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Doppler tomography in cataclysmic variables: an historical perspective

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Abstract. To mark the half-century anniversary of this newly-born field of Cataclysmic Variables, a special emphasis is made in this review, on the Doppler Effect as a tool in astrophysics. The Doppler Effect was in fact, discovered almost 170 years ago, and has been since, one of the most important tools which helped to develop modern astrophysics. We describe and discuss here, its use in Cataclysmic Variables which, combined with another important tool, the tomography, first devised for medical purposes 70 years ago, helped to devise the astronomical Doppler Tomography, developed only two decades ago. A discussion is made since the first trailed spectra provided a one dimensional analysis of these binaries; on the establishment of a 2D velocity profiling of the accretion discs; and unto modern techniques, which include Roche Tomography, time modulation and 3D imaging.

Key words. stars: cataclysmic variables – Doppler tomography – spectroscopy

1. Introduction

Doppler (1842) published his monography *ber das farbige Licht der Doppelsterne und einiger anderer Gestirne des Himmels* to explained the change in colour in binary stars and other stars in the sky. Although not yet based in spectral line shifting, this triggered the works of Ballot in 1945 on sound waves, and that of Fizeau in 1948 on electromagnetic waves and the change of the emitting frequency of an object, as it approaches or recedes. The Doppler effect is, without doubt of the the most important tools in modern astrophysics. Particularly, in the study of spectroscopic binary stars, the Doppler Effect allows us to measure radial velocity curves, and through them, calculate mass ratios and orbital periods, In the case of eclipsing binaries we are able to obtain a full set of orbital parameters which include masses, ratios, orbital separation and inclination angle.

Another important scientific result is the medical tomograph, developed in the 1930s by the radiologist Vallebona, who use the technique of projectional radiography. The mathematical basis for the reconstruction of a tomographic image was established by Radon (1917). The idea, as the name suggests, is to use several slice images taken around an object, and to reconstruct an image. Doppler Tomography would therefore be a technique based on the reconstruction of an object based on doppler obtained, image slices, around an object. Contrary to medical scans, in binary stars we take image slices, as the two stars revolve one orbital cycle around each other, since we cannot go around them, like in the med-

Send offprint requests to: J. Echevarría ical scans. It is obvious that such stars have to be short orbital periods systems, in order to obtain results in a reasonable period of time. Interactive binaries are such a class of objects.

2. Doppler tomography of cataclysmic variables

Although we are concerned here with Cataclysmic Variables (CV's), most of the results discussed in this review apply to interactive binaries in general, i.e any class of double stars in which an exchange of matter occurs. Doppler Tomography of Cataclysmic Variables should be understood as an image reconstruction of its components *via* the doppler shift of the emission or absorption lines, visible in their spectra, along an orbital period. This *image* is subject to interpretation, since we are only dealing with radial velocities and therefore we have to make some assumptions about the location of the material in the stars and around them. Furthermore, as its is in most cases, we do not know the inclination angle of the system and we observe only the projected velocity.

2.1. Trailed spectra

The first tomograms of CV's are, in a sense, the early trailed spectra obtained around the 1960s. An example of this is illustrated in Fig. 1.

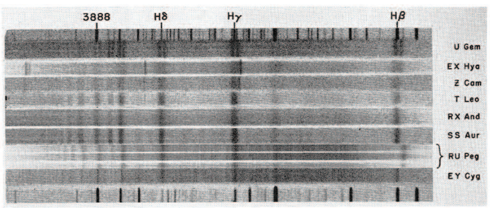

Fig. 1. Trailed spectra of Cataclysmic Variables by Kraft (1962).

The figure shows the photographic spectra of several Dwarf Novae in quiescence, obtained with the prime-focus of the 200-in telescope.These *images* show, visually, the movement of broad emission lines, the presence of asymmetric components and in some cases, like RU Peg, the presence of numerous absorption lines moving in anti-phase with the broad emission lines. The broad emission lines give, in particular, a first picture of the accretion disc, its extension and degree of symmetry, while the asymmetric or S-wave component, show the behavior of the hot spot in the disc, detected in photoelectric light curves like in the case of U Gem (Krzeminski 1965). In the case of EY Cyg, the system was thought to be near pole-on and it took many years to detect the periodic radial velocity variation of its components Echevarría et al. (2007b).

