Iron Kα line widths in magnetic cataclysmic variables

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ABSTRACT
Following a recent report that AO Psc has broad iron Kα emission lines we have looked at the ASCA spectra of 15 magnetic cataclysmic variables. We find that half of the systems have Kα lines broadened by ∼200 eV, while the remainder have narrow lines. We argue that the Doppler effect is insufficient to explain the finding and propose that the lines originate in accretion columns on the verge of optical thickness, where Compton scattering of resonantly-trapped line photons broadens the profile. We suggest that the broadening is a valuable diagnostic of conditions in the accretion column.

Key words: accretion, accretion discs – novae, cataclysmic variables – binaries: close – X-rays: stars.

1 INTRODUCTION

The accretion shock near the surface of a white dwarf in a magnetic cataclysmic variable (MCV) will consist of a highly ionized ∼10 keV plasma cooling by bremsstrahlung emission. Most elements will be fully ionized, leaving iron as the dominant cause of line emission. While model fits to the X-ray spectra of MCVs have traditionally included an iron Kα line (e.g. Norton, Watson & King 1991), it is only with the ASCA satellite that the data have sufficient spectral resolution to investigate the structure of the line.

An analysis of the ASCA data on AO Psc (Hellier et al. 1996) showed that the thermal components of the iron Kα line were broadened by ∼150 eV. However, reports on two other MCVs with the same detectors [Kallman et al. (1996) on BY Cam and Fujimoto & Ishida (1997) on EX Hya] found a Kα complex compatible with narrow emission lines. We have therefore investigated the line widths in the class as a whole. In this paper we present a systematic analysis of lines in 15 MCVs, and discuss the mechanisms responsible for line broadening. Of our sample, AM Her is a phase-locked system (i.e. a polar; see Cropper 1990 for a review), BY Cam is nearly phase-locked, and the remaining 13 are non-phase-locked systems (i.e. intermediate polars; reviewed by Patterson 1994).

2 DATA ANALYSIS

The temperature of the highly-ionized plasma in an accretion shock will typically range from 0.1–30 keV. At the hottest temperatures iron will be completely ionized or hydrogen-like (Fe xxvii or xxvi), and give rise to a Kα line at 6.97 keV (e.g. Makishima 1986). At temperatures of a few keV iron will be helium-like (xxv), producing a Kα line at 6.70 keV. Cold iron can produce a fluorescent line at 6.41 keV. The gap between 6.41 and 6.70 keV could be filled by fluorescence from iron in intermediate states, but no iron species emits between 6.70 and 6.97 keV.

We have used data from the ASCA SIS0 and SIS1 instruments only (see Tanaka, Inoue & Holt 1994), since the GIS instruments have insufficient resolution to separate the lines. A list of observations analysed is given in Table 1. For all cases we used the same, fairly lax, screening parameters, in order to maximise the available photons. We analysed the data in BRIGHT2 mode where that was available for an entire observation (XY Ari, V1223 Sgr, TX Col, EX Hya, BY Cam, RX 1238–38) and in BRIGHT mode otherwise. The resolution of the SIS instruments has declined through the mission owing to radiation damage, so we computed calibration matrices appropriate for each observation using FTOOLS v4.0.

We then analysed the spectra using XSPEC v9. However, since the 6.70 and 6.97 keV lines are themselves blends of many components, we first needed to find the expected natural width, as seen by our instrumentation. To do this we used XSPEC’s CEMKL model (Mewe, Kaastra & Liedahl 1995) to predict the spectrum for a multi-temperature plasma having emission measures distributed with a power-law index of 1, up to a maximum temperature of 20 keV. We then used the FAKEIT utility to create model spectra with the same photon noise and spectral resolution as our datasets. We found that the resulting 6.70 and 6.97 keV lines could be adequately fit with Gaussians. The Gaussians had a best-fitting width of zero, and mean ener-
of 6.676 and 6.960 keV respectively. For a fake dataset modelled on the AO Psc data from 1994 June the Gaussian width (σ) was less than 40 eV (1σ error) or 60 eV (90 per cent confidence). A fake dataset modelled on the RX 1712–24 data of 1996 March gave larger upper limits of 60 and 85 eV respectively, owing to the degradation in resolution. Since intermediate polars often have highly absorbed spectra we have repeated the above procedure with partial-covering absorbers (up to 5×10^{23} cm^{-2}) included in the model. This made essentially no difference to the measured line widths.

