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White dwarf binaries

The white dwarf binaries considered in this chapter are better known as cataclysmic variables (CVs) and are interacting binaries in that the white dwarf is accreting material from its (usually) cool, late-type companion star in a short (of the order of hours) orbital period. They are one of the few classes of object considered in this book that were actually known and observed prior to the twentieth century. The novae become naked-eye objects (e.g. Nova Cyg 1975 which, at a peak of 2nd magnitude, completely transformed the appearance of Cygnus for a few weeks in the summer of 1975) and hence have been observed throughout human history, and dwarf novae were first reported in the middle of the nineteenth century (Hind 1856). It was the non-periodic but continuous eruptions displayed by dwarf novae (such as U Gem and SS Cyg) that led to their cataclysmic designation, a term now widely applied to all interacting binaries where white dwarfs are accreting. However, their physical nature was not understood until the pioneering spectroscopic studies of Kraft in the late 1950s which revealed their binary signature. CVs are of considerable importance for astronomy in general because of the significance of accretion processes on virtually all scales, from star and planetary formation (the proto-star accretes material from its surrounding molecular cloud) to accretion onto supermassive black holes in the centres of active galactic nuclei. Unfortunately, in most of those circumstances, the geometry and mass accretion are very poorly constrained, there are usually multiple emitting sources that are complex to unravel and the timescales can be uncomfortably long relative to human observing lifetimes.

In CVs the visible light we see is normally dominated by the accretion process itself (the transferred material usually forms an accretion disk around the white dwarf and this disk is heated to 5000–10,000 K by internal viscous processes) as

the cool, mass-losing companion is less massive than the Sun and hence very faint. The white dwarf may be hot but it is very small (comparable to the Earth in extent) and hence unable to contribute significantly to the light output except at the shortest wavelengths. CVs are also extremely common throughout our Galaxy and hence there are nearby objects for convenient study (of the several hundred CVs catalogued, the majority are estimated to be within 200–300 pc; Ritter and Kolb 1998, Downes *et al.* 1997). A valuable consequence of this is the low interstellar absorption for most CVs which allows their study over a wide range of wavelengths. This is particularly important for the inner part of the accretion disk and the white dwarf surface which can reach temperatures exceeding 20,000 K and hence the bulk of their radiation is in the far and extreme UV which can only be accessed from space. Furthermore the CV geometry (Figure 1) is well defined by orbital mechanics and Roche surfaces, thereby providing an outstanding astronomical ‘laboratory’ with which to test and improve our understanding of the physics of accretion onto compact objects, in particular the nature of the viscosity which acts within the disk. CVs thereby provide constraints on the basic physical properties of accretion disks which can then be applied in many other fields.

The typical luminosity and range of temperatures produced in CVs can be estimated in the following way. If material is being accreted by the white dwarf at a rate \dot{M} then the release of gravitational potential energy will produce a luminosity $L = GM_{\text{WD}}\dot{M}/R_{\text{WD}}$. For a white dwarf of mass $M_{\text{WD}} = 1M_{\odot}$ and radius $R_{\text{WD}} = 10^4$ km accreting at $\sim 10^{-10} M_{\odot} \text{ yr}^{-1}$ (a rate expected from calculations of the evolution of close interacting binaries) then total luminosities of $\sim 10^{33} \text{ erg s}^{-1}$ will result. And if this is assumed to be radiated uniformly from the white dwarf surface as black-body radiation ($L = 4\pi R^2\sigma T^4$) then $T \sim 30,000$ K and we would expect CVs to be copious sources of ultraviolet (UV)