2.2. 1D tomography

In a strict sense, any slice sections taken around an orbital period should be considered as a tomogram. This is the case of the simplest analysis of the overall radial velocity measurements of the binary components, which gives us a very basic, but fundamental picture of the system. This has been the basis for obtaining orbital periods and mass ratios. One of the first radial velocity *picture* was made by Joy in 1954 for AE Aqr as shown in Fig. 2. The orbital period was overestimated by Joy, but its value was later corrected by Payne-Gaposhkin (1969).

Radial velocity studies of CV's have been a keystone in many ways. They have provided the basics for understanding their nature and variety Warner (1995), as well as their formation and evolution Ritter (2012).

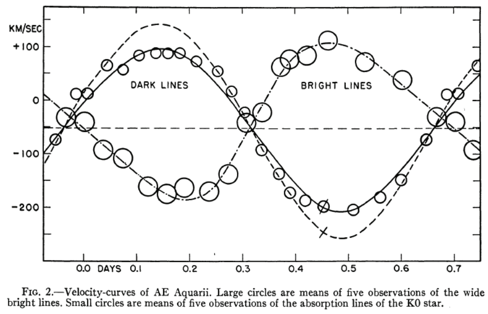

Fig. 2. The radial velocity semi-amplitude of the components of AE Aqr. by Joy (1954).

2.3. Classical tomography

In the late eighties Marsh & Horne (1988) proposed a method to reconstruct images of accretion discs, based on the profiles of their emission lines. These are two-dimensional maps in velocity space. Their proposed method, has been greatly successful. An extensive review can be found in Marsh (2001). An Atlas of Doppler Tomography for Cataclysmic Variables can be found in Kaitchuck et al. (1994).

An example of a velocity space image is shown in Fig. 3, for the Hα emission line in U Geminorum Echevarría et al. (2007a).

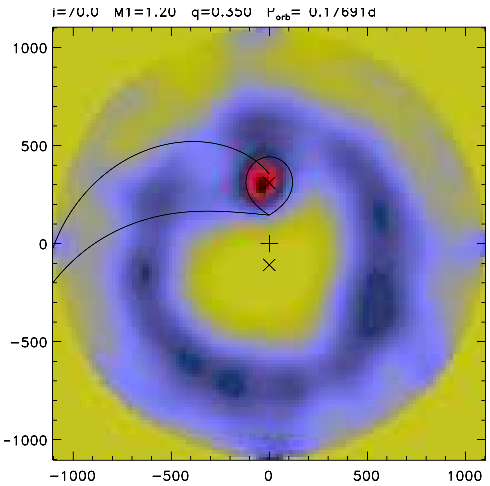

Fig. 3. An Hα velocity map of U Gem Echevarría et al. (2007a).

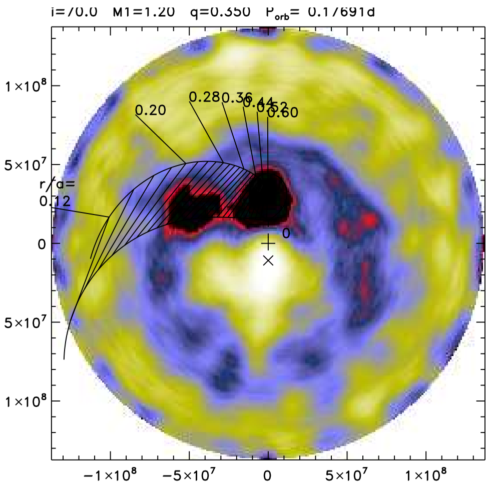

Fig. 4. Velocity map of U Geminorum in 2006 Echevarría et al. (2012b).

