Part (*a*) shows the spectrum for $\lambda\lambda$4200–6000, while part (*b*) presents $\lambda\lambda$5800–7600. Line identifications are given for the strongest lines between Hα and Hγ. One unit of relative flux equals 1.7×10^{-15} ergs cm^{-2} s^{-1} Å^{-1}.

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1981ApJ...249...83G

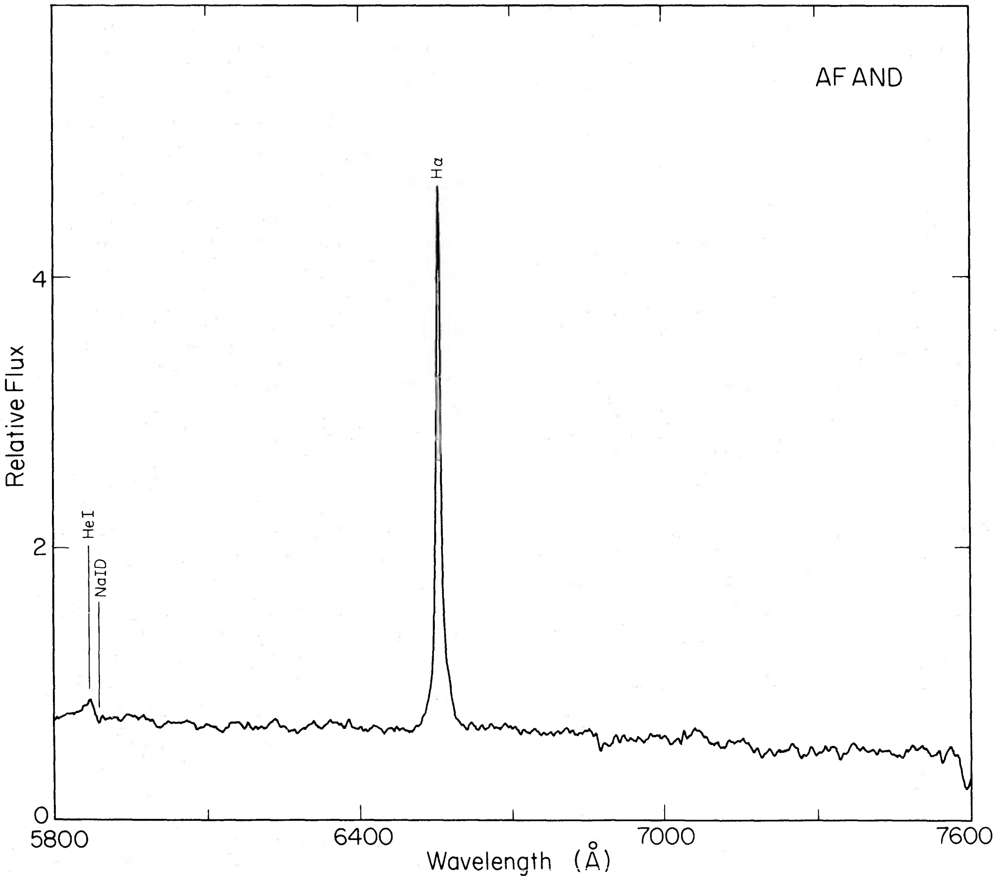

FIG. 1b

at least between Hβ and Hα. Other than the Na D doublet, no definite absorption lines are found.

Emission line identifications and strength estimates are given in Tables 1 and 2. Due to the severe blending of Fe II and [Fe II], it was difficult to obtain accurate flux measurements for individual lines. An approximate deconvolution was made using a program constructed by D. Hunter at Illinois, but in most instances it was difficult to get an accurate value of the local continuum or make a unique fit to a given blend component. We have therefore chosen to categorize the Fe II, [Fe II], and other weaker lines by their strengths relative to Hβ, which are given in Table 2. Here we follow the convention $F/F(H\beta) < 0.1$ are weak lines, moderate lines have $0.1 \lesssim F/F(H\beta) \lesssim 0.25$, and strong lines have $F/F(H\beta) > 0.25$.

The line identifications in Table 2 compare favorably with the higher resolution photographic image intensifier spectra of AF And obtained by Humphreys (1975, 1978), as well as her spectra of A-1 And, and also agree with the λλ4300–6000 A-1 And spectrum by Bianchini and Rosino (1975). There is a hint of evolution in AF And, since we find more Fe II and [Fe II] emission than Humphreys,

TABLE 1

HYDROGEN AND HELIUM EMISSION LINE FLUXES

	AF ANDROMEDAE				A-1 ANDROMEDAE			
FEATURE	Equivalent Width (Å)	F^a (ergs s^{-1})	$F/F(H\beta)$	$I/I^b(H\beta)$	Equivalent Width (Å)	F^a (ergs s^{-1})	$F/F(H\beta)$	$I/I^b(H\beta)$
Hγ	4.3	1.0×10^{-14}	0.48	0.51	...	...	...	...
Hβ	10.6	2.2×10^{-14}	1.0	1.0	14.4	2.1×10^{-14}	1.0	1.0
He I	3.5:	4.3×10^{-15}	0.2:	0.2:	2.6:	2.7×10^{-15}	0.1:	0.1:
Hα	65	7.7×10^{-14}	3.5	3.1	65	7.9×10^{-14}	3.8	3.3

[a] Observed fluxes corrected by 1.7 (AF And) and 1.5 (A-1 And).
[b] Assumes standard extinction curve (Osterbrock 1974) and $E(B-V) = 0.11$.

