FUSE Observations of Active Binaries

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Abstract.

FUSE observations have been instrumental in advancing our understanding of the physical properties and behavior of active binary systems, including cataclysmic variables (CVs) and X-ray binaries (XRBs). FUSE data have allowed observers to study: accretion disks, magnetically-channeled accretion flow, and white dwarf accretors, and how these respond to accretion fluctuations and disk outbursts; the role of binary evolution in determining system properties; the vertical and azimuthal structure in disks and disk winds; and what the variations in active binary properties reveal about accretion physics in compact systems. Results of FUSE observations of active binaries are reviewed here.

1. Introduction

Active binaries are interacting binary systems ($P_{\text{orb}} \approx 1 - 20$ hr) in which a donor star transfers mass to a compact object. In cataclysmic variables (CVs), the compact object is a white dwarf (WD), while in X-ray binaries (XRBs), the compact object is a neutron star or a stellar-mass black hole. In CVs and low-mass XRBs, mass is transferred via Roche lobe overflow of the donor star and in most cases is accreted onto the compact object through an accretion disk. Active binaries are excellent test beds for the study of binary evolution, SN Type Ia progenitors, and accretion and relativistic physics in nearby, unembedded objects. In the FUV, active binaries show emission from the WD, the channeled accretion flow (in magnetic systems), the inner accretion disk ($\leq 20R_{WD}$), and accretion disk winds. The dominant FUV sources and the system morphologies and behaviors vary dramatically in active binaries as a function of compact object type, orbital period, evolutionary history, mass accretion rate, and viewing inclination. To date, more than 90 active binaries have been observed by FUSE: 24 dwarf novae, 25 non-magnetic novalikes, 12 intermediate polars, 17 polars, 4 super-soft XRBs, 5 high-mass XRBs, 2 low-mass XRBs, and 3 unclassified systems. Below, we summarize some of the scientific results obtained from these observations and discuss future work.

2. Results from FUSE Active Binary Observations

2.1. White Dwarfs in CVs

In quiescent dwarf novae (DN), the accretion disk is in a low state and the dominant FUV emission source is the WD. The structures and morphologies of
the WDs in CVs are affected by their histories of ongoing accretion and accretion instabilities. DN outbursts typically recur on time scales of days to years. During outburst, the WD is heated by the accreted material, followed by cooling during quiescence. The WD cooling is shown in the FUV spectra of two DN in Figure 1. The apparent temperature of the WD in U Gem (upper panel) decreases from 43,000 K immediately after outburst to 30,000 K four months into quiescence (Froning et al. 2001; Long & Brammer 2004). The temperature of the WD in VW Hyi (lower panel) drops from 23,000 K to 18,000 K (Godon et al. 2004).

In contrast to field WDs, the spectra of CV WDs show metal absorption lines, reflecting the composition of the material being accreted onto its surface. Detailed models of the metal-enriched WD spectra often show abundance anomalies. In MV Lyr, the WD spectrum can be well fit assuming 0.3 $Z_\odot$ metallicity for all species (Hoard et al. 2004a), but more typical are abundance patterns in which C is underabundant and/or N overabundant, as seen in SS Aur, EY Cyg, U Gem, and WZ Sge (Sion et al. 2004b,a; Froning et al. 2001; Long et al. 2003). The abundances anomalies represent evolutionary effects on the present composition of the systems, a point that will be discussed in more detail in the next section.

In many, perhaps most, quiescent DN, it is clear that a second source contributes to the FUV spectrum. In U Gem, better model fits and correspondence between observed FUV flux and temperature declines can be obtained if it is assumed that 15–20% of the WD cools from 70,000 K to 30,000 K after outburst rather than the entire WD cooling (Long & Brammer 2004). Two-temperature fits to the WD spectrum are also used to model the FUV spectra of SS Aur, Z Cam, EY Cyg, and VW Hyi (Sion et al. 2004b; Hartley et al. 2004; Sion et al. 2004a; Godon et al. 2004). The second source may not be part of the WD, however. In VW Hyi, variations of up to 20% are observed in the FUV spectrum at the shortest wavelengths where the WD does not contribute (Godon et al. 2004). In WZ Sge, the best fits to the quiescent spectrum (seen in the bottom panel of Figure 3) are obtained when the WD atmosphere is veiled by a solar composition absorbing slab of material along the line of sight (Long et al. 2003). The nature of the second source remains poorly understood, although its behavior is clearly tied to the outburst cycle. Possibilities include an accretion belt on the WD surface, emission from the boundary layer between the disk and the WD, or residual accretion during quiescence, either from the disk itself or through coronal processes.

