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A PHOTOMETRIC STUDY OF DWARF NOVAE

Juan Echevarría
Royal Greenwich Observatory
and Astronomy Centre University of Sussex

and

Derek Jones
Royal Greenwich Observatory

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RESUMEN

Se presenta un catálogo de Fotometría Fotoeléctrica *UBVRI* de novas enanas obtenida de la literatura y se compara el diagrama color-color con resultados teóricos de discos de acreción en estado estacionario. Se discute además una correlación entre la magnitud *V* y el ancho de la discontinuidad de Balmer.

ABSTRACT

A catalogue of *UBVRI* photoelectric photometry of dwarf novae available in the literature is presented. A comparison with theoretical colour-colour diagrams from steady state discs is made. A correlation of *V* magnitude with the depth of the Balmer discontinuity is discussed.

Key words: **STARS-DWARF NOVAE – PHOTOMETRY**

I. INTRODUCTION

Photoelectric photometry of dwarf novae has been steadily accumulating during the last twenty five years since Walker's (1954) discovery of flickering in the nova-like object MV Lyr. However most of the observational effort was directed towards fast photoelectric photometry in the *V* or *B* bands rather than simultaneous *UBV* photometry. This is because the occurrence of eclipses in some cataclysmic variables provide an alternative to spectroscopic determinations, of obtaining orbital periods. The *UBV* photometry on the other hand is a convolution of the light of several sources including the disc, hot spot and secondary, and therefore its interpretation is difficult.

Old observations of SS Cyg in outburst by Grant and Abt (1959) show similar colours to those of novae and nova-like objects except during the rising branch when the star has a considerable defect in $(U–B)$. Zuckermann (1962) found two different types of outbursts. One similar to that of Grant and Abt, and a second with only a small defect in $(U–B)$. Chuvayev (1962) finds similar results. More evidence that dwarf novae undergo a loop in the colour-colour diagram was gathered by Paczynski (1963) for WW Cet; Krzeminsky (1965) for U Gem; Pugach (1974) for Z Cam; and more recently by Haefner Schoembs, and Vogt (1979) for VW Hyi. Bailey (1980) discussed these loops for SS Cyg and VW Hyi in terms of accretion models in which a sudden increase in mass transfer favours the outer cooler parts of the disc at the beginning of the outburst (cf. Bath *et al.* 1974; Pringle (1974). Optical and infrared photometry of several dwarf novae by Szkody (1976*a,b*, 1977) show a typical flux distribution at different stages: a steep slope during outburst and a flatter distribution at minimum. Exceptions to this are AB Dra and Z Cam. Szkody compares free-free emission with different contributions from the secondary for each object. *UBVRI* observations on other dwarf novae carried out by Jones *et al.* (1982) also show a flux distribution at maximum steeper than at minimum.

Several disc models are available to compare with the *UBV* observations. Schwarzenberg-Czerny and Rozyczka (1977), Herter *et al.* (1979*a*), Mayo, Wickramasinghe, and Whelan (1980), Schwarzenberg-Czerny (1981), Bath and Pringle (1981) and Tylenda (1981) have calculated theoretical points in the $(U–B, B–V)$ diagrams from their models. Although some comparison with observations is made, they have not used most of the data of dwarf novae from the literature. As no recent analysis of the *UBV* observations has been made it seems appropriate to us to compile a catalogue and present a discussion of some aspects of it, and to compare the $(U–B, B–V)$ diagram with theory. The catalogue includes *R* and *I* observations and is available from the authors.

II. THE DATA

A search in the literature for broad band quasi-simultaneous *UBVRI* observations has yielded in the thirty six dwarf novae presented in Table 1. *V* magnitudes in brackets are non-photometric observations. Only *UBV* Johnson magnitudes are presented. *RI* (Kron-Cousins) and rR_2 (modified Sandage-Smith) observations are also presented. A description of both systems can be found in Jones *et al.* (1982) and Szkody (1976*b*) respectively. No attempt has been made to standardize or weight the data. Instead we have collected every single observation. In a few cases several observations in a same day were found and these are also included.

A plot of (U–B, B–V) for all dwarf novae is shown in Figure 1. There is a well defined quiescent branch (open circles) which covers most of the (B–V) values. The concentration of points around (B–V)∿ 0.0, (U–B)∿ –0.8 corresponds to maximum. Below them lies the rising region. As outburst begins some objects show a considerable decrease in (U–B), so making a loop in the colour-colour diagram. This is shown in Figure 2 for AH Her.

