ULTRAVIOLET OBSERVATIONS OF SOME CLOSE BINARY SYSTEMS BY THE ASTRONOMICAL NETHERLANDS SATELLITE-ANS

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Abstract. Observations of δ Pic, a β Lyr type of eclipsing binary and seven dwarf novae are reported. The ultraviolet light curves of δ Pic indicate the accumulation of matter at the triangular Lagrangian points $L4$ and $L5$, the presence of a hot spot and a higher temperature for the primary star. The implication is that the cooler secondary fills its Roche lobe and is transfering mass to the primary; mass loss to the circumstellar space and possibly to the system may also be appreciable. The temperatures of dwarf novae are derived by comparing their ultraviolet spectral energy distributions with those for normal stars of luminosity classes IV and V. Piecing together observations for different objects, the SS Cyg systems have temperatures of 28 500 K, 10 000 K and 9500 K, respectively, when they are at minimum, immediately before outburst and at the beginning of rise to maximum. At maximum, the temperature is 22 500 K or 17 300 K depending on the interstellar reddening correction for AR And. Immediately before outburst, there is a large excess of flux in the far ultraviolet as indicated by the large value of the ratio of flux at 1550 Å to that at 1800 Å. The observations of Z Cam during standstill gives a temperature of 14 900 K. No excess of flux in the far ultraviolet was observed during the maximum of AR And and the standstill of Z Cam.

We wish to present the first results of the ultraviolet observations of close binary systems with the University of Groningen instrument on board the Astronomical Netherlands Satellite (ANS). The Cassegrain telescope has a light collecting area of 260 cm^2 and provides a field of view of $2.5 \times 2.5'$ with a pointing accuracy of about $0.5'$. The photometric system consists of five energy channels centered at 1550 Å, 1800 Å, 2200 Å, 2500 Å and 3300 Å. The response functions for the channels are almost rectangular with full widths which range from 100 to 200 Å; an additional capability for the 1550 Å channel is that it can be narrowed to 50 Å for monitoring the strength of the CIV λ 1550 line, either in absorption or in emission. A brief account of the instrument and its performance can be found in van Duinen *et al.* (1975).

Ultraviolet observations have been made for a selection of close binary systems such as Algol and β Lyr types of eclipsing binaries, dwarf novae, old novae, symbiotic stars and X-ray binaries. Here, however, only the peculiarities of the light curves of δ Pic, a β Lyr type of eclipsing binary, and the ultraviolet spectral energy distribution of dwarf novae at minimum, rising to maximum and at maximum will be presented and discussed.

1. δ Pictoris

The first observing run of δ Pic was carried out between September 26 and October 4 of 1974. The light curves at the five wavelength bands with the ephemeris of Thackeray (1966) are shown in Figure 1. The error bar for an individual point is smaller than the size of the dot, but occasionally, at separate pointings for the same nonvariable star, the instrument may show instabilities which lead to an inconsistency of ±0.5% for the 3300 Å, 2500 Å and 2200 Å channels and ±2% for the 1800 Å and 1550 Å channels. δ Pic may also be an intrinsic variable as pointed out by Cousins (1966) from the larger than expec-

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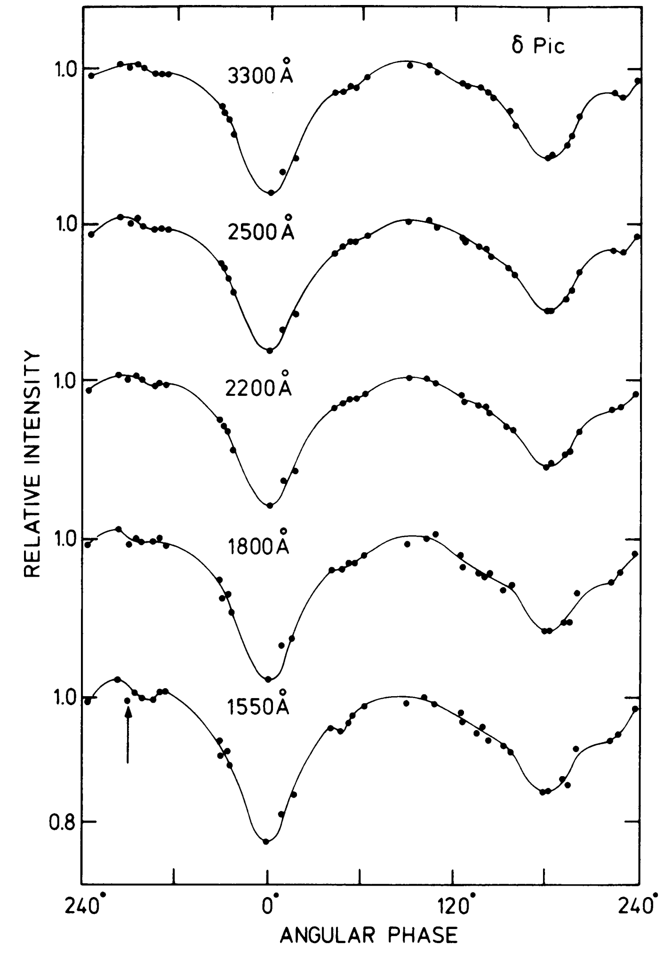

