On jet features in the optical spectra of cataclysmic variables

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ABSTRACT

Blue- and red-shifted Hydrogen and Helium satellite recombination lines have recently been discovered in the optical spectra of at least two supersoft X-ray sources (SSSs), RX J0513-069 and RX J0019.8+2156, and tentatively also in one short-period cataclysmic variable star (CV), the recurrent nova T Pyx. These features are thought to provide evidence for the presence of highly collimated jets in these systems. No similar spectral signatures have been detected in the spectra of other short-period cataclysmic variables, despite a wealth of existing optical data on these systems. Here, we ask if this apparent absence of “jet lines” in the spectra of most CVs already implies the absence of jets of the kind that appear to be present in the SSSs and perhaps T Pyx, or whether the current lack of jet detections in CVs can still be ascribed to observational difficulties.

To answer this question, we derive a simple, approximate scaling relation between the expected equivalent widths of the observed jet lines in both types of systems and the accretion rate through the disk, \( EW(\text{line}) \propto \dot{M}_{\text{acc}}^{3/4} \). We use this relation to predict the strength of jet lines in the spectra of “ordinary” CVs, i.e. systems characterized by somewhat lower accretion rates than T Pyx. Making the assumption that the features seen in T Pyx are indeed jet lines and using this system as a reference point, we find that if jets are present in many CVs, they may be expected to produce optical satellite recombination lines with EWs of a few hundredths to a few tenths of Angstroms in suitably selected systems. A similar prediction is obtained if the SSS RX J0513-069 is used as a reference point. Such equivalent widths are small enough to account for the non-detection of jet features in CVs to date, but large enough to allow them to be detected in data of sufficiently high quality, if they exist.

Key words: accretion, accretion disks — binaries: close — stars: mass loss — novae, cataclysmic variables

1 INTRODUCTION

One of the most intriguing empirical connections that has emerged from observations of accretion-powered objects on all astrophysical scales is that between accretion disks and powerful bipolar outflows and jets. Indeed, the occurrence of mass loss in this form has been established in members of essentially all classes of (presumed) disk-accretors, including close binary systems such as X-ray binaries, supersoft X-ray sources (SSSs) and non-magnetic cataclysmic variable stars (CVs), young stellar objects such as T-Tauri and FU Orionis stars, and active galactic nuclei and quasars. However, a complete theoretical understanding of this empirical diskwind (or disk-jet) connection has not yet been achieved. Recent reviews of the subject with references to the relevant observational literature may be found in Livio (1997a; 1997b).

A potentially vital clue to the origin of mass loss from accretion disk systems is provided by the fact that in at least some members of all but one class of objects the outflow collimation appears to be very tight, with half-opening angles, \( \theta_{\text{max}} \), of no more than a few degrees (we will refer to such flows as jets hereafter). The sole exception to this rule are CVs (see however below). In these systems, the presence of mass loss has nevertheless been clearly established, based on the shapes and eclipse behavior of the ultraviolet (UV) resonance lines (e.g. Drew 1991), but the inferred collimation of the corresponding outflows is weak (\( \theta_{\text{max}} \gtrsim 45^\circ \); Shlosman, Vitello & Mauche 1997; Knigge & Drew 1997).
The apparent absence of jets in CVs may hold the key to an improved theoretical understanding of the disk-wind connection. If confirmed, any “generic” model (in the sense of being applicable to more than a particular class of objects) for the origin of mass loss from accretion disks must be able to explain why this mass loss takes the form of jets in all systems but CVs. This would be quite a restrictive constraint, particularly in the light of two recent observational developments.

The first of these is the detection of blue- and red-shifted satellite emission features to the optical Hydrogen and Helium recombination lines in the SSSs RX J0513-069, RX J0019.8+2156 and (possibly) CAL 83 (Crampton et al. 1987; Crampton et al. 1996; Southwell et al. 1996; Southwell, Livio, & Charles 1997; Becker, Remillard, & Rappaport 1997). These features cannot be attributed to any other ionic species and are therefore thought to arise in some kind of bipolar outflow. The combination of small width and large displacement from line center exhibited by these satellite lines further suggests that the corresponding outflows are very highly collimated, i.e. that they are jets (c.f. the prototypical jet system SS 433; Vermeulen 1993).

If this identification is correct (which we will assume throughout this paper) it is significant, because SSSs and CVs are extremely similar types of objects: both are semi-detached binary systems in which a Roche-lobe filling secondary star transfers material via an accretion disk onto a white dwarf (WD) primary. The main difference between SSSs and CVs is thought to be the rate at which this mass transfer proceeds. In SSSs, the accretion rate is believed to be high enough (\( \dot{M}_{\text{acc}} \sim 10^{-7} - 10^{-6} \, \text{M}_\odot \, \text{yr}^{-1} \)) to fuel steady nuclear hydrogen burning on the surface of the WD (e.g. van den Heuvel et a. 1992). By contrast, the highest accretion rates encountered in CVs are about one order of magnitude lower than this (\( \dot{M}_{\text{acc}} \sim 10^{-8} \, \text{M}_\odot \, \text{yr}^{-1} \)) and thus insufficient to initiate steady nuclear burning on the WD. Instead, the accretion can result in shell flashes which are responsible for nova outbursts. This difference is one of the factors that led Livio (1997a) to propose that the formation of powerful jets (as opposed to more weakly collimated bipolar outflows) may require the presence of an additional wind/energy source at the center of the accretion disk.