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1981ApJ...249...83G

which is consistent with her note that the H line strengths may have decreased in her later spectra. The spectrum of A-1 And appears basically the same as that found by Bianchini and Rosino.

III. PHYSICAL CONDITIONS IN THE STELLAR ENVELOPES

a) *The Hydrogen and Helium Spectrum*

The emission line flux ratios in Table 1 when corrected for a reddening of $E(B-V) = 0.11$ to M31 (McClure and Racine 1969) are basically consistent with the expectations of case B recombination of hydrogen at a temperature of $5\text{–}10 \times 10^3$ K (Osterbrock 1974), and the preferred ionization mechanism is therefore photoionization. There is some indication of extra extinction toward A-1 And, but this star is located in a spiral arm where young stars are present, and detectable interstellar dust therefore would not be unexpected. Thus, we find no evidence for large amounts of "extra" extinction of the type ascribed to the circumstellar dust shell in η Carinae (cf. Davidson 1971) in either star. However, as the emitting region is likely to be quite dense, as evidenced by the weakness of forbidden lines from species within the H^+ zone, it is possible that optical depth effects are important in the H and He spectra, and we could therefore miss modest effects from circumstellar dust.

If we adopt a photoionization model, then the presence of He I emission is inconsistent with the optical color temperature of $\sim 10^4$ K and thus may be indicative of the "true" nature of the underlying stellar photosphere. The ratios of He I λ5876 to Hβ fluxes appear to support the photoionization picture, but caution must be used in interpreting the observed line ratios since the He I and Hβ lines are likely to originate in different regions of the envelope and to have suffered different amounts of absorption within the envelope. From the mere existence of He emission, photoionization requires a stellar temperature of $\gtrsim 25{,}000$ K (Kaler 1978), although excitation as a result of mechanical energy input into the stellar envelope cannot be excluded on the basis of our data.

Combining the corrected fluxes from Table 1 multiplied by 1.45 to account for galactic extinction, we then find $L(\mathrm{H}\beta) = 2 \times 10^{36}$ ergs s^{-1} for both stars, where we have taken a distance of 724 kpc or $(m - M)_0 = 24.3$ for M31 (Sandage and Tammann 1976). From the characteristics of the Fe II and [Fe II] emission in A-1 And, we estimate that $\bar{N}_e \gtrsim 10^8$ in the H^+ zone of A-1 And and is

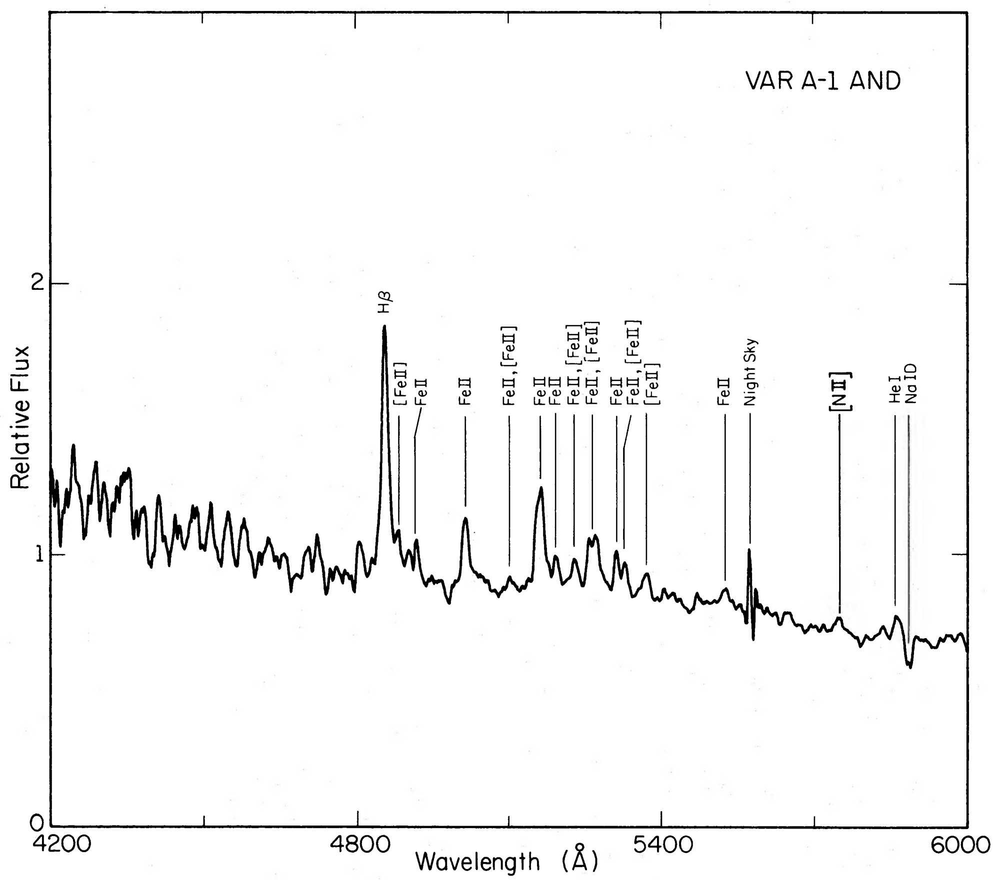

FIG. 2*a*

FIG. 2.—Spectrum of A-1 Andromedae as in Fig. 1. Line identifications are given for the strongest lines between λ4600 and Hβ. One unit of relative flux equals 1.5×10^{-15} ergs cm^{-2} s^{-1} s^{-1} Å^{-1}.