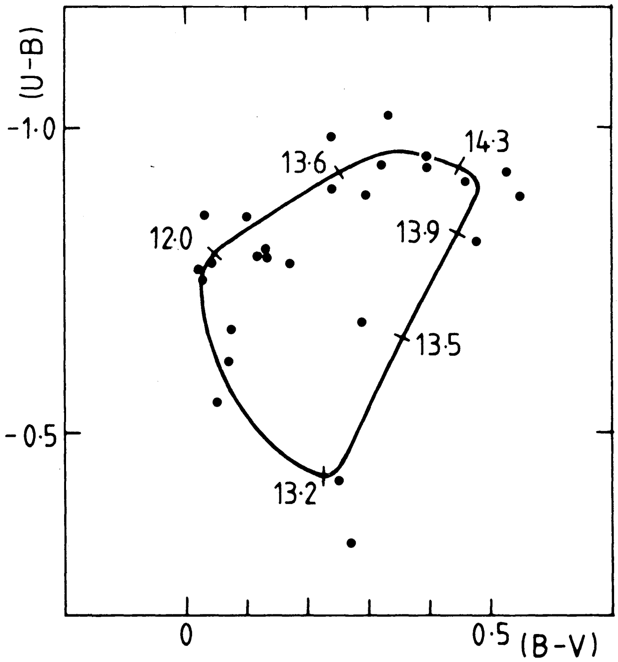

Fig. 2. Colour-colour diagram of AH Herculis. The *V* magnitude change during the outburst loop is shown.

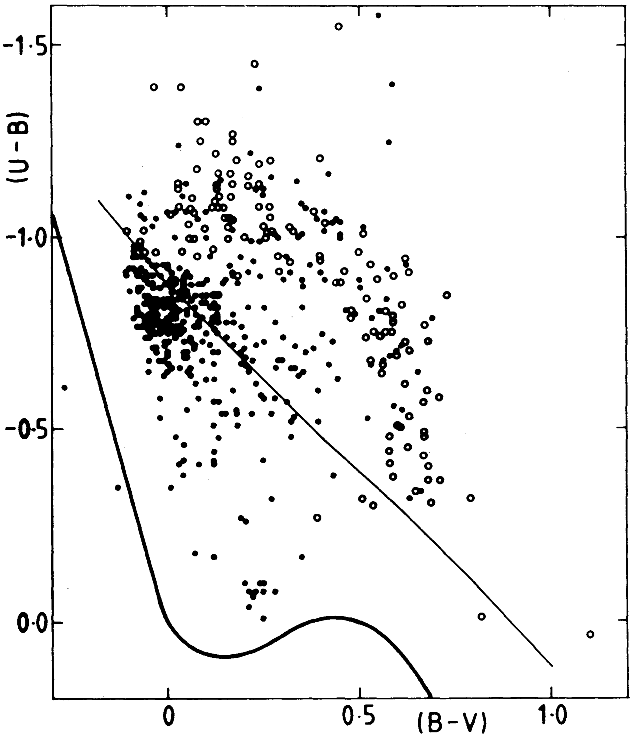

Fig. 1. Colour-colour diagram of dwarf novae. Open circles are observations at minimum. Filled circles are observations during outburst. The main-sequence and blackbody lines are shown.

III. DISCUSSION

a) *Interstellar Reddening*

No attempt has been made to correct colours for interstellar reddening. There is little evidence of a substantial E(B–V) in most dwarf novae. As we do not know for certain the intrinsic colours of the total light from those systems we cannot estimate the E(B–V) as in the case of single stars, but ultraviolet observations of the 2200 Å interstellar feature indicate low values. Szkody (1981) from a study of eight dwarf novae finds that no reddening correction is necessary except for RX And and AB Dra with E(B–V)∿ 0.1. More evidence of low extinction values are given for WZ Sge (Holm *et al.* 1980); RU Peg (Krautter *et al.* 1981); VW Hyi and EX Hya (Bath, Pringle and Whelan 1980). Bath *et al.* find an E(B–V)∿ 0.1 for BV Cen but Vogt and Breysacher (1980) argue that at a distance of probably 500 pc, BV Cen should have a much greater value of ∿ 0.32. TZ Per has E(B–V)∿ 0.3 (Krautter, private communication). Another candidate to have a considerable amount of reddening is UZ Ser. Echevarría *et al.* (1981) find an upper limit of E(B–V)∿ 0.1. However more recent ultraviolet observations (Pringle, private communication) show an E(B–V)∿ 0.3 in accord with the figures considered by Herbig (1944).

