THE ASTROPHYSICAL JOURNAL, 401:L19–L22, 1992 December 10

POSSIBLE FIRST DETECTION OF ULTRAVIOLET PULSES FROM AN INTERMEDIATE POLAR: V603 AQUILA

A. SCHWARZENBERG-CZERNY[1]
Warsaw University Observatory, Al. Ujazdowskie 4, 00-478, Warszawa, Poland
A. UDALSKI[2]
Institute for Space and Terrestrial Science, and Department of Physics, York University, 4700 Keele Street, North York, Ontario, Canada M2R 1Z2
AND
R. MONIER
IUE Observatory, European Space Agency/VILSPA, Villafranca, Apartado 54065, E-28080, Madrid, Spain
Received 1990 August 15; accepted 1992 September 18

ABSTRACT

We report possible independent detection of a pulsation in the UV continuum radiation of the intermediate polar star, V603 Aql, at 2.2 σ level. Since the period of the pulsation of 62.9 minutes is very close to the period of X-ray and optical modulations discovered earlier, its detection combined with previous data confirms reality of UV, X-ray, and optical oscillations at an 4–8 σ level, depending on how robust and sensitive a test one applies. The UV pulses have a sinusoidal shape and amplitude of 8%; i.e., intermediate between those in the X-ray and optical ranges. We believe that the origin of the UV pulses is similar to the pulses in the other ranges, in that they are caused by rotation of the magnetized white dwarf. This detection of the coherent UV variability from V603 Aql, if confirmed, would be the first independent discovery of pulsation in the ultraviolet range for an intermediate polar.

Subject headings: novae, cataclysmic variables — stars: binaries: general — stars: individual (V603 Aql) — stars: magnetic fields

1. INTRODUCTION

Our analysis of optical and X-ray observations of V603 Aql (Nova Aquilae 1918) revealed it to be an intermediate polar (Udalski & Schwarzenberg-Czeny 1989, hereafter USC). However, among intermediate polars (Warner 1985), V603 Aql and TV Col are unusual in that their multiple periods form a pattern encountered previously only in the unique X-ray binary Her X-1 (references in USC). Namely, according to USC the 63 minute (23 cycles day^{-1}, hereafter c/d) modulation of X-rays and light corresponds to the spin period of the magnetized white dwarf, the 3.3 hr (7.3 c/d) spectroscopic period corresponds to the orbital motion, the large amplitude, 3.5 hr modulation of light corresponds to the marching dips period of Her X-1 and the 2.5 day modulation of light corresponds to the precession period of the warped and tilted accretion disk. V603 Aql is the brightest intermediate polar in the optical, UV, and X-rays, and as such it was the first studied in our campaign of multiwavelength observations of intermediate polars. In this *Letter* we report results of our UV observations and comment on their correspondence with other existing evidences.

2. THE OBSERVATIONS: THE INTERMEDIATE BAND UV PHOTOMETRY WITH THE *IUE*

Nineteen low-dispersion short-wavelength UV spectra of V603 Aql were obtained with the Short Wavelength Prime (SWP) camera of the *International Ultraviolet Explorer* (*IUE*) satellite during two European Space Agency (ESA) shifts on 1989 June 11 and 12. The description of the satellite, its telescope and instrumentation is given by Boggess et al. (1978). To improve temporal resolution on several occasions the star was observed twice on the same image, in two different positions within the large aperture. Exposure times were in the range 12–15 minutes; i.e., 0.2–0.25 of the 63 minute spin period. Table 1 gives details of these and 1989 September observations of V603 Aql. We also used the 1980 September observations of Drechsel et al. (1981).

All reductions were performed using the experimental SUN computer version of the Regional Data Analysis Facility (RDAF) software. It included fitting double Gaussians to the perpendicular cross section profile of the spectrum using a modified Gaussian extraction (GEX) procedure (Urry & Reichert 1988). The typical separation of the spectra was ~8″, already enough to prevent significant cross talk and still not enough to cause significant light losses on edges of the 20″ aperture. The tests performed on individual spectra revealed less than 2% differences between the GEX and standard extraction over the wavelength range 1250–1950 Å. The extracted spectra were then corrected for variations in the camera temperature and absolutely calibrated. Resaux marks have been removed by interpolation across them. Finally, we dereddened the spectra assuming the interstellar reddening of V603 Aql equal $E_{B-V} = 0\overset{m}{.}07$ (Gallagher & Holm 1974).