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1981ApJ...249...83G

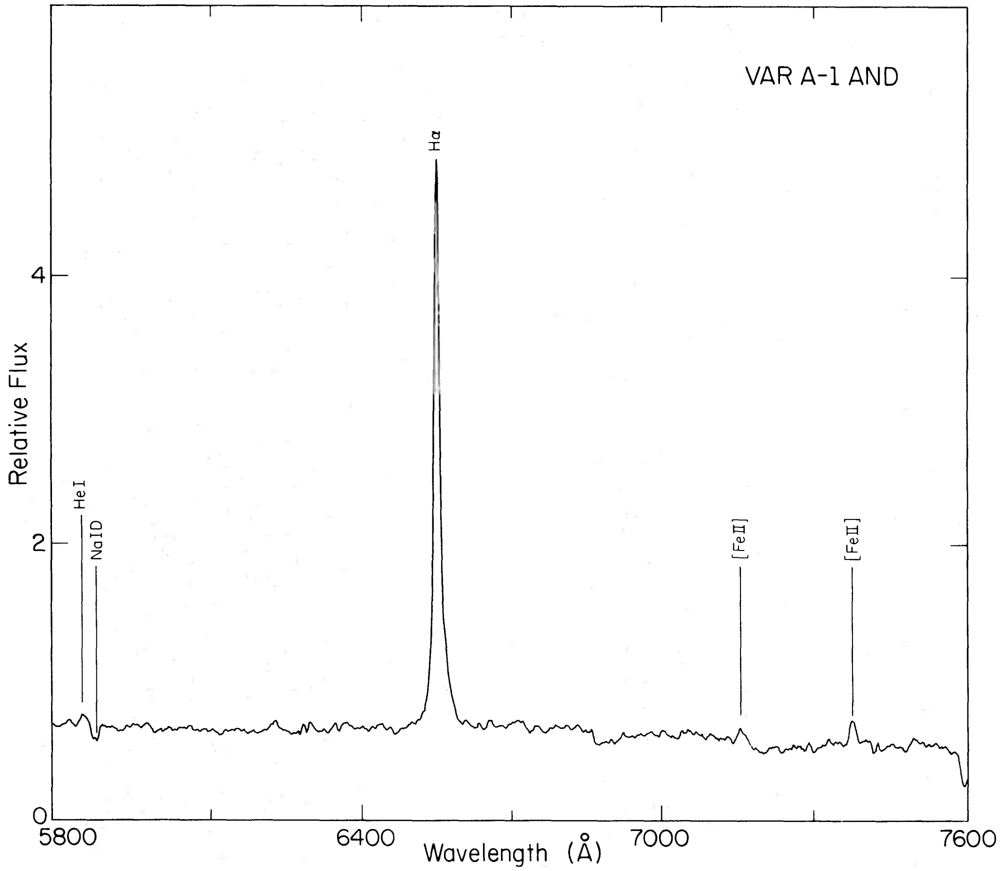

FIG. 2b

perhaps considerably lower in AF And (see below). If the Hβ photon luminosity is S_β, then the *maximum* mass for a constant density H II region which is optically thin in Hβ is

$$M_{\rm H\,II} \lesssim \frac{S_\beta \mu m_{\rm H}}{\alpha_{\rm H\beta}{}^{\rm eff}(T)\bar{N}_e}\,, \tag{1}$$

which implies $M_{\rm env} \sim M_{\rm H\,II} \lesssim 10^{-4}(\bar{N}_e/10^8)^{-1}\,M_\odot$ for our $L({\rm H}\beta)$. The characteristic radius of the ionized zone is $R_{\rm H\,II} \sim 6 \times 10^{14}(\bar{N}_e/10^8)^{-2/3}$ cm, and we can make a very crude estimate of the mass loss rate for an expansion velocity V:

$$\dot{M}_{\rm H\,II} \approx \frac{M_{\rm H\,II} V}{R_{\rm H\,II}}$$

$$= \left(\frac{4\pi}{3}\right)^{1/3}\left(\frac{S_\beta}{\alpha_{\rm H\beta}{}^{\rm eff}(T)}\right)^{2/3}(\bar{N}_e)^{-1/3}\mu M_{\rm H} V\,. \tag{2}$$

Fortunately this expression is not very sensitive to the poorly known density distribution and gives

$$\dot{M} \sim 5 \times 10^{-5}(\bar{N}_e/10^8)^{-1/3}(V/100)\,M_\odot\ {\rm yr}^{-1}\,,$$

where V is in km s^{-1}. This result *suggests* both stars could be in the high mass loss rate regime even if the expansion velocity is as low as 100 km s^{-1}. However, since no velocity information is available for the envelope of either star, the actual mass loss rate remains unknown, although the presence of extensive amounts of circumstellar matter is de facto evidence for mass loss.

b) *The Optical Continuum*

The continua of both variables can be fitted moderately well by blackbodies with $T \sim 10^4$ K when the observed spectra are corrected for $E(B-V) = 0.11$. In A-1 And we again find evidence for additional extinction from the continuum fitting process, which suggests that the actual optical color temperature should somewhat exceed 10^4 K. However, in AF And, for which we have somewhat better continuum measurements, we find the blackbody color temperature smoothly declines with increasing wavelength, an effect which is to be expected in extended atmospheres that are strongly limb-darkened (e.g., Cassinelli 1971). Thus, the atmospheric temperatures cannot be considered as well determined and for the purpose of our present rough analysis we therefore adopt a convenient estimate of $2T_\odot$ for the optical shell temperature in both stars.

