

Ultraviolet studies of interacting binaries

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Abstract

Interacting Binaries consist of a variety of stellar objects in different stages of evolution and those containing accreting compact objects still represent a major challenge to our understanding of not only close binary evolution but also of the chemical evolution of the Galaxy. These end-points of binary star evolution are ideal laboratories for the study of accretion and outflow processes, and provide insight on matter under extreme physical conditions. One of the key-questions of fundamental relevance is the nature of SN Ia progenitors. The study of accreting compact binary systems relies on observations over the entire electromagnetic spectrum and we outline here those unresolved questions for which access to the ultraviolet range is vital, as they cannot be addressed by observations in any other spectral region.

1 Scientific background and astrophysical context

The 20th century saw an impressive leap in the theory of stellar evolution – leading from not even knowing what source of energy powers the Sun to the extremely detailed models of stellar structure and evolution available today. A number of the present-day key research areas, e.g. galaxy evolution, are deeply rooted in our understanding of stellar evolution. However, while we may feel comfortable about our understanding of single stars, observational evidence collected throughout the last few decades makes it increasingly clear that the majority of all stars in the sky are born in binaries, of which many will interact at some point in their lives [Iben1991]. Virtually all of the most exotic objects in the Galaxy are descended from such binary stars, including binary pulsars, all the galactic black-hole candidates, low-mass X-ray binaries (LMXB), millisecond pulsars, cataclysmic variables (CVs), symbiotic stars, and many others. Binary stars are important in many other contexts, too. Sub-dwarf B stars, which now appear to be another product of binary evolution, dominate the ultraviolet light of old galaxies. The Type Ia supernovae, among the most important ‘standard candles’ in the determination of extragalactic distances on a cosmological scale, are thought to arise from exploding white dwarfs driven over their Chandrasekhar mass limit by accretion from a companion star. Even the class of short gamma-ray bursts, the most powerful explosions in the Universe, may be related to the merging of two neutron stars, again products of binary star evolution.

Interacting binary stars are showcases of the processes of mass accretion and outflow, exhibiting a variety of phenomena such as accretion discs, winds, collimated jets and magnetically controlled accretion flows, thermal disc instabilities, and both stable and explosive thermonuclear shell burning. The plasma conditions in these accretion structures span a huge range of physical conditions, including relativistic environments and extreme magnetic field strengths. Consequently, interacting binaries are also extremely versatile plasma physics laboratories.

Despite their great importance for a vast range of astrophysical questions, our understanding of close binary stars and their evolution is still very fragmentary. The ultraviolet (UV) is of outmost importance in the study of interacting binaries, as a large part of their luminosity is radiated away in this wavelength range, and, more importantly, as the UV hosts a multitude of low and high excitation lines of a large variety of chemical species. These transitions can be used both as probes of the plasma conditions, as well as tracers of individual components within the binaries through time-resolved spectroscopy. Moreover, the physical status of the binary components and in particular the accreting white dwarf primaries in cataclysmic variables, symbiotic stars, and double-degenerate binaries can be easily isolated and studied in the UV range. Even though substantial scientific progress has been achieved throughout the last three decades, primarily using the *International Ultraviolet Explorer (IUE)*, the *Hubble Space*

Telescope (HST), and the *Far Ultraviolet Spectroscopic Explorer (FUSE)*, these are still the early days of UV astronomy of interacting binaries, and many key questions are yet without answer. Here we outline the enormous potential that a major UV observatory has for our understanding of interacting binaries, and how the expected findings related to much wider astrophysical contexts, including galaxy evolution and cosmology.

2 Accreting white dwarfs

2.1 The complex interplay between stellar properties and binary evolution

Compared to their isolated relatives, the evolution of white dwarfs in interacting binaries is much more complex, and closely related to the evolution of the binary as a whole, and hence understanding close binary stellar evolution is impossible without detailed knowledge of the properties of the white dwarf components in these stars. The most abundant type of mass-transferring binaries containing a white dwarf are the cataclysmic variables (CVs), which have mass transfer rates in the range $10^{-11} - 10^{-9} M_{\odot} \text{ yr}^{-1}$. The accretion of this material and its associated angular momentum affects practically all fundamental properties of CV white dwarfs.

Compressional heating is depositing energy in the envelope and the core of the white dwarf, effectively compensating the secular cooling, with the result that accreting white dwarfs are substantially hotter than isolated white dwarfs of comparable age and mass. townsley+bildsten02-2,townsley+bildsten03-1 have shown that the white dwarf temperature can indeed be used to establish a measure of the long term average of the accretion rate sustained by the white dwarf. As the secular average accretion rate is directly related to the rate at which the binary is losing orbital angular momentum measuring this parameter is of fundamental importance for any theory of close binary evolution.

Accretion will increase the mass of the white dwarf. Eventually, if nothing else happens and the mass supply of the companion star is sufficient, this will drive the white dwarf over its Chandrasekhar mass limit, and it may turn in into a supernova Type Ia. Accreting white dwarfs as possible SNIa progenitors are discussed in more detail in Sect. 2.2 below. However, in most CVs the accreted hydrogen layer will thermonuclearly ignite once the density and temperature exceed the critical condition. This hydrogen shell burning is typically explosive, observationally designated as a classical nova, and ejects a shell of material into space (see Sect. 2.3). As the critical mass of the accreted hydrogen-rich layer is fairly low ($\sim 10^{-5} - 10^{-3} M_{\odot}$), a CV will undergo hundreds to thousands of nova explosions. Currently, it is not clear what the mass balance during the nova event is, i.e. whether the amount of ejected material is equal to or even exceeds the mass of accreted material, and, hence, the long-term evolution of the white dwarf mass is not known.

Chemical abundances of white dwarf surfaces can be affected by accretion

and greatly modified by nova explosions. While a roughly solar composition is expected for a freshly accreted white dwarf atmosphere, many CVs were recently found to possess an unexpected wide variety of departures from (solar) abundances [Sion1999], opening new horizons in the current understanding of binary evolution. Indeed while in single white dwarfs metallic species and their abundance reveal processes which oppose diffusion, those in cataclysmic variables show a mix of chemical species and abundances that cannot result from accretion from a normal secondary star, thus pointing towards a thermonuclear activity in their past evolution. The hypothesis of CNO processing as the source of the abundances has been further supported by the detection of proton-capture material by sionetal97-1. This has great implications for CV evolution and contributions to the heavy element content of the interstellar medium (see also Sect. 2.2).

Rotation rates of non-magnetic white dwarfs in CVs were unknown prior the *HST* era and its advent opened a new topic in close binary evolution. Global rotational velocities are now measured for a handful of dwarf novae systems [Sion1999] and were found to be much larger ($300\text{--}1200\text{ km s}^{-1}$) than the few tens of km s^{-1} in isolated white dwarfs, implying that accretion efficiently spins-up the primaries. However the measured rates are much lower than expected on the basis of the amount of angular momentum accreted during their characteristic lifetimes [Livio and Pringle1998, King et al.1991] suggesting that part of the accreted angular momentum is removed from the white dwarf during the expanded envelope mass loss phase which follows a nova eruption. This independently suggests that also dwarf nova experience nova outbursts and then return to be dwarf novae again, as suggested by the cyclic evolution scenario. Although this result has an enormous evolutionary implication, it is based on only 5 CV white dwarfs for which reliable rotation rates could be determined.

Whereas accretion alters the properties of white dwarfs in interacting binaries, some of the white dwarf characteristics will in turn deeply affect the accretion process — e.g. the mass of the white dwarf defines the depth of the potential well, and, thereby, the amount of energy released per accreted gram of matter, the rotation rate of the white dwarf determines the luminosity of the boundary layer, i.e. the interface between the inner accretion disc rotating at Keplerian velocities and the white dwarf itself, and finally the magnetic field of the white dwarf determines the accretion geometry.

The observational study of accreting white dwarfs can only be carried out in the UV, as the emission from the accretion flow dilutes or even completely outshines the white dwarf at optical wavelengths. Because of the faintness of most CV white dwarfs, the number of systems for which medium-resolution ($\simeq 1 - 2 \text{ \AA}$) spectroscopic data, adequate for temperature measurements, has been obtained is $\simeq 35$ (sion99-1, szkodyetal02-1, araujo-betancoretal05-2) — out of a total of ~ 1000 CVs known [Downes et al.2001]. High-resolution ($\simeq 0.1 \text{ \AA}$) UV spectroscopy necessary for accurate abundance and rotation rate determinations has been obtained only for a handful of systems, most noticeably for the nearest CV, WZ Sge (Fig. 1, see e.g. sionetal01-1, sionetal03-2, longetal04-1, welshetal03-1), at the expense of > 20 *HST* orbits.

