Part 2. The Status of Stellar Variability
Section 2B. Cataclysmic Variables

Cataclysmic Variables: From Radio to Gamma-Rays

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Abstract Some representative results of observations of cataclysmic variables, made over the whole width of the electromagnetic spectrum, are given. At the longest wavelengths the ejecta from novae have been found to be more massive than previously thought. X-ray to UV flux ratios are well-correlated with rates of mass transfer, but correlations with orbital period are shown to be the result of observational selection. I give some representative results of observations of cataclysmic variable stars (CVs) at different energies.

1. Radio emission

Radio emission from CVs has been known since the detection of Nova Ser 1970 and Nova Del 1967 (Hjellming and Wade 1970). The expanding shells of novae can be imaged at frequencies in the range of 1–20 GHz with interferometric arrays such as VLA and MERLIN, with typically 50-milliarcsecond resolution. This enables the morphology and optical thickness of a nova shell to be followed in some detail (Hjellming 1995; Pavelin *et al.* 1993). For Nova Cyg 1992 (V1974 Cyg), a spherically symmetric model with a linear internal velocity gradient fits the observations quite well (Hjellming 1995), and gives a shell mass of $\Delta M \sim 3 \times 10^{-4}\ M_{\odot}$. This is similar to what was found for Nova Vul 1984 (QU Vul) (Taylor *et al.* 1988), and shows that ejecta masses found from many optical and infrared observations are underestimates by factors of ~10 (see Table 5.7 of Warner 1995a). Shells of such large mass imply average nova recurrence times of $T_R \sim \Delta M / \dot{M} \geq 5 \times 10^4$ y. The most recent computations of CV eruptive evolution agree with this, giving $2 \times 10^2 \leq T_R \leq 4 \times 10^6$ y, with the exception of recurrent novae, for which $16 \leq T_R \leq 90$ y is a result of high $\dot{M}$($> 10^{-8}$ M_s y^{-1}) (Prialnik 1995).

Surveys for radio emission at 5 GHz from CVs at quiescence, and dwarf novae in outburst (Nelson and Spencer 1988; Pavelin *et al.* 1994; Beasley *et al.* 1994; Abada-Simon *et al.* 1993), show that CVs with magnetic primaries are the most likely to be detected, though some outbursting dwarf novae have also been detected (Benz and Guedel 1989). The latter observations suggest that Guedel it is interaction between the disc wind (only strong during outbursts) and the magnetosphere of the *secondary* that generates radio emission. The measured fluxes are such that if the emission mechanism is gyrosynchrotron radiation, then emission volumes several times larger than the volume of the binary itself are implied; this is compatible

with the magnetosphere of the secondary. For primaries with surface fields $\leq 10^5$ G, the secondary has by far the larger magnetic moment: field measurements on isolated K and M dwarfs show that the most rapidly rotating objects have fields up to 5 kG, correlated with spectral type (Saar 1990); CV secondaries rotate an order of magnitude faster than these isolated dwarfs, but the field generation mechanism has probably saturated even at rotation periods of ~4 days, so typical magnetic moments for the secondary are $\sim 10^{34}$ G cm^3, approximately independent of orbital period (Warner 1996).

The magnetic CVs show flaring activity in their radio emission, but there is no clear difference of behavior between the strong field systems (the polars) and the lower field systems (the intermediate polars), which may indicate that here also it is the secondary's magnetosphere that is generating the radio emission (Pavelin *et al.* 1994). The two frequently-detected magnetic CVs are AM Her (Bastian *et al.* 1985) and AE Aqr (Bastian *et al.* 1988; Beasley *et al.* 1994), which are among the closest of CVs.