Fig. 1. Light curves of δ Pic with the solid line drawn in by hand. Each individual observation (11 samplings) has an error bar smaller than the size of the dot. The scatter of the data points seems to increase with time and decreasing wavelength, intrinsic variability of the star and instability of the instrument are the suspected causes. The vertical arrow indicates the last observed point. Note the dips near ±60° of both eclipses and that at 1550 Å and 1800 Å the light level before the primary eclipse is higher than that after the eclipse.

ted scatter of his light curve. For some intrinsic variables (e.g., pulsators), the amplitude of variation increases towards shorter wavelengths; therefore, the scatter shown by the light curves may be caused by the combined effect of the instabilities of the instrument and the intrinsic variation of the star.

The light curves show the following features: (1) dips at phases near ±60° of the primary minimum (about −75° and +50°) and to a lesser extend, around the secondary minimum as well. They are also present on the visual light curve (Cousins, 1966) and the ultraviolet light curves from the TD-1A satellite (Evans, 1974). Cousins suggested that there are rings of absorbing material around both stars which give rise to the dips (or shoulders, as he called them). The problem of these 60-deg dips has been discussed by

Wu (1975) who proposes that they are caused by the material temporarily trapped at the triangular Lagrangian points L_4 and L_5 of the restricted three body problem. The depth of the dips seems to be constant except for the 1550 Å channel which shows additional strength. Probably the gas at L_4 and L_5 has a high degree of ionization and electron scattering is the main source of opacity. At 1550 Å, line scattering by C IV λ 1550 further contributes to the optical depth. (2) At 1800 Å and 1550 Å, the light level before the primary eclipse is higher than that after the eclipse, indicating the presence of a hot spot. Assuming the extra flux at 262° angular phase with respect to that at 90° is emitted by the hot spot, the flux ratio F_{1550}/F_{1800}, whose value is 2.18, exceeds the infinite temperature blackbody value of 1.82. The 1550 Å channel was set to the narrow width of 50 Å 12 s after the wide band (width of 149 Å) measurement, and the flux ratio of the two channel widths indicates that C IV λ 1550 is in absorption. Due to the short baseline in wavelength and the roughness of the flux ratio estimate, it is not realistic here to quote a temperature for the hot spot; however, it has a color temperature significantly higher than that of the B0.5 IV (Lesh, 1972) primary, and can be as high as a blackbody temperature of 2×10^5 K at which F_{1550}/F_{1800} is 1.8 and becoming indistinguishable from that of an infinite temperature blackbody. It is of interest to note that, from the abnormally strong He II λ 4686 and the irregular variation throughout the cycle of the He I λ 4713 to He II λ 4686 line ratio, Thackeray (1966) suggested the existence of localized hot spots on the primary. (3) With the absolute energy calibration given by van Duinen *et al.* (1975), the flux ratio F_{1550}/F_{3300} is 6.80 and 6.96, respectively, for the primary and secondary eclipses. Therefore, the fainter secondary component is also cooler. In conclusion, the three features on the ANS UV light curves of δ Pic, namely the F_{1550}/F_{3300} at mid-eclipses, the hot spot and the relatively strong dips, all indicate that the cooler secondary fills its Roche lobe and is transfering mass to the primary; mass loss to the circumstellar space and possibly to the system as a whole may also be appreciable as suggested by the presence of matter at the triangular Lagrangian points L_4 and L_5.

