Are the INTEGRAL Intermediate Polars Different?

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Are the *INTEGRAL* Intermediate Polars Different?

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Abstract. One of the biggest surprises of the *INTEGRAL* mission was the detection of large numbers of magnetic cataclysmic variables – in particular the intermediate polar (IP) subclass. Not only have many previously known systems been detected, but many new ones have also been found and subsequently classified from optical follow-up observations, increasing the sample of IPs by $\sim 15\%$. We have recently been using a particle hydrodynamic code to investigate the accretion flows of IPs and determine the equilibrium spin-rates and accretion flow patterns across a wide range of orbital periods, mass ratios and magnetic field strengths. We use the results of these accretion flow simulations to examine whether the *INTEGRAL* IPs differ from the overall population and conclude that they do not. Most IPs are likely to be *INTEGRAL* sources, given sufficient exposure. Currently however, none of the 'EX Hya-like' IPs, with large spin-to-orbital period ratios and short orbital periods, are detected by *INTEGRAL*. If this continues to be the case once the whole sky has a comparable *INTEGRAL* exposure, it may indicate that the ring-like mode of accretion which we demonstrate occurs in these systems is responsible for their different appearance.

1. Magnetic Cataclysmic Variables

Magnetic cataclysmic variables (mCVs) consist of a magnetic white dwarf accreting material via Roche lobe overflow from a late type, usually main sequence, donor star (for a comprehensive review see Warner 1995). Two subcategories are recognised. In polars, the magnetic fields of the two stars interact to synchronize the rotation period of the white dwarf to the orbital period of the binary. Furthermore, the accreting plasma attaches to the white dwarf's magnetic field immediately on leaving the inner Lagrangian point, and follows a stream-like trajectory down to the white dwarf's magnetic poles. Polars are characterized by polarized optical/infrared emission and X-ray emission modulated at the orbital period of the system, which is typically less than 4 hours.

In intermediate polars (IPs), the rotation period of the white dwarf is of order a few hundred to a few thousand seconds, and is less than the binary orbital period of typically a few hours. The nature of the accretion flow is uncertain, although in many cases a truncated accretion disc probably forms. At the inner edge of the disc, plasma attaches to the field lines and travels towards the white dwarf's magnetic poles, forming accretion curtains which stand above the white dwarf surface. As it accelerates towards the white dwarf surface, the material undergoes a strong shock, below which material settles onto the surface, cooling as it does so by the emission of optical/infrared cyclotron emission and hard X-ray bremsstrahlung. The white dwarf surface may also be heated directly, so giving rise to a soft X-ray blackbody component. The plasma settling onto the white dwarf surface in IPs is expected to have a characteristic temperature of $\approx 10^8$ K and so will give rise to a hard X-ray bremsstrahlung

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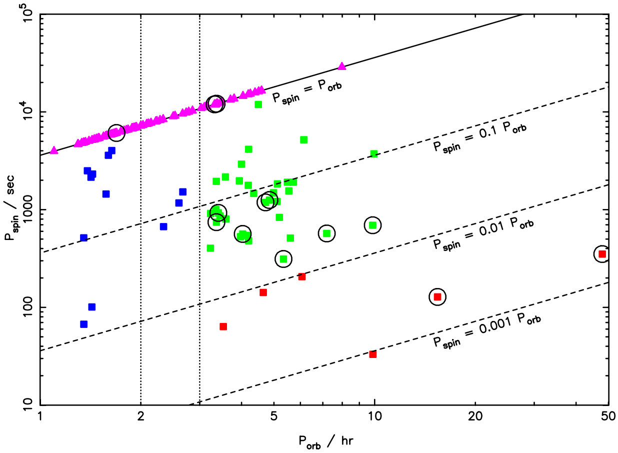

Figure 1. The spin periods and orbital periods of the known polars and intermediate polars. Those systems detected by *INTEGRAL* are shown circled.

component with a temperature of tens of keV. This has been confirmed for many years by studies of the medium energy (2–20 keV) X-ray spectra of IPs with, for example, *EXOSAT*, *Ginga*, *RXTE* and *XMM-Newton* (e.g. Norton & Watson 1989; Suleimanov et al. 2005; Evans & Hellier 2007). It should therefore come as no surprise that *INTEGRAL* detects IPs as hard X-ray sources in the 20–100 keV band. IPs *should be* significant hard X-ray sources.

2. *INTEGRAL* Detections of mCVs

In the third IBIS/ISGRI catalog (Bird et al. 2007), detections are reported of 10 confirmed IPs, 3 polars, and a further 7 candidate IPs. The 7 *INTEGRAL* sources identified as candidate IPs have been associated with previously known *ROSAT* sources, and optical counterparts to them have been identified whose spectra resemble other mCVs (Masetti et al. 2006). The IPs detected by *INTEGRAL* (Barlow et al. 2006) generally lie in directions for which the *INTEGRAL* exposure is around 10^6 s or higher, and consequently many of them lie close to the Galactic plane.

