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# X-RAY EMISSION AND THE WINDS OF CATACLYSMIC VARIABLES

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## ABSTRACT

X-ray and ultraviolet observations of cataclysmic variable stars reveal a variety of exotic behavior -- pulsations, winds, and episodic outbursts -- are these related? what do they tell us about the nature of the outburst? about the environment of the accreting white dwarf? I first summarize the observed changes in the X-ray and UV continuum and spectral features through the outbursts of the dwarf novae. I then discuss how the modeling of these data have refined our ideas about the location and nature of the emissions, and the source of the outburst. I show how comparisons of the X-ray and UV properties of cataclysmic variables with similar phenomena in other astronomical systems -- the solar corona, OB stars, and Be stars -- suggest ways in which the X-ray and UV emissions in CVs may be related, and point to further, specific observations that would elucidate our understanding of the behavior and role of the white dwarf in the outburst.

## 1. Summary of Observed Changes During Outbursts

The most salient feature of dwarf novae is their regular, though aperiodic, pattern of optical outbursts. On a time scale of weeks, such a system may brighten visually by a factor of ten to one-hundred in less than a day, with the subsequent decay from peak brightness usually spanning a few days. During the optical outburst, there is ultraviolet and X-ray variability as well.

X-rays. Observations using the European X-ray astronomy satellite Exosat by van der Woerd, Heise, and Paerels (1984) confirm the existence of a third pulsing, soft X-ray dwarf nova during outburst, VW Hydri. SS Cygni and U Geminorum were previously discovered as similar transient soft X-ray pulsators with HEAO-1 (Córdova et al. 1980a; 1984). This is strong evidence indeed that ultrasoft, pulsed X-ray emission is a common property of dwarf novae in outburst. The detection of VW Hyi is especially significant because HEAO-1 did not detect this star during thirty days of scanning the source through a superoutburst and normal outburst (cf. survey by Córdova et al. 1980b). Exosat can detect sources down to 0.04 keV, far below the HEAO-1 low energy threshold of 0.15 keV. In fact, the pulsed emission from VW Hyi was observed only below 0.07 keV. Other dwarf novae in the

HEAO-1 survey may also not have been detected because their spectra were too soft.

The Exosat observations of VW Hyi also suggest that the soft X-ray outburst is either delayed with respect to the optical outburst, or the soft X-ray flux is extremely variable during the initial part of the outburst. This was first suggested by HEAO-1 data on U Gem (Mason et al. 1978). Soft X-rays were first detected from VW Hyi 2.5 days after the start of an optical superoutburst (van der Woerd et al. 1984).

The pulsation periods of these stars are in the range of 10 - 20 s, and the amplitudes of the pulsations about 20%. The pulsation may sometimes look strictly periodic, as in the case of the first Exosat observations of VW Hyi and in some of the HEAO-1 orbits pointed at SS Cyg, but often the pulsations maintain coherence for only a few pulsation cycles (cf. Córdova et al. 1984).

Although hard X-ray emission (above 2 keV) is detected from many CVs during outburst, as well as quiescence, the hard X-rays are not pulsed. In SS Cyg, the hard X-ray flux decreases substantially during the optical and soft X-ray outburst, suggesting that the increase in accretion supresses hard X-ray production.

Ultraviolet. There presently exists an extensive body of UV spectroscopy, much of it done with the IUE satellite, on a large number of dwarf novae in outburst. Some important work in the EUV (500 Å - 1200 Å) is presently being done with the Voyager spacecraft. The observations show conclusively that the far UV outburst (i.e. about 900 Å to 2000 Å) is substantially delayed with respect to the optical outburst (Hassall et al. 1983; Polidan and Holberg 1984; Córdova, Ladd, and Mason 1984; Verbunt et al. 1984). On the rise to outburst the spectrum between 1100 Å and 3000 Å flattens because the visual light alone increases; about one day later the spectrum steepens dramatically because the far UV brightness increases relative to the optical. The common interpretation of this behavior is that the outburst starts in the outer disk, which contributes more to the optical than the UV part of the spectrum, and then progresses inward (Hassall et al. 1983). Whether or not this hypothesis is consistent with the apparently sudden increase in flux and spectral temperature observed (rather than, for example a slower, monotonic increase in the flux and temperature as the inner disk becomes hotter), has still to be investigated. Measurements after the peak of the UV outburst show a steady decay that keeps pace with the slow decrease in the optical light.

The IUE detector precludes a study of short time variability (i.e. on time scales less than 1/2 hour), so it is not known whether or not the far UV emission is pulsed like the X-rays.

One of the most interesting discoveries yielded by the IUE observations is that most dwarf novae during their outbursts exhibit winds with velocities as high as 5000 km $s^{-1}$. The presence of the wind is inferred from the asymmetric line profiles of, chiefly, the resonance lines C IV, Si IV, and N V. Time-resolved spectroscopy of eclipsing CVs reveals that the wind is large compared to the size of the companion star (King et al. 1983; Córdova and Mason 1985).

