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Far ultraviolet spectroscopy of (non-magnetic) cataclysmic variables

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Abstract

HST and *FUSE* have provided high signal-to-noise, high-resolution spectra of a variety of cataclysmic variables and have allowed a detailed characterization of FUV emission sources in both high and low states. Here, I describe how this has advanced our understanding of non-magnetic CVs. In the high state, the FUV spectra are dominated by disk emission that is modified by scattering in high and low velocity material located above the disk photosphere. Progress is being made towards reproducing the high-state spectra using kinematic prescriptions of the velocity field and new ionization and radiative transfer codes. In conjunction with hydrodynamical simulations of the outflows, accurate estimates of the mass loss rates and determination of the launching mechanism are likely forthcoming. In quiescence, the FUV spectra reveal contributions from the WD and the disk. Quantitative analyses have lead to solid measurements of the temperatures and abundances of a number of WDs in CVs, and of a determination of the response of the WD to an outburst. Basic challenges exist in terms of understanding the other components of the emission in quiescence, however, and these are needed to better understand the structure of the disk and the physical mechanisms resulting in ongoing accretion in quiescence.

Keywords: Accretion disks; Cataclysmic variables; Dwarf novae; White dwarf

1. Introduction

In disk-dominated cataclysmic variables (CVs), mass accretion onto a white dwarf (WD) from a relatively normal secondary star is mediated by a disk that extends close to the surface of the WD. All CVs vary, but the character of the variability probably reflects the time-averaged accretion rate from the secondary (see, e.g. Stehle et al., 2001). Systems with low accretion rate show semi-periodic outburst of 3–5 magnitudes (in m_v) and are known as dwarf novae (DNe). These outbursts are due to a thermal instability that converts the disk from a low temperature, mostly unionized, optically thin (in the continuum) state to a high temperature, ionized, optically thick state. During the outburst, the mass transfer rate $\dot{m}_{disk}$ in the inner disk rises from 10^{-10} to 10^{-8} $M_{\odot}$ yr^{-1}, and, in terms of the simplest picture of the system, the dominant source of FUV emission changes from being the WD to the disk. By contrast, systems with high mass-transfer rates remain in the high state most of the time, and are known as nova-like variables. Finally there are "Z Cam" objects, which undergo normal DN outbursts as well as outbursts that stall during the transition to quiescence for weeks to months at an intermediate magnitude (typically 0.5–1 magnitudes below peak). These are thought to be systems with intermediate rates of mass transfer from the secondary star.

2. Modelling the disks and winds of high state CVs

As first shown using *IUE*, the FUV spectra of disk-dominated CVs in outburst show "blue" continua that can be reasonably approximated in terms of a weighted set of stellar atmospheres, where the weighting is determined by the temperature and gravity of a steady state accretion disk and where each spectrum is broadened to mimic that of a rotating disk annulus. A modern example using data from *FUSE* and *HST*, is shown in Fig. 1. When, as in this case, the distance and inclination are known, the fit depends almost entirely on the observed flux. In these cases, the fact

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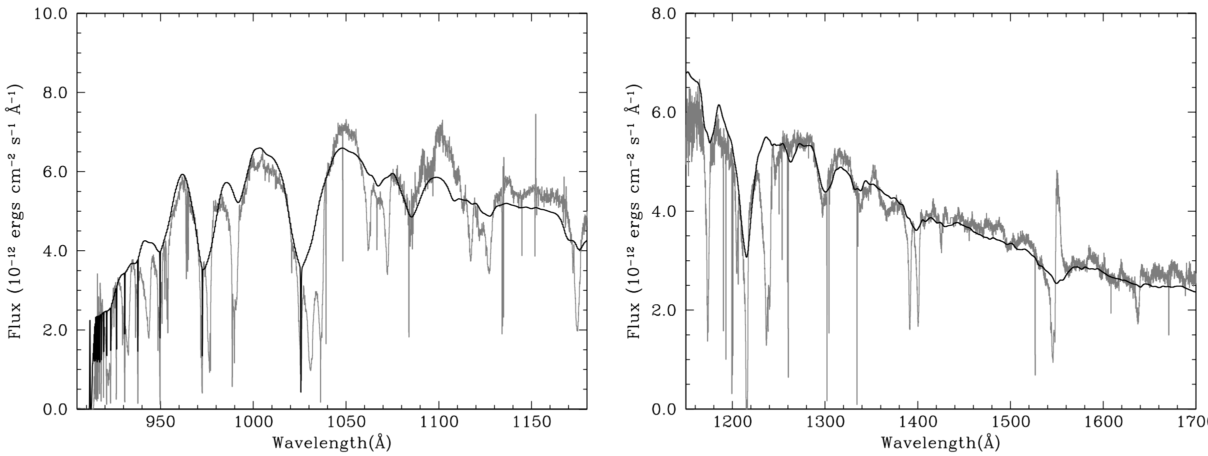