2. Dwarf Novae

For faint objects, like dwarf novae, observations have been made with the offset pointing mode of the satellite attitude control system. This allows each measurement on the star to be sandwiched between two measurements on neighboring sky 5 to 40′ away. An observing sequence typically consists of 6 to 10 pairs of such star-sky measurements each with sampling time of 32 or 64 s. The log of observations and other relevant data are given in Table I. The contents of Table I are self explanatory: column 4 shows the number of observations used, column 5 gives the V magnitudes for the systems at minimum and column 8 is the temperature estimated by comparing the ultraviolet flux distribution with that for normal stars of luminosity classes IV and V. Fluxes are derived by first correcting the net count rates of the object for sensitivity changes in the instrument since launch and for interstellar reddening using the standard extinction curve of Code *et al.* (1975), and then converting into fluxes by means of the laboratory absolute calibration as given by van Duinen *et al.* (1975), except for the 2200 Å channel whose conversion factor has been reduced by 19% due to an increase of the count rate, immediately after launch, of the internal ^{90}Sr Čerenkov calibration source. Instrumental sensitivity change is monitored by observing ϵ Dor at least once a day and assuming it is a non-variable star. The standard

TABLE I

Dwarf novae observed by the ANS

Name	Date	Status	No. of obs	V	E (B−V)	d (pc)	Temp (deg K)
				m	m		
AR And	Jan 28–29 75	maximum	6	17.0	0.15	610	22 500[a]
SS Aur	Mar 22–23 75	minimum	3	14.8	0.06	260	10 000[a]
SS Aur	Mar 23 75	rising	2	14.8	0.06	260	9 500
Z Cam	Apr 5–6 75	standstill	10	14.0	0.04	185	14 900
SS Cyg	Dec 11–13 74	minimum	6	12.1	0.02	80	9 700[a]
U Gem	Apr 16–17 75	minimum	1	14.0	0.04	185	28 000
VW Hyi	May 9–15 75	minimum	6	14.0	0.04	185	28 000
SU UMa	Apr 9–10 75	minimum	4	14.3	0.05	210	29 000

[a] See text.

extinction curve of Code *et al.* (1975) is the same as that of Bless and Savage (1972) in the wavelength range of ANS channels, and $A_\lambda/E(B-V) = 8.16, 7.90, 9.85, 7.30$ and 5.16 respectively for $\lambda = 1550$, 1800, 2200, 2500 and 3300 Å. ANS extinction curves closely reproduce those of Bless and Savage (1972), so that the above values can be used. $E(B-V)$ is estimated by adopting $A_v = 0.8$ mag kpc^{-1} (Allen, 1973) and $R = 3.3$ (Aannestad and Purcell, 1973), and the distance is calculated by using $M_v = 7\overset{m}{.}5$ (Kraft and Luyten 1965) along with the apparent V magnitude at minimum as tabulated in Table I, with one iteration in correcting for the extinction in V. The color excess and distance so calculated are listed in columns 6 and 7 of Table I. Since the observed systems are relatively nearby objects, the reddening correction is small and unlikely to introduce large uncertainty in the energy distribution.

In the following subsections, the flux distributions of several dwarf novae are presented. The temperatures of these systems both at minimum and during outburst are estimated by adopting the temperature scale of Code *et al.* (1975) and the intrinsic $B-V$ colors of Johnson (1963) for normal stars. Here we have assumed that it is valid to equate the temperature of dwarf nova systems with the effective temperature of normal main sequence stars when they have similar spectral energy distribution. Since the flux at 1550 Å may be affected by the C IV line in emission, it is not used for deriving the temperature. Because of the faintness of the objects at 3300 Å, the narrow width of this channel (100 Å), and its high susceptibility to the background particle radiation, the net count rate of this channel is sometimes low and of marginal significance; consequently the flux at 3300 Å is not always plotted in the figures presented below.

2.1. SS CYG, U GEM, VW HYI AND SU UMA AT MINIMUM

Figure 2 gives the energy distributions, normalized at 1800 Å, of the four dwarf novae at minimum, compared with normal stars. U Gem, VW Hyi and SU UMa resemble O9.5–B1.5 stars, and the temperature is estimated to be 28 500 (±3500) K. The value inside the parentheses is the range of temperature indicated by the range of spectral type. SS Cyg does not seem to conform to the pattern of the others, as it has a much higher F_{1550}/F_{1800} ratio. Part of this may be due to C IV λ 1550 in emission; and the ratios for other channels may be influenced by its relatively bright secondary and by a nearby field star (1.2′ away), both of which have comparable visual brightness with the primary during minimum. The high F_{1550}/F_{1800} ratio for SS Cyg, whether it be due to the C IV

