THE HARD X-RAY SPECTRA OF EF ERI AND OTHER CVS

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Abstract. Reflection of the X-ray emission from the surface of the white dwarf should be present in all hard X-ray emitting CV systems. It is clearly identified in the Ginga 2...20 keV spectra of the polars AM Her and EF Eri, and also in the quiescent spectra of the dwarf novae SS Cyg. The inclusion of the hard reflection spectrum lowers the derived continuum temperature, so resolving a long standing problem of the mismatch of the iron line and continuum properties, and, with more realistic multi–temperature continuua, the derived shock temperatures are close to those expected from theoretical models of a strong shock.

1. The hard X-ray spectra of CVs

The AM Her systems, or polars (Cropper 1990), of which EF Eri is a long established example, are binary systems in which a low mass star overflows its Roche lobe onto a magnetised white dwarf companion. The flow is entrained by the magnetic field before it reaches the circularization radius, and thus falls freely through the entire gravitational potential without forming an accretion disk. If the accretion stream shocks above the surface of the white dwarf then all the gravitational energy is released as bremsstrahlung emission (optically thin thermal radiation), with a predicted shock temperature of $kT = 31\, M_{\rm wd}/\, {\rm M}_\odot$ keV, i.e. producing hard X-rays (see e.g. Frank, King & Raine 1992). Since the plasma contains heavy elements, this hot gas produces X-ray line emission as well as continuum. At high temperatures the most important lines are from iron, either at 6.7 keV (from Fe^{+24}, He–like) and/or 6.9 keV (Fe^{+25}, H–like).

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The polars are generally faint, hard X-ray sources so detailed spectral studies are generally not possible. However, the compilation of polar spectra from the Ginga X-ray satellite (2...20 keV) showed that, while the spectra are generally well fit by a single temperature thermal bremsstrahlung continuum with $kT \sim 10 - 30\,\mathrm{keV}$, the iron line emission is at systematically lower energies and higher intensity than predicted by the continuum temperature (Ishida 1991).

Since the hard X-ray emission is expected to be isotropic, this spectrum *must* illuminate the white dwarf surface, and some fraction is reflected back towards the observer. The reflection probability is energy dependent, as at low energies there are many elements on the white dwarf surface that can photoelectrically absorb the incident photon. For example, photons below 1 keV can be absorbed by the K shell of carbon, nitrogen, oxygen etc., thus the reflection probability is small at these energies. However, at higher energies, these low atomic number elements have very little cross section and only high Z elements can contribute to the photoelectric cross section. But these are generally not very abundant, so the total absorption probability decreases and hence the reflected fraction increases. Iron is the last abundant high Z element, so leading to a pronounced feature at the iron K edge, energy in the reflected spectrum and an associated Fe $K\alpha$ fluorescence line at 6.4 keV from the cool reflecting material, i.e. distinct from the more highly ionised lines from the hot plasma. Thus the reflected continuum spectrum is harder than the incident spectrum in the 2...20 keV Ginga range, with an iron Kα fluorescence line superimposed on it. The dependence on photoelectric absorption also means that the reflected spectrum is a function of the ionisation state of the gas (the more the reflector is ionised, the fewer bound electrons are left to provide absorption opacity and so the larger the reflected fraction), its elemental abundance (higher abundance gives more absorption opacity and hence less reflection); see e.g Lightman & White (1988), George & Fabian (1991), Matt, Perola & Piro (1991). The amount of reflection also depends strongly on geometry, both on the solid angle subtended by the reflecting material to the hard X-ray source (the higher the solid angle, the higher the relative normalisation of the reflected continuum with respect to the incident spectrum) and also the inclination of the reflecting region with respect to the observer (the higher the inclination, the longer the path length through the white dwarf photosphere the reflected photon has to travel before escaping, and so the higher its absorption probability and hence the lower its reflected fraction); see e.g. George & Fabian (1991), Matt, Perola & Piro (1991).

The signature of reflection can be clearly seen in the Ginga 2...20 keV hard X-ray spectra of AM Her and EF Eri (Beardmore et al. 1995; Done, Osborne & Beardmore 1995). With a single temperature plasma and com-