The radio observations of AE Aqr are the most extensive for any CV. Flaring occurs, with similar appearance to the optical flares, but the two regimes are uncorrelated (Abada-Simon *et al.* 1995). The 33-second optical and X-ray pulsations caused by rotation of the primary and enhanced during optical flares do not show up as modulations at 8 GHz (Bastian *et al.* 1996), again emphasizing that the radio emission originates separately from the optical. It has been reported that radio emission from AE Aqr can occasionally be resolved as expanding shells (A. Neill, communicated to T. Bastian and others); observing with the VLBA will greatly assist interpretation of the origin of the long wavelength emission in AE Aqr.

2. Millimeter and sub-millimeter emission

In the earliest phases of nova shell ejection, although the shell is optically thick at decametric wavelengths (~3 GHz), it is optically thin around 1 mm. Observations of V1974 Cyg with the James Clerk Maxwell Telescope in the 0.5–2.0 mm region (Ivison *et al.* 1993) show complex structure and are incompatible with the radial velocity gradient and the variable wind models (Seaquist and Palmika 1977; Kwok 1983). Such observations are invaluable for determining the initial conditions of the launch of the nova shell/wind.

Sub-mm observations of non-erupting CVs are unlikely to be successful. A search among old novae detected no surprises (Howell *et al.* 1996).

3. Infrared emission

IR emission is detected from several components in CV binaries: the secondary, the outer parts of the accretion disc (or cyclotron emission in magnetic systems), dust and gas in nova ejecta, and dust condensed from the wind during dwarf nova outbursts.

A study of the IRAS database showed that a large number of old novae were detectable and could be explained by fine-structure forbidden line emission from ejecta gas ionized by the hot white dwarf that resulted from the nova explosion (Harrison and Gehrz 1991, 1994). An apparent detection of numbers of dwarf novae at 100μm, but not at 12, 25, or 60μm (Harrison and Gehrz 1992), has been shown to be caused by infrared cirrus (Howell *et al.* 1996), which leaves open the possibility that some of the nova detections may also be spurious. The use of infrared satellites ISO and SIRTF and the Boeing 747 SOFIA should resolve this issue.

The detection by IRAS of SS Cyg in outburst has been explained as heating of circumstellar dust by the enhanced ultraviolet flux (Jameson *et al.* 1987). A dust mass of $\sim 10^{-11}$ M_s at a temperature of ~400 K is required to provide the excess 12μm emission; this is about the *total* mass lost in one year's worth of wind (at least in Z Cam, where the estimate has been made; see Szkody and Wade 1981). A gas/dust ratio of 100 means that we are seeing the accumulation of a century or more of wind loss. More observations of this type should be made, including observations of nova-like variables where a continuous wind is present. When a nova eruption occurs, the ejecta will sweep through this circumstellar gas; the resultant shocks are observable in the X-ray region. The total mass of circumstellar gas gives an integration over the history of wind ejection since the previous nova eruption, which is related to the average rate of mass transfer from the secondary and the duty cycle between high and low rates.

Infrared observations made during nova eruptions provide a wealth of quantitative information. The review by Gehrz (1995) combines into a single table the derivable parameters. An important conclusion, the consequences of which are evident in visual light curves, is that there are two different kinds of nova eruption. Those that are the result of thermonuclear runaways in the outer layers of C-O white dwarfs produce carbon-rich ejecta in which dust condenses after 30–80 days, often becoming optically thick in the visible and causing the temporary deep minima characteristic of Nova Her 1934, and more recently of Nova Cas 1993. The other class of nova is the result of explosions on O-Ne-Mg white dwarfs and does not produce much dust. These novae have very strong IR emission lines of [NeII] and [NeVI], are known as *neon novae*, and include Nova Cyg 1992 among them.

In a single star evolution, an O-Ne-Mg white dwarf is only formed with mass greater than 1.2 M_s, as the product of evolution from initial masses 8–12 M_s (Truran and Livio 1989). There is, however, another channel open to produce O-Ne-Mg-rich white dwarfs in interacting binaries: systems that emerge from the common envelope phase with secondary masses greater than primary masses experience dynamical mass transfer (at $\sim 10^{-6}$ M_s y^{-1}), which results in mild He flashes that build an outer layer rich in Ne and Mg (Shara and Prialnik 1994). As a result, neon novae can have low-mass white dwarf primaries; this shows observationally in the existence of slow neon novae (e.g., Nova Oph 1988) and large ejected shell masses (e.g., Nova Vul 1984).