The galactic distribution of the dwarf novae studied in this paper is presented in Figure 3. They are widely

TABLE 1

PHOTOMETRIC DATA OF DWARF NOVAE

Name	Subclass	V_{max} V_{min}	Description*	References
AR And	UG	(11.0 - 17.3)	*UBVRI*	1
DX And	. .	(10.9 - 16.4)	*UBVRI*	1
RX And	ZC	10.77 - 13.70	*UBVRI*	1,3,20,21,23
SS Aur	UG	(10.5 - 14.8)	*UBV*	3
Z Cam	ZC	10.45 - 13.77	*UBVRI*	5,10,21,23
SY Cnc	SC	(10.6 - 14.0)	*UBVRI*	1
YZ Cnc	SU	12.48 - 14.96	*UBVRI*	1
HT Cas	UG	(12.6 - 17.0)	*UBVRI*	1
BV Cen	UG	(10.5 - 14.2)	*UBV*	16,25
MU Cen	UG	(12.4 - 15.3)	*UBV*	16,25
WW Cet	ZC	(12.2 - 15.5)	*UBVRI*	1,6,27
Z Cha	SU	(11.7 - 17.0)	*UBV*	16
BP CrA	. .	...	*UBV*	16
EM Cyg	ZC	(11.9 - 14.0)	*UBV*	9,19
SS Cyg	UG	8.42 - 12.10	*UBVRI*	1,3,4,11,14,15 17,20,21,22,23
AB Dra	ZC	(12.0 - 15.5)	*UBVRI*	3,21,23
U Gem	UG	9.46 - 14.71		1,8
AH Her	ZC	11.71 - 14.70	*UBVRI*	1,21,22,23
EX Hya	VG	(11.5 - 13.5)	*UBV*	7,16
VW Hyi	SU	9.06 - 14.38	*UBVRI*	1,13,16,18
WX Hyi	SU	11.64 - 14.96	*UBVRI*	1,26
T Leo	UG	(10.0 - 15.4)	*UBV*	9
X Leo	UG	(11.9 - 15.5)	*UBVRI*	1
HP Nor	ZC	(12.9 - 15.5)	*UBVRI*	1,16
CN Ori	ZC	(11.8 - 15.0)	*UBVRI*	1,9
CZ Ori	UG	(11.8 - 15.0)	*UBVRI*	1
RU Peg	UG	(10.0 - 13.3)	*UBVRI*	1,3
KT Per	ZC	(11.5 - 15.4)	*UBVRI*	1,
TZ Per	ZC	(11.9 - 15.6)	*UBVRI*	1,3,23
BV Pup	UG	(13 - 15.4)	*UBV*	16
WZ Sge	WZ	(7.0 - 16.1)	*UBV*	12
UZ Ser	UG	(12.0 - 16.7)	*UBVRI*	1.24
EK TrA	SU	(11.9 - <17)	*UBV*	2
SU UMa	SU	(11.0 - 14.8)	*UBVRI*	1,3
BB Vel	UG	(13.3 - 15.5)	*UBV*	16
TW Vir	UG	(11.8 - 16.3)	*UBVRI*	1

* *RI* refers to Kron-Cousins and modified Sandage-Smith systems. See text for details.

1. Jones *et al.* 1982
2. Vogt and Semeniuk 1980
3. Mumford 1966
4. Walker 1957
5. Kraft, Krzeminski, and Mumford 1969
6. Paczynski 1963
7. Mumford 1967*a*
8. Krzeminski 1965
9. Mumford 1967*b*
10. Pugach 1974
11. Chuvayev 1962
12. Bruch 1980
13. Haefner, Schoembs and Vogt 1979
14. Lyutyi 1976
15. Grant and Abt 1959
16. Mumford 1971
17. Zuckermann 1962
18. Walker and Marino 1978
19. Mumford and Krzeminski 1969
20. Szkody 1974
21. Szkody 1976*a*
23. Szkody 1977
24. Echevarría *et al.* 1981
25. Marino and Walker 1972
26. Marino and Walker 1978
27. Marino and Walker (in Bateson 1979)

