RELATION OF INTERMEDIATE POLARS TO OTHER CATACLYSMIC BINARIES

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ABSTRACT. Properties of magnetic cataclysmic binaries (CB) are reviewed. Special attention is paid to intermediate polars (IP) and their relation to other CB. X-ray and optical observations are discussed.

1.INTRODUCTION: Dramatis Personae

Cataclysmic Variables are binary stars consisting of a white dwarf and a red companion, usualy a red dwarf. They are close enough that the bigger of the two stars, the red dwarf, overflows its limit surface for dynamic stability against tidal forces, called Roche Lobe. This instability causes mass flow from the surface of the red companion towards the white dwarf. Due to depth of the gravity potential well of the white dwarf the energy released by unit accreted mass reaches 10% of that produced from thermonuclear fuel. At mass transfer rates typicaly above $10^{-9} M_{\odot}/y$ accretion is the main source of energy in these binaries.

Because of small size of the white dwarf and excess angular momentum of the transferred gas, direct hit of the star by the gas stream is unlikely. The gas may form a rotating accretion disk around the white dwarf. Viscosity produced by turbulence in the disk and tidal action by the red companion remove angular momentum from the disk thus forcing its gas to spiral onto keplerian orbits with less angular momentum i.e. nearer and nearer to the white dwarf. The energy dissipated in the process is emitted away as UV and visual radiation of the disc. The disc reveals its presence in distortions of eclipse light curves and/or in double emission lines due to its approaching and receeding parts. Robinson (1976) gave a thorough discussion of the standars CB model.

Above certain threshold rate of mass transfer, in Classical Novae and Nova like stars, accretion proceeds in a stationary fashion. Below the threshold rate, in Dwarf Novae, accretion disks are instable and no stationary accretion is possible. These disks oscillate between bright, high mass transfer outbursts states and faint, low mass transfer quiescence states. These Cataclysmic Binaries in which thermonuclear explosion of white dwarfs were observed are called Classical Novae, or simply Novae. The white dwarfs of Cataclysmic Binaries are built of thermonuclear ashes, i.e. helium or carbon and oxygen and are lacking fuel to support nuclear reactions. However, in Novae white dwarfs accreted enough hydrogen on their surface to ignite there thermonuclear runaway reactions.

In Cataclysmic Binaries with magnetic white dwarfs the accretion scenario alters to some extent. Namely, at least near the surface of the white dwarf its magnetic field takes over control of the flow directing ionised gas along field lines towards magnetic poles. Colision with the stellar surface dissipates kinetic energy of the flow and produces a hot region called an accretion column a scaled up polar aurora. Misalignment of magnetic and rotation axes causes aspect and/or obscuration modulation of observed radiation from the poles. In Polars magnetic field of order of $\sim 10^3$ T on the surface is strong enough to force synchronized rotation and orbital motion and to control the flow all the way from the red star. Thus no accretion disks exist in these stars. Cataclysmic Binaries in which the synchronisation did not occure and modulation of radiation with both periods is observed are called Intermediate Polars. It is belived they are magnetic system too. Sometimes polars and intermediate polars are called AM Her and DQ Her stars from names of first known objects. In our opinion the peculiar nature of DQ Her does not justify this naming convention. Properties of magnetic CB were rieviewed earlier by Warner (1985).

2. X-RAY PROPERTIES OF MAGNETIC SYSTEMS AND SPIN EFFECTS

X-ray properties of all magnetic systems are similar. Gas flows towards the magnetic poles with highly supersonic velocity close to the free fall velocity. A shock front forms just above the surface of the white dwarf where it is slowed down. In the shock front kinetic energy of each falling gas particle is first converted into its thermal energy and then removed by some cooling mechanism. One efficient cooling mechanism in an accretion column is thermal emission. For a typical free fall velocity amounting to several thousands km/s thermal emission produces hard X-rays with energies of several keV. In all polars and in most intermediate polars such primary hard X-ray radiation modulated with the white dwarf spin frequency is observed. This observation enhances our confidence in similarity of Polars and Intermadiate Polars. It is rather difficult to produce such modulated hard X-ray radiation with no magnetic field so these observations identify the magnetic systems unambigously and enable safe determination of spin periods of white dwarfs.

Another, possible cooling mechanism is advection and/or conduction of heat to the stellar surface near the magnetic pole. The heated up area of the surface around the pole becomes a source of secondary soft X-ray radiation with energies less than 1 keV. The soft component is observed mostly in polars and there it may dominate the hard component. For geometric reasons no more than half of uncollimated primary hard X-rays radiation may hit this area so this observation indicates dominant role of advection in cooling of the shock.