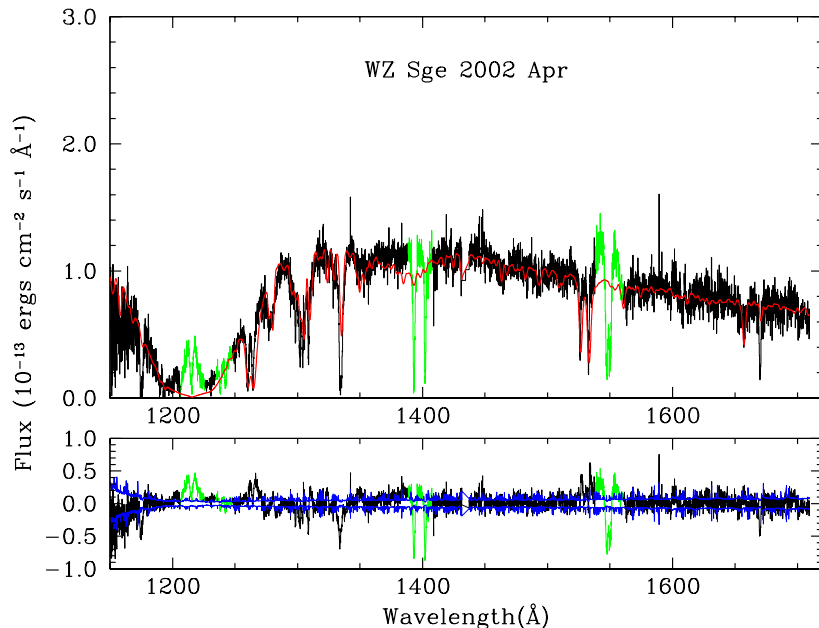


Figure 1: High-quality UV spectroscopy of accreting white dwarfs in CVs is necessary to determine their temperature, mass, rotation rate, and atmospheric abundances from detailed model atmosphere fits. Only a very limited number of CVs has been bright enough to be studied with the STIS high resolution grating, such as e.g. WZ Sge (from longetal04-1).

Future perspectives of UV astronomy. In order to fully assess the interrelation between the white dwarf properties and the evolutionary state of CVs, a sufficiently large number of systems has to be observed. Mapping out the parameter space (T_{wd} , M_{wd} , abundances and rotation rate of the white dwarf, as well as the binary orbital period) will eventually require adequate data for 100–200 systems. Temperature measurements need a broad UV wavelength coverage, optimally from the Lyman edge down to 3000 Å, at a low resolution ($R \simeq 1000 - 2000$). Abundance/rotation rate measurements rely on medium-resolution ($R \simeq 20000$) spectroscopy covering a sufficient number of transitions; the traditional range 1150 Å–1900 Å is adequate even though similar capabilities below Ly α would be desirable. Throughput is the crucial need for this science, as typical flux levels are a few $\simeq 10^{-16}$ erg cm $^{-2}$ s $^{-1}$ Å $^{-1}$.

2.2 Accreting white dwarfs as likely SN Ia progenitors

Whereas SNIa are routinely used as beacons at cosmological distances [Filippenko2004], and generally associated with the thermonuclear disruption of a carbon-oxygen white dwarf [Livio2001], the nature of their progenitors

remains elusive. Two different channels of SN Ia progenitors are currently most favoured [Yungelson and Livio2000]. In the double-degenerate channel two white dwarfs spiral in under the effect of gravitational radiation until they finally merge, exceeding the Chandrasekhar mass limit. Intensive optical surveys have been carried out for this type of SN Ia progenitors, most recently by [Napiwotzki et al.2001], identifying a few potential SN Ia progenitor candidates. In the single-degenerate channel a white dwarf accretes from a main-sequence companion. However, as outlined above, most white dwarfs accreting hydrogen-rich material will go through classical nova explosions and grow only little (or even shrink) in mass. Only if the white dwarf is accreting at a rate sufficiently high to sustain *steady-state hydrogen shell burning* – the accreted hydrogen is thermonuclearly processed at the rate it is accreted. These objects have been predicted (sharaetal77-1, iben82-1, fujimoto82-1) and first found in the EINSTEIN X-ray survey of the Magellanic clouds [Long et al.1981], even though it took a fair amount of time to identify their true nature [van den Heuvel et al.1992]. Based on their observational hallmark – a very large luminosity in soft X-rays, these objects are coined supersoft sources, or more appropriately supersoft X-ray binaries [Gänsicke et al.2000]. The high accretion rates that are necessary to fuel the steady-state shell burning in supersoft X-ray binaries can be provided by a Roche-lobe filling main sequence star if its mass is similar to or exceeds that of the white dwarf. As mass is transferred from the more massive to the less massive star, the binary period shrinks as a consequence of angular momentum conservation, stabilising or even enhancing the mass loss of the donor star. The mass transfer ensues on a time scale which is too short for the donor star to adjust its thermal structure, and in an evolutionary jargon supersoft X-ray binaries are known as thermal time scale mass transfer (TTSM) CVs. In the absence of nova eruptions, the white dwarfs in TTSM CVs grow in mass, and will, if the donor star provides a sufficient amount of material, surpass the Chandrasekhar limit and potentially explode in a SN Ia (distefano96-1, starrfieldetal04-1).

If the donor star in a TTSM runs out of fuel before the white dwarf reaches the Chandrasekhar mass limit, the mass ratio will eventually flip with the donor star being less massive than the white dwarf. Consequently, the mass transfer rate decreases and the shell burning ceases. From this point on, the system will evolve and look (at a first glance) like a normal CV – with the dramatic difference that normal CVs contain main-sequence donor stars, whereas post-TTSM CVs contain the CNO processed core of the previously more massive star. schenkeretal02-1 suggest that a significant fraction (up to 1/3) of all present-day CVs may actually have started out with a companion more massive than the white dwarf, and underwent a phase of TTSM. A recent *HST*/STIS snapshot survey of 70 CVs showed that $\sim 10\%$ of the systems display a significantly enhanced N/C abundance ratio, which suggests that these systems went through a phase of TTSM [Gänsicke et al.2003]. So far, not a single *progenitor* of supersoft X-ray binaries/TTSM CVs has been identified.

Future perspectives of UV astronomy. Mapping out the population of

failed SN Ia = post-TTSMT CVs will require low ($R \simeq 1000 - 2000$) resolution spectroscopy of several 100 CVs down to $\simeq 10^{-16} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ \AA}^{-1}$. Based this large sample, it will be possible to determine the orbital period distribution of post-TTSMT CVs with respect to the “normal” systems, model their evolution, and finally extrapolate these population models to the regime of true SN Ia progenitors. Follow-up the brighter ones at high resolution ($R \simeq 20000$) will be necessary in order to determine their detailed properties. This will also help to answer the very important question on whether the white dwarfs in these systems have grown in mass, i.e. are they more massive than in normal CVs?

Equally important is the search for true SN Ia progenitors. However, as the TTSMT phase is very short the chance of finding systems in this stage is small – in fact, in our Galaxy (where absorption in the plane further decreases the probability of finding such systems) only two supersoft X-ray binaries are known. Supersoft X-ray binaries can be located in local group galaxies using high spatial resolution ($\simeq 1''$) X-ray missions such as Chandra – however, X-ray data alone is typically insufficient to determine the properties of the objects. UV observations can substantially defeat crowding problems (see Sect. 7), and are well-suited to obtain fundamental parameters such as orbital periods. This implies large aperture high spatial resolution UV imaging capabilities (supersoft X-ray binaries in M31 have $V \simeq 23$).

A so far entirely unexplored potential is the search for *SN Ia pre-progenitors*, i.e. detached white dwarf/main sequence binaries with $M_{\text{sec}} > 1.6 M_{\odot}$ (langeretal00-1, han+podsiadlowski04-1). In the optical, these systems will be entirely dominated by the main-sequence star, and follow-up UV studies of main-sequence stars with UV excess (identified e.g. in the GALEX survey) will be necessary to identify them.

2.3 The nova phenomenon

Novae are the most spectacular phenomenon encountered in CVs and represent key objects to understand a wide variety of physical conditions of accreting matter including super-Eddington regimes and the interaction of ejecta in the interstellar medium and its chemical evolution. They are fundamental standard candles up to the Local Group, having hence important implications for cosmological distance calibrations.

