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Concluding Remarks II: Current Problems in Polar and Intermediate Polar Research

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Several outstanding problems in the research of magnetic cataclysmic variable binaries (mCVs) are reviewed. Magnetic cataclysmic variables are divided into the high magnetic field strength (10-230 MG) polars and the intermediate magnetic field strength (0.01 - 10 MG) intermediate polars (IPs). Current problems in polar and intermediate polar research are much the same as those from the foundation of the field and include (1) the long-term orbital period evolution, in particular testing of the disrupted magnetic breaking hypothesis for the formation of the upper edge of the CV period gap, (2) the origin of high and low luminosity/accretion states, (3) the structure white dwarf magnetic field, dipolar or complex and (4) the origin of radio emission in mCVs and measuring the donor magnetic fields. These issues are interconnected in complex ways. Some historical context is given and a summary of the state of progress towards solutions is presented.

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1. introduction

In these brief concluding remarks, I outline several fundamental problems in magnetic CV (mCV) research and highlight progress towards their understanding. Cataclysmic variables, CVs, are binary stars consisting of a white dwarf accreting from a lower main sequence Roche-lobe filling donor. CVs have orbital periods of a few hours. CVs with white dwarf magnetic fields that are sufficiently strong to influence the flow of material onto the magnetic poles are defined to be mCVs; which are further classified into polars and intermediate polars according to the strength of the magnetic field and the mode of accretion. In polars, no accretion disk is formed. Instead, the magnetic pressure causes accretion streams to flow along field lines directly to the surface of the white dwarf. In intermediate polars, an accretion disk forms as in non-magnetic CVs, however the disk is disrupted at its inner edge by the magnetic field of the white dwarf. X-rays are emitted in post-shock regions just above the surface of the white dwarf in both types of mCVs. There are currently about 200 mCVs known. There are recent reviews of long-term optical studies [1] and X-ray properties [2, 3], radio detections [4] as well as magnetic fields in mCVs [5].

2. Problems in mCV research:

2.1 Magnetic CV evolution

The standard model of CV evolution involves a period of common envelope evolution, when the progenitor of the white dwarf expands as a giant to encompass the whole binary. The binary rapidly loses angular momentum within the common envelope and ends up as a close binary pair with a period of a few hours to a few days. The observed properties of white dwarfs in mCVs can be explained by a scenario proposed by Tout et al. [6] where mCV fields are generated by differential rotation as the stars spiral in towards each other during the common envelope phase of CV evolution. If they are too close, they merge and become a single, strongly magnetic white dwarf. If they survive and emerge from the common envelope as detached or semi-detached, they evolve into mCVs. Angular momentum loss drives the evolution of CVs toward shorter periods, so depending on the magnetic field strength, longer period intermediate polars may evolve into shorter period polars [7].

Original studies of CV evolution [8, 9] showed that orbital angular momentum loss solely due to gravitational radiation at orbital periods > 2 hours is insufficient to drive mass transfer. There must be an additional source of angular momentum loss at long orbital periods. The proposed mechanism is known as magnetic braking. In this scenario, the donor star is rotating quickly and a strong dynamo is generated. The outflowing stellar wind from the magnetized donor star carries away angular momentum, effectively applying a braking torque on the binary. This mechanism is sufficiently strong to drive mass transfer from orbital periods of 6 hours down to about 3 hours.

Whyte and Eggelton [10] identified a ‘period-gap" in CVs between approximately 2 and 3-hrs. The idea that the observed CV period-gap is due to a structural change in the donor once it losses enough mass to become fully convective was suggested by Robinson [11] and is the prevailing wisdom today. At periods longer than 3-hrs, the donor is partially convective and strong magnetic fields may be generated due to rapid rotation of the donor. However, at about 3 hours the donor becomes fully convective, which turns off, or at least weakens, magnetic braking. In addition, the structure of the donor changes (the star shrinks an small amount). This transition to full convection happens once the mass drops to about M = 0.2 $M_\odot$ [12]. Critically, the surface of the star no longer fills the Roche-lobe and mass transfer halts. Magnetic breaking of the binary is thus disrupted until the slow process of angular momentum loss by gravitational radiations brings the stars closer together until the donor resumes contact with its Roche-lobe at an orbital period of about 2 hours. This evolutionary scenario explains the paucity of CVs in the period gap as many CV are likely in the gap, but are not transferring matter, so are not among the observed population. The existence of a period-gap in mCV is much weaker and it is not clear exactly why. Most likely, magnetic breaking is less efficient in mCV as compared to non-magnetic CVs and thus it is not disrupted near 3 hours.

