STREAM-FIELD INTERACTIONS IN THE MAGNETIC ACCRETOR AO PISCUM

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ABSTRACT

UV spectra of the magnetic accretor AO Psc show absorption features for half the binary orbit. The absorption is unlike the wind-formed features often seen in similar stars. Instead, we attribute it to a fraction of the stream that overflows the impact with the accretion disk. Rapid velocity variations can be explained by changes in the trajectory of the stream depending on the orientation of the white dwarf’s magnetic field. Hence, we are directly observing the interaction of an accretion stream with a rotating field. We compare this behavior to that seen in other intermediate polar systems and in SW Sex stars.

Subject headings: accretion, accretion disks — binaries: close — novae, cataclysmic variables — stars: individual (AO Piscium)

Online material: color figures

1. INTRODUCTION

Cataclysmic variable (CV) stars (see Warner 1995) give us an opportunity to study accretion under a range of physical conditions. For example, the AM Her class shows an accretion stream interacting with a magnetic dipole that is stationary with respect to the stream. In the intermediate polars (IPs) the white dwarf is generally spinning much faster than the orbit, and the stream material usually circularizes into an accretion disk before threading onto the field. However, there are signs that at least part of the stream often overflows the accretion disk and interacts directly with the magnetic field (e.g., Hellier et al. 1989), giving a more dynamic and poorly understood stream-field interaction. In at least one system, V2400 Oph, stream-fed accretion appears to dominate (Buckley et al. 1995; Hellier & Beardmore 2002).

AO Psc is an IP with a 3.59 hr orbit and an 805 s white dwarf spin period whose optical and X-ray behavior have been well studied (e.g., Hellier et al. 1991, hereafter H91; Hellier et al. 1996; Taylor et al. 1997; Williams 2003). We report here on UV spectroscopy of AO Psc that shows a new type of observational evidence for a stream-field interaction, namely, rapidly varying absorption features in UV metal lines.

2. OBSERVATIONS AND SPECTRA

On 2000 July 15 and 16 we obtained UV observations of AO Psc with the Hubble Space Telescope Space Telescope Imaging Spectrograph (HST STIS). The E140M echelle grating gave 43 orders covering the wavelength range 1140–1710 Å, with a dispersion of 0.015 Å at the 1425 Å central wavelength. The observations were made with the far-UV MAMA detector in time-tag mode, obtaining data trains lasting 2000–3000 s from each of eight HST orbits.

We used the STSDAS package INTTAG in IRAF to bin the data train into 40 s exposures. This gave 474 echelle images that were then reduced to spectra using the STSDAS spectral reduction package CALSTIS.

The summed spectrum is shown in Figure 1. The lines are predominantly in emission, which is unusual among UV spectra of CVs where lines are often strongly in absorption (e.g., Hartley et al. 2002a, 2002b) or showing P Cyg profiles. We attribute this to the higher X-ray and EUV irradiation in a magnetic system. Strong, broad Lyα absorption can be attributed to the white dwarf, while its narrow emission core is geocoronal emission that is not completely subtracted during pipeline reduction.

In addition, the spectrum shows narrow interstellar absorption features that can be used to estimate the column toward AO Psc (e.g., Savage & Sembach 1991). The equivalent width of the Si ii 1528 Å absorption line is 0.159 Å, which, using an oscillator strength of f = 0.2303 (Morton 1991), implies a value of N_{Si} = 2.5 \times 10^{14} cm^{-2}. This suggests (e.g., Gnacinski 2003) that N_{HI} ≲ 10^{20} cm^{-2} and thus that E(B − V) ≤ 0.02.

The continuum and line fluxes, plus the motion of the lines, all show a prominent variation with the spin cycle (see Fig. 2), as expected in an intermediate polar. Fourier analysis of these quantities (not shown) finds no beat-cycle periodicity or other periodicities shorter than the orbital cycle.

The focus of this paper is the behavior over the orbital period. To reveal this, we removed the spin-cycle pulsation by normalizing each spectrum to the continuum. This process removes most of the pulsation but is not perfect, resulting in residual spin-cycle “rippling.”

The observations, broken up by HST’s low-Earth orbit, consist of two “visits,” each with four sections of data ≈0.2 orbital cycles long, separated by gaps of ≈0.3 cycles. It so happens that these sections interleave to produce full coverage of AO Psc’s orbit. We thus display the data against orbital phase as though they were taken in a continuous sequence (although the caveat that they were not should be borne in mind).

Figure 3 shows the region of spectra from 1230 to 1415 Å, which contains the weaker lines, and Figure 4 shows the strongest line, C iv 1550 (the color scales are not the same in the two plots). The lines are purely in emission for half an orbital cycle, but the weaker lines are cut into by prominent absorption features for the other half. C iv is in emission except for blueshifted absorption around phase 0.73. To allow the reader to judge the depth of the absorption, we show in Figure 5 the data from six orbital phases as line profiles.

