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IUE OBSERVATIONS OF THE HIGH-VELOCITY SYMBIOTIC STAR AG DRACONIS. II. THE SPECTRAL VARIATIONS DURING 1979–1983[1]

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ABSTRACT

After a long period of quiescence the high-velocity symbiotic star AG Dra underwent a large outburst in the visual in 1980 November, followed by a second light maximum and by a gradual fading to a new minimum phase in 1983. Following a previous investigation devoted to the study of the ultraviolet spectrum during the active postoutburst phase, we analyze here a complete set of *IUE* spectra covering the period 1979 June to 1983 June. We find that during the outburst, the UV continuum and emission lines have brightened by one order of magnitude, without a large change of the line excitation. After the outburst, the UV continuum and the He II λ1640 line exhibited a wide variation in phase with the visual light curve, while C IV showed only slight variations and N V remained almost constant until the 1982–1983 phase of fading. Continuum and line variability is also present during the preoutburst quiescent phase, in agreement with the *U*-light curve of Meinunger. A P Cygni profile of the N V resonance lines is present in all the well exposed high resolution spectra, suggesting the existence of a *low-velocity* (170 km s^{-1}) *warm wind* both during the active phase and during quiescence. There is also evidence for a systematic radial velocity difference between the resonance and intercombination lines of $+9.5 \pm 2.6$ km s^{-1}. These results seem to support a *binary model* of AG Dra, consisting of a nonvariable K-giant with a strong wind, and a dwarf companion accreting matter from the cool star wind. To explain the quasi-periodic flux variations, we suggest that the UV continuum and emission lines would be mostly emitted from an extended region near the cool star (the upper stellar atmosphere and/or the inner wind) heated by the intense UV and X-ray radiation from the hot source. The 1980 October outburst could be associated with a previous increase of the temperature of the hot source, but to better clarify its nature and the complex phenomenology of this Population II symbiotic star, more investigations in different wavelength ranges are required.

Subject headings: stars: combination spectra — stars: binaries — stars: individual — stars: winds — ultraviolet: spectra

I. INTRODUCTION

The symbiotic star AG Dra (BD+67°922) is peculiar in many aspects: It is a high velocity (Roman 1955), high galactic latitude star which showed in the past a light curve similar to that of the classical symbiotic star Z And (Robinson 1969). More recently the star remained in a phase of minimum luminosity for many years, until 1980 October when a new major outburst occurred, followed by a second maximum in 1981 November and a gradual fading until the present (1983 June) minimum phase. AG Dra was also observed in the IR, but no large variability was found (Kaler 1983; Eiroa *et al.* 1982; Viotti *et al.* 1983*a*) in correspondence to the large light variation. A large *U*-band variability during the preoutburst phase was discovered by Meinunger (1979), who gave a period of about 554 days. This result has been more recently confirmed by Oliversen and Anderson (1982) on the basis of a larger set of data. X-ray observations with the *Einstein Observatory* made in 1980 April revealed that AG Dra had an intense soft X-ray spectrum (Anderson, Cassinelli, and Sanders 1981). The rather large coverage of UV observations since 1979 makes AG Dra a unique case for the study in a broad spectral range of a star before and during a large luminosity outburst, and in the declining phase. Preliminary results on the UV variations of AG Dra were described by Lutz and Lutz (1981), by Altamore *et al.* (1982*a*), and by Viotti *et al.* (1982). A detailed study of the ultraviolet spectrum of AG Dra during activity is given by Viotti *et al.* (1983*b*, hereafter referred to as Paper I). In this paper we give a complete analysis of the spectral variations during five years (1979–1983) of *IUE* observations, and propose an eclipsing binary model for the star which seems to better describe the observations.