Turning to the observations, we fitted the summed spectra from SIS0 and SIS1 simultaneously. To model the continuum we first fitted the energy ranges 4.0–6.0 and 7.5–10.0 keV with a bremsstrahlung together with simple and partial absorption. We then fixed the continuum parameters, extended the fitted range to 4.0–10.0 keV, and added Gaussians to model the iron lines.

We found that the iron lines of all observations could be modelled satisfactorily by 3 Gaussians, corresponding to cold, helium-like and hydrogen-like iron. Although one could argue for the inclusion of iron emission between 6.41 and 6.70, and for an iron edge at 7 keV in addition to that introduced by the absorption, none of the observations required their presence, so they were not included. Next, since many of the observations had only barely enough S/N for our purpose, we constrained the model by fixing the line energies to 6.41, 6.676 and 6.960 keV (as measured from the faked data). We also forced the two thermal lines to have the same width and fixed the width of the fluorescent (6.41 keV) line to zero, since none of the observations indicated that it was broad. Thus we fitted only 3 line normalisations and one width.

The resulting line widths and equivalent widths are given in Table 2. We find that 8 of the stars have thermal lines consistent with zero width, but the remaining 7 stars have broad thermal lines at >90 per cent confidence. We should caution that this analysis is near the limit of the current data. For instance the result for BG CMi, no
detection at 6.70 keV but strong emission at 6.97 keV, is physically unlikely and implies an insecure result. Note also that while the results for AO Psc are qualitatively similar to those from the same data presented in Hellier et al. (1996), in that both require broad thermal lines, the fitted parameters are formally inconsistent. This can be explained by different screening parameters, updated calibration files, and different constraints on the iron line model, but still indicates the uncertainties in the analysis. A further effect is the progressive radiation damage to the SIS detectors, complicating the comparison of different observations. However, this is included in the response matrices, and as can be seen from the values in Table 2, the detected line broadening is in many cases large compared to the resolution.

Thus, while an individual result is uncertain, the finding of broad lines in roughly half the systems studied suggests that they are a reality in MCVs. To illustrate the findings, Fig. 1 shows the data and fitted model for two of the systems with narrow lines and two of those with broad lines.

We have also attempted to find limits on the width of the 6.41 keV fluorescent line (which was fixed at zero in the above analysis). As a free parameter we found it to be consistent with zero width in all cases. The interesting case would be if we could prove the fluorescent line to be narrower than the thermal lines. Because of the limited data quality this was possible only in the case of AO Psc, where the upper limit on the fluorescent line width was 98 eV (1σ) or 129 eV (90 per cent confidence), compared to a 1σ lower limit of 180 eV for the thermal lines (Table 2). This difference is consistent with a separate origin for the fluorescent line (reflection from the white dwarf) compared to the thermal lines (see below).

### 3 BROADENING MECHANISMS

Of the possible line broadening mechanisms, only two are likely to be significant at the level of ΔE/E ∼ 0.04 seen in our data. These are Doppler broadening and Compton scattering.