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2.2 High and low accretion states

The timescales on which high or low states occur are system dependent, see the selection of long term light curves of polars from CRTS [1]. There appears to be a pattern of alternating long and short accretion cycles. Patterns vary significantly from system to system, yet the duty-cycle pattern of a particular source is relatively predictable. This feature in the long-term light curve of AM Her caused Wu and Kiss [13] to suggest that the white dwarf magnetic field may play the key role in mass transfer regulation from the donor star and hence the high/low brightness states. The long term changes, taking months to years, in the brightness and thus accretion rate of mCVs have been suggested that such changes are due to star-spots and solar-type magnetic cycles in the donor star [14], which may be related to radio emission in AM Her. If this is the case, then long-term changes in accretion rate (years to decades) might be due to a possible magnetic cycle of the donor. Investigation of these cycles by long-term photometric monitoring should place strong constraints on the role of the cause of high and low accretion states and the transitions between them [1].

2.3 Magnetic field structure of the white dwarf

Schmidt et al.[15] was the first to present observational evidence for a non-dipolar white dwarf magnetic field, specifically for the isolated white dwarf PG 1031+234. They modeled the field as the sum of an inclined centered dipole and a highly intense spot at the magnetic equator. Meggitt & Wickramasinghe [16] found that the magnetic field of the WD in the EE Eri system can be described by a pure quadrupole field with four accretion spots. Based on theoretical considerations, Wu & Wickramasinghe [17] supposed that a multipole field (dipole plus coaxial quadrupole) should result in three accretion regions, revealing two spots that occur at the magnetic poles of the dipole and the third strip-like accretion region must be located near the intersection of the magnetic equator and the orbital plane. They also propose that the third (equatorial) region may dominate the flow. Following that work, a complex field model was proposed for BY Cam by Mason et al. [18, 19, 20] The existence of higher order magnetic fields (quadrupole, octupole, etc.) in white dwarfs was confirmed by Zeeman tomography of several polars during low accretion states, see Euchner et al. [21] and Beuermann et al.[22]. Those studies revealed the existence of high order field components, up to octupole, of several polars.

As an asynchronous polar, BY Cam provides a laboratory in which to sample complex fields as they direct accretion flows in polars. In the coaxial dipole and quadrupole field models, pole switching [23, 24, 20] occurs between a polar and equatorial accretion spot [25]. Two regions continually alternating their activity on the spin-orbit beat cycle. However, it was found that the equatorial pole drifts in phase in this model while the polar spot remains relatively stationary [25]. In addition, in the aligned dipole plus quadrupole field model, only solutions involving one or two accretion spots at the same time were found. Meanwhile, observations indicate the existence of several spots [26] and even moving spots in particular conditions, which require further complication of potential magnetic field models. The first asynchronous polar to be observed at continuous high cadence was CD Ind, using the TESS telescope [27], revealing 3 or 4 accretion regions active during different parts of the beat cycle [28].

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2.4 Origin of mCV radio emission and donor magnetic field

Radio observations of AM Her at 4.9 GHz using the Very Large Array (VLA) by Chanmugam & Dulk [29] resulted in the first mCV radio detection, with a flux density of 0.67 mJy. No circular polarization was detected. It was concluded that the AM Her radio emission is due to gyrosynchrotron emission (with harmonic number of 30 to 50) from energetic ($\sim$ 350 keV) electrons trapped in the white dwarf magnetosphere. The origin of the energetic electrons was not clear, but they suggest several mechanisms, including shock waves and the unipolar inductor model of Goldreich & Lynden-Bell [30]. Soon after, AM Her was again detected at 4.9 GHz and upper limits at 1.4 and 15 GHz were obtained [31]. Dulk et al. also obtained upper limits of about 0.2 mJy at 4.9 GHz for VV Pup, EF Eri, MR Ser, ST LMi, and AN UMa. They suggest that this quiescent emission of AM Her is the result of energetic electrons ($\sim$ 500 keV) trapped in the magnetosphere of the white dwarf. This requires that the electron energy spectrum be very hard and the spectral hardness, or number density, of the electrons increases with radius. A radio flare lasting about 10-min was also observed from AM Her, with a peak flux of 9.7 mJy, which is about 20 times the quiescent emission. The flare was essentially 100% circularly polarized. Dulk et al. [31]. concluded that the flaring radio emission was due to an electron-cyclotron maser operating near the surface of the donor in a $\sim$ 1 kG magnetic field. Magnetic reconnection events due to the interaction of the magnetic fields of the two stars are a likely source for the high energy electrons that generate maser emission. Observations of AM Her suggested that there are two source of radio emission, quiescent and flaring.