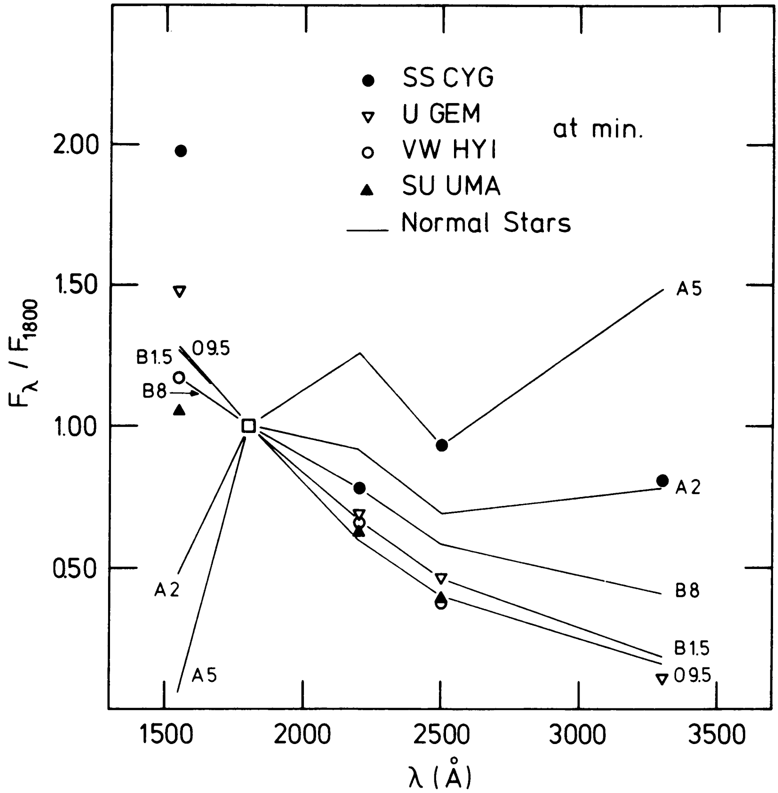

Fig. 2. The comparison of the spectral energy distribution between SS Cyg, U Gem, VW Hyi and SU UMa at minimum and normal stars of luminosity classes IV and V.

line in emission or to a large excess in the far UV, suggests that high temperature region(s), say the hot spot and/or the region immediately next to the white dwarf surface (SS Cyg has low orbital inclination) are visible. It is significant that Heise *et al.* (1975) detected SS Cyg in the soft X-ray region during its minimum (3.1×10^{-12} erg cm^{-2} s^{-1}).

Figure 3 demonstrates the flickering of SS Cyg during minimum. The F_{1550}/F_{1800} ratio increases with increasing flux at 1550 Å. As pointed out earlier, the high flux ratio may be partially due to C IV λ 1550 in emission, but according to Walker and Chincarini (1968), emission line strength does not participate in the flickering of SS Cyg, so that when F_{1550} is higher, the additional flux is continuum radiation. As in the case of U Gem (Warner and Nather, 1971) and Z Cha (Warner, 1974), the flickering activity is shown to be associated with the hot spot. The temperature of the hot spot is higher than the mean temperature of the disk and it is probably independent of the instantaneous rate of mass inflow. However, an increase in mass inflow will brighten up the hot spot relative to the disk and gives the system a higher ratio of F_{1550}/F_{1800}. In Figure 3, two solid lines indicating the F_{1550}/F_{1800} ratio of an infinite temperature blackbody and the hot spot of δ Pic are drawn for comparison. In the case of δ Pic, the high ratio is not due to emission at the C IV λ 1550 line.