The second recent observational finding of significance in the present context is the tentative detection of similar Hα satellite lines in the optical spectrum of one CV, the recurrent nova T Pyx (Shahbaz et al. 1997). It is important to stress that no similar features have ever been detected in any other short-period CV, despite the fact that optical spectra of high enough quality to detect satellite lines of similar strength as in T Pyx (which, on average, have an equivalent width of about 1 Å) should be available for many of them. While it is possible that in some cases they might have been overlooked (previous studies would not have expected to see such features), it would nevertheless appear that satellite lines of the strength seen in T Pyx are not a common feature among CVs. For example, Shahbaz et al. (1997) did not detect similar satellite lines in the spectrum of another recurrent nova, U Sco. (It should be noted that one-sided satellite lines have been seen in the spectra of a few CVs, e.g. S193, V795 Her, BT Mon [Szokody 1995; Haswell et al. 1994; Seitter 1984]; however, these probably arise in other types of high velocity flows in these systems.)

The physical similarities between CVs and SSSs, on the one hand, and the observational similarity between the satellite features in T Pyx and those in SSSs such as RX J0513-069, on the other, suggest that T Pyx may also harbor a well collimated jet. A fundamental assumption we adopt in the present paper is that this is indeed the case. Note that, under this assumption, we would expect T Pyx’s binary inclination to be higher than that of the SSSs listed above, since in T Pyx the ratio of satellite line widths to their displacements from line center is somewhat smaller. A high inclination for T Pyx (\( i \sim 70^\circ \)) is also indicated if one demands that the displacement of the satellite features from line center should roughly correspond to the escape velocity from the WD, as expected if they are formed in a jet (c.f. Shahbaz et al. 1997; Livio 1997a). It is acknowledged, however, that Shahbaz et al. (1997) also derived an inclination estimate from the peak-to-peak separation of the double-peaked Hα line core, which, by contrast, turns out to be very low (\( i \sim 10^\circ \)). While this estimate should be regarded as a lower limit (Shahbaz et al. 1997), the case for a well collimated jet in T Pyx would have to be critically reexamined if the inclination of this system were shown to be \( \leq 50^\circ \) in the future. The analytic scaling relation derived in Section 2 would of course nevertheless be valid and, we believe, useful, even if T Pyx should eventually turn out not to contain a collimated jet.

Actually, the existence of a jet in T Pyx is not entirely unexpected, since it is thought that recurrent novae in general, and T Pyx in particular, are characterized by accretion rates that are higher (i.e. \( \dot{M}_{\text{acc}} \gtrsim 10^{-8} \, \text{M}_\odot \, \text{yr}^{-1} \)) than those in other types of CVs, such as dwarf-novae (DNe) and nova-like variables (NLs). In fact, Webbink et al. (1987) have suggested that intermittent nuclear burning might take place on the surface of the WD in T Pyx even during quiescence, i.e. between nova outbursts. If so, Livio’s (1997a) hypothesis could be used to reconcile the presence of jet lines in SSSs and T Pyx with the absence of similar features in the spectra of other CVs.

The main goal of the present paper is to determine whether such reconciliation is actually required at present. Thus, we will ask whether the apparent absence of jet lines in the existing optical spectra of most CVs, particularly NLs and DNe in outburst (i.e. systems in which an optically thick accretion disk is present but no nuclear burning occurs) already implies the absence of jets of the kind seen in the SSSs and (possibly) T Pyx, or whether the current lack of jet detections in CVs can still be ascribed to observational difficulties. In our attempt to answer this question, we will take as our fundamental working hypothesis that the main difference between CVs and the SSSs (as well as perhaps T Pyx) – the presence of an extremely hot WD at disk center – is irrelevant to the formation of the observed jets. The corollary of this hypothesis is that CVs must actually drive jets of the kind that appear to be present in the SSS and T Pyx. Our goal is to estimate the expected equivalent widths of CV jet lines within the framework of this hypothesis. In so doing, we will try to make as few references as possible to specific models for the jet formation and line emission mechanisms, and instead use only simple and general physical arguments.

As already noted above, under our working hypothesis, jets akin to those in the SSSs must actually be present
CVs. This is not in direct conflict with the relatively wide outflow opening angles that have been inferred for CV winds from modeling the UV resonance lines; these spectral features probe only the near-disk regime of the outflow – out to at most a few hundred $R_{WD}$ – leaving collimation at larger distances as a distinct possibility.

2 A SCALING RELATION FOR THE STRENGTH OF JET-FORMED SATELLITE RECOMBINATION LINES

The main difficulty in deciding whether jet lines should already have been detected in CVs (if these systems do indeed drive jets), lies in the fact that the emission mechanism responsible for producing the observed features in T Pyx and the SSSs has not yet been established. Given the narrowness and distinct location of the lines in the spectra of these objects, the emitting region may well be a shock far downstream in the flow, perhaps at the point where collimation occurs. However, an obvious selection effect is at work here – jet lines are much easier to detect if they are well separated from the main emission line – and thus even this identification is far from secure. Our working hypothesis can therefore not be tested by direct modeling of the proposed jets (which is in any case impossible since the jet driving mechanism in SSSs and other systems is also not precisely known).