Despite the enormous observational effort of the past 15 years, especially with multi-wavelength campaigns and datasets, there remain two fundamental uncertainties: what are the masses and structures of the ejecta and what drives the mass loss during the outburst? Radiative processes, which might be the source of a stellar wind during the ejection phase (e.g. hauschildtetal94-1) depends on the abundances (and therefore the details of the spectral evolution during the initial stages) and the bolometric luminosity. Explosions are powered directly by decays of radioactive isotopes generated during the thermonuclear runaway following the initial envelope expansion, but any subsequent mass loss must be driven by the match of the flux distribution with the envelope opacities [Shore2002]. The UV, now inaccessible to observation, is the driving spectral

region for the phenomenological analysis of novae. Only in this region it is possible to directly probe the properties of the ejecta - abundances, structure, mass - and determine the energetics of the thermonuclear runaway. The reasons are simply that the photometric behaviour is driven at all wavelengths longer than the UV by bolometric flux redistribution from the evolving central remnant white dwarf and that in the UV we can measure the resonance transitions of the dominant ions throughout the first few months of outburst. To date, only novae in the Galaxy and the LMC have been observed.

Novae have been used as distance calibrators for nearly a century through the maximum magnitude - rate of decline (MMRD) relation, but the origin of this relation has only recently been understood. As the ejecta expand, the rapid and enormous increase in the opacity from recombination-driven strengthening of the line absorption redistributes flux into the optical. But the correspondence between these two regions, the completeness of the redistribution process, depends on the details of the ejecta *filling factors*. If the ejecta initially fragment and/or if they are not spherical in the earliest stages, the process will be less efficient and the observed maximum at longer wavelengths will be altered. Without the UV, it is impossible to determine the bolometric luminosity and therefore to constrain its constancy.

The two principal classes of *classical* novae are distinguished by their abundances, which reflect the composition differences of the accreting white dwarf (CO and ONe). The most extreme explosions may produce significantly altered abundance patterns and there is an indication that the ejecta for both of these types are also helium enriched. Without the UV to provide access to resonance lines for the relevant ions, abundance studies - and the determination of structure - are limited by uncertainties in the equation of state for the ejecta.

Among recurrent novae, the two classes; those in compact, cataclysmic-like systems and those with red giant companions, appear to have very low mass ejecta (in agreement with current models) but with abundance patterns that suggest helium enrichment. The UV is the only way to study the ejecta in the optically thick phases (which last only a matter of days) to obtain unambiguously the abundances. It also is not clear whether these systems show discs, or winds, during quiescence. Finally, the interaction between the expanding ejecta and the winds in the symbiotic-like systems (with red giant companions) can only be studied effectively at high spectral resolution in the UV where the resonance lines and continuum of the white dwarf are accessible.

Future perspectives of UV astronomy. With increased aperture, especially in the 4-6 meter range, and high spectral resolution (10 000 or higher), it would be possible to study novae throughout the Local Group, especially M31 in which the full range of novae appear to occur. Novae are important contributors to several rare isotopes, especially ^{22}Ne and possibly ^{22}Na , and also may be important in ionising galactic halos (thus being important for understanding the halo ionisation and properties of Ly α Forest systems formed therein). Since they are recurrent phenomena, on many timescales, and remain hot for long periods they may be important for understanding the UV upturn in ellip-

tical galaxies (they can mimic post-AGB stars, for example). Finally, as bright, transient UV sources, they provide probes of the interstellar medium throughout their host galaxy. Also, the transition from the super-soft phase into the UV is essential but it has always been extremely difficult to determine. Furthermore the determination of chemical abundances in the ejecta is a fundamental parameter to test theories on the processes that lead to the nova phenomenon and to understand the state of the binary system. Indeed in no system these abundances were found to be solar-like (selvelli+gilmozzi99-1) having important implications in the chemical evolution of interstellar medium.

2.4 Symbiotic stars

The symbiotic systems are exotic and intriguing interacting binaries. The nature of the accreting hot companion was longly debated and proofs that the hot accreting companion is most likely a white dwarf and not a main sequence star were provided by UV observations (e.g. erikssonetal04-1). These systems however differ from the CVs because of their wider orbits, with orbital periods from a few to a few dozen years, and because the white dwarf accretes from the stellar wind of a late-type giant rather than through Roche lobe overflow from a main sequence star. The wind from the cool star is ionised by the radiation from the white dwarf resulting in the characteristic combination of sharp nebular emission lines and molecular absorption bands in their UV and optical spectra [Birriel et al.2000]. An increasing number of symbiotic stars are also found to show nova outbursts. In these systems, despite the much smaller outburst amplitudes compared to those observed in novae, the total energy associated with the outburst may significantly exceed that of a classical nova. Currently very little is known about the line-emitting regions associated with the outburst of a symbiotic nova because of the long timescales to reach the maximum and the very much slower decays [Rudy et al.1999]. Symbiotics also fall in the category of the supersoft X-ray sources [Greiner1996] making them potential SNIa progenitors [Hachisu et al.1999]. Furthermore only a handful of symbiotics have been monitored trough their outbursts in the UV, where the evolution of the hot accreting object can be best followed and from which the energetics of the process can be best studied and linked to the soft X-ray emission [González-Riestra et al.1999].

Among the different classes of interacting binaries discussed in this paper, symbiotic stars are by far the physically largest objects, and future UV/optical interferometric missions with sub-milliarcsecond spatial resolutions will be able to resolve the two stellar components, as well as the wind / accretion flow from the companion star, and possibly an accretion disc around the compact star. Carrying out such studies in the different UV resonance lines will allow a detailed mapping of the ionization structure in the accretion flow.

Future perspectives of UV astronomy. To identify the hot accreting component and to determine the UV luminosity and its evolution during outbursts the construction of SED over a wide spectral range is necessary. This

requires low dispersion (~ 2000) spectroscopy in the desirable range from the Lyman limit down to 3400 \AA . Our knowledge of the population of symbiotic novae in our Galaxy and Local group will enormously improve with UV imaging capabilities as described in Sect. 2.2 and 7. Furthermore the study of emission lines mapping a wide variety of physical conditions of the accreted matter and outflow need moderate-to-high dispersion spectroscopy ($R \sim 10\,000 - 20\,000$) in the FUV range. UV imaging at sub-milliarcsec resolution is required to physically resolve the stellar components and accretion flow.

2.5 Accretion flows in magnetic systems

Accretion can be greatly influenced by the presence of magnetic fields of the primary star. In those CVs where the white dwarf is strongly magnetised ($B > 10^5 - 10^8 \text{ G}$) important modifications of the accretion flow occur already at the distance of the donor star. The formation of an accretion disc is prevented in the high field systems ($B > 10 \text{ MG}$) or truncation of the accretion disc can occur in moderately ($B < 5 \text{ MG}$) magnetised CVs. Hence, the wide range of accretion patterns encountered in mCVs allows to test different physical conditions of accretion flow and X-ray irradiation. In particular, previous observations of magnetic systems have shown that the FUV continuum is dominated by the X-ray irradiated white dwarf pole [Gänsicke et al.1995], while the accretion funnel down to the post-shock regions contributes in the NUV continuum and in the FUV emission lines of CNO. The truncated disc is also a source of UV continuum (haswelleetal97-1, demartinoetal99-1, eisenbartetal02-1, belleetal03-1). However there are still important open questions on the physical conditions (kinematics, temperature and density) of the accretion flow:

(1) A strong potential to diagnose ionised gas is provided by the resonance FUV emission lines (CNO), as their FWZI $\sim 2000 - 3000 \text{ km s}^{-1}$ clearly indicates that they map the accretion flow down to the white dwarf surface. However, while past (low resolution) UV observations have allowed significant progress in the understanding of emission line formation ruling out collisional ionisation and strongly favouring photoionisation models [Mauche et al.1997], there is still a great uncertainty in theory, as they cannot simultaneously account for all the line flux ratios observed in CVs. Among the magnetic systems there seems to be a higher ionisation efficiency in the hard X-ray intermediate polar systems with respect to the soft X-ray polar systems [de Martino1999] suggesting that the soft X-rays are efficiently absorbed likely due to larger absorption column densities. Contribution to the FUV lines can also arise from the X-ray irradiated hemisphere of the secondary star and from material located in different parts of the flow [Gänsicke et al.1998], where plasma conditions can be very different from each other. An important improvement can be achieved by obtaining a systematic survey of phase-resolved (white dwarf spin and orbital period) of the FUV lines in magnetic CVs to perform Doppler tomogram analyses and to identify the kinematical properties of the accretion flow as well as to separate the different contributions of emission lines. This can allow a proper test of line formation theory as well as to understand the irradiation effects of the secondary

star.