Two mechanism of modulation of X-rays are important: eclipses and fotoabsorption. At some orientations self eclipses are possible. Namely, the accretion column may disappear on the invisible hemisphere of the white dwarf or be eclipsed by the companion star and/or accretion disk. These eclipses recur with the white dwarf rotation, orbital and disk precession periods, respectively. The disc eclipses recur each time its inclined plane passes an observer. They are directly observed in some accreting neutron binaries (e.g. HZ Her). In CB only indirect effects of disk eclipses on X-ray heating are observed in some intermediate polars (TV Col, V603 Aql and possibly TT Ari). Generally eclipses cut off X-rays at all energies. Several eclipsing polars are known. Sharp profiles of the eclipse light curves support our belief that the accretion column covers small area of the white dwarf. So far only shallow, grazing eclipses were observed in intermediate polars EX Hya and FO Aqr.

Absorption of X-rays by a semitransparent gas cloud is energy dependent so that the amplitude of modulation decreases with X-ray energy increasing. Its dependence reflects energy sensitivity of the fotoabsorption cross section. The absorbing cloud may be the gas stream or the accretion column passing line-of-sight every white dwarf revolution. This type modulation is observed in intermediate polars. Its amplitude reaches 50-100% at 2 keV energy and less at high energies. The observed modulation is significantly non sinusoidal. In some intermediate polars modulation with orbital period was also observed.

The free fall conditions are not well reproduced in non-magnetic cataclasmic binaries involving accrecion disks extending right to the surface of the white dwarf. There gas dissipates its energy and heats up gradualy emitting in the process copious amounts of EUV and soft X-ray radiation, but no hard X-rays. Also some fast optical pulsators, DQ Her, AE Aqr and V533 Her produce no modulated X-rays. It is not clear at present how far these objects differ from ordinary intermediate polars. X-ray observations of magnetic systems were reviewed in detail by Osborne (1988) and by Watson (1986, see also Norton and Watson, 1989).

3. VISUAL PROPERTIES OF MAGNETIC SYSTEMS AND ORBITAL EFFECTS

3.1 The orbital effects

Light curves of polars and intermadiate polars are noisy, suffering from random flickering, similar to one observed in other CBs. Already this observation justifies belief that polars and IP are also accreting binary stars. This belief is supported by spectroscopic and eclipse evidence discussed usualy in the context of ordinary, non-magnetic cataclysmic binaries. Periodic doppler shifts of spectral lines enable unambigous determination of orbital periods of cataclysmic binaries. Ritter's (1990) catalogue is good reference since by definition it includes all known magnetic systems. There are two classes of magnetic systems. These with synchronised orbital and rotational motions are called polars while others are called intermadiate polars (IP). The white dwarf rotation period of a typical IP is factor of 10 or so less than its orbital period. The catalogue demonstrates also a known fact that orbital periods of CBs have bimodal distribution, with a clear gap between 2 and 3 hours.

Eclipses and ellipsoidal effects frequently cause periodic modulation of optical and IR radiation of CB. In magnetic systems strong X-ray radiation causes intense heating of their components. heating effects combined with variable aspect produce characteristic periodic modulation of light with broad minima lasting up to a half of their period. The heating effects are particularly complex in intermediate polars.

3.2 Polars

In polars the orbital periods coincide with the rotation periods deduced from X-ray and/or polarisation observations. Most polars have orbital periods less than 2.5 hour corresponding to the gap in the period histogram. The following direct effects of the magnetic field are observed in optical radiation of polars:

- linear and circular polarisation, strong and periodicly variable, reaching up to 40%;
- Zeeman split of spectral lines and
- cyclotron lines at equal intervals in frequency.

No evidence of accretion disks was observed in polars.

Table 1

AN INVENTORY OF INTERMEDIATE POLARS

Name	Orbital	Spin	Remarks
	Periods		
GK Per	$47^{h}.9$	$^{h}.10$	X, N
AE Aqr	9.9	.01	
TW Pic	6.5	2.1	
TX Col	5.7	.53	X
TV Col	5.5	.53	X
KO Vel	4.9	1.13	
FO Aqr	4.8	.35	X
DQ Her	4.6	.02	, N
AO Psc	3.6	.22	X
V1223 Sgr	3.4	.21	X
V603 Aql	3.3	1.02	X, N
BG CMi	3.2	.25	X
EX Hya	1.6	1.11	X, DN
Candidates and related objects			
V795 Her	14.8:	2.80	a
V426 Oph	6.8	1.00:	X, DN, a
V533 Her	6.7	.02:	, N
TT Ari	3.3	0.3:	X, a, b
V1500 Cyg	3.1	3.1	X, N, c
SW UMa	1.4	.26:	X, DN, a
AM CVn	.28	.15	, d

