

# Doppler tomography of Cataclysmic Variables

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**Abstract.** The study of cataclysmic variables (CVs), and in particular of the evolution of their accretion discs throughout their different brightness states, has benefited largely from the use of indirect imaging techniques. I report on the latest results obtained from Doppler tomography of CVs concentrating mainly on results published since the 2000 Astrotomography meeting in Brussels. Emphasis is given to the spiral structures found in the accretion discs of some CVs, to the evolution of these structures throughout quiescence and outburst, and to our search for them in more systems.

**Key words:** cataclysmic variables - techniques: spectroscopic

## 1. Introduction

Cataclysmic Variables (CVs) are close interacting binaries that consist of a white dwarf (WD) as the compact object and either a main sequence star or a slightly evolved star as the donor component. The companion or donor transfers material to the more massive WD. Due to conservation of angular momentum, and if the magnetic field of the WD is not too strong, the mass being transferred forms an accretion disc around the WD. If the magnetic field of the WD is strong (a few MGs) there are two possible scenarios that can take place: a) the material latches to the magnetic field lines before a disc can be formed and accretion onto the WD occurs along the field lines in which case we have a CV called a polar (Schwope, this volume), or b) the disc does form but it gets disrupted in its inner regions by the magnetic field lines in which case we have a CV called an intermediate polar.

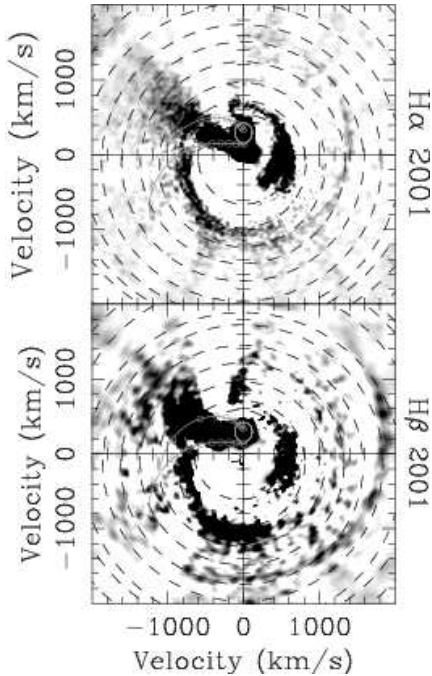
The study of CVs started more than a century ago and many monographs have been dedicated to their study, in particular the book by Warner (1995) gives a very complete description of these systems. The components of a CV cannot be resolved directly as their angular size from Earth is only a few tens of micro-arcseconds, thus the only way to image CVs is by using indirect imaging techniques. Several indirect imaging techniques have been used for their study throughout the years, e.g. Eclipse Mapping, Physical Parameter Eclipse Mapping, Stokes Imaging, Roche Tomography, Doppler Tomography etc. Doppler Tomography (Marsh & Horne 1988, Marsh 2001, Steeghs this volume) uses a series of spectra covering the orbit of the binary and produces 2-dimensional maps of its velocity field. It is then possible to transform this

velocity map into a space map by making the assumption that the accretion flow moves in a Keplerian fashion. We know from observations that this is not always the case (e.g. Marsh & Horne 1990) so it is usually preferable to study the velocity maps themselves.

## 2. Recent results from Doppler tomography

The presence of a disc or ring of gas around the compact object in a CV is usually obvious just by looking at high time resolution trailed spectra covering most of an orbit. Emission lines in CVs are generally more complicated than that, showing many components that arise in different regions of the binary and that move at different velocities. Thus it is usually not so obvious to assign these components to emission regions in the CV. It is in these cases when Doppler tomography plays an important role.

Thanks to Doppler tomography we have been able to identify the presence of spiral structure in the accretion discs of CVs (e.g. IP Peg in outburst: Steeghs, Harlaftis & Horne 1997; Harlaftis et al. 1999; Morales-Rueda, Marsh & Billington 2000, U Gem in outburst: Groot 2001) some ten years after it had been predicted (Sawada, Matsuda & Hachisu 1986). We have also been able to map the accretion stream in magnetic CVs (Schwope, Mantel & Horne 1997, and other examples in this volume) and to map the irradiation of the donor star (Morales-Rueda et al. 2000, Harlaftis 1999, Unda-Sanzana et al. in press). Doppler tomography does not always solve the problem though, in some cases we still do not know what the origin of some components is, i.e. more cases of low velocity emission near the centre of mass of the binary are appearing in the literature and in most cases we do not have an



**Fig. 1.**  $H\alpha$  and  $H\beta$  Doppler maps of U Gem during quiescence. After subtracting the elliptical background Unda-Sanzana et al. (in press), find signatures of spiral structure in the accretion disc.

explanation for it (North et al. 2001, Unda-Sanzana, Marsh & Morales-Rueda, in press).