(2) Magnetic systems have the most complex accretion geometry which is very difficult to parametrise. Spectral energy distributions (SEDs) from optical through the UV to the X-rays are necessary to determine the energy budget and to infer the mass accretion rates [Eisenbart et al.2002]. In the case of truncated discs as in the moderately magnetised systems, the UV SED is crucial to assess temperature profile and extension of disc down to the magnetospheric radius as the SED might show a turn-of in the UV range. Also, the X-rays can be substantially absorbed leading to accretion luminosities which can be much lower than those determined with combined UV and optical observations [Mukai et al.1994]. Up to date only a handful of bright magnetic CVs have been observed in the UV so far, but a systematic UV study has the potential to infer the relation between mass accretion rate and system parameters such as inclination angle and magnetic moments.

Furthermore, it is of fundamental importance to separate the spectral contributions of the heated pole caps of white dwarfs in polars from the unheated underlying white dwarf, thereby determining both the effects of irradiation and the white dwarf temperature. In this respect an important issue is the tendency of white dwarfs in the magnetic CVs to be cooler than those in non magnetic systems (sion99-1, araujo-betancoretal05-2) with significant differences at all orbital periods. This trend might reflect a difference in the mass transfer rate efficiency with respect to non-magnetic CVs as the systems evolve. In particular, the white dwarf magnetic field may reduce the secondary star magnetic braking efficiency [Wickramasinghe and Wu1994], a hypothesis which observations seem to confirm. However, a statistically significant sample of magnetic CVs is needed to be observed especially at periods above the orbital 2–3 hr period gap where only two systems have been covered so far with *HST*. This range of the period distribution is essential as it is dominated by angular momentum loss through magnetic braking. It is therefore important to determine the temperature of the unheated white dwarf atmosphere by means of low resolution UV spectroscopy over a wide wavelength range either when these systems are in a low accretion state or via phase-resolved observations which can allow to isolate the heated atmospheric pole from the unheated white dwarf atmosphere.

Future prospectives of UV astronomy. To map the accretion flow structure will need systematic phase-resolved UV spectroscopy at the orbital and white dwarf rotational periods in high and low dispersion to study the phase dependence of the FUV emission lines and of the SED. In particular the determination of kinematical properties of the accretion flow and the identification of the X-ray irradiated secondary star atmosphere require the coverage of the various FUV emission lines and hence a minimum range, of 1150–1800 Å (1000–1800 Å desirable) with a spectral resolution of $R \sim 20\,000$. Only for a handful of bright magnetic systems high resolution spectroscopy has been performed with *HST* and *FUSE*. Furthermore, the construction of SEDs over the widest spectral range from the Lyman edge down to 3400 Å is essential to determine simultaneously the different spectral components (disc, white dwarf, accretion funnels).

This requires low resolution spectroscopy at $R \sim 2000$ and good quality spectra at levels of a few 10^{-16} erg cm $^{-2}$ s $^{-1}$ Å $^{-1}$. Phase-resolved spectroscopy also demands large throughput in order to achieve reasonable signal-to-noise ratio with short exposure times. Timing capabilities of instrumentation (e.g. photon-counting systems) allowing to explore different types of variability (periodic, quasi-periodic and non periodic) on a wide range of timescales are essential. These can allow the access to the mostly unexplored temporal domain of UV emission in accreting magnetic systems.

3 Accretion discs

In order to form stars and galaxies, or to power active galactic nuclei and gamma-ray bursts, matter must be compressed by many orders of magnitude in size. This is possible while gravity dominates over thermal, magnetic and rotational energy. This can require the radiation of substantial amounts of thermal energy and the diffusion of magnetic field, but ultimately rotation always puts a brake upon this process because in a homologous collapse of a cloud of size R the rotation energy scales as R^{-2} while gravitational energy scales as R^{-1} . Nature's solution to this problem is to re-distribute the angular momentum in an accretion disc. In an accretion disc, gas travels in near-circular orbits gaining angular momentum from material at smaller radii, and losing it to matter at larger radii. The transport of angular momentum is driven by some form of viscosity, and only in recent years has a plausible candidate for this been identified in the magneto-rotational instability [Balbus and Hawley1998]. Despite this progress, our understanding of the viscosity of accretion discs and precisely how energy is dissipated within them remain the central unanswered questions in the field. A major obstacle to making progress is that two important properties of discs, their luminosity and temperature distribution, are independent of viscosity in steady-state discs. Progress can only be made through the study of phenomena that change on the *viscous timescale*, $t_\nu \sim R^2/\nu$ where R is the size of a disc and ν is the kinematic viscosity or by examining the vertical temperature structure of discs through their spectra. The great advantage of close binary stars is their small scales which lead to viscous timescales of only a few days or weeks, making them amenable to direct observation.

The outbursts of dwarf novae are almost universally believed to be driven by changes in the viscosity of the material in their accretion discs. In the standard *disc instability model* developed in the 1980s, in the quiescent state, the viscosity ν is very low, and the viscous timescale, t_ν , is so long that the disc cannot cope with the rate at which matter flows in at its outer edge. Instead, mass piles up in the outer parts of the disc until a critical point is reached and at some radius in the disc the viscosity (and therefore viscous dissipation rate) increases dramatically, by of order 100 times. This jump can take only a few minutes, with the outburst following as a heating wave propagates to all radii within the disc. A major goal of the study of accretion discs is to understand these outbursts: how they propagate, what triggers them, but above

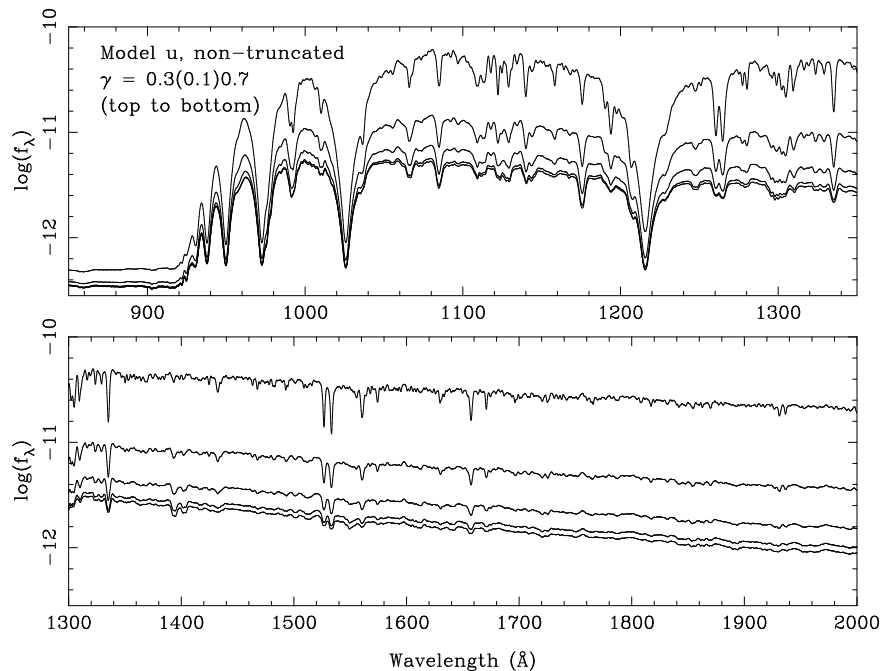


Figure 2: Model spectra of accretion discs with a range of radial temperature profiles, $T_{\text{eff}} \propto R^{-\gamma}$ [Orosz and Wade2003].

all, why the viscosity ramps up so violently. This is thought to be rooted in the ionisation of hydrogen (or in 'ultra-compact' binary stars, helium), but we have no detailed physical mechanism from which we can compute the viscosity for a given composition, density and temperature. All current models, which have been applied to accretion discs in a wide variety of objects, are hence purely phenomenological.

The commonest, nearest and most easily studied accretion discs are those of the cataclysmic variable stars which have white dwarf accretors. Accretion discs around white dwarfs vary in temperature from ~ 6000 K in their outermost parts to over 100000 K close to the white dwarf. The radius of the outer disc is typically 10 to 50 times that of the white dwarf, but it is from the hot, inner few white dwarf radii that most of the energy is released. The UV is the key waveband for seeing these regions. There are three other reasons for UV observation of accretion discs in these binaries. First, one can see absorption lines from the disc photospheres most easily in the FUV (Fig 2).

These give a handle upon ionisation state not available at optical wavelengths where emission from the (barely understood) disc chromosphere is always dominant and photospheric absorption lines are weak. Second, the UV is where disc model atmospheres currently seem to fail most severely, in general appearing too blue compared to observations [Orosz and Wade2003]. The final unique feature

of the UV is its sensitivity to the geometry of the disc because absorption of the inner by the outer disc is most easily seen in the UV and was first established from UV observations [Horne et al.1994].