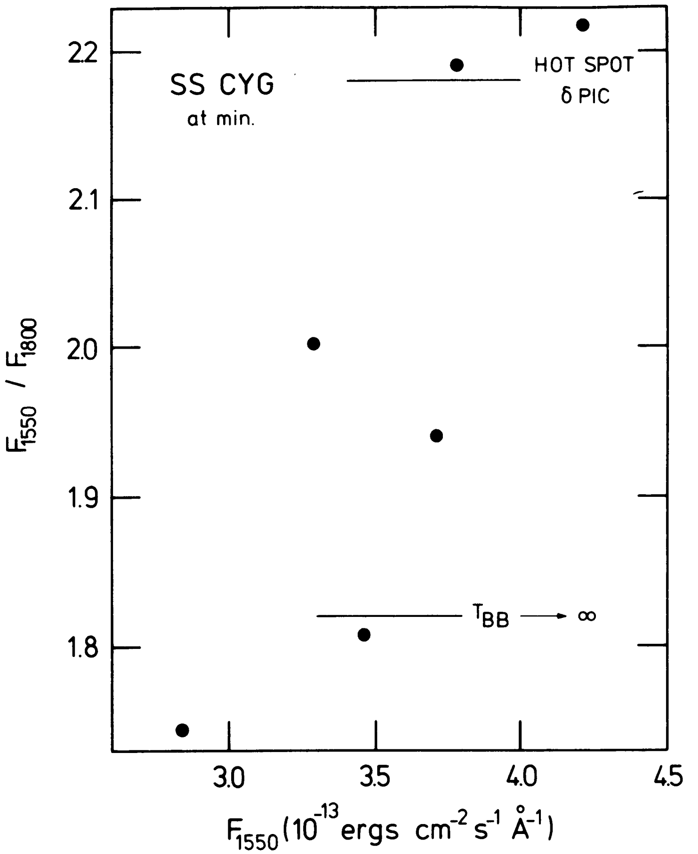

Fig. 3. The flickering of SS Cyg during minimum. It seems that the hot spot which is thought to be the seat of flickering is bluer when it is brighter.

2.2. SS AUR DURING RISE TO MAXIMUM

Within 24 h before the onset of the rapid increase of flux in the UV, SS Aur was observed three times. As shown in Figure 4 (solid dots), a huge far ultraviolet excess was indicated by the large F_{1550}/F_{1800} ratio. Unfortunately, it had not been the general practice to monitor the behavior of the C IV λ 1550 line when the dwarf nova systems were observed for the first time. However it is unlikely that the λ1550 can be strongly in emission, if at all, because during the onset of the optical outburst the usual emission line spectrum observed during minimum is replaced by an absorption spectrum (Krzeminski, 1965; Walker and Chincarini, 1968). Note that the F_{1550}/F_{1800} ratio is 2.44 which is above the infinite temperature blackbody value of 1.82. Therefore, shortly before the onset of the outburst, there is a rapid rise of flux towards the extreme ultraviolet and possibly soft X-ray regions of the spectrum. Simultaneous soft X-ray measurements were made with these ultraviolet observations, but no significant flux was detected: Heise *et al.* (1975) gave a 3σ upper limit of 2.9×10^{-12} erg cm^{-2} s^{-1}. It is likely that the inclination of the disk is sufficiently high for the soft X-rays to be self-absorbed. Longward of 1800 Å,

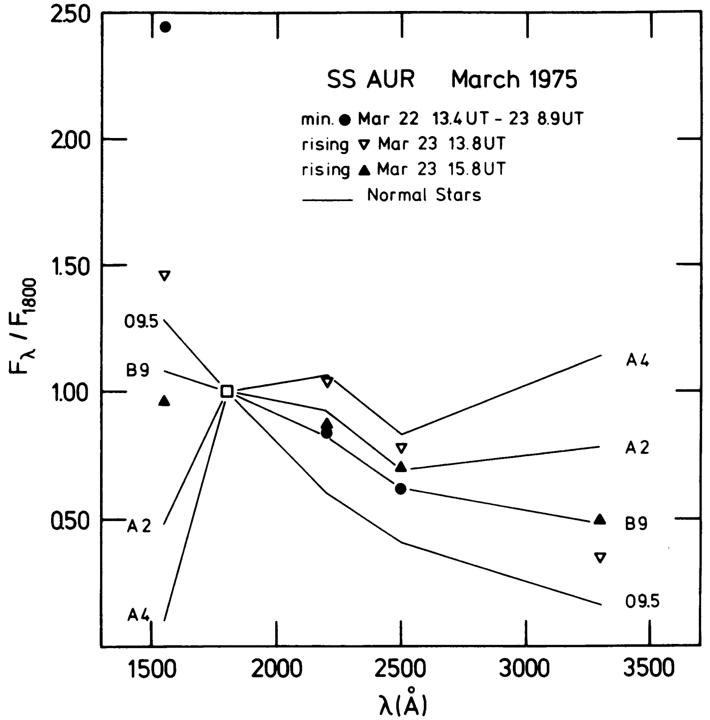

Fig. 4. SS Aur during transition. The filled circles indicate the spectrum immediately before outburst (3 observations in a period of 20 h. Note the huge far ultraviolet excess as indicated by the F_{1550}/F_{1800} ratio. The triangles (filled and unfilled) are observations which show large and rapid increases of flux at all 5 channels, but the large excess of flux at 1550 A has disappeared.

the spectrum is about B9 (~10 000 K) which is substantially redder than due O9.5–B1.5 type of flux distribution during minimum. Two measurements were made two hours from each other and six hours after the last of three measurements made when the system was still at minimum. They showed a large and rapid increase of flux in all channels, but the F_{1550}/F_{1800} ratio had decreased to such an extent that the far UV excess had disappeared. Furthermore, the system continued to redden and looked like a B8 to A4 star, indicating a temperature of about 9500 K.