Improvements in the sensitivity of infrared detector arrays have opened a new window for observation of faint CVs in the near infrared. Surveys have been made by Ramseyer *et al.* (1993), and at a higher resolution by Dhillon and Marsh (1995). In non-magnetic systems, strong broad emission lines from the Paschen and Brackett series of hydrogen and He I lines arise from the accretion disc. There are, in addition, absorption lines of neutral atomic K, Fe, Al, Mg, and Ca, as well as CO and H_2O, which arise in the secondary and can be used to give spectral types (by comparison with similar lines in late-type single main sequence stars).

Unfortunately, in the magnetic systems of lower field strengths—the intermediate polars—the cyclotron humps seen in the IR continua of the more strongly magnetic polars (Cropper *et al.* 1989) are not detectable (Dhillon *et al.* 1997), which eliminates hopes for determining field strengths by using conventional spectrophotometry. Dhillon and Marsh point out that there may still be some hope, however, by increasing sensitivity to cyclotron IR emission through employing IR circular spectropolarimetry.

4. Optical and UV emission

The results from ground-based optical monitoring of CVs and of UV spectroscopy are included in other papers in this volume, so I will restrict my discussion to a new result which opens up possibilities for precision determination of the masses of some CV primaries.

The accretion energy deposited in the outer layers of the primaries prevents them from cooling to the effective temperatures $T_{eff} \leq 9{,}000$ K expected (D'Antona and Mazzitelli 1990) of white dwarfs with ages $> 10^9$ y. The T_{eff} found from UV flux distributions are in good agreement with the suggestion that they are determined by the value of $\dot{M}$, averaged over time scales ≥1 y (Sion 1985; Warner 1995a).

In order to maintain a white dwarf in the temperature range $11000 < T_{eff} < 13{,}000$ K, a $\dot{M} \sim 6 \times 10^{14}$ g s^{-1} is required, which is what is observed for some short-P_{orb} systems, both magnetic (polars) and non-magnetic (the SU UMa stars). The above temperature range corresponds to the instability strip for DA white dwarfs, in which the ZZ Ceti non-radial pulsators are found (Kepler and Nelan 1993). Recently the long outburst interval SU UMa star GW Lib has been found to be a ZZ Ceti pulsator (Warner and van Zyl 1998), which leads to the possibility that the apparent quasi-periodic modulations seen in SW UMa at quiescence (Shafter *et al.* 1986) are also non-radial pulsations of the primary. Great success has been achieved in the analysis of ZZ Ceti stars in determining masses, rotation periods, and interior compositional layering from the observed eigenfrequencies (e.g., Kepler and Bradley 1995). There is now a possibility of performing similar analyses for some CV stars. It will be interesting to see whether the strong magnetic fields of polars suppress or filter the pulsations.

5. X-ray emission

The X-ray light curves of individual CVs furnish useful information on structural details, but the systematics of X-ray emission also provide insight to the general structure of CVs. The standard theory of the boundary layer (BL) between disc and primary predicts that at low $\dot{M}$ the BL is optically thin, and to radiate its energy it must expand into a corona-like region, emitting hard X-rays; but at high $\dot{M}$ ($\geq 3 \times 10^{16}$ g s^{-1}), the BL is optically thick and radiates at ~10^5 K in soft X-rays and the EUVE region (see Section 2.5.4 of Warner 1995a). There should therefore be a correlation between the ratio of X-ray flux (F_x) to UV+optical flux (F_{uv}), decreasing as the rate of mass transfer increases. This is confirmed for systems with an estimated value of $\dot{M}$ (Richman 1996).