The mean UV spectrum of V603 Aql obtained from 1989 June observations presented in Figure 1 resembles that obtained by Drechsel et al. (1981). The individual spectra were passed through numerical filters of rectangular shape. The positions and widths of the filters are marked in Figure 1 by horizontal bars. The spectral lines contribute little in the filter bands, except for the 1325 Å band. In this way we obtained a five-color, intermediate-band, UV photometry of V603 Aql. To remove any long-term trend the individual spectra were normalized by the average spectrum for the shift. We estimate the error of the derived UV magnitudes to be smaller than $0\overset{m}{.}03$ (Garhart & Teays 1988).

[1] Guest observer at the ESA VILSPA.
[2] On leave from Warsaw University Observatory, Poland.

TABLE 1

LOG OF *IUE* OBSERVATIONS

Number	SWP Number	Heliocentric Julian Date (midexposure) 2,447,000+	Exposure Time (minutes)
1.........	36455A	689.4481	12
2.........	36455B	689.4565	12
3.........	36456	689.4925	15
4.........	36457	689.5230	15
5.........	36458	689.5538	15
6.........	36459	689.5832	15
7.........	36460	689.6134	15
8.........	36461	689.6466	15
9.........	36462A	689.6788	15
10.........	36462B	689.6934	15
11.........	36468A	690.4201	15
12.........	36468B	690.4367	15
13.........	36469	690.4661	12
14.........	36470A	690.4973	12
15.........	36470B	690.5100	12
16.........	36471	690.5582	15
17.........	36472	690.6116	12
18.........	36473	690.6466	15
19.........	36474	690.7023	12
20.........	37175	794.1845	12
21.........	37176	794.2139	14
22.........	37177	794.2456	14
23.........	37178	794.2773	14
24.........	37179	794.3082	14
25.........	37180	794.3441	14
26.........	37181	794.3752	14
27.........	37182	794.4060	14
28.........	37183	794.4427	14

3. DISCOVERY OF THE UV PULSES

Both the quality and results of the analysis for each of 5 continuum bands are alike. Thus we discuss in the detail only the results for the 1475 Å band. The power spectra (Deeming 1975) for individual shifts show nothing remarkable. Among the power spectra for combined pairs of shifts only that for 1989 June reveals presence of a conspicuous spectral line. In Figure 2*a* we demonstrate the Scargle (1982) power spectrum computed for 1989 June and the 1475 Å band. It differs from the Deeming spectrum by less than 5% but has the advantage of clear statistical interpretation. The line is centered at the period of 62.9 ± 0.4 minutes and frequency of 22.89 ± 0.15 c/d, close to that found by USC. Our frequency limit of 60 c/d is set by the minimum separation of the observations.

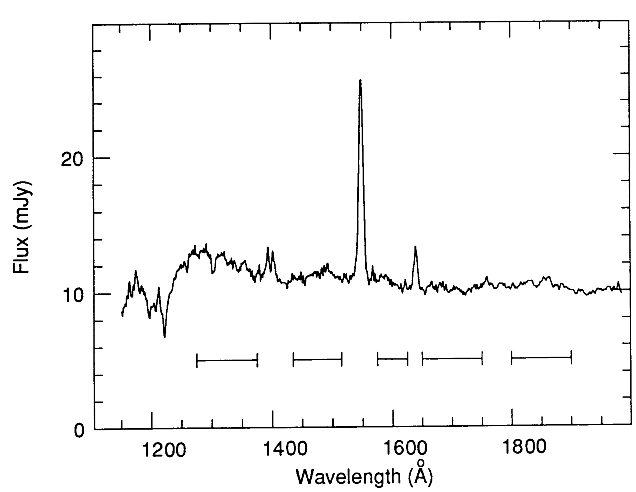

FIG. 1.—The mean UV spectrum of V603 Aql. Wavelength ranges defining the numerically extracted intermediate-band photometry are indicated with horizontal bars.