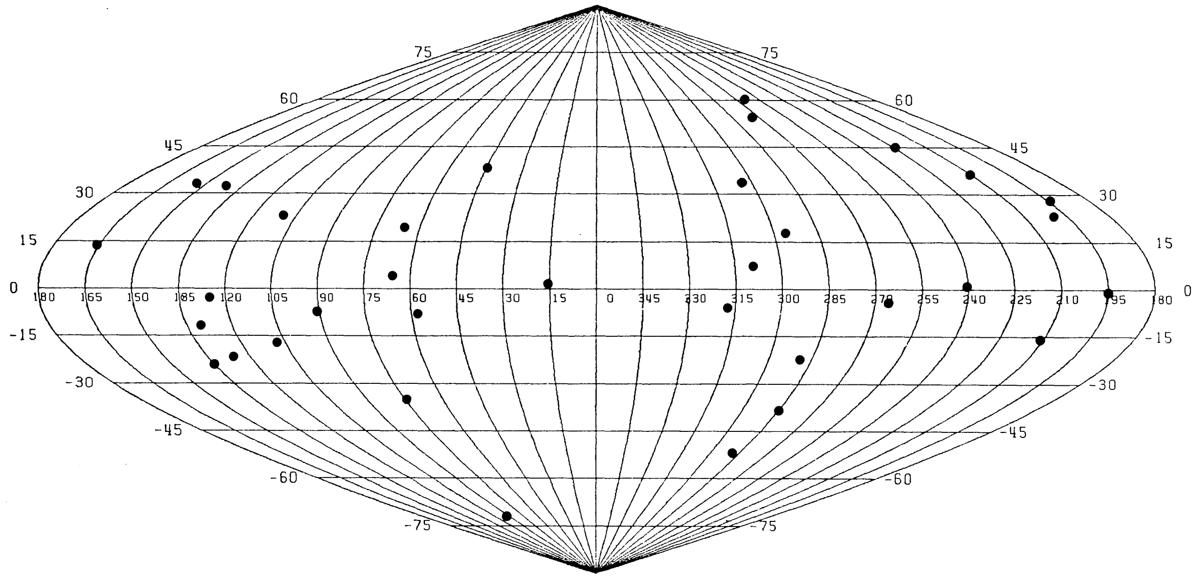

Fig. 3. Galactic distribution of dwarf novae with *UBV* photometry.

distributed in galactic latitude b and only a few are within 10° of the galactic equator, including UZ Ser, BV Cen, WZ Sge and EM Cyg. SS Cyg is also near the galactic plane, but at a distance of $\sim$ 100 pc no appreciable reddening is expected. It would be interesting to obtain ultraviolet spectra of the other systems with $|b| < 10^{\circ}$ (HT Cas, HP Nor, BV Pup, EK TrA and BB Vel) and to measure the colour excess. As dwarf novae at minimum are intrinsically faint we do not expect to see them very far away and therefore the interstellar absorption must be, except for a few cases, very little.

b) *Comparison of Theoretical Colours with Observations*

The theoretical $(U-B)$ and $(B-V)$ colours for several disc models is shown together with the observations in Figure 4. The dotted lines separate the quiescent branch, maximum and rising regions. These limits as well as the outer boundary limit (solid line) are only crude estimates. A few points have been left out. These are isolated observations of AB Dra at $(B-V) \sim 1$, VW Hyi and WX Hyi (below the main sequence) and SU UMa at $(U-B) < -1.4$. More observations are needed to confirm them.

Mayo *et al.* (1980) calculate the emitted spectrum of a plane-parallel atmosphere in a steady-state optically thick disc. They have good agreement with observations at maximum. The best models are their discs *b* (see their Figure 5 and Table 3). The physical parameters of discs *b*, have all white dwarf masses of one solar mass, inner radius $R_1 = 10^9$ cm and mass flux transfer $\dot{M} = 6 \times 10^{-15}$ g s^{-1}. The outer radius varies from 4.4×10^9 cm to 9.6×10^9 cm and the outer temperature run from 10 000 to 5901 °K. Greater outer radii or mass fluxes

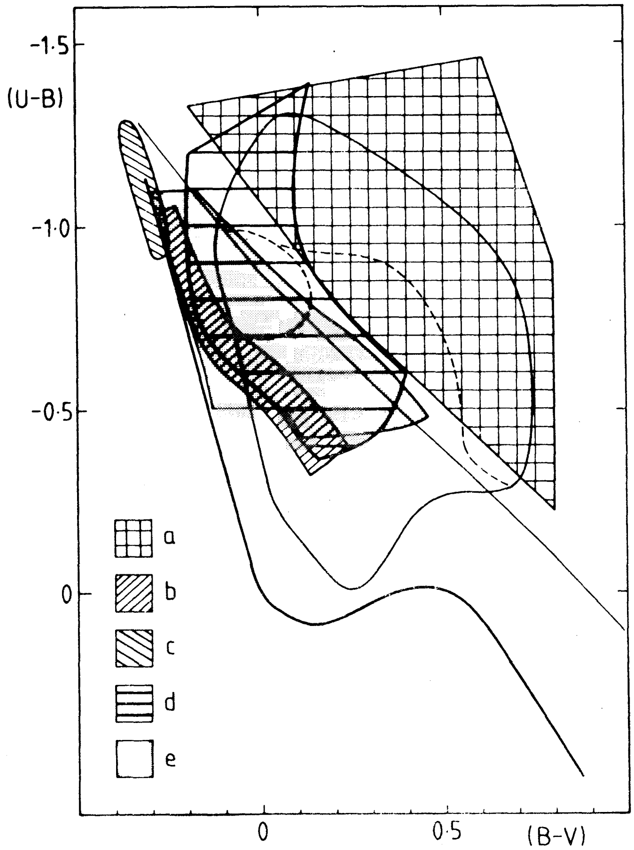

Fig. 4. Observational and theoretical $(U-B, B-V)$ diagram. Models between the main-sequence and black body lines are optically thick. a) Tylenda 1981; b) Schwarzenberg-Czerny and Rozyczka 1977; c) Herter *et al.* 1979; d) Schwarzenberg-Czerny 1981; Mayo *et al.* 1980.

