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DISCUSSION ON SELECTED SYMBIOTIC STARS

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I. INTRODUCTION

Because of its large variety of aspects, the symbiotic phenomenon is not very suitable for a statistical treatment. It is also not clear whether symbiotic stars really represent a homogeneous group of astrophysical objects or a collection of objects of different natures but showing similar phenomena. However, as already discussed in the introduction to the symbiotic stars, in this monograph we are especially interested in the *symbiotic phenomenon*, i.e., in those physical processes occurring in the atmosphere of each individual object and in their time dependence. Such a research can be performed through the detailed analysis of individual objects. This study should be done for a time long enough to cover all the different phases of their activity, in all the spectral ranges. Since the typical time scale of the symbiotic phenomena is up to several years and decades, this represents a problem since, for instance, making astronomy outside the visual region is a quite new field of research. It was a fortunate case that a few symbiotic stars (Z And, AG Dra, CH Cyg, AX Per, and PU Vul) had undergone remarkable light variations (or "outbursts") in recent years, which could have been followed in the space ultraviolet with IUE, and simultaneously in the optical and IR with ground-based telescopes. But, in general, the time coverage of most of the symbiotic objects is too short to have a complete picture of their behavior. In this regard, one should recall Mayall's remark about the light curve of Z And: "Z Andromedae is another variable that shows it will requires several *hundred* years of observations before a good analysis can be made of its variations" (Mayall, 1969).

This pessimistic remark should be considered as a note of caution for those involved in the interpretation of the observations. In the following, we shall discuss a number of individual symbiotic stars for which the amount of observational data is large enough to draw a rather complete picture of their general behavior and to make consistent models. We shall especially illustrate the necessary steps toward an empirical model and take the discussion of the individual objects as a useful occasion to describe different techniques of diagnosis.

II. Z ANDROMEDAE AND THE DIAGNOSTICS OF THE SYMBIOTIC STARS

II.A. INTRODUCTION

Z And has been considered as the prototype of the symbiotic stars, from its light history and the spectral variation during outburst. For a long time, its light curve has been the basis for theoretical studies of the symbiotic stars. The optical spectrum of the star has been studied extensively since the pioneer work of Plaskett (1928). Of particular interest is the work of Swings and Struve (1941; see also Swings, 1970) describing the spectral evolution during and after 1939 outburst, and of Boyarchuck (1968), who discussed the 1960 outburst and the following decline phase. Ultraviolet observations started after the launch of the International Ultraviolet Explorer (Altamore et al., 1981) and continued to the time of writing the present review. In particular, this allowed the study in the UV of the two minor outbursts that

occurred in 1984 and 1985. These observations, together with the extensive monitoring of the IR and of the emission line profiles, still make Z And one of the best-studied symbiotic stars, and an ideal target for investigation the symbiotic phenomenon.

The visual luminosity of Z And is variable between V = 8 to 11 on time scales from a few days to several months, without clear evidence of any periodicity. The full light curve is reproduced in Figure 11-2 in Chapter 11. Figure 13-1 is a condensed plot of 100-day means of photographic and visual observations from 1887 to 1969 (Mayall, 1969).

The light curve is characterized by (1) four main phases of higher luminosity starting in 1895, 1914, 1939, and 1959, and by (2) periods of low luminosity lasting roughly one decade in between. In the following, we shall discuss the behavior of Z And during quiescence and activity.

II.B. THE BEHAVIOR OF Z AND DURING QUIESCENCE

The most recent quiescent phase (1972 to about 1984) of Z And was also the longest, and this fact has allowed a detailed study of the behavior of a symbiotic star during minimum light. The optical-ultraviolet spectrum of Z And at minimum is rich in strong and narrow emission lines of several different atomic species and with a large range of ionization energy. A compendium of the ions whose transitions have been identified in the optical spectrum of Z And was given in Table 11-2. Both permitted and forbidden transitions are present, as well as lines typical of stellar chromospheres, Be, Of, and WR stars, planetary nebulae, coronal regions, etc. These features are also seen in the ultraviolet. Altamore et al. (1981) identified low-excitation lines of OI, MgII, and FeII, and high-ionization lines of HeII, OV, and MgV]. But the main result is that the intensity of the emission lines is largely variable on long time scale. Variation of Hα was reported by Altamore et al. (1979), while Altamore et al. (1982) found that in November 1982, the UV continuum and emission lines were about 40 percent stronger than in August 1980. They also noted that the IR spectrum did not show a significant change since 1981. From a more thorough analysis of the UV observations collected since 1978 with the IUE satellite, Fernandez-Castro et al. (1988) found that the UV continuum and the emission line fluxes vary quasi-periodically on a time scale of about 760 days. The amplitude is larger for the Balmer near-UV continuum and for most of the emission lines, and lower for the far-UV continuum and the CIII] line. The time variation of the SiIII]/CIII] ratio suggests a variable mean electron density of the emitting region from 0.6 to 2.2 x 10^{10} cm^{-3} in phase with the UV light curve. At maximum, the density and the emission measure are larger, while the effective emitting volume is smaller. Thus at maximum, the emission mostly comes from a compact

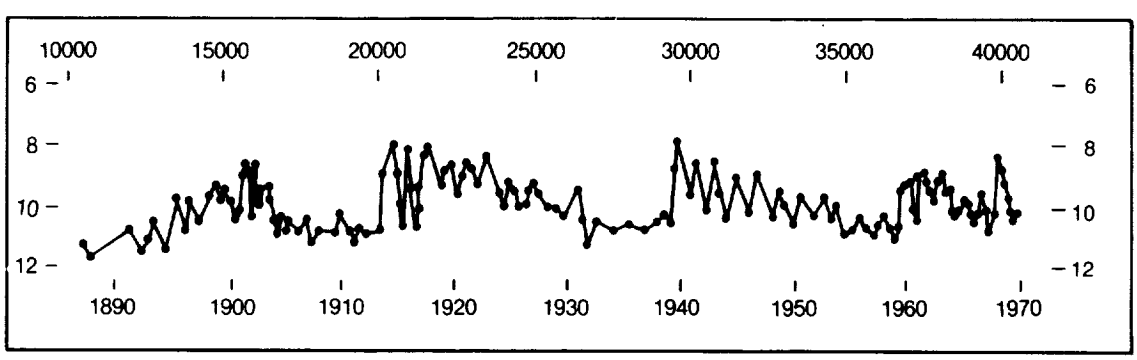


Figure 13-1. Plot of the 100-day average magnitudes of Z And during 1887 to 1969 (from Mayall, 1969).

region, and at minimum, the emitting volume is more diluted. These observations are consistent with a model of highly ionized diffuse region that is periodically occulted, leaving visible only the outer low-density regions.

Much about the nature of Z And can be learned from the simultaneous study in different wavelength regions. Figure 13-2 illustrates the variations of Z And from UV to IR during the last quiescent phase.

The large UV variability is clearly present in the U-band and in the Hα-variation and can be traced back to before the first ultraviolet observation. The variation is less evident in the visual. During minimum, V varied between 10.2 and 11.0 in an apparently irregular mode. This variation during minimum has been noted by several authors, (see Kenyon, 1986), and Kenyon and Webbink (1984), from the analysis of all the minima during quiescence, found that they are clearly periodic with a mean period of 756.85 days in agreement with the UV and Hα results. The radial velocity of the M-giant component was measured by Garcia and Kenyon (1988) over about 6 years. They found a smoothed sinusoidal curve with a period of 750 ± 8 days, and a semiamplitude of K = 8.1 ± 0.5 km s^{-1}. This fact provides further evidence of binarity, but the radial velocity and photometric curves do not have the relative phasing (a quarter of phase) expected from eclipse or reflection effects. This might suggest a more complex geometry of the system, as also suggested by the ultraviolet observations as discussed below. Finally, concerning the infrared, Taranova and Yudin (1981) and others reported small fluctuations, clearly not in phase with the UV variations. These can be attributed to the irregular behavior of the late-type component that is a common feature of the normal (normal = not a symbiotic or peculiar system) late-type giant and supergiant stars. The little variability of the cool component was also noted by Altamore et al. (1979, 1981) who, from their analysis of a collection of blue-infrared objective prism plates taken during October 1977 to June 1979, found that the near-IR continuum remained constant within ±0.1 mag. Larger variations seem to be present at longer wavelengths, but this needs to be confirmed by future observations.

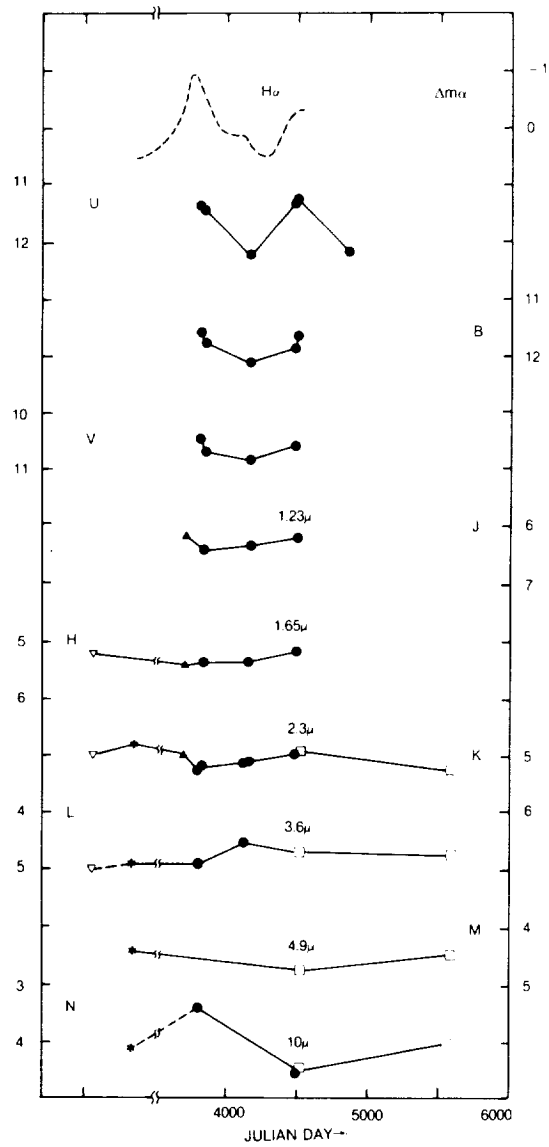
II.C. THE ACTIVE PHASES OF Z AND

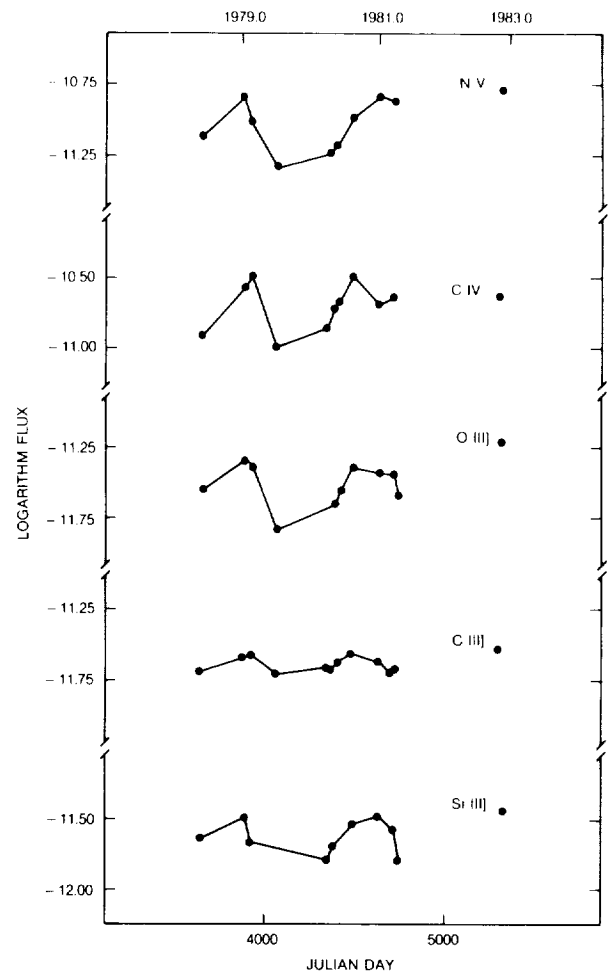
The active phase is characterized mostly by an increase of one to two magnitudes of the visual magnitude after a long-lasting quiescent phase. The brightening is rather slow, the rise time being about 100 days/mag, even compared with the slow novae. This "outburst" is generally followed by a sequence of minima and maxima resembling a damped oscillator. The time interval between two successive maxima (or minima) is not constant, but varies from 310 to 790 days (Mattei 1978) in an irregular way and is not in phase with the UV-variability during quiescence discussed above.

During the rise to outburst and the subsequent oscillations, the optical spectrum undergoes large changes, which have been extensively described in a number of papers. As the stellar luminosity increases, the high-ionization lines fade, and at maximum light, the spectrum displays a strong blue continuum with prominent hydrogen emission. These lines have absorption cores that dominate the emission at the higher members of the Balmer series. In some cases, P Cygni profiles are present in the H and HeI lines. At maximum, the absorption bands of the M spectrum are hardly visible. However, the weakening of the cool spectrum is only apparent since, as it has been found, for instance Boyarchuck (1968), the TiO bands are only veiled by the enhanced blue continuum, while the luminosity of the cool component has not changed within the errors. The high-ionization lines and the TiO absorption bands strengthen again as the blue continuum decreases during the light fading.

Recently, two minor outbursts of Z And were reported. After nearly 12 years of quiescence, the star brightened to V = 9.6 in March 1984 and again to V = 10.1 in September 1985 (Mattei, 1984, 1985). The 1984 outburst displayed a general rise of the line intensity. The largest increase was measured for the high-

ionization lines of HeII, CIV, and OIII, while NV remained unchanged. Of particular interest is the behavior of the continuum: longwards 1400 A the flux appeared larger than previously, while it was weaker in the far-UV, indicating a general decrease of the continuum temperature. This result is not unexpected, since, as discussed above, generally at outburst the excitation of the spectrum decreases. However, this behavior was not followed by the OI emission triplet at 1302-06 A, which markedly faded during outburst. This result could





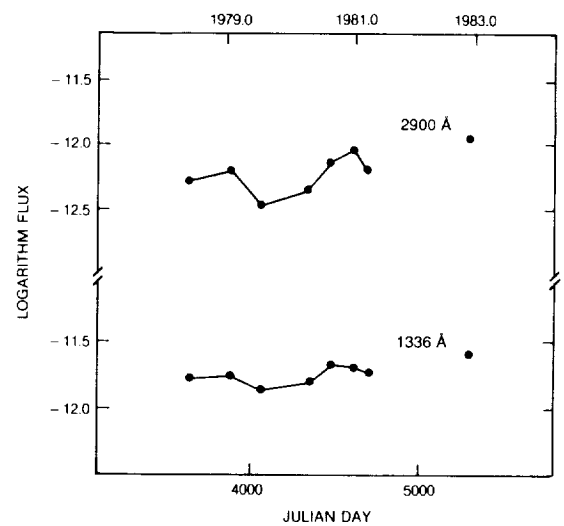


Figure 13-2. Multifrequency monitoring of Z And during quiescence. (a) Near-UV to IR photometry and Hα intensity (Altamore et al., 1979). Taranova and Yudin (1981). Lunel (see Altamore et al., 1981). Ultraviolet line and continuum fluxes during 1978-1982 (Fernandez-Castro et al., 1988).

probably be related to the fact that the 1984 event was not similar to the main outbursts observed in the past. In the months following the outbursts, after the luminosity decline, OI and NV strengthened in the UV (Cassatella et al., 1984). At high resolution, the blue wings of CIV and NV displayed an absorption line at -120 km s^{-1}, which suggests the presence of a low-velocity, warm wind like that observed in AG Dra (Viotti et al., 1983). The high-resolution UV monitoring of Z And after the outburst revealed large variation of the emission line profiles which have been noted since April 1984. Figure 13-3 shows the evolution of the CIV doublet since the 1984 outburst (Cassatella et al., 1988). Evident in the figure is the different shape of the lines at different epochs. P Cygni absorptions are clearly present in three spectra. The intensity ratio of 1548/1551 is smaller than the optically thin value of two, and in one case, even smaller than one (February 1986). This result will be discussed below in Section II.D. Strong broad wings are evident in the June 1985 spectrum, while in the other phases, they are much weaker.

II.D. DIAGNOSTICS

Once a consistent amount of homogeneous data is available for a given target, including also its time behavior (and taking into account all the possible time scales), it is then possible to make the next step, that is, to try to build up an empirical model. In general, the IUE archives provide for most of the symbiotic objects (and for many other categories of astrophysical objects as well) the best homogeneous

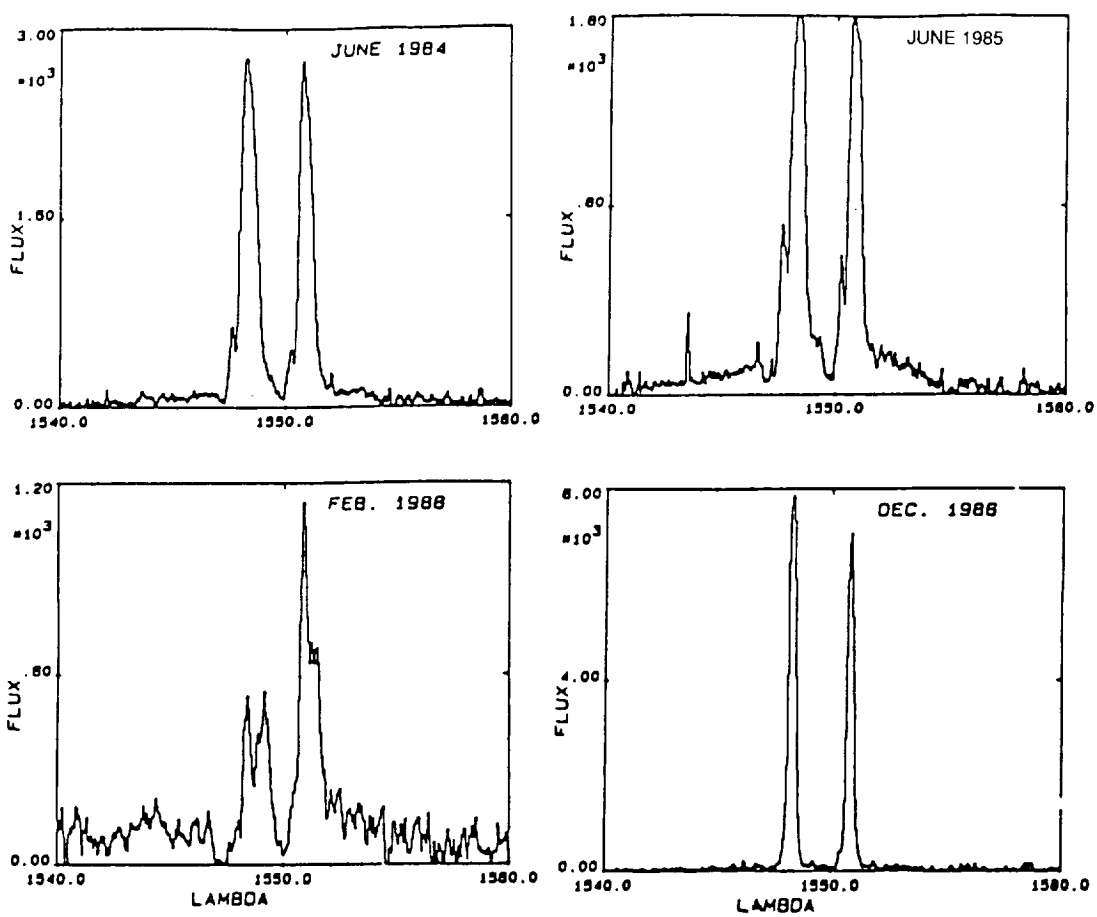


Figure 13-3. Evolution of the CIV doublet in Z And after the March 1984 outburst (Cassatella et al., 1988). Note the P Cygni absorptions which are clearly present in three spectra, and the strong emission wings in June 1985. In February 1986 the 1548/1551 line flux ratio is smaller than the optically thick limiting value of one.

set of calibrated, good quality data. In the meantime, several theoretical computations of the atomic parameters of important UV transitions have been recently performed, so that the line intensities can be used to derive the physical parameters of the emitting region. In the following, we shall discuss the case of Z And also as an illustration of the impact of the new UV observations on our knowledge of the nature of peculiar objects such as the symbiotic stars.

As discussed above, the optical and UV spectrum of Z And includes prominent emission lines of both permitted and intercombination or forbidden transition of different ions. In principle, this should be used to determine the electron density of the emitting region(s). In addition, the presence of different ionization stages of the same element and of ions of different elements can be used as diagnostics of the temperature and chemical composition. Table 13-1 summarizes the main line ratios, that can be used to derive the physical parameters of the symbiotic system.

Altamore et al. (1981) analyzed the NIII] multiplet near 1750 A and determined an electron density (for the N++ region) of (1.7 ± 0.9) x 10^{10} cm^{-3} (Figure 13-4). The line ratio of this multiplet is sensitive to changes in the electron density in the range from 10^{+9} to 10^{11} cm^{-3}, but is rather independent of the electron temperature (Nussbaumer and Storey, 1979). For instance, the NIII] line intensities in the symbiotic novae RR Tel and V1016 Cyg suggest a smaller density of 1.5 x 10^{+9} (Altamore et al., 1981) and of about 10^{+9} cm^{-3} (Nussbaumer and Schild, 1981), for RR Tel and V1016 Cyg, respectively. As shown in Table 13.1, the electron density can also be determined from the relative intensity of the OIV] and CII] multiplets. From the observed OIV] 1404.81/1401.16 ratio of 0.38, Altamore et al. derived log N_e = 10.1, in good agreement with the NIII] estimate. The CII] multiplet is too weak in Z And for density diagnostics. Only the high-density component of the CIII] doublet is visible in the UV spectrum of Z And, which provides a lower limit to Ne of about 10^{+6} cm^{-3}

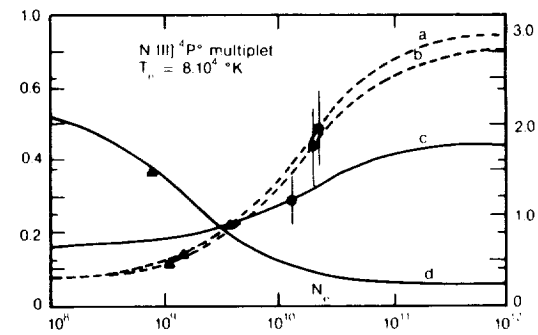


Figure 13-4. The NIII multiplet ratio in Z And and RR Tel (Altamore et al., 1981). The different curves give as a function of the electron density for Te=8x10⁴ K the theoretical line ratios: (a) 1754.0/1752.2; (b) 1748.7/1749.7 (dashed curves, right-hand scale); (c) 1748.7/1749.7; (d) 1746.8/1748.7 (solid curves, left-hand scale). The observed ratios for Z And (dots) and RR Tel (triangles) are indicated.

(Nussbaumer and Schild, 1979). This is again in agreement with the above results, and might also suggest that all the intercombination lines are formed in the same region. This may not be true for all the symbiotic stars. In fact, Nussbaumer and Schild (1981), in their analysis of the UV spectrum of the symbiotic nova V1016 Cyg, found from the CIII] and NIV] double ratios an electron density of 2 x 10^6 and 4 x 10^6 cm^{-3}, respectively. But the intensity of the NIII] multiplet would require a much higher N_e of about 10^{+9} cm^{-3}, which could be related either to a large density gradient in the emitting region or to a particular excitation mechanism.

Altamore et al.(1981) also considered the CIII]/NIII] intensity ratio, and found an electron density of 1.9 x 10^{10} and 1.2 x 10^{+9} cm^{-3} for Z And and RR Tel, respectively, consistent with the results obtained from the NIII] multiplet. More recently, Fernandez-Castro et al. (1988) have used the SiIII]/CIII] flux ratio in Z And to give an estimate of the electron density during different phases of its UV variability. They found N_e to be variable in the range from 0.56 to 2.2 x 10^{10} cm^{-3}, again in agreement with Altamore et al. results. However, when the flux ratios of the lines of different ions are used, the derived density estimates largely depend on the adopted electron temperature, as well as on the ionization equilibrium of each ion and on the C/N abundance ratio. Singly ionized carbon

TABLE 13-1. ULTRAVIOLET INDICATORS OF THE PHYSICAL PARAMETERS IN SYMBIOTIC STARS.

ions	lines	parameter	range	ref.
CII]	2325.4/2328.1	N_e	10^7 - 10^9	(1)
....	2325.4/2326.9		.....	
....	2324.7/2326.9		.....	
NIII]	1754.0/1752.0	N_e	10^9 - 10^{11}	(2)
....	1748.7/1752.0		.....	
....	1748.7/1749.0		.....	
....	1748.7/1746.8		10^8 - 10^{10}	
OIV]	1407.4/1401.2	N_e	10^3-10^5 ; $10^{9.5}$-10^{11}	(3)
	1401.2/1404.8		10^3-10^5 ; 10^9-$10^{10.5}$	
CIII]	1908.7/1906.7	N_e	10^3 - 10^6	(4)
NIV]	1486.4/1483.3	N_e	10^4 - 10^{10}	(5)
SiIII]	1892.0/1882.7	N_e	3.10^3 - 3.10^5	(6)
[NeIV]	1601/2423	N_e	10^4 - 10^8	(7)
	.....	T_e	(for N_e<10^4 or N_e>10^8)	
[FeVII]	2015/3759	N_e	10^7 - 10^{10}	(7)
	.....	T_e	(for N_e<10^7 or >10^{10})	
NIII]/CIII]	1749.7/1908.7	N_e	10^9 - 10^{11}	(1)
SiIII]/CIII]	1892.0/1908.7	N_e	10^9 = 10^{11}	(1)
CII/CIII]	1336/1909	T_e		(9) (10)
CIII]/CIV		T_e	10^4 - $3x10^4$	(9) (10)
	1718/1240			
NIV]/NV		T_e		(9) (10)
OIII]/[OIII]	1661/6300	T_e		(5)
SiIII/SiIII]	1299/1892	T_e	1.2 - 6.10^4 K (for N_e = 10^6-10^{10})	(6)
HeII	1640.4/Fc(1336)	T*		(11)

Notes to the table. (1) Stencel et al. (1981). (2) Altamore et al. (1981). (3) Nussbaumer and Storey (1982). (4) Nussbaumer and Schild (1979). (5) Nussbaumer and Schild (1981). (6) Nussbaumer (1986). (7) Nussbaumer (1982). (8) Nussbaumer and Stencel (1987). (9) Stikland et al. (1981). (10) Nussbaumer and Storey (1984). (11) Fernandez-Castro et al. (1988).

and nitrogen have ionization energies of 24 and 30 eV respectively, which are different enough to give significant differences in the ionization fractions C++/C and N++/N. This also depends on whether the ionization is by electron collisions or by photoionization. Altamore et al. (1981) have computed the CIII]/NIII] ratio assuming ionization by electron impact like that in the solar transition region, and for a cosmic C/N abundance ratio. This last assumption can be justified from the fact that the study of several symbiotics—including Z And—by Boyarchuk (1970) in the optical, and by Nussbaumer et al. (1988) in the ultraviolet generally suggest a close to cosmic abundance for the emitting regions in symbiotics. Altamore et al. also found that the CIII]/NIII] ratio could be largely affected by radiation field (e.g., the diluted hot stellar radiation). The flux ratio observed in Z And would imply an upper limit of 1.5×10^{-16} erg cm^{-3} Hz^{-1} for this radiation in the N++ emitting region, or a dilution factor smaller than 7.5×10^{-5}.

In a planetary nebula-like model of symbiotic stars, such as the one proposed by Nussbaumer and Schild (1981) for V1016 Cyg, the electron temperature should be close to 10^4 K. Photoionization models for Z And were discussed by Fernandez-Castro et al. (1988) and Nussbaumer and Vogel (1988). Alternatively, the high-ionization lines could be produced in a solar-type transition region with much larger T_e, as for instance suggested by Altamore et al. (1981) for Z And. This latter hypothesis is based on several arguments: the small width of the emission lines implies formation in a low-velocity dense region (which excludes line formation in a high-velocity hot star wind, and in a rotating disk). Comparison of the derived CIII] emitting volume of $1 \times 10^{+37}$ cm^3 with the SiIV maximum line thickness indicates that the emission should come from a thin shell, rather than from an extended sphere. In addition, as discussed above, the stellar radiation in the NIII] emitting region should be very weak, hence the region far from the hot star.

Another observable which could put constraints on the possible models is the radial velocity difference between the high-ionization resonance lines and the intercombination lines. From a study of several symbiotics Friedjung et al. (1983) found a systematic redshift of the former lines with respect to the latter, of the order of +10 to +20 km s^{-1}. They interpreted this as the result of radiative transfer in a warm, low-velocity expanding medium, which should be identified with either the cool star wind, or with its base. This model is also supported by the larger width of the higher ionization lines observed in some symbiotics, as discussed in Chapter 11 Sections IV.D. and VIII.D. Friedjung et al. found that in Z And, the radial velocity difference is probably variable but always positive well beyond the measurement errors. Fernandez-Castro et al. (1988) confirmed this result and found a range of variability between +15 to +30 km s^{-1}, but without a clear correlation with the UV line and continuum flux variations.

To decide about possible models, better would be to have a direct estimate of the electron temperature. In most cases, this is difficult, since the temperature indicators generally are weak lines, and their flux ratio may also depend on other parameters. Stikland et al. (1981), Nussbaumer (1982), and Nussbaumer and Storey (1984) discussed, among others, methods of electron temperature determination from emission line ratios. Some useful T_e indicators are listed in Table 13.1. Fernandez-Castro et al. (1988) derived the electron temperature for Z And from the NIV 1718/NV 1240, CII 1336/CIII] 1909, and CIII 1176/CIII] 1909 flux ratios. They found $T_e \simeq 15{,}000$ K, lower than the value assumed by Altamore et al., (1981) which seems to favor a photoionization model. However, the above flux ratios involved emission lines that are rather faint in the UV spectrum of Z And. Thus, the T_e estimates of Fernandez-Castro et al. are rather uncertain, and could well be lower limits.

Once the electron density and temperature are known, the line fluxes can be used to derive the total amount of the emitting ions, and the size of the emitting regions. Altamore et al. (1981), assuming the C++ and N++ regions

homogeneous and transparent, obtained an emitting volume of 1.0 x 10^{36} and 8.2 x 10^{35} cm^3 for C++ an N++ respectively. These values obviously depend on their assumption of a solar-type emitting region with $T_e \simeq$ 80,000 K. It is easy to see that such a warm region cannot be responsible for the ultraviolet continuum observed in Z And. This implies the presence of an optically thick region (or disk) or a hot star with a radius of about 2 x 10^{10} cm. The temperature of the hot source can be obtained using the Zanstra method. Assuming that the emitting region is optically thick to the hot source continuum Fc shortward of 912 Å (ionization from the ground level of H) and of 228 A (He+ ionization), and that the hot component of Z And radiates as a blackbody, we have for a case B He++ recombination (Fernandez-Castro et al., 1988):

$$\frac{I(HeII\ 1640)}{Fc(\lambda')} = 3.303x10^{-28}\ T^3 \times f(\lambda^0, T)\lambda'^5\left(e^{hc/\lambda' T} - 1\right) \quad (13.1)$$

where it is assumed that the HeII 1640 A line is optically thin, and $f(\lambda^o,T)$ is the relative number of photons provided by a blackbody at a temperature T between λ = 0 to λ^o = 228 A. Using the continuum flux at λ' = 1336 A and the HeII 1640 A intensity, dereddened for E(B-V) = 0.35, Fernandez-Castro et al. (1988) derived a HeII temperature of about 10^5 K. This temperature remained nearly constant in spite of the large UV variability. In fact, the NV/CIV flux ratio, which can be considered as an ionization temperature indicator, did not significantly change during the period studied by Fernandez-Castro et al.

The hot continuum is responsible for the short wavelength UV continuum. But there is an excess of the continuum flux in the range from 1500 A to the visual that can be attributed to bound-free and free-free hydrogen emission, as indicated by the marked Balmer discontinuity at 3650 A (Altamore et al., 1981; Blair et al., 1983). Continuum recombination from He++ may also contribute to the UV. Fitting of the observed Balmer continuum with hydrogen and helium continua provides an estimate of the emission measure Ne^2V. Assuming T_e = 15,000 K, Fernandez-Castro et al. (1988) found Ne^2V equal to about 2-6 x 10^{+59} cm^{-3}, a value much larger than the above derived value of 4 x 10^{+57} cm^{-3} for C++, N++ region, assuming cosmic abundance (Altamore et al., 1981). Perhaps the intercombination lines and the Balmer continuum are formed in different regions.

Variability may give important information, especially about the spatial structure of the system, if the variations are associated with an orbital motion of a binary system. In fact, observations at different epochs allow one to observe the system with different lines of sight. The best period is when the symbiotic system is in quiescence, so that the periodic phenomena are not masked by the symbiotic activity, whose time scale is generally comparable with the orbital period. Fernandez-Castro et al. (1988) investigated the periodic UV variability during quiescence and found that the UV continuum and emission line fluxes are variable on a time scale of about 760 days, with maxima and minima in phase with the UBV and Hα variability (see Figure 13-2). From the time variability of the SiIII]/CIII] flux ratio, Fernandez-Castro et al. suggested that the mean electron density in the emitting region varied from 0.6 to 2.2 x 10^{10} cm^{-3}, being higher at maximum. This can be explained with a model of line formation in an asymmetric nebula near the cool giant, which is photoionized by the UV photons of the hot star. This nebula is occulted at minimum, and emission is seen only from the outer, less dense parts. This fact and the small size and high density of the emitting region suggest that it can be identified with the inner parts of the cool giant wind ionized by the hot star radiation. Therefore, the UV emission lines are mostly formed in the cool giant wind, as also is suggested by the systematic radial velocity difference between the high ionization resonance lines and the intercombination lines discussed above.

II.E. POSSIBLE MODELS FOR Z ANDROMEDAE

Let us summarize our present knowledge about the Z And system. The UV to IR energy distribution is characterized by two maxima, one in the near-IR, and another in the unseen EUV (Fernandez-Castro et al., 1988). During the active phases, the second maximum is shifted to longer wavelengths in the UV or in the optical. In the latter case, the apparent "outburst" in the visual is larger. According to Fernandez-Castro et al., the integrated fluxes of the two spectral "bumps" are comparable, around 450 and 880 $L_\odot$ for the hot and cool components, respectively. The "nebular" f-f and b-f continuum contributes another 44-141 $L_\odot$ to the total power from Z And. Therefore, the radiative power emitted in the UV is not a small amount of the visual-IR power. As discussed in Chapter 12, this point rules out the model of active cool star, in which the emission line spectrum and blue continuum are the result of a large surface activity of the cool giant. Thus, the double-bump energy distribution is strongly suggestive of *binarity*. This hypothesis is also supported by the optical and UV variability during quiescence, and by the long-term radial velocity variations of the cool component, even if the phasing is not the expected one. An important point for the following discussion is whether the cool component is filling its Roche lobe. Taking into account the proposed orbital period of 750 d, the luminosity class of the cool component, which implies that its mass should be of a few solar masses (Querci, 1986), and assuming for the hot component the mass of a white dwarf, it can be easily found that the cool giant is well inside its critical Roche surface. A different conclusion will be drawn in the case that the Z And system contains a cool bright giant, for instance, as suggested by the IR spectroscopic observations of Kenyon and Gallagher (1983). This again stresses the importance of future detailed studies of the cool spectral component, in order to derive its surface gravity.