For AF And, which has $V = 16.05$, we can then derive a current photospheric radius of $R_p({\rm opt}) \sim 140\,R_\odot$ (3 AU!), where we have used a conservative bolometric correction of 0.5 mag and an extinction of $A_v = 0.3$ mag. The radius of A-1 And, for which the observables are

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1981ApJ...249...83G

TABLE 2
METAL EMISSION LINE STRENGTHS IN AF ANDROMEDAE AND VARIABLE A-1 ANDROMEDAE

IDENTIFIED WAVELENGTH	MULTIPLET	FLUX AF AND	FLUX A-1 AND
4359 A	[Fe II] 7F	Moderate	---
4414-4416	[Fe II] 6F, 7F	Moderate	---
4489-4493	[Fe II] 6F; Fe II 37	Moderate	---
4576-4584	Fe II 38, 37	Moderate	---
4658	[Fe III] 3F?	Moderate	---
4667	Fe II 37	Moderate	---
4700	[Fe III] 3F?	Moderate	---
4890	[Fe II] 4F	Moderate	Moderate
4924	Fe II 42	Weak	Moderate
5018	Fe II 42	Moderate	Strong
5036:	[Fe II] 4F?	Moderate	Weak:
5056:	Si II 5; [Fe II] 20F; [Fe III] 1F	Moderate	Absent?
5072	[Fe II] 19F	Weak	Weak:
5100-5111	[Fe II] 18F,19F; Fe II 35	Moderate	Weak
5159	[Fe II] 18F, 19F	Moderate	Weak
5169	Fe II 42	Moderate	Strong
5182	[Fe II] 18F	Moderate	Moderate
5198	Fe II 49	Moderate	Moderate
5220	[Fe II] 19F	Weak	Weak:
5235	Fe II 49	Moderate	Moderate
5262	[Fe II] 19F	Moderate	Moderate
5270-5281	Fe II 49; [Fe II] 18F; [Fe III] 1F	Moderate	Strong
5317	Fe II 49	Weak	Moderate
5334	[Fe II] 19F	Weak	Moderate
5363	Fe II 48	?	Weak
5377	[Fe II] 19F	Moderate	Moderate
5527-35	[Fe II] 17F; Fe II 55	Weak:	Weak
5655	[Fe II] 17F?, 39F	---	Weak:
5755	[N II] 3F	---	Weak
5848	[Fe II] 34F?	---	Weak
6238	Fe II 74, 34	---	Weak
6248	Fe II 74	---	Weak
6300	[OI] 1F	---	Weak-Moderate:
6318	Fe II	---	Weak
6366	[OI] 1F; [Ni II] 8F	---	Weak
6385	Fe II	---	Weak
7155:	[Fe II] 14F	---	Weak:
7378:	[Ni II] 2F, [Fe II] 14F	---	Weak:

more poorly determined, is probably somewhat smaller, but still very large for a hot star. If we adopt the photoionization model to explain the observed He I, then we can set the minimum extent of the circumstellar shell by assuming $T_* > 25{,}000$ K at its base. This gives $R_p(\mathrm{opt})/R_p(\mathrm{He}^+) \gtrsim 4.6$, and the envelope thus dominates its stellar core.

A check on the importance of unobserved ultraviolet flux can be obtained from the Hβ luminosity. Note that the usual Zanstra-type arguments will yield faulty results, as the optical continuum arises not from the hot photosphere responsible for photoionization, but probably from radiation reprocessed within the circumstellar shell. Taking case B recombination, then Hβ photons are produced in 1/8.4 of all H$^+$ recombinations, and the total Lyman continuum luminosity will therefore exceed $L(\mathrm{H}\beta)$ by about a factor of 50 (Osterbrock 1974). However, this gives $L(\mathrm{Lyc}) \gtrsim 10^{38}$ ergs s^{-1}, which is still only 10% of the visual luminosity of $\sim 10^{39}$ ergs s^{-1}. On the basis of this calculation we therefore conclude that the shell is relatively optically thick, and most of the input ultraviolet luminosity is converted into visual region continuum emission rather than emission line luminosity, as occurs in lower density H II regions.

The optical depth of the envelope provides an additional means to estimate the amount of circumstellar matter. Taking an average over the envelope, the optical depth is approximately (Ney and Hatfield 1980)

$$\tau_{\mathrm{env}} \approx \frac{\kappa' \mu M_{\mathrm{H}} \bar{N}_e R}{3} . \qquad (3)$$

Since $R \approx R_p(\mathrm{opt})$ and $\kappa' \leq 1$ (Bath 1978), then for $\tau_{\mathrm{env}} \gtrsim 2$ we require $\bar{N}_e \gtrsim 10^{11}$, and the circumstellar envelope with $R_p(\mathrm{opt})$ can therefore possibly account for much of the optical hydrogen line emission. Adopting this model, we can then use equation (2) to find a lower limit to the mass loss rate of $\dot{M} \gtrsim 10^{-5}(V/100)\, M_\odot$ yr^{-1}.