(models *a*) put the colours above and outside the observational region. On the other hand, models *c* with white dwarf masses of 0.5 $M_\odot$, $R_1 = 1.5 \times 10^9$ and $\dot{M} = 6 \times 10^{15}$ g s^{-1} lie below maximum but inside the rising region.

Using a model atmosphere Herter *et al.* (1979) calculate the emergent spectrum of optically thick discs. The synthetized colours occupy a region (see Figure 4) near the main sequence and are too blue in both $(B-V)$ and $(U-B)$ with respect to maximum events. There is some

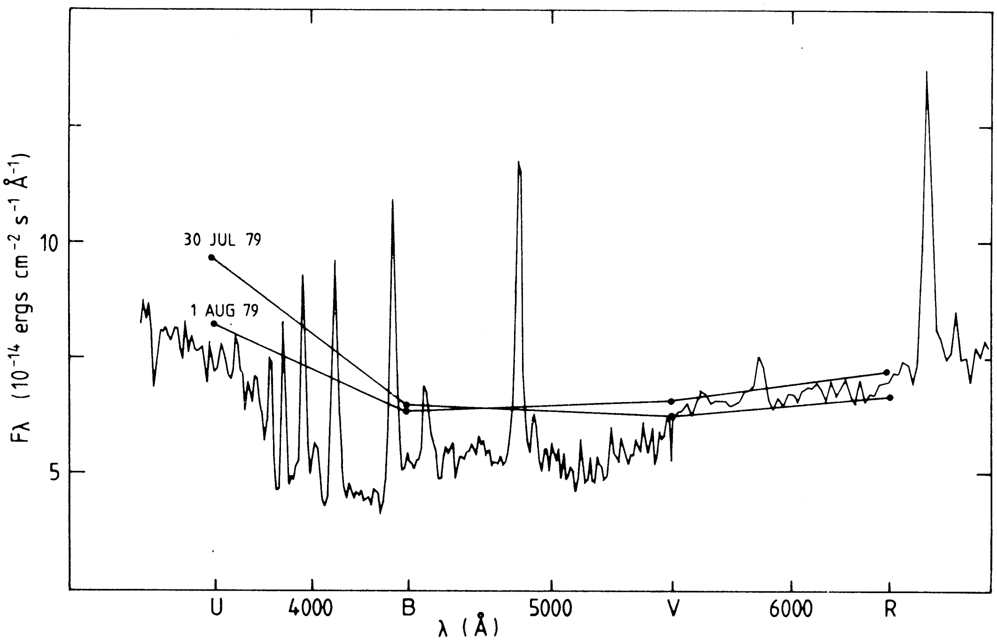

Fig. 5. Spectrum of SS Cyg (Kiplinger 1979) and *UBVR* photometry (Jones *et al.* 1982; at minimum.