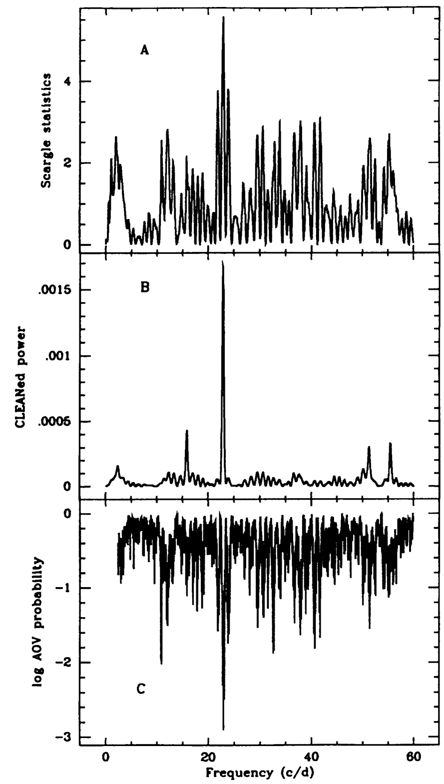

FIG. 2.—(*a*) Scargle (1982) spectrum of the light curve of V603 Aql in 1475 Å band (as defined in Fig. 1) for the combined June 11 and 12 ESA *IUE* shifts. The spectrum is plotted in units of variance in the data, i.e., the noise mean power. The main peak at 23 cycles day^{-1} corresponds to the period of modulation of X-ray and optical radiation which we attribute to rotation of the white dwarf. The sidelobes are artifacts of the window function. Note the conspicuous lack of features at the orbital and photometric frequencies of 7.3 and 6.9 c/d, respectively (see § 1). (*b*) The CLEANed power spectrum for the same data obtained using 10 iterations with gain 0.3 (Roberts et al. 1987). Note that the sidelobes and other features related to the window function disappeared. (*c*) The Analysis of Variance (AOV) periodogram for the same data for two covers of three bins (Schwarzenberg-Czerny 1989). On the vertical axis are plotted log values of Fisher-Snedecor one-sided cumulative probability F(2, 16) corresponding to the AOV test statistics.

On the one hand, the most severe problem with the *IUE* data is caused not by aliasing but by undersampling with periodic pattern. It causes spread of power from the positive and negative frequencies across the whole frequency band. That this is the case can be appreciated by inspection of Figure 2*b* demonstrating the CLEANed power spectrum (Roberts, Lehar, & Dreher 1987) obtained after 10 iterations with the gain of 0.3, where window function ghosts are removed. This problem was very pronounced in 1980 September and 1989 September. In the corresponding window functions the sidelobes at 30 c/d reach 90% and 60%, correspondingly, setting an effective Nyquist limit at 15 c/d. In the power spectrum of the 23 c/d oscillation the ±30 and ±65 c/d sidelobes produce ghosts centered at 7, 42, and 53 c/d. Since the ghosts are up to 10 c/d broad, they contribute substantially to the overall noise level. Additionally, the scatter of the 1980 observations is twice as big as in 1989. On the other hand, our 1989 June observations were obtained on the consecutive *IUE*/ESA shifts and with increased frequency (§ 2) and thus suffer less from aliasing and power spread. For each of the 1989 June shifts no sidelobe exceeded 40%, resulting in reduced noise. In effect the 23 c/d feature becomes progressively less conspicuous in the Deeming spectra for combined 1989 June, all 1989, and all data together, to the extent that it dominates the latter spectrum only marginally.

Probability of random occurrence of the line observed in Figure 2*a* at fixed frequency of 23 c/d is 0.002, corresponding to 2.9 σ detection (Scargle 1982). Except for the ± 1 c/d sidelobes of the line, no other peak has more than 2 σ significance. The noise estimate in the Scargle test must include power of the oscillation and its value of $\sigma_v^2 = 0.007$ mag^2 was estimated here using the signal variance and Parseval's theorem. To claim detection independent of any other observations, one has to multiply the probability by number of independent frequency bands investigated (see, e.g., Horne & Baliunas 1986). Because of aliasing the resolution of all spectra is the same, 0.8 c/d, corresponding to 75 independent frequencies. The corrected probability is 0.2, and thus results of Scargle test enable no claim of independent detection of oscillation.

We prefer to use the analysis of variance (AOV) test (Schwarzenberg-Czerny 1989), separating the oscillation from noise by design. According to the AOV statistics using two covers of three bins the probability of random occurrence of the observed feature is 0.0012 (corresponding to 3.25 σ), 0.00035 (3.57 σ), and 0.00439 (2.85 σ) for 1989 June, all of 1989, and all data together, correspondingly. Thus ignoring other available evidence (see § 5) our detection corrected for the frequency band would have at best 2.2 σ significance. This indicates possible independent detection of the UV oscillation.