2. The Location and Nature of the Emissions

The Pulsations. There are a few facts that we know for certain with respect to the X-ray pulsations of dwarf novae during outburst: they appear only in soft, not hard, X-rays; they are usually not coherent; and the magnetic fields of the objects in which they occur are probably small (less than $10^6$ G).

The high-energy spectrum, short time scale, and high amplitude of the soft X-ray pulsations make it likely that they originate in the vicinity of the white dwarf. The low coherence of the pulsations suggests they arise not in the body of the compact star, but in a surface layer(s). Córdova et al. (1980a) showed they could model the pulsation noise with a stable oscillator whose phase varies randomly.

This model has a nearby analogue in the Sun. Power spectra of more than 11 years of solar wind speed data show a broad band of power near 27 days (the solar rotation period) with several distinct peaks (Fenimore et al. 1978). These can not be attributed to differential rotation; instead, they are explained as due to recurring high speed streams lasting for a varying number of solar rotations and appearing in a preferred range of longitudes. Subsequent streams have the same period, but are shifted in phase because they appear at a somewhat different longitude. The power spectra of these solar data compare well, at least qualitatively, with the X-ray power spectra of the dwarf novae (Córdova et al. 1984), and with models for wave trains of pulses with a constant period, but different phases.

King (1984) has offered a model that produces qualitatively similar data and explains the salient facts about the dwarf nova oscillations. King notes that if the white dwarf has transient, weak magnetic fields, presumably generated by dynamo action in the star's envelope, differential rotation of the star's envelope will force localized, magnetic reconnections to occur. Transport processes, specifically electron thermal conduction, will carry energy from a hard X-ray corona into the white dwarf, from which it can be radiated as soft X-rays. The radiation will appear to be pulsed because of the rotation of the envelope, with a coherence timescale on the order of the lifetime of a magnetic loop.

The wind. The wind is most likely driven by radiation pressure in the spectral lines (Córdova and Mason 1982; Drew and Verbunt 1985), the same mechanism thought to be responsible for driving the winds of early-type stars. The most significant difference between the winds of CVs and those of OB stars is the higher gravity of the white dwarf, which causes the optical depth to be significantly smaller than for OB stars, and the higher ionization of the winds of CVs, owing to the presence of the accreting degenerate dwarf (cf. Drew and Verbunt 1985).

The high velocities in the wind exclude an origin in the outer disk or companion star, and make the inner disk/white dwarf region a likely candidate. The emission line ratios of two CVs observed at high inclination suggest that photoionization is important (King et al. 1983; Córdova and Mason 1985).

UV spectroscopy of CVs at a range of inclination angles demonstrate that a shortward-shifted absorption component is only observed when the mass accretion rate is high (i.e. the system is UV bright) and the disk is viewed face on -- the absorption then indicates that we observe the wind projected against the bright UV continuum source. The base level of the absorption components remain the same when the far UV continuum rises and decreases during the outburst, indicating that the entire UV continuum source (i.e. above the UV quiescent flux level) is seen behind the wind, and the wind is optically thick in the lines.

There are many observations that suggest that the wind may not be spherically symmetric: the shapes of the line profiles, the ratios of the emission component to the absorption component of the lines, and the emission line ratios (Córdova and Mason 1982; Greenstein and Oke 1982; Raymond 1984; Drew and Verbunt 1985). In addition, the line profiles are variable (e.g. Hutchings 1980; Sion 1985), suggesting that the wind is either nonspherical or inhomogeneous.

Several models have been explored which give ionization fractions and line ratios for different photoionizing spectra. Córdova and Mason (1982) compare the UV absorption line parameters of the outbursting dwarf nova TW Vir with models of Olson (1982) for early-type stars and find that the observed ion fluxes cannot be produced simultaneously unless Nitrogen is overabundant or the assumption of spherical symmetry is invalid. Drew and Verbunt (1985) show that resonance scattering rather than collisional excitation dominates the line formation at large radii, and that the lines must be saturated. Their models are compared to the asymmetric emission line profiles of two eclipsing CVs. They also find that the observed Si IV and N V fluxes cannot be produced in any of their spherical models.

Kallman (1983) compared the ionization abundance derived from measured parameters of the absorption components of the P Cygni lines of a dwarf nova in outburst to nebular models in which the ionization parameter, $L/nr^2$, is the dominating factor in determining the ionization structure of the wind. He found it difficult to produce the observed ion ratios using blackbody or bremsstrahlung models. Drew and Verbunt (1985) noted that the use of the ionization parameter assumes that the continuum and lines are optically thin, a situation that is not true if there is significant $He^+$ opacity.

UV spectroscopy of eclipsing CVs shows that the ionization of the wind must increase outward to account for the deeper eclipse of Si IV relative to N V and C IV (King et al. 1983; Córdova and Mason 1985; Drew and Verbunt 1985). None of the models investigated by Drew and Verbunt (1985) have this feature, causing those researchers to conclude that a zoned ionization structure may be required for the wind -- this could be obtained with a nonspherical ionizing radiation flux. In the

Section below I outline one way in which such a radiation pattern might be produced.

