Compton-scattered line profiles from cataclysmic variable accretion columns

Coel Hellier
Department of Physics, Keele University, Keele, Staffordshire, ST5 5BG, U.K.

J. P. Osborne
Department of Physics and Astronomy, University of Leicester, Leicester LE1 7RH, U.K.

Koji Mukai
Laboratory for High Energy Astrophysics, Code 660.1, NASA/GSFC, Greenbelt, MD 20771, USA

ABSTRACT

We find that in half of the magnetic cataclysmic variables observed with *ASCA* the iron Kα lines are broadened by more than can be accounted for by Doppler shifts. We suggest that this can be explained by Compton scattering of resonantly-trapped line photons in emission regions on the verge of optical thickness. Comparing Compton-broadened profiles from different systems could be a valuable probe of accretion columns.

1. Introduction and Data

ASCA is the first X-ray satellite able to resolve the 6.7-keV iron line complex into separate lines arising from different ionization states. In observing magnetic cataclysmic variables with *ASCA*, however, we found that in some systems the 6.97-keV line from hydrogen-like iron and the 6.70-keV line from helium-like iron are merged together, implying significant broadening. We have now looked for this effect in a sample of 15 magnetic CVs. The results have been reported in Hellier, Mukai & Osborne (1998) and are summarised here.

Table 1 records the observed widths of the thermal lines (6.70 & 6.97 keV) in the *ASCA* SIS data. Roughly half of the systems show significant broadening by a few hundred eV while the rest don't. The contrast between systems with narrow lines and those with broadened thermal lines is illustrated in Fig. 1.

2. Interpretation

Although Doppler broadening due to bulk motion will have a significant effect on the line profiles, it is insufficient to explain our results. This is because the free-falling material slows by a factor 4 in the stand-off shock above the white dwarf surface. Coupled with a further reduction for projection onto the line-of-sight, and the fact that any blue-shifted emission will be hidden from

Table 1: Widths and equivalent widths of Kα iron lines in magnetic cataclysmic variables. The maximum, minimum and error values are 1-σ limits.

Star	Equivalent widths (eV)			Thermal line width (σ in eV)			χ^2_ν
	6.41 keV	6.70 keV	6.97 keV	Min	Best	Max	($\nu \sim 300$)
V405 Aur	65 ± 25	380 ± 60	0^{+40}	300	450	530	0.95
PQ Gem	100 ± 30	50^{+90}_{-50}	120^{+150}_{-120}	190	330	620	0.98
AO Psc	100 ± 40	220 ± 90	100 ± 40	180	250	280	1.06
BG CMi	95 ± 30	0^{+40}	300 ± 70	175	230	332	1.02
RX 1712–24	65 ± 20	160 ± 40	85 ± 30	170	220	260	0.91
TV Col	70 ± 30	170 ± 70	175 ± 50	150	200	250	0.96
RX 1238–38	0^{+70}	260 ± 60	120 ± 75	100	160	210	1.06
EX Hya	10^{+12}_{-7}	390 ± 25	110 ± 15	54	62	80	1.00
AM Her	145 ± 15	175 ± 20	180 ± 20	53	67	88	1.07
FO Aqr	140 ± 20	90 ± 20	85 ± 20	30	55	85	1.07
XY Ari	10^{+25}_{-10}	230 ± 45	0^{+15}	0	44	95	0.95
V1223 Sgr	105 ± 10	75 ± 10	80 ± 10	0	34	58	1.04
TX Col	100 ± 40	150 ± 50	70 ± 55	0	0	100	0.97
GK Per	50 ± 20	70 ± 25	0^{+20}	0	0	86	0.90
BY Cam	100 ± 20	70 ± 20	130 ± 35	0	0	69	0.99

us by the white dwarf, this means that Doppler broadening can only be at most $\sim$50 eV. The thermal broadening at these temperatures is only $\sim$4 eV.