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1981ApJ...249...83G

c) *Iron Emission Lines*

Both stars have extensive emission spectra of Fe II and [Fe II] (see Table 2). However, only weak [Fe III] is seen in AF And (the strong lines at λ4658 and λ5270 are probably present; see Thackeray (1977); there is no evidence for Fe I or [Fe I] features in either star. Thus, the physical conditions in the forbidden line region of the envelope must be narrowly constrained, and mechanical energy is therefore unlikely to be important in this zone since mechanically heated gases tend to contain a broad range of ionized species. From the presence of [Fe II], we also see that the forbidden line region must have sufficiently low electron density so that metastable levels of iron are not collisionally deexcited and yet be dense enough so that other forbidden lines (e.g., [S II], [O I]) are weak. These conditions can be satisfied only over a relatively small density range, $10^7 \lesssim N_e \lesssim 10^{10}$ (cf. Osterbrock 1974; Viotti 1976). The combination of sharply defined ionization and density conditions suggests the forbidden emission occurs in a localized volume whose size is determined by some basic characteristic of the envelope, e.g., in the transition region between the H^+ and H° zones of the envelope.

The data summary in Table 2 and the spectra of Figures 1 and 2 show that there is a systematic difference in the ratio of [Fe II] to Fe II in the two stars. In A-1 And the Fe II lines dominate, with [Fe II] being $\lesssim \frac{1}{2}$ as strong. The weakness of the forbidden lines can be understood if the density is near the critical value for collisional deexcitation (cf. Viotti 1976), and from the similar strengths of lines in Fe II multiples 42 and 49 and the absence of Si II λ5979, we conclude the lines are primarily collisionally excited (Phillips 1978). AF And has a richer and stronger [Fe II] spectrum than A-1 And, which means the electron density must be lower.

A more precise limit can be set for N_e in AF And from a comparison of the fluxes in Fe II multiplet 42 which feeds into the a^6S level with those of multiplet 7F which radiatively deexcites this level. In the low density limit, the photon flux N in multipet 7F should equal or exceed that from multiplet 42. Our data show that $N(42)/N(7F) \lesssim 0.1$, where we have used the measured fluxes of λ4414 of 7F and λ5169 of 42 normalized by the transition probabilities given by Garstang (1962) and Phillips (1979) to give total rates for the respective multiplets. Although this ratio is not empirically well determined since the flux of Fe II λ4924 of multiplet 42 is too small, most likely as a result of optical depth effects (cf. Phillips 1978), we can, however, still safely conclude that the forbidden line zone in AF And is in the low density regime where most excitations of the a^6S metastable level lead to radiative decays. This then implies $\bar{N}_e \lesssim 10^8$.

We therefore find that despite the qualitative similarities between the spectra of A-1 And and AF And, the envelopes have significantly different densities. However, it is interesting that in both stars the ratio of combined Fe II and [Fe II] luminosity to H Balmer line luminosity is roughly the same. Davidson's (1971) model in which the Fe emission is due to cooling of the dense envelope probably can explain this feature of the data.

In Figure 3 we have combined all of our analysis to make a schematic model of both stars. The extent of the Fe II-[Fe II] emitting volume is shown to be sharply bounded, which follows from our assumption of collisional excitation. For this to occur, we require temperatures near 10^4 K, especially if the upper states which are ~ 3 eV above the ground states are to be reached in the nebular case. In order to maintain high electron densities without excessive total gas densities, we also require that electrons be provided by H. Under these circumstances the amount of Fe II-[Fe II] emission will be strongly dependent on the local gas temperature: once the temperature drops below $\sim 5 \times 10^3$ K, both N_e and the collisional excitation rate decline precipitously, and the iron emission turns off. The location of this point in the envelope depends on structural details, but on the basis of radiative equilibrium is unlikely to exceed $4R_p$(opt) for either star. Finally, we also note that the absence of [O I] allows us to exclude the presence of any very extended low density envelope with $T_e \gtrsim 3 \times 10^3$ K, as might have been formed by relics of recent episodic ejection events.

d) *Comparison with η Carinae*

i) *Luminosities*

The historic visual maxima of A-1 And and AF And have been 14.5 and 15.2, respectively (Humphreys 1978), which correspond to $M_v \sim -10.1$ and $M_v \sim -9.4$. Thus, in both cases the peak visual luminosity is at least 1 mag less than η Carinae (see HD) and, as we have seen that large bolometric corrections associated with either unobserved ultraviolet luminosity or infrared radiation are unlikely in the M31 variables, we conclude this difference also applies to the bolometric luminosities. Similarly, the

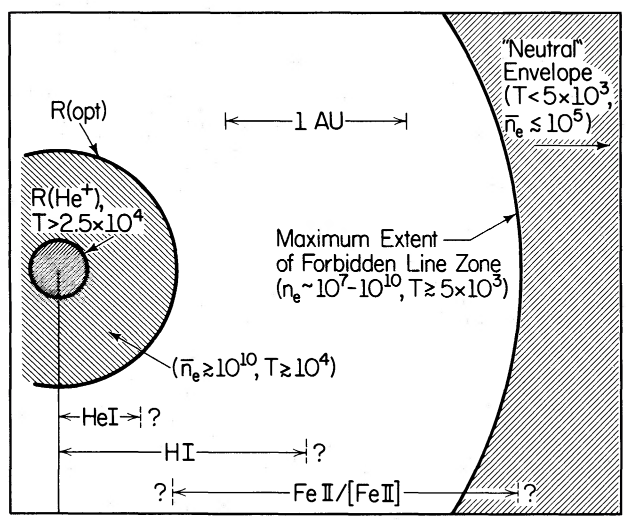

FIG. 3.—Schematic photoionization model for the extended atmospheres of AF and A-1 Andromedae. Approximate densities and temperatures are indicated for the regions discussed in the text. The symbols at the bottom mark the extent of the emission line zones.