As may be seen from Figure 1, compared with polars, IPs occupy a wide range of parameter space in the spin period versus orbital period plane. However, the IPs so far detected by *INTEGRAL* lie largely amongst the 'typical' IPs with orbital periods greater than 3 hours and spin-to-orbital period ratios of $P_{\rm spin}/P_{\rm orb} \sim 0.01 - 0.1$.

3. Accretion Flows from the Magnetic Model

We use a particle hydrodynamic code known as HYDISC (see Norton, Wynn & Somerscales (2004) for details). This code utilises a simplified treatment of magnetic fields which is valid

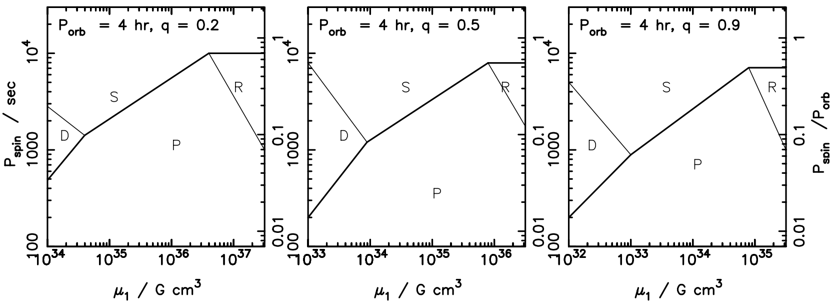

Figure 2. The accretion flow phase diagrams for an orbital period of 4 h and mass ratios of 0.2, 0.5 and 0.9. The regions in which disc-like, stream-like, propeller-like and ring-like flows occur are indicated.

throughout the flow, except for very close to the white dwarf itself. The parameterisation of the magnetic field strength is in terms of a 'drag parameter' which relates the magnetic acceleration to the relative velocity between the plasma and the field lines.

We used HYDISC to generate a grid of models for various combinations of orbital period (ranging from 80 min to 10 h), white dwarf spin period (from 100 s to the orbital period), mass ratio (0.2, 0.5 and 0.9) and white dwarf magnetic moment (from about 10^{32} G cm^3 to 10^{37} G cm^3). Each model was allowed to run to steady state before the resulting accretion flow was examined. A comprehensive analysis of the results presented in this section may be found in Norton et al. (2008), but in summary the models reveal that broadly four types of accretion flow are produced. These are: **propellers** in which most of the material transferred from the secondary star is magnetically propelled away from the system by the rapidly spinning magnetosphere of the white dwarf; **discs** in which most of the material forms a circulating flattened structure around the white dwarf, truncated at its inner edge by the white dwarf magnetosphere where material attaches to the magnetic field lines before accreting onto the white dwarf surface; **streams** in which most of the material latches onto the field lines immediately and follows these on a direct path down to the white dwarf; and **rings** in which most of the material forms a narrow annulus circling the white dwarf at the outer edge of its Roche lobe, with material stripped from its inner edge by the magnetic field lines before being channeled down to the white dwarf surface.

The regions of parameter space occupied by these flow types may be seen in Figure 2, where we show the white dwarf spin period versus magnetic moment plane corresponding to an orbital period of 4 h for mass ratios of 0.2, 0.5 and 0.9. As can be seen, there are two 'triple points' at which flows may exist that are a combination of either disc-like, stream-like and propeller-like accretion (the lower left triple point) or stream-like, ring-like and propeller-like accretion (the upper right triple point). For a mass ratio of 0.5 for instance, these triple points occur at $P_{\rm spin}/P_{\rm orb} \sim 0.1$ and ~ 0.6 respectively.

The equilibrium between spin-up and spin-down of the white dwarf lies at the boundary between disc/stream-like flows and ring/propeller-like flows. If a system finds itself in the upper part of the plane shown in Figure 2, the disc-like or stream-like flows will spin-up the white dwarf, so moving it vertically downwards in the plane towards the equilibrium line. Conversely, if a system finds itself in the lower part of the plane shown in Figure 2, the propeller-like or ring-like flows will spin-down the white dwarf, so moving it vertically upwards in the plane towards the equilibrium line.

Other orbital periods have similar phase diagrams to Figure 2, but with the following differences. The triple points at which disc-stream-propeller and stream-ring-propeller flows can co-exist shift to *smaller* magnetic moments and *shorter* spin periods as the orbital period *decreases*. However, the triple points exist at the *same* spin-to-orbital period ratio at all orbital periods, for a given mass ratio. As can be seen in Figure 2, the triple points shift to *larger* magnetic moments and *larger* spin-to-orbital period ratios as the mass ratio *decreases*.