Marsh (2001) gave a summary of all the Doppler maps published in the literature since the start of tomography in astronomy. Here we extend his summary by presenting in Table 1 all the CVs that have been mapped since then. A highlight of this summary are the tomograms obtained during the rare (once every 33 years approximately) superoutburst of WZ Sge in 2001. These showed the presence of a strong spiral structure during the start of the outburst, weakening as the flux decays, appearing again during a re-brightening and finally disappearing as the disc cools down. The maps also show the presence of the donor star in the system which is visible due to an increase in irradiation during the outburst. The detection of the donor star in the Doppler maps allowed the determination of basic system parameters such as the radial velocity amplitudes of both components. These measurements helped constrain the masses of the donor star and the white dwarf (Steehgs et al. 2001). More details on the 2001 outburst of WZ Sge are discussed by Steehgs (this volume) and references therein. Other highlights include two maps of U Gem one obtained at outburst maximum and the other four days later showing that both spiral arms evolve in a different way indicating asymmetric evolution of the disc. The spiral structure not only varies in strength but also in size and position in the disc (Boffin & Steehgs 2002). Also of interest are the maps of helium CVs like AM CVn, that allowed the authors to constrain the system parameters (Nelemans et al. 2001) and GP Com, that showed a rather complicated structure in the bright spot emission (Morales-Rueda et al. 2003), maps of IP Peg during quiescence possibly showing the pres-

ence of spiral structure (Neustroev et al. 2002), and maps of magnetic systems that allowed the authors to constrain the accretion geometry (Schwope 2001).

## 2.1. Doppler tomography of discs: spiral structure

Since their observational discovery in 1996 astronomers have found spiral structure in the accretion discs of six CVs. IP Peg, U Gem and WZ Sge are the best studied systems of the six with spiral structure having been detected in several different sets of data. In the case of WZ Sge the spectra were all taken during the same high state (as this system only outbursts every 20-30 years) whereas for IP Peg the structure has been seen in three different outbursts and for U Gem in two. For IP Peg and U Gem some authors have also found indication of spiral structure during quiescence (IP Peg: Neustroev et al. 2002, U Gem: Unda-Sanzana et al., in press, see Fig. 1). The other three CVs that show spiral structure are SS Cyg, EX Dra and V347 Pup. All, apart from V347 Pup which is a nova-like, are dwarf novae.

The presence of spiral structure in the accretion disc is of great importance as spiral shocks have been called upon as a possible way to get rid of angular momentum in the accretion disc. Magnetorotational instabilities (Hawley & Balbus 1995) are the widely accepted way to explain the effective viscosity in outburst discs but there still is some debate regarding angular momentum transport in quiescent discs. Hydrodynamic tidal stresses (Sawada, Matsuda & Hachisu 1986) that result in spiral shocks could also contribute to the viscosity together with magnetorotational instabilities.

More recently, Smak (2001) and Ogilvie (2002) have interpreted these spiral structures in the accretion disc as vertical enhancements of the disc being irradiated by the white dwarf. The predictions of this tidal model are viscosity-dependent, therefore Smak's and Ogilvie's model has the potential to measure the viscosity in discs.

Shocks and vertical enhancements would evolve in different ways when the disc cools down and heats up during quiescence and outburst respectively. In the case of shocks, as the Mach numbers in the disc increase during quiescence, we would expect the opening angle of the spirals to decrease, producing very wound up spirals as opposed to the large opening angle spirals seen during outburst. According to Ogilvie (2002), in the case of vertical structure caused by tidal interactions with the donor star, the cooling down of the disc only contributes to decreasing the luminosity of the central regions of the CV and the irradiation of the tidal distortions. The spiral structure will appear fainter but it would not move its position in the disc. During quiescence accretion discs are also known to shrink (e.g. Wood et al. 1989) thus if the radius of the disc becomes smaller than the tidal radius, the vertical structure will not form.