This tomogram has the typical layout for a CV. The Roche Lobe of the secondary is shown, as well as the keplerian and stream trajectories of the transferred matter. It is important to stress out that in this representation in space velocity, the inner disc corresponds to the outer geometrical boundary, while the external disc, at the higher velocities has a cutoff at the boundary layer. It is therefore necessary to interpret this map, as there is not a one to one correspondence between velocity and space. As an example of this ambivalence we point out at the position of the hot spot in the diagram. Although the material seems to be located in the forward face of the secondary, it is also possible that the emission comes from the L_1 point and has rapidly acquired a keplerian velocity. This is unusual in U Gem, as we should have expected to see the hot spot much further away, along the keplerian line, colliding with the disk to the left of the V_y axis. However, at least in the case of the Balmer lines, the hot-spot appears to come, at times, from a mixture of disc and stream velocities Marsh et al. (1990), often with an average velocity between them. This is clearly the case, shown in Fig. 4, from a tomogram derived for U Gem (Echevarría et al. 2012b).

2.3.1. On the basic assumptions

We also assume that all the visible material is in the orbital plane, which might not be the real case, especially in polars, where the material is funneled into the white dwarf by the magnetic poles, outside the orbital plane. The principles of standard Doppler Tomography have been discussed by (Marsh 2005). Some of them are obviously contravened, like polar flow, emission from the mass donor and systems in outbursts. Therefore, one has to be careful in the spatial interpretation of any tomogram.

2.3.2. Achievements

New discoveries have been achieved with Doppler Tomography, which include the presence of spiral structures in discs; bright-spots from the secondaries stars; missing discs in nova-like systems; as well as stream emission in polars. The Dwarf Nova IP Peg, was the first system found to have a spiral-arm structure during their outbursts (Steeghs et al. 1997). Since this important discovery, this spiral structure has been detected in several systems. Among them are the nova-like V3885 Sgr (Hartley et al. 2005) and UX UMa (Neustroev et al. 2011); WZ Sge during its 2001 super-outburst (Baba et al. 2002) (Fig. 5) and (Echevarría et al. 2012a) (Figs. 6 and 7); and the dwarf nova U Gem during outburst (Groot 2001). During quiescence Neustroev et al. (2004) have found indications of a spiral structure in U Gem. Echevarría et al. (2012b) have also found that, at this stage, U Gem has a complex behavior, including spiral structures as shown also in Fig. 8.

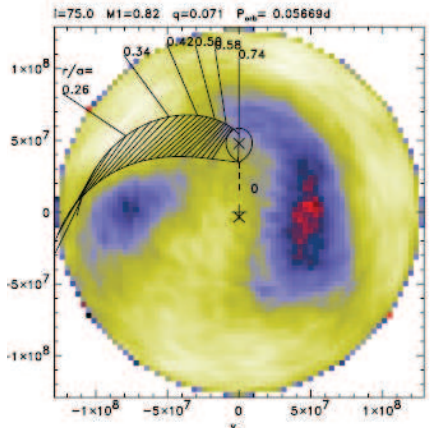

Fig. 5. He II tomogram of WZ Sge during the 2001 super-outburst by Baba et al. (2002).

During the 2001 super-outburst of WZ Sge, evidence has been found by Patterson et al. (2002) and Echevarría et al. (2012a) (see also Fig. 7) that the hot-spot increases substantially. As remarked by Patterson, it is possible that enhanced mass transfer from the secondary plays a major role in the eruption.

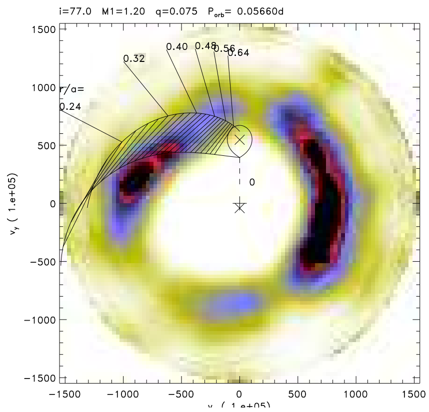

Fig. 6. *Hβ* tomogram of WZ Sge during super-outburst taken on 2001, July 6 (Echevarría et al. 2012a).