3.1 Modelling the spectra of accretion discs

Since the early days of black-body models, followed by models based upon sums over standard stellar atmospheres [Wade1984], accretion discs models based upon modern model atmosphere codes have been developed [Wade and Hubeny1998, Orosz and Wade2003]. Such models are however undermined by our ignorance of the mechanism of viscosity and hence of the vertical temperature structure of discs. In principle, spectra can be used in reverse to determine vertical structure, but, so far, little progress has been made in this area. A problem of long standing is that disc model atmosphere spectra do not work very well, especially at FUV wavelengths. This might be down to the vertical structure, or it could be that the steady-state (radial) temperature distributions used so far are not accurate [Orosz and Wade2003], even though it is hard to understand how this can be the case in systems that hardly change on many viscous timescales. The problem comes from the small size of accretion discs in close binary stars, with a typical radius of a few 10^{10} cm. While their sizes help keep viscous timescales small, so that thermal instabilities are easily observed over the course of days to months, it means that the discs are not spatially resolvable as they subtend at best a few $\simeq 0.01$ milli-arcseconds for the closest systems. Direct imaging of the accretion discs will be possible in the foreseeable future only in the much larger symbiotic stars (Sect. 2.4), in which, however, the viscous time scales are substantially longer, and the temporal variability of symbiotics in terms of disc instabilities is much less established compared to the situation in CVs. Thus the spectra we see are the integrated spectra from all radii in the disc. This makes it hard to know whether it is the radial or vertical structure that is causing the problem. With integrated spectra, one cannot be sure whether all radii are poorly modelled or whether only specific effective temperatures are involved, and thus it is not clear how to adapt models. We need spatially resolved spectra, which can be achieved through a technique known as eclipse mapping [Horne1985]. Applied at UV wavelengths, this technique has the capability to provide spatially resolved spectra of the inner parts of accretion discs where most energy is released. We can then see where it is in the discs that model atmospheres fail most severely.

The principle of eclipse mapping is as follows: in an eclipsing system, the light-curve of the disc as it is eclipsed depends upon how concentrated the surface brightness is. For instance a flat distribution of brightness leads to a shallow V-shaped light curve, whereas a distribution which is strongly peaked towards the centre of the disc has a deep U-shaped light curve (Fig. 3)

Thus, in essence, the light curves can be used to deduce the variation of surface brightness with radius. Eclipse mapping was developed by horne85-1 for broad-band optical light curves. A significant step in eclipse mapping came with its extension to spectra [Rutten et al.1993, Rutten et al.1994]. The simple,

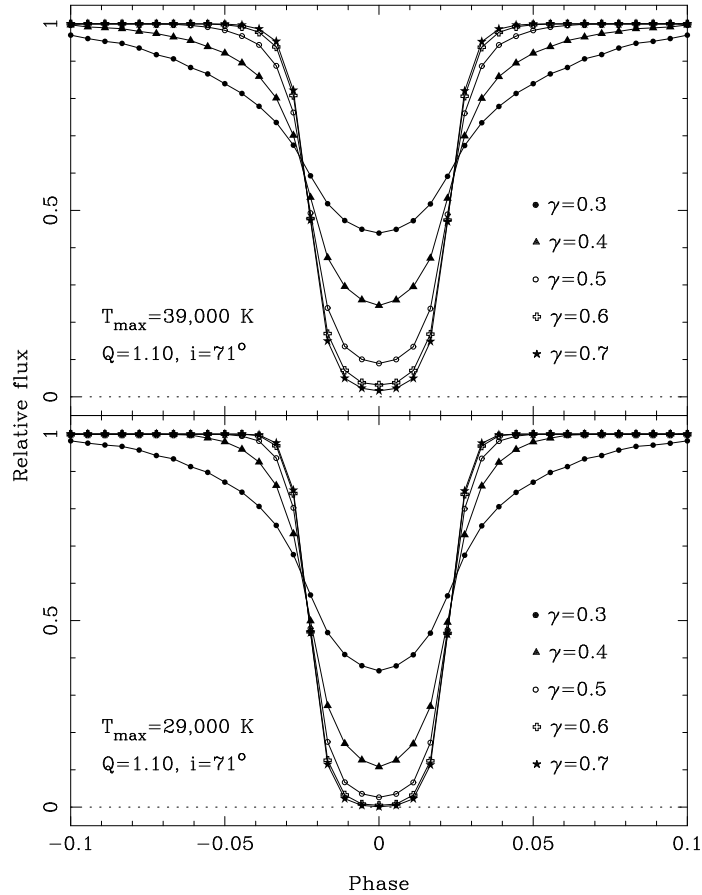


Figure 3: Model eclipses in the continuum from 1410 to 1530 Å for black-body (top) and model atmosphere discs for a range of radial temperature profiles, $T_{\text{eff}} \propto R^{-\gamma}$ [Orosz and Wade2003].

beautiful, idea was to carry out eclipse mapping on each pixel of low-resolution spectra to produce spectra at every point of discs. This technique applied to UV data has the capability of giving us spatially-resolved spectra of the inner accretion discs of close binary stars. Only one such analysis has been carried out in the UV with *HST*/FOS (baptistaetal98-1, Fig. 4) of the brightest of all high-state systems, UX UMa.

Even on this, the brightest suitable system, the study was limited by signal-to-noise ratio, especially at FUV wavelengths, precisely the most important part of the spectrum. The signal-to-noise ratio in this region of the spectrum is a modest 10% and yet the radial resolution is still only ~ 4 white dwarf radii, which means that we are still seeing the integrated light from a region which varies by a factor of three in temperature from the inner to outer edge of the

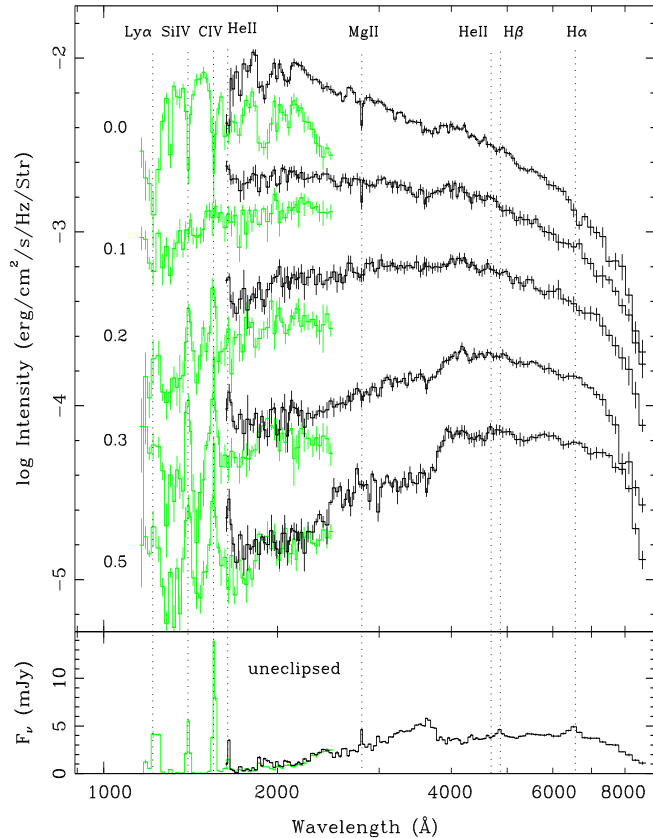


Figure 4: The spectra of the steady-state system UX UMA as a function of radius deduced from *HST*/FOS observations of its eclipse [Baptista et al.1998]. The spectra are those of annuli with central radius indicated in units of the distance to the inner Lagrangian point. Note that the spectra are plotted in f_ν ; the UV is dominant energetically.

annulus. In other words the problem of integrated spectra is only partially solved in this study.

Future perspectives of UV astronomy. To substantially improve our ability to model the spectra of accretion discs requires a low resolution, wide wavelength coverage UV spectrograph of much greater sensitivity than has been available to date. Low resolution ($R \sim 300$) because the spectral eclipse mapping technique cannot resolve the $\sim 1000 \text{ km s}^{-1}$ motions within the disc. UV because, as said before, this is where most luminosity is radiated and where the current disc atmospheres fail most severely. Wide wavelength coverage (at

least 1000 to 3000 Å, and if possible extending to the Lyman edge) because it is the variation of continuum flux with wavelength which tells us most directly about the vertical structure in stellar atmospheres. Finally, and perhaps above all, in comparison to any UV mission to date, high sensitivity is needed in order to improve both the signal-to-noise ratio in the deconvolved spectra and their radial resolution down to of order a single white dwarf radius and so that the method can be applied to systems fainter than UX UMa. Two other requirements needed for this work are an ability to take short exposures (< 2 seconds) which are accurately timed with absolute times good to better than one-hundredth of the exposure length.

