Ten Years of Intermediate Polar X-ray Light Curve Interpretation

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Abstract. X-ray light curves provide some of the best clues to understanding the accretion and emission processes in intermediate polars (IPs). In particular, the spin-folded data contain a wealth of information about the location and shape of the accretion and emission regions, the method by which the accretion occurs, and other physical parameters of the system. The problem is one of interpreting the light curves in order to discover these parameters.

About 10 years ago, the first attempts were made to do this, assuming the modulation to be caused entirely by self occultation of the emission region by the white dwarf. With the advent of energy resolved pulse profiles obtained using EXOSAT, it became clear that photoelectric absorption played a major part in shaping the profiles too. Interpretations based around the idea of ‘accretion curtains’ were then proposed. Higher quality Ginga and ROSAT data have more recently thrown up further complications. Firstly, not all the pulse profiles are roughly sinusoidal. This indicates that there must be some asymmetry in the system, either between the properties of the polar emitting regions, or between their shape, size or location. Secondly, some systems show evidence for modulation at the ‘beat period’ between the spin and orbit. This indicates that some of the accretion flow does not pass through the accretion disc, but attaches to the field lines directly.

Any attempt to determine system parameters from the X-ray pulse profiles must take these factors into account. Therefore, ‘fitting’ or ‘modelling’ the light curves is a complicated procedure, but nevertheless offers some of the best hope for resolving many of the unanswered questions about IPs.

1. Early Ideas

The first attempt at interpreting the X-ray light curves of IPs was presented by King & Shaviv (1984). Their so called ‘occultation model’ suggested that the spin modulation seen was due to self-occultation of the emission area by the white dwarf. Hence, as the magnetic pole disappears over the limb of the white dwarf, so the X-ray flux decreases. At the time of this suggestion, there was little or no evidence for any energy dependence in the pulse profiles seen, so the model was adequate. Pulse profiles that were either sinusoidal, flat-topped,
flat-bottomed or square-wave could be produced. The profile shape depended on just three parameters: the fractional area occupied by the emission region, the system inclination angle and the magnetic axis offset angle. Two restrictions of the model, however, were that it assumed the emission region to be circular, centred on the magnetic pole, and that only one pole was visible, or accreting, at any time.

2. **EXOSAT data**

EXOSAT observed eight confirmed IPs between July 1983 and November 1985, most on at least two occasions. It soon became clear that the pulse profiles of these objects (GK Per, FO Aqr, TV Col, TX Col, V1223 Sgr, BG CMi, AO Psc and EX Hya) had certain similarities (Mason 1985, Watson 1986, Norton & Watson 1989). Firstly, all the pulse profiles were roughly sinusoidal in shape, and secondly the modulation depth decreased with increasing energy (over the range 1–10 keV) in each case. This clearly indicated that photoelectric absorption made some contribution to the observed modulation and ruled out the occultation model in its simplest form.

However, Norton & Watson (1989) noted that the rate of change of modulation depth with energy could not be accounted for by a single absorbing column. For example, modelling the low energy modulation in terms of a phase varying column density resulted in a predicted modulation depth at higher energies that was far too small. It was also noted that the X-ray spectra of these objects were also often poorly fit with a single absorbing column. In order to reconcile these observations it was suggested that there may be a partial, or patchy, absorbing structure and that occultation also contributed to the modulation, in phase with the photoelectric absorption.

A simple picture of the accretion column as a filled cylinder led to expressions for the optical depth perpendicular to \( \tau_v \) and parallel to \( \tau_h \) the surface of the white dwarf (Fabian, Pringle & Rees 1976, King & Shaviv 1984). In this picture, \( \tau_h < \tau_v \) unless the accreting fraction is greater than about 9% of the surface area of the white dwarf. Hence, for small accretion regions, occultation and absorption will act out of phase at a single pole, and only for large accretion regions will occultation and absorption act in phase at a single pole. This led Norton & Watson (1989) to suggest the so called ‘large polecap model’ to explain the EXOSAT data.

Although this adequately modelled the existing X-ray data at the time, I don’t believe it now and suspect that the true situation is far more complicated!

3. **Accretion Curtains**

Around the same time as the work discussed above, the so called ‘accretion curtain’ model was first proposed to explain the EXOSAT data from EX Hya (Rosen, Mason & Córdova 1988) and later the Ginga data as well (Rosen et al. 1991). In this model, the emission region was a tall, thin, arc-shaped curtain whose footprint occupied only a very small fraction of the white dwarf surface. Emission from two sites, both above and below the orbital plane, was included, and these sites were assumed to be raised above the surface so that only the
lower site was occulted by the white dwarf. The inner edge of an accretion disc absorbed the low energy X-rays from the lower pole, and phase varying absorption at the upper pole gave rise to the modulation. At higher energies, an asymmetry between the two poles was invoked to allow the two sites to combine to give a net modulation. Clearly, quite a complex model was required to explain the available data, even at this time. Such a model was also later applied to the EXOSAT data from AO Psc by Hellier, Cropper & Mason (1991).