II. OBSERVATIONS AND RESULTS

For the present investigation we used, in addition to our observations obtained at VILSPA, the archive low and high resolution *IUE* images collected at the Goddard *IUE* Observatory during 1979–1981. The spectra of low quality were rejected. The data analysis was carried out with the IHAP software at VILSPA and at ESO-Garching. From the study of the energy distribution near 2200 Å in the better exposed low-resolution images, we derived a mean value of the interstellar extinction of $E(B-V) = 0.06 \pm 0.02$, in agreement with the result of Paper I. Next all the spectra were dereddened using the average interstellar extinction curve given by Savage and Mathis (1979). We have derived the continuum flux in two emission-line–free regions near 1340 and 2860 Å, which are a measure of the two continuum components discussed in Paper I. In addition we have measured some of the most prominent

[1] Based on observations by the *International Ultraviolet Explorer* collected at the Villafranca Satellite Tracking Station of the European Space Agency, and on archive *IUE* data obtained from VILSPA.

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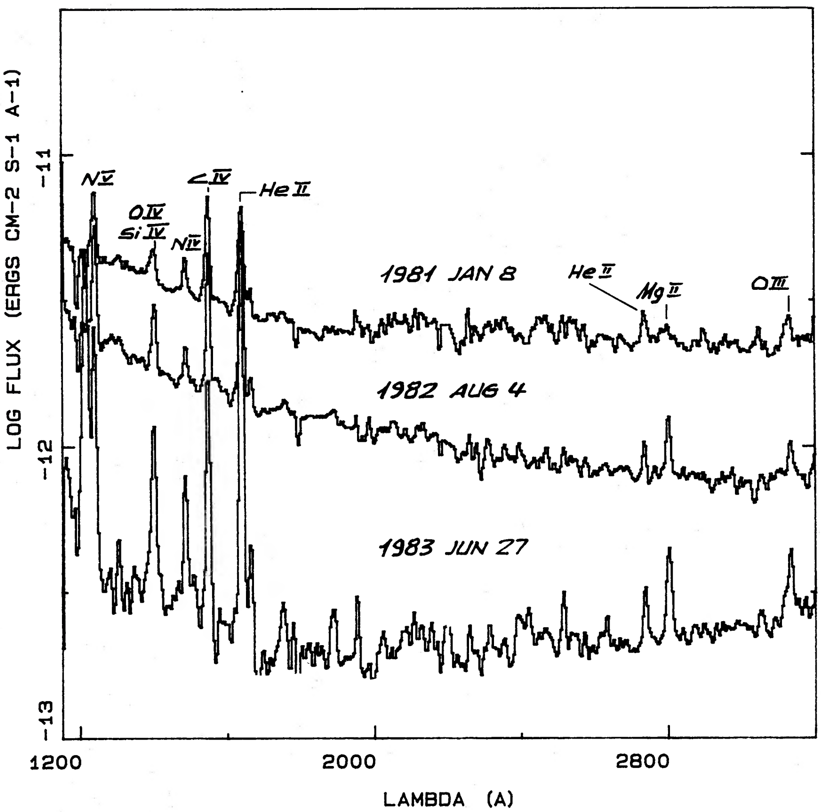

FIG. 1.—The ultraviolet spectrum of AG Dra during different activity phases. From top to bottom: 1981 Jan 8 ($V = 8.4$), 1982 Aug 4 (9.3), and 1983 June 27 (9.8). Ordinates are log fluxes in ergs cm^{-2} s^{-1} Å^{-1}, corrected for an interstellar extinction of $E(B-V) = 0.06$. The He II 1640 Å line is saturated.

emission lines (N V, N IV], C IV, He II 1640) from both low and high resolution spectra. For the high resolution images, the calibration by Cassatella, Ponz, and Selvelli (1981) for emission-line objects was used. In the majority of the large aperture images the He II line at 1641 Å is overexposed, and its intensity, when possible, was derived from the small aperture images using a constant correction factor of 2.0, which should be accurate at least within $\pm 30\%$. Figure 1 shows some representative *IUE* spectra of AG Dra in order to illustrate the large spectral variations which occurred before and after the outburst. The dereddened continuum and line fluxes are summarized in Table 1, which also contains, when available, the counts of the Fine Error Sensor (FES) onboard *IUE* (passband peaked at around 5000 Å), and the V magnitude derived from the AAVSO observations (Mattei 1982). The U-phase is referred to the Meinunger (1979) elements of the U-light curve during quiescence. The results are presented in Figures 2 and 3.