Once progress in understanding gross properties of spectra has been made, there will be a need for higher resolution observations. Models can predict the changes in detailed line profiles expected during eclipse [Orosz and Wade2003]. Again disc broadening means that moderate resolution is sufficient ($R \sim 5000$), but high-sensitivity in order to allow short exposures and therefore high spatial definition of the disc are a must. The study of integrated spectra provides the most stringent requirement for spectral resolution because face-on discs (no eclipse) have significantly narrower line profiles and suffer less from blending. For these $R \sim 20\,000$ would be useful, covering from 900 Å to 1700 Å.

3.2 Disc instabilities

It is the study of dwarf nova outbursts that lead to the disc instability theory and the discovery of the strong dependence of viscosity with the physical conditions within the disc. The disc instability model has largely been used to explain the gross features of outbursts, such as their duration and amplitude, but there have not been convincing detections of the heating fronts which would allow us to confirm predictions of the models in detail. Attempts have been made from optical observations of eclipses, but these lose resolution in the inner disc because the outer disc dominates the light output at optical wavelengths. The propagation of the heating fronts into the inner disc is of particular interest because there is evidence to suggest that the inner disc is strongly depleted during quiescence [Schreiber et al.2004]. This is needed to prevent outbursts triggering in the inner disc, which in some systems would lead to too high an outburst rate. Propagation of heating fronts can be measured from the development of photospheric line profiles from the disc. As the front progresses inwards, the contribution from smaller radii in the disc will contribute to broadening the line profiles because Doppler broadening is largest in the inner disc. The photospheric lines are strongest by far in the UV and develop dramatically during outburst (Fig. 5).

Future perspectives of UV astronomy. So far this sort of study has not been possible because of limited sensitivity at FUV wavelengths. It also requires a much higher duty cycle than possible with *HST* as outbursts take of order a few hours to a day to start. Observations such as these could also show the development of winds through the resonance lines which are only visible

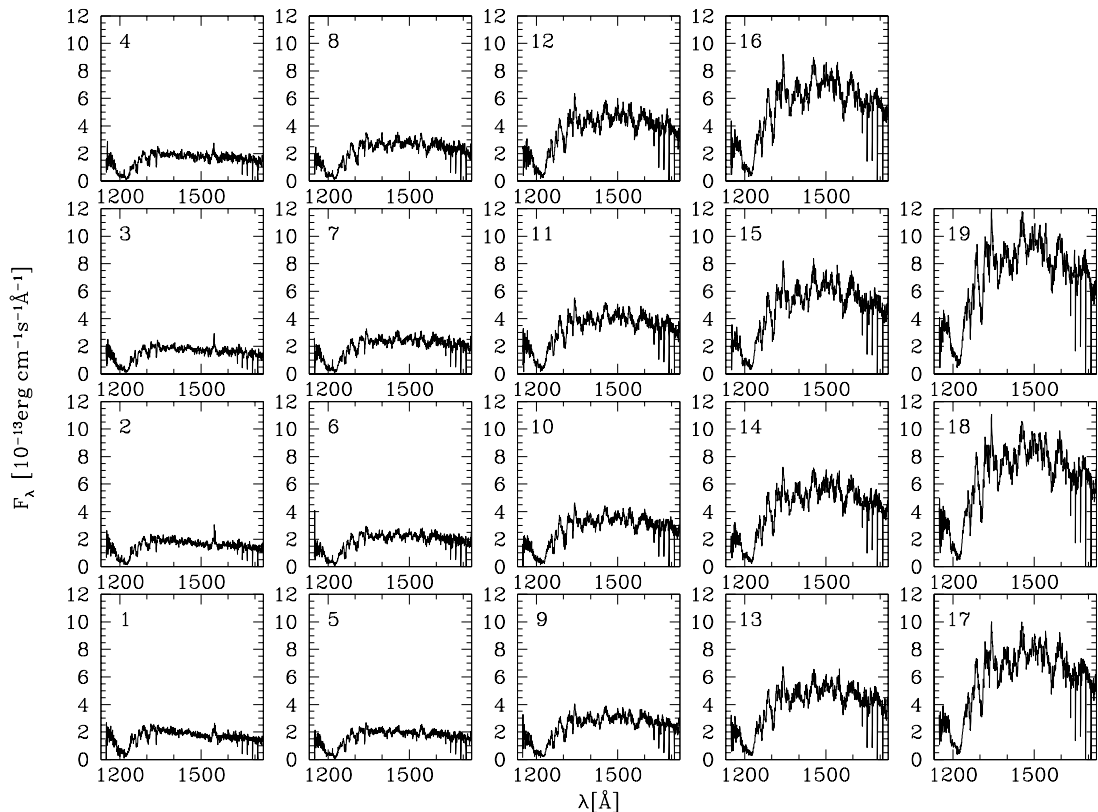


Figure 5: The spectra of the dwarf nova VW Hyi caught at the start of an outburst with *HST/STIS* [Sion et al.2004]. At first the spectra are dominated by the white dwarf but strong photospheric absorption lines develop as the heating front reaches the inner disc.

at UV wavelengths. A spectrograph covering 900 to 1700 Å with a resolution $R > 5000$ is needed for this work.

4 Hydrogen-deficient systems

A unique aspect of close binary stars is that owing to the evolution of their mass donor stars, some systems can show very unusual abundances, adding an extra dimension to the development of atmospheric models. The AM CVn systems for example have helium white dwarf donors and accretion discs which are $> 95\%$ helium. Ultra-compact neutron star/white dwarf binaries can have carbon-oxygen and oxygen-neon-magnesium donor stars. The element abundances are

crucial to understanding the evolution that leads to such stars. For instance, an evolutionary path from cataclysmic variable stars to AM CVn stars typically leaves a small amount of hydrogen [Podsiadlowski et al.2003], whereas a route via double white dwarf mergers does not. Similarly, the ratios of the CNO elements in such stars depends upon the initial mass of the donor stars. Such information is invaluable in pinning down evolutionary pathways, and therefore to predicting the numbers of systems. These binaries are so compact that they can fit comfortably inside the Sun. At the same time their short orbital periods means that gravitational radiation is strong (such systems will be significant sources for *LISA*) and mass transfer rates can be high. As a result, they emit mostly at UV wavelengths and the UV is where photospheric lines from the disc are strongest.

Future prospectives of UV astronomy. Over the next few years many more AM CVn systems are likely to be discovered, but as they are relatively rare, the majority will be faint. As for the hydrogen-rich systems, a $R \sim 20\,000$ spectrograph covering 900\AA to 1700\AA is needed, with high sensitivity the key feature.

5 Accretion winds

Mass loss is an ubiquitous feature of astrophysical systems and the evidence of mass loss in disc-dominated cataclysmic variables is unambiguous. In the wavelength range accessible to *IUE* ($\simeq 1150 - 3200\text{\AA}$), the existence of outflows in systems observed a lower inclination is indicated by P-Cygni-like and/or blue shifted absorption profiles in resonance transitions of N v, Si iv, and most commonly C iv. Velocity widths of $3000 - 5000\text{ km s}^{-1}$, comparable to the escape velocity from the primary, are regularly seen, especially in C iv. The features are understood to result largely from scattering of disc photons by the outflow. At low inclinations, the process removes photons along the line of sight to the disc; emission wings arise from photons scattered into the line of sight of the observer, just as in the stellar winds of massive stars. At higher inclinations, less direct light is observed from the disc, and the resonance lines generally appear as broad emission features. Indeed, after analysing $850 - 1850\text{\AA}$ spectra of Z Cam obtained with the *Hopkins Ultraviolet Telescope* kniggeetal97-1 suggested that virtually all of the lines in the UV spectrum of a typical high-state CV are formed in the outflow, either in the supersonic portion of the wind or in a lower velocity portion of the wind near the interface with the disc photosphere.

Although the strong 1s-2p transitions of Li-like or Na-like ions dominate the line spectra of disc-CVs observed with *IUE* and *HST*, the FUV spectra obtained with *FUSE* often show narrower features from intermediate ionisation state transitions of abundant ions such as N III, C III, Si III, and Si IV. These intermediate level ionisation state lines often show orbital phase dependent effects, even in systems of intermediate inclination such as Z Cam [Hartley et al.2005] that suggest the effects of the accretion stream must be included to complete the picture of extra-planar gas in disc-dominated systems. In RW Sex and

V592 Cas, enigmatic orbital variations in the blue edges of broad C III profiles indicate departures from bi-conical symmetry in the high-velocity wind [Prinja et al.2003, Prinja et al.2004]. Whether these are associated with disc tilts or the accretion stream or some other mechanism is not understood. Unfortunately the number of systems in which appropriate studies have been undertaken is small, and generally speaking not intensive or lengthy enough to fully characterise the phenomenology of the effects.