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1981ApJ...249...83G

Hβ luminosity of η Carinae exceeds that of these two M31 variables by roughly a factor of 10 (cf. Davidson 1971).

ii) *Emission Spectra*

All three stars are qualitatively alike in their emission line characteristics: H Balmer lines dominate the optical spectrum, while rich Fe II and [Fe II] emission is seen at lower intensity. However, η Carinae is clearly in the low density limit (Thackeray 1967; Viotti 1976) and in this respect is quite different than A-1 And. The strongest noniron forbidden line in η Carinae within the spectral region we have covered is [N II] λ5755; this line is probably present at a weak level in A-1 And but is absent in AF And. As in η Carinae, the traditional nebular lines of [O III] are not detected in either M31 variable.

iii) *Circumstellar Dust*

There is compelling evidence that the great 19th century visual event in η Carinae resulted in the ejection of material which subsequently produced an extensive dust shell (e.g., Westphal and Neugebauer 1969; Davidson 1971; Gallagher 1977). In A-1 And and AF And we find no optical indication for such dense circumstellar matter which might support dust condensation; this is in agreement with the lack of large infrared excesses in these two stars (R. M. Humphreys, private communication).

iv) *Environment*

η Carinae is located in a spectacular environment. It is surrounded by an extraordinary OB association, and a bright H II region covers η Carinae itself (Gratton 1963). By comparison, both A-1 And and AF And are in unremarkable locations. A-1 And is within a spiral arm, and luminous stars can be seen in the immediate vicinity of the variable. A comparison with the Baade and Arp (1964) catalog of H II regions shows that the nearest H II region is at a projected distance of $\sim$ 150 pc along the arm, which is in agreement with the absence of nebular lines in our spectra. The level of star formation activity around AF And is even lower, and in its interarm location we see no related association of luminous stars, while the nearest Baade and Arp H II regions are $\sim$ 500 pc projected distance.

IV. DISCUSSION

From the photoionization model developed in the previous section, we envision a typical Hubble-Sandage variable to consist of an optically thick core with $T_{\rm eff} \gtrsim 25{,}000$ K and a luminosity of $\sim 5 \times 10^5\ L_\odot$ (but perhaps with excursions up to $\sim 10^6\ L_\odot$) which is surrounded by a moderately dense, translucent envelope extending to a radius of several AU. It is this envelope that controls the fraction of the core luminosity radiated at optical wavelengths and also accounts for the usual spectroscopic characteristics of these stars. As a result, it is the envelope characteristics that will control the location of these stars on an observational H-R diagram, and thus their presence in the supergiant region is not *a priori* evidence that they are evolved stars (cf. HD). Understanding the S Doradus stars therefore hinges on understanding the origin and evolutionary significance of their circumstellar shells.

The possibility that this material is a remnant of the formation process of a massive star appears to be ruled out for the two stars studied here. First, neither star shows optical or infrared evidence for extensive amounts of circumstellar dust, while very young massive stars are usually found in dusty environments. Second, young massive stars tend to occur in groups, which at later stages in their evolution from H II regions that contain more mass than the stars themselves. However, we find no indication of either a compact or normal H II region containing significant mass in the vicinity of either variable (cf. Habing and Israel 1979). We therefore conclude that we are dealing with stars that have reached at least a mid-main sequence evolutionary phase so that any natal circumstellar matter has had time to dissipate.

Since it is likely that the stars in our program are no younger than the main sequence phase, we can get an upper limit to the mass from the observed maximum radiated luminosity of $\sim 10^6\ L_\odot$, which will be generated by a core hydrogen-burning star of $\sim 80\ M_\odot$ (Chiosi, Nasi, and Sreenivasan 1978). The minimum mass for a stable configuration is set by requiring that the Eddington limit not be exceeded, and thus $M \geq 25\ M_\odot$. Any stellar mass between these two extremes is feasible and in fact can probably be produced by normal stellar evolution with mass loss.

Massive main sequence stars, while exceedingly luminous, are still well above the mass at which their luminosity would reach the Eddington critical value, e.g., in the case of an 80 $M_\odot$ star $M_{\rm MS}/M_{\rm Edd} \sim 3$. Extreme mass loss rates associated with a dramatic decrease in surface gravity due to radiation pressure are therefore not expected and in fact are not observed. Instead, main sequence stars are found to have optically thin winds which are capable of producing $\dot{M} \lesssim 10^{-5}\ M_\odot\ {\rm yr}^{-1}$, but are characterized by high velocity, low density flows (Cassinelli 1979). Both our and Humphreys's (1975, 1978) data rule out velocities of $\gtrsim 300\ {\rm km\ s}^{-1}$, and thus we see that a simple extension of main sequence winds to higher mass loss rates will not produce the low velocity, high density envelopes of the S Doradus stars (see also Wolf, Appenzellor, and Cassatella 1980), and these stars are therefore unlikely to be single main sequence stars.