a) The Continuum Variations

Figure 2 (curves B and C) shows the variation of the UV continuum according to the *IUE* observations. For comparison we also give the *IUE*–FES counts (curve A). The UV continuum underwent a large increase between 1980 October 23 and November 25, corresponding to the optical outburst, with a subsequent further increase up to the 1981 January maximum. The amplitude of the flux increase is nearly the same in the whole UV range (about a factor 10), while in the visual the variation was much smaller (curve A in Fig. 2). This difference may be accounted for by the large contribution (expecially at minimum) to the yellow-red of AG Dra of the

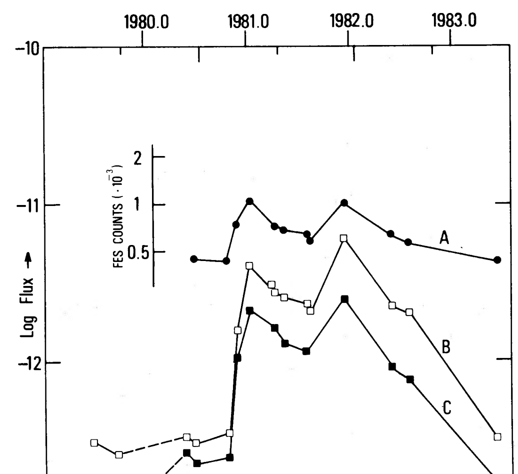

FIG. 2.—The UV continuum in AG Dra at 1340 Å (diagram B) and 2860 Å (diagram C) during 1979–1983. The *IUE* FES counts (diagram A) are also given for comparison. Abscissae are phases according to the U-light curve of Meinunger (1979). Ordinates are log fluxes in ergs cm^{-2} s^{-1} Å^{-1}, or log FES counts.

TABLE 1

CONTINUUM AND EMISSION LINE FLUXES[a]

Date	FES IUE	V	U-Phase	Continuum 1340	Continuum 2860	N V 1240	N IV] 1486	C IV 1550	He II 1640[b]	He II/F_{1340}
1979:										
Jun 29	...	9.8	0.30	31	14	11.2	3.2	11.1	27.8	90
Sep 25	...	9.9	0.46	26	10	8.8	1.8	6.5	23.6	91
1980:										
May 23	...	9.8	0.90	33	27:	19.9	4.0	17.6	=	=
Jun 27	457	9.8	0.96	33	22	21.6	4.8	17.3	58.4	177
Jun 27[c]	...	...	0.96	=	=	24.8	5.2	17.5	≥45.3	=
Oct 23	433	9.8	0.17	35	25	13.6	3.0	14.1	45.9	131
Nov 15	753	9.1	0.21	158	113	34.9	9.2	49.7	202.	128
1981:										
Jan 8	1032	8.4	0.31	406	215	36.7	10.9	53.9	226.	56
Mar 28	...	8.9	0.45	312	=	53.3	9.0	65.1	sat.	=
Apr 4[c]	...	8.9	0.47	=	=	41.0	7.0	51.5	≥202.[d]	=
Apr 6	742	8.9	0.47	278	162	57.1	9.2	58.7	196.	71
Apr 24[c]	723	9.0	0.50	235:	138:	40.0	6.5	45.5	188.[d]	80
May 10	671	9.0	0.53	255	129	56.0	9.8	49.5	sat.	=
Aug 3	632	9.2	0.68	229	115	56.9	9.2	48.4	108.	47
Aug 3[c]	...	...	0.68	235:	116:	52.9	7.6	52.1	sat.	=
Aug 14	589	9.1	0.70	204	=	53.2	12.8	59.7	120.	59
Dec 11	1010	8.5	0.92	603	253	52.0	14.3:	66.0	177.	29
Dec 11[c]	...	...	0.92	=	=	52.4	5.7	67.7	218.[d]	36
1982:										
Jun 2	645	9.1	0.23	224	93	49.0	8.1	42.9	sat.	=
Aug 4	565	9.3	0.34	202	75	37.6	6.4	33.6	105.	52
1983:										
Jun 7	432	9.8	0.90	=	17	=	=	=	=	=
Jun 7[c]	...	...	0.90	=	=	23.5	3.0	15.3	sat.	=
Jun 12	...	...	0.90	32	=	24.3	4.3	19.0	68.8	215