The nature of the hot component is so far unveiled, but a model of a hot subdwarf, or of a rejuvenated white dwarf is favored. In any case, its structure could have been largely affected by the mass-transfer processes during the earlier stages of evolution of the binary system. In particular, we do not know if it presently has the same mass and radius of a white dwarf, and this makes our modelling rather uncertain. In Z And, the dwarf component seems to accrete mass from the cool star wind, not through Roche lobe overflow. The accreted matter could form a disk around the dwarf star. But so far, there is no evidence of an accretion disk in Z And, whose presence could, for instance, be indicated by broad high-ionization emission lines. This problem will probably be solved with future high-quality observations of the emission line profiles in the visual and UV. Mass accretion M_a onto the degenerate star results in an increased luminosity L_{acc} of the star. The actual values of M_a and L_{acc} critically depend on many poorly known parameters, the mass-loss rate and wind velocity of the cool giant, the orbital parameters, the mass and radius of the dwarf star. Thus, our picture of Z And (and of all the other symbiotic stars, as well) is necessarily limited because of the *a priori* assumptions we have to make. The matter flowing from the red giant is ionized by the hot star radiation, and emits in the radio. The radio flux from Z And observed by Seaquist et al. (1984) has a spectral index $\alpha = +0.62$, close to the theoretical value for a photoionized wind (cf. Seaquist and Gregory, 1973). Using the formulations of Wright and Barlow (1975) and taking for the wind velocity the value of 40 km s^{-1}, and the observed radio flux at 4.885 Ghz, Fernandez-Castro et al. (1988) derived for the cool giant a mass-loss rate of about 2×10^{-7} $M_\odot$ yr^{-1}, in good agreement with the typical values of M giants (e.g., Goldberg, 1986). Using their parameters for the Z And system, Fernandez-Castro et al. also derived an accretion rate of 4.5×10^{-9} $M_\odot$ yr^{-1}, and an accretion luminosity of 1.2 $L_\odot$. This luminosity is about two orders of magnitude lower than the recombination continuum, and, therefore, it cannot be accounted for by accretion processes. Conversely, accretion seems not to play an important role in the energy budget of Z And. It can anyhow be responsible for some of the symbi-

otic phenomena, and, in particular for the recurrent "outbursts". In fact, the above derived accretion rate is well below the minimum accretion rate for steady burning discussed in Section 12.IV.A, but implies occurrence of recurrent thermonuclear events.

A schematic model for Z And during quiescence is shown in Figure 13-5. The UV photons from the hot component ionize the cool-star wind until a limiting surface which is separating the HI and HII regions. According to Taylor and Seaquist (1984), the shape of this surface is determined by a parameter X defined as:

$$X = (4 \pi a L_{ph} / \alpha) \cdot \mu^2 m^2_H \cdot (V/\dot{M})^2, \qquad (13.2)$$

where a is the binary separation, L_{ph}, the number of hydrogen ionizing photons per second from the hot component, α, the recombination coefficient to all but the ground state of hydrogen, μ, the mean molecular weight, m_H, the hydrogen mass, and V and $\dot{M}$, the red giant's wind velocity and mass-loss rate, respectively. For Z And, Fernandez-Castro et al. (1988) obtained X = 14, implying that the ionization front is close to the red giant surface with a shape as shown in the figure. It should be considered that the particle density in the wind rapidly falls down outwards. Since the continuum and line emission in the HII region is proportional to N_e^2, the regions near the ionization front are the main contributors to the nebular spectrum. Therefore, in deriving the physical parameters of the emitting region, it is crucial to take into account the geometry, which could be far from homogeneity and from spherical symmetry. In addition, because of the different dependence on the electron density, the mean regions of formation of different emission lines and continua could be significantly different. The corresponding electron densities and emission measures, therefore, can be largely different, even if the lines are formed in the same medium. This can explain the different values found in Z And, as discussed above, and in many other symbiotic stars as well. Formation of emission lines in a low-velocity medium, such as the red giant's wind, is also in agreement with the line narrowness. According to Fernandez-Castro et al., the observed time variability of the line fluxes should be the result of the orbital motion: the effective emitting volume is different, if the line of sight is different. As discussed by Nussbaumer et al. (1986) for V1329 Cyg, one should thus expect a "modulation" of the line profile with the orbital phase. Observations have not yet shown this effect, at least during quies-

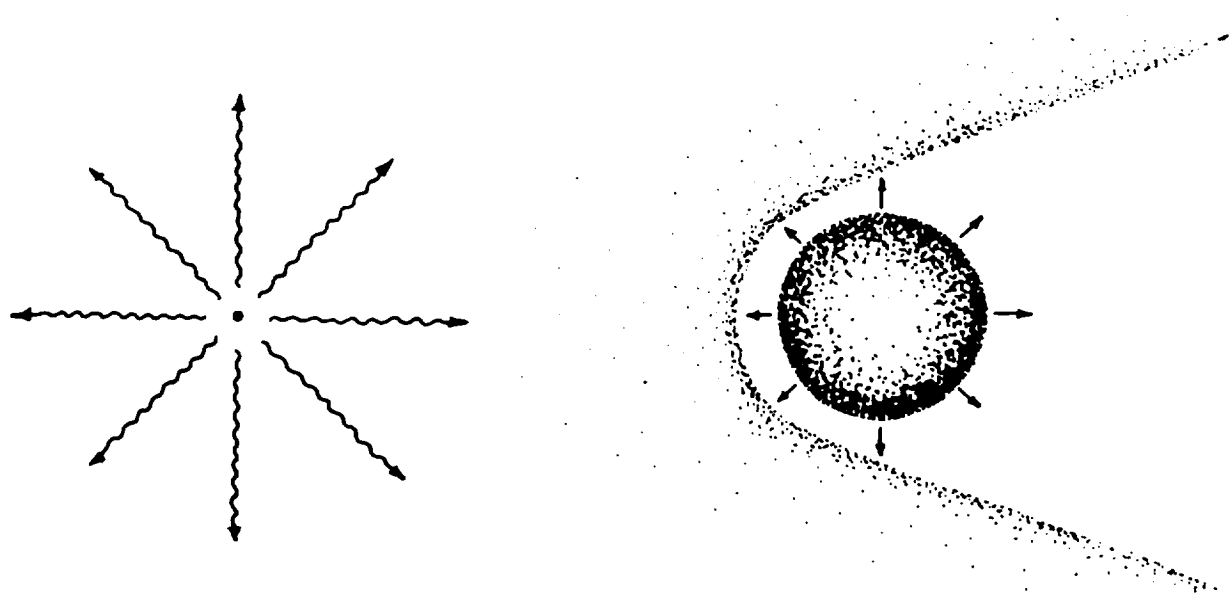


Figure 13-5. Schematic binary model for Z And, according to Fernandez-Castro et al. (1988).

cence, probably because of their fairly poor quality. [Profile changes as those reported by Cassatella et al. (1988) should be attributed to the stellar "activity", rather than to orbital motion.] Partial occultation from the red giant may partly account for the observed flux variability. The effect obviously depends on the (unknown) inclination. Alternatively, the orbit could be *eccentric*: in this case, one would expect a larger nebular emission and a higher electron density at the passage near the periastron, as observed. However, it is hard to fit all the observational data with this fairly simplified model. Nussbaumer and Vogel (1988) recently showed that the coexistence of two winds can substantially modify the ionization structure. The presence of two winds will also modify eclipse effects in different ionization stages.

In conclusion, the binary model may account for many of the properties of Z And. Being a detached system, the stellar wind(s) play an important role, both during "quiescence" and during the "outbursts". Many of the system parameters-inclination, stellar masses, etc.—are uncertain and prevent a more thorough study of the Z And complex. Yet the object appears a very promising target for the study of many important aspects of the symbiotic phenomenon. But high quality observations are essential for a real progress on the matter.

III. THE HIGH-VELOCITY SYMBIOTIC STAR AG DRACONIS

III.A. INTRODUCTION

The symbiotic star AG Dra has many interesting peculiarities with respect to what is generally considered as a "classical" symbiotic. First, it is a high-velocity (Roman, 1955), high-galactic latitude object (b= +41^0, Table 11-12); i.e., it belongs to *Pop II*. Its cool spectral component appears less cool (K-type) than in most other symbiotic stars, whereas the excitation of the emission line spectrum is quite high, as indicated by the high-ionization lines of NV, and SV in the UV, and of [FeV], [FeVI], and the 6830 A feature in the visible. HeII is quite strong in emission in both the spectral domains. Also, the far-UV continuum is very hot and intense. Moving to even shorter wavelengths, we find an intense X-ray flux, the most intense among symbiotic stars (taking into account the X-ray spectrum and the interstellar absorption). This is also in contrast with the fact that X-rays were mostly detected in D-type symbiotics, while AG Dra is S-type. Perhaps, the most interesting aspect of this object concerns the major outburst (followed by three other ones of lesser strength), which occurred in recent times, allowing a detailed study of a symbiotic star during the whole duration of an active phase.

III.B. THE LIGHT HISTORY

The light history of AG Dra is quite similar to that of Z And, in spite of the several differences between the two objects, as discussed below. Robinson (1969), from a detailed study of its light curve, identified 11 outbursts between 1890 and 1966. Since then, AG Dra remained at minimum until the end of 1980, when it brightened again from V = 9.8 to 8.5 in a few days. During the following fading phase, the star had a new minor maximum in 1982, then it reached the minimum luminosity in mid-1983. More recently, two new low-amplitude "outbursts" were observed in March 1985 and January 1986 (Mattei, 1987). The schematic light curve of the star is show in Figure 13-6.

This long-term behavior is close to that of Z And, i.e., recurrent phases of activity followed by long periods of quiescence. As in Z And, small amplitude variations were found in AG Dra during quiescence, with an amplitude increasing towards shorter wavelengths (Belyakina, 1969; Meinunger, 1979), and which are possibly periodic with a period of about 554 days (Meinunger, 1979). This behavior is also present in the space-UV, where large amplitude UV variations were observed before and after the 1980-82 outburst (Viotti et al., 1984a; Viotti, 1988a). Recently, Kaler (1987)

studied the variation of AG Dra in 11 intermediate and narrow photometric bands, between 3473 A and 8200 A. The observations were made from March 1977 to October 1980, during the quiescent phase preceeding the recent active phase, and covered about 2.4 cycles. The periodic variations are present in several bands and are by far the largest in the near-UV with an amplitude of about 1 mag. The amplitude decreases towards the red, but the variations are also present to some extent in the narrow bands centered on strong emission lines. Kaler also noted indications of a "secondary eclipse" of the K giant at some wavelengths.

Of particular interest is the recent activity of the star with one major outburst in 1980 and three minor maxima in 1982, 1985, and 1986 (see Figure 13-6). These events occurred at the right time to perform multifrequency observations of a symbiotic star during activity from both ground-based and space observatories. This active phase, in fact, occurred when the IUE satellite was fully operational, which gave the opportunity to collect a complete set of ultraviolet spectra throughout the whole light curve (Viotti et al., 1984a; Lutz et al., 1987). In addition, two X-ray satellites, HEAO-2 and EXOSAT, were operating during this period, and, as discussed in Section 11.IX, X-rays from AG Dra were positively detected on four different occasions (Anderson et al., 1981; Cassatella et al., 1987).

III.C. THE OPTICAL AND ULTRAVIOLET SPECTRUM

Near minimum, the yellow-red spectrum of AG Dra presents the absorption line spectrum typical of a luminous K-type star, with several narrow absorptions of neutral and ionized metals (e.g., Huang, 1982; Lutz et al., 1987). The relative strength of these absorptions suggests an early-K spectral type and a luminosity class III. However, some anomalies are present, such as the strength of the BaII and SrII lines, which might imply a higher luminosity class, for instance, as suggested by Huang (1982), or, more probably, a composition anomaly as discussed by Lutz et al. (1987). In this regard, Iijima et al. (1987) found that the absorption spectrum can be classified as G7V, in agreement with earlier classifications (e.g., Wilson, 1943), but not in agreement with the red-IR colors. They attributed this discrepancy to a metal deficiency of the cool star, as also suggested by its Pop II nature, which may affect the usual spectral classification criteria. The optical-IR energy distribution at minimum is, in fact, consistent with a K-giant spectrum. Viotti et al. (1983a) derived a K3-5III spectral type from the broad-band photometry. During outburst, the K-type spectrum is veiled (Huang, 1982) by the intense blue continuum.

The optical spectrum of AG Dra (Figure 13-7) shows prominent emissions of H, HeI, HeII, OIII, and of iron, from FeII up to [FeV] and [FeVI], and the unidentified high-excitation features at 6830 and 7088 A (Boyarchuk 1966; Bopp and Smith, 1981; Huang, 1982; Blair et al., 1983; Iijima et al., 1987. Hα is very strong in emission. Smith and Bopp (1981) and Oliversen and Anderson (1982) found large profile variations of the line which they attributed to activity on the K-star surface. In the UV, the star displays weak intercombination lines of CIII, OIII, OIV, and SiIII, and strong permitted lines of NV, CIV, and especially HeII 1640 A (Figure 11-31a). Other identified species include the low-ionization OI and MgII lines, and the high-ionization OV and SV lines (Viotti et al., 1983). The HeII 1640 A line presents extended wings, while the NV doublet displays a P Cygni profile with absorption components extending to -170 km s^{-1} (Viotti et al., 1984a). Two separate components can be identified in the UV continuum: in the near-UV, a flat continuum probably of nebular origin, and shortwards of 1600 A, a steep and strong continuum, close to the Rayleigh-Jeans tail of the energy spectrum of a hot star (Figure 11-30). However, the high-resolution observations do not reveal any absorption of possible photospheric origin. Actually, at such an effective temperature we should expect to observe strong photospheric absorptions of HeII 1640 A and of the high-ionization resonance lines of NV and CIV. These features should be completely hidden by

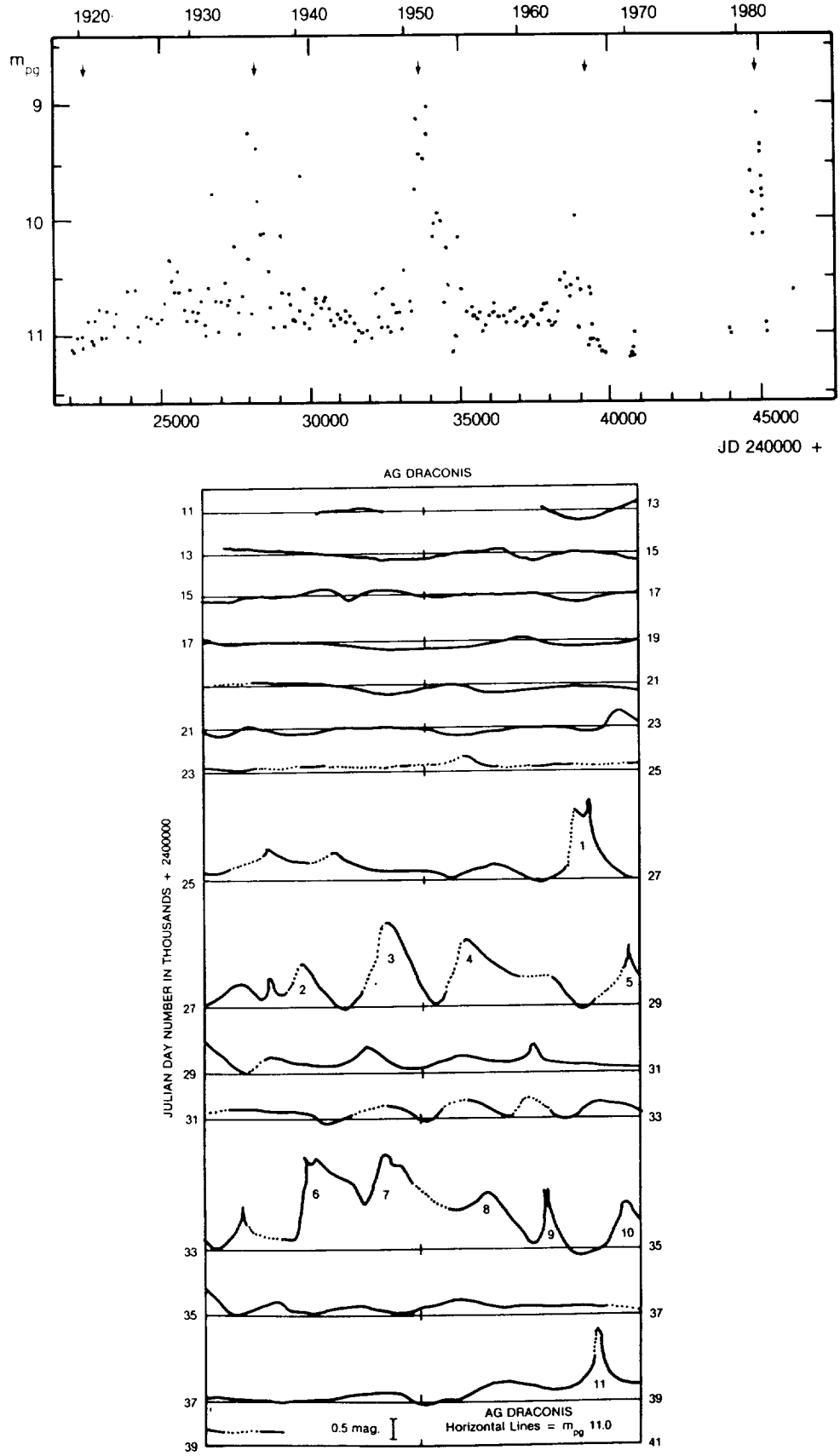
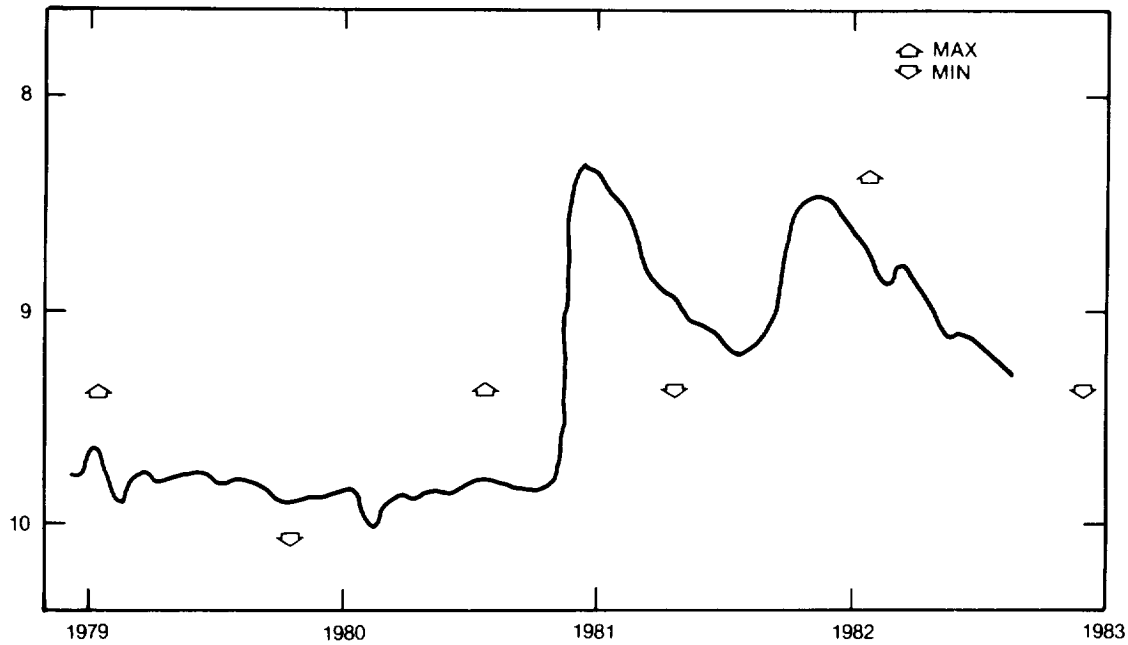


Figure 13-6. (a) The light history of AG Dra from 1890 to 1966 (Robinson, 1966).



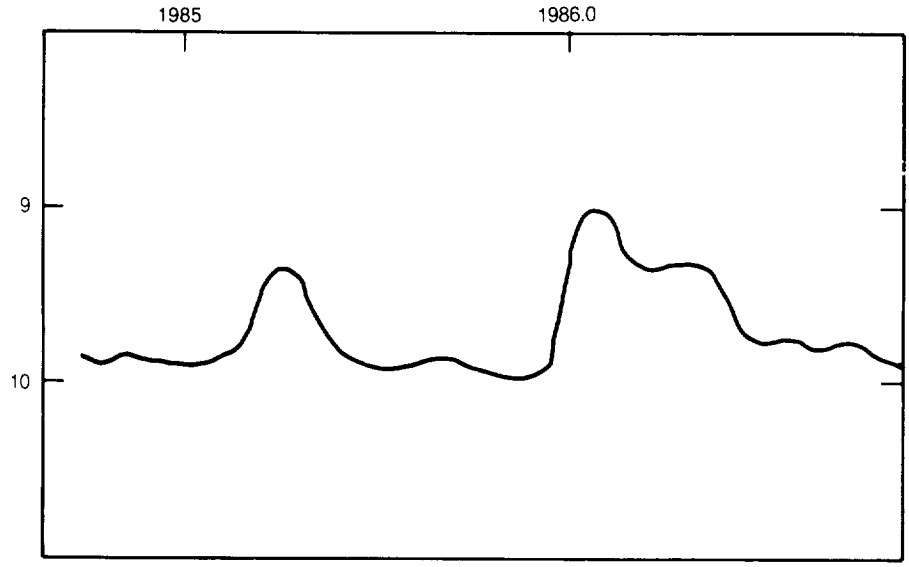


Figure 13-6. (b) The recent light curve of AG Dra from 1979 to 1986 (Mattei, 1987). Three outbursts have been recorded in November 1980, February 1985, and January 1986. The vertical arrows show the epochs of ultraviolet (IUE) and X-ray (HEAO-2, EXOSAT) observations.

the prominent nebular emissions. But, according to the IUE observations of hot subdwarfs of Rossi et al. (1984), we should also expect to observe excited lines of highly ionized C, N, and O, and especially FeIV and FeV near 1400 A, which have not been seen in the UV spectra of AG Dra. The only absorptions are the interstellar ones (see Figure 11-29c), which are rather strong indeed if compared with the low interstellar extinction of E(B-V) = 0.06 of the star (Viotti et al., 1983). This fact, however, is not unusual among halo stars.

The radial velocity of the absorption lines is high, about -140 ÷ -146 km s^{-1} (Roman, 1953; Garcia and Kenyon, 1988). This point and the high galactic latitude clearly indicate that AG Dra is a *halo object*. Huang (1982) observed a variability of the absorption and emission line radial velocity. More recently, Garcia (1986) and Garcia and Kenyon (1988) found that the K-star lines vary periodically, with an amplitude of K = 5.3 ± 0.3 and with about the same period as that of the photometric one (see Figure 11-14). In this case the phase shift between the radial velocity and photometric curves is the expected one and clearly confirms the binarity of the object.

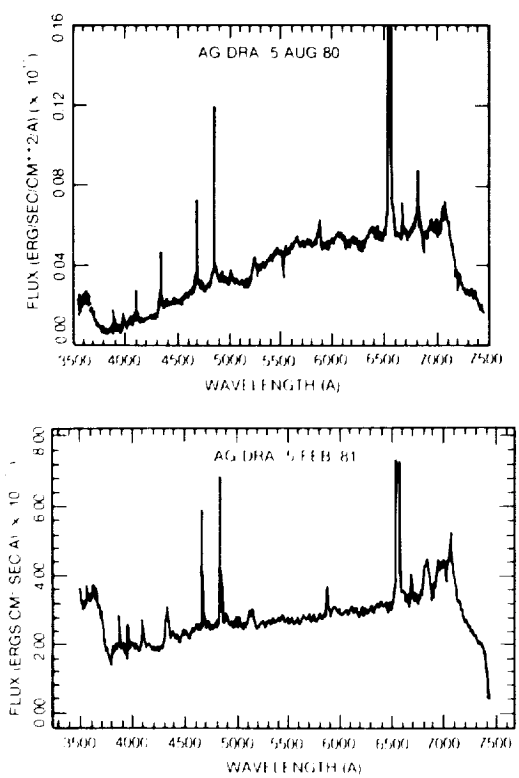


Figure 13-7. The optical spectrum of AG Dra at two different activity phases: August 6, 1980 and February 6, 1981. Note the strength of the HeII 4686 A line, and of the Balmer discontinuity in both spectra (Blair et al., 1983).

III.D. THE RECENT OUTBURSTS

The main outburst that occurred in November 1980 represented an excellent occasion to study in many spectral regions the behavior of a symbiotic star during an active phase. The optical photometric variations during outburst and those of the UV spectrum are described among others by Kaler et al. (1987) and Viotti et al. (1984a), respectively. The outburst was most energetic in the ultraviolet. The amplitude of the first rise was of two magnitudes in the u band (near 3500 A), and only 0.5 A at 8200 A (Kaler et al., 1987). The IUE observations (Viotti et al., 1984a) show that the UV continuum underwent a large increase between October and November 1980, at the time of the optical outburst, with a subsequent further increase until January 1981. The overall rise was of about a factor 10, much larger than in the visual (Figure 13-8a). In the following months, the trend in the UV nearly followed the visual, with a minimum by mid-1981, and a second maximum in December. Then, the continuum flux gradually faded to minimum. A similar trend was displayed by the emission lines. The main difference was the absence of the secondary minimum in the high-ionization NV doublet, and the constancy of the ionization before and after the outburst, as indicated by the NV/CIV line ratio (Figure 13-8b). This behavior of AG Dra was confirmed by the optical observations showing the persistence of the high-ionization emission lines (e.g., the HeII 4686 A line) also after the outburst (see Figure 13-7).

An intense X-ray flux from AG Dra was first detected with HEAO-2 in April 1980 when the star was at minimum (Anderson et al. 1981). The star was pointed to again with HEAO-2 after November 1980, but a technical problem prevented the observations (Seward, 1985).

More recently, AG Dra was observed with EXOSAT during the 1985 and 1986 outbursts and during the minimum phase in between. These observations, already described in Section 11.IX.C, indicate a modulation of the X-ray flux by the stellar activity, while there is no indication of a dependence on the 554-day period.

It is interesting to note that IR observations collected before and after the outburst only showed small variation, indicating that the K star remained substantially stable during this period (Viotti et al., 1983b, Piro et al., 1985).

Radio emission at 6 cm was first detected from AG Dra in June 1986 by Torbett and Campbell (1987) who found a flux larger than 0.5 mJy. Previously, Seaquist et al. (1984) reported only an upper limit of 0.41 mJy, for a 6-cm observation made in February 1982. Torbett and Campbell also resolved AG Dra into two close components separated by about 1.3". This increased radio activity, and the presence of a structure could be related to the recent activity of AG Dra. It would be interesting to follow the further development of this star in the radio.

III.E. INTERPRETATION

In contrast with the majority of the other symbiotic object, our observational data on AG Dra are fairly complete to make a clear picture of the system. First, AG Dra is binary. The cool component is a K giant, which, taking into account the orbital parameters, is not filling its Roche lobe. Assuming that it has the same absolute luminosity of single red giants, for E(B-V) = 0.06, a distance of 730 pc is derived, 500 pc above the galactic plane (Friedjung, 1988). It should be considered that, if one assumes that the cool component fills its Roche lobe, it should be a bright giant with a distance of about 3 kpc. Such a large distance and the corresponding large height on the galactic plane are, however, in contrast with the weakness of the interstellar CIV lines in the UV. Concerning the other stellar component of the

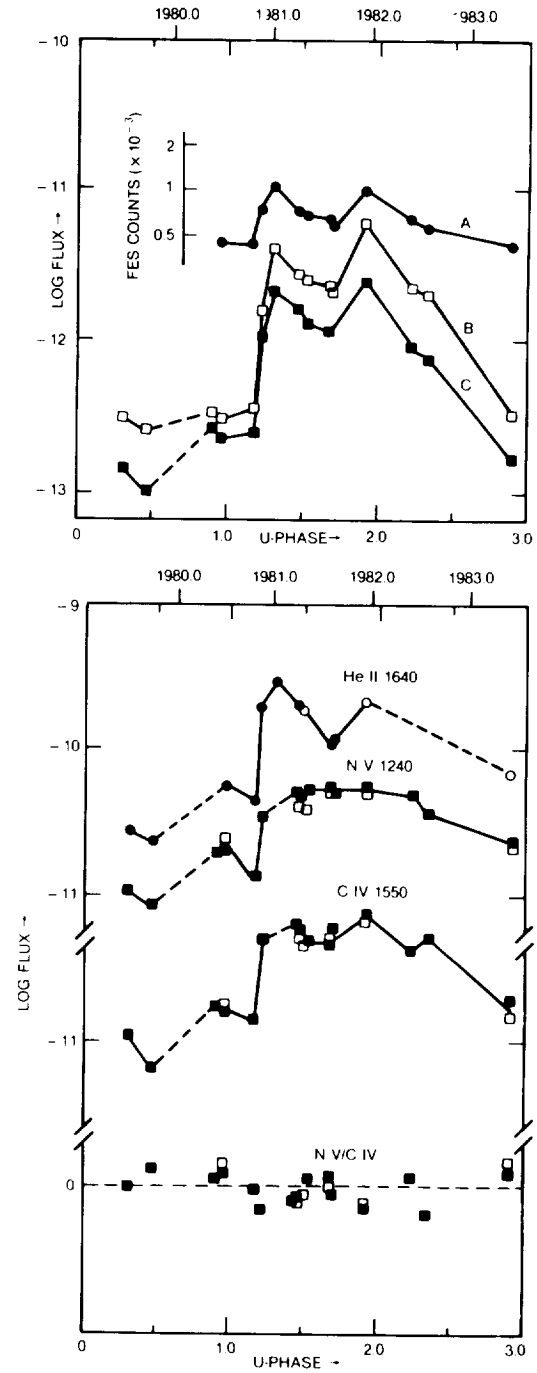


Figure 13-8. The ultraviolet variations of AG Dra during 1979 to 1983 (Viotti et al., 1984). (a) The UV continuum near 1340 A (curve B) and 2860 A (curve C) compared with the visual light curve (curve A) derived from the IUE FES count rates. (b) The variation of the high ionization UV emission lines and of the NV/CIV line flux ratio.

system, Kenyon and Webbink (1984) interpreted the UV energy distribution of AG Dra as due to a hot star without an accretion disk. In-

deed, the fact that the red giant does not fill its Roche lobe implies that the accretion rate is too low to produce a disk. According to Viotti et al. (1983), the temperature of the hot component is about 100,000 K. The corresponding effective radius in mid-1981 was 0.02 $R_\odot$, typical of a white dwarf. A higher temperature of about 160,000 K was also determined by Kenyon and Webbink (1984), and Iijima et al. (1987). However, the hot component of AG Dra cannot be considered a normal hot star, since, as discussed above, no "photospheric" absorption lines have been so far identified.

Let us turn our attention to the "nebular" component. Emission lines and the strong Balmer continuum can be attributed to a nebula excited by the hot star radiation (Boyarchuk, 1966b). Such a simple nebular model, however, fails to explain the large ionization range observed in AG Dra, with neutral to several times ionized species. Other "ingredients" need to be added to explain the many peculiarities. The HeII 1640 A line has broad wings which, according to Viotti et al. (1983), seem not to be produced by Thomson scattering. Another possibility is that the wings are formed in an accretion disk, or in a high velocity (10^3 km s^{-1}) warm wind. To verify these possibilities, high S/N observations of the emission line profiles are required, which are not available with IUE. The P Cygni profile of NV, which is present during all the (orbital and activity) phases of AG Dra, and the simultaneous absence of such a profile in CIV, suggests the existence of a low-velocity (-170 km s^{-1}) warm wind in the system (Viotti et al., 1984a). This velocity is too low to be associated with a stellar wind from the hot star, which should have a much larger velocity, unless the structure of its atmosphere is very peculiar because of the accretion processes. As discussed by Viotti et al., a dense, "torrid" wind (with a temperature higher than 10^5 K), for instance, could be produced from the polar regions, or near hot spots. Since all nitrogen is in the form of at least NIV, no NV lines are formed there. At a certain distance from the star's surface, the wind slows down. This fact causes a decrease of the density with the radial distance r slower than r^{-2}; that, together with the geometrical dilution and the increased far-UV opacity, would contribute to recombine nitrogen ions to NV and would then produce the observed P Cygni profile. Still further out, in almost stationary regions, the CIV ions are produced that would not show a P Cygni profile. In this case, the absence of CIV could also be a geometrical effect, for the more extended CIV region is not homogeneous and would not hide the stellar disk. It should be considered that, according to this model, we should expect the OVI lines in the far-UV to have a P Cygni profile broader than that of NV. This is an interesting study for future astronomical satellites.

A more plausible model for the low-velocity wind observed in NV is ejection from the cool giant surface. The observed wind velocity of about 170 km s^{-1} is close to the stellar escape velocity, but quite large with respect to the wind velocities generally observed in normal cool giants. The high ionization should be the result of the presence of an extended solar-type transition region or, more probably, of ionization from the hot star radiation. Like the model proposed for Z And, the near-UV continuum and the emission lines are probably mostly emitted from an extended region of the cool star, and their emission is modulated by the orbital motion of the system as a result of variation of the visibility of the region (e.g., Viotti et al., 1984a). The variability during quiescence can also be explained if the orbit is elliptical. In this regard Iijima (1987) suggested that the photometric variations are due to variation of the mass-transfer rate during the orbital cycle. However, the results of Garcia (1986) and Garcia and Kenyon (1988) are in better agreement with a low eccentricity of the system.

The light history of AG Dra was characterized by recurrent phases of activity and long periods of quiescence. By combining the photographic magnitude estimates of AG Dra since 1920, Iijima et al. (1987) suggested a recurrence period of the outbursts of roughly 15 years, corresponding to about ten 554 d cycles. Iijima et al. suggest that the outbursts are pro-

duced by mild hydrogen flashes on a massive (~1.2 $M_\odot$) white dwarf undergoing large mass accretion (~10^{-7} $M_\odot$ yr^{-1}). However, such an accretion rate is not conceivable for AG Dra, since the cool star seems not to fill its Roche lobe. IUE observations have shown that during the 1980 outburst, the far-UV continuum increased significantly. Viotti et al. (1984a) found that the variation occurred at nearly constant temperature, implying that the effective stellar radius should have increased by a factor of two to three during outburst. Kenyon and Webbink (1984) considered that the 1980 outburst was thermonuclear, but substantially less developed than the large-scale events observed in other symbiotic stars, such as the symbiotic novae. The white dwarf would not have developed a very extended envelope, so that its effective temperature would have remained high. It should be important to find possible probes of the hot star structure close to the time of the outburst. Figure 13-9 shows the variation of the ratio of the flux of the HeII 1640 A emission line and of the far-UV continuum at 1340 A before and after the 1980 outburst (Viotti et al. 1984a). This ratio, as discussed in the previous sections, is a measure of the far-UV temperature of the star, if one assumes that the HeII line is radiatively excited and that the 1340 A continuum belongs to the hot star. The figure shows that the ratio was the same just before and after the outburst (the observations were made in October 23 and November 15, respectively, when, according to Viotti et al., the visual magnitude changed by -0.7 mag, and the UV fluxes by -1.6 mag). The HeII/Fc(1340A) ratio largely decreased in the period following the first light rise, and reached again the preoutburst value in 1984. The 1982 minimum can be explained by a lower color temperature of the hot star (about 80,000 K), after the outburst, but it remains difficult to explain the long delay of the change. It should be considered that before the outburst, there was a slight increase of the HeII/Fc(1340A) ratio, which could be an indication of a heating of the stellar surface before the event, which can be associated with the onset of the thermonuclear outburst.