2.3. AR AND AT MAXIMUM AND Z CAM AT STANDSTILL

As shown in Figure 5, AR And has a temperature of 22 500 ± 1500 K (B2–B2.5 IV–V star) during outburst and Z Cam is 14 900 ± 900 K (B4–B6 IV–V star) at standstill. The ratio of F_{2200}/F_{1800} for both systems is above that for the normal stars; it seems unlikely that this is the result of over-correcting for the interstellar reddening. The reddening correction applied to Z Cam is for $E(B-V)$ of 0.04, which is small, and the F_{2200}/F_{1800} ratio will still be higher than the value for normal stars even if no correction is made. Therefore, in the case of Z Cam, uncertainty introduced by interstellar extinction is small. As for AR And, it is possible that $E(B-V)$ of 0.15 is an overestimate and the temperature given above is too high. If we assume F_{2200}/F_{1800} to be the same for AR And

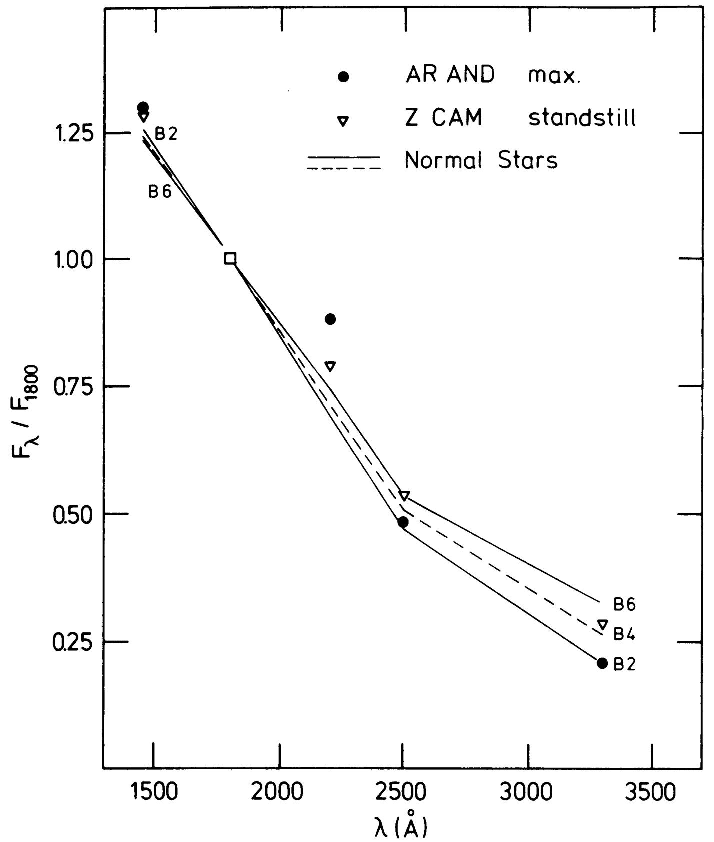

Fig. 5. AR And at maximum and Z Cam at standstill. No large excess in the far UV is evident. See text for the discussion of the interstellar extinction correction.

and Z Cam, then $E(B-V)$ = 0.08 for AR And and a temperature of 17 300 ± 800 K (B3–B4 IV–V star) is derived. The quoted uncertainty in temperature reflects only the range of spectral type indicated by the flux distribution of the system. So it seems that Z Cam at standstill is slightly cooler than AR And during outburst. However, it is not certain at this moment that the standstill of the Z Cam subtype is in general at a lower temperature than the outburst of the SS Cyg subtype. Another point of interest in Figure 5 is the lack of far ultraviolet excess as indicated by the normal F_{1550}/F_{1800} ratio.

Figure 6 gives the light curve of AR And during outburst. The spectral energy distribution shown in Figure 5 is for the highest point in Figure 6. Finally, Figure 7 shows that there is no significant change of temperature at maximum and subsequent early stages of decline.