The situation is much more favorable for an evolved star, especially if the mass of the hydrogen-rich envelope has been reduced to much less than the helium core mass by stellar winds on the main sequence (see Dearborn, Tinsley, and Schramm 1978). In this case helium cores of appropriate luminosity have $M_{\rm He} \sim 30\ M_\odot$ and therefore approach the Eddington limit, $M_{\rm He}/M_{\rm Edd} \approx 1.3$, for $L = 10^6\ L_\odot$ (Arnett 1972; Choisi, Nasi, and Sreenivasan 1978; Brunish and Truran 1981*a*, *b*). For these stars, radiation pressure is expected to be a serious destabilizing influence. However, it is not clear that a circumstellar shell will be directly produced by radiation pressure in such an evolved star. For optically *thick* winds, which

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1981ApJ...249...83G

have the required low velocities and are formed beneath the photosphere, it is necessary for radiation pressure to exceed gravity in the region of mass acceleration (Bath 1978; Ruggles and Bath 1979). Obviously this does not occur in the stripped He core model for the Hubble-Sandage variables if the opacity is due purely to electron scattering. However, even a modest opacity increase would bring these stars into the regime where radiation pressure exceeds gravity and an extended envelope, optically thick wind model becomes feasible. Whether the opacity is in reality sufficiently large to support such a wind is difficult to ascertain from our uncertain knowledge of conditions at the base of the circumstellar envelopes, but this model is at least a possibility.

If the winds cannot form a dense shell directly, it may then be necessary to invoke a mechanical mass loss driver. From our picture of a He core surrounded by a low mass envelope, pulsational instability seems possible. Any matter that was moved out from its equilibrium position would cool, thereby increasing its opacity and susceptability to acceleration by continuum radiation pressure. Thus, the envelope might exist in a marginally stable state. The S Doradus stars therefore may be related to the unstable supergiants, such as ρ Cas, which also undergo shell ejection events (e.g., Sargent 1961; Cassinelli 1979). This type of single star model differs from the possibilities discussed in HD in that the S Doradus phase is not necessarily associated with catastrophic mass loss, but rather is a natural result of the evolution of very massive stars. We favor an unstable supergiant model for A-1 And, since it is embedded in a star-forming region and is therefore likely to be young.

As an alternative to a nuclear power source, Bath (1979) has suggested accretion in mass-transferring binary stars. These systems would be running at near $L_{\rm Edd}$, and thus the mass of the accreting star would currently have to be $\sim 25\ M_\odot$. High accretion rates associated with mass exchange on a dynamical time scale would also be required. The precursors of such binaries do seem to exist, and as Tutukov and Yungel'son (1980) have emphazised, massive close binaries must play a role in the production of luminous supergiants. They also emphasize that the result of rapid mass transfer on the structure of the binary is to produce a common envelope dinary (Paczynski 1976). It is this envelope, and not the accretion process, which would be observed as a peculiar luminous supergiant (Taam, Bodenheimer, and Ostriker 1978; Taam 1979). In this situation energy is being supplied by *both* accretion and stirring by the binary. Independent of the details of the particular model, the binary hypothesis has the advantage of requiring less total mass which could initially be distributed in stars with individual masses of $M \lesssim 15\ M_\odot$. This increases the possible main sequence lifetime of the system to $\gtrsim 10^7$ yr and may therefore provide a more comfortable explanation of relatively isolated stars such as AF And than the massive star models which have 10 times shorter lives.

V. SUMMARY

From spectrophotometry obtained with the 2.3 m Steward Observatory telescope, we have developed a photoionization model for the two Hubble-Sandage variables AF And and A-1 And. This model is pictured schematically in Figure 3. A hot "star" ($T_* \approx 25{,}000$ K) provides the energy to support a cooler, extended envelope with $T \approx 10{,}000$ K and $N_e \approx 10^7$–10^{10} cm^{-3}. Emission lines of He I are formed in a region near this star, while H Balmer and lines of iron (Fe II and [Fe II]) are formed farther out in the shell. The density then drops quickly in the predominantly neutral envelope.

These two stars are not energetically similar to the extraordinary object η Carinae and therefore may represent a different type of phenomenon, even though conditions in the circumstellar envelopes may in some ways be analogous. Both variables, however, do seem to be typical members of the M31 and M33 Hubble-Sandage class, and in particular all of the M33 variables are like A-1 And in being near sites of active star formation. Although only very crude estimates are currently available, the mass loss rates ($\sim 10^{-5}\ M_\odot$ yr^{-1}) are about average for stars in the upper left portion of the H-R diagram. From theoretical evolutionary tracks, we have proposed that A-1 And could be a massive star ($M \gtrsim 30\ M_\odot$) now burning helium in its core. Such a star requires an initial mass $\gtrsim 80\ M_\odot$ which lost mass at $\sim 2 \times 10^{-5}\ M_\odot$ yr^{-1} over its main sequence lifetime, in good agreement with the evolutionary tracks of massive stars calculated by Chiosi, Nasi, and Sreenivasan (1978) and Brunish (1981*a*, *b*). There is, however, also the possibility that A-1 And is due to binary evolution, perhaps in a massive young system. Although the observations of AF And also fit either interpretation, we have argued that its isolated location in M31 is more supportive of a binary model.

Future observations should concentrate on determining the structure of the extended atmosphere. High resolution spectra are needed to look for P Cygni profiles and to measure emission line Doppler widths, which will allow us to calculate mass loss rates. Polarization studies might also be helpful in probing the nature of the atmosphere (binary ejecta are likely to be asymmetrical which might lead to a high net polarization). Finally the structure of the central stellar core could be more effectively explored if ultraviolet spectra could be obtained.