Unlike the other S-type symbiotics, AG Dra is a strong X-ray source. The X-ray spectrum is very soft, with an integrated luminosity of 2.1 x 10^{-12} erg cm^{-2} s^{-1} in the 0.2-1.0 keV range (Anderson et al., 1981). If the X-rays are produced by the cool giant, the ratio of the X-ray flux to the bolometric flux (in the usual units for the HEAO-2 observations) is equal to 2.1 x 10^{-4}, which is three orders of magnitude larger than that observed in the Hyades K giants (Stern et al., 1981a). AG Dra should have an exceptionally enhanced chromospheric activity giving origin to an extended corona, for instance, as observed in some dwarf stars (Stern et al. 1981b.). From the analysis of the HEAO-2 data, Anderson et al. (1982) obtained a plasma temperature of 1.1 x 10^6 K, and an emission measure of 2.6 x 10^{55} cm^{-3}, much lower than that derived from the HeII 1640 A line, but close to the values for the intercombination lines (e.g., Viotti et al., 1983). Alternatively, X-rays are formed in a hot "area" emitting as a black body with a temperature of 1.5 x 10^5 K, and a radius of 1.4 x 10^3 km (Anderson et al., 1982). This area can be identified with an active region on the K-giant surface. Actually, Oliversen and Anderson (1982b) proposed for AG Dra a model of a (single) star with active regions of enhanced surface brightness to explain the modulation of the U-light curve. Although we cannot exclude that the cool component in symbiotic system has some kind of enhanced activity (and this point needs to be further investigated), it is difficult to accept that this activity regards a large fraction of the stellar energy output.

Garcia (1986) considered the X-ray luminosity as converted gravitational energy due to capture of matter from the cool star's wind. But the required mass-loss rate from the K giant turned out to be too high for a normal giant (10^{-7} $M_\odot$ yr^{-1}). The X-rays are most easily explained as the high-energy tail of the hot component spectrum. Slovak et al. (1987) found that HEAO-2 and far-UV IUE data (during the quiescent phase of mid-April 1980) can be fitted by a black-body with a temperature of 191,000 K and a luminosity of 174 $L_\odot$. AG Dra

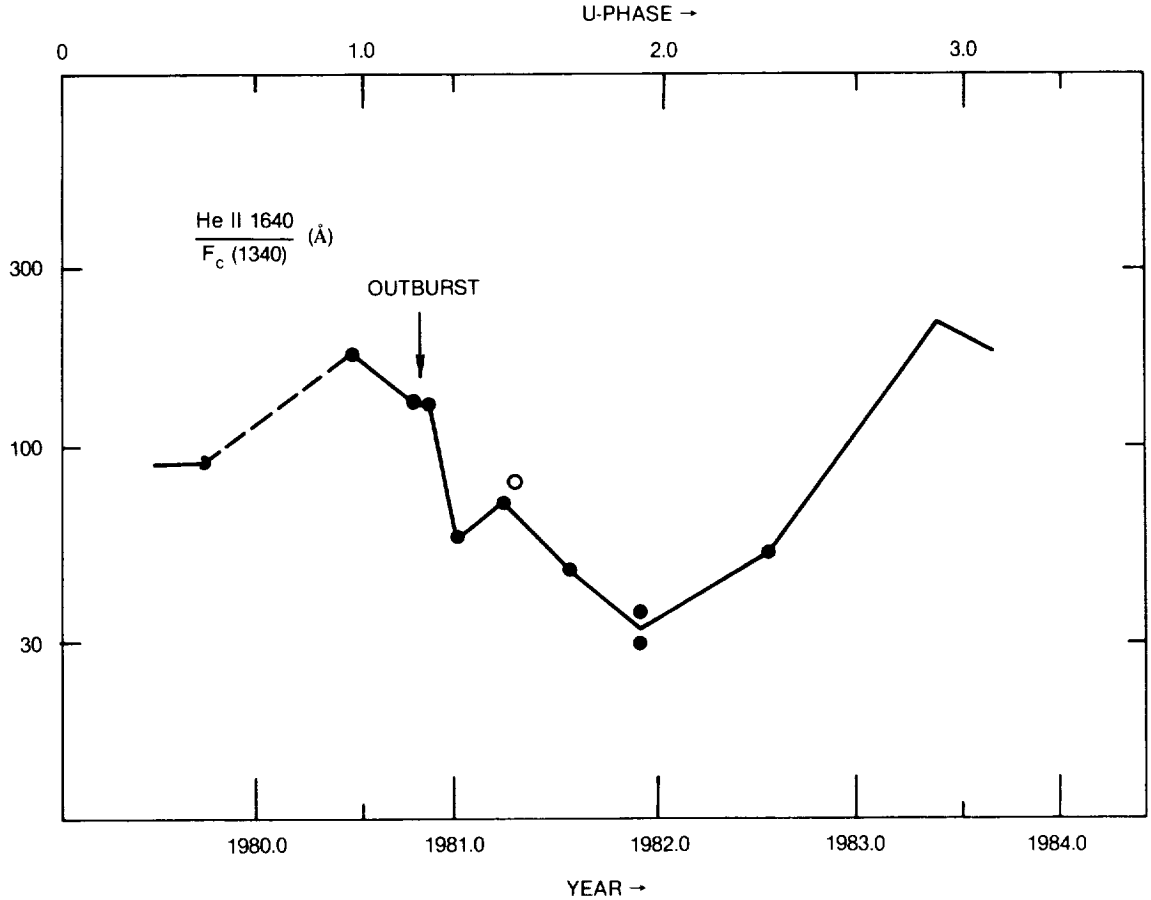


Figure 13-9. The HeII 1640A/Fc (1340A) flux ratio in AG Dra before and after the 1980 outburst.

was observed again with EXOSAT in June 1985 by Piro et al. (1985), who found that the observations can be fitted with a Bremsstrahlung model with log N(H) = 20.2, kT = 24 keV and a flux of 3.4 x 10^{-13} erg cm^{-2} s^{-1} in the 0.2-1.0 keV range. (It should be recalled that all these flux estimates strongly depend on the adopted interstellar extinction. For instance, Anderson et al. (1982) assumed log N(H) = 20.5, while Slovak et al. (1987) have made no reddening corrections. Piro et al. used the N(H) value derived by Viotti et al. (1983) from the interstellar Lyα). If the X-rays are produced near the hot component, and if the orbit of the AG Dra system is seen nearly edge-on, we should expect an eclipse at phase 0.5 of the Meinunger's light curve. In fact, AG Dra was observed again with EXOSAT in November 1985, at the time of the expected eclipse, but the X-ray flux was the same (Cassatella et al., 1987). Cassatella et al. also found a large decrease of the flux during the small outbursts of 1985 and 1986, without a similar decrease of the ionization of the emission line spectrum (see Figure 11-34). The cause of this rather unexpected behavior is not clear, but seems to suggest that X-rays do not represent the tail of the hot star spectrum. They are probably produced in nearby region. If the region is heated by the stellar radiation, its angular extension should be small, so as to capture only a small fraction of the stellar EUV photons, in agreement with the very large HeII/X-ray emission measure ratio.

To summarize, the presently available observational material on AG Dra is best interpreted in the framework of a detached binary model, formed by a rather normal K-type giant, and a degenerate star that is "heated" by slow mass accretion from the giant's wind. The accretion is probably responsible for the recurrent outburst. The K-giant could be peculiar for

having an anomalous chemical abundance, in agreement with its Pop II nature, and a rather high-velocity wind. But it is not clear whether these facts are associated with the symbiotic phenomenon. It is also not yet clarified if there is any enhanced surface activity of the giant. More detailed models of the AG Dra system require a careful analysis of the available and future data, especially the time variability in different frequencies. Of particular importance would be the systematic study of the cool spectrum at high resolution, to derive the basic data (abundance, surface gravity, turbulence, rotation, etc.), but also to improve the orbital parameters of the system, and high-quality emission line profiles collected during the orbital cycles and at different activity phases.

IV. THE SYMBIOTIC NOVAE

IV.A. INTRODUCTION

In describing the light curves of symbiotic stars in Section 11.III, we have shown that there exists a small group of objects characterized by the fact that they have undergone *one single outburst* in their known light history. This group (or subgroup) was first identified by Allen (1980b), who called them *symbiotic novae*. Attention was directed onto these stars after the recent outburst of a few northern objects, namely V1016 Cyg, V1329 Cyg, and HM Sge, whose behavior was found to be similar to those of slow novae. These objects were extensively studied in all the wavelength ranges for several years after their outburst. Thus our present knowledge of their behavior is rather complete. Other objects have displayed, in the past, a similar behavior, the most remarkable ones are RR Tel, which will be discussed in the next section, and AG Peg. AG Peg is the oldest known symbiotic nova. In the middle of the past century, the star underwent a major nova-like outburst, with a very slow increase of the visual luminosity from the 9th to the 6th magnitude in one to two decades, and a still longer decline to the present magnitude, which is close to the reported preoutburst luminosity (Figure 13-10).

At present, AG Peg displays a typical symbiotic spectrum with a cool (red) continuum and strong TiO absorption bands. The emission lines of low and high ionization are very prominent in the visible and UV spectrum, with a hot continuum extending to the far-UV (e.g., Boyarchuck, 1967; Hutchings et al., 1975). AG Peg was the first symbiotic star observed in the ultraviolet with OAO-2 (Gallagher et al., 1979). The star was extensively studied with the IUE satellite (e.g., Keyes and Plavec, 1980; Penston and Allen, 1985). Some high-resolution profiles of UV features are shown in Figure 11.31c. In many respects, the emission line spectrum is similar to that of a WN6 star, and AG Peg is often classified as M+WR, although the luminosity of the hot spectral component actually is lower than that of normal WR stars. The WR features are more probably associated with interactive phenomena in a binary system, as discussed later. It should be noted that without the knowledge of the light curve of AG Peg so many years ago, its nova-like nature would not have been recognized on the basis of its

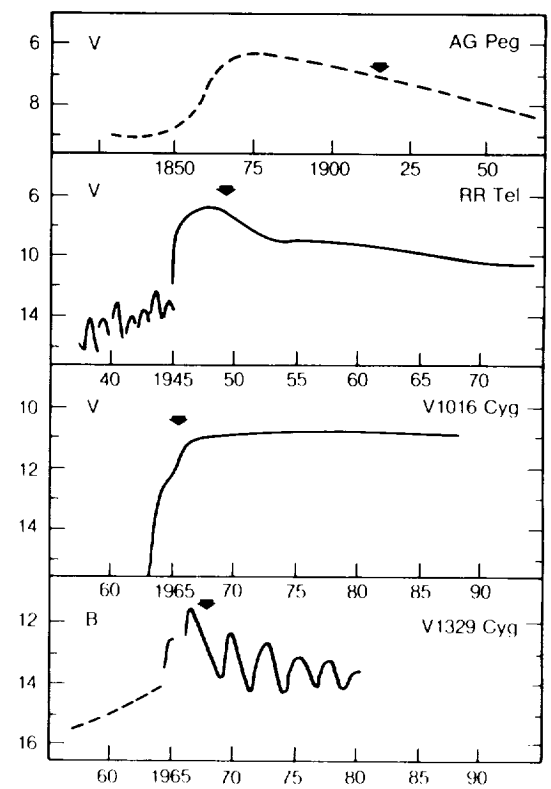


Figure 13-10. The comparative light curves of some symbiotic novae: AG Peg, RR Tel, V1016 Cyg, and V1329 Cyg (= HBV 475).

present behavior alone. The star is, in fact, quite different from the other "classical" symbiotic novae, such as RR Tel, V1016 Cyg, and HM Sge, all of which are D-type without the prominent M-spectrum of AG Peg. It is quite conceivable that several other symbiotic objects actually belong to the category of symbiotic novae, because they underwent in the past a nova-like outburst. But, owing to the long time scale involved, and the low frequency of the phenomenon, their main outburst has not been recorded.

Allen (1980b) listed seven stars having the character of very slow novae: AG Peg, RT Ser, RR Tel, V1016 Cyg (MHα328-116), V1329 Cyg, (HBV 475), HM Sge and V2110 Oph (AS 239). More recently, a new event—the outburst of PU Vul—was recorded, and the star added to this small class of objects. Figure 13-10 shows the schematic light curves of some symbiotic novae. The basic parameters are summarized in Table 13-2 (from Viotti, 1988b). In the following, we shall discuss in detail the case of RR Tel, which, for its luminosity and spectral evolution, can be considered as the best representative of the category of symbiotic novae. The main observational properties of most of these object were already presented in the different sections of Chapter 11. The general properties of symbiotic novae, for instance, were discussed by Kenyon (1986a), and Viotti (1988b, 1989).

IV.B. RR TELESCOPII

RR Tel was discovered as variable by Mrs. Fleming (1908) many decades before its main outburst. The light curve, based on 600 Harvard observations from 1889 to 1947 was described by Mayall (1949), and is schematically shown in Figure 13-10. According to Mrs. Mayall, RR Tel showed little evidence of periodic variations from 1889 to 1930, the observed range being about 1.5 mag with maxima ranging from 12.5 to 14 mag. After 1930, the periodicity of the variation became clearer, and a mean period of about 387 days could be derived with an amplitude of about 3 magnitudes. This behavior is typical of a long-period variable, and is presently barely visible at optical wavelengths with a period of about 374 d (Heck and Manfroid, 1982; Kenyon and Bateson, 1984). The period, however, seems to be variable between 350 and 410 d (Heck and Manfroid, 1985). As already discussed in Section 11.F, the Mira-type pulsation is evident at IR frequencies (Feast et al., 1983a). In late 1944, the periodicity stopped and the star rapidly brightened from m_{pg} = 14 to 10 in a few days, then rose to 7 mag by mid-1945. In the

TABLE 13-2. THE SYMBIOTIC NOVAE

Star	To[1]	Tmax[2]	Magnitude pre[3]	max[4]	post[5]	Spectrum cool	max	Type IR
AG Peg	1855	1871	9	6	8.3	M3		S
RT Ser	1909:	1923:	>16	9.5	13	M5.5	A8	S
V2110 Oph	.....	1940:		11:	22	>M3		D
RR Tel	1944	1948	14v	6	11	M5	F5	D
V1016 Cyg	1964	1967	14	11	11	>M4	neb	D
V1329 Cyg	1966	1967	14v	11.5	13-14	>M4	neb	S
HM Sge	1975	1975	>17	11	11	>M4	neb	D
PU Vul	1978	1982-83	15v	8.8	8.8	M4	A7	S

Notes to the table. (1) Year of beginning of the outburst. (2) Year of maximum luminosity. (3) Preoutburst magnitude. (4) Maximum luminosity. (5) Present (1986-88) postoutburst magnitude.

following years, RR Tel remained at maximum luminosity until 1949, reaching the sixth magnitude during 1948. Then the star gradually faded to the present V = 10 in about 14 years (see Kenyon, 1986). Although the star was quite bright at maximum, it was discovered only in 1949, three years after the outburst. Therefore no spectroscopic information is available on the early development of RR Tel. Nevertheless, since late 1949 the star underwent a major spectral evolution which was followed at the Bosque Alegre (Argentina) and Radcliffe (South Africa) observatories. Figure 13-11 illustrates the spectral evolution of RR Tel between April 1949 to July 1971 based on a collection of spectra obtained at Bosque Alegre.

The first spectrum taken at Bosque Alegre in April 1949 showed a strong continuum with many absorption lines of singly ionized metals. Some absorptions are flanked at longer wavelengths by a weak emission component, indicating a marginal P Cygni profile. This emission became more prominent in July 1949. By mid-September, the continuum appeared weaker and the emission lines dominated the spectrum of RR Tel, although the mean line excitation was still low. The first spectra taken at the Radcliffe Observatory of South Africa were discussed by Thackeray (1950), who found strong absorption of CaII and hydrogen in June-August 1949. TiII was present in absorption, and Hβ was absent, probably filled in by emission. Mayall (1949) reports on low-quality, low-dispersion spectra taken when RR Tel was at maximum brightness. All these earlier observations agree in giving an F-supergiant spectral type (cF5, according to Thackeray, 1950). In a later paper, Thackeray (1977) reports that the relative shift of the absorption lines was - 100 km s^{-1}. The remarkable spectral change, which occurred between August and September 1949, was first noted by Thackeray (1950), where reported that in his spectra all the absorption lines disappeared and a rich emission - line spectrum appeared with prominent hydrogen, CaII and especially FeII emission, close resembling the spectrum of the peculiar variable Eta Car (Thackeray, 1953). According to the Bosque Alegre spectra shown in Figure 13-11, the spectral variations should have taken place in *less than one week*, and maybe in a few days.

The spectral evolution of RR Tel in the following years is best described by A. D. Thackeray's review (Thackeray, 1977). Since 1949, the star has shown a gradual increase of the mean ionization of the emission line spectrum. HeII and NIII appeared around August 1950 (see also Pottasch and Varsavsky, 1960). These authors also identified HeI absorption with a velocity of -685 km s^{-1} (in 1951) and -865 km s^{-1} (in 1952). Then, between 1951 and 1952, [OIII] and [NeIII] flared while the permitted FeII lines faded (Thackeray, 1953). The increase of the level of ionization continued through 1953 and 1954 and is best illustrated by the sequential appearance of higher and higher ionization stages of iron, from FeIII to FeVII. This sequence is shown in Figure 13-12. First, the spectrum only showed the low-ionization lines of permitted FeII. Then, the forbidden [FeII] lines appeared and gradually strengthened with respect to FeII, indicating a decrease of the density of the emitting medium (cf. Viotti 1976).

The sequence continued with [FeIII], whose lines brightened in 1952; [FeIV] (1952-53); [FeV] (1954-56); [FeVI] (1956-59); and finally [FeVII] (1959-64). This behavior is similar to that found in novae after the optical maximum, but with the important differences that in RR Tel (and in other symbiotic novae), the trend was much slower. In any case, RR Tel was the first nova-like object in which this phenomenon was studied in such detail. It should also be noted that at the time of Thackeray's observations, the spectrum of three to five times ionized metals was very poorly known. His careful study of the spectral evolution of RR Tel, and the theoretical computations of B. Edlen and R.H. Garstang led to the first identification of many forbidden lines of FeIV to FeVI, and of other highly ionized metals. From this point of view, RR Tel has also been a good laboratory for atomic spectroscopy.

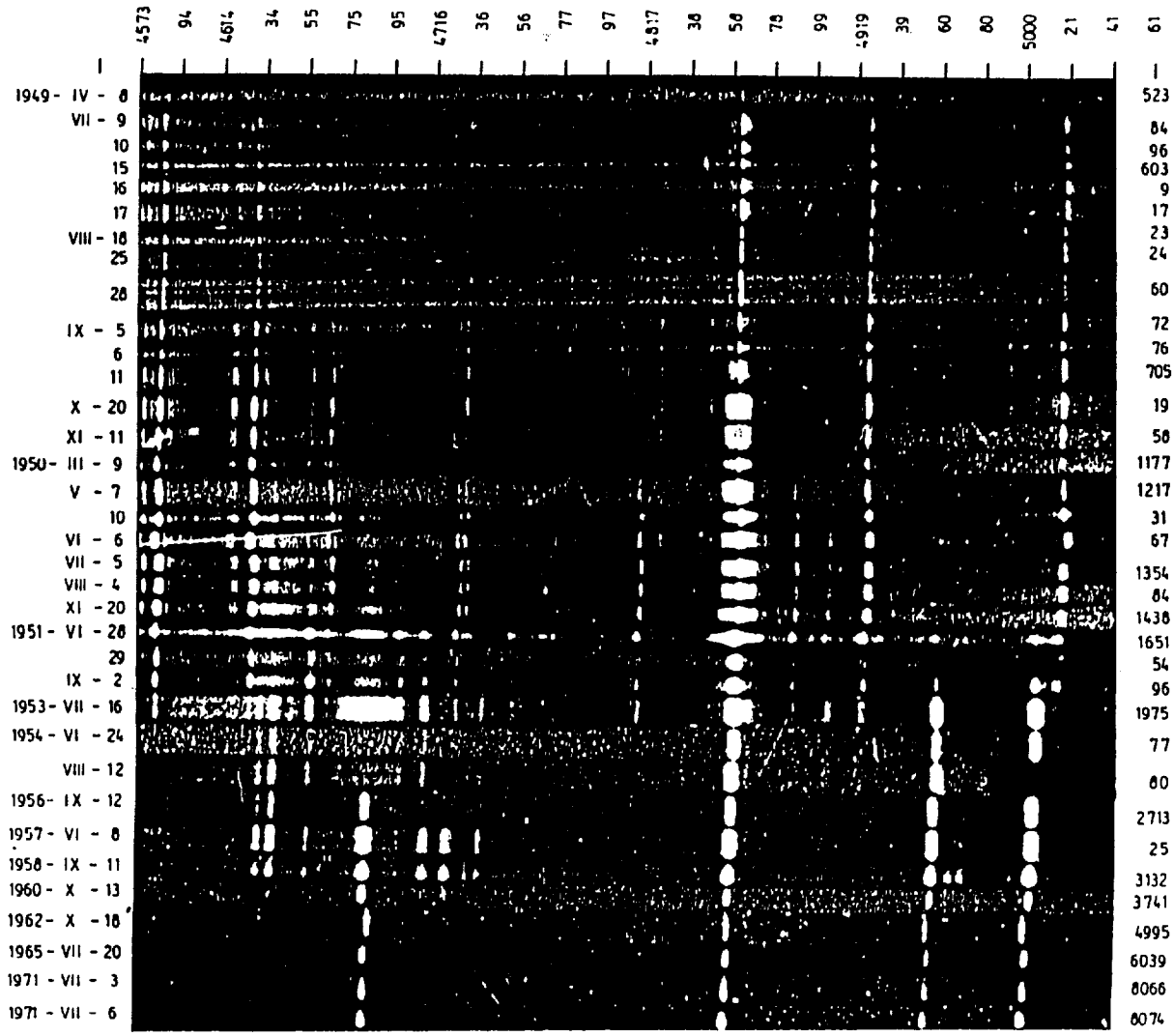


Figure 13-11. (Plate) the blue spectrum of the symbiotic nova RR Tel between April 1949 and July 1971. This is a reproduction of spectrograms taken at the 150-cm telescope of Bosque Alegre Observatory (Argentina). The original reciprocal dispersion is 41 A mm^{-1}. Note the dramatic spectral change occurred in September 1949. Courtesy of Professor Jorge Sahade.

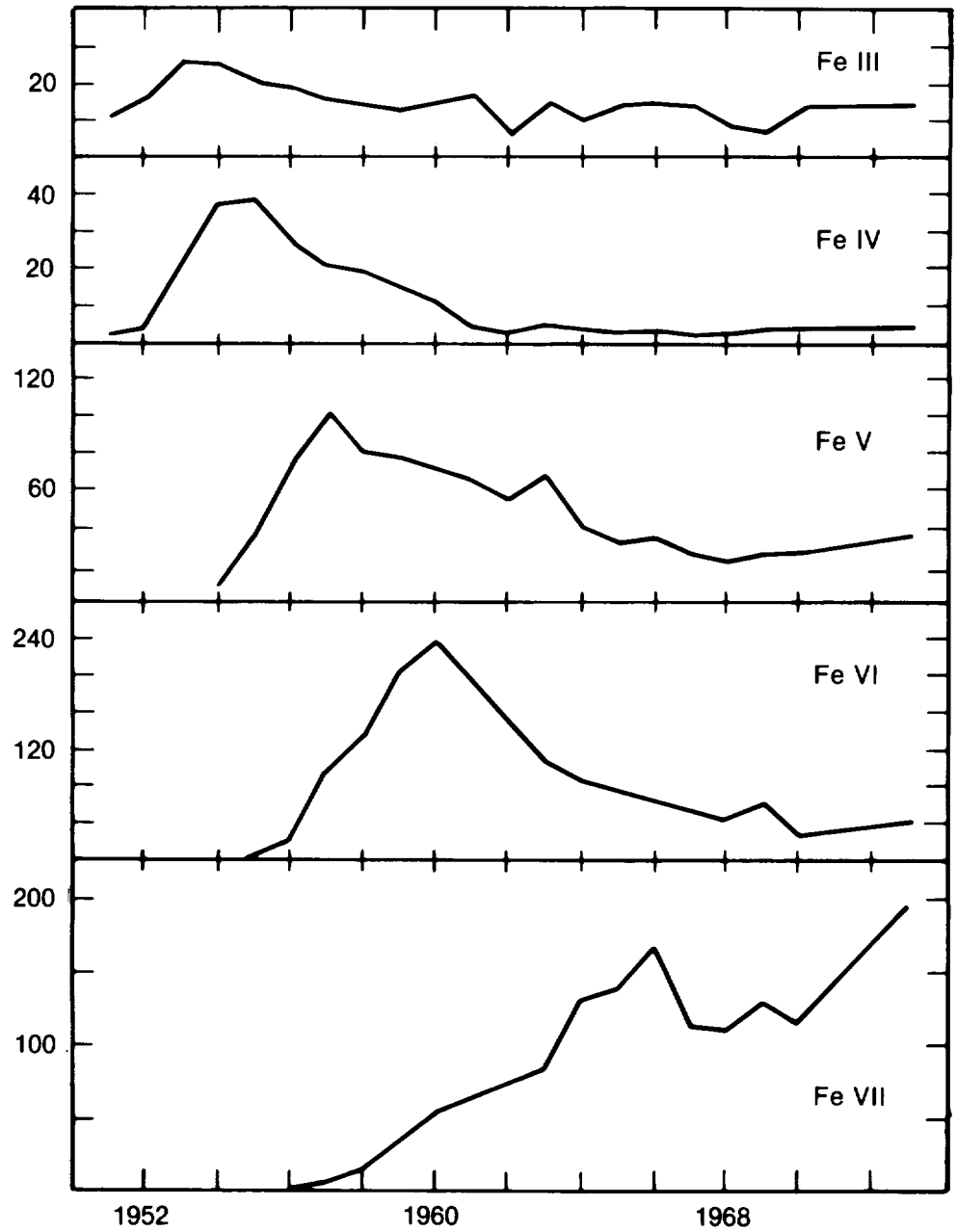


Figure 13-12. The evolution of the intensity of the lines of the different ionization stages of iron in RR Tel during 1952 to 1964 as described by Thackerary (1977). Note the gradual increase of the ionization of the emitting envelope as indicated by the appearance of the evolution of the successive ionization stages of iron (Viotti, 1987).

In the ultraviolet, the star presents a very rich emission spectrum with a wide range of ionization, from neutral species to five times ionized calcium (Penston et al., 1983). More recently, Raassen (1985) suggested the identification of a line at 2648.9 A with the $3P^2$ - $1D^2$ transition of [FeXI], which could thus be the highest ionization stage so far observed in RR Tel (possibly excluding the yet unidentified high-temperature features at 6830 and 7088 A). Penston et al. (1983) found that the width of the emission lines varies between different atomic species and increases from 40 to about 80km s^{-1} from low- to high-ionization lines. Similar correlation between line width and ionization energy was previously reported by Friedjung (1966) and Thackeray (1977) for the optical lines. This behavior was also found in other

symbiotic novae, such as V1016 Cyg and HM Sge.

IV.C. GENERAL PROPERTIES OF THE SYMBIOTIC NOVAE

Like RR Tel, the other symbiotic novae also have the common property of having undergone a single major outburst and of showing a symbiotic spectrum. Since there exists in the few objects classified as symbiotic novae a large variety of behavior, it is important to investigate their general properties and whether they represent an extreme case of symbiotic stars or have to be associated with the category of novae. In the following, we summarize the different aspects of the phenomenon.

a. The preoutburst phase and the red component.

The preoutburst phase is known in some detail only for V1329 Cyg and RR Tel. Both appeared largely variable, on a long time scale. In V1329 Cyg, the variability is interpreted as due to eclipses of a binary system, and this is also supported by recent radial velocity measurements (e.g., Grygar et al., 1979; Nussbaumer et al., 1986). On the contrary, in the cases of RR Tel, the long-term variability is attributed to a Mira-type pulsation, as also confirmed by the recent optical and IR monitoring (Heck and Manfroid, 1982; Feast et al., 1983a). The orbital period of RR Tel, as in other D-type symbiotics, is believed to be much longer.

In these two objects and in V1016 Cyg, the preoutburst spectrum was M-type. It is quite possible that the luminosity (and spectrum) of the preoutburst M star was the same as that of the present red component of the symbiotic systems. This obviously implies that the outburst was not (at least directly) caused by the red star, but rather by its companion. An M-giant spectrum was also observed during the deep 1980 minimum of PU Vul, and in AG Peg and RT Ser after decline from maximum. In V1016 Cyg and HM Sge, which have not (yet) declined, the M spectrum in the visible is masked by the strong continuum and line emission from the circumstellar regions. In these stars, the presence of a late-type component is supported by the Mira-type variations in the near-IR. As in RR Tel, the Mira star could be hidden by a dense circumstellar dust shell (Kenyon et al., 1986). Indeed, in the D-type symbiotic novae, the Mira component should be subject to large mass overflow, followed by formation of dense gas and dust clouds. Table 13-3 (from Viotti, 1988b) summarizes the typical time scales of the cool components of symbiotic novae. The spectral types found from the literature are given in Table 13-2. The luminosity class is III for AG Peg and PU Vul, and for the Mira components of the D-type objects as well.

b. The outburst.

As seen in Figure 13-10 and in Table 13.3, the rise to maximum was fast in V1329 Cyg, HM Sge, and RR Tel, and very slow in V1016 Cyg and especially in AG Peg and RT Ser. It is noticeable that the rise time is apparently not related to the other features (e.g., the IR-type) of the symbiotic novae. The amplitude of the outburst, ranges from 3 mag (AG Peg) to more than 6 mag (HM Sge, RT Ser). It is also important to consider that this difference is not due (or not only due) to the actual amplitude of the outburst, but rather to the relative brightness of the late-type component (with respect to the luminosity of the symbiotic nova at maximum), which is high in AG Peg and V1329 Cyg, and very low in RT Ser, V2110 Oph, and HM Sge. The actual visual luminosity increase of the red-giant companion is unknown.

The spectrum at maximum is another intriguing problem. As in classical novae, some objects (RT Ser, RR Tel, and PU Vul) displayed an intermediate (A-F) equivalent spectral type, possibly of supergiant class, but without the highly violet-displaced absorption lines

TABLE 13-3. CHARACTERISTICS TIME SCALES OF SYMBIOTIC NOVAE.

Star	Rise (a)	Decay (b)	Mira (c)	Orbit (d)	K (e)
AG Peg	16	40	==	816.5	5.1
RT Ser	14	7:	==	==	==
RR Tel	<0.3	9	374.2	==	==
V1016 Cyg	2-3	>125	472	==	==
V1329 Cyg	0.3	12-20	==	950	62
HM Sge	<0.4	>65	500-600	==	==
PU Vul	1	>38	==	==	==

Notes to the table. (a) Rise time of the visual luminosity in years. (b) The e-folding decay time of the visual luminosity in years. (c) Period (in days) of the Mira pulsation. (d) Orbital period (in days). (e) Semiamplitude of the radial velocity curve (in km s^{-1}).

that are seen in novae. No similar absorption spectra have been observed in the other symbiotic novae. The simplest explanation is that the absorption-spectrum phase occurred during a period not covered by the observations, and we missed it. In fact, V1016 Cyg was first observed spectroscopically near the end of its long-lasting rise to maximum (indicated by an arrow in Figure 13-10). The first spectra of V1329 Cyg were taken at the end of 1969, one year after its light maximum, and showed a rich emission line spectrum, which could be compared with the post-maximum spectrum of classical novae. In this regard, RR Tel represents a rather fortunate case, since its A-type spectrum suddenly disappeared in late 1949, just a few months after the discovery that the star had "exploded". Suppose that the discovery would have been made 4-5 months later, in late September or in October 1949, instead of in April. We would have missed the absorption-spectrum phase, and perhaps have placed RR Tel in a different subcategory of symbiotic novae (see, e.g., Kenyon and Truran, 1983). Thus it is important to take into account these selection effects in any modeling of the phenomenon.

Like the classical novae, the symbiotic novae after the outburst display a rich emission line spectrum with wide ionization energy range. But unlike novae, the emission line profiles are narrow, in general, indicating a low expansion velocity of the main emitting region. There are, however, a number of interesting exceptions. Crampton et al. (1970) found in V1329 Cyg the [OIII] and [NeIII] lines having a multiple structure, with emission peaks ranging from -240 to +250 km s^{-1}. This line multiplicity was also present in later spectra of the star (Grygar et al., 1979; Tamura, 1988) (Figure 13-13; see also Figure 11-13).

As discovered by Crampton et al. (1970) and confirmed by Baratta et al. (1974), the low-resolution spectra of the star show several broad and shallow emission features, which were identified with WN5-type lines having an expansion velocity of about 2300 km s^{-1} (figure 11-10). As discussed above, broad WR structures have also been seen in AG Peg and RR Tel, while high-velocity P Cygni profiles were observed in RR Tel during decline. Therefore, in some symbiotic novae, at least, there is evidence for the presence of high temperature, high-expansion velocity regions, but this should only represent a small portion of their emitting envelope. This result is probably related to the velocity gradient found in some objects from the analysis of the line width of the narrow emissions, with the higher energy ions (and the corresponding higher temperature-emitting regions) having larger expansion velocity, as suggested by the observed correlation between emission line width and ionization energy (see Chapter 11 Section VIII.D.) It

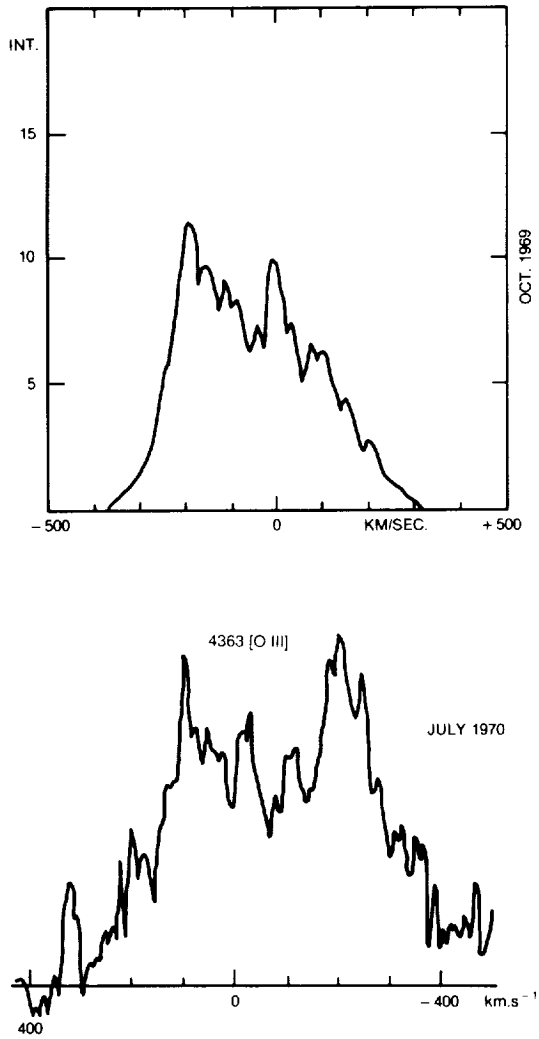


Figure 13-13. Emission line profiles of the forbidden lines in the spectrum of the symbiotic nova V1329 Cyg. Top: Mean profile of [O III] and [Ne III] lines in October 1969 (Crampton et al., 1970). Bottom: profile of the /O III/ 4363 line in July 1979 (Grygar etal., 1979).

is also conceivable that the WR features observed, especially in V1329 Cyg, originate in a dense expanding envelope or wind of the hot star, which behaves like some WR-type nuclei of Planetary Nebulae. In view of possible models, it would be interesting to know if these WR features are present far away in time from the outburst, or in the spectroscopic records of the preoutburst phase.

The emission line spectrum should be formed in an extended circumstellar or circumsystem nebula, which is supposed to be ionized by the radiation of a hot source (a hot star or the hottest parts of an accretion disk) in the system. Collisional ionization is another possible mechanism to explain the very high ionization features and the X-rays. It might occur in shocks formed by the interaction of the winds of the two stellar components, for instance, as suggested by Willson et al. (1984), or by collision of the stellar wind(s) with the circumstellar matter. In general, the analysis of the high-ionization emission line fluxes and of the far-UV continuum leads to a model of a hot central source with temperatures (around 10^5K) and radii (0.1 $R_\odot$ or less) typical of the nuclei of Planetary Nebulae (e.g. Nussbaumer and Schild, 1981; Tamura 1981; Mueller and Nussbaumer, 1985; Hayes and Nussbaumer, 1986).

c. The decline phase.