Thus we turn to Compton scattering to explain our results. Some of the Kα photons will be reflected towards us by the white dwarf surface, and these will be Compton down-scattered by up to 2 Compton wavelengths, or $\sim$ 170 eV. However such photons will amount to only $\sim$10% of the line (e.g. Done, Osborne & Beardmore 1995) and so this effect is also insufficient to explain our findings.

A single Compton scattering within the post-shock accretion column itself, though, can broaden lines by $\Delta E/E \sim 0.1$ (e.g. Sunyaev 1980). This explains our data provided that the lines emerge predominantly singly scattered. Resonant trapping of Kα photons enables this since the cross-section to resonant scattering of Kα photons is $\sim$450 times that of Thomson scattering at 5 keV (e.g. Pozdnyakov et al. 1983; Matt, Brandt & Fabian 1996). Thus if the continuum

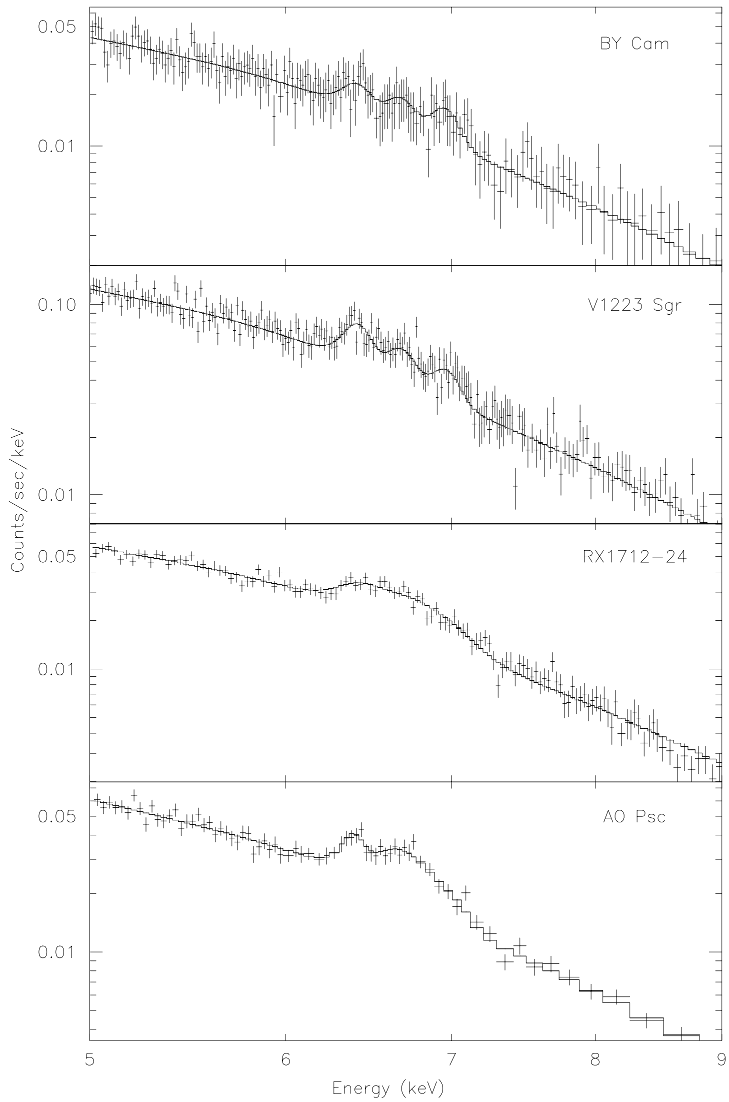

Fig. 1.— The SIS spectra of 4 MCVs, the upper two showing narrow emission at 6.41, 6.70 & 6.97 keV, and the lower two showing broad thermal lines. Fitted parameters are in Table 1.

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 in the range 0.05–0.2 $\lesssim \tau \lesssim 1$ almost all photons will be Compton scattered once and only once (Illarionov et al. 1979; Pozdnyakov et al. 1983).

