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Detecting Chromospheric Activity on the Secondary Star of Cataclysmic Variables

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Abstract. Chromospheric activity on the secondary stars of cataclysmic variables (CVs) is a key ingredient for angular momentum loss from the system via magnetic braking. This effect is thought to drive the evolution of the system and is invoked to explain a number of observed properties of CV light curves, such as long-term modulations and high/low states. However, obtaining observational support for magnetic activity has proven difficult. We present a new method of studying chromospheric activity on the secondary stars of CVs, using near-IR spectral features. We discuss in particular the magnetic CV AM Herculis, in which satellites to the H-alpha emission line are interpreted as arising from magnetically confined gas streams (prominences). This phenomenon provides a new technique for mapping magnetic structures on CV secondaries, and advances our understanding of the nature of magnetic structures and activity on CV secondaries.

Keywords. cataclysmic variables, stars: individual (AM Her, ST LMi, VV Pup), stars: activity stars: flare

1. Introduction

Cataclysmic variables (CVs) are semi-detached binaries in which a white dwarf (primary star) is accreting from its lower main sequence (K/M dwarf) Roche-lobe filling companion. Depending on the strength of the magnetic field of the white dwarf, CVs can be classified in two major categories. In disk systems (DCVs) the accreted material forms an accretion disk around the white dwarf primary. In magnetic systems (hereafter MCVs) the strong magnetic field of the WD ($B \geqslant 10^7$G) disrupts the formation of a disk and leads the accretion stream through the magnetic field lines of the white dwarf towards its magnetic poles. A detailed review of all the subcategories of CVs can be found in Warner (1995) and will not be repeated here.

The secular evolution of CVs is controlled by angular momentum loss via magnetic braking through a wind originating from the secondary star (Ritter 1984). Magnetic activity on the secondary star is also considered responsible for a number of observed phenomena in CVs. Semi-periodic long-term modulations of the optical brightness of several CVs are attributed to magnetic cycles on the secondary (Bianchini 1987). Warner (1988) proposed that variations of the mean luminosity and outburst intervals of dwarf novae are in agreement with the presence of magnetic cycles on the secondary star. Erratic but prominent (up to 4 magnitudes) drops of brightness in both DCVs and MCVs are interpreted as temporary interruption of the mass transfer process by the presence of starspots in front of the L1 point (Livio & Pringle 1994; Kafka & Honeycutt 2005). In disk systems (IP Peg and SS Cyg), low velocity components revealed the presence of a stationary "compact source" located outside the orbital plane of the systems, but near the center of mass of the two stars and is attributed to slingshot prominences, similar to those observed in fast rotating single stars (Steeghs *et al.* 1996). Finally, the detection of intense radio outbursts from a MCV (AM Her) is interpreted as originating from electron-cyclotron masers near the surface of the magnetic (∼1000G) secondary (Chanmugam & Dulk 1982; Dulk, Bastian & Chanmugam 1983). The above are just a few examples on the variety of observed phenomena in CVs pointing to activity on their secondary star for their interpretation. However, direct observations of such activity appear to be difficult to gather, since accretion masks or, even worse, mimics signatures of activity such as X-rays and Hα emission.

Perhaps the only time where accretion is absent, or significantly reduced, is during VY Scl low states. Such low states, which are defined photometrically as intense (up to 5 mag) drops of the brightness of the system, occur in both DCVs and MCVs. They are erratic and unpredictable in occurence and duration; however, they allow the two components to be revealed, offering a unique opportunity to explore the presence of activity on the secondary star.

2. AM Her leading the way

We were fortunate to observe one of the MCVs, AM Her, during its extended 2003-2005 low state both photometrically and spectroscopically. AM Her is the prototype for the MCV (or polar) category; as such, it has been the subject of a large number of studies. Therefore, we now know that it consists of a magnetic white dwarf (B∼12.5±0.5 MG; Bonnet-Bidaud *et al.* 2000) which is accreting material from its ∼M4–M5 donor star (Bailey *et al.* 1988; Gänsicke *et al.* 1995; Kafka *et al.* 2005a) through one of its magnetic poles. Its long-term optical light curve (Figure 1, top) reveals numerous low states, in which the magnitude of the system drops to 15.6 in V (from 13-14 mag in the high state). When in the low state, it exhibits events, which have been attributed to either accretion bursts or activity (flares) on the secondary star. One of the better resolved ones it presented by Shakhovskoy *et al.* (1993): it appeared as a 2-mag, 20-min brightening during the 1992 low state, similar to UV Cet-type (M dwarf) flares. During a photometric monitoring campaign of the system, Kafka *et al.* (2005a) revealed a series of events having durations of ∼15-90 min, amplitudes of ∼0.2-0.6 mag and duty cycles of ∼35%; these were tentatively attributed to stellar activity (flares) on the secondary star. Furthermore, low state X-ray flux has been assigned to coronal emission from an active secondary star (de Martino *et al.* 1998). Therefore, there were previous indications that the secondary star in AM Her could be active.