Remarks: X) An X-ray pulsating source; N) a classical nova; DN) a dwarf nova; a) Second period uncorfirmed; b) an intermediate polar with unknown rotation period, but 2 other known periods; c) slight nonsynchronism of this polar star may be caused by its recent nova outburst; d) this system contains a helium secondary and thus is a peculiar cataclysmic binary. It is not clear whether its periodicities are caused by magnetic or pulsation effects.
References Ritter (1990)

3.3 Intermediate Polars

The rotation periods of intermediate polars are shorter than their orbital periods typicaly by a factor of 10 or so. In the one extreme, two objects with relatively longest rotation periods, V1500 Cyg and EX Hya are nearly in 1:1 and 2:3 resonances. In the other extreme are fastest rotators which have atypical X-ray properties and possibly are not IP at all. All intermediate polars except EX Hya and SW UMa have orbital periods longer than 2.5 hours corresponding to the period gap. None of the direct effects of magnetic field was observed in intermediate polars, except for weak polarisation of BG CMi (Penning et al., 1986). On the contrary, observations yield evidence of existence of accretion disks in these stars. Thus it was natural to assume that their field is weaker than that of polars. In Table 1 we present an inventory of intermediate polars. Several objects await confirmation as intermediate polars. TT Ari resembles very closely V603 Aql and TV Aql, except that its rotation period was never observed (however cf. Semeniuk et al., 1987) Nevertheless it must be already classified as an intermediate polar since it exhibits two other coherent periods. The rotation periods of V426 Oph and SW UMa or orbital period of V795 Her await confirmation. In our opinion it is premature to question the intermediate polar nature of V533 Her on the ground of cessation of its oscillations. Temporal complete dissappearance of pulsations was already observed elsewhere (Slovak, 1981).

Modulation due to X-ray heating is particularly complex in IP. It matters wheather the incident X-ray radiation is constant or modualted due to white dwarf rotation. These X-rays are reprocessed into light on surfaces of the components of the binary. Depending on geometry of these surfaces, their radiation may suffer further modulation due to aspect effects. This applies to asymmetric surfaces, such as a stream/disk collision region (a hot spot) and the illuminated hemisphere of the companion. However, no aspect effect is produced by an axialy symmetric and flat accretion disk. For sinusoidal modulation and linear heating response alone we obtain at least four different frequencies (Table 2). Any non-

Table 2

Modulation of IP light due to X-ray heating

Surface geometry \ X-ray flux	constant	rotationaly modulated
symmetric (disk)	∞	ν_{Rot}
asymmetric (stream, hot spot, companion)	ν_{Orb}	$\nu_{Rot} - \nu_{Orb}$

linear effect produce their harmonics and linear combinations. These effects are discussed generaly in signal transmission theory. Warner (1986) discussed them specificaly in the present context.

4. RELATION OF INTERMEDIATE POLARS TO OTHER CATACLYSMIC BINARIES

4.1 The Rosetta Stones

It is hoped that these magnetic systems which are also members of some other class of CBs will play a role in understanding their physics similar to that played by the bilingual inscription on Rosetta stone in understanding hieroglyphs. Although most magnetic systems were originaly classified as novalike stars, at least 5 listed in Table 1 and possibly GQ Mus are magnetic novae. EX Hye and possibly V 426 Oph and SW UMa are magnetic dwarf novae. There are no doubts that V 1500 Cyg is magnetic since it resembles polars in every respect except for several percent nonsynchronism of its spin and orbital periods. However, such a small nonsynchronism might arise due to white dwarfs expansion during a recent nova outburst.

4.2 Relation between Intermediate Polars and Polars

Summarising what was said in the past section, IP differ morphologicaly from polars by having shorter periods, evidence of an accretion disc, lack of direct magnetic field effects (polarisation, Zeeman effect and cyclotron lines). They are also brighter from polars, so presumably their accretion rate is smaller. We shall discuss later whether evolution of both classes is connected. The orthodox hypothesis states that these differences are due to polars having stronger field than intermediate polars. We shall discuss it later.

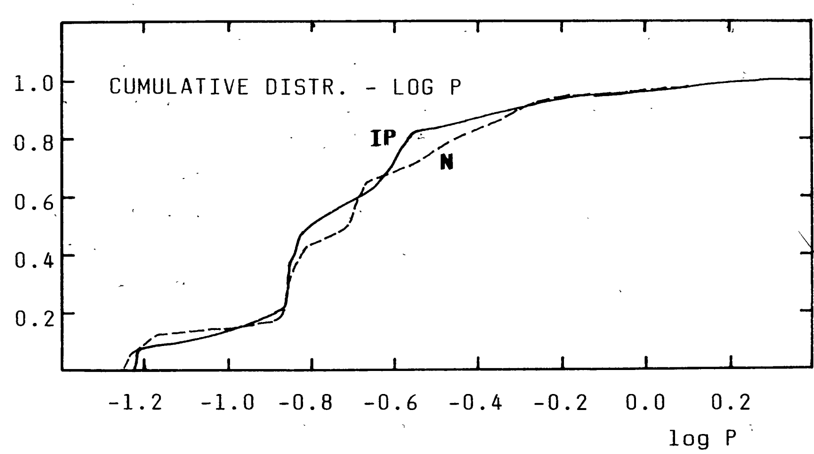

Fig. 1. Cumulative distributions of log orbital periods of novae (N) and intermediate polars (IP), in days. The two distributions do not differ statisticaly.