To overcome this difficulty, we take an extremely general approach to the problem and rely as much as possible on the similarity between T Pyx and the SSSs, on the one hand, and “normal” CVs on the other. Thus we only derive a rough, simple scaling relation between the equivalent widths (EWs) of these features and the relevant physical parameters of a given system, which we expect to be approximately valid regardless of the detailed flow dynamics and line emission mechanism. Such generality comes at a price, of course. In particular, we will have to make some, hopefully plausible, simplifying assumptions to arrive at our scaling relation, and will only be able to use it to compare similar systems (i.e. systems sharing common jet driving and line emission mechanisms). Under our working hypothesis, the SSSs, T Pyx and other CVs are similar in this sense.

We begin by exploring the dependence of jet line EWs on the mass transfer rate through the disk, since this is likely to be the most relevant parameter in this respect. Assuming the optical light of both CVs and SSSs to be dominated by radiation from an optically thick, steady-state accretion disk, we expect the optical continuum flux to scale roughly as (e.g. Webbink et al. 1987)

$$F_{\text{c,opt}} \propto M_{\text{acc}}^2. \quad (1)$$

This assumption is almost certainly valid for CVs in a state of high mass accretion rate, i.e. NLs and DNes in outburst: optical eclipse mapping studies show that most high-state CVs do approximately follow the expected disk temperature distribution $T_{\text{eff}}(R) \propto R^{-3/4}$ that is the most fundamental prediction of steady-state accretion disk theory (e.g. Horne & Stiening 1985; Rutten et al. 1992, Baptista et al. 1995). And while model disk spectra based on the same theory do not always match observed spectra in detail (e.g. Knigge et al. 1997, 1998), the corresponding discrepancies should be of minor importance in the present context.

To test whether Equation 1 is also plausible for SSSs, we have calculated the expected contribution of a very hot ($T_{\text{eff}} = 500,000$ K), 1$M_{\odot}$ WD to the total optical light from such a system, assuming an accretion rate through the disk of $M_{\text{acc}} = 10^{-7} M_{\odot}$ yr$^{-1}$, a disk radius of $R_{\text{disk}} = 50 R_{WD}$ and a representative inclination of $i = 60^\circ$. Within the framework of the usual approximations – that the disk is optically thick, and that it and the WD both emit as (ensembles of) blackbodies – we find that the WD contributes only about 2% to the flux near Hα. For larger disk radii and/or accretion rates, and for systems viewed at lower inclinations, the disk would dominate the visual flux even more. Nevertheless, this number is almost certainly an underestimate, since our calculation neglected the possibility that some of the WD radiation might be reprocessed by the disk and the secondary. Because of this, we consider this assumption to be the weakest link in our chain of arguments when applied to SSSs and will return to it in Section 3.2.

Even if direct and reprocessed WD radiation are unimportant, Relation (1) is only valid provided that

$$T_{\text{max}} >> \frac{h \nu}{k} >> T_{\text{out}}, \quad (2)$$

where $T_{\text{max}}$ is the maximum disk temperature, $T_{\text{out}}$ is the temperature at the outer disk edge, $\lambda$ corresponds to the optical waveband and all other symbols have their usual meaning. For CVs, this condition is usually satisfied approximately, though not in detail. It is therefore useful to derive some upper and lower limits on the power law index in Relation (1) that are independent of this condition.

An upper limit can be derived by noting that the total disk luminosity corresponds to one half of the accretion luminosity and thus scales as $L_{\text{disk}} \propto M_{\text{acc}}$. Given that the the peak of the disk spectrum will lie shortward of the optical waveband for all reasonable parameters, the steepest possible scaling of the optical continuum flux with accretion rate, which corresponds to taking the spectral shape to remain constant as $M_{\text{acc}}$ increases, is $F_{\text{c,opt}} \propto M_{\text{acc}}$. In reality, the spectrum will of course become bluer as the disk becomes hotter with increasing $M_{\text{acc}}$. A corresponding lower limit on the power law index in Relation (1) may therefore be derived by assuming that the optical waveband lies on the Rayleigh-Jeans tail of the spectrum. In this case, $F_{\text{c,opt}} \propto T \propto L_{\text{disk}} \propto M_{\text{acc}}^{1/4}$. Taking these limits into account, Relation (1) becomes

$$F_{\text{c,opt}} \propto M_{\text{acc}}^{-5/12}. \quad (3)$$

It is worth stressing that our quoted “errors” on the power law index in Relation (3) are quite conservative, in the sense that they are likely to bracket the dependence of the optical flux on accretion rate for any plausible, optically thick model of radiation liberated as a result of accretion. As a check, we have constructed the function $F_{\text{c,opt}}(M_{\text{acc}})$ directly from numerical models in which the accretion disk is assumed to be in a steady-state and to radiate as an ensemble of blackbodies or stellar atmospheres (see, for example, Knigge et al. 1997). We find that (i) this function is well described by a power law over ranges in $M_{\text{acc}}$ of up to at least an order of magnitude and (ii) the corresponding power law indices are well within the limits in Relation (3) (e.g. the index is $\approx 0.7$ for both types of models for accretion rates appropriate to CVs).
Relation (3) establishes a connection between the expected optical continuum flux and the accretion rate. This is the first ingredient needed in a scaling relation between jet line EWs and $M_{\text{acc}}$. The second and final ingredient is a relation between the expected jet line luminosity and the accretion rate.