We identify the lower left triple point with the condition that the co-rotation radius (i.e. that radius at which material would orbit the white dwarf with the same period as the white dwarf spins) is equal to the circularisation radius (i.e. that radius at which the specific angular momentum equals that of matter at the inner Lagrangian point). Theory then predicts (King & Wynn 1999) that $P_{\rm spin}/P_{\rm orb} \sim (1+q)^2\,(0.500 - 0.227\log q)^6$. Similarly we identify the upper right triple point with the condition that the corotation radius is equal to the distance from the white dwarf to the inner Lagrangian point. In this case, theory predicts that $P_{\rm spin}/P_{\rm orb} \sim (0.500 - 0.227\log q)^{3/2}$. The observed spin-to-orbital period ratios of the triple points from the various phase diagrams at different mass ratios are in very good agreement with these theoretical predictions. This gives strong support to our identification of the conditions which are satisfied at these locations in parameter space.

Many IPs cluster around $P_{\rm spin}/P_{\rm orb} \sim 0.05 - 0.15$ (Figure 1). This period ratio corresponds to the stream-disc-propeller triple point for plausible mass ratios. In contrast, the EX Hya-like IPs at an orbital period below 2 h with relatively large spin-to-orbital period ratios, probably display ring-like accretion. This conclusion has been supported by recent observational evidence from optical spectroscopy of EX Hya itself (Mhlahlo et al. 2007).

4. The Evolution of mCVs

In order to investigate how the accretion flows of IPs are likely to change as the systems evolve, we took a standard evolutionary sequence of a CV, starting at an orbital period of 9 hr with a mass ratio of 1.2 and evolving to an orbital period of 80 min with a mass ratio of 0.1. At hourly intervals along its evolutionary track we extracted its mass ratio and mass accretion rate. We then ran HYDISC models with these parameters at each orbital period step for a range of three white dwarf magnetic field strengths: 60 MG, 6 MG and 0.6 MG, corresponding to white dwarf magnetic moments of 10^{34} G cm^3, 10^{33} G cm^3, and 10^{32} G cm^3 respectively. Each accretion flow simulation was allowed to spin-up or spin-down the white dwarf until it reached a stable equilibrium period. The resulting evolutionary tracks of these systems are plotted in Figure 3.

As IPs evolve, both their mass ratio and orbital period decrease. As noted earlier, these trends individually cause opposite shifts in the spin-to-orbital period ratio at which the triple points occur in the accretion flow phase diagrams. Consequently, the variation in equilibrium spin-to-orbital period ratio cannot be easily predicted. Nonetheless, the tracks in Figure 3 demonstrate that 'typical' IPs with a magnetic field strength of a few megagauss will evolve from being disc-like accretors at long orbital period (where $P_{\rm spin}/P_{\rm orb} \approx 0.1$), to ring-like accretors at short orbital period (where $P_{\rm spin}/P_{\rm orb} \approx 0.6$), providing that they don't synchronize along the way and become polars. This is the likely history of the IPs that currently sit alongside EX Hya in the spin period / orbital period plane. So we conclude that EX Hya-like IPs are systems which have avoided synchronisation as they have evolved to short orbital periods, and now display ring-like accretion.

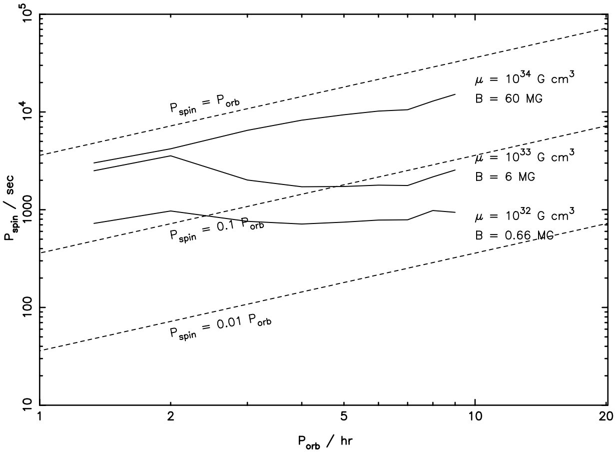

Figure 3. Evolutionary tracks of mCVs with three different magnetic field strengths in the spin period versus orbital period plane. For plausible mass ratios, disc-like flows will occur at $P_{\rm spin}/P_{\rm orb} \sim 0.05 - 0.15$ and ring-like flows will occur at $P_{\rm spin}/P_{\rm orb} \sim 0.4 - 0.7$.

5. Conclusions

The short answer to the question 'Are the *INTEGRAL* intermediate polars different?' is 'No'. We expect that most IPs will be detected by *INTEGRAL* once the whole sky is subject to the same *INTEGRAL* exposure. However, if the EX Hya-like IPs continue to remain undetected by *INTEGRAL*, even when their sky locations have been subjected to longer duration exposures, this may suggest that the ring-like accretion which occurs in these systems produces less hard X-ray emission than in the disc-fed systems at longer orbital periods.

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