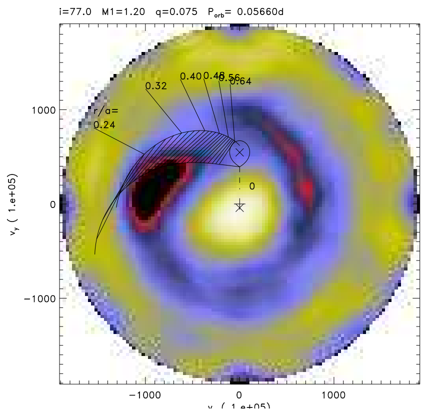

Fig. 7. HeII tomogram of WZ Sge during super-outburst taken on 2001, July 1-3 (Echevarría et al. 2012a).

Bright-spots from the secondary stars have been detected in several systems like U Gem (see Marsh et al. 1990; Unda-Sanzana et al. 2006; Echevarría et al. 2007a); BY Cam (Schwarz et al. 2005), and OY Car in outburst (Harlaftis & Marsh 1996), among others (see also Harlaftis and Marsh and references therein). These emissions can be interpreted in some cases as mass transfer seeing through the L_1, which collide with a large accretion disc, producing a hot-spot near the lagrangian point

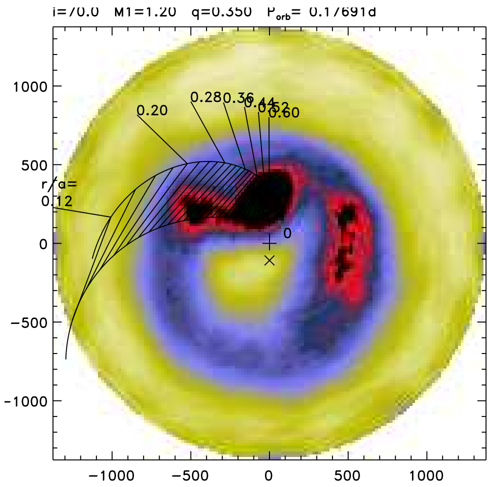

Fig. 8. Velocity map of U Geminorum in 2008 Echevarría et al. (2012b).

(Echevarría et al. 2007a); or from irradiation on the secondary star by the inner disc (Marsh 2001). As pointed out by Harlaftis and Marsh, the origin of this emission, coming from all type of stars and in different states, has yet to be determined.

In some nova-like stars there is little evidence of a full accretion disc, like in UU Aqr, V413 Aql, V363 Aur, AC Cnc, VZ Scl, LX Ser, SW Sex, RW Tri and SW UMa (see Kaitchuck et al. 1994). In some cases a ring is seen, but in many cases there is a large blob of material only in the second and third quadrant of the disc or a dense blob near the location of the white dwarf. The high transfer rates in nova-like systems is thought to be a probable cause of this, as the material is jettisoned along the stream trajectory and returns to the disc at the opposite direction of the secondary star, producing either the large blob, or captured in the vicinity of the white dwarf. Such is the case of J0644+3344, a newly discovered eclipsing binary, classified as a CV by Sing et al. (2007) and discussed in these proceedings by Hernández Santisteban (2012). The $H\alpha$ and $H\beta$ maps show a large blob around the third quadrant. There is also evidence of material near the white dwarf in the $H\alpha$ tomogram and, as in other objects, HeII shows a strong and narrow emission near the vicinity of the white dwarf, as shown in Fig. 9 (Hernández Santisteban et al. 2012).

The characteristics of the system indicates that this is a SW Sex type system rather than a UX UMa one. Both classifications were suggested by Sing et al. (2007).

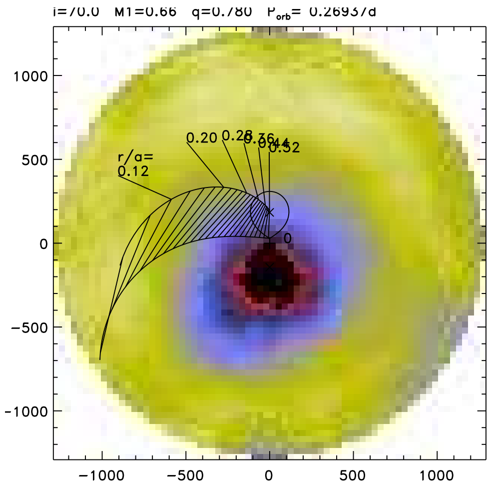

Fig. 9. HeII velocity map of J0644 Hernández Santisteban et al. (2012).