## 3. The Relationship of the X-ray and UV Emissions

The conclusion from the previous Section is that both the X-rays and the wind probably come from near the white dwarf. How then could they be related?

Clues may be found in the details of the spectral lines.

The observations and modeling described above show that while the assumption of a radiatively driven wind in CVs is probably a good one, the assumption of a spherically symmetric, constant wind is not consistent with the line profiles. In CVs there is evidence that the line profiles are variable on time scales at least as short as the binary orbital period (refs. Hutchings 1980; Guinan and Sion 1981; Guinan 1985), and the absorption wing of the P Cygni profile often has an "emission" feature superimposed on the blue-shifted absorption component (Raymond 1984; Sion 1985). It is highly likely, then, that the wind has either an unusual geometry (e.g. modified by rotation of the underlying white dwarf and the binary system) and/or is inhomogeneous. What are clearly needed are UV spectroscopic measurements around the binary orbit of a CV: none of the presently published data covers much more than one orbital cycle.

For early-type stars there exist UV spectral data with much better resolution than that achieved for most CVs. The line profiles of the early-type stars reveal a wealth of detail, e.g. narrow, variable, high-velocity absorption components in many of the Be stars and the more luminous OB stars. Sometimes these components are superimposed on a broad P Cygni absorption wing. An interpretation of the narrow absorption features is that they result from variable mass loss, or "puffs", accelerated by radiation pressure in the lines (cf. Henrichs 1984). Another interpretation is that the wind is composed of high and low density pockets which are caused by instabilities, or shocks, in the flow (e.g. Lucy 1983). The multiple shocks in the wind are thought to be the origin of the $10^6$ K X-rays observed in these stars. All of the present researchers have investigated bremsstrahlung and blackbody models only in making models for the ionization structure of the CV wind; a very different ionization structure would result if there were hard X-ray shocks in the wind. In fact, Raymond (1984) pointed out that shocks in the wind could compress the gas and increase the ionization fractions of N V and C IV. In this manner the ionization of the wind would be increasing rather than decreasing outward, thus solving the problem of why Si IV has a greater eclipse depth than the more highly ionized species in the wind.

An interesting observation concerning mass loss in Be stars is the detection of evidence for non-radial pulsations based on transient distortions of the absorption lines of these stars in their quiet (i.e. non-Be) states (Vogt and Penrod 1983). Because they find a correlation between the observed amplitude of the oscillations and the outbursts of these stars, Vogt and Penrod suggest that the release of excess pulsational energy during mode-switching could trigger the enhanced mass loss of these stars, i.e. the Be star phenomenon. Drastic changes in the narrow, high-velocity absorption components have been detected simultaneously with the changes in amplitude of the oscillations (Howarth et al. 1984), implying that structural changes in the atmosphere of the star are coupled to structural changes far out in the wind. The implication (see Henrichs 1984) is that these stars do not have stable, continuous winds.

Non-radial oscillations in the surface layer of the white dwarf have been proposed as the origin of the oscillations of the dwarf novae (Papaloizou and Pringle 1978); could mode-switching be responsible for variable mass ejection from the surface of a white dwarf during the outburst? Córdova et al. (1984) have discussed reasons why it is difficult to attribute the dwarf nova X-ray pulsations to non-radial surface modes (e.g. the high amplitude of the X-ray oscillations, the difficulty in exciting only one mode, and the difficulty in switching modes in less than a pulsation cycle), but these authors note that if the accretion were confined to one point on the white dwarf's surface, or a low-order mode number were excited (not likely in the Pringle and Papaloizou models which require high-order modes), then large amplitude X-ray pulsations might occur. If the oscillations and mass loss were related in a similar way to that in Be stars, we would expect to see correlations in the coherence time scale of the oscillations and the variability of features in the wind line profiles.

In any case, whatever the origin of the pulsation, if the CV wind were illuminated anisotropically by a pulsed soft X-ray source it could cause variability in the spectral lines on the timescale of the binary orbital period.

## 4. Afterword

There are several factors limiting interpretation of the CV X-ray and UV data. The observations that I have discussed were not, in general, simultaneous. This is a severe limitation because CVs are violently variable on extremely short time scales. Second, many of these objects are too faint to do high-resolution ultraviolet spectroscopy with either IUE or the present X-ray satellite instrumentation; hence, what spectral data exist are coarse and lend themselves to wildly different interpretations. Third, the time-resolution of the IUE satellite is limited by the readout scheme of the cameras to about 30 minutes, mitigating against understanding many high-energy phenomera that occur in these objects on a much shorter time scale. Fourth, there simply has not been enough time invested in studying selected objects. These limitations are instrumental in nature and there is thus the promise of dramatic improvement in the future.

Much attention has focused on the parameters of CVs that are most easily measured -- the changes in luminosity as a function of wavelength, and the changes in the continuum slope as a function of outburst phase. What I have tried to point out here is that there is a wealth of detail, e.g. in the spectral line profiles and in the pulsation properties, that also deserves close scrutiny. It is this detail that is presently opening up a whole new understanding of the Sun, the winds of OB stars, and the nature of the Be star phenomenon, and could also illuminate our understanding of the variability of CVs.

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