Additionally we performed bootstrap analysis in the following way. The 11 point (i.e., 58%) subsamples were drawn randomly from the 1989 July shifts and their power spectra were computed. In the overwhelming number of cases the spectra did show strong line at 23 c/d. This raises our confidence that our detection is not due to the small number statistics. All results of this section hold for the remaining UV continuum bands.

4. THE LIGHT CURVE

Both the optical and the X-ray pulses in V603 Aql have a nonsinusoidal shape. Our UV power spectra show no power in the first harmonic, thus indicating little nonsinusoidal distortion of the light curve. However, they are damped at high frequencies due to long exposure times. For the 1475 Å data we obtained the following least-squares best-fit sinusoid:

$$[F(\mathrm{HJD})/\langle F\rangle]_{1475} = 1 + a_0 \cos 2\pi[(t - t_0)/P] ,$$

where $a_0 = 0.075 \pm 0.018$, $t_0 = 2{,}447{,}689.4114 \pm 0.0014$, $P = 0^{\mathrm{d}}04367 \pm 0.00013$.

The residuals show no correlation over time so the errors should be realistic (see Schwarzenberg-Czerny 1991). The residuals (flickering) are strongly correlated over wavelength, which suggests broad-band response to accretion rate fluctuations or, less likely, some calibration errors. We found no significant amplitude change over the UV bands. The folded light curve and the fitted sinusoid are presented in Figure 3. The figure reveals clearly coherent nature of the UV pulsation. The exposure-length–corrected amplitude of the UV pulsation of 8% has an intermediate value between those for X-ray and optical modulation, 15% and 2%, respectively.

5. CONCLUSIONS

Because of the brightness and long spin period of V603 Aql and technique employed to increase frequency of our observations, we were able to attain sufficient resolution and sensitivity to detect for the first time the UV pulsation of an intermediate polar star, in 5 UV continuum bands. Although

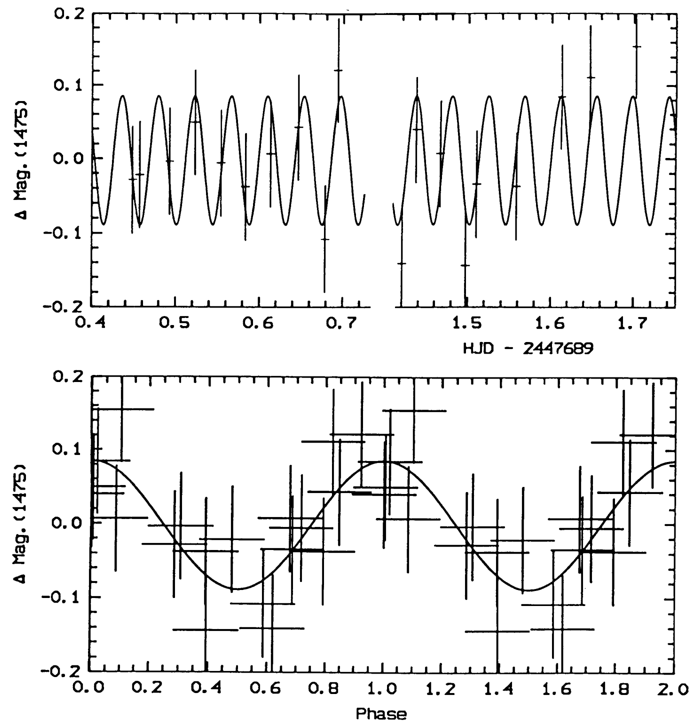

FIG. 3.—The 1989 June light curves of V603 Aql in the 1475 Å band (*a*) plotted against time and (*b*) folded using the rotation phase (eq. [1]) and repeated twice. In order to eliminate any long-term trend, observations were normalized using the mean flux for each *IUE* shift. The least-squares fit sinusoid is also indicated. The vertical error bars correspond to $\pm 2\,\sigma$ range.

alone our detection of the UV pulses (§ 3) has only modest statistical significance of 2.2 σ, consistent with a possible detection, it provides strong evidence on the nature of V603 Aql when combined with the other existing data. In Table 2 we list the relevant parameters derived from the optical (with the $3^{\mathrm{h}}5$ period removed, USC) UV (this paper), and X-ray (Drechsel et al. 1983; see USC) observations of V603 Aql. For homogeneity, all data were extracted anew in the similar way: frequencies and errors from the least-squares fit of a sinusoid and probabilities from the values of the AOV statistics for two covers of three bins. The noise correlation length N_{corr}, due to flickering, was accounted for both in fit variances and AOV degrees of freedom (Schwarzenberg-Czerny 1991). The probabilities in Table 2 do not account for the width of the frequency band.