To derive such a relation without having to make reference to the relevant emission mechanism, we proceed in a very formal way. Noting that all observed jet lines are Hydrogen or Helium recombination lines, we may write quite generally

$$L(\text{line}) = 4\pi j_{\text{line}} \times EM.$$  

(4)

In this relation, $j_{\text{line}}$ is the line emissivity corresponding to the relevant emission mechanism which, according to our working hypothesis, is the same in SSSs, T Pyx and other CVs. In principle, account should be taken of the fact that $j_{\text{line}}$ will be a function of the temperature and density in the emitting regions, although any such dependence is likely to be minor compared to the effect of the emission measure,

$$EM = \int \pi n_e n_p dV \approx n_e^2 V.$$  

(5)

Here, the integral is over the volume, $V$, of the line-emitting region, and $n_e, n_p$ are the electron and proton number densities, respectively, in this region.

We now note that the electron density in the line-emitting region must scale with the density and hence with the mass-loss rate, $M_{\text{jet}}$, in the jet. Moreover, for a jet driven from an accretion disk we expect $M_{\text{jet}} \propto M_{\text{acc}}$ to a first approximation, essentially regardless of the jet driving mechanism (see e.g. Livio 1997a for a discussion). We thus have

$$L(\text{line}) \propto EM \propto n_e^2 \propto M_{\text{jet}}^2 \propto M_{\text{acc}}^2,$$  

(6)

which is the desired relation between jet line luminosity and accretion rate. Note that scaling relations between mass-loss rates and line luminosities have been used in studies of T Tauri stars (e.g. Hartigan, Edwards & Ghandour 1995). In particular, the study by Hartigan et al. (1995) shows that a clear correlation between $M_{\text{jet}}$ and $M_{\text{acc}}$ does exist in T Tauri stars, in line with our assumption that $M_{\text{jet}} \propto M_{\text{acc}}$.

However, it is also acknowledged that the correlation found by Hartigan et al. (1995) exhibits substantial scatter. At the moment, it is not clear to what extent this corresponds to differences between the parameters of individual systems (e.g. disk sizes), that could in principle be corrected for (see below).

Let us examine the fundamental step in the derivation of Relation (6) — the assumption of a direct proportionality between mass loss and accretion rates — in slightly more depth. Most importantly, it should be kept in mind that this proportionality is indeed an assumption. For example, if jets are driven by some form of radiation pressure the luminosity of the central object will almost certainly play a role in regulating the mass loss rate (Proga, Stone, & Drew 1997).* However, our fundamental working hypothesis is that energy sources unrelated to the accretion process are not needed for the formation of powerful jets. In that context, the assumption that $M_{\text{jet}} \propto M_{\text{acc}}$ is appropriate, as it corresponds to the simplest, most literal interpretation of that hypothesis. (Turning the argument around, we find, conversely, that jet driving by radiation pressure is probably not consistent with our working hypothesis.) Some deviations from a precise proportionality between mass loss and accretion rates are, of course, nevertheless possible. However, we shall assume that they are smaller than the very conservative uncertainties that we have allowed for in the dependence of optical flux on accretion rate (Relation 3).

Now, the equivalent width of an emission line is defined as

$$\text{EW}(\text{line}) = \int_{\lambda_{\text{line}}} \left( \frac{F_\lambda - F_c}{F_c} \right) d\lambda,$$  

(7)

where the integral is over the line profile and $F_\lambda$, $F_c$ are, respectively, the total (line+continuum) and continuum fluxes at a given wavelength. Similarly, the observed line luminosity can be written as

$$L(\text{line}) = 4\pi d^2 \times \int_{\lambda_{\text{line}}} \left( F_\lambda - F_c \right) d\lambda.$$  

(8)

where $d$ is the distance between the (isotropically) emitting source and the observer. We can combine these two equations to give

$$L(\text{line}) = 4\pi d^2 \text{EW}(\text{line}) F_c \propto \text{EW}(\text{line}) F_c,$$  

(9)

where the continuum has been taken to be roughly constant over the line profile. This is an excellent approximation for narrow spectral features such as jet lines.