4. Ginga and ROSAT data

Ginga and ROSAT have each observed many IPs, producing light curves with extremely high signal-to-noise in many cases, and the spin pulse profiles continue to throw up more complications. Whilst the pulse profiles of some sources, such as EX Hya (Rosen et al. 1991) still appear roughly sinusoidal there are indications that additional structure may be present in others. For example, the combined ROSAT and Ginga pulse profiles of AO Psc and V1223 Sgr (Figures 1 and 2) show evidence for a small notch superimposed on the peak of the pulse. In AO Psc it occurs just after phase zero and in V1223 Sgr the notch occurs just before phase zero. At least two objects, GK Per and XY Ari (H0253+193), show pulse profiles that are double peaked (Ishida et al. 1992, Kamata & Koyama 1993 respectively) indicating still more complicated behaviour.

Some of the most complex pulse profiles are those seen from FO Aqr, BG CMi and PQ Gem (RE0751+14) as reported by Norton et al. (1992a,
Figure 2. The combined ROSAT and Ginga pulse profiles of V1223 Sgr shown in six independent energy bands

1992b) and Duck et al. (1994) respectively. FO Aqr clearly shows a narrow notch superimposed on a broadly sinusoidal modulation, with a pulse profile that changes dramatically as a function of orbital phase. BG CMi also shows a variation of profile shape at different orbital phases and a similarly complex pulse. Perhaps the most intriguing of all is the newly discovered soft X-ray source PQ Gem. The notch seen here in the lowest energy band is extremely narrow and the profile has a different shape in different energy bands.

5. Further Complications

Another complication hiding in the X-ray data is the existence of strong ‘beat’ periods in the X-ray power spectra of some IPs. (The beat period is the spin period of the white dwarf in the reference frame of the binary.) EXOSAT had already revealed a strong beat period signal in TX Col and weaker signals in AO Psc and V1223 Sgr (Hellier 1992). Ginga revealed a strong beat period signal in FO Aqr (Norton et al. 1992a) and (possibly) a dominant beat period in BG CMi (Norton et al. 1992b).

The observation of a strong X-ray signal at the beat period implies that accretion does not arise exclusively from an accretion disc. If it did, all ‘knowledge’ of the orbital period would be lost to the accreting material and there is no possibility of beat period modulations. The most likely explanation for this is that accretion occurs via some form of ‘non-accretion disc’ or ‘disc overflow’
(e.g. King & Lasota 1991) and hence some of the accretion occurs directly from an accretion stream, as in polars.

It is likely that the footprints of the field lines onto which the disc-fed accretion attaches are semi-circular X-ray emitting arcs around each magnetic pole, and are fixed on the surface of the white dwarf. By contrast, the field lines to which the stream-fed accretion attaches are likely to have smaller footprints at each magnetic pole and these will ‘migrate’ around the pole to follow the incoming stream, as a function of the beat phase. This will naturally give rise to an X-ray modulation at the beat period as well as at the spin period.

6. Orbital Modulations

It should also be noted that IPs frequently show strong orbital modulations in their X-ray light curves. The compilation by Hellier et al. (1993) of EXOSAT data showed that FO Aqr, EX Hya, BG CMi and AO Psc all have orbital dips characterised by increased photoelectric absorption around orbital phase 0.8. They concluded that the cause was likely to be similar to that in low mass X-ray binaries and due to material thrown out of the orbital plane by the stream impact with the disc or the magnetosphere.

Alternatively, or additionally, a spin pulse profile that varies with orbital phase (such as will arise naturally in a stream-fed or disc-overflow model) will naturally give rise to an orbital modulation. It is likely that this effect contributes to the observed orbital modulation, at least in some systems.

7. Realistic Models for the X-ray Light Curves

So what are the likely contributors to the X-ray light curve modulations seen in IPs? Almost certainly, there are many contributing factors and some of these are listed below, classified according to their nature.

- Geometric factors
  - Occultation of emission regions by the white dwarf
  - Different sizes and shapes of emission regions at the upper and lower magnetic poles
  - Offset dipoles and multiple magnetic poles
  - Occultation of the lower pole by the inner edge of a disc

- Absorption effects
  - Phase varying optical depth due to the changing aspect angle of the emission regions and accretion curtain
  - Multiple column densities and/or patchy absorbers due to a ‘blobby’ accretion flow
  - Absorption at a site fixed in the orbital frame due to material thrown out of the plane by stream impact with disk or magnetosphere
• Accretion effects
  – A combination of disc-fed and stream-fed accretion
  – Variation in the accretion rate of the stream-fed portion as a function of beat phase
  – Variation in the accretion rate as a function of azimuth around the accretion curtains
  – Random changes in the mass accretion rate

• Spectral factors
  – Multiple emission components of different temperatures at different heights in the accretion curtain
  – Possible reflection components and blackbody components
  – Hot spots or multiple regions with different emission characteristics

Some first attempts at modelling the light curves by taking into account many of these features have been presented by Wynn & King (1992), Norton (1993) and Taylor et al. (this conference).

8. Conclusions

Any interpretation of the X-ray light curves of IPs must be reflected in a plausible physical model. It is no good to say simply that some portion of the pulse profile is due to absorption whilst another feature is due to occultation – the time has come for detailed modelling of the light curves. Conversely, any model for IPs must be able to reproduce the spin, beat and orbital behaviour that is seen in the X-ray light curves. The ‘true’ interpretation of these X-ray light curves and the model for their production may well be very complicated.

References

Watson, M.G. 1986, Lec. Notes in Physics, 266, 97