The proximity of the UV, optical, and X-ray periods of V603 Aql alone suffice to strengthen the USC conclusion on its intermediate polar nature. Namely, the corrected for bandwidth probability that the strongest spectral lines in N power spectra of pure noise fall into the given frequency interval $\delta\nu$ is $P = (\delta\nu/\Delta\nu)^{N-1}$. Substituting from Table 2 $N = 3$, $\delta\nu = 0.6$ c/d, and $\Delta\nu = 60$ c/d, we obtain $P = 0.0001$ or 3.9 σ significance. This is a very robust result, and it holds still if all 1989 and 1980 UV observations of V603 Aql are combined for the UV power spectrum.

A more sensitive test should combine the probabilities of detection in the UV and X-ray bands, P_o, P_{uv}, and P_x, respectively (Table 2). The combined probability that the observed features at the fixed frequency ν_o arise from a random signal is simply the product $P_o P_{\mathrm{uv}} P_x$. The probability of observing the features anywhere in the band $\Delta\nu$ is $P = (\Delta\nu/\sigma_\nu)P_o P_{\mathrm{uv}} P_x$. Here σ_ν denotes the combined frequency resolution $1/\sigma_\nu^2 = 1/\sigma_o^2 + 1/\sigma_{\mathrm{uv}}^2 + 1/\sigma_x^2$ and σ_o, σ_{uv}, and σ_x are the individual resolutions. This combined probability that all three signals are random, corrected for the frequency band, is 3×10^{-17},

TABLE 2

MEASUREMENTS OF WHITE DWARF SPIN FREQUENCY

Band	Frequency Cycles day^{-1}	Error c/d	Resolution c/d	S/N	P_{rand} AOV	N_{obs}	N_{corr}
Optical	23.46	0.03	0.03	0.15	10^{-14}	4300	25
UV	22.90	0.07	0.8	0.9	0.0012	19	1
X	22.89	0.5	3.4	0.5	0.00012	119	1

which corresponds to a 8.3 σ detection of the 23 c/d oscillations.

The 63 minute (23 c/d) oscillation was detected using four instruments (two satellites + two telescopes) working in three widely differing energy bands. In the $\Delta t = 9$ yr interval between the *Einstein* and *IUE* observations, its frequency remained constant to better than $\delta\nu = 0.6$ c/d, i.e., 2.5%, despite pronounced changes in the system, e.g., in its X-ray luminosity. Thus the underlying clock must be robust and stable over at least $\nu\Delta t/\delta\nu \sim 350$ yr. Since the only sufficiently fast and stable clock known in cataclysmic variables is rotation of the magnetized white dwarf hence our confidence that V603 Aql is an intermediate polar. If so, then, from existence of the 3.5 hr oscillation (Haefner & Metz 1985; USC; Bruch 1991; Patterson & Richman 1991), by elimination we conclude that the accretion disk must exist in V603 Aql and must house its third clock.

There are no reasons to assume that the spin modulation of light must have constant amplitude in intermediate polars and remain always detectable. In fact, in TV Col the spin modulation was never observed optically, and in GK Per it was observed only in a fraction of light curves (Patterson 1991). It is likely that the seasonal changes in the X-ray luminosity of V603 Aql over a factor of 10 (Haefner, Pietsch, & Metz 1986; Schwarzenberg-Czerny & Pietsch 1993) are reflected in the changes of the amplitude of the optical modulation. Thus nondetections of the spin modulation by Schwarzenberg-Czerny & Buckley (1993), Bruch (1991), Patterson & Richman (1991), Haefner & Metz (1985), and of the usually over 0.1 mag strong 3.5 hr oscillation by Slovak (1980) in their photometries does not surprise us. However, by no means does this lack of evidence constitute an evidence of lack, in our opinion.