Armed with this, we monitored the system spectroscopically during three observing runs in 2003-2005, using the WIYN 3.5-m and the KPNO 2-m telescopes. Typical exposure times range between 450 and 750 sec. We chose to observe the system in the near IR region (5700-8500 Å) with the hope to distinguish components that do not originate from the white dwarf or any residual accretion. A sample spectrum of the system is presented in Figure 1 (bottom, left). The continuum is modulated by pronounced TiO bands, which are characteristics of an M-type secondary star. Features from the secondary's photosphere, such as the KI and NaI doublet allowed us to determine a new spectroscopic ephemeris for the system, defining phase zero at inferior conjunction of the secondary star:

$$T_0 = \text{HJD } 2,446,603,403(5) + 0.12892704(1) \text{ E}$$

The Hα line is in emission; occasionally, we see the HeI lines (at 5876, 6678 and 7065 Å) in emission too.

The interesting finding in our work was that the Hα line has structure: the central peak appears to have blue/red satellites, whose visibility changes with orbit. These satellites

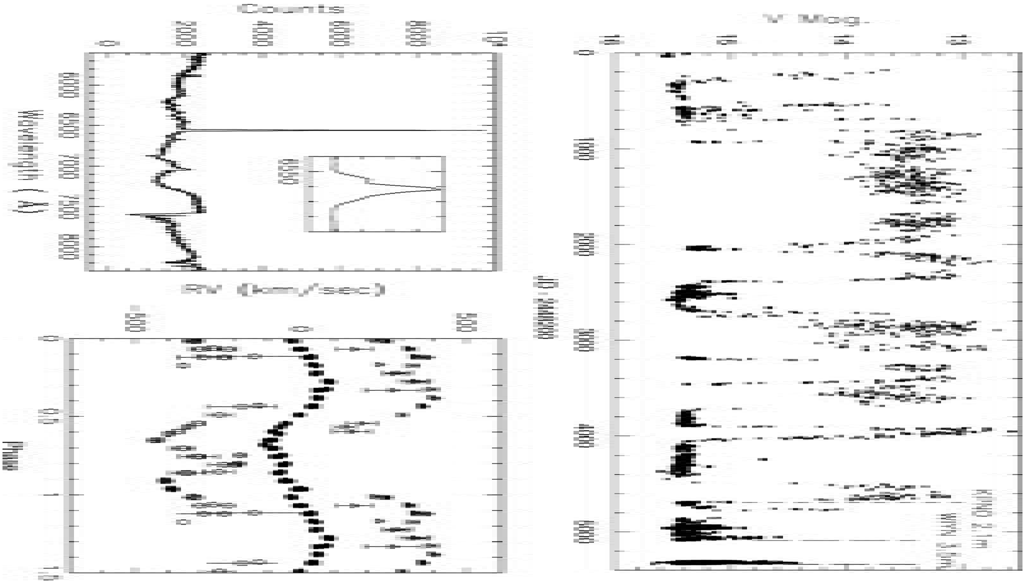

Figure 1. Top: 1990-2005 light curve of AM Her (from Kafka & Honeycutt 2005); Bottom left: low-state spectrum of AM Her, with the main features labeled (inset: zoom in on Hα), right: Hα radial velocity of the central peak (filled circles) and the satellites (open circles) for one night in 2005 (from Kafka *et al.* 2006).

appeared immediatelly after the system dropped in the low state in 2003 indicating that they were probably present even when the system was in the high state, but were masked by accretion (Kafka *et al.* 2005b). The presence of the satellites in 2005 imply that the underlying structures are persistent and long-lived. To decompose the lines, we used Gaussian fits to the satellites and the central peak. The number of Gaussians are, generally speaking, unambiguous for most of the components, reproducing the cumulative profile of the line. Using the spectroscopic ephemeris from above, we constructed phased RV curves for the central peak and its components; an example is presented in Figure 1 (bottom, right).