The emission moves in velocity, being blueshifted at phase ≈0.6. The absorption has the same overall velocity trend as the emission, being reddest at phase ≈0.1, but has additional, rapid velocity variations. We should note that, with only ≈1.5 orbital cycles of data, we cannot be certain from this data alone that the
absorption repeats with the orbital cycle. However, the behavior is similar to that of the optical Balmer and He i lines, and of the X-ray continuum, which all show absorption dips occurring at these orbital phases (H91).

Inspection of Figure 2 (e.g., near 1330 Å around orbital phase 0.8, and near 1400 Å around orbital phase 0) suggests that the absorption also varies over the spin cycle, in that it is often more pronounced at the minima of the spin pulsation. However, this is hard to prove conclusively since it is a transient effect and, as can be deduced from Figure 2, all measures of the line are dominated by a spin-cycle variation.

3. WIND FEATURES?

Absorption features owing to winds are common in the UV lines of CVs, and the feature seen at phase 0.73 in C iv $\lambda$1550 looks like the classic P Cygni signature. However, we consider that there are reasons to develop a nonwind model for the absorption features in this star.

1. Most models suggest that winds are driven from a boundary layer or inner disk. In an intermediate polar such as AO Psc there is no boundary layer or inner disk (an 805 s rotator in equilibrium would have an inner disk disrupted out to $\approx 2 \times 10^8$ m).

2. The absorption in the weaker lines does not give typical P Cygni profiles. Instead, the absorption is often in the line core, although there is a bias to the blue.

3. The absorption troughs have a lower velocity (out to $\approx 1000$ km s$^{-1}$ in the weaker lines, $-1300$ km s$^{-1}$ in C iv) than usual in wind-formed P Cygni lines. For example, $-5000$ km s$^{-1}$ is observed in BZ Cam (Prinja et al. 2000), and maximum velocities are often comparable to the white dwarf escape velocity.

4. The features are generally narrower and show more pronounced variability than in wind-lined systems (e.g., compare the features with the data shown in Prinja et al. [2000], Hartley et al. [2002a, 2002b], and Witherick et al. [2003]; note that many of these papers display the data after subtracting the mean profile to enhance the variations, which we have not done here). There have been reports of narrow, rapidly varying wind-formed lines, which are attributed to clumps in an outflow (e.g., Hartley et al. 2002a), but these are components of broader, deeper P Cygni troughs and thus are unlike those in AO Psc.

It is also worth remarking that the absorption in AO Psc is markedly dependent on orbital phase, being absent for half the cycle. Any deduction from this is unclear, however, since, while there is no particular reason to expect wind-formed lines to depend on orbital phase, and usually they do not (e.g., BZ Cam; Prinja et al. 2000), there are systems in which this is indeed seen (e.g., V592 Cas; Prinja et al. 2004) for reasons that are not understood.

4. STREAM-FIELD INTERACTIONS?

The fact that the absorption features are so dependent on orbital phase is a strong indicator that they originate in the accretion stream. This is supported by the presence of X-ray absorption dips lasting for $\approx 0.2$ cycles, which are coincident with absorption dips in the cores of the optical lines (H91). Such dips are well known from X-ray binaries (e.g., White 1989) and are often seen in IPs (Hellier et al. 1993); they are attributed to obscuration by disk bulges created where the stream hits the disk.

We thus outline an interpretation of the UV absorption features as originating in the stream. Note that H91 concluded that the motion of the optical lines was dominated by the stream (rather than by disk motions). Thus, maximum redshift occurs when the stream is flowing away, near orbital phase 0.9. This coincides with the optical and X-ray dips.

With this phasing the UV absorption features occur at phases 0.65–1.15. We suggest that they arise from the fraction of the accretion stream that overflows the disk-stream impact. In the standard picture of an IP, the magnetic field is squeezed in the orbital
plane by the dense accretion disk. However, less dense material from stream overflow will encounter field lines farther out than the disk-disruption radius. The material would have to cross field lines to follow a ballistic trajectory and thus would experience a magnetic drag, as discussed in the diamagnetic blob model of Wynn & King (1995).

This interaction would explain why the absorption varies with the spin cycle. In the standard model for AO Psc’s spin pulse, minimum flux occurs when the upper magnetic pole points toward us (H91). It presents a magnetic barrier to the inward flow of the stream lasting for approximately a quarter of a spin cycle, hence causing an accumulation of material until the dipole has turned, allowing the material to flow on. If so, this might explain why the absorption increases in the pulse minimum.

Can we also explain the rapid velocity shifts seen in Figure 3, for example, at phase 0.70, where the Si iv line moves 1000 km s⁻¹ to the blue and then back redward on a timescale much faster than the orbit but comparable to the spin cycle? Well, a clue is that it occurs at the specific orbital phase when the stream-field interaction region is likely to be viewed in front of the white dwarf (see Fig. 6). An “accretion gating” scenario in which the material is either pushed outward or allowed to flow inward, as the magnetic pole sweeps across the region, would produce motion along the line of sight and hence the rapid changes in Doppler shift seen. The restriction to one part of the orbit, and the sudden onset of the features at phase 0.7, would then be explained if we see the absorption features only when this region is in front of the white dwarf, which acts as a UV backlight.