The only long X-ray observation of V603 Aql by Drechsel et al. (1983) was analyzed by Eracleous, Patterson, & Halpern (1991, hereafter EPH), who extracted the data anew from the *Einstein* data base, and by USC. The periodograms of EPH and USC (their Fig. 5) and the light curves folded with the 63 minute period are alike in both papers in that they show the strongest periodicity at 23 c/d (63 minutes) and similar amplitudes, large compared to errors. Note that EPH quote small Poisson errors while USC conservative errors account also for flickering. The values of χ^2 given by EPH, even after correction for flickering, are still consistent with over 10 σ detection at 23 c/d and 4.5 σ less probable detection at 46 c/d. The figures differ in that EPH find evidence of presence of the first harmonic in both their periodogram and in the light curve, a likely effect of their improved binning and phase resolution. As EPH argue for GK Per, the harmonic could arise if both magnetic poles are visible. Alternatively the secondary minimum can be produced by obscuration by the stream.

The results of USC and EPH power spectrum analysis are discordant. USC found the 23 c/d oscillation first in their optical data and for X-rays found probability of random detection at this particular frequency of $P_x = 0.00012$ (Table 2). EPH assumed no past knowledge of any period and computed the probability of random detection at any of $N_\nu \sim 10^4$ frequencies $P_{EPH} = N_\nu P_x \sim 1$. Because of low sensitivity, Eadie et al. (1971) advise against examining broad bands for evaluation of significance.

If the optical pulsation arises via reprocessing of X-rays in the tilted and precessing accretion disk its frequency could correspond to the beat of the rotation and precession frequencies of 22.90 (from UV) and 0.40 c/d, at 22.50 c/d and correspond to the observed optical alias at frequency of 22.46 c/d. The alias was preferred over the 23.46 c/d one by USC AOV analysis. The systematic mismatch of the frequencies would not affect our statistical considerations significantly as long as the shift remains small and predicted by a functional relation.

We would like to thank A. Cassatella for his expert support during our observations. We also thank N. R. Evans for her advice concerning observing strategy and data reductions, and J. Udalska for her help in data reductions. A. S. C. would like to thank W. Wamsteker and M. Rees for their hospitality at VILSPA, Madrid and Institute of Astronomy, Cambridge, respectively. We are obliged to M. Kaluzny, the president of CompArt, Ltd., Warsaw, for free use of their facilities. A. U. acknowledges the support from The National Research Science and Engineering Council of Canada through a grant to S. M. Rucinski. A. S. C. acknowledges with gratitude support of his visit to Cambridge by Mary Corbridge Trust at Robinson College.

REFERENCES

Boggess, A., et al. 1978, Nature, 275, 387
Bruch, A. 1991, Acta Astron., 41, 101
Deeming, T. J. 1975, Ap&SS, 36, 137; erratum 42,257
Drechsel, H., Rahe, J., Holm, A., & Krautter, J. 1981, A&A, 99, 166
Drechsel, H., Rahe, J., Seward, F. D., Wang, Z. R., & Wargau, W. 1983, A&A, 126, 367
Eadie, W. T., Drijard, D., James, F. E., Roos, M., & Sadoulet, B. 1971, Statistical Methods in Experimental Physics (Amsterdam: North Holland), 272
Eracleous, M., Patterson, J., & Halpern, J. 1991, ApJ, 370, 330
Gallagher, J. S., & Holm, A. V. 1974, ApJ, 189, L123
Garhart, M. P., & Teays, T. J. 1988, NASA *IUE* Newsletter, 35, 99
Haefner, R., & Metz, K. 1985, A&A, 145, 311
Haefner, R., Pietsch, W., & Metz, K. 1986, A&A, 200, 75
Horne, J. H., & Baliunas, S. L. 1986, ApJ, 302, 757
Patterson, J. 1991, PASP, 103, 1149
Patterson, J., & Richman, H. 1991, PASP, 103, 735
Roberts, D. H., Lehar, J., & Dreher, J. W. 1987, AJ, 93, 968
Scargle, J. D. 1982, ApJ, 263, 835
Schwarzenberg-Czerny, A. 1989, MNRAS, 241, 153
———. 1991, MNRAS, 253, 198
Schwarzenberg-Czerny, A., & Buckley, P. 1993, in preparation
Schwarzenberg-Czerny, A., & Pietsch, W. 1993, A&A, in press
Slovak, M. H., 1981, ApJ, 248, 1059
Udalski, A., & Schwarzenberg-Czerny, A. 1989, Acta Astron., 39, 125
Urry, M., & Reichert, G. 1988, NASA *IUE* Newsletter, 34, 96
Warner, B. 1985, in Cataclysmic Variables and Low-Mass X-Ray Binaries, ed. D. Q. Lamb & J. Patterson (Dordrecht: Reidel), 269
———. 1986, MNRAS, 219, 347