The behavior of symbiotic novae after the outburst is very different from case to case. Four objects showed a gradual fading of the visual luminosity that took several years to decades (Figure 13-10). The e-folding decline time varied from 7-9 years for RT Ser and RR Tel to 12-20 years for V1329 Cyg and 40 years for AG Peg (Table 13-3). In the case of V1329 Cyg, the decline time was derived from a fit of the UV emission line flux variation, taking into account the 950 d periodicity (Nussbaumer et al., 1986). We recall that Allen (1981) and Willson et al. (1984), from the analysis of the X-ray flux in three symbiotic novae, V1016 Cyg, HM Sge, and RR Tel, suggested a very slow decrease of the X-ray flux after the outburst, with an e-folding decay time of 5 to 50 years. But this result needs to be confirmed.

Three recent symbiotic novae, V1016 Cyg, HM Sge, and PU Vul, have not significantly faded since their outburst, although a small visual luminosity decrease has been recently noted for PU Vul (Gershberg and Shakhovskoj, 1988). Their decay time is probably similar to that of AG Peg, or even much larger. Once again we recollect that in symbiotic stars, emission lines largely contribute to the broad-band photometry, so that the observed light

C-9.

curve of an object does not necessarily describe its global time behavior, but should also reflect local fluctuations of the physical structure of the emitting envelope. Therefore, it is possible that some precious information remains masked in the broadband light history.

As in RR Tel and in classical novae, the spectral evolution of V1016 Cyg and HM Sge was characterized by the gradual increase of the ionization level of the emission line spectrum. WR features were first detected in HM Sge two years after the outburst (Ciatti et al., 1978). As these faded, HeII and [FeVII] emerged with very intense lines (Blair et al., 1981). We recall that, unlike in the novae, the spectral evolution of V1016 Cyg and HM Sge occurred at nearly constant visual luminosity.

Symbiotic novae were also followed at radio wavelengths, sometimes over a period of several years (see Section 11.VII). Radio observations of HM Sge started in 1977, two years after the outburst, and disclosed a gradual evolution, with a steady increase of the radio flux at 15 GHz from 40 mJy in 1977 to 150 mJy in 1985. The radio spectrum remained optically thick all the time, indicating that, unlike classical novae, the expanding HII region was still dense several years after the outburst (Kwok et al., 1981; Kwok, 1988). An optically thick radio spectrum is also displayed by V1016 Cyg. The star was first observed in 1973, nine years after the outburst, but no significant flux change has been detected since then. Probably it reached a stationary stage before 1973. We finally recall the large and probably irregular radio variability of the other symbiotic nova V1329 Cyg.

One particular case is PU Vul. This star, after the main brightening phase that took about 1 year, remained at maximum for another year, showing an F-supergiant spectrum (e.g., Nakagiri and Yamashita, 1982; Kolotilov, 1983). Then, during the first half of 1980, the visual luminosity gradually dropped from V = 8.8 to 13.5 (Figure 13-14), and the M-type spectrum appeared. PU Vul remained at minimum for about 200 days, then gradually flared up again to V = 8.5, followed by the very slow decline discussed above. During this phase, the visual and ultraviolet spectrum remained dominated by the hot component, but with a gradual evolution from F5 to A2 during 1983-1986 (Gershberg and Shakhovskoj, 1988). In late 1987, Maitzen et al. (1987) noticed an increase of the emission line strength. The 1980 minimum was also followed by Friedjung et al. (1984) beyond the visual range. As shown in Figure 13-14, the amplitude of the minimum was much larger at shorter wavelengths, and just detectable in the near infrared. Also the duration of the eclipse was longer in the UV. Friedjung et al. interpreted the deep minimum as a result of temporary obscuration of the "exploded" star by dust condensated from the ejected shell. Dust might also have been produced by the red giant. Alternatively, the hotter star has been eclipsed by the M giant (Kenyon, 1986b). From the duration of the minimum, Kenyon derived an orbital period of about 700 years. In both hypotheses, the M spectrum observed at minimum should be that of the cool giant component of the system, which at maximum is completely masked by the radiation of the early type component.

IV.D. POSSIBLE MODELS FOR SYMBIOTIC NOVAE

Let us now examine the above "main properties" of symbiotic novae in the light of possible models. Other aspects of the problem are discussed in Viotti (1989). Although the preoutburst phase is very poorly known, it is clear that the large increase of the visual luminosity, mostly due to the appearance and strengthening of emission lines, was associated with a sudden increase of the flux of far-UV photons from the M-giant's companion. The hot source should have largely increased its brightness temperature and bolometric luminosity with respect to the previous unknown stage. As discussed in Section 12.IV.A, such an event can be explained as a result of sudden thermonuclear burning of the hydrogen-rich matter accreted by a degenerate star from the red giant wind. According to the models developed, among others, by Paczynski and Rudak (1980), Fujimoto (1982a,b), Kenyon and Truran (1983),

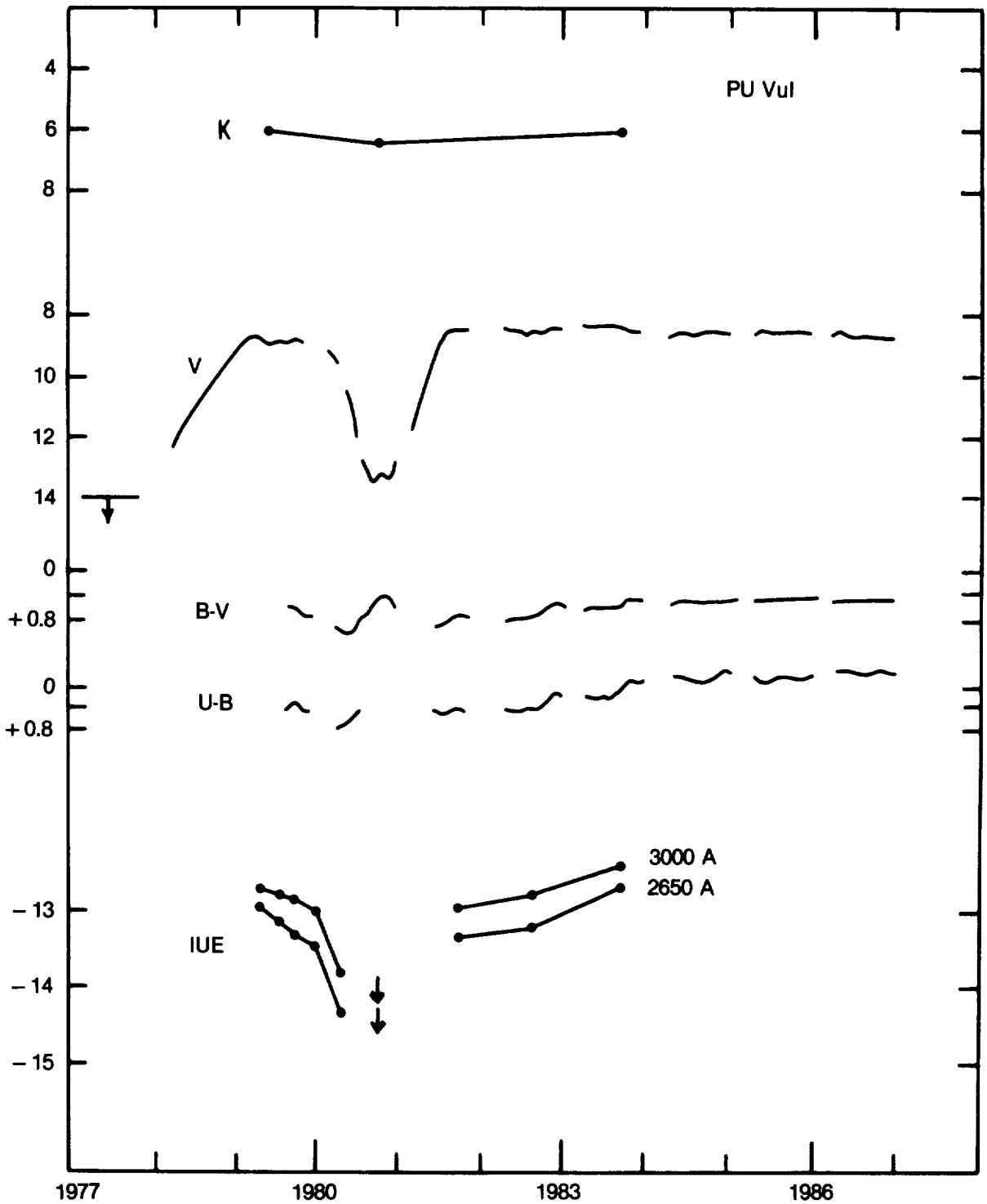


Figure 13-14. The infrared, optical, and ultraviolet light curve of PU Vul during the recent outburst (Friedjung et al., 1984; and Kenyon, 1986, adapted).

Kenyon (1988), and Livio et al. (1989), the accretion rate should be smaller than that required to have a stable burning of the matter as it is accreted, and larger than that which characterizes the classical nova outburst. Since the first case is supposed to occur in at least some Z And-type symbiotic stars, symbiotic novae should represent the dividing line between Z And-type variables and classical novae. Due to the larger separation of the components in

symbiotic novae, the accretion from the red-giant wind (the systems are clearly detached) should be smaller than in other symbiotic systems, even if we expect denser winds in those symbiotic novae containing a Mira.

According to Kenyon (1988), thermonuclear flash models imply that, if the accretion rate is fairly low, the white dwarf envelope is completely degenerate. Under these conditions, the luminosity of the star first increases at nearly constant radius, then a slow expansion at constant bolometric luminosity follows until an A-F supergiant configuration is reached (see Figure 12-4). Later, after a rather long time, the star evolves again to high effective temperatures. This *degenerate flash* model possibly applies to AG Peg, RT Ser, RR Tel, and especially PU Vul. However, in the case of RR Tel, it is difficult to explain the rapid evolution of its spectrum from F-supergiant to emission line.

If the accretion rate onto the white dwarf is larger, the accretion results in a non-degenerate envelope, and produces a relatively weak shell flash. These weak *non-degenerate flashes* (Kenyon, 1988) do not evolve into the A-F supergiant stage discussed above, but the star remains hot throughout the eruption. This could be the case of V1016 Cyg, V1329 Cyg, and HM Sge, which have probably not developed the intermediate-type spectrum in the earlier stages of their outburst. In any event, such a phase, if it occurred during an early unobserved phase, should have lasted quite a short time, one year or less, which is difficult to explain in the light of the proposed models. The amplitude of the outburst in the visual should be larger in the former case of a degenerate outburst, as a consequence of the small bolometric correction at maximum. Although the amplitude of some well-documentated objects (RR Tel and PU Vul, on one side, V1016 Cyg and V1329 Cyg, on the other) apparently seems to support this model, in the reality, the preoutburst visual magnitude in all these objects is that of the red giant, since the preoutburst spectrum is M. The actual amplitude of the white dwarf outburst should be larger, and probably much larger, than that given in Table 13-2. We finally consider that during the high-temperature phase, the exploded star should have a dense hot wind, which might have produced the WR features observed in several cases. This point, however, has not yet been investigated in detail, especially in order to find possible differences with the hot components of symbiotic systems whose high surface temperature is not the result of accretion processes. In particular, the chemical composition of the wind should reflect the recent violent history of the star, and this problem should require more studies.

The outburst of symbiotic novae might be explained by instabilities of an accretion disk (cf., Duschl, 1986b), but this model should require high accretion rates, which do not appear to be realistic for detached systems. Alternately, the outburst can be the result of a sudden onset of a strong stellar wind from the cool giant (Nussbaumer and Vogel, 1988). The wind will produce an extended envelope surrounding the system. The luminosity increase is the result of the ionization of the envelope by the UV radiation of the hot stellar component. This model has to be worked out in more detail, with special attention to the time scales involved in the processes. Periodic enhancements of the accretion rate could occur if the orbit is highly eccentric, and the red giant is going to fill its Roche lobe at periastron. Such a model was proposed by Kafatos and Michalitsianos (1982) to explain the outbursts of R Aqr (See the next section V.), but obviously it does not apply to those symbiotic novae, AG Peg and V1329 Cyg, whose period appears too short for the time scale involved in the symbiotic nova phenomenon. Other observational and theoretical aspects of the phenomenon that need to be further investigated are the identification of other symbiotic novae whose main outburst has not been observed, the recurrence of the phenomenon, and the structure of the circumstellar nebula. But we especially need the basic parameters of the binary systems.

V. R AQUARII: A SYMBIOTIC MIRA WITH JET

R Aqr is one of the most peculiar astrophysi-

cal objects, since the characteristics of many different astrophysical categories are present in the same object (Michalitsianos, 1984). R Aqr is symbiotic for its composite spectrum characterized in the visual by many emission lines and a late-type MIII component. R Aqr is also a Mira-type variable with a period of 387 days, but the light curve presents important irregularities. A SiO maser emission was also detected. The star is interesting for being at the center of a planetary nebula with a mid-ionization nebular spectrum. The central part of the nebula, studied at radio wavelengths, is highly variable with jet-like features. Finally, as discussed in Chapter 11 Section IX.E, R Aqr was recently detected as X-ray source with EXOSAT (Viotti et al., 1987). Thus, it is difficult to put R Aqr in one specific category. In addition, the star is rather different from the "classical" concept of symbiotic stars. However, we may consider that the symbiotic phenomenon is particularly evident in this object and that its study could give an important contribution to the problems that we are discussing in this monograph. This is the reason for having devoted a full section to this interesting object. Many aspects of R Aqr have also been discussed by Querci (1986) in the previous volume on M-stars of this monograph series.

V.A. THE MIRA VARIABLE

R Aqr, as indicated by the letter "R", was the first variable discovered in the Aquarius constellation. It was found as variable by Harding in early 1800, and since then it has been studied by several astronomers. Thus, its light history has been fairly well known for almost two centuries. The light curve from 1887 to 1980 is reproduced in Figure 13-15.

R Aqr is a red giant that shows large and quasi-regular light variations rather typical of a Mira variable. The mean period is 387 days. The mean light curve generally presents a broad minimum lasting 6-7 months, followed by a rapid rise to maximum. There are ample variations from cycle to cycle, in both the shape and amplitude of the light curve. In some cases the variability nearly disappeared. For instance, this has happened in the years 1905-10, 1928-30, and 1974-78. Thus, the light curve presents a kind of a long time scale "modulation" of the amplitude of oscillation. Willson et al. (1981) suggested that these irregularities should be caused by eclipses of a close binary system orbiting in a highly eccentric orbit with a period of 44 years.

R Aqr was monitored in the infrared (JHKL) at SAAO during 1975 to 1981 (Catchpole et al., 1979; Whitelock et al. 1983b). These observations confirmed the visual periodicity of 387 days. The light curve in the L-band (about 3.6 μm) is slightly different from the visual curve, with a steeper decline after maximum, and a slower rise to maximum, which is reached slightly later than in the visual. This is fairly normal for a Mira variable. Whitelock et al. (1983b) noted that the infrared fluxes appeared depressed during 1975-78. They attributed this to an obscuration by an opaque dust cloud as suggested by Willson et al. (1981).

The Mira character of R Aqr is also indicated by the positive detection of SiO maser emission (Lepine et al., 1978), which is normally associated with LPV's. So far, R Aqr is the only symbiotic star showing detectable maser emission (Lepine et al. 1978, Cohen and Ghigo, 1980). The negative detection of OH (Wilson and Barrett, 1972) and H_2O lines (Dickinson, 1976) is probably related to the inhibition by the hot close companion of the Mira. More recently, Hollis et al. (1986) reported interferometer SiO observations indicating that the maser emission occurs in the nebulosity about one arcsec away from the optical position of the Mira (see Figure 13-17). This result is clearly in disagreement with a model of collisionally pumped SiO emission (e.g., Elitzur, 1981).

V.B. THE NEBULA

The planetary nebula around R Aqr is essentially composed of two distinct structures: the outer nebula with an oval shape with is formed by two arcs symmetrically extending to the

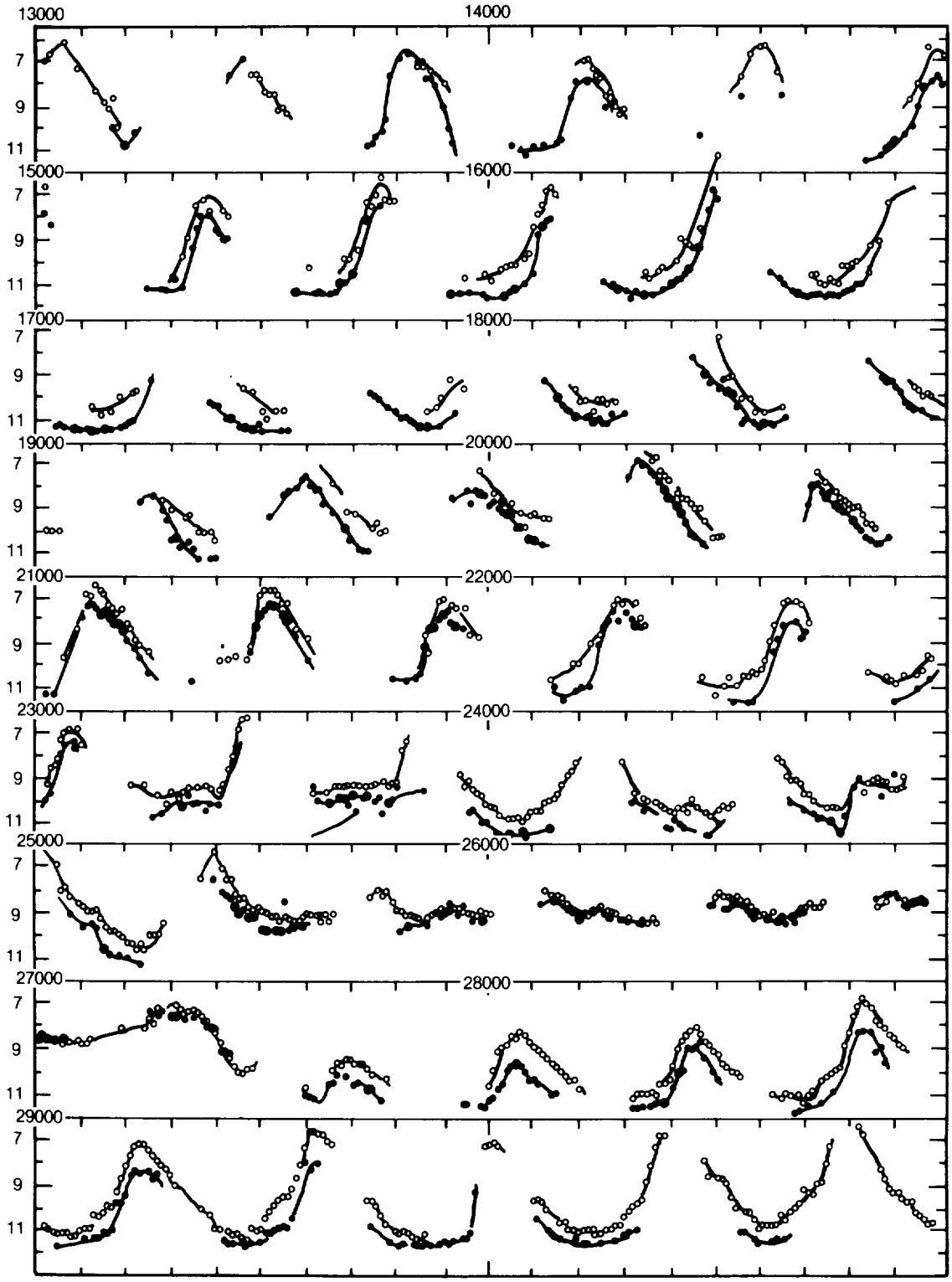


Figure 13-15. The light curve of R Aqr from 1895 to 1941 Mattei, 1979). The visual magnitude is periodically variable between V = 6 and V = 11, with large variations from cycle to cycle. Note, in particular, the anomalies during 1905-10, 1928-30, and 1974-78, which could be associated with enhanced activity of the hot component. The mean Mira period is 387 days.

East and West from the central star giving to the nebula the aspect of a double lens (Figure 13-16).

The R Aqr nebula has been recently studied by Solf and Ulrich (1983) who found that the nebula is composed of two separate shells, which are expanding at velocity of 30-50 km s^{-1}. These shells should have been ejected from the central object 185 and 640 years ago. The spectrum of the nebula is typical of a (low excitation) planetary nebula. The problem is to find the central ionizing source, which could be identified with the unobserved hot companion of the red giant.

A few years ago Wallerstein and Greenstein (1980) first reported the detection in a 1977 plate of R Aqr of a "spike" of emission nebulosity that appeared as an elongation of the stellar image towards North-East, never reported previously. Using Lick plates, Herbig (1980) and Sopka et al. (1982) confirmed the jet-like feature that was, however, not present in a 1970 plate of R Aqr. Therefore, the jet should have appeared between 1970 and 1977. Sopka et al. also found the presence of an elongation in the radio map at 6 cm at the position of the optical jet. Later, higher spatial resolution radio observations obtained with the NRAO VLA of Socorro led to the identification of five separate radio sources (Figure 13-17), the "jet" (source B), a second jet closer to R Aqr, (A), a "counter-jet" (A'), while the central source C was resolved in two components separated by 0.5" (Hollis et al, 1985; 1986).

The radio jet is cospatial with the optical jet, and, because of the higher spatial resolution, can be studied with much more accuracy. Radio observations suggest an ordered geometry of ejecta: the distance of each knot, C2, A and B, from the central source C1 is linearly dependent on position angle (Hollis et al, 1986), and this should be associated with the mode of expulsion of the jets. According to Kafatos et al. (1986), components B, A, and C2 were formed during successive outbursts of the system, C2 being the most recent ejection, probably related to the mid-1970s event discussed above, while the two further ones should have been ejected long ago, during previous active phases of the object. At any rate, it should be considered that no expansion of the radio knots has been so far detected (e.g., Hollis et al. 1985).

High-resolution optical imagery of the R Aqr complex should provide precious complementary information on the nebula. Michalitsianos et al. (1988b) have recently studied the large-scale structure of the nebula using a CCD camera and narrow-band interference filters. Paresce et al. (1988) used a coronograph in conjunction with narrow band filters to imagine the immediate surroundings of R Aqr (1 to about 15 arcsec) at subarcsec spatial resolution. These observations have put in evidence an S-shaped bipolar shape which comprises the

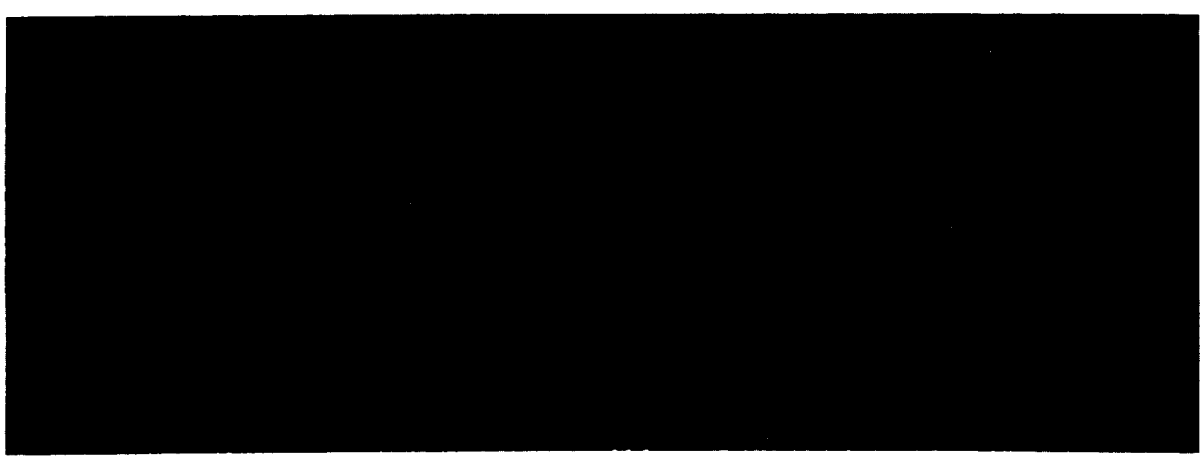


Figure 13-16. (Plate) The planetary nebula around the symbiotic-Mira R Aqr (Kafatos and Michalitsianos, 1984).

radio jet features described above. The optical image is extended in both directions and at much larger distances than observable at radio wavelengths. Observations have also revealed the presence of several knots, including one not seen at radio wavelengths. This bipolar symmetry of the R Aqr inner nebula suggests a symmetric collimated flow from R Aqr, associated with a rotation or precession of the central object. For any consideration of this kind, the knowledge of the precise position of the star-like counterpart is very important. Michalitsianos et al. (1988b) derived the astrometric position of the Mira variable within about ±0.05". The star position is about 0.15" SW of the central radio source C1 (Figure 13-17) and provides clues to the origin and ionization structure of the HII region surrounding the R Aqr system. As discussed above, the SiO maser source is not coincident with the astrometric position of the Mira variable, as one would have been expected, but it is placed 1" SE from C1 and LPV, in the opposite direction of the radio jets. Again, this result has to be further investigated and compared with observations with similar accuracy of other symbiotic and Mira variables.

V.C. THE SYMBIOTIC SPECTRUM

The optical spectrum of R Aqr is rich in emission lines which are difficult to observe when the star is near maximum light. The hydrogen lines and the nebular [OIII] and [NeIII] are strong in emission. As in other symbiotics, the energy range is wide, as indicated by the presence of low- (FeII, [FeII], etc.) and high-ionization lines (HeII, NIII, CIII). During the optical outbursts, the latter ones become stronger and broader. Zirin (1976) reported the identification of the coronal [FeXIII] line at 10747 A in spectra made in 1970-71. But there are no other observations of this line.

The UV spectrum of R Aqr has been investigated since 1979 and has revealed the presence

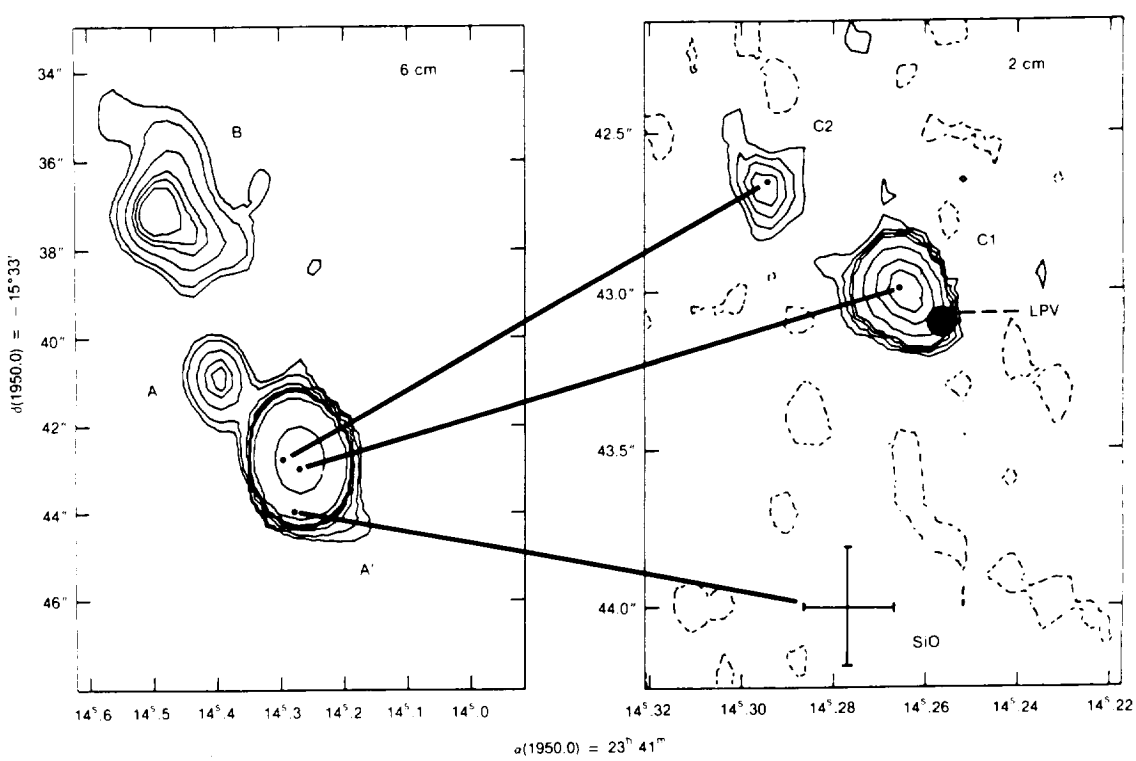


Figure 13-17. The high-resolution radio map of the central region of R Aqr. Left is the 6 cm map showing the "jet-like" features A and B, and, marginally, the counterjet A. Right the central source is resolved into two components—C1 and C2. The astrometric position of the Mira variable (LPV) and of the SiO maser emission is also indicated (from Michalitsianos et al., 1988).

of moderate-excitation emission lines with prominent CIII] and CIV, and weaker OI, CII, SiIV, OIV], and NIII] emissions. The overall far-UV spectrum is remarkably similar to that of Mira itself as described by Reimers and Cassatella (1985). The high-ionization lines of NV and HeII are weakly present. Kafatos et al. (1986) found that the line intensities for the central HII region are rather stable, in spite of the large Mira variations in the visual. On the contrary, the UV emission lines are largely variable in the jet A and B features. The high-ionization lines of NV and HeII were greatly intensified in the jet in 1982 and became even stronger than in the spectrum of the central source. Kafatos et al. (1986) noted that this increase of the ionization could be related to the first detection of X-rays from R Aqr (Viotti et al., 1987). During 1982-1986 the emission line intensities varied in a quasi-periodic way, with minima in 1983 and 1985, and maxima in early 1984 and possibly in late 1986 (Kafatos et al, 1986, and unpublished results). This one-and-half year modulation is larger than the Mira pulsation period, but could be related to it. In fact, if one takes into account the relative motion of the binary system following the recent close approach, the increasing distance between the two stars should cause a delay of the time of arrival of the matter from the Mira wind.

Emission line profiles observed at high resolution can tell us about the dynamical structure of the system. For this reason and to have as much information as possible on R Aqr, Michalitsianos et al. (1988a) recently attempted to obtain high-resolution ultraviolet images of R Aqr and its NE jet. Because of the faintness of the sources, these observations required about half a day of exposure, but the results were quite instructive. Michalitsianos et al. found that the CIV doublet in the nebula appeared broad, possibly double, with a FWHM of about 250 km s^{-1}. The doublet intensity ratio I(1548/I(1550) was close to the optically thin value of 2. In the central R Aqr core, the CIV doublet presented some multicomponent structure with 2 or 3 sharp components separated by about 40 km s^{-1}. In the core, the doublet intensity ratio I(1548)/I(1550) was found equal to about 0.5, i.e., much lower than the optically thick limit of unity. This anomalous *CIV doublet ratio intensity effect* has been observed in other symbiotic stars at least during some phases of their activity, such as in the case of CH Cyg (Marsi and Selvelli, 1987; see Table 11-8). Michalitsianos et al. (1988a) found that in RX Pup, the ratio I(1548)/I(1550) is variable in time, and that it is inversely correlated with the CIV line intensity, as well as with the visual luminosity. In Z And, Cassatella et al. (1988a) noted that the CIV doublet ratio was much smaller than one in February 1986, i.e., during the active phase started in September 1985, while it was slightly larger than one during minimum. An anomalous intensity for the NV resonance doublet was observed in the 1979 spectrum of AG Peg (Figure 11-31c). The "anomalous" doublet ratio intensity cannot be explained by simple considerations on the line opacity. In some cases, it could be the result of intense high-temperature interstellar lines, since in this case, the stronger emission component of the multiplet should also be the more depressed one by the interstellar line. Actually, we have already noted in Section 11.VIII.B that, in some cases, the anomalous intensity ratios of the OI resonance multiplet observed in the UV spectrum of some symbiotic stars has to be attributed to the interstellar line absorption. In R Aqr, the interstellar lines are weak. We cannot exclude that they could be partly responsible for the CIV structure in the core and in the nebula, but this possibility is excluded for the largely anomalous CIV doublet ratio in the core. As Michalitsianos et al. (1988a) discussed, to explain the observed profile complex, radiative transfer effects should be considered, which require a complete analysis under multiscattering conditions. According to spherically symmetric wind models for hot stars computed by Olson (1982) for resonance doublets whose separation is comparable to, or smaller than, the wind velocity, the source function of the longer wavelength doublet component depends on non local values of the shorter wavelength source function. Radiation scattered in our line of sight by the blue compo-

nent can be scattered again by the red line, enhancing emission in the red wing of the 1550 A line.

The presence of a high-velocity wind can be put in evidence by overlapping the two doublet components as shown in Figure 13-18. In the figure, the shaded area represents those points of the line profile, in velocity space, where the monochromatic flux of the 1548 A line is smaller than that of the 1550 A line. Taking into account the wavelength shift between the components, the shaded area corresponds to a velocity range from about -500 to -700 km s^{-1}. This should be the range of the P Cygni absorption of the 1550 A line in order to reduce the emission of the 1548 A line. Similar wind velocities can be derived for the other symbiotic stars showing this anomaly and represent an indirect evidence for the presence of high-velocity winds in symbiotic systems.