### 2.2. Channeled Accretion Flow in CVs

For CVs in which the WD accretor has a strong magnetic field, the accretion disk is disrupted and accretion onto the WD occurs via channeled flow along the magnetic field lines. For magnetic field strengths $\geq 100$ kG, the disk is only partially disrupted; these are the intermediate polar (IP) systems. When the magnetic field strength reaches $B \simeq 10 - 250$ MG in the polars, the accretion disk is completely disrupted and material from the accretion stream is directly entrained onto the WD field lines. The FUV emission in these CVs is dominated by the channeled accretion flow and the accretion poles where the flow impacts the WD surface. Example FUV spectra of two magnetic CVs, the IP TW Pic and the polar AN UMa, are shown in Figure 2. Both are characterized by blue
Figure 1. FUSE observations of the DN U Gem and VW Hyi in quiescence. The upper panel shows the FUV spectrum of U Gem obtained at two times after (different) outbursts. In black is the spectrum obtained immediately after an outburst, while in gray is a spectrum obtained approximately 4 months after outburst. The lower panel shows spectra of VW Hyi: the spectrum in black was obtained 11 days after outburst while the spectrum in gray was obtained about 2 months after the previous outburst. Prominent lines are labeled. All spectra are binned to 0.1 Å dispersion.

continua on which is superimposed strong, broad emission lines of CIII, NIII, SiIII, SiIV, SIV, and OVI.

To date, analyses of the FUSE observations of the polars AM Her (Hutchings et al. 2002), BY Cam (Mouchet et al. 2003), VV Pup (Hoard et al. 2002), and AR UMa (Hoard et al. 2004b); and the IP V405 Aur (Sing et al. 2004) have been published. In AM Her and VV Pup, the FUV spectrum is dominated by OVI in emission from the channeled accretion flow and by continuum emission from the accretion pole ($T \geq 90,000$ K for a blackbody source in VV Pup). The con-
Continuum flux increases in both systems as the dominant accretion pole rotates into the direct line of sight. V405 Aur also has OVI emission from the accretion flow as well as a broader emission feature from the accretion disk. By Cam shows strong emission features but with anomalous line ratios: weak C and O lines combined with strong N emission. Mouchet et al. demonstrated that the observed line ratios cannot be reproduced by varying the photoionization structure of the channeled accretion stream and instead require, as with the WD spectra in the previous section, non-solar abundances in the accreted material. These abundance anomalies provide clues to the role binary evolution plays in determining the properties of active binaries, but the cause is not yet known; current models invoke CNO processing in the binary or partial evolution of the

Figure 2. Magnetic CVs AN UMa and TW Pic. The top panel shows the spectrum of the intermediate polar TW Pic while the bottom panel shows the time-averaged spectrum of the polar AN UMa. The TW Pic spectrum is binned to 0.1 Å and the spectrum of AN UMa is binned to 0.3 Å.
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donor star. FUSE observations have also probed magnetic field effects on WD atmospheres. AR UMa has the strongest magnetic field strength of any known polar ($B \simeq 240$ MG). FUSE observations taken when AR UMa was in a low accretion state show a 20,000 K WD spectrum modified by the strong magentic field, which manifests itself in Zeeman absorption features of the Lyman series lines. Also observed are normally forbidden Zeeman transitions that become enabled in the presence of the strong electric fields.

2.3. Accretion Disks and Outflows in CVs and XRBs

In high accretion rate CVs, where the disk is more luminous than the WD, and in XRBs (where there is no WD) the accretion disk is the dominant source of emission in the FUV. The FUV continua of active binaries are sensitive to the mass accretion rate in the disk as the peak temperatures in the inner disks ($\simeq 50,000$ K) leads to a turnover in their spectral energy distributions in the FUSE waveband. FUSE spectra have been modeled with steady-state accretion disk models to measure accretion rates during high states and on decline from DN outbursts (Froning et al. 2001; Long et al. 2003). An illustration of how the spectra of quiescent and disk-dominated active binaries differ is given in Figure 3, which shows how the FUV spectrum of the DN WZ Sge evolved after its 2001 outburst (Long et al. 2003). At outburst peak (the uppermost panel), the spectrum is dominated by the accretion disk and a strong disk outflow, manifested primarily in OVI. The lower three panels show the changes in the spectrum on the decline from outburst as the wind ceases, the disk fades, and the cool (23,000 K) WD begins to dominate the FUV spectrum.

FUSE observations have revealed the importance of vertical structure in accretion disks on the observed behavior of active binaries: simple models of thin, flat disks are poor descriptions of FUV disk morphologies. The spectrum of the DN U Gem in outburst shows a rich line absorption spectrum (the spectrum can be seen in the lower panel of Figure 5; Froning et al. 2001). The absorption becomes stronger from orbital phases 0.5 – 0.8, the same phases at which X-ray and EUV light curve dips are observed in the system. The dips and the increased absorption occur at the phases in which the mass accretion stream from the donor star rotates into the line of sight and are believed to be caused by a bulge where the stream impacts the accretion disk or by overflow of the stream above the disk downstream of the impact point. Similar azimuthally-dependent increases in line absorption have been seen in FUSE observations of the DN Z Cam (Hartley et al. 2004).

