CONTINUUM DISTRIBUTIONS AND LINE PROFILES OF UX UMA-TYPE NOVALIKE SYSTEMS[+]

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ABSTRACT. Combined UV, optical and, in part, IR continuum distributions of the UX UMa-systems CPD-48°1577, V3885 Sgr, RW Sex and of the recently discovered cataclysmic system PHL 227 were determined from multi-wavelength spectroscopic and photometric data to search for general characteristics of these systems. The observed variations of the UV to IR spectral indices are qualitatively very similar for all systems, whereas the absolute values show significant differences in the far and near UV ranges. The wavelength dependence of the optical and IR spectral indices as well as the variations of the Balmer line profiles lie within the range of model spectra of optically thick and stationary accretion disks with stellar atmosphere characteristics. The different behavior of the far UV spectral indices can be explained by the excess radiation from an extended and optically thick boundary layer, which depends mainly on the orbital inclination.

[+] Based on observations collected at the European Southern Observatory, La Silla, Chile, and with the International Ultraviolet Explorer Satellite at the Villafanca ground station.

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1. INTRODUCTION

The study of UX UMa-systems is of general interest due to the fact that their spectral features (continuum gradients, Balmer absorption line profiles, colors) are stationary (ignoring short-term variability) and can therefore be used to test stationary accretion disk theory. The novalike systems CPD-48°1577, V3885 Sgr and RW Sex are the brightest members of the UX UMa-subclass of cataclysmic binaries and are studied since 1968 (for a review, see Wargau et al., 1983; Haug and Drechsel, 1985; Greenstein and Oke, 1982; and references therein). Only recently, PHL 227 (m_V=13^m.6) was discovered by Hunger et al. (1985) to exhibit UV and optical spectral behavior very similar to that of V3885 Sgr, though its binary nature has not yet been proven. In the present investigation the energy distributions between UV and IR ranges and Balmer line profiles of several UX UMa-systems were determined to find out general properties as well as systematic differences in the continuum gradients and residual line depths, and are compared with synthetic accretion disk spectra.

2. SPECTROSCOPIC AND PHOTOMETRIC DATA

IUE low dispersion spectra (1200-2900Å), optical spectroscopic data (4000-10000Å) obtained with the ESO 1.52m telescope equipped with IDS and RETICON detectors were combined with UBV($R_C I_C$) and JHK(L) IR data obtained with the ESO 1m and 50cm telescopes for CPD-48°1577, V3885 Sgr and RW Sex. The UV spectra SWP 18578 and LWR 14655 of CPD-48°1577 were retrieved from the VILSPA data archive. Part of the optical spectra of CPD-48°1577 and the spectroscopic and photometric data of PHL 227 were taken from measurements published by Wargau et al. (1983) and Hunger et al. (1985). UBV photometric data of CPD-48°1577 and IR-JHK measurements of V3885 Sgr are from Bruch (1984) and Epchtein (1985). Typical errors of the optical and IR photome-

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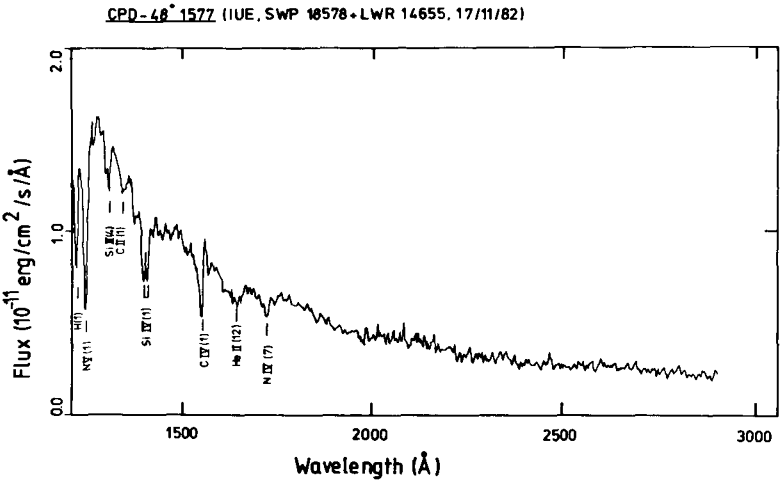
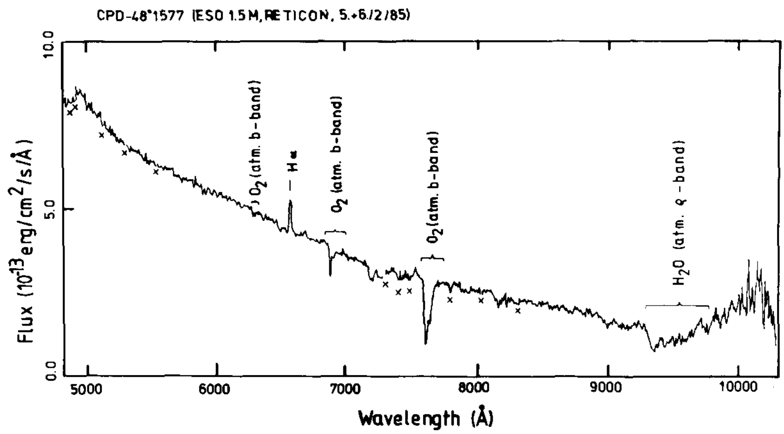