#### 3.1 Doppler Broadening

Doppler broadening through the thermal motion of the ions in the plasma will be of order ΔE/E ∼ (2kT/mc^2)^1/2, which for our values is typically 4 eV and so not significant. However, the infalling material will hit the accretion shock at a speed near the white dwarf escape velocity, which is 4000–16 000 km s^{-1} for white dwarfs of 0.5–1.4 M_{⊙}. The speed decreases by a factor of 4 in the shock (e.g. Frank, King & Raine 1992) so that the X-ray emitting plasma will have a bulk motion of 1000–4000 km s^{-1}. This would produce a Doppler shift of 20–90 eV. The projection of this onto the line of sight would depend on the geometry and would also vary with the white dwarf spin phase, so the observed values would be lower still. Further, we would not see emission with large blueshifts, since approaching material which was close to the surface would be hidden by the white dwarf. We might see blueshifted photons reflected towards us by the white dwarf, but these would be Compton down-scattered by an amount comparable to their blueshift (see next section). Thus, we expect Doppler broadening to have a signif-

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**Table 1.** The ASCA observations of MCVs. The time is the amount of good data after screening.

| Star   | Date     | Time (ks) |
|--------|----------|-----------|
| FO Aqr | 1993 May 20 | 35        |
| EX Hya | 1993 Jul 16 | 36        |
| AM Her | 1993 Sep 27 | 39        |
| BY Cam | 1994 Mar 11 | 48        |
| V1223 Sgr | 1994 Apr 24 | 59        |
| AO Psc | 1994 Jun 22 | 81        |
| TX Col | 1994 Oct 03 | 39        |
| PQ Gem | 1994 Nov 04 | 77        |
| GK Per | 1995 Feb 04 | 39        |
| TV Col | 1995 Feb 28 | 38        |
| XY Ari | 1995 Aug 06 | 34        |
| RX1712–24 | 1996 Mar 18 | 84        |
| BG CMi | 1996 Apr 14 | 82        |
| V405 Aur (0558+53) | 1996 Oct 05 | 74        |
| RX1238–38 | 1997 Jan 14 | 58        |
3.2 Compton scattering

Roughly half of the X-rays from the accretion column will be directed towards the white dwarf surface, and some will be reflected back towards us. Done, Osborne & Beardmore (1995) and Beardmore et al. (1995) find evidence for a reflection component in the X-ray continua of MCVs, and propose reflection from the white dwarf as the most likely cause of the 6.4 keV fluorescent emission seen in their data and in the tabulation of Table 2.

The reflected Kα photons will be Compton down-scattered by up to 2 Compton wavelengths, depending on the scattering angle (e.g. Rybicki & Lightman 1979; Done et al. 1995). Thus the 6.70 and 6.97 keV lines will develop wings extending for 170 eV to lower energies. These will have equivalent widths of ∼10 per cent of the incident line (e.g. Done et al. 1995). Thus, although the broadening is of the right magnitude to explain our results, and the 6.4 keV emission shows that it must be occurring, the inefficiency of reflection suggests that it would have a relatively small effect on the overall line profile. Further, if the line broadening were dominated by the reflection effect we might expect that systems with broad lines had stronger 6.41 keV emission, however Table 2 shows no such effect. Note, though, that the equivalent widths of the Kα lines are poorly understood, with smaller than expected fluxes indicating either an underabundance of iron or optically thick lines (Done et al. 1995).

We thus consider Compton scattering of the line photons within the accretion column. For photons from a point source scattered once by electrons in a surrounding ∼5 keV cloud the profile is broadened to Δσ/E ∼ (kT/m_e c^2)^(1/2) or ∼0.1 (e.g. Sunyaev 1980; Pozdnyakov, Sobol & Sunyaev 1983). Thus the broad lines could be explained if the column has an optical depth sufficient to scatter most of the photons once, but not so great that the lines are destroyed by multiple scattering. Resonant line trapping enables this, since the cross-section to resonant scattering of Kα photons is ∼450 times that of Thomson scattering at 5 keV (e.g. Pozdnyakov et al. 1983; Matt, Brandt & Fabian 1996). Thus if the continuum is optically thin, the Kα photons in the line core can be resonantly trapped, but will escape immediately once they are Compton scattered out of the core. For continuum optical depths of 0.05–0.2 ∼< τ < 1 almost all photons will be Compton scattered once and only once (Illarionov et al. 1979; Pozdnyakov et al. 1983).