Figure 4 shows the effects of azimuthal asymmetries in the disk structure on the FUV light curve of the eclipsing novalike CV, UX UMa (Froning et al. 2003). The upper three panels show the 1 sec FUV light curve of UX UMa, constructed from FUSE time-tag event files of the observation. The light curves exhibit the rapid variability, or flickering, associated with disks in active binaries. The bottom panel shows the orbital phase binned average of the observation. In addition to the eclipse of the disk at orbital phase 1, there is a broad dip in the FUV flux centered around phase 0.6, suggestive of azimuthal changes in the vertical scale height of the absorbing outer disk. Similar behavior is seen in the super-soft XRB, RXJ0513–69 (Hutchings et al. 2002). In extreme cases, flaring of the outer disk rim can completely obstruct the view of the inner accretion
Figure 3. The evolution of the FUV spectrum of the DN, WZ Sge, after outburst. Figure adapted from Long et al. 2003.

disk, as is the case in the high inclination CV, DW UMa [Hoard et al. 2003]. DW UMa illustrates the complexity of behavior of active binaries in the FUV, as it contains both a self-occluding disk and vertically-extended emitting material that produces a strong emission line spectrum.

The FUV line spectra of disk-dominated active binaries vary widely. In many high accretion rate systems, the line emission originates in a disk outflow in the form of a fast wind. An example of a wind spectrum is given in the top panel of Figure 5, which shows the FUV spectrum of the novalike IX Vel. The lines are broad and blue-shifted and appear in a wide range of species and ionization levels. As the viewing inclination increases, the winds appear as P Cygni profiles and then purely in emission from photons scattered into the line of sight (as in the spectrum of WZ Sge in the top panel of Figure 3). FUSE observations have shown that the winds in active binaries are also affected
by departures from axisymmetry in the accretion disk, causing the wind lines to be modulated in strength and profile on the orbital period (Hutchings et al. 2001; Prinja et al. 2003, 2004). Studies of the changes in the FUV spectrum of UX UMa through eclipse have shown that its wind varies with scale height above the disk, changing from a low outflow velocity, dense region to the fast, vertically-extended outflow (Froning et al. 2003).

Disk-dominated active binaries do not always show wind lines in the FUV, however. In the aforementioned outburst spectrum of U Gem, shown in the lower panel of Figure 5, the absorption lines are too narrow and at too low a velocity to originate in a wind. Aside from the weak signatures of the wind in OVI, the wind in U Gem does not appear in the FUV, though a highly ionized outflow does manifest itself in the EUV. The super-soft XRB RXJ0513–69 shows very broad ($\simeq 4000$ km s$^{-1}$) emission lines of OVI that are believed to originate in the inner accretion disk (Hutchings et al. 2002). Similarly, the FUV spectra of the super-soft XRB Cal 83 and the black hole XRB Cyg X-3 show broad OVI emission (Schmidtke et al. 2004, Hutchings et al. 2003). Emission features in OVI and other transitions regularly appear in the FUV spectra of CVs in which the mass accretion rate is too low to sustain a wind. The emission lines are believed to originate in a chromosphere or corona overlying the bulk of the...
accretion disk, but no models yet exist that fully explain their formation and the properties of the line emitting region.

Figure 5. Differing behavior in two high accretion rate CVs. The upper panel shows the time-averaged spectrum of the NL, IX Vel. The lower panel shows the time-averaged spectrum of the DN, U Gem, at outburst peak.

3. Conclusions and Future Work

After five years, FUSE has observed most of the bright CVs and all of the bright XRBs available to the telescope. In doing so, it has revealed much about the properties and behavior of active binaries: the response of disks and WDs to accretion events; the role of binary evolution in setting system abundances; the importance of vertical structure in disks and disk outflows; and the strengths and limitations in our picture of the launching mechanism for disk winds. Future work will concentrate on utilizing the large FUSE database to probe the general
properties of active binaries and on expanding our understanding of accretion physics through intensive studies and modeling of single systems. A survey of the FUV properties of CVs as a function of mass accretion rate, orbital period, evolutionary history, and binary viewing inclination is ongoing [Froning et al. 2003]. Also ongoing are large programs devoted to observations of single systems that will undertake detailed analysis and modeling of time variability to determine the structure and properties of the WDs, disk and magnetic accretion regions, and outflows in active binaries. FUSE has opened a new window into the study of active binaries and will continue to provide cutting-edge scientific observations of these systems for some time to come.

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