<u>Fig. 1:</u> IUE spectrum (SWP 18578 + LWR 14655) of CPD-48°1577 obtained on 17/11/82 with identification of the most prominent lines.



<u>Fig. 2:</u> RETICON spectrum of CPD-48°1577 obtained on 5/2/85 (7300-10200Å) and 6/2/85 (4800-7700Å) with the ESO 1.52m telescope. The crosses denote the positions where wrong pixels have been removed from the spectrum.

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tric data amount to $0^m.02$ and $0^m.05$, respectively. As representative examples for the observed spectra of UX UMa-systems combined IUE and RETICON-spectra of CPD-48°1577 are shown in Figs. 1 and 2, respectively. The UV spectra of UX UMa-systems exhibit a relatively strong far UV continuum with a pronounced increase of the continuum slope in the SWP range with regard to the much flatter LWR range. In the blue optical range very broad and shallow Balmer absorption lines with superimposed emission components are observed (e.g., Haug and Drechsel, 1985). The continuum intensity decreases monotonically towards the red visual range. The Hα-emission line is the only prominent stellar feature in the RETICON spectra of CPD-48°1577 and RW SEX.

Fig. 3a (top): Flux distributions of CPD-48°1577 (1), V3885 Sgr (2), RW Sex (3) and PHL 227 (4) covering the intervall 1200Å to 22000Å. Meaning of symbols: IUE data (big triangles), IDS data (filled circles), RETICON data (open circles), UBV(R_cI_c), uvby, JHK(L) data (squares); IUE spectrum LWR 16575 of V3885 Sgr (small triangles). The data of V3885 Sgr and RW Sex have been shifted by $0^m.50$ and $1^m.25$, respectively, as is indicated by the arrows. For the UV data of PHL 227 an interstellar reddening correction of $E(B-V)=0^m.05$ has been applied. The IDS spectroscopic data of PHL 227 have been normalized in order to fit the Stroemgren v magnitude at 4100Å.

Fig. 3b (bottom): Continuous stationary accretion disk spectrum according to La Dous (1986; dotted line) using the following system parameters (primary mass: $M_{wd}=1\ M_\odot$; mass flux rate: $\dot{M} = 10^{-9}\ M_\odot/yr$; orbital inclination: $i = 28°$; inner and outer disk radius: $r_i = 10^{9.2}$ cm, $r_a = 10^{10.6}$ cm). The model curve was uniformly discretized (open circles) and linearly interpolated in different wavelength ranges (see text) as indicated in the figure by the straight lines connecting consecutive arrows and extrapolated by dashed lines for clarity. The spectral variation due to inclusion of line opacity in the vicinity of the Balmer jump edge is also indicated in the figure by a dashed line (same scaling as in Fig. 3a, top).