We should also consider the tendency of the absorption to be blueshifted, in that while it is often close to the rest wavelength, it is typically ~100 km s⁻¹ bluer than the emission centroid. Note that outside the corotation radius the field will be moving faster than the stream material and will thus act as a propeller, tending to slow down the material’s infall (which would result in a relative blueshift for the half-orbit during which we see absorption, when the stream is on the near side of the white dwarf). Also, both the field’s kick and the initial impact with the disk could tend to push the material out of the plane, adding to the blueshift.

Given the propeller effect of the field, it is unclear whether the overflowing material ends up accreting, or whether it is slowed down, and perhaps pushed outward to some extent, so that it ends up merging with the disk (with an 805 s spin period, any propeller would not be powerful enough to expel material from the system, unlike that proposed for faster rotators such as the 33 s system AE Aqr).

If material does accrete while remaining confined in orbital phase, it should produce an X-ray modulation at the beat frequency between the orbital and spin periods, since the accretion geometry changes on that cycle (e.g., Hellier 1991; Wynn & King 1992). Beat-cycle modulations are not a usual feature of AO Psc’s X-ray light curves, but they have been reported in EXOSAT data (Hellier 1991). This suggests that a small amount of the overflow might be accreting on some occasions, but the dominance of the spin pulse in the X-ray light curves indicates that most of the accretion flows through the disk.

5. COMPARISON WITH SW SEX STARS

We have presented evidence that the accretion stream overflows the accretion disk in AO Psc, based on an interpretation of absorption features in the UV lines. The idea of an overflowing stream was originated as far back as Lubow & Shu (1976; see also Lubow 1989). It has since been adopted to explain observational features of several types of CVs. For example, many IPs show the X-ray beat periods that are characteristic of disk-overflow accretion (e.g., Hellier 1991; Beardmore et al. 1998). FO Aqr not only shows intermittent beat periods—suggesting
that overflow is a variable phenomena—but also optical absorption features from the overflowing stream (Hellier et al. 1990) that are similar to the UV features reported here in AO Psc. Further, in many nonmagnetic systems, eclipse profiles reveal evidence of a bright stream overflowing the disk (e.g., Baptista et al. 1998). However, stream overflow has been most widely discussed over its role in the SW Sex phenomenon, a set of observational characteristics named by Thorstensen et al. (1991). Early on, Shafter et al. (1988) proposed that overflow was occurring in one of these stars, while Hellier & Robinson (1994) proposed that overflow was the cause of the main SW Sex characteristics, namely, "phase 0.5" absorption features from the stream as it flowed over the disk, and high-velocity line wings from the reimpact of the stream with the disk. Knigge et al. (2004) showed that phase-0.5 absorption also occurs in the UV lines of at least one SW Sex star, while Hynes et al. (2000) found...
similar SW Sex characteristics in a low-mass X-ray binary, suggesting that overflow can also occur in disks around neutron stars.

We can thus compare AO Psc to SW Sex stars and conclude that stream overflow is likely occurring in both. Indeed, it is becoming clear that overflow is widespread in many types of CVs, which means that “SW Sex star” becomes less a well-defined class of star and more a set of observational characteristics resulting from (1) overflow, (2) high accretion rate (which appears to be a feature of classic SW Sex stars), and (3) being viewed at high inclination (see, e.g., Knigge et al. 2000).

If, however, the UV absorption features seen in AO Psc have a similar origin to the “phase 0.5” absorption characteristic of SW Sex stars, why do they have virtually the opposite phasing, being seen at phases 0.65–1.25 in AO Psc, but at phases 0.2–0.6 in SW Sex stars? Our explanation is as follows.

The conventional SW Sex stars are high-inclination eclipsing systems in which the white dwarf is usually hidden by the optically dim wall of a flared disk. We thus see bright disk surface only beyond the white dwarf. In the model developed by Hellier (1996, 1998) the optical absorption features result when the overflowing stream obscures the optically bright disk surface, which is only during phases 0.2–0.6.

Now, AO Psc is a lower inclination, noneclipsing system in which any disk flare will have a lesser effect. Further, the UV absorption features require a UV backlight, which can only be provided by regions near the white dwarf and not by the cooler outer disk. These differences could explain the marked change in which absorption is visible in AO Psc, even though its origin is similar to that in SW Sex stars.

It is noteworthy that in AO Psc, SW Sex characteristics occur in a system that is undoubtedly magnetic. This is important, first, in that it enables us to observe the interaction of the overflow with the field of the white dwarf, which results in rapid variability as the stream appears to waggle about under the influence of the spinning dipole. Second, it bears on the suggestion by Rodríguez-Gil et al. (2001; see also Patterson et al. 2002) that all SW Sex stars are magnetic, and that the magnetism is fundamentally liked to SW Sex behavior.

If SW Sex characteristics are largely a consequence of stream overflow, then this can indeed occur in a magnetic system but is unlikely to be caused by the magnetism. Thus, SW Sex characteristics would be merely coincidental to AO Psc’s magnetism. This would concur with the fact that many SW Sex stars are not strong X-ray sources, let alone show the X-ray pulsations that are prominent in AO Psc, and are thus unlikely to have fields strong enough to control the accretion flow.

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