Van Teeseling and Verbunt (1994) found for non-magnetic CVs a correlation between F_x/F_{uv} and orbital period in the sense that F_x/F_{uv} decreases as P_{orb} increases. This has also been found with more extensive observations from ROSAT (van Teeseling *et al.* 1996; Figure 1).

This is interpreted as being a consequence of the apparent increase of $\dot{M}$ with P_{orb} (Patterson 1984). The three high points at large P_{orb} in Figure 1 are V426 Oph, WW Cet, and EI UMa, which have a F_x/F_{uv} characteristic of low $\dot{M}$ systems; van Teeseling *et al.* (1996) point out that two of these have low UV+optical luminosities, in agreement with this (based on distance given by Warner (1987), where the faint absolute visual magnitude M_v of WW Cet and of V426 Oph were already noted). Not plotted in Figure 1 is U Gem, which has P_{orb} = 4.2 hours and an M_v about 3 magnitudes fainter than V426 Oph (Warner 1987), which makes it also a low-$\dot{M}$ system. These stars demonstrate that the top right-hand region of Figure 1 is certainly populated by CVs, but it is undersampled, probably because of the relative intrinsic faintness of these systems in both F_x and F_{uv}. What about the bottom left region of Figure 1, in which no CVs are plotted? To be in this region requires short P_{orb} and high $\dot{M}$. Until recently, no such systems were recognized, and none happen to be included in the pointed ROSAT observations used to produce Figure 1. However, three types of short P_{orb} non-magnetic CV are now known to inhabit this region of $P_{orb} - \dot{M}$ space:

- The V1159 Ori stars, which comprise V1159 Ori, ER UMa, and RZ LMi (Robertson *et al.* 1995), and DI UMa (Kato *et al.* 1996); all have P_{orb} ~1½ hours and dwarf nova outbursts at intervals of ~4 days (and superoutbursts every ~10 days). These have been shown to have $\dot{M}$ near the critical value $\dot{M}_{crit}$ for disc stability (Warner 1995b; Osaki 1996), and hence ~5×10^{16} g s^{-1}. Such a value is a factor of 10–100 greater than that found in the normal SU UMa stars.

- BK Lyn is a nova-like variable with P_{orb} = 1.8 hours and low-mplitude superhumps (Skillman and Patterson 1993). With a stable accretion disc, BK Lyn must have $\dot{M}$ higher than that of the V1159 Ori stars.

- Three nova remnants with P_{orb} ~2 hours are known, with superhumps in high $\dot{M}$ discs (CP Pup: Patterson and Warner 1998; 1974 Cyg: De Young and

Schmidt 1994; T Pyx: Schaefer *et al.* 1992; Patterson, private communication, later published in Patterson *et al.* 1998).

We predict that measurement of F_x/F_{uv} for the above stars will begin to populate the lower left region of Figure 1. The result will be that, just as there is *no physical connection between* $\dot{M}$ and P_{orb}, it will be found that there is no connection between F_x/F_{uv} and P_{orb}. In both diagrams, the correlations initially found have been the result of selection effects pre-existing among the optically-recognized CV subtypes. The physical connection is between F_x/F_{uv} and $\dot{M}$, and at any P_{orb} there is a wide range (up to a factor of 10^3) of $\dot{M}$. There is still no certainty as to what produces the range of $\dot{M}$ at a given P_{orb}. Current theory of magnetic braking and the orbital evolution of CVs (Chapter 9 of Warner 1995) requires the *long-term average* (e.g. over > 10^4 years) to be primarily a function of P_{orb}; the large departures, both above and below, from the secular mean may simply be the result of the range of temporarily stable $\dot{M}$ values that result from irradiation heating of the secondaries (Wu *et al.* 1995), or there may be some other parameter (e.g., connected with the magnetic structure of the secondary) that is responsible.