Originally, the possibility that the wind was a radial wind was considered, but observations of eclipsing systems showed changes in profiles shapes that are most straightforwardly interpreted as an indication of rotation, thereby indicating that the wind emanates from the inner disc [Drew1987]. Consequently, our basic picture of the high velocity wind first observed with *IUE* is of a bi-conical flow emanating from the inner portion of the disc and/or rapidly rotating boundary layer. vitello+shlosman93-1 were the first to attempt to actually model the profile shapes of wind lines as observed in high state CVs in terms of kinematic prescription for a bi-conical wind. They found that the *IUE*-derived ($R = 200$) C IV profiles of three systems – RW Sex, RW Tri, and V Sge – could be reproduced with moderately collimated winds with the local mass loss rates of order 10% of the disc accretion rate and terminal velocities of 1–3 times the escape velocity at the footprint of each streamline. Subsequently, knigge+drew97-1 succeeded, using a somewhat different kinematic parameterisation for a bi-conical flow, in reproducing the C IV profile of UX UMa through an eclipse. This analysis was important, not only because it was the first attempt to model changes in the profile through eclipse, but also because it suggested, at least in UX UMa, the existence of a relatively dense, high column density, slowly outflowing transition region between the disc photosphere and the fast moving wind. Both the Vitello & Shlosman and Knigge & Drew analyses suggested that the characteristic acceleration length for the high velocity winds observed in disc dominated CVs is quite long, or order $100 R_{\text{wd}}$. Most of the analyses of the spectra of disc winds were limited to single lines, but more recently long+knigge02-1 have developed Monte Carlo radiative transfer codes which in a few cases (see Fig. 6) are able to qualitative reproduce the full UV spectrum of a disc dominated CV. Hydrodynamical simulations of radiatively-driven CV winds are also been undertaken, and when combined with a radiative transfer code, these are also beginning to be compared to observed spectra with mixed results (see, e.g., proga03-1).

Although, modelling of CV winds has progressed, fundamental basic questions about the winds still remain. We are unable to measure basic parameters like the mass-loss rate, and although the wind is assumed to be radiatively driven, the observational and theoretical evidence for this is at best murky. For example, on the observational side, if the wind is radiatively driven, one might expect that the observational signatures of wind lines would be strongest when systems are brightest. But hartleyetal02-1 found there was no correlation between the strength of wind features and continuum brightness in the spectra of three observations each of the two nova-like variables IX Vel and V3885 Sgr with *HST*. (Unfortunately, the number of high state systems that

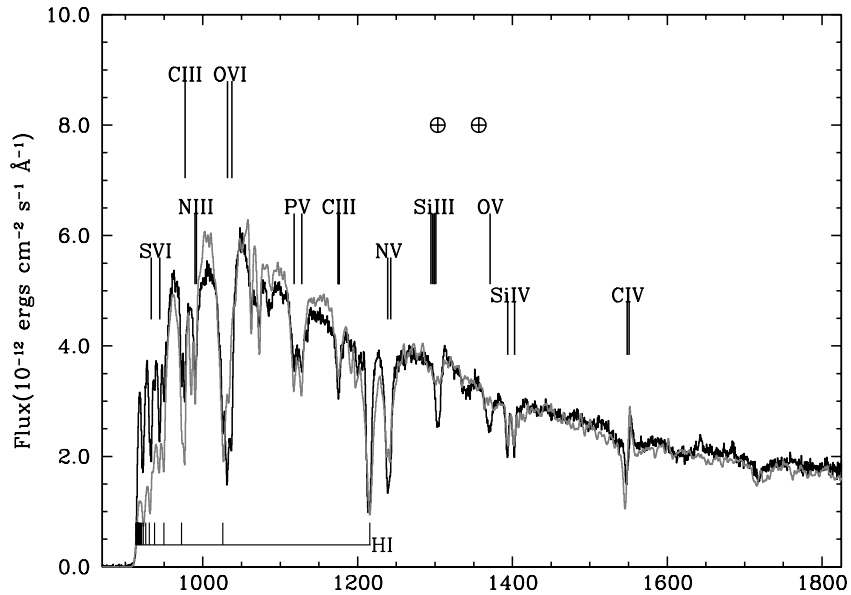


Figure 6: *HUT* spectrum of the wind dominated spectrum of IX Vel modelled compared to one of the models of long+knigge02-1

have been observed enough to begin to characterise their behaviour with time is quite limited.) And drew+proga00-1 have argued that the luminosity of discs is at best marginally enough to accelerate a high velocity wind. Thus, alternatives to the emission or additions to radiation pressure must be considered instead. These include viscous heating of the upper portion of the disc atmosphere [Czerny and King1989b], and irradiation [Czerny and King1989a] as well as magneto-centrifugal forces producing constant angular velocity out to the Alven surface [Cannizzo and Pudritz1988].

Future perspectives of UV astronomy. As observations of high mass transfer discs and winds in CVs have improved, so has the complexity of phenomenological descriptions of the wind structures emanating from the disc, especially as the wavelength coverage has extended in the the UV. But very few systems have been studied in enough detail to isolate common from uncommon behaviour. Furthermore, it is quite clear that the appearance of disc dominated systems is strongly modified by inclination, and as a result one needs to observe a number of similar systems to the same level of detail to be able to go beyond the general variations that were observed with *IUE*. To carry out a study of this type higher sensitivity is required so that the pool of targets that can be studied is substantial and so that the observations can be made at the resolution needed to resolve the narrower lines that exist particularly in the FUV short-ward of

1200 Å.

Higher sensitivity observations are also required to obtain a better short term characterisation of the wind flow. Some systems seem to have little or no short term temporal variability, whereas others, e.g BZ Cam [Prinja et al.2000] are highly variable. We do not know whether this is due to some fundamental difference in the systems – a magnetic white dwarf for example – or is it due simply to differences in the accretion rate. What is the role of outer disc in the creation of disc wind? Some hydrodynamical simulations show fast steady flows emanating from the inner disc, but complex time variable flows in the outer discs.

More systems need to be measured with high signal-to-noise ratio. The number of systems actually observed with *HST* were far fewer than observed with *IUE*, a fact that was partially a result of the way *IUE* was scheduled compared to *HST* and the fact that *HST* was never designed to be a dedicated UV observatory, but a multi-purpose / multi-wavelength facility. Instead the observations with *HST* have focused on a few key systems. Therefore it has been quite difficult to determine whether many of the phenomenological models proposed to explain the wind features of disc dominated features are founded on general characteristics of winds in disc dominated CVs and how many are due to individual systems.

To maximally constrain models of the wind, the wavelength coverage of a new mission should extend to the region containing O VI, and possible to the Lyman limit. Including O VI (along with N IV, Si IV, C IV, and He II) is important not only because O VI represents the next step up in the temperature space ladder, but also because the FUV below 1150 Å is rich in lines of intermediate ionisation states. These lines establish stringent constraints on physical conditions in the region near the disc plane.

6 Black-hole binary stars

Most of the dynamically-confirmed black hole binaries are transients, which spend most of their time in a low-luminosity state. Recently there has been much debate surrounding comparison of these quiescent black holes with their neutron star analogues in the attempt to detect "direct" evidence of event horizons in the former systems. Neutron stars are brighter in X-rays, as might be expected if the black holes advect accretion energy through the event horizon. The theoretical models for low-luminosity accretion flows onto black holes, however, include variants where the flow is unbound so that much of the accretion energy may be carried away as kinetic energy of an outflow. Hence it is crucial to identify the correct theoretical model before claiming event horizons have been detected. The UV is a vital window for achieving this: almost any model can reproduce the X-ray data alone by varying the fit parameters, but simultaneously fitting the UV spectra is much more exacting while optical and infrared wavelengths are hopelessly contaminated by the donor star and outer disc. The problem is that these systems are faint in quiescence and only three quiescent UV spectra exist

to date: of the black holes A 0620-00 and XTE J1118+480 and of the neutron star Cen X-4. The black hole spectra resemble each other and differ markedly from Cen X-4's. This suggests a real physical difference, but clearly insufficient to decide definitively between models. We need to observe more systems, and obtain simultaneous X-ray and UV data.