[a] Continuum and emission-line fluxes are in 10^{-14} ergs cm^{-2} s^{-1} Å^{-1}, and 10^{-12} ergs cm^{-2} s^{-1}, respectively, dereddened for $E(B-V) = 0.06$.

[b] Line fluxes, for low-resolution images, derived from the SA spectra, multiplied by a factor 2.

[c] High-resolution image.

[d] Narrow emission plus broad wings.

probably constant spectrum of the cool star. A variability of the UV continuum is evident during the quiescent phase before the outburst, with a flux minimum near phase 0.5 of the Meinunger (1979) *U*-light curve. A slight flux decrease is present just before the 1980 October outburst, again in agreement with Meinunger. After the 1981 January maximum, the UV continuum flux decreased down to a minimum value about 40% below the maximum. Then a new maximum was reached near the end of 1981 followed by a subsequent fading until the very low minimum of 1983 June. It should be noted that the same trend, but with a smaller amplitude, was displayed by the visual light curve, suggesting that during the whole active phase of AG Dra there was a large contribution of the variable *hot* continuum to the visual luminosity.

b) The Emission Lines

Figure 3 shows the intensity variation of the most prominent UV emission lines. All the emission lines exhibit clear evidence of a large intensity increase during the 1980 October outburst, but with an amplitude smaller than that displayed by the UV continuum. A variability is also present during the quiescent phase which is well correlated with the UV continuum variation (Fig. 2). Following the large outburst increase, the emission lines have shown a different behavior. In fact, the He II 1640 Å line displayed a clear minimum in 1981 August when the UV continuum flux was also lower. On the other hand, the N V resonance doublet remained nearly constant from 1981 March to 1982 June. The C IV doublet is characterized by a postoutburst minimum smaller than that presented by the UV continuum. The N IV] line at 1486 Å shows a trend similar to that of C IV and N V. In Figure 3 we show the time variation of the N V/C IV intensity ratio during 1979–1983. Apart from a possible slight decrease during the luminosity rise phase, the ratio remained fairly constant within the errors of measurement, suggesting that the ionization degree of the emitting region did not change significantly during the period covered by the *IUE* observations.

Figure 4 shows the profile of the N V doublet during four different epochs. It is clear in the figure that a P Cygni profile is present, at least in the stronger 1238 Å line, in all the spectra. This line is always characterized by a sharper blue wing of the emission. This asymmetry, which is ascribed to the blueshifted absorption, is present also in the less exposed spectra where the UV continuum is not detected. The mean radial velocity difference between the emission and absorption components is 110 ± 15 km s^{-1} (see Table 2). The low continuum level near 1240 Å does not allow us to look for possible velocity variations. These results clearly suggest that a low-velocity warm