V.D. POSSIBLE MODELS FOR R AQR

The large amount of available data on R Aqr in all the spectral range should in principle aid in building detailed models of the system. However, it is difficult to find models which are capable of describing in a consistent way the whole observational information. In addition, some fundamental parameters such as the distance of R Aqr and the interstellar extinction are still uncertain. In the framework of binary models, the Mira should have an unseen companion producing the high-energy photons that ionize the compact central HII region, and the nebula (Michalitsianos, 1984). The hot companion is probably hidden by a disk or by opaque matter in the orbital plane which is seen nearly edge-on (Figure 13-19), and/or by circumstellar dust. Its nature is still uncertain: present infor-

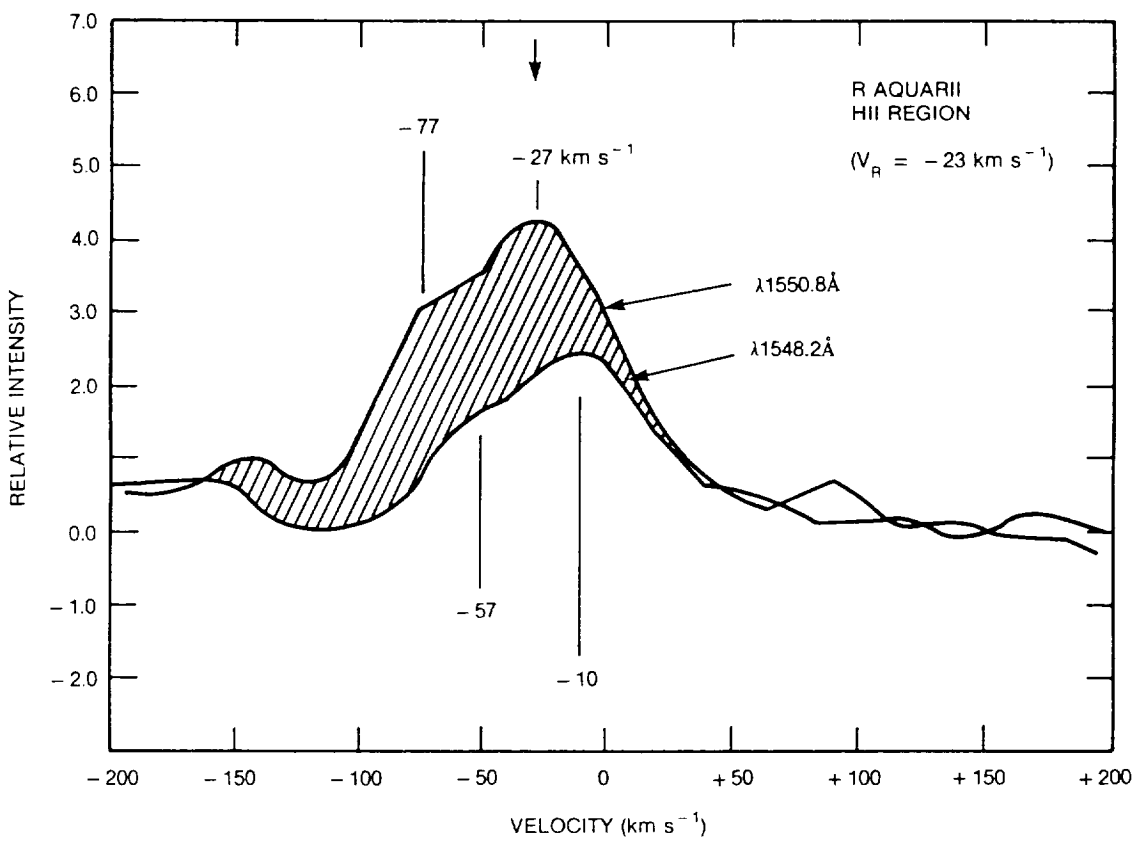


Figure 13-18. Comparison of the profile of the two components of the CIV doublet in the spectrum of the central core of R Aqr. The 1548 A line appears much fainter than the 1550 A line. Probably as the result of absorption by a high-velocity (500-700 km s^{-1}) wind. The shaded area indicates the region in the velocity space over which I(1548) /I(1550)< 1 (Michalitsianos et al., 1988a).

mation is not sufficient to decide whether the high-temperature source is a hot, possibly rejuvenated dwarf or the inner boundaries of an accretion disk. In any case, the disk would be considerably extended in the outer regions, where it should be much cooler and probably cause the temporary obscuration of the Mira discussed by Whitelock et al. (1983 a and b). The radiation from the central source is largely absorbed by the circumstellar matter. Therefore, in order to explain the highly ionized nebula, and the X-rays emerging from it, one has to suppose that the ionizing photons are mostly emitted perpendicularly to the line of sight, from regions that are less occulted (Viotti et al., 1987). Indeed, Kafatos et al. (1986)

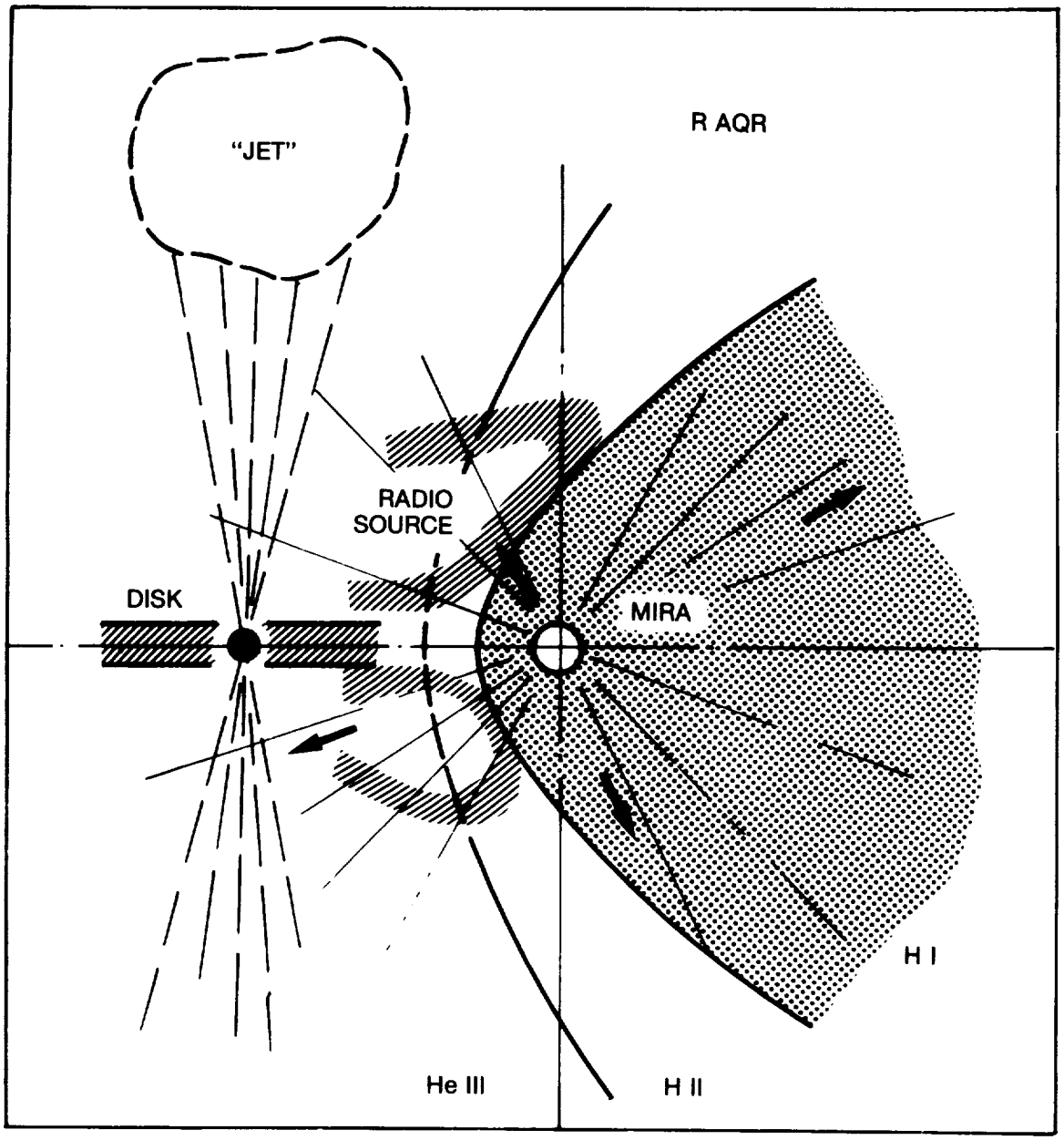


Figure 13-19. A model for R Aqr. The neutral wind from the Mira giant is ionized by the UV radiation from the hot subdwarf and /or the accretion disk, and originates the intense central radio source. The hot source is obscured in the direction of the line of sight (perpendicular to the figure) by the accretion disk or by matter in the equatorial plane. Intense ionizing radiation is emitted from the poles inside a cone, and hits the circumstellar cloud (the 'jets'), producing the high-ionization features (NV, HeII) and X-rays. Alternatively, the jets could be heated by shocks produced by the interaction of the hot source wind with the circumstellar environment.

explained the peculiar radio morphology of R Aqr as a consequence of photoionization of ejected material lying inside an ionizing radiation cone, whose axis is perpendicular to the orbital plane, and having an opening angle of about 150°. The hot source might also generate the high-velocity wind revealed by the anomalous CIV resonance doublet discussed above.

The high-temperature emission from the nebula can be alternatively interpreted as emission from a hot plasma, which can be heated material previously ejected from the central hot star. But, taking the electron density on the jet of 4×10^4 cm^{-3} derived by Kafatos et al. (1986) and an electron temperature of 3×10^5 K, the cooling time should be around 5×10^6 s, much shorter than the supposed time elapsed since the ejection. Such a warm matter, therefore, would cool in a rather short time. A possible heating mechanism could be the interaction of the ejected material with the circumstellar environment, producing shock waves. Viotti et al. (1988) found that, in this case, the emission measure of the HeII emitting region, assumed to have a temperature of 3×10^5 K, would be close to that derived from the X-ray flux assumed to be optically thin thermal emission at the same temperature. The low-electron temperature derived by Kafatos et al. (1986) using the CII] and CIII] line ratios would then be referred to cooler, not shocked parts of the nebula. A shockwave heating (or photoionization by a power law continuum) is also suggested by the [NII]/Hα ratio of 1.2 to 1.8 found by Paresce et al. (1988) in the nebula. But so far, it is not possible to decide which is the dominant heating mechanism of the jets.

The orbital elements of the R Aqr system are unknown. The period might be of several decades, as suggested by the modulation of the light curve (Willson et al., 1981). Such a period seems to be supported by radial velocity measurements (Andarao et al., 1985; Wallerstein, 1986). The separation of the stellar components should be large to account for a large mass transfer from the Mira to the dwarf star, and to feed the hot source. To overcome this problem, Kafatos and Michalitsianos (1982) proposed a high eccentricity of the orbit, in order to allow large mass accretion through Roche lobe overflow at the periastron passage. A geometrically accretion disk formed during this phase would produce at its inner boundary high-temperature photons, and possibly periodic ejection of matter. The intensified radiation field would also cause ejecta from previous outburst to brighten (Kafatos et al., 1986). This might explain the sudden (but apparent) appearance of the A and B jets around 1970, while according to Kafatos et al., the feature C2 (Figure 13-17) would represent the most recent ejection. The disk may also be formed by the capture of the Mira wind, which is enhanced during some periods by the close passage of the binary components in a moderately eccentric ($e \lesssim 0.5$) orbit (Kafatos et al., 1986). Again, such a model better explains the episodic outbursts and ejections observed in R Aqr. To give a better insight into this problem, accurate measurements of the Mira radial velocity over a few decades are needed.

V.E. PLANS FOR FUTURE OBSERVATIONS

R Aqr, for its relatively close distance (180-300 pc). and the many peculiarities represents an ideal target for future observations involving space experiments and high-technology ground telescopes. In particular, of special importance will be the high-resolution imagery at different wavelengths.

Figure 3-20 shows a set of CCD images of R Aqr obtained using the Space Telescope Science Institute coronograph, which occults the bright central star, thus, allowing a detailed study of the nebula very close to R Aqr with a subarcsec spatial resolution. Figure 13-21 shows the derived contour maps in the light of Hα and [NII] 6584 emission lines, where many emission knots are easily detected. Ultraviolet and visual images and polarimetry with subarcsec resolution will be possible with the Faint Object Camera of the Hubble Space Telescope, and should provide information about the location and physical structure of the high-temperature regions, including the X-ray source, and about the presence and nature of circumstellar dust. Concerning this prob-

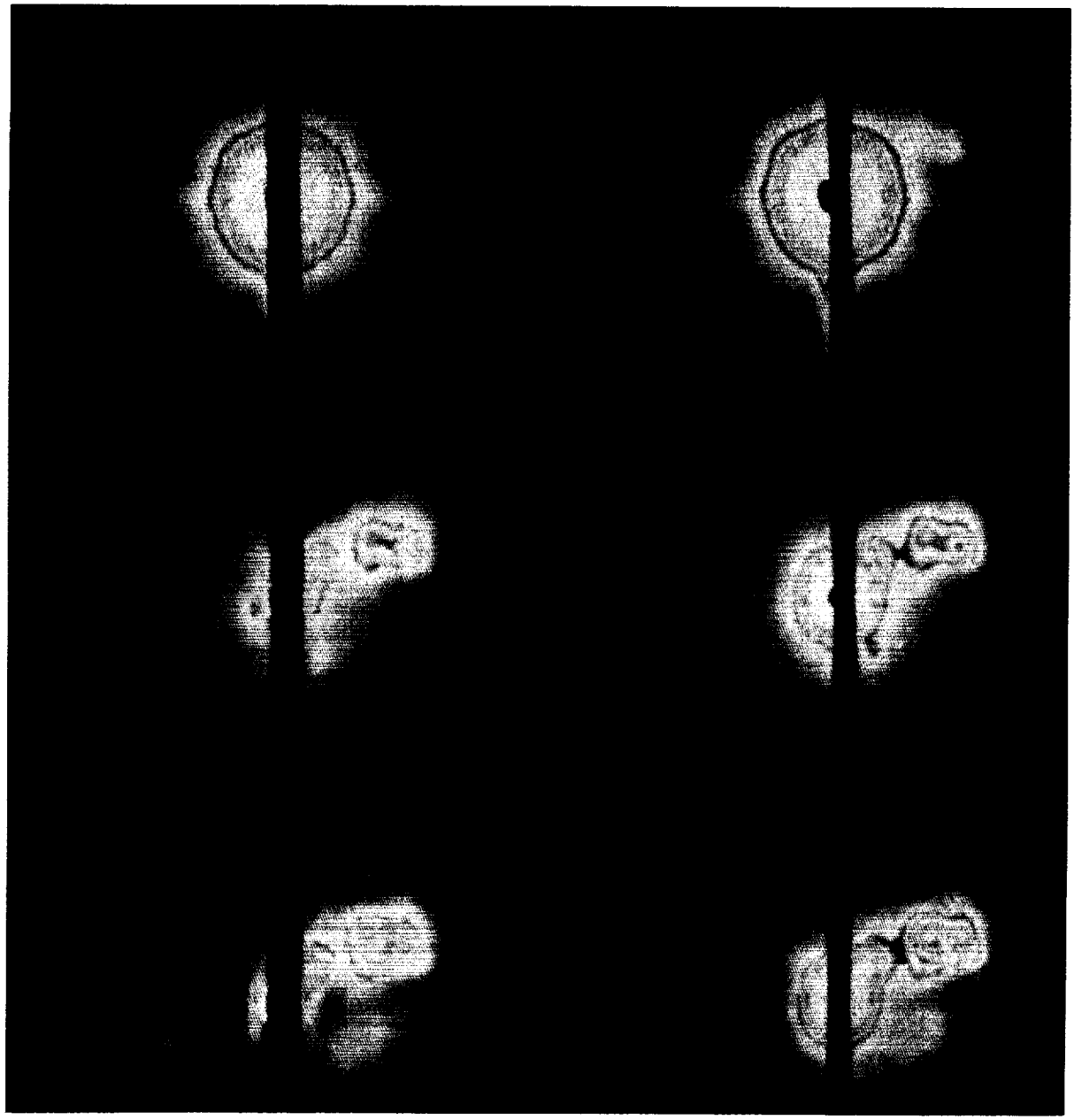


Figure 13-20. CCD images of R Aqr in a broadband R filter (left), and in narrowband filters centered on Hα (center) and [N II] 6584 (right). North is up and East to the left. Top row: original images, bottom row: final images in which the emission line contribution is subtracted from the R filter image, and the glow from the central star is subtracted from the narrowband filters (from Paresce et al., 1988).

lem, we expect very interesting results from the new high-quality infrared arrays. Recent IR imagery of R Aqr at 3.45 μm led to the discovery of an extended spherically symmetric halo that extends to about 15 arcsec from the central star (Schwarz et al., 1987.) Higher resolution IR imagery is needed to determine the spatial distribution of the cool matter and dust. In this regard, R Aqr probably represents a unique target to study the nature and structure of circumstellar dust, and the interaction of the stellar radiation and wind with the circumstellar environment in an evolved object.

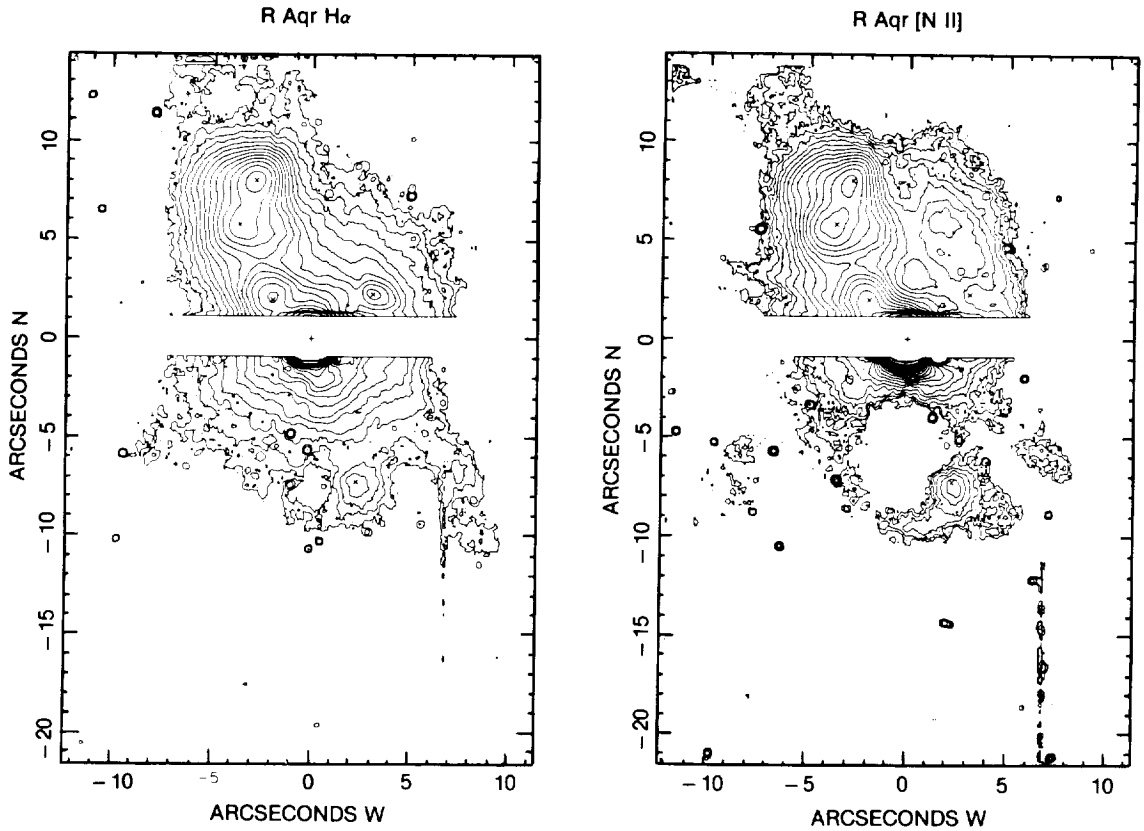


Figure 13-21. Contour maps of R Aqr in the light of Hα (left) and [NII] 6584 (right) as derived from the images in Fig 3-20 (Paresce et al., 1988).

VI. CH CYGNI: ANOTHER SYMBIOTIC VARIABLE WITH A JET

VI.A. INTRODUCTION

CH Cyg is classified as an Mb star in the HD catalogue. It has long been known for its semiregular light variability with a period ranging from 97 to 101 days (Wilson, 1942; Gaposchkin, 1952; Payne-Gaposchkin, 1954) and was classified M6 III. Beside this short-time variability, a long cycle of 4700 days or 12.8 years was found, not very different from that recently derived by using all the radial velocity measurements found in the literature by Yamashita and Maehara (1979) of 5750 ± 250 d and by Hack et al. (1986) of 5,000 ± 450 days. According to C. Payne-Gaposchkin (1954), the median maximum photographic magnitude was 7.97 and the median minimum, 8.44. Joy (1942) measured the radial velocity at different epochs and found an almost constant velocity (from -51 to -59 km/sec) for the M6 absorption lines. No emission lines were present in his spectra. Smak (1964) observed CH Cyg using narrow filter photometry during a period of 82 days. The visual magnitude varies from 7.06 to 6.64, and the color indices indicate that the star was bluer when fainter. This behavior is common to all M-type variables and could be ascribed to the TiO absorption bands, that affect the magnitudes B and V but not U, and are stronger at minimum. The photographic magnitude has been observed to vary between 7.9 and 9.1.

All the existing observations of CH Cyg before 1963 indicate a normal M6 III semiregular variable. In September 1963, Deutsch (1964) observed that CH Cyg "showed a composite spectrum. A hot, blue continuum was superposed over the late-type spectrum, together with emission lines of H (strong and wide), He I (weak and wide), [Fe II] (strong and narrow) and Ca II (also strong and narrow). The spectrum of the recurrent nova T Cr B closely resembled this in June 1945, a few months before the outburst of 1946. No doubt, there is a nova-like variable star in CH Cyg

system,too. However, a spectrogram of March 1961 showed no trace of the hot spectrum, which has faded appreciably since its discovery in September 1963." One high-resolution spectrum taken at the Haute Provence Observatory in August 1965 (Faraggiana and Hack, 1969) shows no evidence of symbiotic characteristics. The only peculiarity was an emission at H alpha and H beta and possibly at H gamma.

A second symbiotic episode started in June 1967 (Deutsch, 1967) and was over by late autumn 1970. A third episode started in 1977 and is almost over at the time of writing this report (July 1988). Luud et al. (1978) detected no trace of H alpha emission in spectra taken on May 1976, but in May 1977, H alpha and H beta showed a double emission peak with V/R>1. In August 1977, the presence of a blue continuum and of several emission lines was evident (Fehrenbach, 1977; Morris, 1977).

Spectra taken in July 1986 show the presence of numerous strong emissions, although the hot continuum has practically disappeared between November 1984 and January 1985. The emissions are fainter in 1987, but they are still easily detectable. In 1988, only Hα and Hβ are strong in emission. The strongest [Fe II] emissions are very faint, while the Fe II permitted emission lines have almost completely disappeared.

This last outburst episode has been observed with the IUE satellite since April 1978 (see Section VI.D.3 on the UV spectrum).

VI.B. THE LIGHT CURVE OF CH CYGNI

The light curve of CH Cyg from 1899 to 1975 has been described by Gusev (1976) and is illustrated in Figure 13-22. Until 1960, only small amplitude variations are present. The following period is described by Hopp and Witzigmann (1981), by Duschl (1983), Panov et al. (1985), and Mikolajewski and Tomov (1986). After the 1963 outburst, the oscillations became more evident and regular with a mean period of 700-800 days during 1967 to 1977. During the third outburst, the semiregular variations were no more detectable; the star reached V = 6.4 at the beginning of the outburst, and after three years at almost constant magnitude, reached V = 5.6 at the end of 1981 and remained close to this value until mid-1984. A sudden luminosity drop of about one magnitude occurred between July and August 1984 and was accompanied by strong spectral variation (for instance, weakening of the blue continuum, see Section VI.D.1)

The variation of the B-V and U-B colors from 1967 to 1985 are described by Hopp and Witzigmann; by Panov et al. and by Mikolajewski and Tomov.

In the period of quiescence 1970-1976, B-V is generally bluer at minimum as it was observed by Smak. In general, U-B is in phase with B-V with stronger fluctuations. Both indices become smaller (star bluer) at the beginning of the third outburst. During the outburst, B-V fluctuated between 0.4 and 0.6 and increased from 0.49 to 0.82 from Aug. 10, 1984, to September 30, 1984. U-B varies from 0.6 in mid-1976 to about -0.4 during the outburst, with oscillations between -0.3 and -0.7. After July 1984, U-B gradually increased. On November 24, 1984, it was equal to -0.29, and in May 1985, to about 0.0. (see Figure 13-22, light curve and color variation).

In addition to these long-period variations, which are typical of semiregular late-type variables, short-time scale (minutes), small amplitude variability has been observed during the periods of activity and will be described in the following sections.

VI.C. THE 1967 OUTBURST

The outburst of 1967-70 was followed both photometrically and spectroscopically by several observers.

A detailed description of the spectral variations from July 1967 to December 1970, covering the whole duration of the second observed outburst, has been given by Faraggiana and Hack (1971). Photometric observations during the same period have been made by several authors,

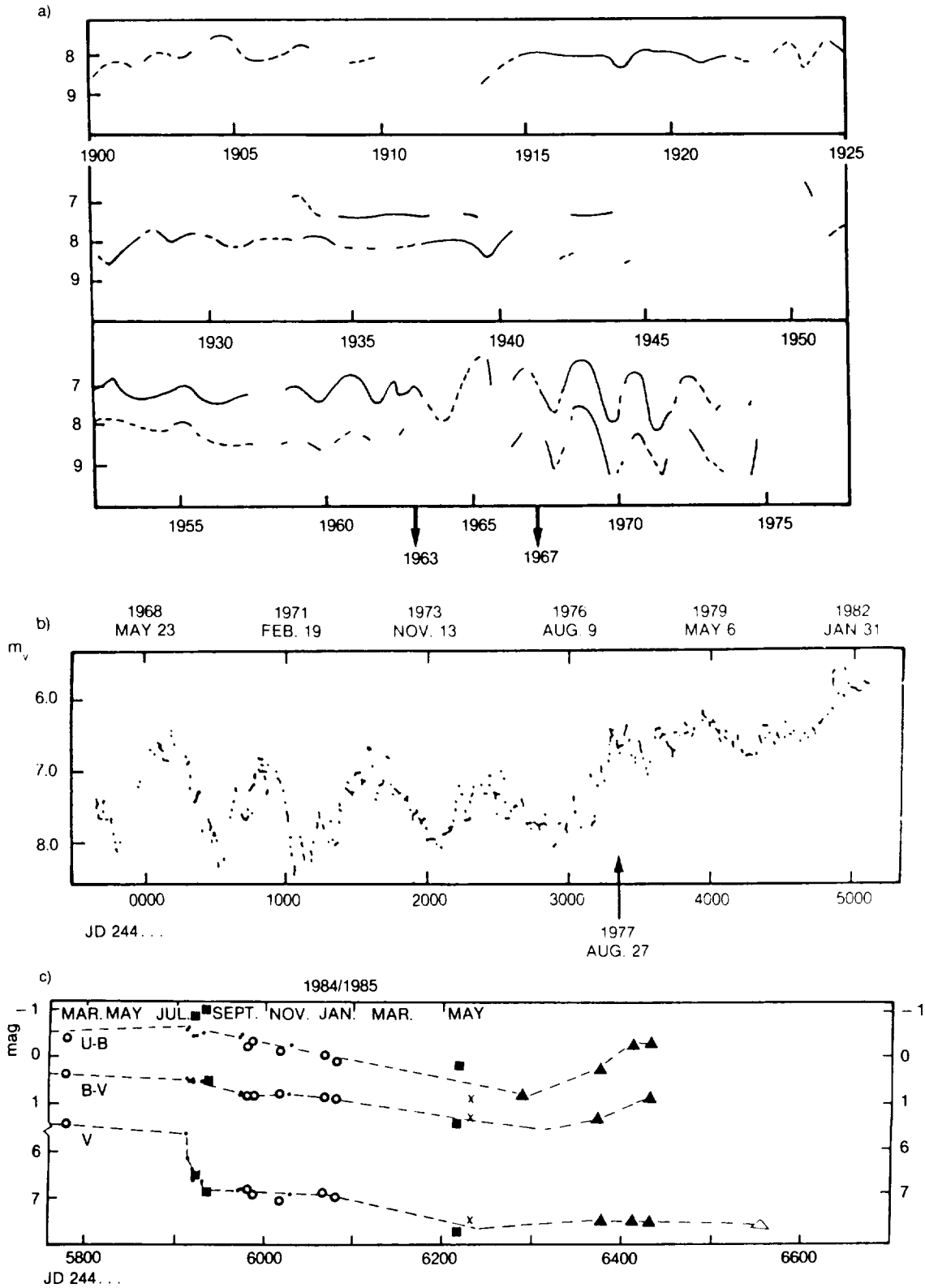
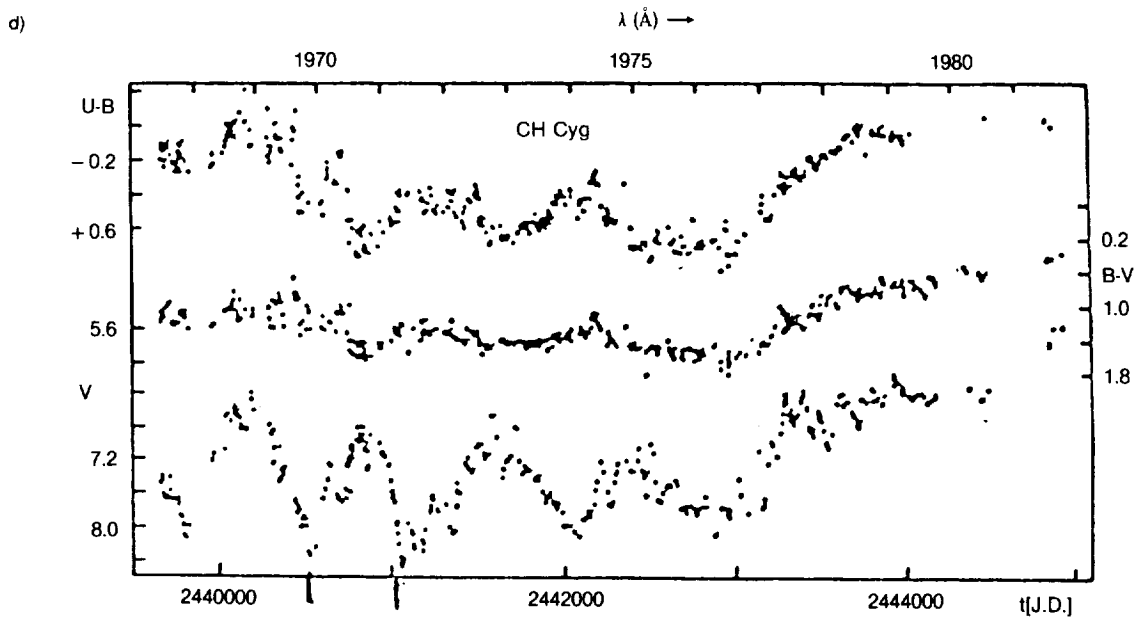


Figure 13-22. a) The visual light curve of CH Cyg from 1900 to 1975. The arrows indicate the epoch of starting of the two outbursts of 1963 and 1967. b) Visual light curve from 1968 to 1981. The arrow indicates the starting of the outburst of 1977. c) Visual light curve and B-V, U-B variation in 1984-1985. d) light curve and U-B variation from 1967 to 1982 (from Gusev, 1976; Duschl, 1983; Mikolajewski and Tomov, 1986; Mikolajewski, 1985; Panov et al., 1985; Mikolajewski and Wikierski, 1986; Hopp and Witzigmann, 1981).



The rapid variations (flickering) were first noted by Cester (1968) and by Wallerstein (1968). The amplitude was of the order of 0.1 mag on a few minutes time scale. Cester (1969) found that the variations were strongly correlated in different colors, and the color indices were quite different from those typical of an M6 III star: B-V oscillates between +1.3 and +1.0, and U-B, between –0.05 and -0.6. As a rule, the amplitude of the flickering is larger at shorter wavelengths. For instance, Shao and Liller (1971) reported variations of 32% at 3,200 A and of only 2% at 7,000 A. Figure 13.23 shows the flickering observed in U by Luud et al. (1970) on November 5, 1968. Walker et al. (1969) made photoelectric spectral scans from 3300 to 5000 A during August 1967. Figure 13.23 shows the excess continuum radiation relative to the standard M6 IIIab spectrum of 45 Ari for several scans made during the night of August 3, 1967. Variations on time scale of a few minutes are evident.

The main characteristics of the spectrum and its variations during the second outburst can be summarized as follows (Faraggiana and Hack, 1971):

a) The M6 spectrum is veiled by a continuum that partially fills the absorption lines and increases in intensity toward the violet. This continuum was absent in August 1965 and in September 1970; it appeared in June 1967 (Deutsch, 1967) and reached a maximum in August 1968. The color temperature of the blue continuum was about 10,000 K. No measurable Balmer discontinuity was observable.

b) Emission lines of He I, Fe II, [FeII] and [SII] are present. The Balmer lines and the H and K lines of Ca II present a P Cygni profile. In July and August, H and K presented two sharp absorption cores at radial velocity of about -75 and -160 km/s, while the radial velocity of the photospheric lines (TiO bands and nonresonance lines of neutral metallic atoms) ranges between -50 and -60. In July 1968, the nebular line 5007 [OIII] appeared; 4959 and 4363 [OIII] were not visible. The emissions reached maximum intensity in August 1968 and again in August 1969. In 1965 and 1966 and in September-December 1970, the spectrum was a normal M6 III type, except that H alpha and H beta presented emission components.

c) Low-excitation absorption lines of metallic ions appeared in the ultraviolet continuum in July 1968. In May 1970, several lines of neutral elements appeared. At this epoch, the ultraviolet lines of low excitation ions and the strong resonance lines give radial velocities more negative than the other lines having the same low level by about 20 km/s and are not filled in by the blue continuum. This may suggest that they were formed in the blue continuum like a kind

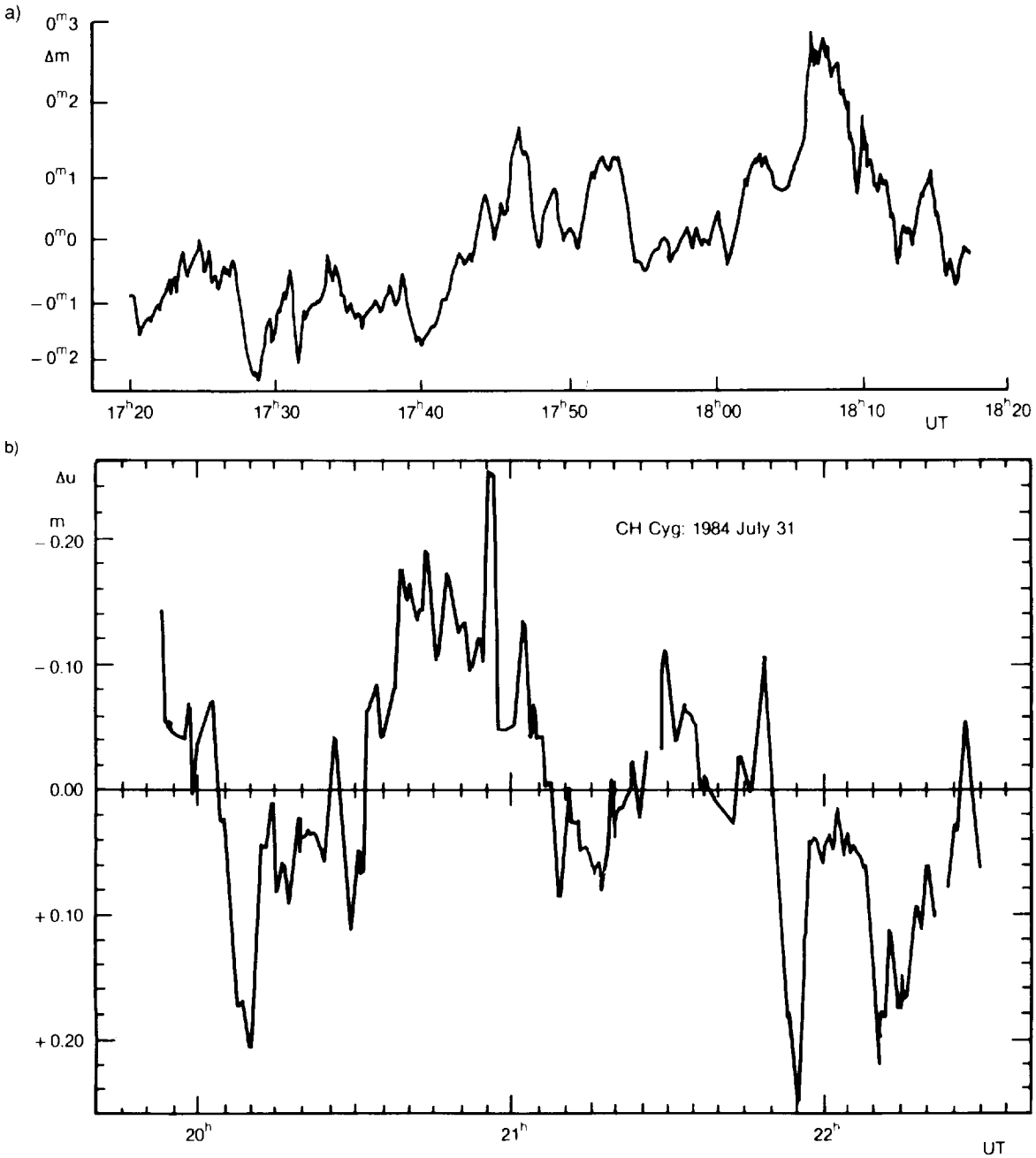


Figure 13-23. a) Observations of U flickering on November 5, 1968 (from Luud et al., 1970), b) and on July 31, 1984 (from Panov et al., 1985.

of shell absorption. Significant spectral variations have been observed over a few days. For instance, the Balmer lines were in emission on May 13, 1970, and in absorption on May 16, 1970.

The ratio [FeII]/Fe II is constant during the whole outburst, indicating no change in density, while the line intensity was variable.

VI.D. THE OUTBURST STARTED IN 1977

The last outburst began in 1977 and was followed by several observers in a wide spectral range from UV and X-rays to optical, infrared, and radio.