Thus we can envisage several regions to an accretion column, as illustrated in Fig. 2. Immediately below the shock, the low-density, highly-ionized, optically-thin material will emit little Kα emission, but the little that emerges will be narrow. At the column base, the cooler,

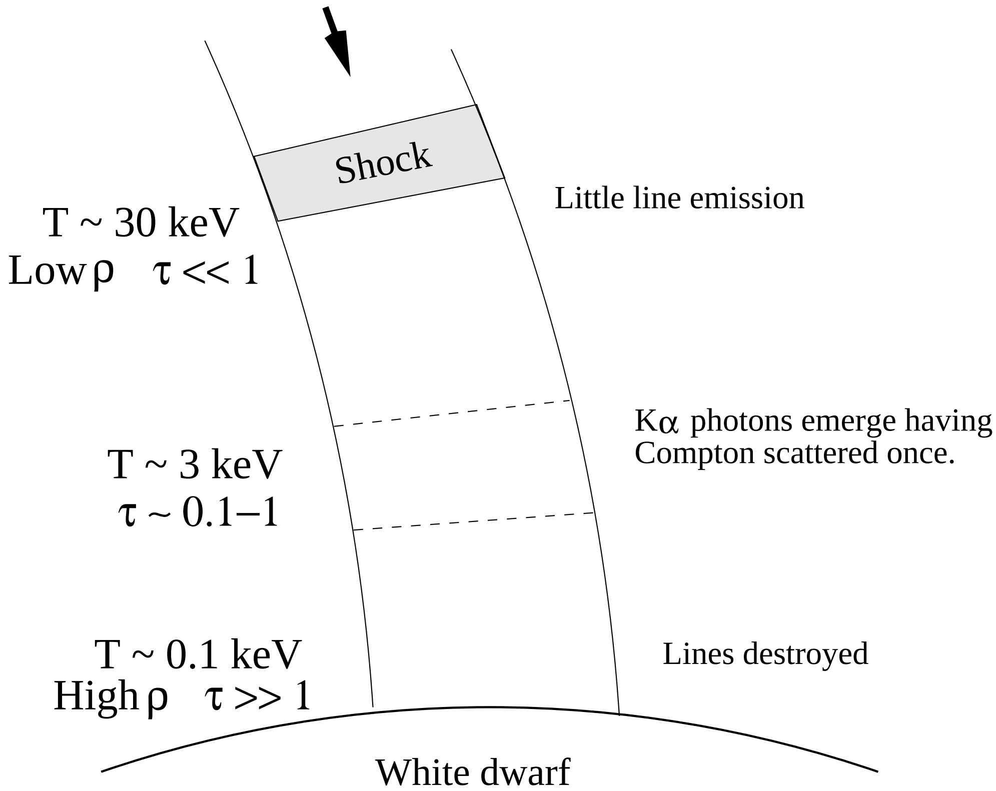

Fig. 2.— An schematic illustration of the accretion column in a magnetic cataclysmic variable.

denser material will be optically thick and any lines will be destroyed by multiple scatterings. The transition region of $\tau \sim 0.1$–1 will produce broadened singly-scattered lines. Since this region is the coolest and densest of the regions from which we see line emission, the broad lines from here will dominate the overall profile (although this needs to be confirmed by a fuller calculation of the line profiles from a column, including the stratification in temperature and density).

We note that analysis of how the X-ray continuum changes over the spin cycle in some magnetic CVs also indicates an electron column density sufficient to produce a Thompson depth of a few (e.g. Hellier et al. 1996 on AO Psc), which is consistent with the above.

If our interpretation is correct, we can proceed to suggest why some magnetic CVs have broadened lines while others show narrow lines. If the transition to optical thickness in an accretion column occurs at a low enough temperature that little Kα emission arises from the transition region, the lines will be from optically thin regions only, and will thus be narrow (this would be the case in stars such as V1223 Sgr). Where the transition region is hotter (>3 keV) broad lines will be seen (explaining stars such as AO Psc).

Thus we can look forward to Compton-scattered Kα profiles providing a probe of temperatures and densities in accretion columns of magnetic CVs. We can also test this whole picture by linking it to studies of the X-ray pulse profiles in different systems, which give complementary insights into conditions within accretion columns.

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