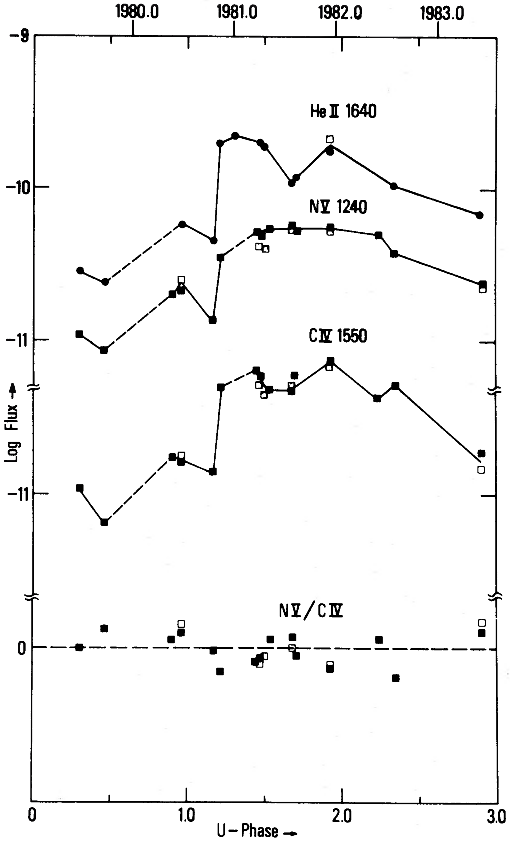

FIG. 3.—The variation of the strongest emission lines in AG Dra during 1979–1983. The different symbols are: *Filled circles*, small-aperture, low-resolution line fluxes corrected by a factor 2. *Filled squares*, fluxes from large-aperture images. *Open squares*, fluxes from high-resolution images. Ordinates are log fluxes in ergs cm^{-2} s^{-1}. The last graph gives the N v/C IV flux ratio; the dashed line corresponds to a ratio equal to unity.

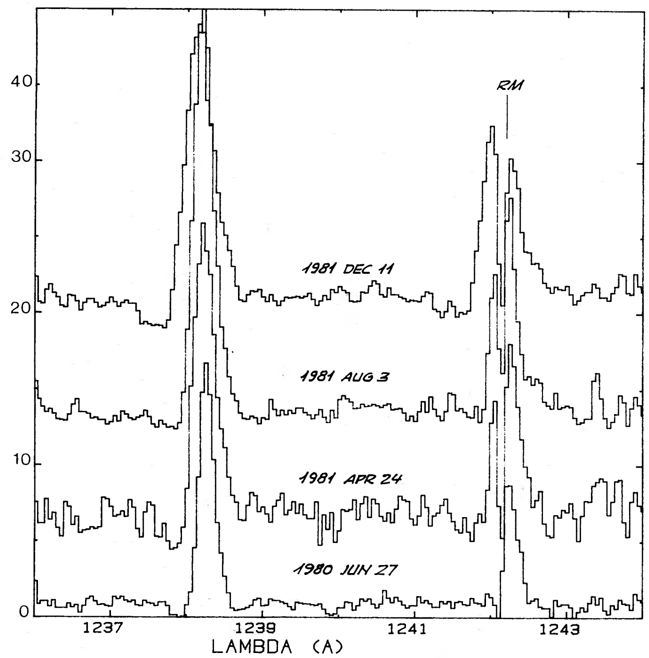

FIG. 4.—The profile of the N v lines in four different epochs. From bottom: 1980 June 27 ($V = 9.8$), 1981 April 24 (9.0), 1981 August 3 (9.2), and 1981 December 11 (8.5). The vertical scale is in 10^{-12} ergs cm^{-2} s^{-1} Å^{-1} (undereddened fluxes). The successive spectra are vertically shifted by a constant value. A violet-shifted absorption of the N v 1238 Å line (and probably also of the 1242 Å line) is present in all the spectra. The 1242 Å line is strongly affected by a reseau mark.

wind from one of the two components of the system is present both during minimum luminosity and during the active phases of AG Dra. A terminal velocity of about 170 km s^{-1} is estimated for the stellar wind (see Paper I). Figure 4 also shows that the N v lines are broader when the luminosity of AG Dra is higher, a result which is also observable in the He II 1640 Å line.