In outburst, transients brighten by factors of ~ 1000 across the optical-UV-Xray spectra regions. This is attributed to the same disc instability that drives the outbursts of cataclysmic variable stars, but the black-hole binaries are complicated by (i) irradiation of the optical-UV emitting disc by the central X-ray source which changes the effective temperature distribution and causes warping of the disc, (ii) by large discs which have no global stable high-state configuration below the Eddington limit, (iii) for reasons which are not yet fully understood, the inner accretion disc is often missing, being replaced within a transition radius, R_{tr} , by an optically thin, inefficiently-radiating advective flow. These factors substantially alter the character of the sources: luminosity generation, outflows, duty cycle, and the mass accumulation by the black hole are all changed. To understand these complications, UV observations are essential: the optical is dominated by the outermost disc (which behaves more like CV discs) and by the donor stars. The UV is required to see unambiguously the signatures of irradiation in the SED, to detect self-occultation by warping, and to measure the transition radii.

Future perspectives of UV astronomy. Only a handful of black hole X-ray transient outbursts have had their SEDs monitored throughout the outburst, and their behaviour has been diverse. Transients outburst on time-scales of decades and there are many that we have yet to detect. To understand the outbursts in a systematic way, more SED monitoring, including the UV, is required. Broad wavelength coverage at low resolution and high throughput are essential for this kind of studies.

7 Star clusters as laboratories for close binary evolution

It has been known since the mid-1970s that there is a 100-fold or so overabundance of bright LMXBs in globular clusters (GCs), relative to the galactic field (e.g. katz75-1). This quickly led to the realization that the high stellar densities in the cores of GCs might open up entirely new *dynamical* channels for the formation of interacting close binaries. The most famous of these is tidal capture, a 2-body process resulting from a close encounter between a compact object (white dwarf or neutron star) and an "ordinary" cluster members (main sequence star or giant). During such an encounter, the latter star experiences tidal distortions. This dissipates orbital energy and can therefore lead to capture and binary formation [Fabian et al.1975]. However, interacting binaries can also be formed via 3- and 4-body interactions, i.e. processes involving existing binaries. For example, in a close encounter between a low-mass (e.g. MS/MS)

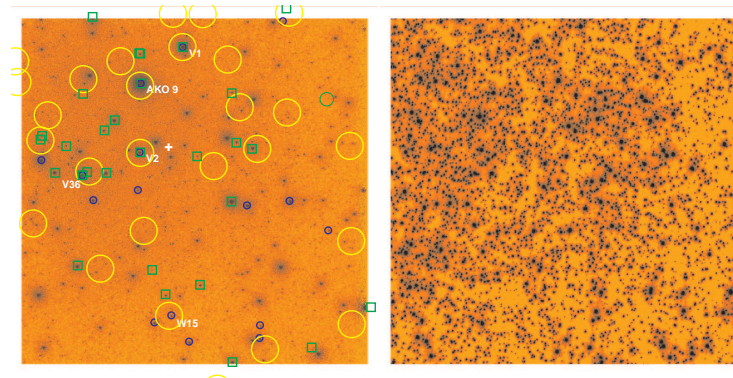


Figure 7: *Left Panel:* A deep *HST*/STIS FUV image of the core of 47 Tuc. The image is approximately $25'' \times 25''$ in size and includes the cluster centre (marked as a white cross). For comparison, 47 Tuc’s core radius is $23''$. The positions of previously known blue objects (green squares), Chandra X-ray sources (large yellow circles) and CV candidates (small blue circles) are marked. The four confirmed CVs within the field of view are labelled with their most common designations. The image is displayed on a logarithmic intensity scale and with limited dynamic range so as to bring out some of the fainter FUV sources. *Right Panel:* The co-added *HST*/WFPC2/F336W (roughly U-band) image of the same field. This image, too, is shown with a logarithmic intensity scale and limited dynamic range. Figure reproduced from kniggeetal02-1 (© 2002 The American Astronomical Society.)

binary system and a high mass (e.g. NS) single star, the most likely outcome is ejection of the lowest mass participant and formation of a NS/MS binary system [Sigurdsson and Phinney1993].

Interacting binaries in GCs deserve careful study for two basic reasons. First, they can in principle provide us with large, uniformly-selected samples of systems at known distances. This is precisely what is needed to test theoretical binary evolution scenarios. Second, close binaries are actually key players in controlling the late dynamical evolution of GC themselves. Thus interacting binaries can actually be used as tracers of the dynamically-formed close binary population in observational studies of GC evolution. In practice, the inevitable feedback between binary and cluster evolution will complicate things, but there is no doubt that interacting binaries in GCs can provide us with unique insights into both types of evolution.

UV astronomy has a key role to play in this area. Accreting binaries tend to have much bluer spectral energy distributions than the late-type main sequence stars that make up the bulk of stellar clusters and galaxies. This immediately implies that FUV observations should be an excellent way to find and study these populations, even in optically crowded fields, such as GC cores. This expectation is strikingly confirmed in Figure 7, which shows FUV and U-

band images of the same central regions of the GC 47 Tuc. The difference in crowding is obvious, and several CVs and new CV candidates pop up nicely in the FUV image. This image represents the deepest FUV survey of any GC carried out to date, and utilises observations obtained with STIS onboard *HST* [Knigge et al.2002]. Earlier generations of FUV/NUV detectors on *HST* have also been used to search for and study interacting binaries in GCs (e.g. parescetal92-1, demarchietal93-1, ferraro+paresce93-1, demarchi+paresce94-1, demarchi+paresce96-1, paresce+demarchi94-1, cooletal95-1, sosin+cool95-1). In the case of 47 Tuc, the lack of crowding in the FUV even makes it possible to carry out slitless, multi-object spectroscopy in the cluster core [Knigge et al.2003, Knigge2004].

In principle, open clusters and local group galaxies could also be used as binary evolution laboratories. However, open clusters contain fewer stars than GCs and are characterised by lower central densities. Thus interacting binaries are not as abundant in open clusters as in GCs, and the construction of a statistically interesting sample would probably have to involve studies of many such clusters. Local group galaxies obviously harbour large interacting binary population as well. However, even with a 4 m class space telescope, UV observations reaching the depths required to study the quiescent interacting binary populations will be extremely challenging for the Magellanic Clouds and probably impossible for all other local group galaxies.

Future perspectives of UV astronomy. Several additional galactic GCs have recently been imaged in the UV with *HST*, so the UV picture of their interacting binary populations will become clearer as soon as these new data sets have been analysed. However, all of these studies are seriously constrained by the small field of view of both the STIS and ACS UV detectors (roughly $30'' \times 30''$); this often makes it impossible to obtain a complete census of the interacting binary population. For example, the deep UV image of 47 Tuc in Figure 7 covers only about 1/3 of the cluster core. GALEX will be of some use in this regard (e.g. to find sources in GC outskirts and open clusters), although the benefit of its larger field of view is partially offset by its poorer spatial resolution and lower sensitivity (relative to *HST*).

The optimal future UV imaging instrument would consist of a large (≥ 4 m) mirror feeding a large-format detector producing images with diffraction-limited spatial resolution. However, the ability to obtain spectral information is also crucial to allow secure classifications of the detected UV sources. Single-slit/single-object spectroscopy is an extremely inefficient way of obtaining this information in a cluster setting. As noted above, slitless spectroscopy may be used in special cases, but what is really needed is a more generally applicable way to carry out multi-object spectroscopy (MOS) in the UV. MOS using optical fibres is probably not an option, since fibre losses rise steeply towards short wavelengths (at least in the current generation of fibres). Configurable slit masks are probably also impractical in a space-based observatory, since their use would require a large number of delicate moving parts. A simple, low-tech solution is to provide a reasonably large selection of narrow-band filters.

An intriguing high-tech solution might involve superconducting tunnel junction (STJ) detectors (e.g. cropperetal03-1,verhoeve02-1, see also romanietal99-1). These are able to provide an energy estimate for every photon detected, so imaging and spectroscopy could, in principle, be done in a single observation.

8 Requirements on future UV instrumentation

Here we summarise the instrumental requirements defined by the scientific goals above.

1. Low-resolution spectroscopy ($R \simeq 1000 - 2000$), with a wavelength coverage as large as possible. Optimum would be simultaneous data from Lyman edge down into the blue optical ($\simeq 5500 \text{ \AA}$). The first priority is the broadband coverage, and highest throughput. Continuum signal-to-noise ratio of $\simeq 10$ at flux levels of a few $10^{-16} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ \AA}^{-1}$ should be achieved short exposures (10 – 30 min).
2. Medium-resolution spectroscopy ($R \sim 20000$). The “standard” wavelength range 1150 – 1800 \AA would be adequate, covering the entire far UV down to the Lyman limit would be preferable.
3. Detectors. Both low and medium spectrographs should have photon counting detectors with absolute times accurate down to fractions of a second.
4. Large field-of-view UV imager (10 arcmin) with high spatial resolution (diffraction limited). Broad-band UV filters. Photon counting with accurate timing information. UV/optical interferometrie providing sub-milliarcsec spatial resolution.

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