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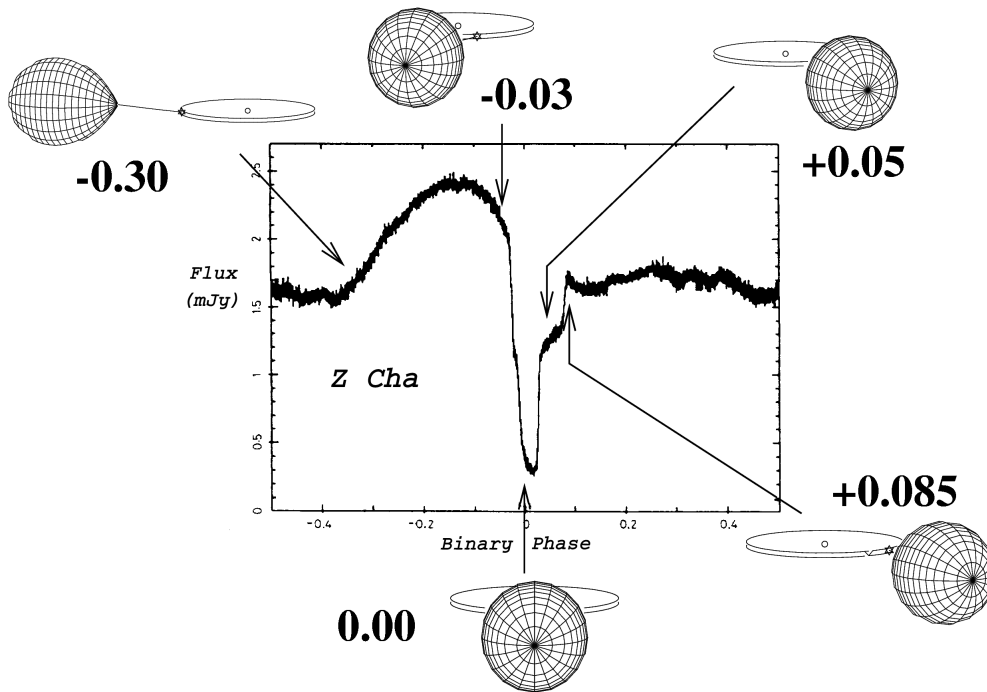


Figure 1 Basic geometry of a white dwarf interacting binary, in which a low-mass normal star transfers material into an accretion disk surrounding the white dwarf. Note that the mass-transfer stream produces a bright spot on the accretion disk, which is seen as the large hump in the light curve. The binary and resulting light curve is shown at different orbital phases using quiescent (low-state) observations of the eclipsing dwarf nova Z Cha as an example. (Adapted from Marsh 2001).

radiation. Indeed, most CVs show very blue colours rising at the UV end of the optical to imply that the bulk of the emission will lie at shorter wavelengths. However, if the accreting material is in free-fall onto the white dwarf surface then it should reach velocities of $\sim 5000 \text{ km s}^{-1}$ which correspond to temperatures of $\sim 10^9 \text{ K}$ and we would therefore expect hard X-ray emission to be produced. With these expectations both UV and X-ray satellite instruments were used to study these objects in the early days of space astronomy.

HISTORICAL SUMMARY

Dwarf novae are CVs which exhibit major optical outbursts (increasing in brightness by several magnitudes or more) at irregular intervals (usually of the order of weeks–months). The brightest are accessible with binoculars (e.g. SS Cyg and U Gem, both of which reach $V \sim 8\text{--}9$ at peak of outburst) and amateur groups have made fundamental contributions to their long-term light curves for more than a hundred years (Warner 1995). Walker's discovery (Walker 1954) that DQ Her is an eclipsing binary, combined with spectroscopic observations revealing occasional absorption and emission components, culminated in Kraft's (1962)

survey of CVs that definitively established their binary nature. The presence of a white dwarf in these systems as the primary was first demonstrated observationally by Crawford and Kraft (1956). These events and others are given chronologically in Table 1, and the properties of a selection of dwarf novae are summarised in Table 2.

Both spectroscopy and photometry demonstrated that the continuum emission from CVs almost always exhibited a hot, blue, non-stellar component. With orbital periods of hours and stellar companions of usually $\sim \text{G-M}$ spectral type, it became clear that the cool star (referred to as the 'secondary star' or 'companion') must be filling its Roche (equipotential) surface and hence transferring material into the hot accretion disk (Figure 1) that gives rise to the emission lines and blue continuum. For details (and equations) of the Roche geometry in interacting binaries see Warner (1995), the primary reference source for CV properties.

The accretion disk: importance of multi-wavelength studies

The material leaving the secondary's inner Lagrangian point carries its parent star's orbital angular momentum and hence cannot (in the absence of other forces) accrete