As regards the He II lines, we have measured the dereddened intensities of the He II 1640 Å line and of the Pickering series in different epochs, from 1980 June to 1981 December, and found that, in spite of the large light variations of the star, the dereddened relative intensities agree within the estimated errors with the theoretical computations of Seaton (1978), thus confirming and extending the conclusions of Paper I.

c) *Radial Velocities*

Friedjung, Stencel, and Viotti (1983) have shown that in several symbiotic stars there is a systematic radial velocity difference between the high ionization resonance lines and the intercombination lines, which is explained by line formation in a wind probably from the cool components. We have measured the radial velocities of the emission lines in all the high resolution SWP images at our disposal. Table 2 gives the heliocentric radial velocities of the intercombination lines and of the permitted lines. The He II 1640 Å line and the N v resonance doublet were excluded from the mean since their radial velo-

TABLE 2

MEAN RADIAL VELOCITIES

Parameter	1980 Jun 27		1981 Apr 4	1981 Apr 24		1981 Aug 3	1981 Dec 11		1983 Jun 7
SWP image	9383	9384	13651	13793	13794	14641	15710	15712	20162
Intercombination lines	−144	−146	−149	−145	−138	−146	−146	...	−156
	±11	±8	±5	±8	±11	±9	±9		±5
Permitted lines	−133	−132	−138	−140	−128	−139	−139	−153	−147
	±11	±6	±4	±6	±7	±9	±9	±6	±4
He II λ1640	−140	−152	−155	−148	−144	−155	−164	−164	−172
N v em	−114	−116	−120	−130	−123	−139	−143	−156	−151
N v 1238 e-a	...	85:	90:	...	115:	120:	125:	115::	...
Permitted minus intercombination	+11	+14	+11	+5	+10	+7	+7	...	+9
	±15	±10	±7	±10	±13	±13	±13		±6

NOTE.—Heliocentric radial velocities only from SWP high-resolution *IUE* images.

cities largely deviate from the mean velocity of the other permitted lines. The difference between the two groups of lines given in the table is of the order of one standard deviation, but it has always the same sign in agreement with the general behavior found by Friedjung, Stencel, and Viotti (1983) for the symbiotic stars. A statistical analysis of the results leads us to conclude that this difference is real, with a mean value of $+9.5 \pm 2.6$ km s^{-1}.

III. DISCUSSION

Let us now discuss the above results in the light of the possible models for AG Dra. To explain the large U-band variability Oliversen and Anderson (1982) proposed a model of a rotating spotted star model, in which the preoutburst UV variability is explained by the presence of hot spots on the surface of the K star. However, as discussed in Paper I, the amount of UV flux expecially during the active phase is comparable with the cool star radiation, and it can hardly be substained by a late-type stellar atmosphere. In addition, the small IR variability (cf. Viotti *et al.* 1983*a*) suggests that the cool stellar component of AG Dra should be relatively stable. Thus the large ultraviolet variability represents a clue for the model of AG Dra.

During the preoutburst phase (1979–1980) a considerable UV continuum and line variation took place. This variation is nearly in phase with the Meinunger (1979) U-light curve (see Figs. 2 and 3). The quasi-periodic variation of the U-flux during quiescence could be explained by a binary model in which the hot component is eclipsed by the star. Anderson, Cassinelli, and Sanders (1981) and Smith and Bopp (1981) give arguments against this hypothesis, since the broad minimum of the U-light curve would imply a very extended hot component. From the preliminary analysis of the *IUE* spectra, Viotti *et al.* (Paper I) concluded that the far-UV radiation should be formed in a very small (0.068 $R_\odot$) hot region or star, with a temperature of about 10^5 K. If this hot source is eclipsed by the cool component, we should expect to observe periodic narrow minima of the far-UV continuum flux, instead of the observed broad minima. On the other hand, the upper atmosphere and/or the inner wind of the cool star facing the hot source might be ionized and heated by the intense UV radiation (and possibly X-radiation) of the hot source. Therefore, a large amount of UV radiation could be emitted by such an extended region whose visibility would vary smoothly with phase, so giving rise to an extended minimum. It should be noted that this model has some resemblances to the rotating spotted model of Oliversen and Anderson (1982), since in both models the U-variability is attributed to hot region(s) on the surface of the cool star.