The observed line luminosities in Equations (8) and (9) can now be identified with the intrinsic ones in Relations (4) and (6), provided that (self-)absorption effects are unimportant. On combining (9) with (3) and (6), we thus arrive at the simple scaling relation between jet line EW and accretion rate that was our goal:

$$\text{EW}(\text{line}) \propto \frac{L(\text{line})}{F_c} \propto \frac{M_{\text{acc}}^2}{M_{\text{acc}}^{1/3}} \propto M_{\text{acc}}^{-1/3}.$$

(10)

We can improve on this relation in terms of its application to different systems by considering the effects of other system parameters. One obvious factor that should be taken into account is the binary inclination. If the optical continuum is indeed dominated by radiation emitted by an optically thick disk, the observed continuum flux will be affected by both foreshortening and limb-darkening. It will therefore scale as $\cos i \eta(i)$, where $\eta(i)$ is the appropriate limb-darkening law. In the Eddington approximation, which may be appropriate for CVs (Warner 1986), $\eta(i) = \frac{1}{4}(1 + \frac{1}{2}\cos i)$. Consequently, the RHS of Relation (10) should be multiplied by a factor of $[\cos i \eta(i)]^{-1/3}$ to account for inclination effects.

In principle, the binary inclination will not affect the jet line luminosity, so long as the line emitting volume is optically thin to recombination line photons. However, in practice the back side of the jet may be hidden from view by the optically thick disk in very low inclination systems. In this case only a blue-shifted satellite feature will appear in the spectrum, as seen in some T Tauri stars (e.g. Edwards...
et al. 1987). Also, in very high inclination systems, the line of sight velocity component of the outflowing material may be too small for the jet line to appear well separated from the line core.

A second parameter that should be taken into account is the disk size, since this may set the scale of the jet cross-section, R_{jet}. As it stands, Relation (10) should only be applied when comparing objects for which these cross-sections are approximately equal in the vicinity of the line-forming regions. This is because, in a smooth flow, the emission measure will scale as EM \propto A^{-1}_{jet} (n_e scales as A^{-1}_{jet} and V as A_{jet}). In general, we might expect the size of the jet cross-section to be set by some characteristic jet-formation radius, R_{jet}, in the accretion disk, which must lie somewhere between the radius of the object at the center of the accretion disk, R_{WD}, and the full disk radius, R_{disk}. So unless R_{jet} \approx R_{WD}, Relation (6) should be modified to contain an additional factor that accounts for possible differences in disk radii between the objects being compared.

To find a reasonable compromise between the two extreme possible scalings of R_{jet}, with R_{WD} on the one hand, and R_{disk} on the other, we fleetingly appeal to a specific physical picture for the origin of jets. We first note that the jet cross-section at some large distance, l, from the disk plane will be proportional to (\theta l)^2 for any highly collimated jet with approximately constant opening angle \theta. Now, if jets are collimated by a mechanism similar to poloidal collimation (e.g. Blandford 1993; Ostriker 1997), then we might expect that the distance down the jet to the line forming region scales as l \propto R_{A,Alfven} \propto R_{disk} (where R_{A,Alfven} is the Alfvén radius) and also that \theta \propto (R_{WD}/R_{disk})^{1/2} (e.g. Spruit 1996; Livio 1997a). We then have A_{jet} \propto (\theta l)^2 \propto (R_{WD}R_{disk}), which implies that the relevant characteristic radius is (R_{WD}/R_{disk})^{1/2}, i.e. the geometric mean of the two limiting radii. Guided by this, we adopt R_{jet} \propto R_{disk}^{1/2 \pm 1/2}, where the size of the “error” has been set so as to include the most extreme plausible scalings.

Disk radii are relatively hard to measure observationally. In our present application, it is therefore preferable to use Kepler’s law to recast any dependence on R_{disk} into one on the orbital period, P_{orb}. This can be done by noting that the binary separation, a_{bin}, is related to P_{orb} by a_{bin} \propto P_{orb}^{2/3}. Provided that the mass ratios of the systems being compared are not too dissimilar, their disk radii will be roughly equal fractions of their respective binary separations and will therefore also scale as P_{orb}^{2/3}. Thus the right hand side of Relation (10) should by multiplied by a factor A_{jet} \propto R_{disk}^{1/2} \propto P_{orb}^{2/3}.

With the additional dependences on inclination and disk radius included, Relation (10) now reads

\[ EW(line) \propto H_fj_{line}f_{jilt}\frac{\eta^{5/12}}{M_{line}^{-1/3}}\frac{P_{orb}^{\frac{4}{3}}}{\cos i \eta(i)}. \]  

(11)

In this new relation, we have also made explicit the linear scalings of the jet line EW with (i) H, the “vertical” scale height of the line emitting region; (ii) j_{line}, the line emissivity (which will depend weakly on the density and somewhat more strongly on the temperature in this region); (iii) f_{jilt}, the filling factor, which accounts for the possibility that the flow is not smooth and the line forming region is not uniformly filled with emitting gas. In principle, these could themselves depend indirectly on the accretion rate, and in ways that might be different for different dynamical models. Here, we take the plausible, but unproven view that any such dependencies are likely to be small compared to the direct ones that we have accounted for. Based on our hypothesis that SSSs, T Pyx and other CVs all drive jets and share the same jet driving and line emission mechanisms, we thus take H_f, j_{line}, f_{jilt} to have similar values in all of these systems and ignore these additional parameters in inter-comparisons.