At present there seem to be arguments in favour and against both explanations. For example, in favour of the shocks we have Baptista's (this volume) signatures of sub-Keplerian velocity in the disc in eclipse maps of IP Peg during outburst. We would expect the gas to slow down as it reaches the shocks, which is what these sub-Keplerian velocities seem to be indicating. This is not to be confused with the

sub-Keplerian velocities seen in the outer discs of some CVs which can be either produced by the collision of the accretion stream with the disc, or intrinsic to the outer disc, e.g. Marsh 1988. On the other hand, Neustroev et al. (2002) and Unda-Sanzana et al. (in press) find indications of the presence of spiral structure in the discs of IP Peg and U Gem respectively *during quiescence* (see Fig. 1). If confirmed, this would indicate that the spiral structure is not a wave or a shock that evolves to smaller opening angles when the disc cools down, but the result of tidally thickened sectors of the disc being irradiated by the white dwarf, boundary layer and/or inner disc. During quiescence the luminosity of the central regions of the disc will be smaller and the spiral pattern will be fainter than during outburst.

Currently there are two data sets known to the author that cover a large part of the outburst of two CVs known to show spiral structure in their discs. The first one consists of 5 nights taken at the INT and several at the MMT during the April/May 2001 outburst of U Gem (Steeeghs et al. in preparation). The second one corresponds to the 2001 outburst of WZ Sge and is discussed by Steeghs (this volume). From these two data sets we can see how the spiral structure changes from night to night during the outburst. In the case of U Gem the last two nights of data were taken when the system was declining from outburst. The spirals are no longer present in the spectra taken in these two nights. Unfortunately, due to large gaps in the coverage of the quiescence-outburst-quiescence transitions none of these data sets allow us to see whether the spirals wind themselves up or remain the same but just go fainter.

We envisage that the only way to study in detail these state transitions and therefore to discern between the two models proposed to explain the spirals, is by making use of the target of opportunity and monitoring capabilities of a robotic telescope. We believe that the 2 m Liverpool telescope + spectrograph (Morales-Rueda et al., this volume) will be the best combination to obtain the data that will allow us to answer these questions.

### 3. Conclusions

Doppler tomography has proved to be a very powerful technique to study CVs. Recent results include the detection of the donor star in WZ Sge during outburst, the detection of spiral structure in WZ Sge during outburst and in IP Peg and U Gem during quiescence.

We believe that Doppler tomography will be the key to understanding the evolution of spiral structure in accretion discs during the accretion state transitions and therefore will help us distinguish between the models proposed for the formation of this structure with important consequences regarding the viscosity in outburst discs.

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**Table 1.** List of Cataclysmic Variables for which Doppler tomograms have been obtained. The codes used in the table are the same as those in Marsh (2001). Types include: dwarf novae (DN), old nova (N), nova-like (NL), helium CV (HeCV), intermediate polar (IP), polar (P). States include: quiescence (Q) or outburst (O), superoutburst (SO), standstill (SS), flaring (F), high (H), low (L) and middle (M). The features found in the maps are rings (1), spots (2), the donor star (3), spiral structure (4), the gas stream (5) and low velocity emission (6). The four quadrants of the map are marked from “a” to “d” starting with the upper left quadrant and moving anticlockwise. Note 1: maps obtained on several nights during outburst are presented showing the evolution of the emission sites. Note 2: data obtained in the decline from outburst. Note 3: the gas stream emission does not follow a ballistic trajectory.