6. Gamma-ray emission

Detections of V834 Cen and VV Pup at MeV energies were claimed by Bhat (1990) and Bhat *et al.* (1989), but a survey (with the Compton/EGRET detector) of all magnetic CVs by Barrett *et al.* (1995) to flux limits a factor of ten lower than the previous COS-B measurements has failed to detect these or any other such sources. The upper limit on MeV flux from AM Her is two orders of magnitude lower than the TeV flux earlier observed (Bhat *et al.* 1991). The independent detections of AE Aqr with good signal-to-noise (Brink *et al.* 1990; Bowden *et al.* 1992) are probably the only secure evidence of a CV emitting at TeV energies. The detection is aided by the presence of a 33-second modulation, as seen also at optical and X-ray energies. As in the optical region, the 33-second pulsations appear at red-shifted frequencies (relative to the steady 33.08-second modulation) during flares lasting minutes. The rapid rotation of the primary in AE Aqr may be the clue to its unique emission of TeV radiation (the velocity of light cylinder of the white dwarf lies within the binary separation). In 1993, an attempt to monitor AE Aqr at TeV to radio wavelengths simultaneously during a World Astronomy Day campaign, and with the Whole Earth Telescope, was frustrated by bad weather and equipment failures. Another such campaign should be attempted, particularly to check that optical, radio, and TeV flares are not necessarily simultaneous (Abada-Simon *et al.* 1995).

References

Abada-Simon, M., Bastian, T. S., Horne, K., Robinson, E. L., and Bookbinder, J. A. 1995, in *Cape Workshop on Magnetic Cataclysmic Variables*, eds. D. A. H.Buckley and B. Warner, *ASP Conf. Ser.*, **85**, 355.

Abada-Simon, M., Lecacheux, A., Bastian, T. S., Bookbinder, J. A., and Dulk, G. A. 1993, *Astrophys. J.*, **406**, 692.

Barrett, P., Schlegel, E., de Jager, O. C., Chanmugam, G. 1995, in *Cataclysmic Variables*, eds. A. Bianchini, M. Della Valle, and M. Orio, Kluwer, Dordrecht, 104.

Bastian, T. S., Beasley, A. J., and Bookbinder, J. A. 1996, *Astrophys. J.*, **461**, 1016.

Bastian, T. S., Dulk, G. A., and Chanmugam, G. 1988, *Astrophys. J.*, **324**, 431.

Bastian, T. S., *et al.* 1985, in *Radio Stars*, eds. R. M. Hjellming and D. M. Gibson, Kluwer, Dordrecht, 225.

Beasley, A. J., Bastian, T. S., Ball, L., and Wu, K. 1994, *Astron. J.*, **108**, 2207.

Benz, A. O., and Guedel, M. 1989, *Astron. Astrophys.*, **218**, 317.

Bhat, C. L. 1990, *Bull. Astron. Soc. India*, **18**, 215.

Bhat, C. L., Kaul, R. K., Rawat, H. S., Senecha, V. K., Rannot, R. C., Sapru, M. L., Tickoo, A. K., Razdan, H. 1991, *Astron. J.*, **369**, 475.

Bhat, C. L., Richardson, K. M., and Wolfendale, A. W. 1989, in *Proc. GRO Workshop*, ed. W. W. Johnson, Naval Res. Lab., Washington, DC., 4/57.

Bowden, C. C. G., *et al.* 1992, *Astroparticle Phys.*, **1**, 47.

Brink, C., Cheng, S. K., de Jager, C. O., Meintjies, J. P., Nel, I. H., North, R. A., Raubenheimer, C. B., van der Walt, J. D. 1990, in *Proc. 21st ICRC*, **2**, 283.

Cropper, M. S., *et al.* 1989, *Mon. Not. Roy. Astron. Soc.*, **236**, 29.

D'Antona, F., and Mazzitelli, I. 1990, *Ann. Rev. Astron. Astrophys.*, **28**, 139.