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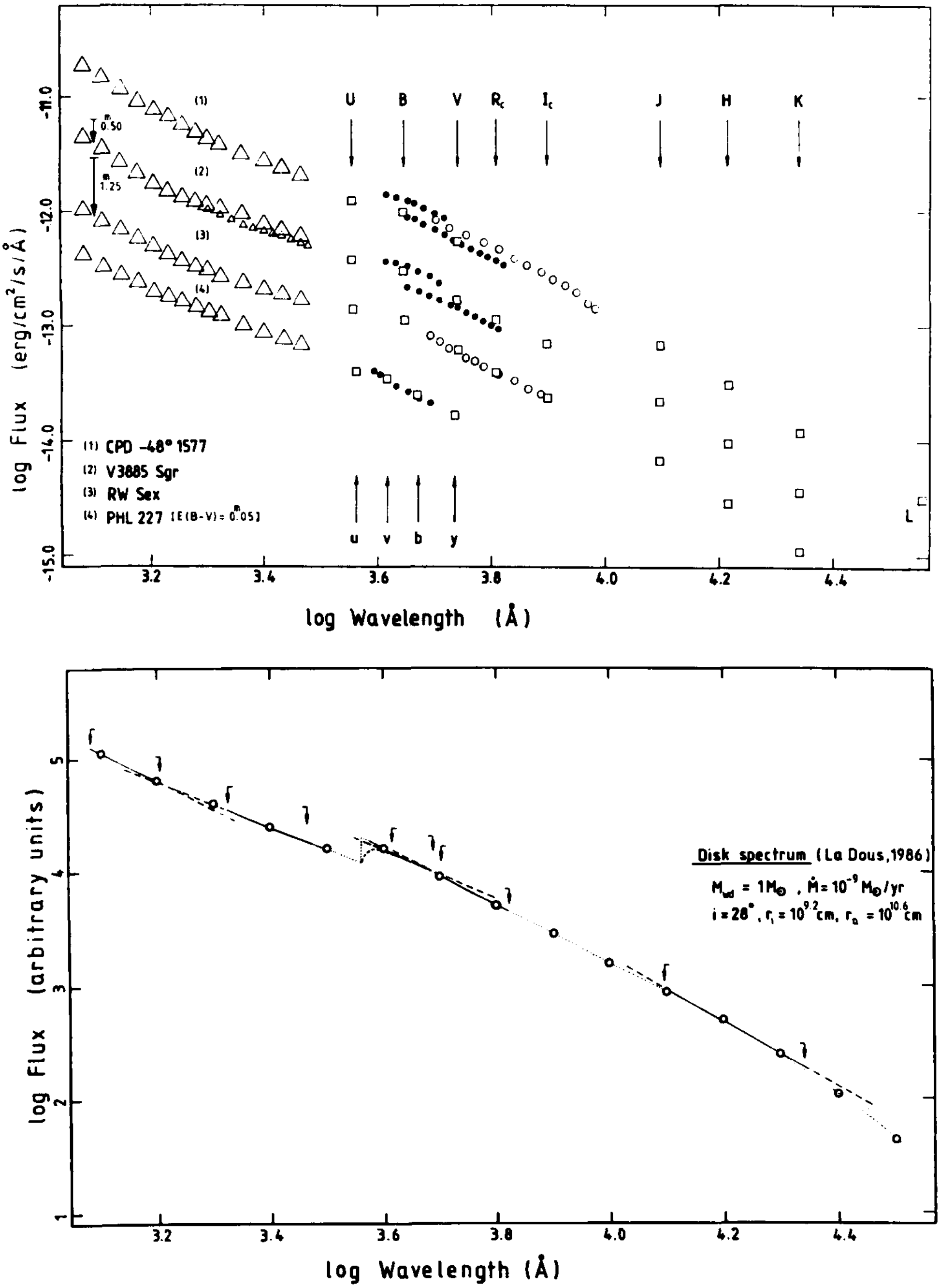

Fig. 3.

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3. ENERGY DISTRIBUTIONS

The combined UV, optical and IR observations were used to determine the continuum flux distributions between 1200Å and 22000Å for CPD-48°1577, V3885 Sgr and RW Sex and between 1200Å and 5400Å for PHL 227, which are shown in Fig. 3a. Comparing the combined energy distributions two statements can be made. First: the overall shape of the continuum distributions is very similar for all systems. A monotonic increase over three orders of magnitude of the continuous radiation from the mid-IR (22000Å) towards the far-UV regions (1200Å) can be observed. Probably, a Balmer absorption edge is present, which is suggested by the (U-B) and (u-v) color indices (for V3885 Sgr, see also: Panek, 1979). Second: the observations show significant differences in the spectral indices α ($\log F_\lambda \sim -\alpha \log \lambda$) differing mostly in the far and near UV ranges, as can be seen from Figs. 3a and 4. The probable errors for the far UV spectral indices amount to 0.1-0.2 and to about 0.1 in the optical ranges as can be estimated from independent measurements and flux calibrations. A linear approximation of the measurements for the relation $\log F_\lambda$ versus $\log \lambda$ is well satisfied, since the correlation coeffients amount to 0.990-0.999 being very close to +1.0 (straight line). The observations suggest that the use of the observed (4-5) spectral indices is sufficient to characterize the energy distributions of UX UMa-systems in an easy way. These values are also suitable for a comparison with theoretical continua. As an example, the observed energy distributions were compared with the model spectrum of an optically thick and stationary accretion disk as was recently calculated by La Dous (1985;1986) and is shown in Fig. 3b for the system parameters indicated in the figure. From the comparison of the observations with the model spectrum (Figs. 3a;b) one recognizes that the overall shape of the continuum distri-