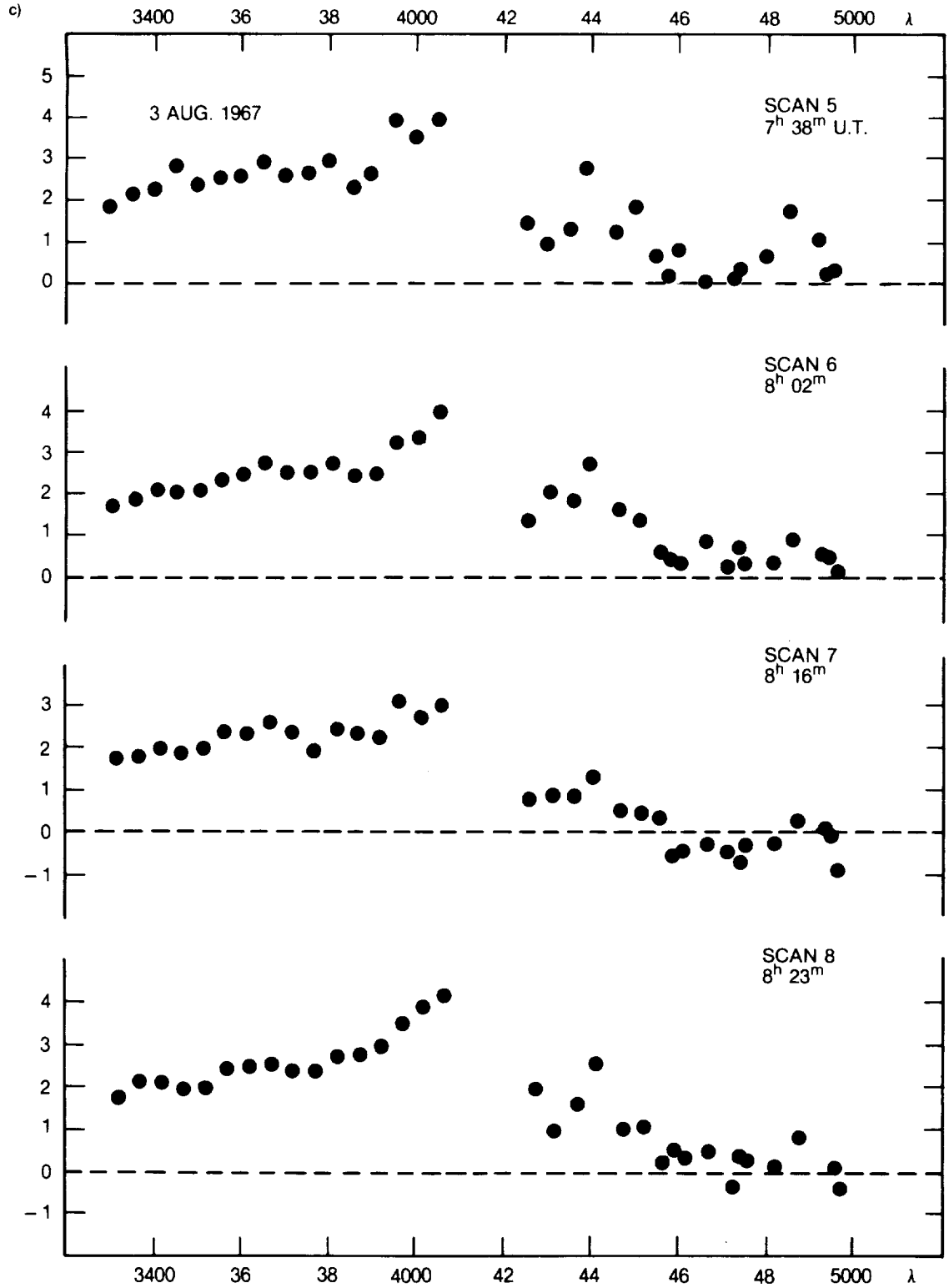


Figure 13-23. c) Excess continuum radiation in the spectrum of CH Cyg relative to the standard M6IIIab spectrum of 45 Ari, for twelve scans taken on the night of August 3, 1967. Ordinate is in flux units with an arbitrary scale factor applied (from Walker et al., 1969).

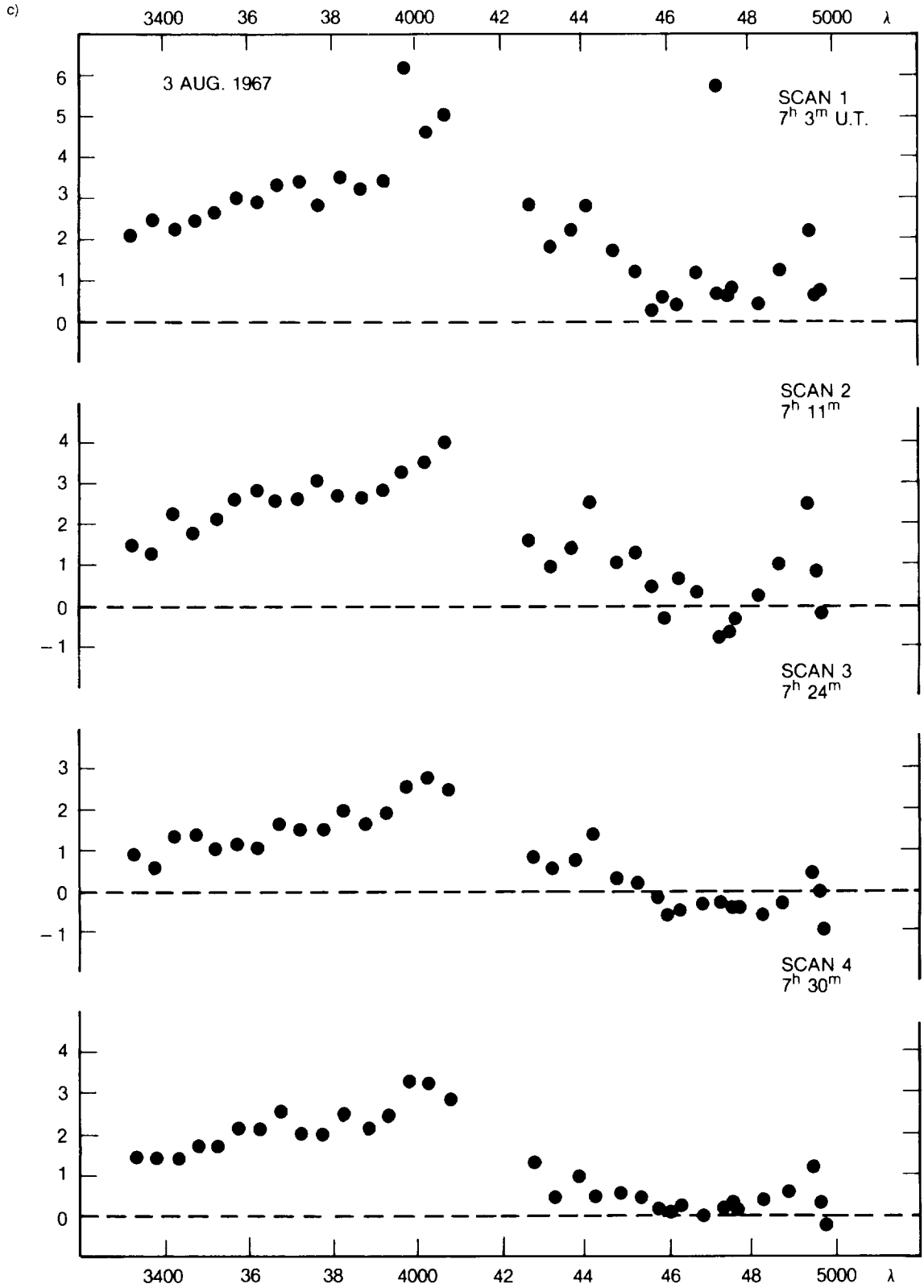


Figure 13-23. c) continued.

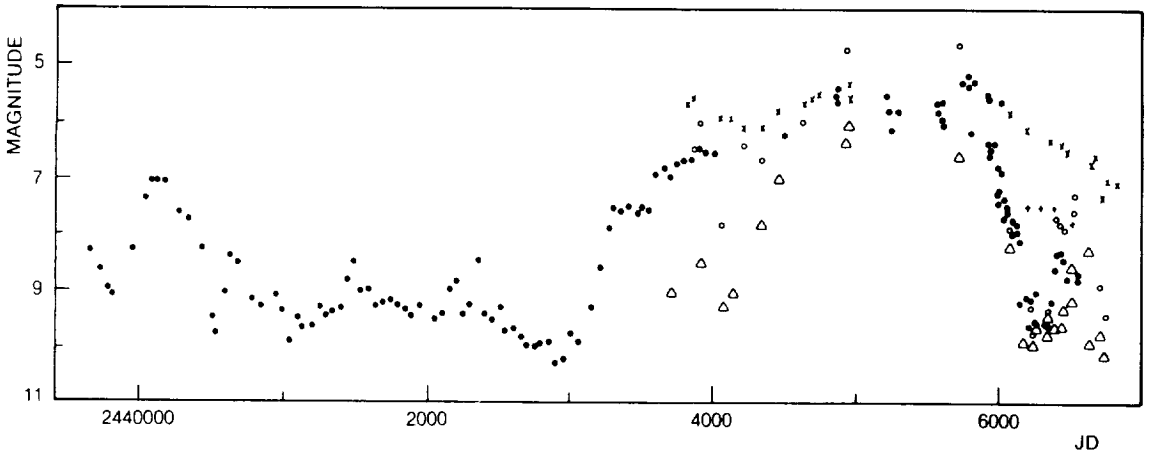


Figure 13-24. Ultraviolet light curve of CH Cyg showing the two minima in 1969 and 1985. (●) U magnitude, + V magnitude measured from the ground (x) V magnitude measured with the Faint Error Sensor, (FES) aboard IUE, (o) m (3000 A) derived from the IUE fluxes: m(3000) = -2.5 log F(3000) -22; (Δ) m(1440) = -2.5 log F(1440) -22. The constant 22 has been arbitrarily chosen.

The International Ultraviolet Explorer (IUE) has given us the opportunity of follow the outburst in the ultraviolet since April 1978.

VI.D.1. PHOTOMETRIC OBSERVATIONS

As we have observed in Section VI.B, the semiregular light variations with a period of 700-800 days disappeared during the third outburst when V gradually rose to 6.4 at the beginning of the outburst, then rose to 5.6 and remained at this value until July 1984, when its brightness dropped by about one magnitude (Mikolajewski and Tomov, 1986). One year later, V was equal to 7.8.

The U magnitude and the ultraviolet flux measured with IUE displayed a different behavior (Mikolajewski et al., 1987; Mikolajewski et al., 1988), i.e., a minimum lasting about 150 days (May - Oct. 1985). A broad minimum, especially in the U band (Cester, 1972; Luud et al., 1977), was observed in 1969. The possibility has been suggested that these two minima—separated by about 5700 days—were two consecutive eclipses of the hot companion of a binary system (Mikolajewski et al., 1987) (Figure 13-24).

Although the evidence of orbital motion given by radial velocities measured from 1942 to 1986 is weak because of the large scatter due to the irregular radial velocity variations, which are typically observed in late-type giants and supergiants, these measurements suggest a period of 13 to 15.5 years (Yamashita and Maehara, 1979; Hack et al., 1986). Our last observations, added to all those existing since 1961, suggest P = 14.4 years or 5250 days, not very far from the value suggested above. (see Figure 13-27, radial velocity curve). High-speed photometry confirmed the presence of flickering during the present phase. Slovak and Africano (1978) observed an amplitude of about 0.10 mag in the ultraviolet and violet light (u and v filters) and of only 0.03 mag in y filter. Actually, two features characterize the light curve: rapid flickering on time scale of 5 min and amplitude 0.02-0.04 mag and slow, large amplitude flares (0.10 mag) lasting 15-20 minutes. Panov et al. (1985) give a summary of the flickering amplitudes observed during this outburst (Table 13-4). The data obtained by Cester (1969) during the outburst of 1967 are given for comparison.

After the drop in brightness of July 1984, a drastic change in the spectrum was observed at the end of 1984, with the almost complete disappearance of the hot continuum (see next section), while a large rise of the radio flux was observed between April 1984 and May 1985 (Taylor and Seaquist, 1985; Taylor et al., 1986).

A fresh outbreak of activity (the end of the eclipse?) is indicated by the photometric observa-

TABLE 13-4. FLICKERING AMPLITUDES OF CH CYGNI FROM 1977 TO 1984 (FROM PANOV ET AL., 1985) AND IN 1968 (CESTER 1969).

Observers	δu	δB	δV
Slovak and Africano (1978)	0.10		0.03
Ichimura et al. (1979)	0.18	0.13	0.10
Luud et al. (1982)	0.20		
Spiesman (1984)	0.23	0.21	0.15
Reshetnikov and Khudyakova (1984)	0.20	0.20	0.20
Panov et al. (July 31, 1984)	0.6		
Panov et al. (Nov. 24, 1984)	0.24	0.17	0.12
Cester, 1969 (July 13, 1968 UT 23h 15)	0.24	0.24	
Cester, 1969 (Aug. 20, 1968 21h 45)	0.24	0.12	
Cester, 1969 (Aug. 24, 1968 22h 28)	0.44	0.24	
Cester, 1969 (Aug. 25, 1968 23h 05)	0.24	0.12	
Cester, 1969 (Aug. 25, 1968 24h 00)	0.36	0.24	

tions of Panov et al. (1985): On August 17, 1985, U = 7.38, U-B = 0.97, i.e., the color normally observed for CH Cyg in quiescence (Smak, 1964), as well as for several late-type semiregular variables. On December 9, 1985, U = 7.31, U-B = -0.021. As we shall also see in the following, the spectral changes confirm a slight strenghtening of the blue continuum, which was very weak in January 1985.

VI.D.2. SPECTROSCOPIC OBSERVATIONS

High-resolution spectroscopic observations of CH Cygni during the period 1977-1986 were made by several groups (Hack et al., 1982; 1986; 1988; Mikolajewski and Biernikowicz, 1986; Mikolajewski et al., 1987; Tomov and Luud 1984; Wallerstein, 1981; 1983; Wallerstein et al., 1986; Yoo and Yamashita, 1984). A general description of the visual spectrum and its variations was given by Hack et al. (1986, 1988). The spectrum, from the beginning of the outburst, in May 1977 to November 1984 is characterized by a continuum, that is stronger at shorter wavelengths but is also present in the red part of the spectrum, and partially or almost completely veils the M6 absorption features. The strength of this continuum is evident when comparing the regions of the TiO band heads or that of the broad absorption of Ca I at 4227 A observed during the outburst with those observed in 1970, after the end of the second outburst, or in 1988, when the outburst was almost over (Figure 13-25).

The prelude to the end of the outburst was observed from December 1984 to January 1985, when the visual spectrum became again that typical for an M6 III star, after the disappearance of the blue continuum. The emission lines, however, were still present and prominent; moreover, beside the emission lines of H I, Fe II, [Fe II], [O I], He I, [SII], emissions of [O III] and [Ne III] appeared in November 1984 and rapidly increased in intensity. The complex vari-

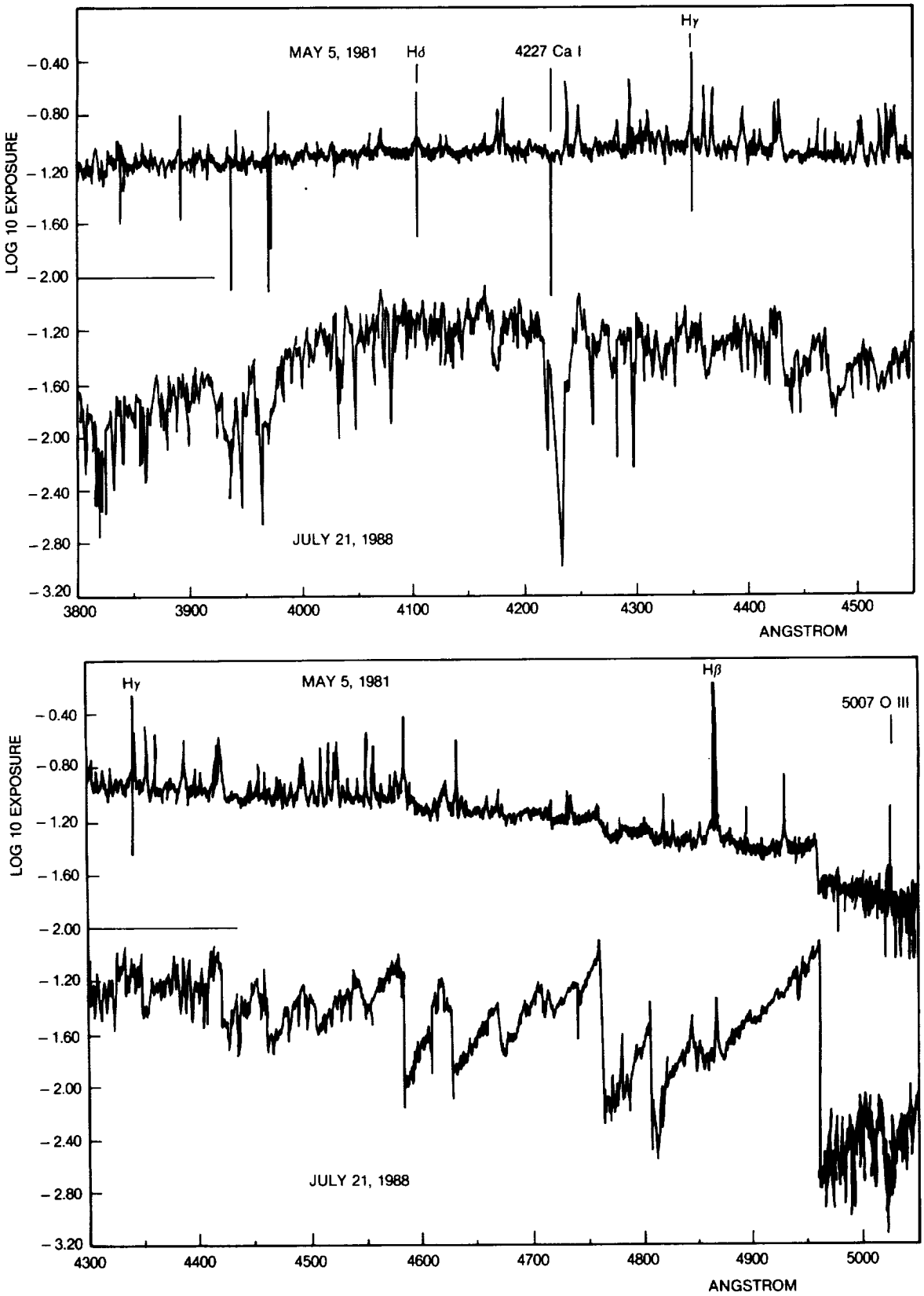


Figure 13-25. Intensity tracings of two spectra obtained on May 5, 1981 during the outburst and in July 21,1988, when the outburst is almost finished (Spectra obtained at the Haute Provence Observatory).

ability of the line intensities, line profiles, and radial velocities is described by Hack et al. (1986, 1988). Figures 11-8, and 13-26 give some examples of line variability.

It should be noted that the M6III photospheric lines and the forbidden and permitted Fe II emission lines have radial velocities that are 180° out of phase, suggesting that the Fe II emissions are associated with the companion (Figure 13-27). The relative amplitudes of the two curves suggests a mass ratio of the two components close to 1. Also, the absorption cores of the inverse P Cygni profiles of the metallic ions give radial velocities 180° out of phase with the primary photospheric lines (Figure 13-28). Mikolajewski et al. (1987), by the metallic ion absorption lines, derive $3 < m1/m2 < 4$. However, the radial velocities of the inverse P Cygni absorptions are affected by the presence of the emission wings, which partly mask the absorption cores affecting their measured shifts.

The most characteristic features that distinguish the second and third outburst are the following:

1) A similar behavior of the blue continuum, however, it was bluer in 1977-84.

2) At certain epochs during the outburst, several metallic ions and Balmer lines showed direct P Cygni profiles in 1967-70 and inverse P Cygni profiles in 1977-84.

3) The Ca II H and K lines, on the contrary, displayed the same behavior during the two outburst showing one or two, occasionally three, violet-shifted absorption components and always direct P Cyg profiles, which clearly indicate the existence of one or several expanding envelopes. The highest observed expansion velocity is -100 km/s.

4) In both outbursts, emission lines of fairly high excitation were observed, i.e., He I during the whole outburst and [O III] at some phases. [Ne III] 3868,74 was observed only during the latter outburst.

5) The ratio between Fe II and [FeII] remained

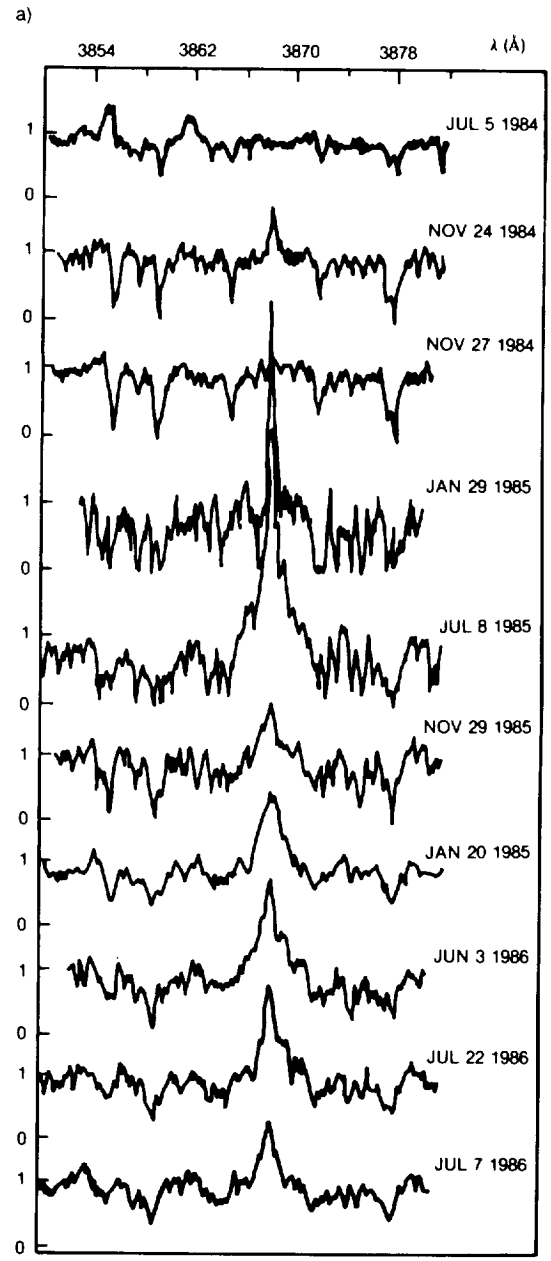
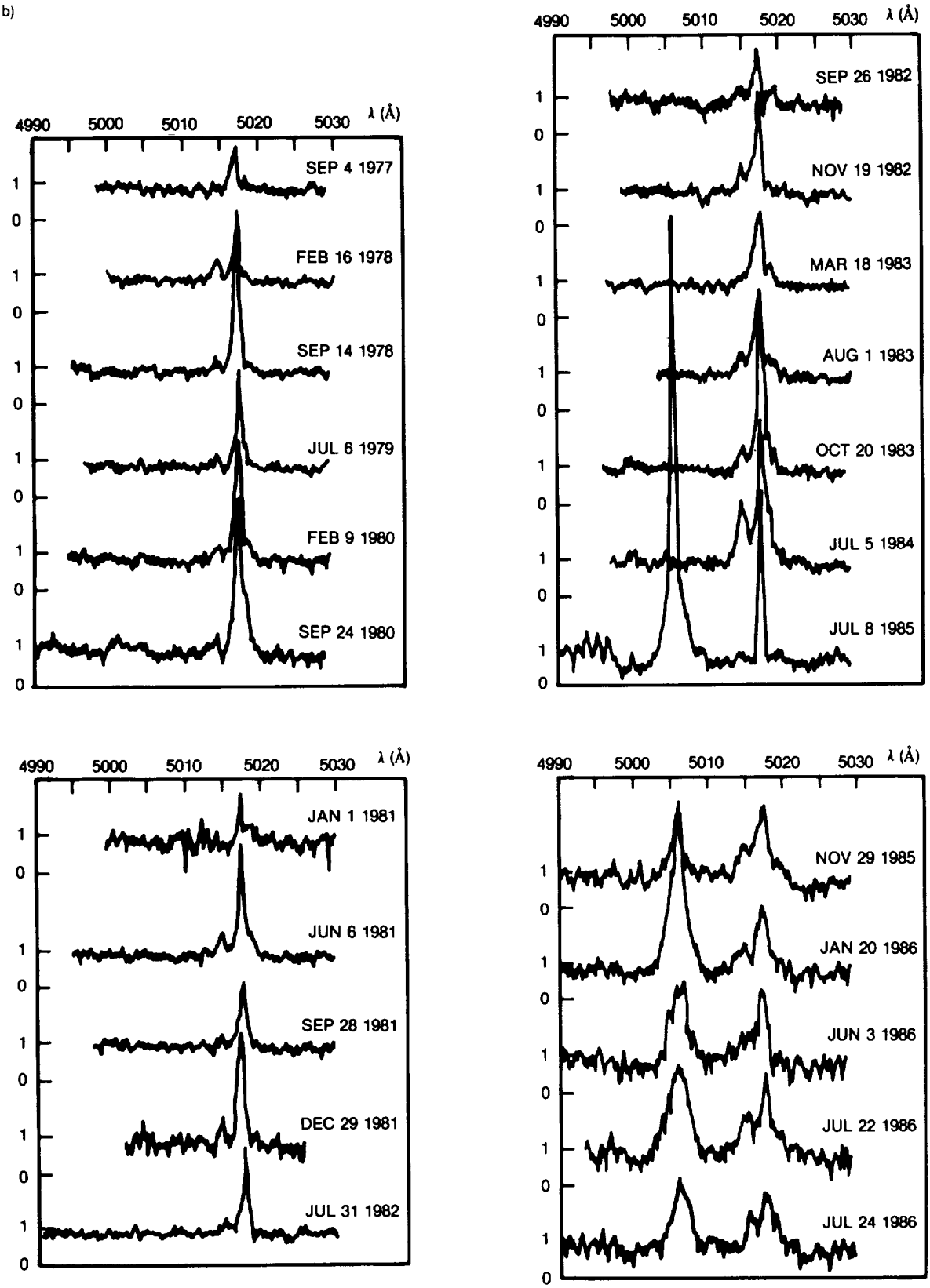


Figure 13-26. a) The region of 3868 [Ne III] from July 5, 1984, to July 7, 1986. b) The region of 5006.84 [O III], 5015.675 He I and 5018.434 Fe II (Spectra obtained at the Haute Provence Observatory).

constant during the 1967-70 outburst, while during the 1977 outburst, it was variable with a significant decrease at the end of the outburst. These ratios indicate that the density in the region where the permitted and forbidden lines of Fe II are formed was lower in 1967-70 than during the latter outburst. The presence of the lines of [O I] at 6300, 6363 A indicate a density of about 10^6 cm^{-3}, while [FeII] indicates 10^8 -10^9 cm^{-3}.

b)


4990
5000
5010
5020
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λ (Å)
SEP 4 1977
FEB 16 1978
SEP 14 1978
JUL 6 1979
FEB 9 1980
SEP 24 1980
SEP 26 1982
NOV 19 1982
MAR 18 1983
AUG 1 1983
OCT 20 1983
JUL 5 1984
JUL 8 1985
JAN 1 1981
JUN 6 1981
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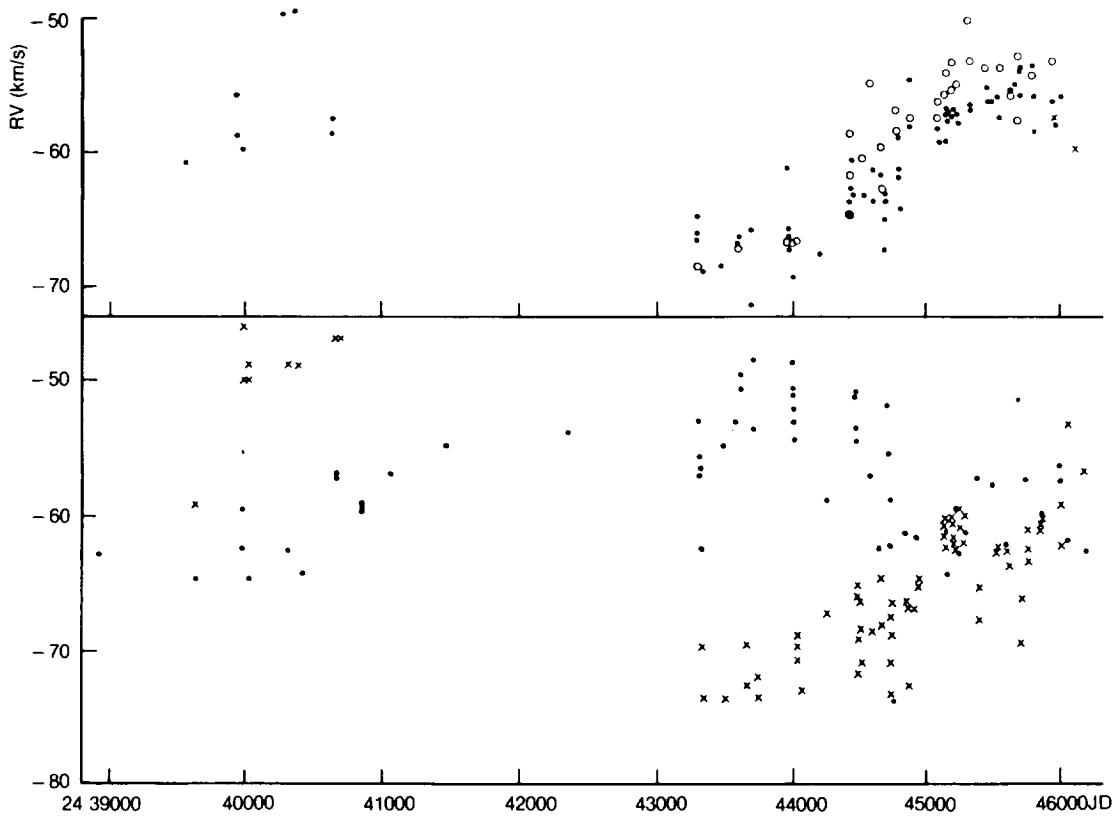


Figure 13-27. Bottom: radial velocities of the M6 III photospheric lines (●) and of Fe II permitted emission lines (x) vs. J.D. Top: Radial velocities of the forbidden lines of Fe II (●), O I (o) and O III (x), from Hack et al., 1986).

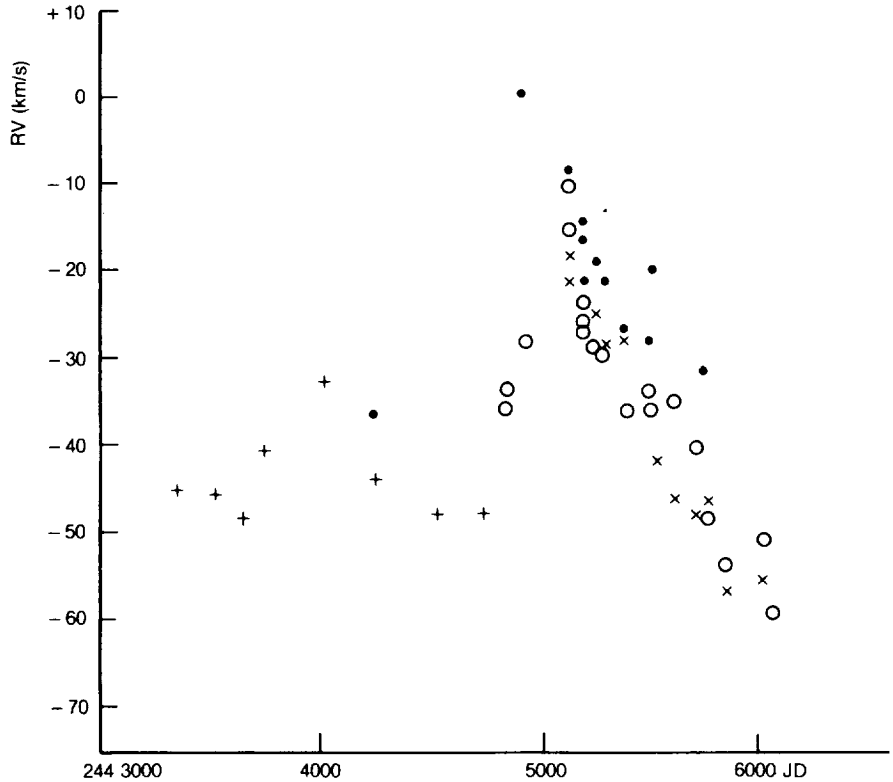


Figure 13-28. Radial velocities of the absorption cores of Fe II (o), Ti II (●), Mg I (x) and mean of Ti II, V II, Cr II, Mn II (+) (from Hack et al., 1986).