For comparison we expect an accretion column to have a dense, optically-thick base at a temperature <1 keV. It decreases in density and optical depth while increasing in temperature as one moves up the column to an optically thin ∼20 keV accretion shock (e.g. Aizu 1973; Frank et al. 1992). We can therefore envisage several regimes in the column: the optically thin base produces no line emission; at continuum optical depths of ∼0.1–1 the line photons emerge with a singly-scattered profile characteristic of the local temperature; higher up the column the Compton-scattered component drops to insignificance once the column becomes optically thin in the line core, and from here upwards the line emission is narrow.

The temperatures at which these transitions occur are poorly known, but could account for the difference in line widths in different systems. If the τ = 0.1–1 regime occurs where the plasma is sufficiently hot to emit Kα photons (∼3 keV) we would expect the broadened lines from this region to dominate the Kα profile. Superimposed on it would be weaker, narrow emission from the less dense, optically thin region, which would reduce the overall width of the observed profile. If, in contrast, the transition from optical thickness occurs at a lower temperature (∼3 keV), so that regions hot

| Star          | Equivalent widths (eV) | Thermal line width (σ in eV) | SIS-1 res |
|--------------|------------------------|-----------------------------|-----------|
|              | 6.41 keV | 6.70 keV | 6.97 keV | Min | Best | Max | χ^2 | (ν ∼ 300) |
| X405 Aur     | 65 ± 25 | 380 ± 60 | 0 ±40 | 300 | 450 | 530 | 0.95 | 110 |
| PQ Gem       | 100 ± 30 | 500 ±50 | 120 ±150 | 190 | 330 | 620 | 0.98 | 87 |
| AO Pac       | 100 ± 40 | 220 ±90 | 100 ±40 | 180 | 250 | 280 | 1.06 | 81 |
| BG CMi       | 95 ± 30 | 0 ±40 | 300 ±70 | 175 | 230 | 332 | 1.02 | 105 |
| RX1712–24    | 65 ± 20 | 160 ±40 | 85 ±30 | 170 | 220 | 260 | 0.91 | 104 |
| TV Col       | 70 ± 30 | 170 ±70 | 175 ±50 | 150 | 200 | 250 | 0.96 | 91 |
| RX 1238–38   | 0 ±70 | 260 ±60 | 120 ±75 | 100 | 160 | 210 | 1.06 | 114 |
| EX Hya       | 10 ±12 | 390 ±25 | 110 ±15 | 54 | 62 | 80 | 1.00 | 65 |
| AM Her       | 145 ±15 | 175 ±20 | 180 ±20 | 53 | 67 | 88 | 1.07 | 69 |
| FO Aqr       | 140 ±20 | 90 ±20 | 85 ±20 | 30 | 55 | 85 | 1.07 | 62 |
| XY Ari       | 10 ±25 | 230 ±45 | 0 ±15 | 0 | 44 | 95 | 0.95 | 97 |
| V1223 Sgr    | 105 ±10 | 75 ±10 | 80 ±10 | 0 | 34 | 58 | 1.04 | 78 |
| TX Col       | 100 ±40 | 150 ±50 | 70 ±55 | 0 | 0 | 100 | 0.97 | 85 |
| GK Per       | 50 ±20 | 70 ±25 | 0 ±20 | 0 | 0 | 86 | 0.90 | 90 |
| BY Cam       | 100 ±20 | 70 ±20 | 130 ±35 | 0 | 0 | 69 | 0.99 | 76 |

Table 2. Widths and equivalent widths of Kα iron lines in magnetic cataclysmic variables. The maximum, minimum and error values are 1-σ limits. The last column gives the nominal resolution of the SIS-1 detector at 6.5 keV at the time of each observation (that for the SIS-0 is marginally better).
enough to emit Kα are all optically thin in the continuum, we would expect to see narrow lines.