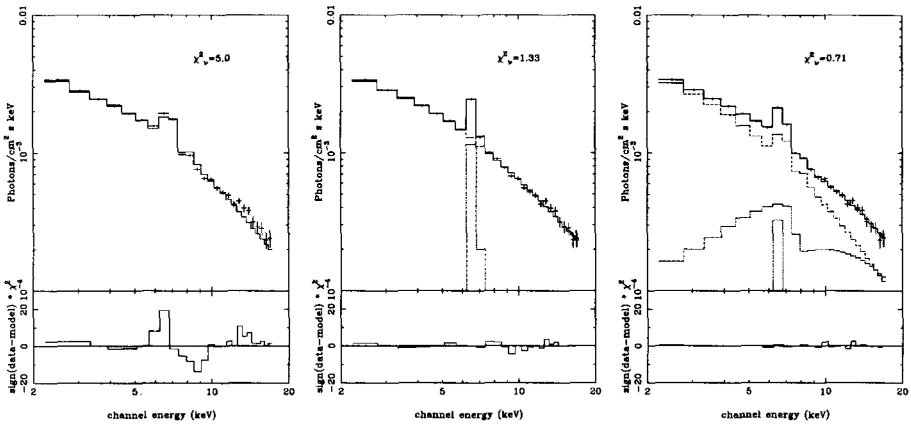

Figure 1. Spectra and residuals to data from AM Her at X-ray maximum. From left to right the model is (a) an optically thin thermal plasma (includes continuum and self consistent line emission); (b) optically thin thermal bremsstrahlung and arbitrary line emission; (c) an optically thin thermal plasma and its reflection spectrum.

plex absorption the resulting fit is unacceptable, as shown in Fig. 1a, with a $\chi^2_\nu = 5$ (for a temperature of 14.5 keV and best fit abundance of solar). The problem derives again from a mismatch between the line properties and continuum temperature. Fig. 1b shows the results from fitting a bremsstrahlung continuum, together with arbitrary Gaussian line emission and complex absorption. This is statistically (just) acceptable, with $\chi^2_\nu = 1.3$ for a temperature of 21 keV, line energy of 6.7 keV and equivalent width 640 eV. However, in a plasma at 21 keV, much of the iron will be completely ionised, and the little that remains will have just 1 electron (H–like), which gives a line energy of 6.9 keV, and with solar abundances this should have an equivalent width of 420 eV. Fig. 1c shows the significant improvement in the fit ($\chi^2_\nu = 0.71$) from a single temperature plasma model that results from inclusion of the reflected spectrum and its associated 6.4 keV fluoresence line emission. As reflection is a hard spectral component, its inclusion means that not all the high energy photons have to be produced from the intrinsic continuum spectrum, leading to a marked decrease in the derived plasma temperature, ~ 12 keV, compared to the ~ 21 keV required in the bremsstrahlung fits. This in turn leads to a prediction of a lower iron line energy and a higher iron line intensity, matching the observed trend in these objects.

A similar set of plots for EF Eri again show that reflection is significantly detected in the spectrum (see Done, Osborne & Beardmore 1995), but that here the iron line both from the hot plasma and that associated with the reflection continuum are smaller by a factor 2 than those seen in AM Her. The plasma codes used to model the spectra are produced in the coronal approximation, which almost certainly does not hold for these objects (Done, Osborne & Beardmore 1995). In particular, the iron lines from the hot plasma are probably optically thick and so will be scattered many times before escaping. However, as there seems to be no viable alternative decay path for the Lyα transition which produces the lines then it is difficult to see how the lines can be suppressed. Also, the 6.4 keV fluoresence line from the reflection spectrum cannot be affected by the hot plasma line (6.7 and 6.9 keV) optical depth effects, so the only explanation seems to be a true underabundance of iron in this system.

While the inclusion of reflection is extremely successful in obtaining a good fit to the spectrum, the derived continuum temperature of $\sim$ 10 keV is much lower than the 31 $M_{\rm wd}/\,{\rm M}_\odot$ keV predicted by the simple strong shock models. However, we also do not expect the continuum to be described by a single temperature. The material must cool as it settles from the shock to the white dwarf photosphere, so the expected spectrum is a density weighted sum of multiple temperature hot plasma spectra. This can be modeled simply by assuming that the bremsstrahlung cooling is dominant and that the pressure and gravitational potential remain constant throughout the cooling structure (Done, Osborne & Beardmore 1995). These cooling spectra give very similar line and continuum emission to a single temperature 10 keV plasma when the maximum shock temperature is of order 25 keV, matching well with that expected from a solar mass white dwarf.

Of course, reflection is not limited to one particular type of object. The dwarf nova SS Cyg produces hard X-rays in quiescence. Fitting this spectrum with a single temperature plasma results in a very poor fit ($\chi^2_\nu =$ 2.7 for kT = 15 keV). Including a second temperature component, as is often suggested (see e.g. Nousek et al. 1994), does not help substantially, with $\chi^2_\nu = 2.0$ for 7.5 keV and 60 keV components, but a single temperature plasma and its reflection give an excellent fit to the data (χ^2_ν = 1.0 for kT = 10 keV).

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