3 DISCUSSION

3.1 A prediction for the strength of jet lines in CVs

We are now in a position to use Relation (11) to predict the jet line EWs we would expect to see in “ordinary” CVs, according to our working hypothesis. Since T Pyx is in fact a CV, its system parameters are more typical of “normal” CVs than are those of the SSSs exhibiting jet lines. It is therefore preferable to use T Pyx as a reference point in making predictions for other CVs, because the ratios of the relevant factors in Relation (11) will be closer to unity and the associated uncertainties will be smaller. However, in Section 3.2 below we will check whether Relation (11) is at least consistent with the observed accretion rate and EW ratios of T Pyx and the SSS RX J0513-069. (See also the note at the end of the manuscript, in which we show that the prediction derived in this section by using T Pyx as a reference datum is consistent with what is be obtained if RX J0513-069 is used instead.)

Concerning T Pyx, Webbink et al. (1987) give $M_{acc}(T \, Pyx) \gtrsim 10^{-8} \, M_{\odot} \, yr^{-1}$ based on the short recurrence time scale of its eruptions and $M_{acc}(T \, Pyx) \sim 5 \times 10^{-8} \, M_{\odot} \, yr^{-1}$ based on its optical colors. Here, we adopt the latter estimate, which assumes that the optical light is due to the accretion disk, rather than to direct and/or reprocessed light from a hot WD. This is in line with our working hypothesis that a wind/energy source at disk center is not required to drive jets from accretion disks. T Pyx’s orbital period is thought to be $P_{orb}(T \, Pyx) \sim 1.8 \, hrs$ (Schaefer et al. 1992), placing the system below the period gap. As noted in Section 1, the inclination angle of T Pyx is not well constrained observationally, although the appearance of the satellite recombination lines themselves suggests a high value $i(T \, Pyx) \gtrsim 70^\circ$ if these features are formed in a well collimated jet. Finally, the equivalent widths of the Hα jet lines in T Pyx can be measured from the data of Shababz et al. (1997) and turn out to be about EW(T Pyx) \approx 1 \, Å on average, with the strongest feature in any one of the observing epochs reaching about twice this value (Shababz, private communication).

We now need to make some assumptions about the typical properties of “ordinary” CVs. The form of Relation (11) shows that if jets are present in these objects, the associated satellite recombination lines are likely to be strongest in systems with high mass accretion rates, short orbital periods and high inclinations (though not so high as to shift the jet lines into the line core). Since it would be sufficient to fal-
sify our working hypothesis for CVs with these properties, we adopt $M_{\text{acc}}(CV) \geq 1 \times 10^{-8} \, M_\odot \, \text{yr}^{-1}$ (appropriate to NLs and DNe in outburst), $P_{\text{orb}}(CV) \approx P_{\text{orb}}(T \, \text{Pyx})$, and $i(CV) \approx i(T \, \text{Pyx})$. (We note in passing that there are actually no well-established non-magnetic NL variables with periods shorter than 3.2 hrs, although there is a fair number of DNe with $P_{\text{orb}} \leq 2 \, \text{hrs}$.)

We can now use Relation (11) to predict the jet line EWs we expect to see in this most favorable sub-group of “ordinary” CVs, according to our working hypothesis. To this end, we take the ratio of the two separate relations (one for the normal CVs, one for T Pyx), solve for $EW(CV)$ and substitute our adopted parameters. This yields $EW(CV) \approx 0.14 \pm 0.04 \, \AA$. While it may be possible to increase the upper limit implied by this result somewhat—by taking $P_{\text{orb}}(CV)$ to be shorter or $i(CV)$ to be higher, for example—it is clear that CV jet lines, if they exist, would be at best marginally detectable in typical optical spectra. As a result, we are forced to conclude that our working hypothesis and its corollary—that a hot central object is essential to the formation of jets and that CVs do in fact drive jets—cannot yet be ruled out.

Let us take a step back at this point to make it clear what we are—and are not—claiming. We started by adopting the working hypothesis that the formation of powerful jets does not require the presence of an additional energy source at disk center. As a corollary, we assumed that “ordinary” CVs harbor the same kind of jets that may be present in T Pyx (as indicated by the satellite recombination lines that are observed in that object). We then showed that based on these assumptions one can derive a simple scaling law which can be used to predict the expected strength of these jet lines in the optical spectra of ordinary CVs. The predicted jet line EWs for these systems turned out to be very small, even for objects with nearly optimal system parameters. We therefore concluded that the lack of jet line detections in the optical spectra of ordinary CVs is not yet in conflict with our working hypothesis, i.e. that jets may be present in ordinary CVs. Note that we do not claim to have shown that ordinary CVs actually do contain jets. After all, an inability to falsify a hypothesis does not prove it. Summarized succinctly, our conclusion is that the non-detection of jet lines in existing optical spectra of “ordinary” CVs should not yet be taken to imply that these systems cannot harbor collimated jets.

Two further points need to be made regarding this statement. First, even though we have been unable to rule out the presence of jets in “ordinary” CVs on the basis of existing data, the predicted EWs of a few hundredths up to a few tenths of Angstroms may not be beyond the reach of high resolution, high signal-to-noise optical spectra. Thus we strongly encourage observers to search for the signatures of jets in the spectra of appropriately selected CVs.