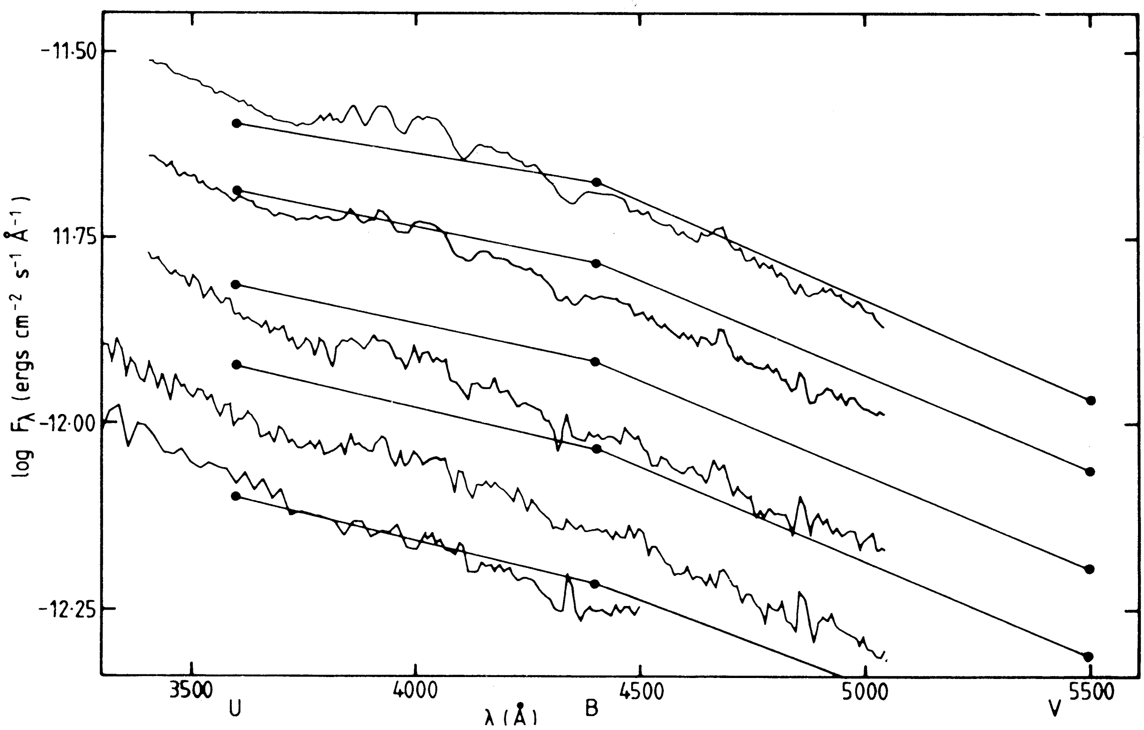

Fig. 6. Spectra of SS Cyg (Kiplinger 1979) and *UBV* photometry (Chuvayev 1962) during decline from maximum.

overlap with models *a* of Mayo *et al.* The *UBV* colours calculated by Schwarzenberg-Czerny and Rozyczka (1977) occupy a rather large and thin area as also shown in Figure 4. No agreement with observations near maximum is achieved. More recently Schwarzenberg-Czerny (1981) has taken into account the optically thin emission from a chromosphere of the disc. His models are in agreement with dwarf novae during outburst and also with the bluest objects at minimum.

Tylenda (1981) calculates theoretical colours over a wide range of physical parameters in a steady state disc. The optical depth is essentially a free parameter described by the transfer equation in a plane parallel atmosphere with LTE. It is found that the optical depth is small in the continuum (i.e., an optically thin region is formed) at the outer parts of the disc when a suitable combination of mass transfer and outer radius is chosen. In general low-mass transfer and big outer radius yield optically thin outer regions. The emission lines however are not optically thin. The match with observations at minimum is excellent as shown in Figure 4. A full discussion of observations at minimum and a comparison with the models of Tylenda will be given elsewhere (Echevarría and Jones 1982).

c) *The Balmer Discontinuity during Outburst*

Photometric observations of several dwarf novae at minimum by Szkody (1976) and Jones *et al.* (1982) show the observed fluxes F_λ with a much steeper slope at $\lambda <$

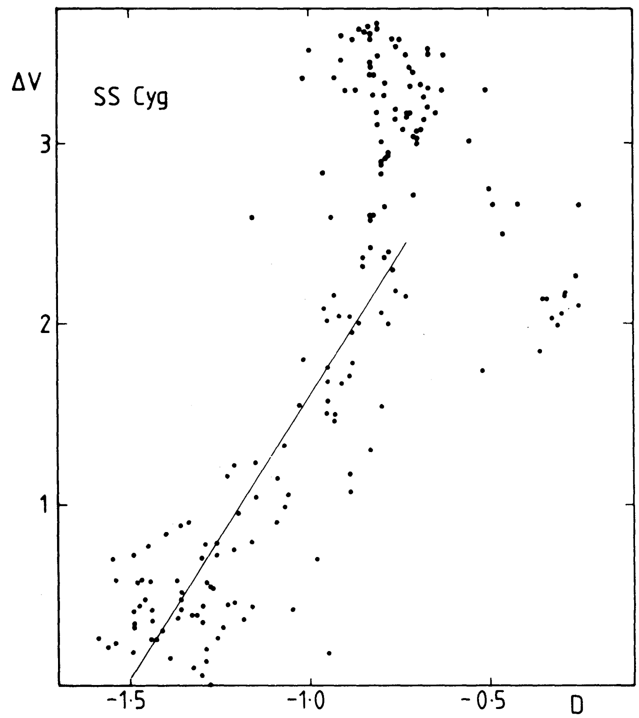

Fig. 8. Balmer discontinuity index versus change in visual magnitude for SS Cyg (see text).