The 1980 October outburst occurred in all the spectral regions, from visual to ultraviolet at the same time (Fig. 2). Both UV continuum and emission line intensities increased by about one order of magnitude, and this was followed by a minimum which was seen in the continuum at different wavelengths and in the He II emission, but was only weakly observable in C IV and probably absent in N V (Fig. 3). The phase of the minimum (0.6) is later than that which would be expected from the behavior before the outburst, according to the U-light curve of Meinunger (1979). Conversely, the second maximum (of the visual and UV continuum, and of He II emission) occurred at phase 0.85, before the expected maximum of the U-light curve. The question is therefore whether the minimum was due to occultation or eclipse of an extended hot region by the K-component, or to a new outburst about 1 year after the first one.

In the first case, the N V emission after the outburst would be formed in a noneclipsed region much more extended than during the preoutburst phase, when N V was variable. On the contrary, the hot continuum and the He II emission during the active phase would originate in a less extended region which is partially occulted near phase 0.6. The alternative hypothesis that the second maximum at the end of 1981 was due to a new outburst seems difficult to reconcile with the nearly constancy of N V during 1981, in contrast to the large increase of this doublet observed at the 1980 October outburst.

The ionization did not change spectacularly during and after the outburst, as suggested, for example, by the N V/C IV ratio in Figure 3. This fact and the constancy of the N V emission during the active phase may suggest that the rise to the second maximum was due not to another outburst, but rather to the egress from a phase of occultation of the hot source after the 1981 August minimum.

Finally, we have studied the behavior of the flux ratio R(He II/F_{1340}) of the He II λ1640 line and the far-UV continuum near 1340 Å (last column of Table 1). As discussed in Paper I, this ratio might be regarded as a measure of the temperature of the hot ionizing source. We have observed that before the 1980 October outburst there was a small increase in this ratio, followed by a gradual decrease without a significant change corresponding to the outburst and the second maximum. But between 1982 August and 1983 June R(He II/F_{1340}) increased again by a factor of about 7 and recovered the preoutburst value of 1980 June. This behavior of the He II line seems to indicate that the main outburst could have been a consequence of the heating of the hot ionizing component which started before the outburst, and which was followed by a gradual cooling. Such behavior is also shown by thermonuclear runaway outburst models (Kenyon and Truran 1983); it remains to be seen whether detailed agreement is possible. In addition, noting the small but significant UV continuum and line fading just before the outburst, we cannot exclude a really larger amplitude of the brightening than that actually observed, because of a partial eclipse of the hot source at that phase.

The observations of 1983 June apparently suggest a return of AG Dra to the preoutburst state, although in view of the previous photometric behavior of AG Dra (Robinson 1969) and of other symbiotic stars, like Z And (Mattei 1978), one would expect other maxima of smaller amplitude to occur before the settling down of the star into a new quiescent phase. An indication of this kind might also be supported by the large He II/F_{1340} ratio in 1983 June, suggesting a process of heating of the hot source which could be followed by a new outburst.

In conclusion, the present study of the spectral variations of AG Dra in the UV seems to support a binary model in which the UV variations are due to periodic occultations of an extended photoionized region by the cool star, superposed on large-amplitude variations caused by the activity of the hot source. The extended hot region could be the upper atmosphere and/or the inner wind of the cool star heated by the radiation of the hot companion. The high galactic latitude and high velocity indicate that AG Dra is a *nonmassive Population II system.* An intense warm wind probably produced by the cool star appears present during all the phases of AG Dra, and part of it is probably accreted by the unseen companion, causing the complex phenomenology of AG Dra. The cool star itself could be peculiar by having a stellar wind more intense than that observed in other K stars, and probably an extended chromosphere and transition region. The physics of the accretion process, the structure, temperature, instability of the accretion region (or disk), are still unknown, mainly because of the lack of some fundamental physical data on AG Dra which might be derived only from a detailed study of the observational data collected in all the spectral regions.

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