The first radio detection of an intermediate polar, namely the propeller system AE Aqr, was obtained by Bookbinder & Lamb [32] who found, using the VLA, strong radio emission from AE Aqr (15 mJy at 4.9 GHz and 5 mJy at 1.4 GHz). No radio emission was detected from five other intermediate polars (FO Aqr, AO Psc, BG CMi, TV Col, and EX Hya). Several polars were then detected as flaring sources. V834 Cen was reported to have strongly variable emission ($\sim$ 2 mJy) at 8.4 GHz, with a flare of 13.7 mJy [33]. ST LMi was detected at 5 GHz on two out of three occasions [34]. The strongest of these was a flare of 2.0 mJy, a 6 σ detection. Continued progress remained disappointingly slow. Bastian [35] observed 15 MCVs, with zero detections, using the VLA at 1.5, 4.9, and 15 GHz. Beasley et al. [36] used the VLA and the Australian Telescope Compact Array to observe an additional 22 MCVs without success. The asynchronous polar BY Cam was observed using the VLA, an upper-limit was obtained [37]. This non detection, strongly disfavors the unipolar inductor model for persistent radio emission.

Mason & Gray [38] performed a survey of 9 MCVs at 8.4 GHz, and detected AR UMa at flux density of $\sim$ 0.6 μJy. AR UMa was not expected to be a radio emitter in the case of the unipolar inductor model, as it has the highest known magnetic field of all polars at 230 MG, and thus should be tightly synchronized, while AM Her has a white dwarf magnetic field that at the lower end for polars at 13 MG [39]. AM Her was again detected at a flux density of 584 μJy. The other seven targets (LW Cam, DO Dra, FIRST J1023.8+0038, SDSS J1553+5516, V2301 Oph, RX J1846.9+5538, and WZ Sge) were not detected at a flux density limit of $\sim$ 120 μJy.

The problem was sensitivity as the few observed sources were also the only ones close enough to be detected. That all changed with improved sensitivity of the Jansky VLA allowing Barrett et al. [4] to detect 19 mCV binaries. Most of those detections were at 8.7 GHz (X-band) with a few at 5.4 and 21.1 GHz (C- and K-bands). Remarkably, fourteen of the detections show approximately 100% circularly polarized emission, like the original AM Her flare. This is suggestive of electron-cyclotron maser emission in those cases. They conclude that mCVs might be divided into two classes of radio emitters: those dominated by weakly polarized gyro-synchrotron emission and those by highly polarized electron-cyclotron maser emission. The maser measurements allow for a direct determination of the donor magnetic field strength.

3. Conclusions

Several current problems in polar and intermediate polar research have been described in these concluding remarks. It is far from an exhaustive list. What we can be sure of is that, as many new binaries are discovered and characterized, interesting rare objects will illuminate current understanding as well as bring new challenges. The problems discussed briefly here are the same as those from the foundation of the field. We find that much progress has been made, but much remains: (1) the long-term orbital period evolution; in particular long-term monitoring eclipsing binaries will help test the disrupted magnetic breaking hypothesis for the formation of the upper edge of the CV period gap, (2) the origin of high and low luminosity/accretion states is also aided by long-term monitoring of all mCVs, (3) the structure of the white dwarf magnetic field, dipolar or complex, appears to favor complex fields, and (4) progress has been made on the origin of radio emission in mCVs and it appears to allow the measurement of the donor magnetic fields.

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