In summary, we have observed the minimum, rising and maximum states of activity for seven dwarf nova systems. Assuming it is valid to piece together observations of dif-

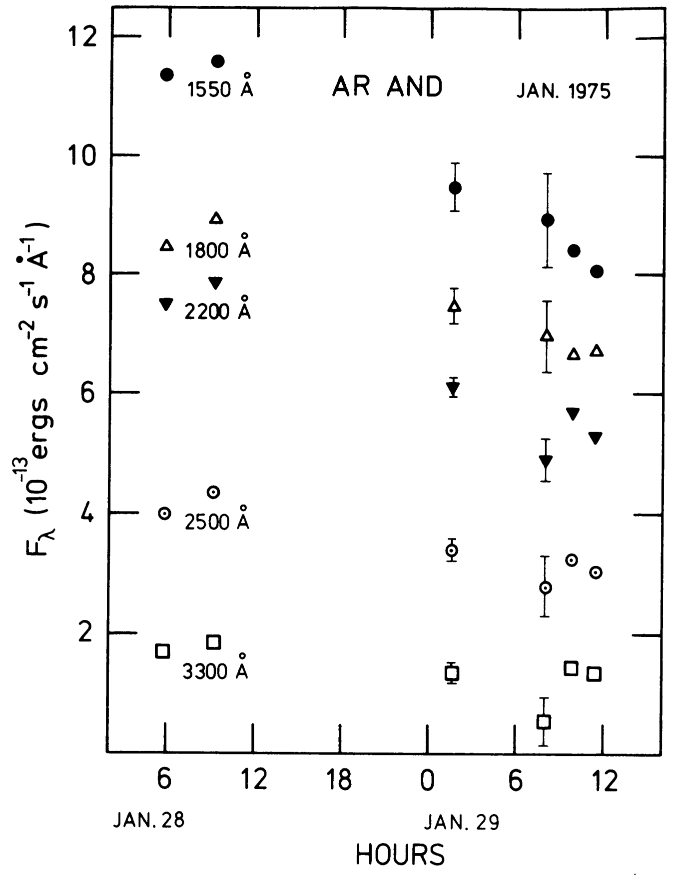

Fig. 6. The light curve of AR And during outburst. The larger error bars are for the one observation made with the 16-s sampling time. The other five observations have the 64-s sampling time and the smaller error bars are representative for all five.

ferent systems, then the following scenario emerges. An SS Cyg type of dwarf nova at minimum has a temperature of 28 500 K. Shortly before outburst (here defined as the brightening between 1550 and 3300 Å), the system has cooled to about 10 000 K, but this is accompanied by a large far ultraviolet excess. During the rise to maximum, the system continues to redden to a temperature of about 9500 K and the excess flux at 1550 Å has rapidly decreased. At maximum, it is 22 500 K or 17 300 K depending on the interstellar extinction correction for AR And, and there is no far ultraviolet excess in the spectrum. It is of interest to compare our results with those from OA0-2. For SS Cyg Holm and Gallagher (1974) reported 22 000 ± 5000 K, 16 000 K and 19 200 ± 3000 K respectively, for the minimum, rise to maximum and maximum states. As for Z Cam type of dwarf novae, only Z Cam itself has been observed during standstill and a temperature of 14 900 K is derived.