De Young, J. A., and Schmidt, R. E. 1994, *Astrophys. J., Lett.*, **431**, L47.

Dhillon, V. S., and Marsh, T. R. 1995, *Mon. Not. Roy. Astron. Soc.*, **275**, 89.

Dhillon, V. S., Marsh, T. R., Duck, S. R., and Rosen, S. R. 1997, *Mon. Not. Roy. Astron. Soc.*, **285**, 95.

Gehrz, R. D. 1995, in *Cataclysmic Variables*, eds. A. Bianchini, M. della Valle, and M. Orio, Kluwer, Dordrecht, 29.

Harrison, T. E., and Gehrz, R. D. 1991, *Astron. J.*, **101**, 587.

Harrison, T. E., and Gehrz, R. D. 1992, *Astron. J.*, **103**, 243.

Harrison, T. E., and Gehrz, R. D. 1994, *Astron. J.*, **108**, 1899.

Hjellming, R. M. 1995, in *Cataclysmic Variables*, eds. A. Bianchini, M. della Valle, and M. Orio, Kluwer, Dordrecht, 139.

Hjellming, R. M., and Wade, C. M. 1970, *Astrophys. J., Lett.*, **162**, L1.

Howell, S. B., Herzog, A., and Robson, I. 1996, *Astron. J.*, **111**, 899.

Ivison, R. J., Hughes, D. H., Lloyd, H. M., Bang, M. K., and Bode, M. F. 1993, *Mon. Not. Roy. Astron. Soc.*, **263**, L43.

Jameson, R. F., King, A. R., Bode, M. F., and Evans, A. 1987, *Observatory*, **107**, 72.

Kato, T., Nogami, D., and Baba, H. 1996, *Publ. Astron. Soc. Japan*, **48**, L93.

Kepler, S. O., and Bradley, P. A. 1995, *Baltic Astron.*, **4**, 166.