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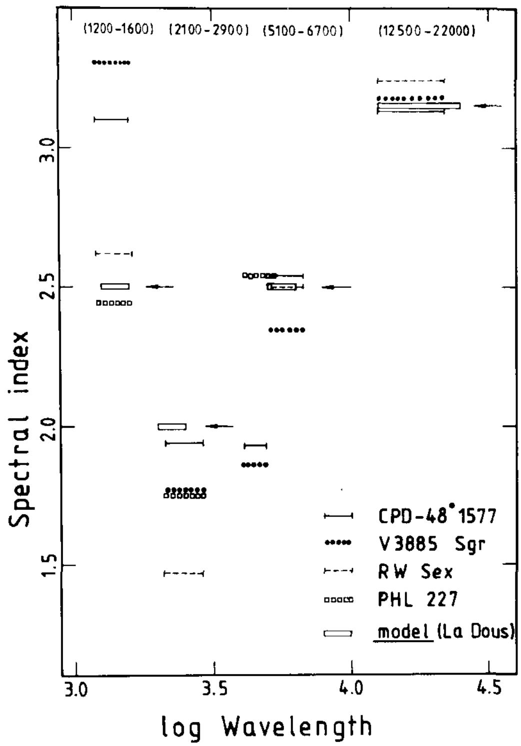

Fig. 4: Spectral indices of CPD-48°1577, V3885 Sgr, RW Sex and PHL 227 plotted as a function of logarithmic wavelength (Å) for the intervals given in the figure. The arrows indicate theoretical predictions from the accretion disk model spectrum of La Dous (1986).

butions of UX UMa-systems is well reproduced by the model spectrum of an optically thick stationary accretion disk; this becomes even more evident by comparing the wavelength-dependent spectral indices of the four systems with the theoretical values, which lie well within the observed parameter ranges (see Fig. 4). On the other side there is obviously no wide-band agreement of the suggested model with the observations of a specific system.

4. BALMER LINE PROFILES

The line profiles of Hβ , Hγ , Hδ were extracted from IDS spectra of

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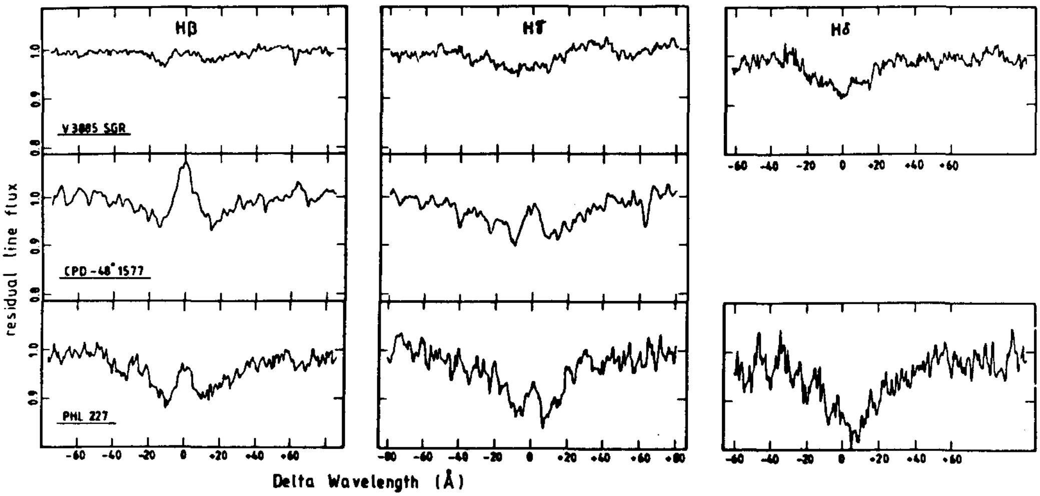

Fig. 5: Residual line profiles of $H\beta$, $H\gamma$, $H\delta$ as observed in summed IDS spectra of V3885 Sgr (25/8/83; top), CPD-48°1577 (30/12/82; middle) and PHL 227 (15/9/83; bottom).