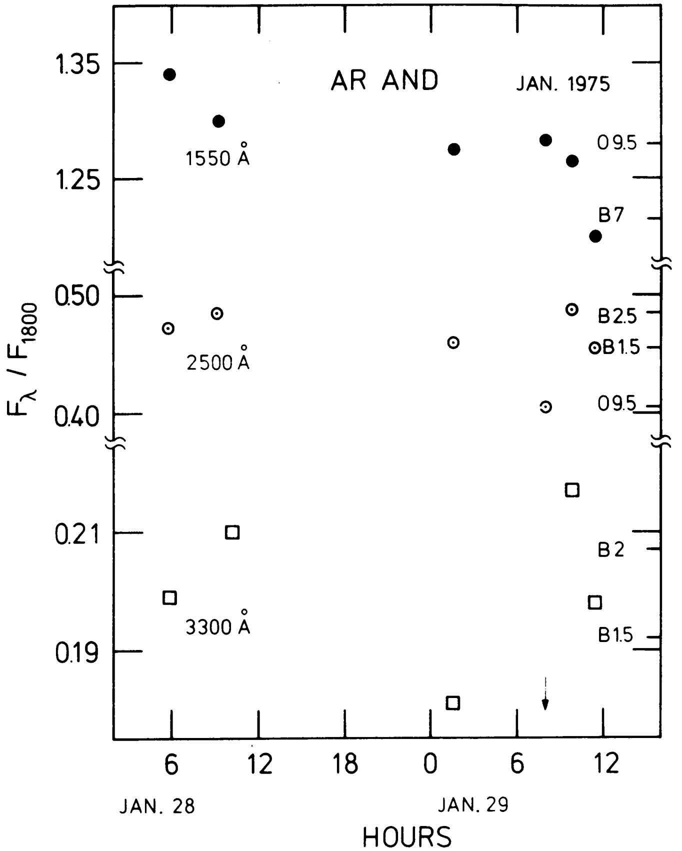

Fig. 7. Flux distribution of AR And at maximum. Giving a lower weight to the observation with the 16-s sampling time, no appreciable change in the spectral energy distribution is evident. The vertical arrow indicates that the point for F_{3300}/F_{1800} is below the scale of this graph.

Acknowledgements

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References

Aannestad, P. A. and Purcell, E. M.: 1973, *Ann. Rev. Astron. Astrophys.* **11**, 309.
Allen, C. W.: 1973, *Astrophysical Quantities*, Athlone Press, London.
Bless, R. C. and Savage, B. D.: 1972, *Astrophys. J.* **171**, 293.
Code, A. D., Davis, J., Bless, R. C., and Hanbury Brown, R.: 1975, *Astrophys. J.* (submitted).
Cousins, A. W. J.: 1966, *Monthly Notices Roy. Astron. Soc.* **131**, 443.

Duinen, R. J. van, Aalders, J. W. G., Wesselius, P. R., Wildeman, K. J., Wu, C. C., Luinge, W., and Snel, D.: 1975, *Astron. Astrophys.* **39**, 159.
Evans, R. G.: 1974, *Monthly Notices Roy. Astron. Soc.* **167**, 517.
Heise, J., Brinkman, A. C., Schrijver, J., Mewe, R., Groneschild, E., and Boggende, A. den: 1975, (preprint).
Holm, A. V. and Gallagher, J. S., III: 1974, *Astrophys. J.* **192**, 425.
Johnson, H. L.: 1963, in K. Aa. Strand (ed.), *Basic Astronomical Data*, Univ. of Chicago Press, Chicago, p. 204.
Kraft, R. P. and Luyten, W.: 1965, *Astrophys. J.* **142**, 1041.
Krzeminski, W.: 1965, *Astrophys. J.* **142**, 1051.
Lesh, J. R.: 1972, *Astron. Astrophys. Suppl.* **5**, 129.
Thackeray, A. D.: 1966, *Monthly Notices Roy. Astron. Soc.* **131**, 435.
Walker, M. F. and Chincarini, G.: 1968, *Astrophys. J.* **154**, 157.
Warner, B.: 1974, *Monthly Notices Roy. Astron. Soc.* **168**, 235.
Warner, B. and Nather, R. E.: 1971, *Monthly Notices Roy. Astron. Soc.* **152**, 219.
Wu, C.-C.: 1975, *Astrophys. Space Sci.* (in press).

DISCUSSION

Rucinski: My remark concerns the possibility that perhaps the Roche geometry is involved in producing the absorption dips observed in UV in δ Pic. The Roche critical surfaces intersect at L_1 at an angle close to 57°; this angle is independent of the mass-ratio. Could not it be the gaseous matter between stellar surfaces and critical Roche surfaces that produces these absorptions?

Wu: In order for matter at L_1 to produce dips near ±60° of both eclipses, it requires both stellar components to fill their Roche lobe (contact system). This condition cannot be satisfied by Algol systems which are semi-detached, and especially not by DQ Her which is an old nova and has a very small primary. In fact, the eclipses caused by matter at L_1 fall inside the primary and secondary eclipses; they cannot cause dips in the light curve.

Geyer: You explain the 60° dips in the light curves with absorption of matter in or around the Lagrangian points L_4, L_5. To explain the variations of the light curves of XY UMa, I was also thinking of lumps of matter (absorbing and scattering) in the ovals of these Lagrange points. But according to celestial mechanics this is only possible if the mass ratio of the binary components is smaller than 0.4. This is the case in the Sun-Jupiter system, therefore the Trojan planetesimals can exist.

Wu: Mass accumulation at L_4 and L_5 is a transient phenomenon as indicated by the varying depths of the dips observed at different cycles, and sometimes the dips may even be absent. So, indeed, for the mass ratio appropriate for Algol systems, L_4 and L_5 are not permanently stable points.