In principle one could use the measured line widths to deduce the temperatures of these transitions in each object. However, apart from the limitations of the data, this requires simulations of Compton-scattered profiles summing over the range of temperatures, densities and optical depths in an accretion column model (e.g. Aizu 1973), rather than the current single-temperature simulations (e.g. Pozdnyakov et al. 1983). Further, published simulations concentrate the source photons into a point, rather than distributing them through the column, a difference shown to be substantial by Sunyaev & Titarchuk (1980). The addition of optically thinner regions in the outer parts and higher up the column would help to reduce the theoretical broadening of $\Delta E/E \sim 0.1$ at 5 keV (e.g. Sunyaev 1980) to the observed $\Delta E/E \sim 0.04$ in our data.

A last complication is the shape of the accretion column, expected to have an arc-shaped footprint and to extend vertically, and its varying projection onto the line of sight. The line photons will escape preferentially in the direction of least scattering depth (e.g. Swank, Fabian & Ross 1984) causing line flux changes as the white dwarf spins. Further, changes in the line-of-sight optical depth round the spin cycle could cause the temperature which corresponds to an optical depth of $\sim 1$ to vary, and so produce phase-dependent changes in the observed line widths. These would be undetectable in current data, through lack of photons, but are worth looking for with future missions.

4 DISCUSSION AND CONCLUSIONS

From the above discussion we conclude that the broad Kα iron lines found in roughly half of the MCVs studied are caused by a mixture of Doppler broadening due to radial infall, Compton down-shifted line emission from a reflected component, and, probably most importantly, Compton scat-
tering of the line emission in the accretion column. A significant optical depth to scattering in the column may also be required to explain the line fluxes (e.g. Swank et al. 1984; Done et al. 1995).

We have suggested that the broadening originates in the transition region between optical thickness and optical thinness; that systems in which this transition occurs at a temperature too low for significant Kα emission have narrow lines; and that systems with broad lines must have regions of column which are still optically thick at a higher temperature (> 3 keV).

We can test this by comparison with other work, taking the well studied stars EX Hya, as an example of a system with narrow lines, and AO Psc, the system with the clearest line broadening. In EX Hya the presence of lines of elements with a lower ionization than iron implies a transition to optical thickness at < 1 keV (Fujimoto & Ishida 1997). In AO Psc the line ratios imply a higher temperature transition [Fujimoto & Ishida (1995) quote < 3 keV, although this estimate is less certain due to the weaker lines] in agreement with the above reasoning.

Further, we can detect optical thickness in the accretion column by looking at changes in the X-ray continuum as the white dwarf spins. From spin-resolved ASCA spectroscopy of AO Psc, Hellier et al. (1996) found that the column contained several phases of absorption. The densest, affecting regions of the column emitting at energies of at least 8 keV, requires an electron scattering column which would not show a counterpart of the white dwarf surface (Hellier et al. 1996), values which are in line with current estimates for intermediate polars (e.g. Patterson 1994; Hellier 1997). In contrast, EX Hya shows much less absorption, and in ASCA data has no spin modulation above 6 keV (Ishida, Mukai & Osborne 1994; Allan, Hellier & Beardmore 1998), implying that it is optically thin throughout the hard X-ray emitting regions.

We can extend this difference into a test of our explanation, and predict that the other systems with clearly narrow lines, such as V1223 Sgr, will also be optically thin in the hard X-ray emitting regions. Thus spin-resolved spectroscopy with ASCA would not show a counterpart of the very dense absorber revealed in AO Psc. Unfortunately the test isn’t clear cut since we need to distinguish between a flux reduction caused by an optically thick accretion column, and a flux reduction caused by emitting regions passing over the limb of the white dwarf. However, at any one pole, occultation effects and absorption effects are likely to occur in anti-phase in MCVs (e.g. Hellier, Cropper & Mason 1991) allowing the test to be performed given ASCA-quality spectroscopy and an understanding of the spin pulse in each system. Analysis of X-ray spectroscopy of other MCVs is thus needed to confirm these ideas.

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