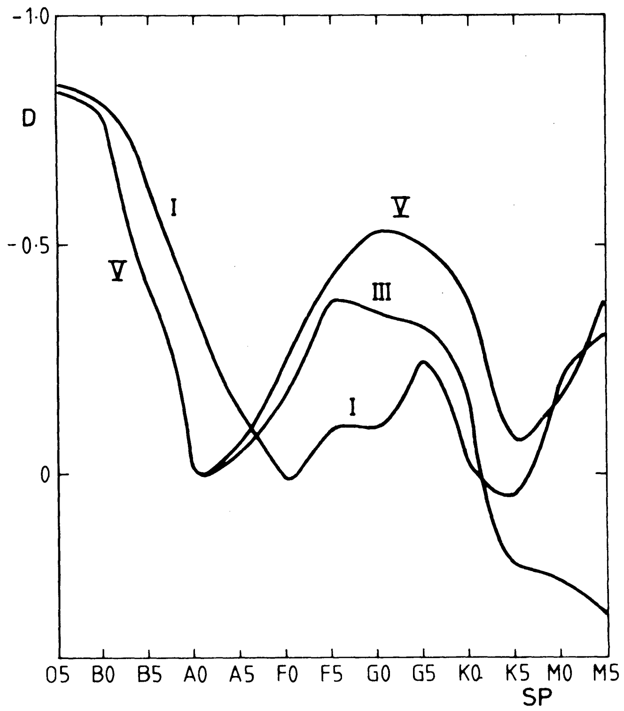

Fig. 7. Balmer discontinuity index $D = (U-B, B-V)$ versus spectral type for stars with different luminosity classes.

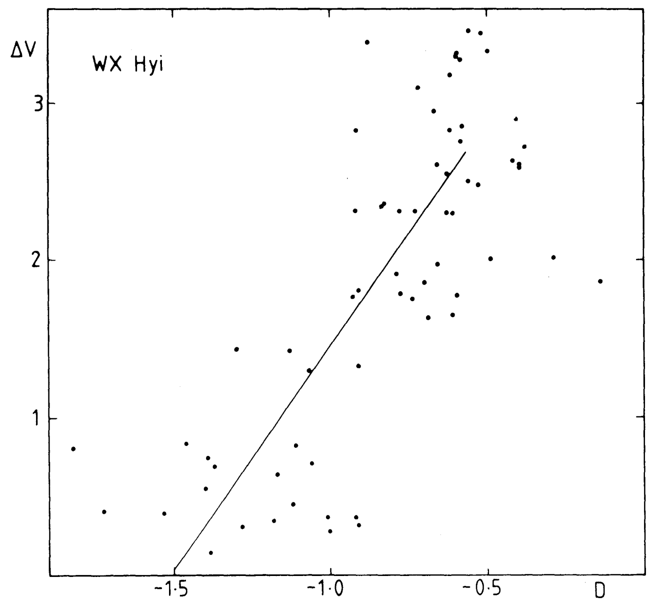

Fig. 9. Balmer discontinuity index versus change in visual magnitude for WX Hyi (see text).

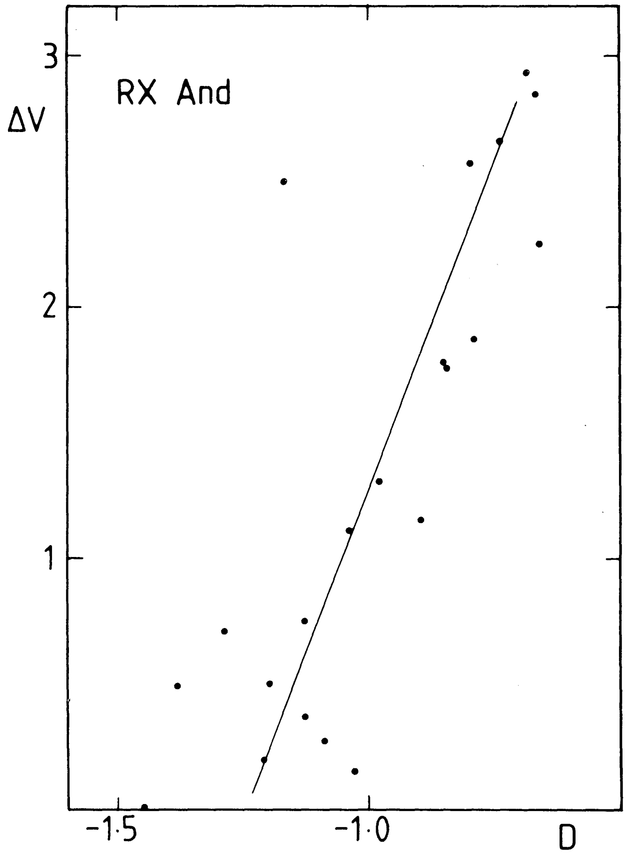

Fig. 10. Balmer discontinuity index versus change in visual magnitude for RX And (see text).