Second, it was assumed above that T Pyx’s optical continuum is dominated by the radiation field emitted by a standard accretion disk. However, if (intermittent) nuclear burning really does take place in T Pyx, the surface of the WD at the center of the disk will be extremely hot. It is therefore worth asking whether (some of) the optical continuum could actually be direct or reprocessed radiation emitted by the WD, and what effect this may have on our conclusions.

A numerical calculation similar to that described following Relation (1) in Section 2 shows that direct light from the WD is unlikely to be of any importance, even if the temperature of the WD is as high as a few times $10^5 \, \text{K}$, and the accretion rates as low as $10^{-8} \, M_\odot \, \text{yr}^{-1}$. To judge the potential significance of reprocessed WD radiation, we rely on the recent work of King (1997), who derived a simple condition that can be used to estimate the relative importance of dissipation and reprocessing in a CV accretion disk. More specifically, King (1997) showed that reprocessing of WD radiation will begin to have a dominant effect on the local disk temperature if $L_{WD} \gtrsim 2.5 L_{acc}(1 - \beta)^{-1}$, where $L_{WD} = 4 \pi R_{WD}^2 \sigma T^4_W D$ and $L_{acc} = G M_{WD} M_{acc}/R_{WD}$ are the WD and total accretion luminosities, respectively, and $\beta$ is the albedo of the disk surface. To give a numerical example, we note that if reprocessing is assumed to be efficient ($\beta \approx 0$), the temperature distribution in a disk around a $1M_\odot$ WD accreting at a rate of $M_{acc} = 10^{-8} M_\odot \, \text{yr}^{-1}$ will be dominated by reprocessing if $T_{WD} \gtrsim 2 \times 10^5 \, \text{K}$.

If reprocessed WD radiation is in fact contributing significantly to T Pyx’s optical continuum, then our previous prediction for the strength of jet lines in other CVs no longer applies, since our continuum scaling law, Relation (3), ceases to be valid. Qualitatively, the effect of this will be to increase the predicted EWs significantly, since (a) the adopted accretion rate for T Pyx is almost certainly an overestimate in this case, and (b) the additional contribution to the continuum that is ultimately due to nuclear burning on the WD (and not to accretion) is making the jet lines appear weaker than if only the disk were producing the continuum. Quantitatively, these effects can be corrected for by multiplying the predicted EWs by a factor of $f_M^{-2}$, where $f_M > 1$ is the factor by which T Pyx’s accretion rate has been overestimated. The dependence on $f_M$ squared arises because the part of correction (a) that is related to the scaling of the continuum flux with accretion rate exactly cancels correction (b). This leaves the scaling of the line luminosity with accretion rate as the only relevant factor.

It is now easy to see that if irradiation is very important in T Pyx and has caused us to overestimate the accretion rate by a significant amount, then the non-detection of jet lines in the spectra of other CVs does become inconsistent with the presence of jets in these systems. Indeed, if $f_M \gtrsim 4$, then even the previously derived lower limit of 0.06 $\AA$ on the jet line EWs in (suitably selected) CVs becomes as large as 1 $\AA$ and thus comparable to the strength of the same features in T Pyx. In practical terms, this means that studies of T Pyx aimed at deriving $T_{WD}$ (or, more precisely, $L_{WD}/L_{acc}$) for this system may provide yet another way to falsify our working hypothesis observationally in the future.

3.2 The scaling relation applied to T Pyx and the SSSs

Given that the jets in T Pyx and the SSSs are presumably of the same type, it is natural to try and use these systems to check our scaling relation for the jet line EWs. Unfortunately, the accretion rates of the relevant SSSs are only poorly constrained and, in addition, disk irradiation by the hot WD is likely to be very strong in the SSSs. As a consequence, a rigorous test of Relation (11) via this route is not possible. However, we will nevertheless proceed to apply our
scaling relation to T Pyx and the SSS RX J0513-069, partly to illustrate these problems, and partly to perform at least a rough consistency check.

In their study of RX J0513-069, Southwell et al. (1996) state that $M_{\text{acc}} \sim 10^{-5} \, M_\odot \, \text{yr}^{-1}$ is required if the optical luminosity of this system is to be ascribed entirely to a standard accretion disk. An accretion rate this high is of the order of the Eddington value, and Southwell et al. (1996) therefore conclude that it is almost certainly an overestimate. They argue that irradiation of the disk and secondary star, as well as (perhaps) direct light from the hot WD are likely to contribute significantly to the optical light. Consequently, they prefer a lower value of about $10^{-6} \, M_\odot \, \text{yr}^{-1}$ for the accretion rate. To make progress in the face of this uncertainty, we will adopt the higher value to start with and then check a posteriori what value this implies for the correction factor $f_M^i$. Regarding RX J0513-069’s other relevant parameters, Southwell et al. (1996) give values of $P_{\text{orb}} \approx 18$ hrs for the orbital period, and, based on the mass function of the system, $i \approx 10^\circ$ for the inclination.