A striking first characteristic of all the RVs is that they follow the motion of the secondary star. The velocity of the central peak advocates for an origin to the inner hemisphere of the secondary star; we tentatively attribute it to irradiation. The RVs of the satellites are more intricate. They appear for half a cycle each, whereas both of them are present around phases 0.0 and 0.5, and they have structure at phase 0.8. Their phasing, amplitude and curvature advocate for an origin on the secondary star; however their γ velocity of $\sim$300 km sec^{-1} does not agree with the γ velocity of the secondary star. Also, the satellites can not originate from a jet-like structure, otherwise their RV would cross the path of the RV of the central peak (instead of transitioning from one side to the other). They rather have the appearance of a partial ring about the secondary. However, a circumbinary ring would not follow the orbital motion of the secondary alone, and there are no stable orbits around the secondary star alone, given that the it fills its Roche lobe. Ruling out the white dwarf, irradiation and system dynamics, the only logical choice for the origin of the satellites is that they are produced by the magnetic field of the secondary star, likely in the form of prominences or prominence-like structures that extend half way around the star, similar to slingshot prominences in fast rotating stars (Collier-Cameron & Robinson 1989). Such loops can be transient and extended, resembling a partial ring, with material flowing along the magnetic field lines of the secondary. We cannot completely rule out an alternative explanation of infall velocites

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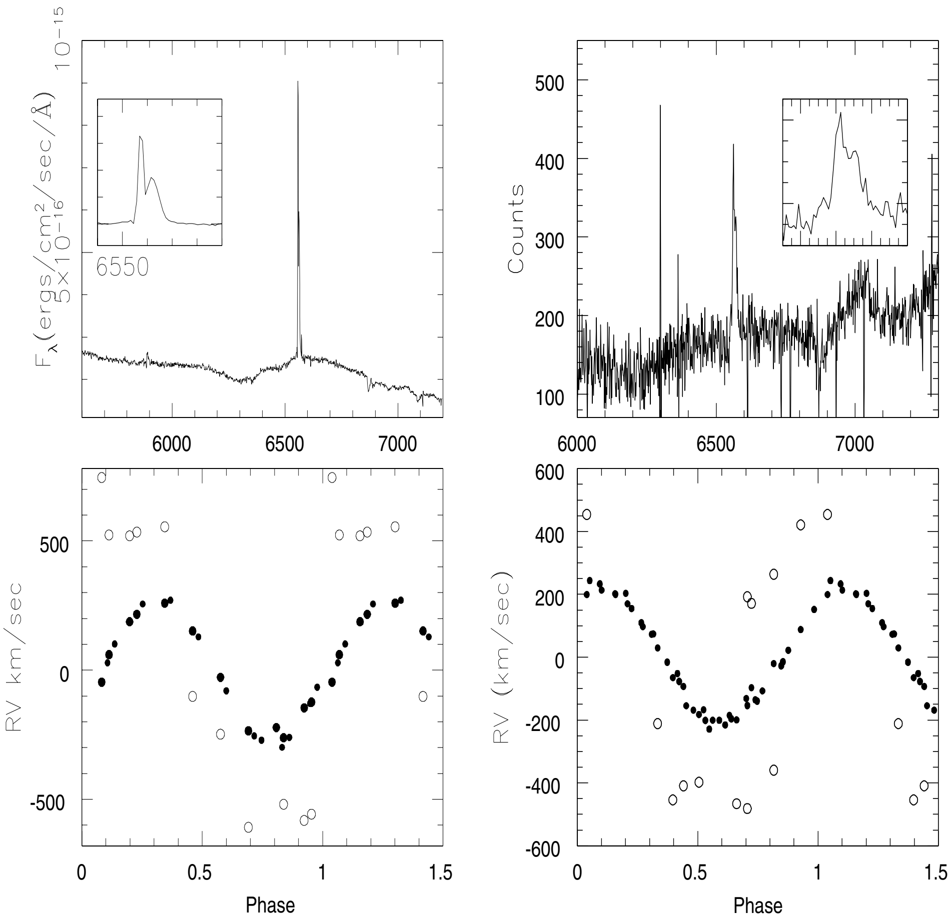