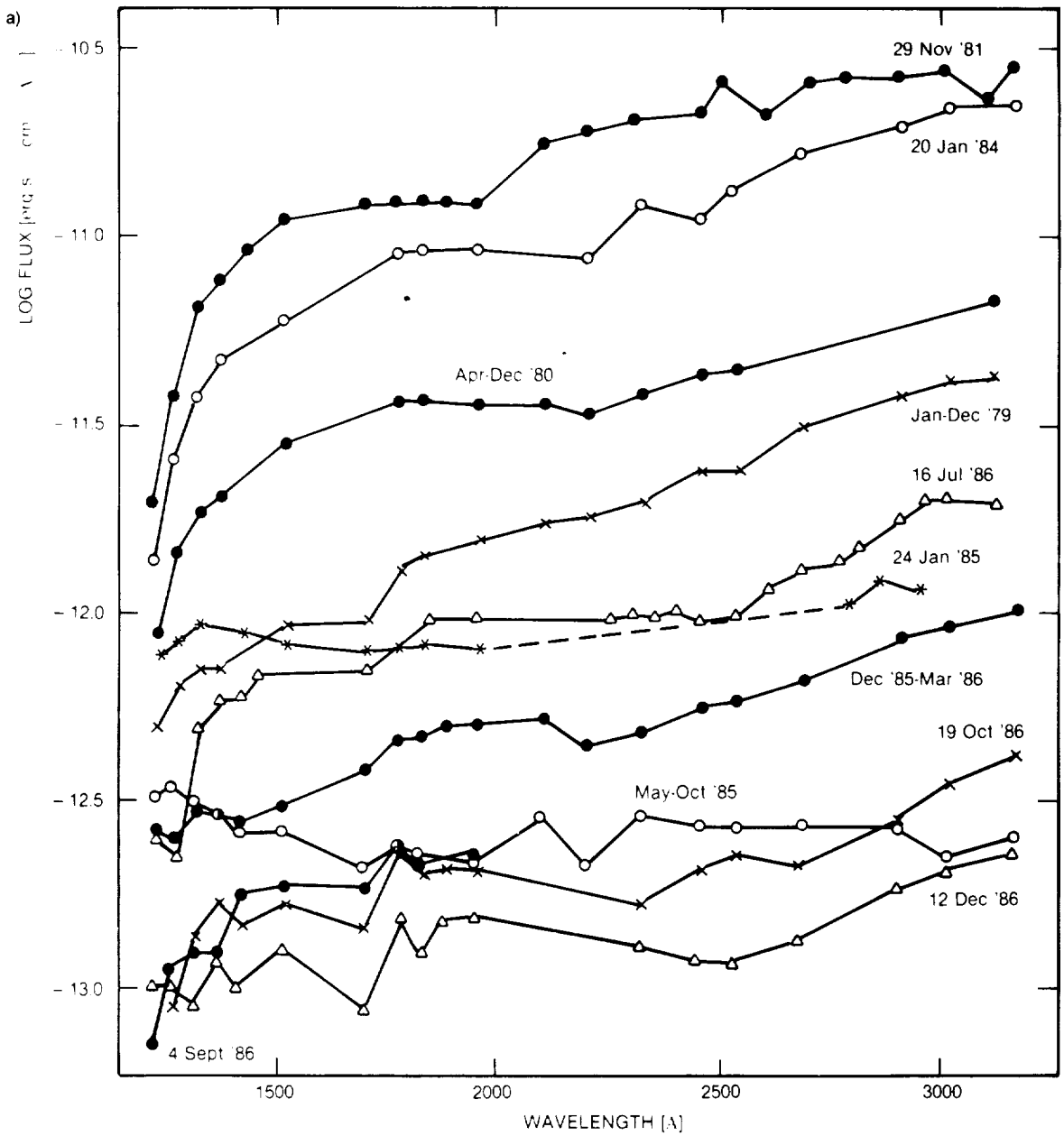
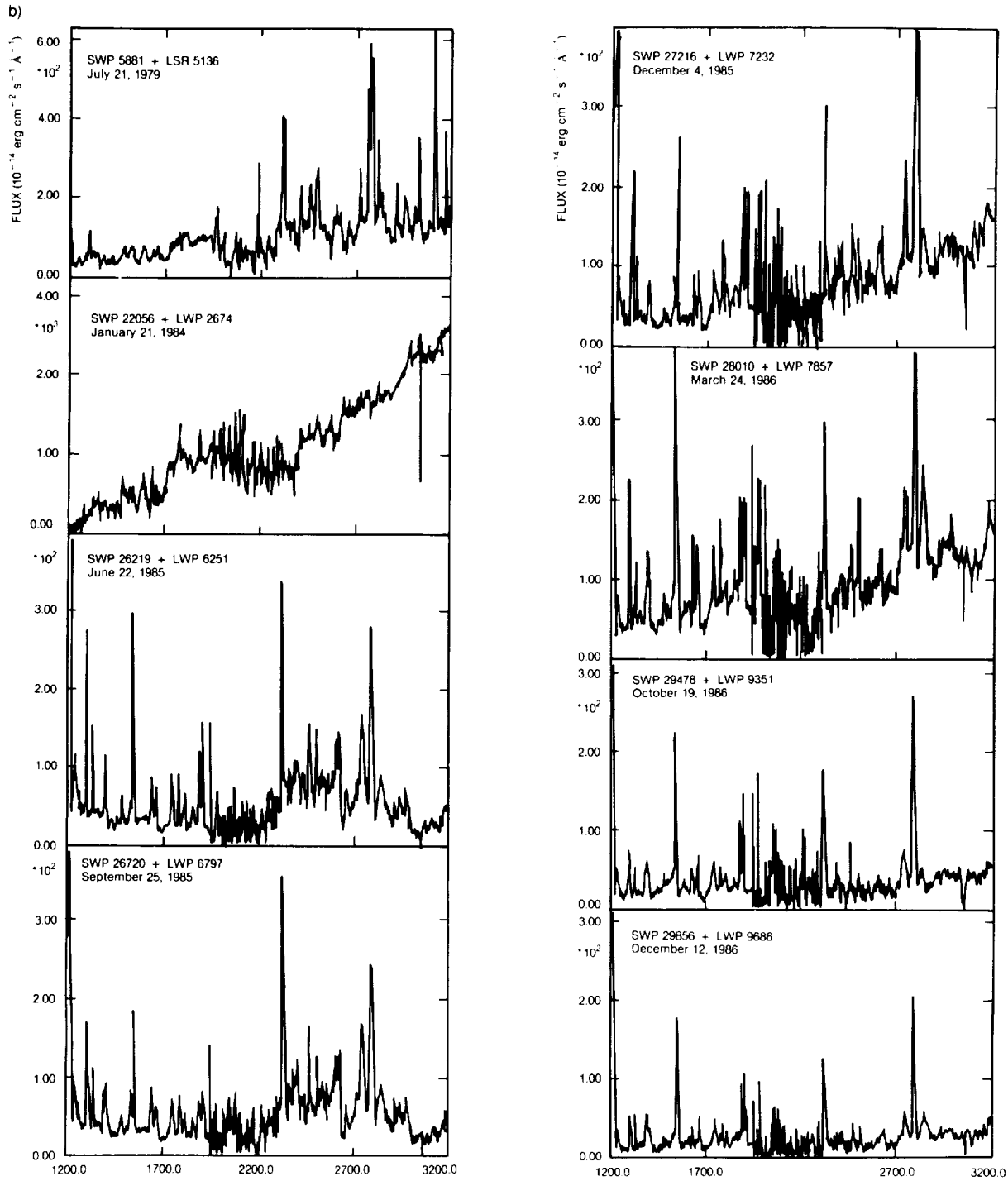


Figure 13-29. a) Continuum energy distribution in CH Cyg; b) Combined UV low-resolution spectra (1200-3200 A) of CH Cyg; c) Far UV low-resolution specta of CH Cyg. (from Mikolajewska et al., 1988).

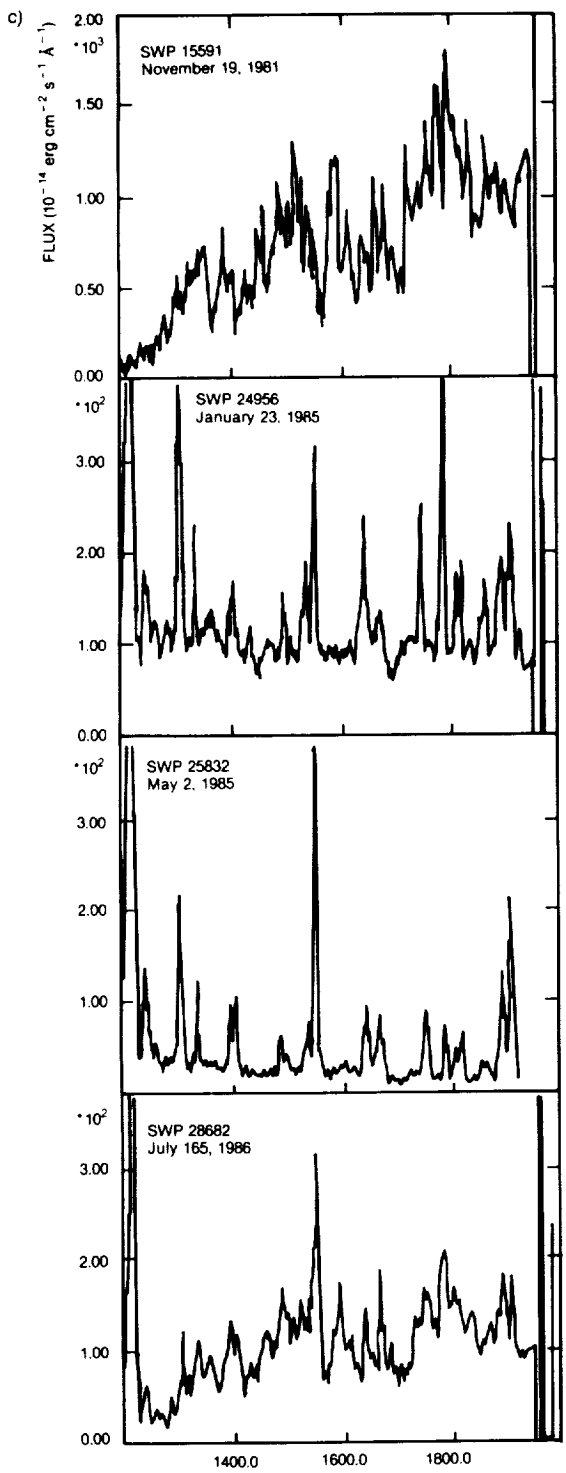
VI.D.3. THE ULTRAVIOLET SPECTRUM

The ultraviolet spectrum was also observed during the whole outburst with IUE in the low-resolution mode (6 A) and, when possible, also in the high-resolution mode (0.2A). The variation of the UV continuous flux from 1200 to 3200 A during the period 1978 to 1986 was studied by Mikolajewska et al. (1987, 1988). Figure 13-29 shows the ultraviolet energy distribution and its strong variation with time. Not only the flux varies but also the shape of the continuum, which becomes completely flat in January 1985, remains flat to October 1985 and starts increasing toward the longer wavelengths in December 1985. A drop in the flux intensity by a factor of three was observed between January 24, 1985, and May 27, 1985. Unfortunately, no other IUE observations were made during the rest of 1984. Hence, we cannot decide whether the drop observed in visual light in August 1984



was also present in the UV. In December 1985, the far ultraviolet flux started to rise again (in concomitance with the increase of the continuum observed in the visual) and reached a secondary maximum in July 1986, while in Septemper 1986 it declined back to the level of October 1985 (see also Figure 13-24). In 1988, the flux in the far UV had decreased considerably (to about 20 times weaker than in 1986), but it is interesting to note that at λ 1300 A, there is evidence of a slight increase of the flux toward the shorter wavelengths, suggesting that we are now observing the Rayleigh-Jeans tail of a hot-body radiation, a tail whose presence had been previously excluded on the basis of observations obtained until 1986-1987.

The ultraviolet line spectrum and its variations



during the outburst are described by Hack (1979), Hack et al. (1982), Hack and Selvelli (1982), Boehm et al. (1984), Persic et al. (1984) and by Selvelli and Hack (1985a,b). High-resolution spectra were obtained for the first time on March 1979 in the near UV (2000-3200 Å) and on September 1980 in the far UV (1200-2000 Å). The spectrum was characterized by the presence of both emission and absorption lines. We observed the emission lines of O I 1304 and O I] 1641, C III] 1909. 73, Si III] 1892, the multiplet 191 of Fe II at 1785, while all the other Fe II lines in the far UV were in absorption. Other absorption lines present in the spectrum of September 1980 were C IV, Si IV, Al II resonance lines, and a large number of ground level lines of Ni II. The strong Fe III lines from excited levels were not present. The Mg II resonance doublet presented a P Cygni profile with two absorption components, one at almost the rest velocity, probably of interstellar origin, and another shortward-shifted by about -110 km/s.

Hack and Selvelli (1982) discuss the excitation mechanisms for the O I and Fe II lines, which present some intriguing problems. For instance, the semiforbidden line 1641 O I] has about the same intensity as the strongest of the three permitted O I lines at 1302-1306 A, and the observed intensity ratio within the triplet 1302, 1304, and 1306 in September 1980 was 1:9.4:6.5 instead of the theoretical one of 5:3:1. The large optical thickness indicated by the strength of the permitted multiplet means that the 1304 photons will scatter many times before escaping from the region of neutral oxygen. Substantial reabsorption will occur mostly from the 0.00 eV level, and, therefore, the 1302 line will be weaker than the two other lines. There is a small but finite chance that at each coherent resonance scattering, decay from the upper term 3s $^3S^o$ will occur through the 1641 line, which shares the upper term with the 1304 multiplet. Hence, the great optical depth of the 1304 multiplet has the effect of converting the resonantly trapped photons into 1641 photons, which will escape easily. This phenomenon is observed in several emission line stars, like Z And, V 1016 Cyg, RR Tel, HD 45667: all present an anomalous intensity ratio in the 1304 triplet and the strong 1641 emission. Another characteristic common to several stars with extended envelopes is the presence of multiplet 191 of Fe II in emission, while the other far ultraviolet Fe II lines are in absorption. In this

case, we have a resonance fluorescence mechanism, i.e., absorption in the far ultraviolet followed by reemission at longer wavelengths:

a^6D ----> x^6P^o (UV mult. 9, λ~ 1260 in absorption)

x^6P^o ----> a^6S (UV mult. 191, λ~ 1785 in emission)

a^6S ----> a^6D (opt. mult. 7F, 4287-4475 in emission)

The spectrum observed in the high-resolution mode at the end of 1981 has about the same general appearance as it had in September 1980. It is noticeable the presence of practically all the Ni II absorption lines up to multiplet 30 (low EP=2.8 eV).

Unfortunately, no observations were made from the end of 1981 to January 1984. The spectrum in 1984 shows that the multiplet at 1303 of OI 1302-6). The high-resolution spectra are dominated by numerous and strong emission lines the same as in 1981. A spectacular change was detected in Junuary 1985, at about the same epoch of the disappearance of the blue continuum in the visual range (Selvelli and Hack, 1985a). The continuum in January 1985 has become completely flat, and the line spectrum has dramatically changed from an absorption-like to an emission-like spectrum (Figures 13-30 and 13-31); see also Figure 11-29a Lyα, and Figure 11-29b OI 1302-6). The high-resolution spectra are dominated by numerous and strong emission lines whose peak intensity rises to about 100 times the continuum. No absorptions are observable, also due to the weakness of the continuum. The emissions range from neutral species like O I and N I to highly ionized species like C IV, N V, and Si IV. New remarkable characteristics of the 1985 spectrum are:

a) The appearance of a strong and wide Ly Alpha emission (Full width at zero intensity = 16.4 A). The emission is cut by an absorption centered at rest wavelength (possibly of interstellar origin) 3.8 A wide.

b) The appearance of the other faint C III] line at 1906.68; all the other spectra only showed the strongest line of the doublet at 1908.73. The intensity ratio of the two lines indicates a decrease of the electron density to about 5 x 10^6 cm^{-3}.

The N V resonance doublet, which was never observed before either in emission or in absorption, and C IV, and Si IV, which were previouly present in absorption, are now in emission. The strong multiplet 34 of Fe III is present in emission. Fe II, which before January 1985 was one of the principal components of the absorption line spectrum in the far UV, starting with January 1985, changed completely to emission.

VI.D.4. INFRARED, RADIO AND X-RAY OBSERVATIONS

IR (1-20 μm) observations during the outburst have been made by Ipatov et al. (1984). The near-IR low-resolution spectrum of CH Cygni observed at different epochs in quiescence and in outburst remained nearly unchanged for wavelengths longer than 7000 A and is very similar to that of the M giants Alpha Her and g Her.

The light curve from 1978 to mid-1983 in J (1.25 μm) and in H (1.6 μm) shows long-term variability never exceeding 0.4 mag.

The IR energy distribution observed in 1982 is compared with the standard energy distribution of an M6 III star. An IR excess is present longward of 3.5 μm up to a factor of 10 at 20 μm.

The Infrared astronomical satellite (IRAS), which operated for 10 months in 1983, has observed CH Cygni (Kenyon et al., 1988), which allows us to extend its energy distribution curve in 1982 to 100 μm. The flux at 12 and 25 μm agrees well with the ground-based observations by Ipatov et al. at 10 and 20μm. The infrared excess in the IRAS range remains of the order of 10 with respect to the standard M6 III energy distribution (Figure 13-32). IR spectra (1.5-2.5 μm covering the time interval February 1979 to the end of 1984 have been made by Hinkle et al. (1985). The spectrum is that of a typical M giant, with the exception of very weak Brackett gamma emission. The velocities have been measured from the CO bands. It varies with a time scale of several hundred days but does not have a single

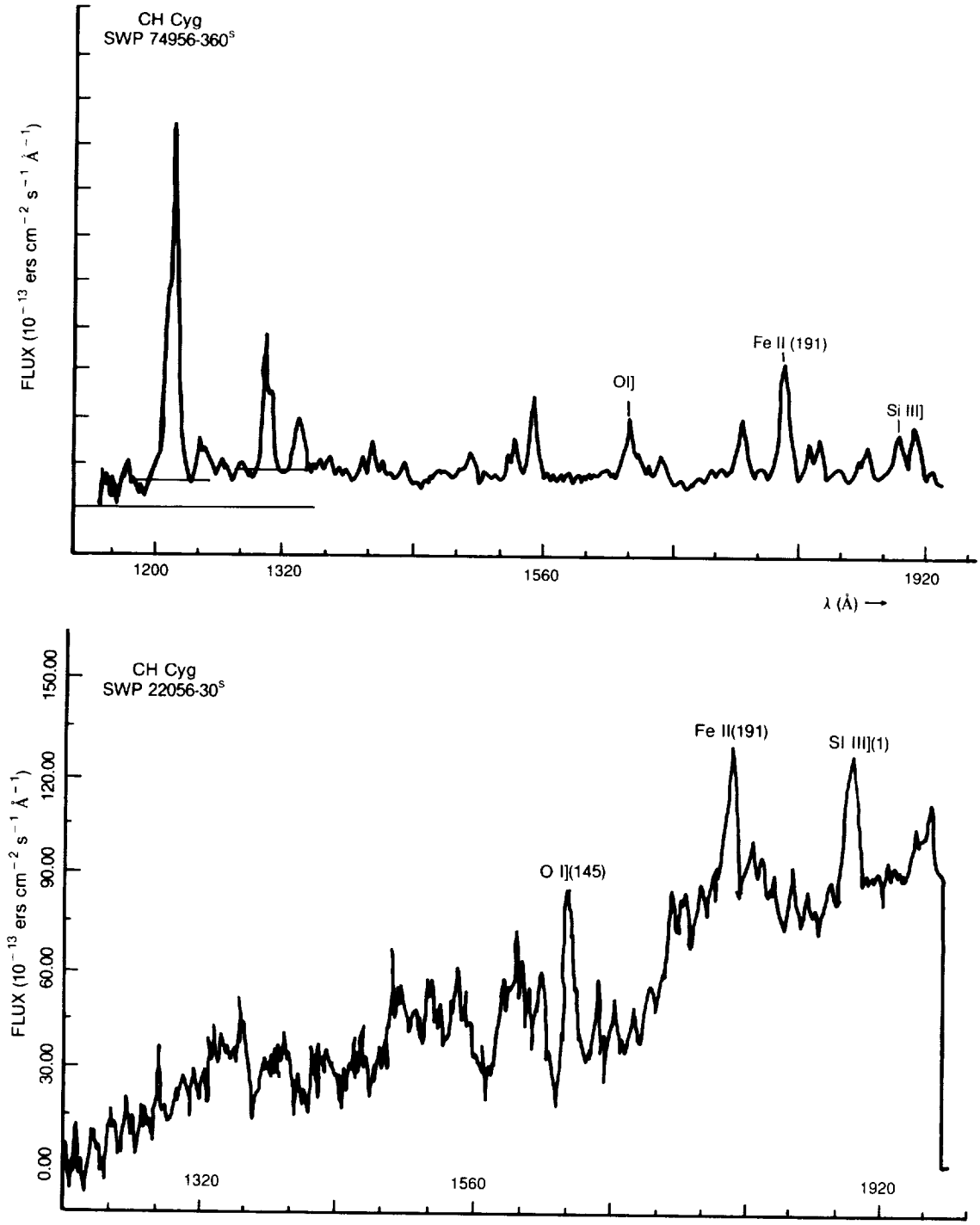


Figure 13-30. Far UV low-resolution spectra of CH Cyg taken on January 23, 1985 (top), and on January 20, 1984 (bottom).

periodicity, according to these authors. They found a median velocity of -63.5 km/s with an amplitude of 9 km/s, close to the values obtained from the visual region.

Hence, the IR observations do not show any clear evidence of the outburst that so strongly affects the optical and UV region. Observations in the radio range give more exciting results.

Taylor and Seaquist (1985) were monitoring several symbiotic stars. During the period April 1984 and May 1985, they discovered that CH Cyg underwent a strong radio outburst coincident

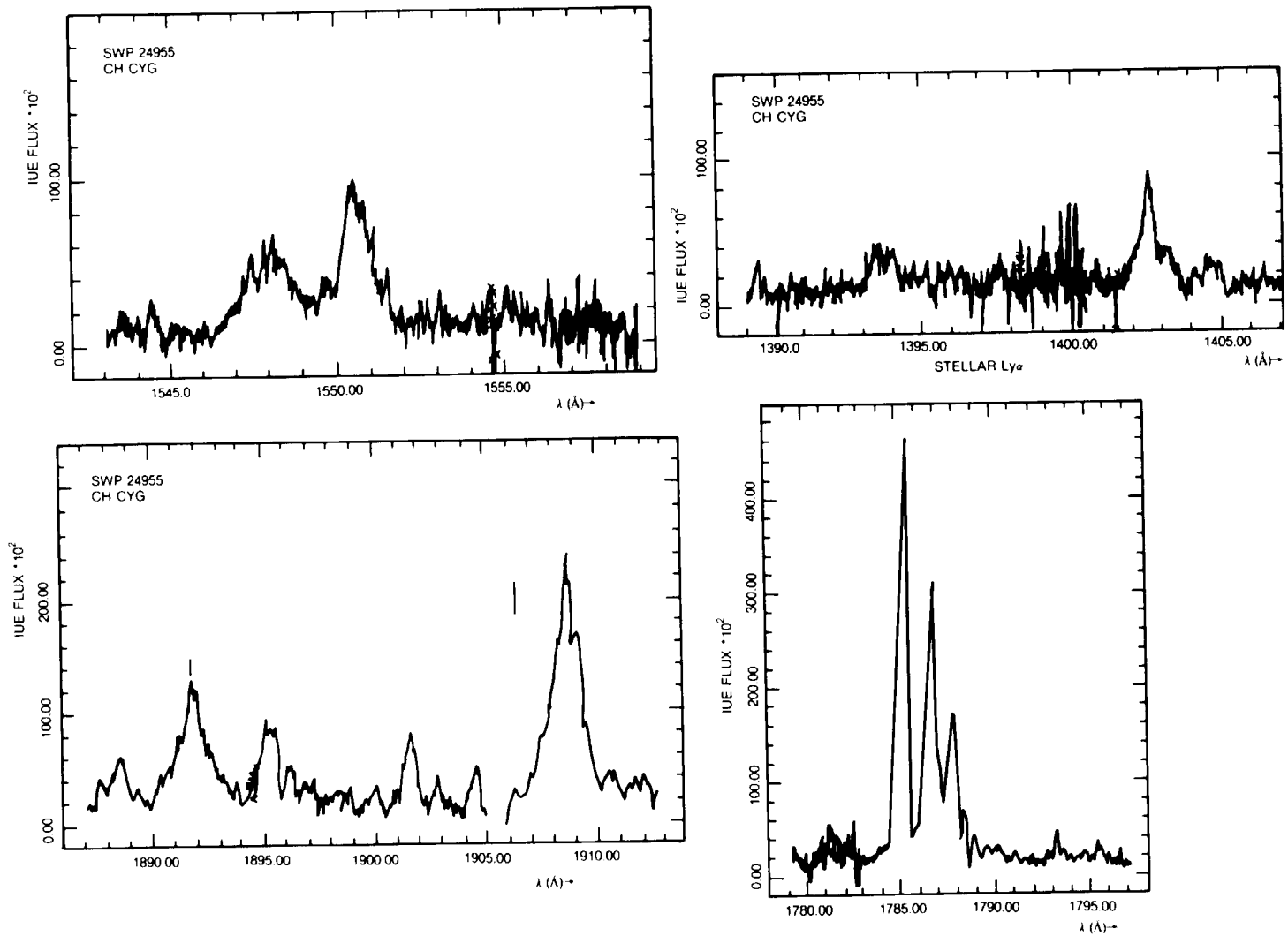


Figure 13-31. High-resolution UV line profiles observed in January 1985. a) C IV resonance doublet, b) Si IV resonance doublet; c) semiforbidden lines of C III at 1906 and 1909; d) the multiplet 191 of Fe II.

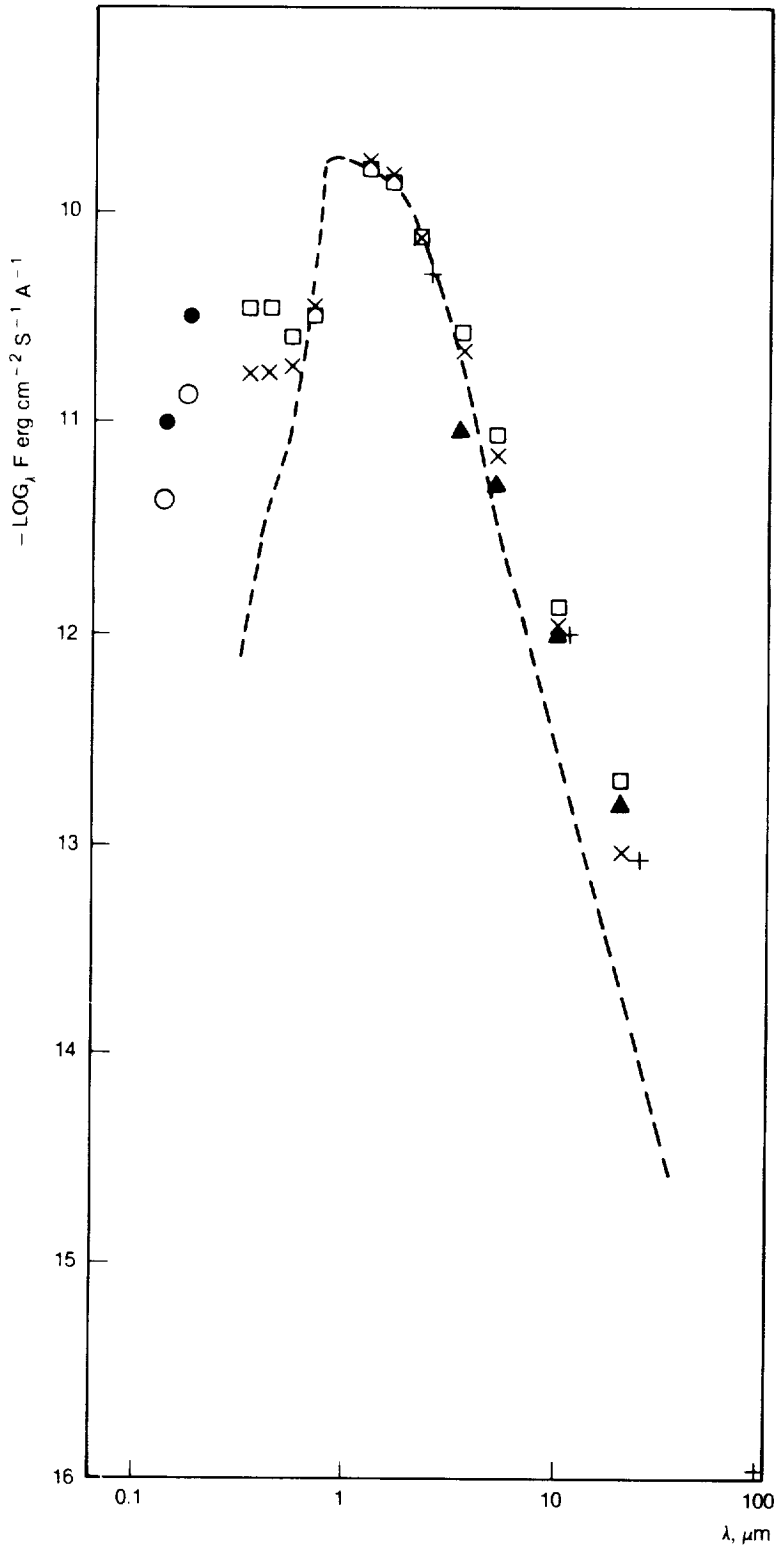


Figure 13-32. Composite energy distribution of CH Cygni corrected for an interstellar extinction of E(B- V) = 0.07 compared with a standard M6 III distribution (dashed line). o September 1980; □ June 1981; ● December 1981; x May-June 1982, ▲ IR observations from Ipatov et al., 1984; + IR observations from IRAS (from Kenyon et al., 1988) (adapted from Ipatov et al., 1984)

with the appearance of a multicomponent jet, expanding at a rate of 1.1 arc - s/yr (Taylor et al., 1986; also see Figure 11-27). The onset of the radio outburst coincided with the observed drop in visual light in July 1984. The radio light curve at 2-cm wavelength indicated a flux increase by a factor of about 50 from April 1984 to May 1985. The flux increased with increasing frequency, indicating a thermal origin. The expansional velocity was of the order of 2500 km/s, of the same order as the values given by the full widths of Lyα and the Balmer lines at about the same epochs: 3950 km/s for Ly alpha (Selvelli and Hack, 1985), 1200 km/s for H alpha and 1100 for H beta (Hack et al. 1986).

The radio jet from CH Cyg is an unusual and complex event. The only other symbiotic star known to show a jet-like feature is R Aqr: it was observed both at optical and radio wavelengths. Also in the case of CH Cyg, there is evidence of the presence of a jet emitting in the optical and-possibly- in the UV. Solf (1987) obtained high-resolution spectra of CH Cyg on September 1986. His data reveal a very compact nebulosity located about 1" northwest of the star and emitting in the light of [O III] at 5007 A, i.e., in the same direction as the radio jet. An attempt to observe it in the UV with the IUE satellite was made by Selvelli et al. (1987, IAU Circ. 4491) in November 1987, when the 20" slit was oriented in the same direction of the jet. By placing the star at one end of the slit, a stellar spectrum with P Cyg features was observed at one side, while at the other (at about 19 arcsec from the star), few emission features were observed (SiIII 1892, NIII 1750, OIII 1663). An attempt to observe the jet again in May 1988, when the slit had the same orientation, gave negative results.

Attempts to detect X-ray emission from CH Cygni were made with the X-ray satellite EINSTEIN with negative results. The european satellite EXOSAT observed again CH Cygni on May 24, 1985 (Leahy and Taylor, 1987), and at this time soft-X-ray flux was detected of 1.3×10^{-11} erg cm^{-2} s^{-1}.

Actually, there is some suspicion that CH Cygni is the optical counterpart of a hard X-ray source H1926+503, Int.= 1.22 count/s. In fact, it falls near the center of the error box of a hard-X-ray source measured by the satellite HEAO A-2 on November 1977 at 2-6 keV (about 3 Å) (Marshall et al., 1979). The doubt with this identification is that the other symbiotic stars that have been detected in the X-ray range are soft-X-ray emitters; none is known to emit in the hard-X-ray range.

VI.E. TOWARD A MODEL FOR CH CYG

The long and homogeneous series of spectroscopic observations made from 1965 to 1986 at the Haute Provence Observatory by Hack and collaborators, together with those made by Deutsch et al. (1974) since 1961, suggest that the radial velocity variations in the photospheric lines of the M6 III star are due to orbital motion on which are superposed some erratic variations commonly observed in giants and supergiants. The presence of a companion seems to be proved by the behavior of the permitted and forbidden emissions, showing radial velocity varying in antiphase with that of the M6 photospheric lines. The evidence for the presence of this companion is reinforced by the minimum in the U magnitude and in the UV flux observed in 1969 and in 1985, suggesting the occurrence of an eclipse of the companion by the cool star. Moreover, the detection of a slight increase of the flux toward wavelengths shorter than 1300 A observed in 1988 suggest that the accretion disk has become very thin, and we can observe the continuous spectrum of a faint hot companion.

A period of 16 years is not in disagreement with the values indicated by the radial velocity curve. However, the large scatter of the radial velocity data do not permit one to derive reliable parameters for the orbit, but just to estimate a mass ratio of about unity.

The observed flickering, with time scales of a few minutes, is a typical phenomenon observed in dwarf novae and quiescent novae and believed to arise in the hot spot where the mass flux from the cool star impinges on the accretion disk. The presence of flickering in CH Cyg and its higher

amplitude in the U magnitude are additional proofs that CH Cyg is a binary system and that the flickering occurs in the hot component of the system.

The ultraviolet continuum may be explained as superposition of a stellar continuum with T eff ranging between 8500 K (at maximum UV brightness) and 15, 000 K (at the end of the outburst) and b-f +f-f hydrogen emission (Mikolajewska et al., 1987; 1988).

However the indication obtained in 1988 of the presence of a Rayleigh-Jeans tail at λλ1200-1300 suggest the presence of a hotter object.

Assuming as reasonable values for the masses m(M6) = m(comp.) = 1 solar mass, and P = 15.7 yrs, the resulting distance of the two stars is of the order of 7.8 A.U. or 1.2 x 10^{14} cm, i.e., about 10 times the radius of the red giant. Hence, the system is detached, and if what we observe during the outburst is the spectrum of an accretion disk, it must be formed by accumulation of matter from the red giant wind. During the rising part of the outburst the disk becomes thicker and more extended as indicated: a) by the increasing intensity of the blue and UV continuum; b) by the appearance of absorption lines of once-ionized metals, and also of multi-ionized atoms (e.g., C IV, Si IV); c) by the increasing width of the Balmer lines. At the end of the outburst, the disk becomes less dense, as indicated by the ratio of forbidden to permitted lines of Fe II, the appearance of C III] 1906 and of [O III] 4959 and 5007, and by the diminution or disappearance of the UV-blue continuum. An indication of the decrease in density is also given by the transition of UV absorption-dominated spectrum (because the UV continuum is strong, the disk is optically thick in the UV) to an emission-dominated UV spectrum (because the disk become optically thin in the continuum). The appearance of Ly Alpha emission in January 85 probably has the same origin. The Ly Alpha absorption was not observable at earlier dates, probably because the continuum is very low at 1215 A on account of the low sensitivity of IUE at that wavelength and because of interstellar absorption.

The large widths of the Ly Alpha (about 4000 km/s), H alpha (about 1200 km/s) and H beta (about 1100 km/s) at the beginning of 1985 suggest that the disk becomes larger by expanding, and this has the effect of increasing the RV gradient in the disk and, hence, the broadening of the strong lines, and of decreasing the density. The EXOSAT detection of X-ray emission, while previous observations with EINSTEIN gave negative results, may indicate that the vanishing of the outer parts of the disk makes it possible to observe the inner hotter parts and, in 1988, also the Rayleigh-Jeans tail of the companion.

The duration of an outburst and the intervals between two consecutive outbursts may have very different lengths depending on the ellipticity of the orbit. If the critical mass for outburst in the disk is reached in the vicinity of periastron, the activity may be longer than if it is reached near apoastron, because of a larger accretion of matter through the stellar wind. The intervals between the two outbursts may be shorter if, at the end of one outburst, the star is near the periastron and may more rapidly replenish the disk or longer if, at the end of one outburst, the star is at the apoastron.

Although the orbital parameters derived by Yamashita and Maehara (1979) are very uncertain because of the scatter of the observed radial velocities, we have computed the phases of the epochs of the three observed outbursts. The outburst of 1963 occurred at phase 0.7 (counted from the epoch of periastron), and the outburst of 1967-70 started at phase 0.94. The 1977 outburst occurred at phase 0.58; it was near to the end in January 1985, at phase 0.05. Hence, the shorter time interval between the first and the second outbursts (4 years) and the longer interval between the end of the second and the beginning of the third outburst (7 years) may be justified by the above hypothesis. However, it is not easy to justify the strength and length of the third outburst, started when the companion was near to the apoastron.

To have a better explanation for the origin of the outburst, we need much longer series of radial

velocities for computing more reliable orbital data, and, hopefully, new outburst observations.

The model adopted by Warner (1972) to explain the luminosity of Mira Ceti B as due to accretion from the wind of Mira Ceti A can be applied to CH Cyg. Assuming $m_1 = m_2 = 1$ solar masses, P = 15.74 yrs, the semiaxis a of the orbit is equal to 7.75 A.U. or 1.16 10^{14} cm. For $m_1 = 1$ and $m_2 = 0.25$ (as suggested by Mikolajewski et al., 1987), a = 6.6 A.U.

The mass lost by the primary is given by $dm/dt = 4\pi a^2 \rho V_{out}$ where Vout is the expansional velocity observed during the outburst. For an observed particle density of 10^6 (as indicated by the forbidden emissions appearing at the end of the outburst) or of 10^9 (as indicated by the forbidden and permitted emissions of Fe II at maximum outburst) and for $V_{out} = 50$ km/s, it follows $1.5\ 10^{-8}\ m_\odot$ /yr < dm/dt < $2.4\ 10^{-5}\ m_\odot$ / yr.

The radio structure observed by Taylor et al. (1986) from April 84 to January 85 indicates $dm/dt \approx 7\ 10^{-6}\ m_\odot$ /yr. The luminosity, due to accretion only, of the object which is gaining mass, is given by

$$L = \frac{G^3 m_2^3}{2(V_{rel}^2 + V_s^2)^{3/2} V_{out}} \frac{}{\pi^2 a^2} dm/dt, \quad 13.3$$

where V_{rel} is the velocity of the companion moving at orbital velocity, relative to the wind of the companion, V_s is the sound velocity in the outflowing envelope, $V_s \approx 1$km/s, m_2 is the mass, and r_2 the radius of the companion.

For $m_2 = 1$, $r_2 = 0.1$ (both in solar units), V_{orb} = 8km/s, $V_{rel} = V_{out}$ and $dm/dt = 10^{-5}\ m_\odot$/yr, it follows L = 9.6 10^{33} erg/s. For $m_2 = 0.25$, V_{orb} =32 km/s, V_{rel} = 59 km/s, assuming $r_2 = 0.01$, it follows L = 1.75 10^{33} erg/s.