Kepler, S. O., and Nelan, E. P. 1993, *Astron. J.*, **105**, 608.
Kwok, S. 1983, *Mon. Not. Roy. Astron. Soc.*, **202**, 1149.
Neill, A. 19—, private communication to T. Bastian and others.
Nelson, R. F., and Spencer, R. E. 1988, *Mon. Not. Roy. Astron. Soc.*, **234**, 1105.
Osaki, Y. 1996, *Publ. Astron. Soc. Pacific*, **108**, 39.
Patterson, J. 1984, *Astrophys. J., Suppl. Ser.*, **54**, 443.
Patterson, J., and Warner, B. 1998, *Publ. Astron. Soc. Pacific*, **110**, 1026.
Patterson, J., *et al*. 1998, *Publ. Astron. Soc. Pacific*, **110**, 380.
Pavelin, P. E., Davis, R. J., Morrison, L. V., Bode, M. F., and Ivison, R. J. 1993, *Nature*, **363**, 424.
Pavelin, P. E., Spencer, R. E., and Davis, R. J. 1994, *Mon. Not. Roy. Astron. Soc.*, **269**, 779.
Prialnik, D. 1995, in *Cataclysmic Variables*, eds. A. Bianchini, M. della Valle, and M. Orio, Kluwer, Dordrecht, 217.
Ramseyer, T. F., Dinerstein, H. L., Lester, D. F., and Provencal, J. 1993, *Astron. J.*, **106**, 1191.
Richman, H. R. 1996, *Astrophys. J.*, **462**, 404.
Robertson, J. W., Honeycutt, R. K., and Turner, G. W. 1995, *Publ. Astron. Soc. Pacific*, **107**, 443.
Saar, S. H. 1990, in *The Solar Photosphere: Structure, Convection, and Magnetic Fields*, ed. J. O. Stenflo, *IAU Symp.* **138**, Kluwer, Dordrecht, 427.
Schaefer, B. E., Landolt, A. U., Vogt, N., Buckley, D., Warner, B., Walker, A., Bond, H. 1992, *Astrophys. J., Suppl. Ser.*, **81**, 321.
Seaquist, E. R., and Palimaka, J. 1977, *Astrophys. J.*, **217**, 781.
Shafter, A. W., Szkody, P., and Thorstensen, J. 1986, *Astrophys. J.*, **308**, 765.
Shara, M. M., and Prialnik, D. 1994, *Astron. J.*, **107**, 1542.
Sion, E. 1985, *Astrophys. J.*, **292**, 601.
Skillman, D. R., and Patterson, J. 1993, *Astrophys. J.*, **417**, 298.
Szkody, P., and Wade, R. A. 1981, *Astrophys. J.*, **251**, 201.
Taylor, A. R., Hjellming, R. M., Seaquist, E. R., and Gehrz, R. D. 1988, *Nature*, **335**, 235.
Truran, J. W., and Livio, M. 1989, *Lect. Notes Phys.*, **328**, 498.
van Teeseling, A., Beuermann, K., and Verbunt, F. 1996, *Astron. Astrophys.*, **315**, 467.
van Teeseling, A., and Verbunt, F. 1994, *Astron. Astrophys.*, **292**, 519.
Warner, B. 1987, *Mon. Not. Roy. Astron. Soc.*, **227**, 23.
Warner, B. 1995a, *Cataclysmic Variable Stars*, Cambridge Univ. P., Cambridge.
Warner, B. 1995b, *Astrophys. Space Sci.*, **226**, 187.
Warner, B. 1996, *Astrophys. Space Sci.*, **241**, 263.
Warner, B., and van Zyl, L. 1998, in *New Eyes to See Inside the Sun and Stars*, eds. F.- L. Deubner, J. Christensen-Dalsgaard, and D. Kurtz, *IAU Symp.* **185**, Kluwer, Dordrecht, 321.
Wu, K., Wickramasinghe, D. T., and Warner, B. 1995, in *Cataclysmic Variables*, eds. A Bianchini, M. della Valle, and M. Orio, Kluwer, Dordrecht, 320.

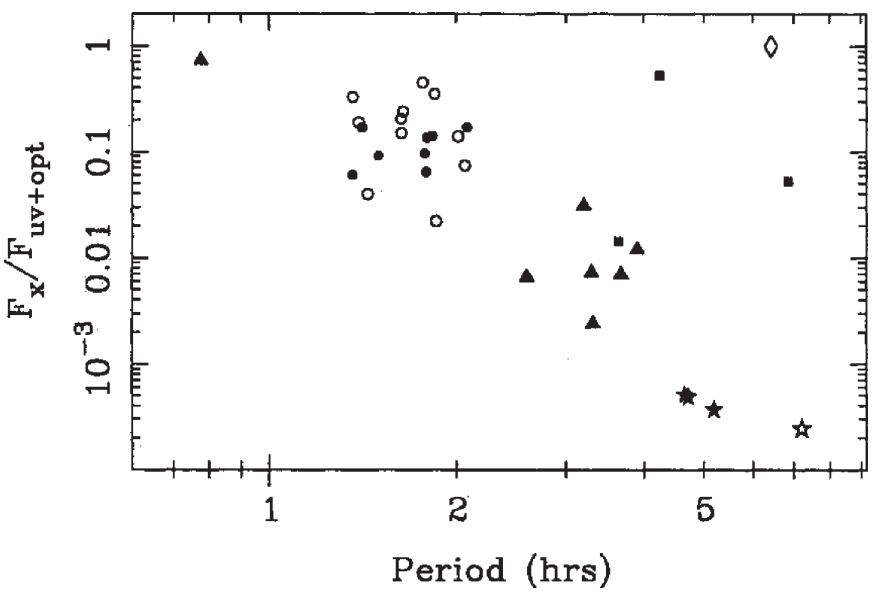

Figure 1. Flux ratio versus orbital period for CVs.