We would like to thank George Will for his able operation of the Steward Observatory 2.3 m telescope during these observations, and Deidre Hunter for her help in taking plates of M31 and for the use of her software. Wendee Brunish provided us with insights into the effects of mass loss on the evolution of luminous stars and also promptly translated the Tutukov and Yungel'son paper from the Russian. We are also grateful to Kris Davidson, Icko Iben, Roberta Humphreys, Susan Lamb, Jim Truran, and Ron Webbink for their comments on this project.

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1981ApJ...249...83G

REFERENCES

Arnett, W. D. 1972, *Ap. J.*, **176**, 681.
Baade, W., and Arp, H. 1964, *Ap. J.*, **139**, 1027.
Bath, G. T. 1978, *M.N.R.A.S.*, **182**, 35.
———. 1979, *Nature*, **282**, 274.
Bianchini, A., and Rosino, L. 1975, *Astr. Ap.*, **42**, 289.
Brunish, W. M., and Truran, J. W. 1981*a*, *Bull. AAS*, **12**, 805
———. 1981*b*, preprint.
Burgess, R. D. 1976, Ph.D. thesis, Indiana University.
Cassinelli, J. P. 1971, *Ann. Rev. Astr. Ap.*, **17**, 275.
———. 1979, *Ap.J.*, **165**, 265.
Choisi, C., Nasi, E., and Sreenivasan, S. R. 1978, *Astr. Ap.*, **63**, 103.
Davidson, K. 1971, *M.N.R.A.S.*, **154**, 415.
Dearborn, D., Tinsley, B. M., and Schramm, D. N. 1978, *Ap. J.*, **223**, 557.
Gallagher, J. S. 1977, *A.J.*, **82**, 209.
Garstang, R. H. 1962, *M.N.R.A.S.*, **124**, 321.
Gratton, L. 1963, in *Stellar Evolution*, ed. L. Gratton (New York: Academic).
Habing, H. J., and Israel, F. P. 1979, *Ann. Rev. Astr. Ap.*, **17**, 345.
Hege, E. K., Cromwell, R. H., and Woolf, N. J. 1979, *Adv. Electronics Electron Phys.*, **52**, 397.
Hubble, E., and Sandage, A. 1953, *Ap. J.*, **118**, 353.
Humphreys, R. M. 1975, *Ap. J.*, **200**, 426.
———. 1978, *Ap. J.*, **219**, 445.
Humphreys, R. M., and Davidson, K. 1979, *Ap. J.*, **232**, 409.
Humphreys, R. M., and Warner, J. W. 1978, *Ap. J.* (*Letters*), **221**, L73.
Kaler, J. B. 1978, *Ap. J.*, **226**, 947.
Kukarkin, B. V., *et al.* 1974, *Second Supplement to the Third Edition of the General Catalogue of Variable Stars* (Moscow: Akad. Nank.).
McClure, R. D., and Racine, R. 1969, *Ap. J.*, **74**, 1000.
Ney, E. P., and Hatfield, B. F. 1980, *A.J.*, **85**, 1292.
Oke, J. B. 1974, *Ap. J. Suppl.*, **27**, 21.
Osterbrock, D. E. 1974, *Astrophysics of Gaseous Nebulae* (San Francisco: W. H. Freeman).
Paczynski, B. 1976, *Structure and Evolution of Close Binary Systems*, ed. P. Eggleton, S. Mitton and J. Whelan (Dordrecht: Reidel).
Phillips, M. M. 1978, *Ap. J. Suppl.*, **38**, 187.
———. 1979, *Ap. J. Suppl.*, **39**, 377.
Rosino, L., and Bianchini, A. 1973, *Astr. Ap.*, **22**, 453.
Ruggles, C. L. N., and Bath, G. T. 1979, *Astr. Ap.*, **80**, 97.
Sandage, A., and Tammann, G. A. 1976, *Ap. J.*, **210**, 7.
Sargent, W. L. W. 1961, *Ap. J.*, **134**, 142.
Sharov, A. S., Esipov, V. F., and Lyutyj, V. M. 1975, *Soviet Astr.—AJ* (*Letters*), **1**, p. 30.
Taam, R. E. 1979, *Ap. Letters*, **20**, 29.
Taam, R. E., Bodenheimer, P., and Ostriker, J. 1978, *Ap. J.*, **222**, 269.
Thackeray, A. D. 1964, *M.N.R.A.S.*, **129**, 169.
———. 1967, *M.N.R.A.S.*, **135**, 51.
———. 1977, *M.N.R.A.S.*, **83**, 1.
Tutukov, A. V., and Yungel'son, L. R. 1980, *Soviet Astr.—AJ*, *Letters*, **6**, 491.
Viotti, R. 1976, *Ap. J.*, **204**, 293.
Westphal, J. A., and Neugebauer, G. 1969, *Ap. J*, (*Letters*), **156**, L45.
Wolf, B., Appenzeller, I., and Cassatella, A. 1980, *Astr. Ap.*, **88**, 15.

J. S. GALLAGHER and S. J. KENYON: Department of Astronomy, 1011 W. Springfield Ave., University of Illinois, Urbana, IL 61801

E. K. HEGE: Steward Observatory, University of Arizona, Tucson, AZ 85721

© American Astronomical Society • Provided by the NASA Astrophysics Data System