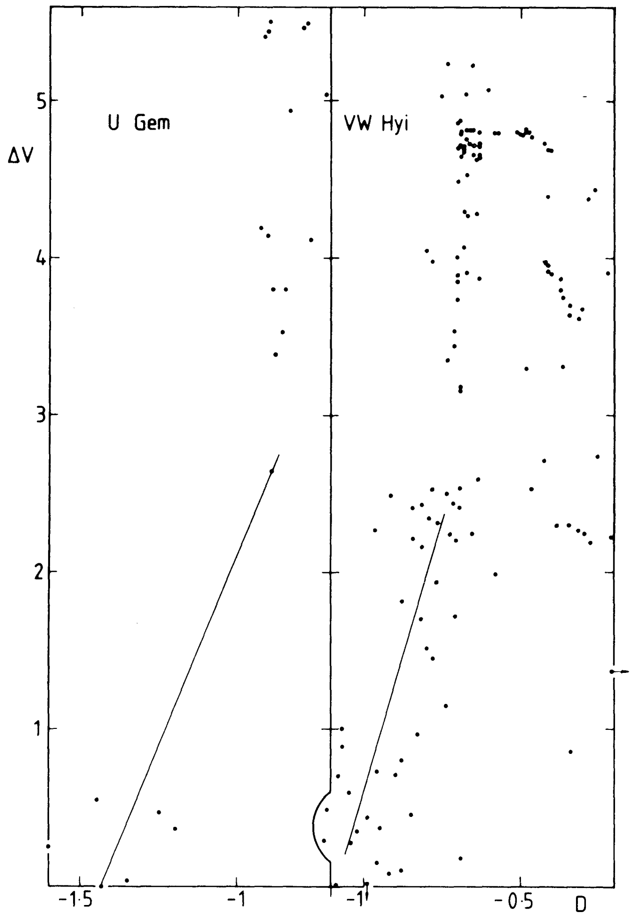

Fig. 11. Balmer discontinuity index versus change in visual magnitude for VW Hyi and U Gem (see text).

4000 Å than at longer wavelengths. As the object goes into outburst this curvature gradually disappears and at maximum the slope at $\lambda < 4000$ Å is somewhat steeper than at shorter wavelengths. Spectra of dwarf novae at minimum show in general a strong Balmer jump in emission (Wade 1981; Kiplinger 1979) while at maximum there is a small Balmer jump in absorption, or no Balmer jump at all. Figure 5 shows a spectrum of SS Cyg at minimum (Kiplinger 1979) together with *UBVR* observations by Jones *et al.* (1982). The *VR* fluxes closely match the continuum while the *B* flux is bigger due to the strong Balmer lines. In Figure 6 spectra of SS Cyg during decline (Kiplinger 1979) are shown together with *UBV* observations by Chuvayev (1962), converted to fluxes using the procedure of Jones *et al.* From these results we interpret the change in shape of the continuum mainly as a change in the Balmer jump from emission to absorption. A convenient way to measure this jump is to take the discontinuity index $D = (U-B) - (B-V)$. The real Balmer discontinuity measurement will probably be higher than D because the colours depend on the emission lines as shown by Figure 5. To achieve a better understanding of what D means we have plotted it in Figure 7 against spectral type for stars with different luminosity classes (Mihalas and Binney 1981). We note that O5 stars have $D \sim 0.83$ while typical values of dwarf novae at minimum are $D \sim -1.30$. We have examined the behaviour of the index D with V magnitude during both rise and decline of dwarf novae. For each object we have chosen the faintest V observation and express the change of magnitude as ΔV. Some of the results are plotted in Figures 8 to 11. There is a very good correlation of D with ΔV for all cases. During the rise, D values are smaller because of the defect in $(U-B)$ (see Section I). During decline there is an approximate linear behaviour for $\Delta V < 3$. The lines drawn in Figures 8 to 11 are only eye estimates. For $\Delta V > 3$ there is very little or no effect at all on D. This is particularly strong for VW Hyi, U Gem (Figure 11) an also for SS Cyg (Figure 8). The fact that D does not increase positively for $\Delta V \gtrsim 3$ agrees well with the small Balmer jumps in absorption observed in the spectra of dwarf novae. This could also be related to the shallow absorption lines observed at maximum. If we make the reasonable assumption that the Balmer jump is correlated with optical depth, then some region in the disc may be becoming optically thin as the energy of the outburst is radiated away.

IV. CONCLUSIONS

A catalogue has been compiled from most of the *UBVRI* observations of dwarf novae available in the literature. From the galactic distribution and ultraviolet observations of these objects we expect no substantial interstellar reddening except for a few systems like BV Cen, TZ Per and UZ Ser. The theoretical $(U-B)$ and $(B-V)$ colours of several disc models have been compared with observations. Some models of Mayo *et al.* (1980) have good agreement with dwarf novae at maximum. Recent models of Schwarzenberg-Czerny (1981), which include a chromosphere, match observations at maximum and also some of the bluest systems at minimum. The models of optically thin discs by Tylenda (1981) cover an extended region in colour-colour diagram and agree with most of the observations at minimum. A discussion of the Balmer jump shows a correlation with change in V magnitude.

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Juan Echevarría: Astronomy Centre, University of Sussex, Falmer, Brighton BN1 9QH, Great Britain.
Derek Jones: Royal Greenwich Observatory, Herstmonceux Castle, Hailsham, Sussex BN27 1RP, Great Britain.