Figure 2. VV Pup (left; from Mason *et al.* 2007) and ST LMi (right; from Kafka *et al.* 2006). In both cases, the top panel displays a low state spectrum of the system (with the Hα line in the inset) and the bottom panel the radial velocity of the central Hα peak (filled circles) and the satellites (open circles).

from residual accretion being responsible for the satellites (or a part of the observed emission). However we have concluded that gas motions in loops about the secondary star are strongly favored mainly because 1) accretion is very low or absent at the times of our observations, and 2) the radial velocities of the satellites appear to follow the motion of the secondary star.

Our 3Å resolution allows us to resolve only three components in the profile of the Hα line; however, it is likely that this line has a more complicated structure. Considering that the satellites are present in the system for more than one year, irradiation from the L1 point of the system should not be the major component of the observed emission from the L1 point. Future higher resolution data could distinguish the various components and determine the presence of active regions at L1.

3. Other CVs?

The question that arises here is, whether this signature of activity is common in CV secondary stars, or if AM Her is just an exception. Recent observations came to test our discovery: Mason *et al.* (2007) in their low state data of the MCV VV Pup, present three epochs of spectroscopic observations of the system. During one of these epochs, the Hα line has satellites similar to those in AM Her (Figure 2, left). The RVs of all three peaks of the lines follow the secondary star, and reveal structures with velocities reaching 500 km sec^{-1}. In addition, Kafka *et al.* (2006) present new data of the recent low state of ST LMi, in which the Hα line is also triple-peaked, pointing to the secondary star for the origin of all three components (Figure 2, right). In VV Pup, the satellites appear during only one of the epochs of observing, indicating that the underlying structures are variable on timescales of weeks. In ST LMi, the EW variations of the Hα line indicate the presence of an active region on the side of the secondary (Kafka *et al.* 2006).

With VV Pup and ST LMi in the growing group of systems in which the Hα line reveals magnetic activity on the secondary stars, we have now a new technique of tracing and mapping activity-related magnetic structures in CV secondaries. Using the observed structures, we can reach a better understanding of the formation and evolution of such structures allowing us to test our theories of angular momentum loss via magnetic braking on CV evolution and the effect of fast rotation and tidal/magnetic interactions on activity. Differences in the character of magnetic activity in various systems is expected, since the secondary stars are of different spectral types. For CVs above the period gap (such as AM Her), the secondary star is expected to have a radiative core; activity is then induced via an α-Ω dynamo, in a manner similar to activity in the sun. In CVs such as ST LMi and VV Pup, the secondary star is fully convective; however the presence of activity and loop prominences advocate towards the presence of a global magnetic field in their secondary. All three systems in our sample are magnetic CVs, which raises the question of the effect of the white dwarf's magnetic field on the activity levels of its companion. Therefore, a critical test for this technique is to look for similar structures during the low state of a DCV, which is among our future plans.

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Discussion

JUAN MANUEL ECHEVARRIA: Have you tried to combine Roche Tomography with your analysis and can you rule out Zeeman splitting in the Hα line?

KAFKA: We can securely rule out Zeeman splitting as a possible source for the lines. I am not aware of a case in which Zeeman splitting results in line emission. Furthermore, the separation of the "peaks" of the satellites (or "dips" in the line) does not coincide with the expected position of the $\sigma^{\pm}$ components of a 12MG magnetic field (which is the white dwarf field for AM Her). We have not attempted Roche Tomography due to the low resolution of our data.

GEORGE SONNEBORN: Magnetic activity and prominences are usually hotter than the K/M V secondary. Are there other spectral signatures of chromospheric activity, especially higher ionization lines?

KAFKA: In bluer wavelengths, one would expect the CaII H&K lines to be in emission, in a manner similar to chromospherically active stars. In the UV, the CIV and SiIV lines are good indicators of chromospheric activity. For AM Her, signatures of activity in the UV lines are reported in poster presented in this meeting by Steve Saar *et al.*("The Ultraviolet Universe: Stars from Birth to Death", 26th meeting of the IAU, Joint Discussion 4, 16-17 August 2006, Prague, Czech Republic, JD04, #30, 4) Our observations are concentrated around H-alpha; there are no higher ionization species there.

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