Object	Type	State	Resolution km s <sup>-1</sup>	Line(s)	Features	References
IYUMA	DN	Q	220	H $\alpha$ , H $\beta$ , He I $\lambda$ 5876 Å	1, 2a	Rolfe et al. (2001)
"	"	O	?	H $\alpha$	1, 2abc, 3 <sup>1</sup>	Rolfe et al. (2002)
WX Cet	DN	Q	206	H $\alpha$	2cd, 3	Tappert et al. (2003)
AK Cnc	DN	O	91	H $\alpha$	6	Tappert et al. (2003)
AQ Eri	DN	Q	91	H $\alpha$	3, 6	Tappert et al. (2003)
VW Hyi	DN	O/Q <sup>2</sup>	50	H $\alpha$	1, 3, 5	Tappert et al. (2003)
RZ Leo	DN	Q	274, 206	H $\alpha$	2abcd	Tappert et al. (2003)
TU Men	DN	Q	91	H $\alpha$	1, 3	Tappert et al. (2003)
HS Vir	DN	Q	114	H $\alpha$	2a, 6	Tappert et al. (2003)
IP Peg	DN	Q	125, 73	H $\alpha$ , H $\beta$ , H $\gamma$ , H $\delta$	1, 2a, 2c, 4?	Neustroev et al. (2002)
FS Aur	DN	Q	171	H $\beta$ , H $\gamma$ , He I $\lambda$ 4472 Å	6	Neustroev (2002)
"	"	"	"	He II $\lambda$ 4686 Å	1 in He II?	Neustroev (2002)
WZ Sge	DN	O	36	H $\alpha$	1, 3, 4?	Steehgs et al. (2001)
"	"	O	100	He II $\lambda$ 4686 Å	4?	Baba et al. (2001)
"	"	O	53	He II $\lambda$ 4686 Å	4	Kuulkers et al. (2002)
"	"	O	?	P $\beta$ , P $\gamma$	2acd	Howell et al. (2003)
"	"	O	?	He I 1.083 $\mu$ , He II 1.163 $\mu$	1, 2ab, 2cd	Howell et al. (2003)
BV Pup	DN	Q	67	H $\beta$	H $\beta$ : 1, 2a	Bianchini et al. (2001)
"	"	"	"	He II $\lambda$ 4686 Å	He II 2b	Bianchini et al. (2001)
EM Cyg	DN	SS	36	H $\alpha$	1, 3	North et al. (2001, 2002)
V426 Oph	DN	Q	36	H $\alpha$	6	North et al. (2001, 2002)
SS Cyg	DN	Q	36	H $\alpha$	3, 6	North et al. (2001, 2002)
AH Her	DN	Q	36	H $\alpha$	3, 6	North et al. (2001, 2002)
U Gem	DN	O	30	He II $\lambda$ 4686 Å	1, 3, 4	Boffin & Steeghs (2002)
"	"	Q	13	He II $\lambda$ 4686 Å	2a	Unda-Sanzana & Marsh (2002)
"	"	Q	18	He I $\lambda$ 6678 Å	2a, 3, 6	Unda-Sanzana & Marsh (2002)
OY Car	DN	O	?	H $\alpha$	3, 5	Mason & Howell (2002)
EX Hya	IP	-	?	H $\alpha$	1, 2ab	Wynn (2001)
V1025 Cen	IP	-	86	H $\beta$	1, 3, 5	Hellier et al. (2002)
UZ For	P	-	?	He II $\lambda$ 4686 Å	3, 5	Schwope (2001)
V1309 Ori	P	-	115	H $\gamma$ , He I $\lambda$ 4472 Å	3, 5	Staude et al. (2001)
"	"	"	115	He II $\lambda$ 4686 Å	3, 5	Staude et al. (2001)
"	"	"	84	He I $\lambda$ 8236 Å	3, 5	Staude et al. (2001)
BY Cam	P	-	?	H $\beta$	6	Schwope (2001)
V1432 Aql	P	-	?	He II $\lambda$ 4686 Å	6	Schwope (2001)
RXJ1313	P	H	91 - 137	H $\alpha$	3	van der Heyden et al. (2002)
"	"	"	133	H $\beta$ , H $\gamma$ , He II $\lambda$ 4686 Å	3, 5	van der Heyden et al. (2002)
V834 Cen	P	-	?	He II $\lambda$ 4686 Å	3, 5	Potter et al. (2001)
AM Her	P	-	80	He II $\lambda$ 4686 Å	3, 5 <sup>3</sup>	Schwarz et al. (2002)
"	"	"	50	Na I, Ca II	3	Schwarz et al. (2002)
UW Pic	P	-	93	H $\beta$ , He II $\lambda$ 4686 Å	3, 5	Romero-Colmenero et al. (2003)
V895 Cen	P	H	229	H $\alpha$	3, 5?	Salvi et al. (2002)
V841 Oph	N	-	82 - 91	H $\alpha$ , He I $\lambda$ 6678 Å	1?, 3, 6	Diaz & Ribeiro (2003)
RR Pic	N	-	112	H $\alpha$ , He I $\lambda$ 6678 Å	1, 2ac	Schmidtobreick et al. (2003)
GP Com	HeCV	-	56(red), 38(blue)	HeI, HeII	1, 2a, 6	Morales-Rueda et al. (2001, 2003)
AM CVn	HeCV	Q	138	He I $\lambda$ 4472 Å	1, 2a	Nelemans et al. (2001)