Table 1 Chronology of white dwarf binaries

| Year | Discovery |
|-------------|---|
| Pre-history | Naked-eye observations of nova outbursts |
| 1855 | U Gem at maximum light (Hind 1856) |
| 1896 | SS Cyg found from Harvard plates (Wells 1896) |
| 1938 | Term ‘dwarf novae’ coined by Payne-Gaposchkin and Gaposchkin (1938) |
| 1949 | Flickering found in UX UMa (Linnell 1949, 1950) |
| 1956 | 71 s pulsations in DQ Her (Walker 1956) |
| 1956 | Identification of WD as primary in CVs |
| | AE Aqr secondary filling Roche lobe (Crawford and Kraft 1956) |
| 1962 | All CVs are binaries undergoing mass transfer onto WD (Kraft 1962) |
| 1971 | Accretion disk responsible for outburst light (Warner and Nather 1971) |
| 1972 | Hard X-rays detected from EX Hya (Warner 1972) |
| 1974 | Novae at maximum seen in UV by OAO 2 (Gallagher and Code 1974) |
| 1977 | Large, variable polarization in soft X-ray source AM Her (Tapia 1977) |
| 1977 | Term ‘polars’ coined by Krzeminski and Serkowski (1977) for AM Her systems |
| 1978 | Soft X-rays from SS Cyg in outburst and quiescence (Heise <i>et al.</i> 1978) |
| 1980 | 14.3 min X-ray pulsations in H2252-035 (Patterson and Price 1980) |
| 1981 | ‘Supersoft sources’ (SSS) found by <i>Einstein</i> in LMC (Long <i>et al.</i> 1981) |
| 1981 | Term ‘intermediate polars’ coined by Krzeminski for asynchronous WD rotation |
| 1983 | <i>Einstein</i> X-ray survey of CVs (Córdova and Mason 1983) |
| 1991 | IUE spectra reveal cooling of U Gem WD between outbursts (Kiplinger <i>et al.</i>) |
| 1992 | Steady nuclear burning WD model for SSS (van den Heuvel <i>et al.</i> 1992) |
| 1996 | AE Aqr ‘magnetic propellor’ model (Eracleous and Horne 1996) |

WD = white dwarf.

Table 2 Properties of selected dwarf novae

| CV type | P_{orb} (h) | V | | | τ_{rec} (d) | τ_{decay} (d) | τ_{sup} (yr) | Spectral type |
|---------------|-------------------------|------|--------|------|----------------------------|------------------------------|-----------------------------|------------------|
| | | min. | inter. | max. | | | | |
| U Gem | | | | | | | | |
| IP Peg | 3.8 | 15.8 | | 12.3 | 95 | 1.5 | | M4V |
| U Gem | 4.2 | 14.6 | | 9.4 | 101 | 1.2 | | M4.5V |
| SS Cyg | 6.6 | 11.7 | | 8.2 | 40 | 2.4 | | K5V |
| RU Peg | 9.0 | 12.7 | | 9.0 | 65 | 3.4 | | K2V |
| BV Cen | 14.6 | 12.6 | | 10.7 | 149 | 7 | | G5-8IV-V |
| Z Cam | | | | | | | | |
| KT Per | 3.9 | 16.0 | 12.3 | 11.7 | 26 | 1.3 | | M3 |
| RX And | 5.0 | 13.6 | 11.8 | 10.9 | 13 | 1.7 | | |
| Z Cam | 7.0 | 13.6 | 11.7 | 10.4 | 23 | 2.6 | | K7V |
| EM Cyg | 7.2 | 14.2 | 12.9 | 12.0 | 22 | 3.6 | | K5V |
| SY Cnc | 9.1 | 13.7 | 12.2 | 11.1 | 27 | 2.3 | | G8V |
| SU UMa | | | | | | | | |
| WZ Sge | 1.36 | 14.9 | — | 7.1 | | | 30 | |
| OY Car | 1.51 | 15.6 | 12.4 | 11.5 | 50 | — | 1 | |
| IR Gem | 1.64 | 15.5 | 11.7 | 11.2 | 26 | 0.8 | 0.5 | |
| VW Hyi | 1.78 | 13.3 | 9.5 | 8.5 | 27 | 0.7 | 0.5 | |
| Z Cha | 1.79 | 16.0 | 12.4 | 11.9 | 82 | — | 0.6 | M5.5V |
| SU UMa | 1.83 | 14.8 | 12.2 | 11.2 | 19 | 1.4 | 0.4 | |
| YZ Cnc | 2.09 | 14.5 | 11.9 | 10.5 | 12 | 0.9 | 0.4 | |

(i) in the V magnitude range, “inter” corresponds to the standstill brightness of Z Cam stars, and the normal maximum of SU UMa stars.(ii) τ_{rec} is the mean recurrence time between outbursts. τ_{decay} is the decay time from outburst. τ_{sup} is the mean recurrence time between super outbursts.

directly onto the white dwarf. It therefore forms an extended, rotating accretion disk which has the compact object at its centre, and some physical process acting within the disk creates an internal viscosity which allows angular momentum to be transported outward in the disk, and material to accrete inwards. The nature of this viscosity has been one of the major unsolved problems in modern astrophysics, and is being actively investigated today (e.g. Balbus and Hawley 1998). Nevertheless, by wrapping up our lack of understanding of viscosity into the parameter $\alpha = \nu/c_s H$ (ν is the effective turbulent viscosity, c_s the sound speed and H the half-thickness of the disk), Shakura and Sunyaev (1973) produced the so-called α -disks which formed the starting point for observers and theorists alike. In the steady state, the radiated spectrum of the disk does not depend on α , but not surprisingly the disk's response time to changes in accretion rate does. Consequently, it is the outbursts of dwarf novae and the intervals between them which can constrain α and hence the physical processes that must be occurring (e.g. Lasota 2001).