CPD-48°1577 (only $H\beta$ and $H\gamma$), V3885 Sgr and PHL 227 and are normalized relative to the local continuum (see Fig. 5). The equivalent widths, residual line depths and FWHM values for the Balmer absorption lines were determined from smoothed line profiles after subtraction of the superimposed emission components and are summarized in Table I. The uncertainties for the $H\beta$ and $H\gamma$ equivalent widths amount to 20-25% due to the uncertain emission contributions. As can be seen from Fig. 5 and Table I significantly different residual line depths, line widths and equivalent widths of the Balmer absorption lines are observed for the three systems being strongest for PHL 227. The residual $H\gamma$-line profiles of V3885 Sgr and PHL 227 were compared with model profiles of Herter et al. (1979) and La Dous (1985;1986) for a stationary and optically thick accretion disk (see Fig. 6). Comparing the normalized $H\gamma$-line profile of V3885 Sgr with the model

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TABLE I: Observed Balmer absorption line parameters (c.f., Fig. 5). Errors correspond to the rms deviations obtained from upper and lower boundaries for the given quantities.

	W_λ (Å)	FWHM (Å)	residual line depth (%)
V3885 Sgr			
Hβ	1.7:	35 (±5)	5 (±1)
Hγ	1.6:	38 (±8)	6 (±1)
Hδ	3.3 (±.5)	39 (±5)	9 (±1)
CPD-48°1577			
Hβ	3.8:	43 (±7)	9 (±3)
Hγ	6.6:	55 (±7)	12 (±2)
PHL 227			
Hβ	7.3:	58 (±7)	13 (±2)
Hγ	7.2:	43 (±5)	16 (±2)
Hδ	10.2 (±1.9)	42 (±7)	19 (±2)

calculations for $i = 60^{\circ}$ one recognizes a remarkable agreement of the line shape and depth of the observed profile with the model profile of La Dous (non flux-constant model) in contrast to the one of Herter et al. (flux-constant model), which differs significantly from the observed profiles of V3885 Sgr and PHL 227.

5. SUMMARY AND DISCUSSION

As was shown in Section 3, the energy distributions of the selected UX UMa-systems between UV and IR can be characterized by 4 to 5 spectral indices, which are very similar for different systems from about 4000Å to 22000Å. On the other side there exist pronounced differences in the UV spectral indices being strongest in the spectral range from 1200Å to 1600Å, where a characteristic steepening of the energy distributions towards shorter wavelengths is observed (see also Hunger et al., 1985, Fig. 3). The spectral

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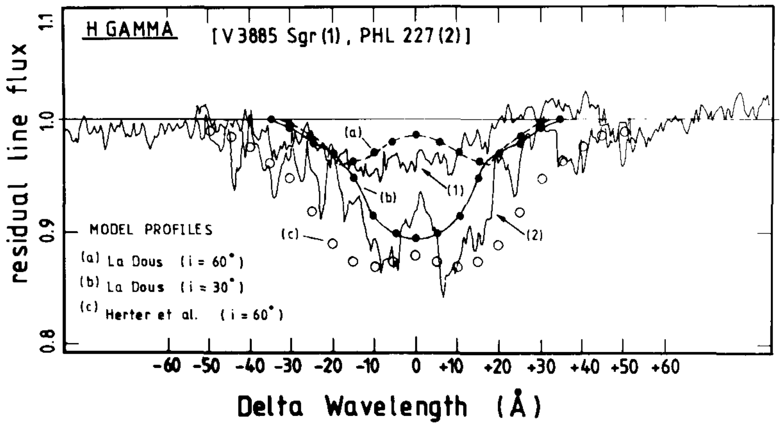