Fig. 1. V3885 Sgr as observed with *FUSE* (left) and *HST* (right) compared to disk models constructed from summed stellar spectra. In fitting the models, the only free parameter was $\dot{m}_{disk}$. The distance to the object and the inclination was fixed.

that the model qualitatively reproduces many of the features in the spectrum suggests that the derived $\dot{m}_{disk}$ is close to the correct value. On the other hand, models based on stellar atmospheres have generally been shown to fail to reproduce the spectrum over large wavelength ranges, particular if the range spans the Balmer limit. Stellar atmospheres have a pronounced Balmer jump in contrast to what is observed in high state disk systems. This is surely due to differences between disk and stellar atmospheres. Ad hoc solutions, such as including a transition region above the surface of the disk, are capable of addressing the problem but do not discriminate between likely mechanisms, which include viscous energy dissipation in or illumination of the disk atmosphere. To date there have been very few published attempts to create more physically correct model disk spectra and perform detailed comparisons to high quality spectra. However, this is likely to happen soon (see, e.g. Wade and Hubeny, 1998).

The disk model fits will not provide a complete solution, however, because FUV spectra of high state systems show clear evidence of winds. P Cygni like profiles in N V, Si IV, and (most commonly) C IV are observed in some systems, and the centroids of these lines are blue-shifted in others. Blue edge velocities of 2000–5000 km s^{-1} are observed. Recently, a number of systems have been observed in the 900–1185 Å range with *FUSE*. These show surprising diversity. In particular, although some systems do show high-velocity wind emission from S VI and O VI, it is common to see relatively narrow lines with small (100 km s^{-1}) blue-shifts from intermediate ionization states (Froning et al., 2001, 2004). The velocity widths of these lines are too narrow for either the disk or the high-velocity outflow represented by C IV in the *HST* range.

Shortly after winds were first discovered in CVs, observations of eclipsing systems showed changes in profiles shapes that indicate substantial rotation, suggesting a disk origin for the outflow (Córdova and Mason, 1982). Consequently, our basic picture of the high-velocity winds is of a bi-conical flow emanating from the inner disk. Vitello and Shlosman (1993) were the first to attempt to model the profile shapes of wind lines as observed in high state CVs in terms of a 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 mass-loss rates ($\dot{m}_{wind}$) of order 10% of the disk accretion rate ($\dot{m}_{disk}$) and terminal velocities of 1–3 times the escape velocity of each streamline. Subsequently, (Knigge and Drew, 1997) succeeded, using a different parametrization for a bi-conical flow, in reproducing the C IV profile of UX UMa though an eclipse as observed at $R = 2000$ with *HST*/GHRS. This analysis was the first attempt to model changes in the profile through eclipse, and suggested in UX UMa the existence of a relatively dense, high-column-density, slowly outflowing transition region between the disk photosphere and the fast moving wind.

Recently, my collaborators and I have developed a new Monte Carlo radiative transfer code that invokes a Sobolev approximation with escape probabilities to follow photons through an axially symmetric wind. "Python" is designed to produce a complete spectrum of disk dominated CVs (Long and Knigge, 2002). Emission sources include the disk, the WD, a boundary layer and the wind itself. The code consists of two separate MC radiative transfer calculations. In the first, the ionization structure of the wind is calculated using a modified on-the-spot approximation. In the second, a detailed spectrum is calculated for a specific wavelength range of interest. A fair summary of progress to date is as follows: MC methods, such as Python, can be used to obtain spectral verisimilitude to individual lines fairly easily. An example of this is shown in Fig. 2. Systematic searches are now needed to determine whether one can actually model all the lines with a single wind geometry, and to determine how well one can do on average. Several of us are beginning this effort.

Our goal is to determine the basic parameters, such as the mass-loss rate, degree of collimation, and ionization state, of the winds of high state CVs. Until this is done,