4.3 Relation between Intermediate Polars and Non-magnetic Cataclysmic Binaries

Among novae with known orbital periods roughly half are magnetic systems. Most other magnetic systems were classified as nova-like stars before their true nature was revealed. Particularly close is similarity of IP and Novae. To both classes belong typicaly long period CBs. Their period distributions are very close (Fig. 1). In both classes accretion rates are high. Although some connection of these types is obvious its nature remains mysterious. Ejecta of novae are frequently asymmetric. If this is magnetic effect, it must be a subtle one since fields of novae are too weak to affect directly expansion of their envelope during an outburst. Current models of novae predict their white dwarfs are more massive than on average in CBs. Thus determination of masses of white dwarfs of N and IP offers an independent test of their relationship (see Hameury et al., 1989).

Deficiency of novae with periods shorter than the period gap is usualy explained by their lesser frequency of outbursts caused by a smaller accretion rate. In the standard evolutionary scenario for IPs some selection effects are invoked in order to explain deficiency of system below the gap. If this selection were connected to the accretion rate than similar period distributions of IP and N would result in a natural way. This line of reasoning is somewhat undermined by yet uncorfirmed discovery of SW UMa, a dwarf nova, i.e. a low accretion rate system and an intermediate polar below the period gap.

5. MAGNETIC SYSTEMS AND CBs' EVOLUTION SCENARIOS

Progenitors of all CBs are common envelope binaries. Due to several breaking mechanisms a CB looses energy and angular momentum so that its size and the size of its Roche lobe shrinks. Thus more and more of the envelope of the red star sticks above Roche lobe and becomes lost in the dynamical time scale. In this way shrinking Roche lobe sustains mass transfer thus maintaining accretion light sources in the binary. Therefore all CBs evolve from long period ones. If so, many systems must cross the period gap. Above the gap breaking is so fast that drives the mass loosing star out of thermal equilibrium causing its expansion. It is commonly belived that at the border of the gap breaking eases so much that the star has time to regain its equilibrium (Mestel and Spruit, 1987). Thus the star shrinks a little bit. While beeing inside its Roche lobe it suspends temporialy mass transfer while continuing angular momentum loss, i.e. period shortening. Eventualy due to continued shrinking of Roche lobe its size matches again the stellar size and mass transfer resumes, for orbital period shorter than the gap. This explanation of the gap is valid only for systems which started their evolution as CB with long periods.

Reconciliation of observations of magnetic systems and current evolutionary scenarioes is difficult. Degenerate electrons are good conductors, whether in ordinary metals or in white dwarfs. So magnetic fields are well conserved during white dwarf evolution. Since according to the orthodox hypothesis field strenghs of IP and polars differ, they must evolve along separate lines. This immediately raises questions where are i) short period descendants of IPs and ii) long period progenitors of polars? Observation selection effects were called to explain deficiency of short period IP. However, most magnetic systems are discovered in X-rays where their spectra are so characteristic and amplitudes of modulation so large that selection should play small role. If common envelope evolution for polars ends with short periods, than the old explanation of the gap does not apply. However, independent occurence of the gap for polars at the same location does not seem likely.

In order to avoid these difficulties King et al. (1985) proposed that polars are short period and synchronised descendads of intermediate polars. Thus, according to this unorthodox hypothesis, their fields have comparable strength. Reconciling lack of direct field effects in IP with their postulated strong field is main difficulty of his hypothesis. The better are understood mechanisms of radiation of accretion columns, the less likely is King hypothesis. In dynamics it is also difficult to explain how rotating plasma accretion disks in IP could form despite strong field.

6. PROBLEMS AND FUTURE PROSPECTS

We conclude by listing some questions concerning intermediate polars and their relation to other CB. First we list these of the issues which require new observations.

- Are there many IP among CB and what is their distribution among CB's classes? In particular, are all novae magnetic, perhaps?
- What happens to short orbital period IP?
- If novae and IP are related, are their white dwarfs massive as suggested by current TNR theory? This is an independent test of their relationship, not particularly sensitive on periods distribution.

Progress in theory is required to answer some further questions:

- Why so much energy is pumped into soft X-rays and what role plays strength of magnetic field in it?
- Does magnetic field stimulate novae outbursts?
- Why polars do not end their common envelope evolution inside the period gap?
- Why precessing disks exist in some magnetic CVs?

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