Fig. 6: Theoretical Hγ-line profiles for an optically thick accretion disk ($M_{wd} = 1 M_\odot$, $\dot{M} = 10^{-9}\ M_\odot$/yr, $r_a = 8.85 \times 10^9$ cm) after La Dous (1986; filled circles) and Herter et al. (1979; open circles) for different orbital inclination angles (i = 30°, 60°) in comparison with observed profiles of V3885 Sgr and PHL 227 (solid lines 1 and 2, respectively).

index in the far UV range is considerably larger for the higher inclined systems CPD-48°1577 (i ≈ 60°; Wargau et al., 1983) and V3885 Sgr (60° < i < 80°; Haug and Drechsel, 1985) than for the lower inclined system RW Sex (25° < i < 30°, Cowley et al., 1977). The observed wide-range variations of the UV to IR spectral indices lie well within the range of optically thick and stationary accretion disk spectra (see Figs. 3;4). However, the observed far-UV turnover of the continua of the higher inclined systems can probably not be reproduced by proper variations of the free parameters of the accretion disk spectra as can be deduced from the model calculations of La Dous (1986, p.115ff). A possible explanation for the considerably increased spectral indices in the far-UV ranges of higher inclined UX UMa-systems may be the presence of an optically thick and geometrically extended boundary layer on the surface of the white dwarf primary. Recent theoretical calculations by Burkert and Hensler (1985) for an extended boundary layer which completely covers the surface of the white dwarf and having an ellipsoidal geometry, in fact demonstrate an increase of the relative amount for the boundary layer radiation with increasing orbital inclination. As a consequence of this model, the temperature of the extended boundary layer will be in the order of 1-3 x 10^5 K and the slope of the combined disk + boundary layer radiation becomes remarkably steeper with increasing aspect angle in the UV range. As an example, the calculated spectral indices in the range 1000Å to 3000Å amount to +2.2 for i = 0°, and +2.5 for i = 85°, for a disk model with an accretion rate of 10^{-8} $M_\odot$/yr and a primary mass of 1 $M_\odot$, assuming local blackbody radiation. For comparison, the observed spectral indices in the range 1200Å to 2500Å as derived from IUE spectra of CPD-48°1577, V3885 Sgr, RW Sex and PHL 227 amount to +2.6, +2.3(+2.6), +2.2, +2.1, respectively. So the observations lie well in the range of the theoretical predictions, favoring the model of an extended boundary layer to explain the far UV excess radiation in UX UMa-systems. Significant differences in absorption line widths, residual line depths and equivalent widths were observed comparing the Hβ, Hγ, Hδ lines of different UX UMa-systems as expected due to individually distinct values of the orbital inclinations, disk radii and/or mass accretion rates of these systems. More detailed model calculations with accretion rates of about 10^{-8} $M_\odot$/yr and different values of the orbital inclinations will be carried out in an ongoing program. The accuracy in the determination of the system parameters of these systems should also be improved in order to reproduce the observed continua and line spectra in a better and consistent way.

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REFERENCES

Brown, A., Kilkenny, D.: 1979, Monthly Notices Roy. Astron. Soc. **187**, 823

Bruch, A.: 1984, Astron. Astrophys. Suppl. Ser. **56**, 441

Burkert, A., Hensler, G.: 1985, in Proc. ESA Workshop: Recent Results on Cataclysmic Variables, Bamberg, ESA SP-**236**, p67

Cowley, A.P., Crampton, D., Hesser, J.E.: 1977, Publ. Astron. Soc. Pacific **89**, 716

Epchtein, N.: 1985, private communication

Greenstein, J.L., Oke, J.B.: 1982, Astrophys. J. **258**, 209

Haug, K., Drechsel, H.: 1985, Astron. Astrophys. **151**, 157

Herter, T., Lacasse, M.G., Wesemael, F., Winget, D.E.: 1979, Astrophys. J. Suppl. **39**, 513

Hunger, K., Heber, U., Koester, D.: 1985, Astron. Astrophys. **149**, L4

La Dous, C.: 1985, in Proc. ESA Workshop: Recent Results on Cataclysmic Variables, Bamberg, ESA SP-**236**, p217

La Dous, C.: 1986, in Synthetische Spektren stationaerer Akkretionsscheiben, PhD-thesis, Ludwig-Maximilians-Universitaet, Munich, F.R.G.

Panek, R.J.: 1979, Astrophys. J. **234**, 1016

Wargau, W., Drechsel, H., Rahe, J., Bruch, A.: 1983, Monthly Notices Roy. Astron. Soc. **204**, 35p

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