Adopting these parameters for RX J0513-069, and using the same parameters as above for T Pyx, we would predict a best-bet ratio for the EWs of the jet lines in these two systems of about 50 (in favor of the SSS). Now, Southwell et al. (1996) measure the equivalent widths of the blue and red Hα jet satellite lines in RX J0513-069 to be EW(SSS,blue) $\simeq 1.6$ Å and EW(SSS,red) $\simeq 2.6$ Å, respectively. Thus the actual ratio of the jet line EWs in RX J0513-069 and T Pyx is only about 2. If we interpret this as a result of disk irradiation in the SSS, then the correction factor $f_M^i \simeq 25$ and $f_M \simeq 5$. Consequently, we would predict the true accretion rate in RX J0513-069 to be about $M_{\text{acc}} \approx 2 \times 10^{-6} \, M_\odot \, \text{yr}^{-1}$, which is in line with the value of $10^{-6} \, M_\odot \, \text{yr}^{-1}$ preferred by Southwell et al. (1996). We do not attach too much weight to this apparent consistency, because there are large observational uncertainties associated with the ratios constructed from two of the relevant parameters (accretion rate and inclination). Moreover, the accretion rate and orbital period ratios are so large for these systems that the theoretical uncertainties expressed by the “errors” in Relation (11) also become rather large.

It is finally interesting to consider briefly the implications of adopting the complement of our working hypothesis. Specifically, we may ask whether a consistent physical picture capable of accounting for the relative strengths of the jet lines in T Pyx and RX J0513-069 can also be found if we assume that a hot, central object is in fact present in both systems and is crucial for driving the observed jets. To answer this question, we take $f_M^i \propto L_{\text{acc}}$ and assume the extreme case of $L_{\text{WD}} \gg L_{\text{acc}}$. The disk is still quite likely to dominate the optical flux (e.g. the numerical estimates for the direct WD contribution given previously), but its local temperature distribution will be dominated by irradiation, not dissipation (see Section 2.3). Since the disk will be extremely hot in this case, we may further assume that the optical waveband lies on the Rayleigh-Jeans tail of the disk spectrum now, i.e. $F_{\text{opt}} \propto T_{\text{disk}}^{1/4} \propto F_{\text{WD}}^{1/4}$ (the latter holds since $L_{\text{disk}}$ is now dominated by $L_{\text{WD}}$). We can then replace the dependence on $M_{\text{acc}}$ in Relation (11) with one on $L_{\text{WD}}$, giving $EW(\text{line}) \propto L_{\text{WD}}^{2} \propto T_{\text{WD}}$. Adopting again an EW ratio of 2 for RX J0513-069 and T Pyx, we find that $T_{\text{WD}}(\text{SSS}) \simeq 2 T_{\text{WD}}(T\, \text{Pyx})$ in this simplistic picture, if the remaining parameter dependences in Relation (11) are assumed to stay unchanged.

This reasonable looking result should of course not be taken too seriously. However, the moral of this simple calculation is that it is certainly possible to account for the jet line EW differences between T Pyx and RX J0513-069 in the context of a model in which the presence of an energy source at disk center is a crucial ingredient in driving the observed jets. This prompts us to stress again that our analysis in this paper has only shown that the presence of jets in CVs should not be ruled out simply because no jet lines have so far been detected in the optical spectra of these systems. We have by no means demonstrated that jets are actually present, or are even likely to be present, in ordinary CVs.\footnote{Note that if jets are present in CVs but jet lines are not seen in T Pyx, the absence of the latter would have to be attributed to one or both of the following: (i) T Pyx’s inclination is much lower than 70$^\circ$; (ii) irradiation is increasing the brightness of the accretion disk in T Pyx substantially.}

Note added: After this paper was accepted for publication, we received a draft of a work by Margon & Deutsch, in which it is argued that the satellite lines seen in T Pyx are in fact due to [N ii] $\lambda 6548,6584$ and are formed in the complex velocity field of T Pyx’s nova shell(s). While the analytic scaling relation we derived in Section 2 retains its validity (and, we believe, usefulness) if this interpretation turns out to be correct, the same is not true for the prediction we made for the jet line EWs in ordinary CVs (since this is based on the assumption that T Pyx’s satellite lines are jet features). The best we can do in this case is to derive a new prediction by scaling down directly from one of the SSSs to CVs. To do this, we use Southwell et al.’s (1997) inclination, orbital period and accretion rate estimates for RX J0513-069 ($i \approx 10^\circ$; $P_{\text{orb}} \approx 18$ hrs; $M_{\text{acc}}(\text{apparent}) \sim 10^{-5} \, M_\odot \, \text{yr}^{-1}$ with $f_M = 10$) and, as before, parameters appropriate to an optimally selected, “ordinary” CV ($i \approx 70^\circ$; $P_{\text{orb}} \approx 1.8$ hrs; $M_{\text{acc}} \sim 10^{-8} \, M_\odot \, \text{yr}^{-1}$). Ignoring limb-darkening ($\eta(i) = 1$), we obtain a new prediction of $EW(\text{CV}) \sim 0.3$ Å. Even though the uncertainties on this number are substantial and hard to quantify (see Section 2.3), this estimate still suggests it would be premature to rule out the presence of jets in CVs completely at this stage.\footnote{Note that if jets are present in CVs but jet lines are not seen in T Pyx, the absence of the latter would have to be attributed to one or both of the following: (i) T Pyx’s inclination is much lower than 70$^\circ$; (ii) irradiation is increasing the brightness of the accretion disk in T Pyx substantially.}

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