Now, assuming that the flux due to the M6 giant is completely negligible below 1600 A, we observe that the flux at the Earth of the companion in the period of maximum activity in the interval of maximum emission, 1200-1600 A, is F = 4 10^{-9} erg cm^{-2} s^{-1}. Hence, the luminosity L, assuming for the distance of CH Cyg about 250 or 300 parsecs, results equal to about 10^{34} erg/s. Hence, a mass loss of $10^{-5}\ m_\odot$ /yr, as indicated by the optical and radio observations, is sufficient to explain the observed luminosity of the companion of mass about 1 solar mass and radius about 1/10 the solar radius.

14

SUMMARY OF OUR PRESENT KNOWLEDGE ABOUT SYMBIOTIC STARS

M. Friedjung and R. Viotti

At the end of these Chapters 11, 12, and 13, where the different observational and theoretical aspects of the symbiotic stars have been discussed, with special attention to a few well-studied objects, it is now necessary to clarify to the reader the present status of our research, and to find out the lines for future work on the field. In the following, we shall summarize the main points concerning the symbiotic phenomenon.

I. SYMBIOTIC STARS AS INTERACTIVE BINARIES

There is now strong evidence that most, if not all, symbiotic stars are interactive binary systems. Indeed, this conclusion is so much believed by specialists, that if a star previously classified as symbiotic had been found not to be binary it would then have been classified as something else! One component is thought to accrete from the other. One, the mass loser, is supposed to be a cool giant, while the mass gainer should be a main sequence star or a white dwarf or possibly a neutron star. Accretion is supposed to occur either from Roche lobe overflow via a disk, or from the wind of the cool component. When the accretor is a white dwarf, the accreted hydrogen can be burned almost continuously or in shell flashes. However, even accepting this basic picture, many "details" are not understood, while it has to be related to the behavior of particular symbiotic stars.

In the case of S-type symbiotic systems, the evidence for binarity has grown. The orbital periods seem to be of the order of several hundred days. In some cases (e.g., CI Cyg and AR Pav), observations can be interpreted if there is a main sequence accretor surrounded by a disk. However, such a situation does not explain what is seen for many (probably most) S-type symbiotics. For these, wind accretion on to a white dwarf appears more probable. In the latter cases a high mass-loss rate from the cool giant might be suggested; actually, Kenyon and Fernandez-Castro (1987), Kenyon et al. (1988), and Kenyon (1988) found evidence of enhanced mass-loss rates compared with those of normal cool giants of the same types. The last conclusion is clearly dependent on the accuracy of the spectral classification, and especially on mass-loss rates determined from continuum radio emission and masses of dust present. Indeed, the accuracy of mass-loss rates is not so good; radio emission, in particular, needs to be modeled taking into account ionization of the cool-giant wind by radiation from the hot component (see Chapter 12). It can be noted that the mass-loss rate for the D-type symbiotic H1-36 found from the model of Taylor and Seaquist (1984), which is obtained by assuming the same wind velocity as those authors give, but with the distance from Kenyon et al. (1988), is two to eight times larger than that derived by Kenyon et al. if one assumes spherical symmetry.

For the D-type symbiotics such as RR Tel and V1016 Cyg, it has not been possible to derive an orbital period, although there are many reasons to state that they also are binary (e.g., from energy balance considerations). Their periods are often believed to be much larger than those of S-type systems (10^1 to 10^3 years), thus implying larger separations and less interaction phenomena unless the components are more "active." In fact, the cool giant in such systems appears to be a

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Mira variable, having a larger mass-loss rate than that of other cool giants. It appears that it is the presence of a Mira which explains the different properties of such systems, and it now seems best to call them *symbiotic Miras* (Whitelock, 1988). Their large mass-loss rate is considered to be associated with the condensation of a large amount of dust. Indeed, the infrared properties of symbiotic Miras might be understood by supposing a much larger extinction of the light of the Mira than that of its companion, as the result of the presence of a massive circumstellar dust envelope (Kenyon et al., 1988).

When speaking of *interaction* in symbiotic binaries, we need to consider quite a number of different processes. These include (1) mass exchange following mass loss from one component leading to transfer and accretion by the companion, perhaps modulated by varying stellar separation during an orbital period; (2) possible nuclear burning of hydrogen accreted by a white dwarf; (3) interaction of radiation of one component with the environment of the other; (4) collision between the winds from each component, etc. The interaction of radiation of one component with the environment of the other can take many forms, including heating of a disk and/or of a companion's atmosphere, ionization of the wind and upper atmosphere of the cool component (this can well vary with time), heating and possible destruction of grains, and acceleration of the cool star's wind by radiation pressure in the lines, etc. Up to now, studies have concentrated on one process at a time, so that a proper global picture of interaction still does not exist.

II. NATURE OF THE COMPONENTS OF THE SYMBIOTIC SYSTEMS

To make consistent models of the phenomena here studied, we especially need to know the nature of the components. It is now clear that the cool component very much resembles a normal cool giant or bright giant, for S-type symbiotics, and a Mira for D-type symbiotics. Here by "normal" we mean that the cool component appears very much to resemble the corresponding type of single star. This result needs to be checked in much more detail in the future. The claim of an increased mass-loss rate for the cool components of S-type symbiotics should be verified using proper binary star modeling for infrared dust and radio emission. The atmospheric structure needs to be studied using high resolution infrared spectra (e.g., from Fourier Transform Spectroscopy), which can also be used to measure stellar surface gravity, turbulence, and rotation velocity.

It appears, however, that binarity is the main cause of the properties of symbiotic stars; it now is very likely that they can be ascribed to the peculiar properties of the cool component. Indeed, the normality of this component is largely used to derive the distances of symbiotic systems. These distances need to be refined, but almost certainly will not be substantially changed in the future.

The exact nature of the *hot component* is still more open and controversial. In some cases, it appears to be like a hot subdwarf, and can be understood as being an expanded white dwarf undergoing shell burning. Then it often is similar to the nucleus of a planetary nebula, and temperature and radius estimates are derived as for the latter from the ultraviolet energy distribution and emission line fluxes. The temperature can be so high that the observed ultraviolet continuum is quite insensitive to its exact value. The properties of certain hot components during outbursts (e.g., CH Cyg and PU Vul) somewhat resembling a supergiant of intermediate temperature, might then be explained by expansion of the outer layers of the white dwarf to supergiant dimensions, following a shell flash. However, in this case, the luminosity would have to be ~ 59250 ($M_{core}/M_{\odot}$ -0.522) $L_{\odot}$ (Kenyon, 1986). According to Mikolajewska et al. (1988), CH Cyg did not have a maximum luminosity of more than 10^3 $L_{\odot}$. Therefore, in order for this explanation to work for CH Cyg, the white dwarf core mass would have to be quite low, of the order of 0.54 $M_{\odot}$.

The hot component can sometimes be understood as an *accretion disk* plus boundary layer around a main sequence star. Such a disk may be

formed from Roche lobe overflow and sometimes from wind accretion, but in the latter case, a disk does not seem easy to be formed. In any case, the detailed interpretation of the hot component as a disk still involves a number of uncertainties because of the gaps in the present theory of disks. Studies assuming a disk to radiate as a sum of blackbodies or even as a sum of normal stellar atmospheres cannot lead to highly reliable results. Other physical effects can also be present. Among these, one should mention heating of the disk by a central stellar component, which can be an expanded white dwarf undergoing shell burning. The heated disk could reradiate as a result of the heating at a rate much larger than that due to gravitational dissipation in the disk. If the hot component is a disk, one can envisage an explanation of active phases of symbiotic stars, by mechanisms similar to those invoked for dwarf nova outbursts. In addition, it is not certain whether a disk, if formed, would always be present. For instance, it might temporarily appear during activity, if it were formed by accretion from the wind of the companion. The properties of the latter or the separation of the stellar components would have to change.

The presence of a disk should lead to observational consequences other than those exhibited if only an object similar to a hot star were present. Not only is the continuum energy distribution changed, but also the emisssion and absorption line profiles (or at least contributions to the profiles), as well as all the variations in eclipse, can be expected to have characteristic properties. High-quality observations, combined with better theory, should help to eliminate these problems. In any case, the correct identification of the nature of the hot component for a particular system is important for deducing which processes dominate. In addition, such information is essential for understanding the system's evolution.

III. EMISSION LINES

The picture just described obviously has a bearing on the formation of the emission lines. If formed by electron collisions or by cascade following recombination in an ionized region, one might, in the simplest situation, expect line formation near the hot component. In fact, the situation is more complex, as material does not appear to be distributed uniformly. The fairly narrow emission lines seen very often are most easily understood as formed in regions connected with the cool component (wind, outer atmosphere). Line narrowness implies formation in a low-velocity region far from any compact accreting object. In addition, a study of inter-combination lines of Z And and RR Tel indicated line formation where radiation coming from the hot component at 1176 and 772 A (Altamore et al., 1981) was diluted.

A similar kind of situation is believed to exist for zeta Aur binaries where a hot main sequence star appears to be immersed in the wind of a cool supergiant companion (Shroeder, 1988). The wind scatters photons from the hot main sequence star in resonance lines according to successful models for such stars, and information on wind velocities and mass-loss rates can be obtained. Such stars provide lessons for the study of symbiotic systems.

Symbiotic stars, however, are more complex. As discussed in Chapter 12, not only is the geometry of regions of the cool star wind ionized by the hot component complex, but other physical processes determine line formation regions also. Evidence of a high-velocity wind from the hot component, in particular, can be seen for AG Peg, this producing the broad component of line profiles. Collision between the two winds, when important, can also lead to another line formation region, whose properties really have not been studied up to now. Emission-line formation can occur near an accretion disk (plus perhaps a bright spot formed where a current from a companion losing mass by Roche lobe overflow strikes the disk). It may be noted that such a disk might also produce a wind. The influences of these and other effects on emission-line formation still need to be fully elucidated.

IV. CHEMICAL COMPOSITION

Some of the models discussed above imply that the matter in the symbiotic system should be processed. Abundances different from cosmic

values are also expected for the high-velocity objects, such as AG Dra. Therefore, the determination of the chemical composition of all the components of the symbiotic systems is a crucial parameter. Obviously, nothing can be directly said about the hot component, since no truly photospheric lines are visible. The spectrum of the cool component can be studied with the classical curve-of-growth method, provided that high-resolution, high-S/N spectrograms are available, which is not the case for the large majority of symbiotic stars. In addition, in order to avoid errors introduced by the veiling of the variable blue continuum (see Chapter 11, Section IV.A), the analysis should be made on high-resolution spectrograms taken in the red, or even in the near-IR, which is not so easy at present. So far, the abundance analyses of the brightest objects are very few. From a curve-of-growth analysis of the optical spectrum of the symbiotic nova PU Vul, Belyakina et al. (1984) found some chemical anomalies, such as Ca and Fe deficiency, and excess of the other iron group elements and of some rare earths (cf. Gershberg and Shakhovskoj, 1988). Lutz et al. (1987) found that in AG Dra, the BaII and SrII lines are probably enhanced. Unfortunately, these authors were unable to perform a detailed abundance analysis for lack of a good calibration of their echelle spectra.

Concerning the "nebular" emission-line spectrum, the abundance determinations are strongly model-dependent. Several estimates have been made based on the optical and UV line fluxes. The results of CNO abundance determinations from *IUE* are summarized by Nussbaumer et al. (1988), who used the emission-line fluxes of CIII, CIV, NIII, NIV and OIII, supposed to be formed in a common region. They also supposed the ionizing hot source to have an effective temperature equal to or larger than 10^5K, and the nebular regions to be uniform with an electron temperature of 12,000 K and an electron density of 10^{+9} cm^{-3}. Line emissivities were found to be insensitive to the assumed electron temperature, as well as to the assumed electron density, at least for N_e below 10^{+9} cm^{-3}. Nussbaumer et al. found that in symbiotic stars the abundance ratios are close to those for M giants, suggesting that the line-emitting material come originally from the cool-giant companion. The latter would have its abundances somewhat modified by CNO cycling. The only symbiotic system that shows clear signs of deviation is HM Sge, for which C/N/O ratios were found to be similar to that of novae. It would be important to extend these results to other ions, and to check to what extent the abundance estimates are dependent on the assumptions and on the adopted model. Future work on both (and simultaneously) the emission-and absorption-line spectra using high quality material are urgently required to make any progress in this field.

V. VARIABILITY

The variability of symbiotic stars is a fundamental property of these objects. It is the result of many mechanisms, which in many cases are far from being well-understood. Various time scales are involved, and we mention here (nearly in order of increasing time scale):

- The *flickering* of CH Cyg with time scales of 5 and 15-20 min seen during activity, which might be physically related to the flickering seen for cataclysmic variables.

- Variations during the orbital cycle, which may not be only geometrical (eclipses, reflection effects, etc.), but also physical, associated with a varying separation of the stellar components. In the latter case, the orbit must be *eccentric*. It should be noted that accretion variations due to varying separation cannot have much effect on the brightnesses of AG Dra, AX Per and AG Peg; otherwise, the determination of orbital elements from the reflection effect as discussed by Leibowitz and Formiggini (1988) would not work.

- When the cool companion is a Mira, variations occur over its pulsational period, which are of the same order as the *orbital* period, if it is an S-type system. Accretion and dust condensation might sometimes be modulated.

- Active phases can occur over time-scales of

decades. Within each, oscillations of activity can occur. Some, but probably not all, of the active phases, might be explainable by accretion events. The active phases of other symbiotics (e.g., AG Dra) may be hard to understand without invoking shell burning of a white dwarf.

- D-type symbiotics can have faint phases lasting one to several years. These are possibly due to dust obscuration, and/or to phenomena associated with the periastron passage.

- Only one outburst has been observed for each symbiotic nova. Such events have been explained by shell flashes of white dwarfs.

However, the explanations invoked for different events are not to be believed dogmatically. Certain dividing lines between different classes of event may turn out to be artificial.

VI. NEBULAE

Small nebulae have been discovered around many symbiotics, especially at radio wavelengths. Image deviations from circular (therefore from spherical) symmetry are observed, with indications of the presence of bipolar flows and jets (Taylor, 1988; Solf, 1988). According to Taylor, one should distinguish between ejecta and stellar winds. The former are clumpy and associated with a known outburst of the system, while the latter are smooth and featureless with an angular size that increases with frequency. It is the ejecta following outbursts that show bipolar flow (or jet-like) structures.

The physics behind the origin of nebular structure is not really known. For wind-produced nebulae, the ionization of the cool component's wind by the hot component and collision between winds from both components may play major roles. A system seen in the plane of its orbit could show apparently linear structure in certain cases because of these mechanisms. However, such an explanation is not expected to be generally true. Bipolar flows and jets are common in other astrophysical situations such as radio galaxies, active galactic nuclei, young stellar objects, etc. Their existence may be linked to the existence of disks, but it would be dangerous to extrapolate this type of "explanation" to symbiotic systems, and to conclude that disks are very often present. Conversely, the study of bipolar nebulae and ejecta in symbiotic systems might be useful to understand their nature. A large progress in this field is expected from the new astronomical technologies for imagery and polarimetry, and from HST.

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15

PERSPECTIVES AND UNSOLVED PROBLEMS

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In this book we reviewed the observations of dwarf novae, nova-like stars, novae, recurrent novae and symbiotic stars, and the current state of their interpretation. We tried to demonstrate the immense variety and variability of phenomena found in these objects.

As is probably true in all other fields of science, we are facing a dilemma. On one hand the availability of new observational material- from satellite telescopes as well as from ever more advanced and sophisticated ground-based devices - is opening our eyes to ever new phenomena in cataclysmic variables which help clarifying some questions. On the other hand, however, unexpected new questions and problems arise. The general picture becomes clearer; for instance there is little doubt left that in principle the Roche model is rather well suited for explaining the basic physics of cataclysmic variables (with the possible exception of symbiotic stars), but curious assumptions and concepts flourish if details of individual observations are to be explained. And, not surprisingly, conceptual understanding has evolved much further than our ability to carry out detailed, meaningful computations.

Let us consider dwarf novae and nova-like stars. A few intriguing statistical differences between the different sub-classes of these systems seem to exist, with respect to the distribution of orbital periods and the masses of the stellar components. Furthermore, judging from their spectroscopic and photometric appearance, nova-like stars belonging to the sub-class of UX Ursae Majoris stars, anti-dwarf novae and dwarf novae appear to be basically the same kind of objects. In most respects also the DQ Herculis stars are very similar to them. They are suspected, however, to possess a moderately strong magnetic white dwarf. And finally, the appearance and behavior of AM Herculis stars can be understood, if it is assumed that they also are basically the same kind of objects, but that their white dwarfs possess a very strong magnetic field. AM Canum Venaticorum stars, on the other hand, represent a different kind of system. The complete absence of hydrogen lines from their spectra, in conjunction with the extremely short orbital periods, suggest that these systems consist of two white dwarfs and, therefore, that their evolutionary history must be different than that of the other systems which are believed to consist of a white dwarf and a red dwarf.

Although nova-like stars are commonly believed to be dwarf novae in a permanent state of outburst, statistical differences in the photometric and spectroscopic appearance of members of both classes suggest that the physical differences between them might lie beyond mere outburst behavior.

In spite of the very large number of observations of dwarf novae, the very start of rise to an outburst, due to the unpredictability of the event, has so far escaped detailed observations. However, this particular phase in the activity cycle of dwarf novae is very likely to contain valuable clues to the structure and dynamics of the accretion discs. Thus, what is called for in order to help the situation is continuing monitoring of a few selected objects, both photometrically and spectroscopically, in as large a spectral range and over as long a time interval as possible.

In both dwarf novae and nova-like systems the companion stars are cool main-sequence stars which in all probability undergo solar-type activity cycles. These activities, in turn, are likely to influence the brightness variability of cataclysmic variables. Moreover, according to theoretical considerations, the secondary stars are forced to co-rotate with the binary orbit at a considerably higher velocity than normal for stars of this spectral type. It is not known yet what effect this has on the star, nor is it known what effect it must have for it to be confined to the non-spherical shape of the Roche lobe. All these problems should be taken into account by a new generation of theoretical models.

A weak point in the computation of models is also the structure of the accretion discs. So far only very simplified models have been consid-

ered. Two-dimensional hydrodynamics computations depend strongly on the assumptions about the viscosity. Moreover, the vertical stratification has been included in the computations only in a rather crude way, yielding correspondingly vague results. A further complication is presented by the hot spot. The geometrical structure and the position of it in the disc, which are a theoretical rather than a controversial issue, are bound to influence the structure and dynamics of the disc. Similarly, spectrum computations, too, severely suffer from the poorly known physical structure of the accretion discs.

Classical and recurrent novae, both in quiescence and in outburst, present plenty of open problems. We summarize here some of them, and will try to indicate which course to pursue for tackling them.

One main question is: are dwarf novae, nova-like stars and old novae the same class of objects, just seen in different stages of activity? Actually the only known statistical difference among these three groups, besides the outburst activity, is their absolute magnitude: the magnitudes at minimum of old classical novae cluster around +4.5, those of quiescent dwarf novae around +7, and the nova-like stars have magnitudes clustering around +5. This difference might be due to a weakening of the accretion disc in very old novae. Furthermore, there is some indication that very old novae, like CK Vul, are several magnitudes fainter than old novae just a few decades after the outburst. Also two of them, CK Vul, and WY Sge, are reminiscent in their photometric behavior of dwarf novae. Both these observations can be taken as a sugestion that dwarf novae merely are very old novae. It is not clear, however, where the apparently closely related nova-like variables fit into this picture.

Actually we observe 50 novae per year in M 31. In 15 billion years there should occur 7.5×10^{11} novae. Hence we have two possibilities. Either practically all stars in M 31 will become or have been novae, or each nova must suffer f outbursts (with f the ratio of the total number of stars in M 31 to the number of nova systems). Since we observe that only 1/1000 binary systems are formed of a close white dwarf plus a red dwarf, able to produce a nova outburst, the second possibility is the only one which can be accepted. The hibernation theory follows, according to which each nova will erupt thousand of times and stay in a low state for centuries between one outburst and the following one. Although many details are not completely explained, the hibernation theory gives a unifying picture of dwarf novae, nova-like stars and novae, explaining the change from one class of cataclysmic variables to another with the change of mass transfer over the millennia.

Another question is why novae are so similar to each other at minimum, and so different from each other in outburst? Actually it is difficult to say if an old nova behaved as a fast nova or a slow nova, just looking at its characteristics in quiescence.

Fundamental parameters like the masses of the two components, or even as basic as the orbital periods, of a cataclysmic variable system are badly known. There is a need for simultaneous as well as long-term observations of light curves and radial velocity curves, so far available for just a few individuals.

Still, careful analysis of observations indicates that the problem of deriving system parameters is not as straightforward as one might naively assume. Besides the technical problems of suitable data analysis, such as properly taking into account irradiation effects in the system, some difficulties seem to be even more basic, reflecting that the underlying physics probably is not quite as simple as would be desirable. For instance, in some systems the photometric periods seem to be variable on unreasonably short time-scales. In other systems the spectroscopic and photometric periods are different from each other.

It is very important to get better determinations of the chemical composition of the ejecta of novae, both for obtaining information on the phenomena occurring at the surface of the hot degenerate star when it accretes matter from the boundary layer of the accretion disc, and also for obtaining information on the characteristics of the white dwarf itself.

The impact of ultraviolet observations on our knowledge of cataclysmic variables has been very important. Not only because it has given us the possibility to obtain abundance determinations from ions not observable in the optical range, but also for having given us proofs of the reality of the existence of accretion discs from the shape of the continua, which are generally fitted by a power law. Only in few cases can a Rayleigh-Jeans tail, imputable to the hot member, be detected. The importance of extending the observations to shorter wavelengths than those accessible to IUE is clear. However the hope of detecting the spectrum of the hot companion at shorter wavelengths than those accessible with IUE will not necessarily be satisfied. In fact the few data from Voyager actually indicate that the same power law explaining the IUE range is not valid for the shorter wavelengths, but neither is it explicable by a hot black body emission. The spectrum instead is generally very flat.

Few nova outbursts have been observed in the near infrared. From these data it seems that a different behavior characterizes the fast novae (no appreciable formation of a dust shell), the intermediate novae (formation of an optically thin dust shell) and the slow novae (formation of a thick dust shell, although the few data for two very slow novae indicate absence of a dust shell). It is not yet clear how general these relations are. A larger sample is certainly needed, in order to firmly support the notion that these behaviors really are correlated to the speed class of a nova. The mechanism of dust formation is not clear either. Dust may be preexisting to the outburst or it may form in the envelope when it cools off.

The foremost problem with recurrent novae is one of classification, thus one of what one imagines their basic structure to be.

It is not obvious that they can be addressed as a reasonably homogeneous class at all. Only five individuals (*) are known which can be divided into at least three sub-classes: T Pyx and U Sco are similar to classical novae, V 1017 Sgr has a behavior more reminiscent of that of symbiotic stars, and finally, T CrB and RS Oph have a red giant in their system (rather than a red dwarf as the other cataclysmic variables). T Pyx, unlike other recurrent novae, presents a very steep rise of the ultraviolet flux toward the shortest wavelengths accessible to IUE.

Also, the distinction between novae and symbiotic stars is not as neat as one would like it to be. Symbiotic stars are known, like V 1016 Cyg and V 1329 Cyg, which behave much like classical novae. On the other hand RT Ser and RR Tel, both commonly classified as old novae, behave much like symbiotic stars.

Since the basic structures of novae and symbiotic stars might be rather different from each other, but since recurrent novae bear characteristics of both, their investigation might yield valuable clues to the nature of both, old novae and symbiotic stars.

Because of the length of the orbital periods of those symbiotics that have been ascertained to be binary systems, the interaction between the cool giant and its companion must occur, in the majority of cases, by accretion through winds rather than by overflow of the Roche lobe. It is possible that many characteristics of the outbursts are affected by the properties of the orbits, by their eccentricity, etc. It should be, therefore, necessary to obtain better determinations of the radial velocity curve, over long periods of time, covering more than one orbital period. In fact one main difficulty in obtaining reliable radial velocity curves is that the amplitudes are generally small and comparable with the irregular fluctuations often present in the atmospheres of cool giants and supergiants.

The problems of line blending of the wide Doppler broadened lines mean that outburst spectra in different spectral regions must be studied using spectral synthesis. The use of spectral synthesis requires the finding of parameters which are sensitive to unknown quantities connected

(*) A sixth recurrent nova has been recently discovered: V394 CrA 1949 which had a second outburst in 1987. It behaves similarly to T Pyx and U Sco. (Liller, 1987)

with the model, abundances, etc. A vague resemblance of the results of a calculation to what is observed is not sufficient.

Besides better observations we certainly need better and more realistic models.

Parameters which affect the absolute magnitudes at maximum, the shape of the outburst light curve, and the ejection velocities, etc. can be the mass and chemical composition of the white dwarf, the mass of the accreted material and the accretion rate, the degree of mixing of white dwarf material into accreted hydrogen-rich shell material, the orbital elements and the inclination of the orbit, and the presence and strength of magnetic fields, etc. Unfortunately the majority of these data are only poorly known or altogether unknown. Through extensive comparison between theoretical models and observations it should be possible to get a better handle on physically reasonable parameter ranges for more sophisticated models. Such new models then clearly should take into account non-LTE effects, circumstellar absorption and dust, and the hydrodynamics and thermodynamics of shocks, etc., before spectral synthesis is attempted.

As long as such a theory is not available or not usable, semi-empirical methods of analysis need to be further developed, among these the self-absorption curve method by Friedjung and Muratorio (1987) for studying spectra of ions where there are very many lines, such as Fe II, should be mentioned. In such methods the fit is made to assumed physical situations which, because of physical uncertainties involved, have more free parameters than a self-consistent theory.

Simultaneous or nearly simultaneous multifrequency observations are required for comparison with spectral synthesis leading to determination of the total bolometric luminosity, the mass-loss rate and velocity distribution of the continuously ejected wind, and the disc structure, etc.

Novae often go through post-maximum oscillations; and to understand their nature, multifrequency observations closely spaced in time are needed.

Observations of high spatial resolution in various spectral bands can give more information about the geometry of the ejected envelope, including deviations from spherical symmetry. It will be particularly interesting to resolve the envelope as early as possible after the outburst of a nova and to follow the evolution of its structure with time. Study of the spectrum of different parts of the nebula will not only give information about differences in physical conditions, but also about the velocity distribution in the line of sight (from line profiles), leading to the possibility of the three-dimensional reconstruction of envelope structure.

It must be emphasized that the study of nebular expansion, combined with knowledge of the expansion velocity, is the best method for determining the distance of a nova.

The theory of classical-nova outbursts needs to be further developed taking into account deviations from spherical symmetry and the influence of the companion.

In addition magnetic fields appear to be important for some old novae. The old nova V 1500 Cyg seems to be a polar object and GK Per an intermediate polar one. Strong fields should have a major effect on the outburst.

The causes of recurrent-nova outbursts are still not clear, and it is possible that some of the important physical processes involved are completely unknown. More work on accretion events and thermonuclear runaways at very short intervals of time may help to solve these problems.

A very large amount of work needs to be done before one can claim to understand novae reasonably well.

In the chapters devoted to the observation and modeling of symbiotic stars, attention has been focused on the *symbiotic phenomenon*, rather than on a group of stars. The reason was that (1) it is not clear whether symbiotic stars really represent a well-defined category of stars, and (2) our main interests are the physical processes occurring in the atmospheres of stars, rather than the nature of the stellar objects.

Actually, symbiotic stars represent only a comparatively small number of objects, and there should be no reason to dedicate so much time to their study, unless we expect from it - as is in fact the case- results of much wider interest.

We have shown in the previous chapters that symbiotic stars, as other cataclysmic variables, are characterized by non-LTE phenomena that have been observed in many different categories of astrophysical objects. These phenomena include: stellar chromospheres, mass loss and stellar winds, circumstellar nebulae, accretion phenomena in close binaries, superionization and X-ray emission, etc. These phenomena characterize several differents fields of astrophysics such as: formation of planetary nebulae, cool-and hot-star winds, circumstellar dust, jets, maser sources, pulsation, X-ray sources, accretion disks, thermonuclear runaway, and close binary evolution. Therefore, symbiotic stars are linked with many astrophysical categories of stars, including M-giants, Miras, Zeta Aur/VV Cep stars, hot subdwarfs, planetary nebulae, and obviously close binary systems, besides active galactic nuclei too. This is why symbiotic stars have always attracted the interest of so many investigators from different fields. Their hopes were, and are, to have a better insight into the physics of their own objects from the study of the symbiotic phenomenon, where the same mechanisms are probably present but with a larger strength, or on a different spatial scale.

On the other hand, we have found that the diagnostics of the symbiotic phenomenon are not very straightforward. First we need as complete an observational description of the phenomenon as possible. However, because of their long timescale variability, symbiotic stars must be studied for several decades, before a reasonably complete picture can be drawn. In addition coordinated observations in a broad frequency range are required, since, as discussed in previous chapters, different spectral regions involve different physical phenomena. In practice, this requirement was (at least partly) fullfilled in only a few cases.

On the other hand, a large amount of observational data on very broad samples of symbiotic stars has been collected in many different fields, from radio to X-rays, which in principle could be very useful for a statistical approach. But some concern should be expressed on the criteria which have been used in the selection of the targets in these surveys. It seems to us that these data have not yet been satisfactorily analyzed with the standard methods of statistical analysis. Thus new surveys, and extensive use of statistical methods, are aspects which require more work in the future. Selection effects will, however, have to be properly studied, and fully taken into account.

Another major problem is associated with the techniques of determination of the physical parameters from the observations. To develop an empirical model, we need to use diagnostics of the environment of the symbiotic stars derived from observational data. For instance, radio observations can provide information about ionized circumstellar envelopes, while the infrared rather gives information about the cool giant and circumstellar dust. Emission-line ratios provide first-approximation estimates of electron densities and electron temperatures in the line emitting regions. However, such regions are not uniform, which can explain differences in the parameters determined using different emission-line ratios; moreover the physical constants involved in the calculations are not too certain.

To overcome these type of difficulties, we need to calculate observable quantities from detailed models. The latter must take into account many different physical effects, including ionization of the wind of one stellar component by the other component, collision between winds, etc. These calculations use many unknowns, thus future work will have to involve convergence between models and observations. The ideas behind the former will have to be confronted by the facts provided by the latter.

In order to make progress from the observational point of view we need better orbital data about the binary systems. This requires the accurate determination of the radial-velocity variations of the cool component. *High resolution infrared spectra* will not only yield this, but will also provide information about the "normality" or "non normality" of the cool component. In addi-

tion, it may be noted that in this spectral region one can detect absorption between the observer and the cool component, so the envelope can be studied using absorption lines produced by it in such positions.

Diagnostic methods need to be enlarged. For instance, symbiotic stars are rich of Fe II emission lines which have proved to be very useful for the investigation of emission line objects. But still a large amount of data on this and other ions have not yet been studied. It should also be emphasized that the profiles of spectral lines formed by circumstellar material, rather than their radial velocities, needs to be examined. The radial velocity, in fact, gives only a kind of "integrated" information about the region of line formation, while the study of the line profile at high spectral resolution is basic for a detailed modeling. Finally, those systems showing *eclipses* can give a lot of information about the geometry and physical conditions of different regions.

Observations of *spatial structure* at *very high resolution* are essential. In this regard, we expect very exciting results from the Hubble Space Telescope as well as from the large ground-based telescopes equipped with new sophisticated instrumentation. In particular, information about jets and bipolar flows should be obtainable. *Polarization studies* will provide precious additional information on the geometry.

On the theroretical side, much is still to be understood about *accretion discs* in symbiotic systems, and in particular those formed following wind accretion. The reprocessing of radiation from a central object by a disc needs to be treated in a much more rigorous way than previously.

Effects of symbiotic binarity on the cool-star upper atmosphere and wind have not yet been fully studied. This aspect is obviously also linked to the uncertainties one still has about single cool giants. Perhaps the symbiotic phenomenon will be of help for a better understanding of the outer atmosphere of normal cool stars.

Colliding wind models need to be worked out in much more detail, in order, for instance, to better predict emission-line fluxes. Other situations where shock formation should occur also exist, and they must be carefully examined, in particular for wind accretion.

It is only when ideas based on much more careful research are confronted with better observations spanning many years that significant progress will be made about the symbiotic phenomenon.

Finally, along which lines should further reasearch be developed? We realize that new sophisticated observations really raise more questions than they yield answers. Each of us has made the claim "We need more observations". We surely do. But we need certain particular kinds of observations. We need observations involving a somewhat different approach than that which has been useful and appropriate so far. The traditional tendency to obtain bits and pieces of observations on as many objects as possible needs to be supplemented. There are many obvious gaps in the records of observation; many are even relatively easy to fill in. It is sobering to realize how little is actually known. For instance, we know little about spectra of dwarf novae during the outburst state, or about how they develop on time-scales of minutes or hours (rather than days), or what orbital photometric variations occur during outbursts, or whether they are of orbital (geometrical) origin or only occur on orbital time-scales. And we still don't know what triggers a dwarf nova outburst, or what causes many nova-like stars to drop in brightness. We believe the mass-transfer rate is responsible, but it is not clear why it changes in the first place; i.e., what the trigger is.

Furthermore, we now know that whatever observations of a system we obtain, these are not likely to be entirely characteristic of the particular brightness state we happened to monitor, but are likely to be merely one possible pattern. Observations at the same brightness level well may yield another result at some later time. Currently, we have only glimpses of the actual life of individual systems, without being able to appreciate how the most intricate interactions of all kinds of phenomena finally result in, for instance, the violent outburst events.

So what actullay is called for is long-term semi-continuous monitoring, in as many wavelength ranges and by as many means as possible. This has been tried for very few objects, with rather amazing, and quite unexpected results. Campaigns like these need to be repeated, and observing plans and schedules of the various working groups should be coordinated for observing times and for objects to be monitored. The priorities of committees for the allocation of telescope time need to be changed so that they finally realize that there is after all a lot of potential scientific merit in re-observing the same object over and over again. Results should be communicated quickly, rather than accumulating dust in offices and archives. Already existing material, belonging to individuals as well as hidden away in archives, needs to be made widely available and studied. And, last but not least, the countless amateur astronomers could and should be involved in systematic monitoring activities. They have the telescope time and the enthusiasm to observe, both of which many professional astronomers are lacking.

Astronomical satellites dedicated to the monitoring of stellar variability from X-ray to optical wavelengths are now being projected, and we hope they will soon be realized.

As for the theory, it seems that any possible progress heavily depends on observations to set limits to the nearly infinite number of possible combinations of parameters that govern computations of all aspects of cataclysmic variables. And here, at the current, still very general, state of the theory, it is necessary to resort to statistically significant samples of observations, in order to not mistake idiosynchrasies of individual systems for general patterns of the entire class. Investigations of this sort are still largely lacking. From comparison of features of such statistical samples with the theoretical results obtained from variations of parameters over wide limits (after parameters of only secondary importance have been ruled out beforehand) hopefully possible values can be limited to reasonably narrow ranges that then might yield realistic results; while most theoretically possible values can then be ruled out. Once such narrower limits will have been established, there is hope that computations could be used to actually determine systemic parameters from comparison with observations.

One further aspect of research in cataclysmic variables (but this is valid also for several other fields of research) should be changed, so work in later years can remain fruitful. The number and quality of publications should, in the first case decrease, in the second case increase. Over the last 20 years the number of papers, only restricted to the narrow field of cataclysmic variables and related stars, has increased almost exponentially, so that probably already by now a stage has been reached where it is practically impossible to read and fully assimilate all that is being published. Many fractional results are being turned out as individual publications, rather than as the results of complete investigations made available once all the work is done. Furthermore, there clearly is no need for publishing the same results several times in different journals or proceedings.

Our hope is that the monograph at hand will make it easy for theorists as well for observers to find their way into and through the jungle of results and papers. We tried to point out relations and gaps of knowledge. We hope this will become a useful reference book.

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