The original Shakura and Sunyaev formulation is summarized in the review by Pringle (1981), and can be used to demonstrate the importance of multi-wavelength observations of CVs. The circular, thin disk is divided radially into annuli of radius r , each of which is assumed to radiate as a black body at temperature $T(r)$ where

$$T(r)^4 = T_{\max}^4 (r/R_{\text{WD}})^{-3} [1 - (R_{\text{WD}}/r)^{1/2}] \quad (1)$$

and T_{\max} is the disk's maximum temperature given by

$$T_{\max} = 41,000 (\dot{M} M_{\text{WD}} / R_{\text{WD}}^3)^{0.25} \text{ K} \quad (2)$$

where the mass transfer rate \dot{M} is in units of 10^{16} g s^{-1} , the white dwarf mass M_{WD} is in solar masses and the radius R_{WD} is in units of 10^4 km . The total radiated emission from the disk is then the sum of all the contributions from these annuli, as demonstrated in Figure 2 (La Dous 1989), the result of which is the continuum rising into the blue and UV regions. This produces the characteristic UV excess by which many CVs have been discovered. At this range of temperatures it is necessary to observe from the near-IR into the far-UV to fully characterise the spectrum of the disk.

By application of the virial theorem it can be shown that half of the total accretion luminosity ($GM_{\text{WD}}\dot{M}/R_{\text{WD}}$) is deposited in the disk, the other half in the boundary layer with the white dwarf. An optically thick boundary layer has temperatures of $\sim 10^{5-6} \text{ K}$ and thus radiates predominantly in the EUV and soft X-ray regions.

Early UV and X-ray Observations

This basic model of a CV is very similar to that of a low-mass X-ray binary (Chapter 34), apart from the difference in radius of the compact object (by a factor of $\sim 10^3$) when the neutron star is replaced by a white dwarf. Early (non-imaging) X-ray satellites of the 1970s (Uhuru, Ariel-5,

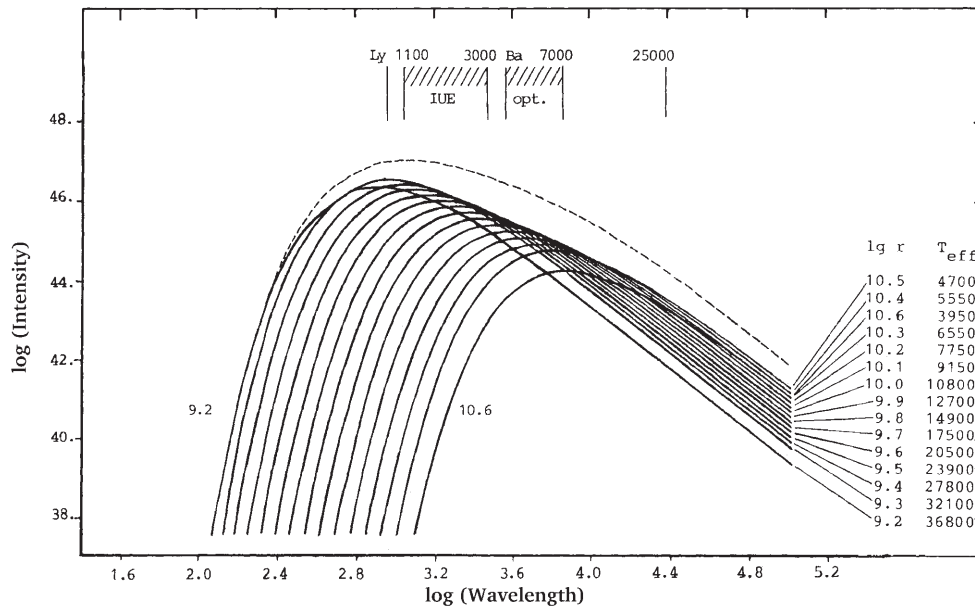


Figure 2 Simulated spectrum (dashed line) of an accretion disk computed by adding the contributions of individual rings or annuli in the disk, each of which is assumed to radiate as a black body. The contribution of each ring is labelled with its radius and temperature (coolest on the outer edge). (Adapted from La Dous 1989).



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