Doppler tomograms of polars have shown unmistakably the presence of stream-like flow unto the magnetic poles of the primary stars, like in HU Aqr (Heerlein et al. 1999) and UZ For (Schwope et al. 1999). In the case of the asynchronous polar BY Cam (Schwarz et al. 2005) a curtain emission is rather detected, while in the semi-polar V2306 Cyg (Zharikov et al. 2001) an accretion ring is observed, as well as hot-spots caused by the X-ray beam and from the interaction of the mass transfer stream, as shown in Fig. 10.

We point out again, that what we *see* in these tomograms is an interpretation of where the observed material is in the geometrical space of the binary. As discussed, one of the assumptions to construct classical Doppler Tomography is to assume that all the material is in the orbital plane, which evidently in polars, might not be the case at all!

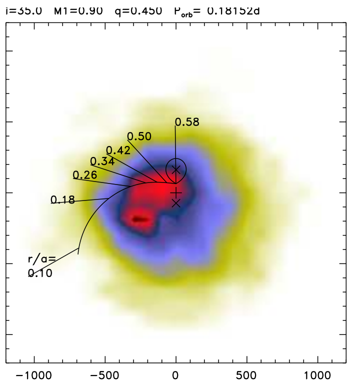

Fig. 10. *Hβ* velocity map of V2306 Cyg Zharikov et al. (2001).

2.4. Roche tomography

A tomographic application to study the secondary stars in Cataclysmic Variable has been developed in the last two decades. Roche Tomography (Rutten & Dhillon 1994; Smith 1995) use the absorption lines profile which is interactively fitted to a grid of square specific fluxes lying on the surface the critical potential surface that defines the Roche Lobe. A full extent of the procedure and basic assumptions can be found in Dhillon & Watson (2001). Roche Tomography from single line data like the Na I doublet, used in AM Her, IP Peg and QQ Vul (Watson et al. 2003), reveal only partial information such as irradiation Smith (2012). Similar results have been obtained in HU Aqr by these authors, using the He II 4686 emission line, and on EX Hya by Beuermann & Reinsch (2008) using the NaI doublet in absorption and emission, as well as CaII 8498 in emission.

To detect spots on the secondary surface many spectral lines are needed (Dhillon & Watson 2001), using techniques such as the Least-Squares Deconvolution (LSD), developed for single rapidly rotating active stars (Donati et al. 1997). First results have been obtained on AE Aqr by Watson et al. (2006) (see Fig. 11). The secondary star shows several large, cool star-spots and the presence of a large, high-latitude spot, similar to that seen in rapidly rotating isolated stars. Similar results have been obtained on BV Cen by Watson et al. (2007) and on RU Peg by Dunford et al. 2001 (see Smith 2012).

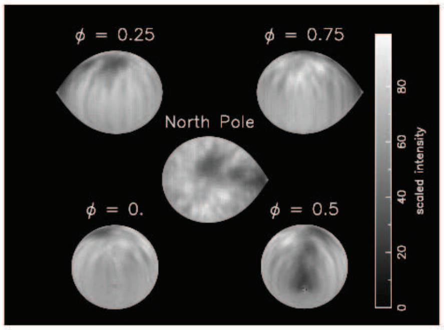

Fig. 11. Roche Tomography of AE Aqr from Watson et al. (2006).

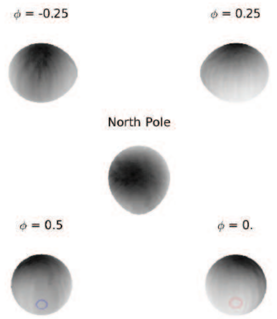

Fig. 12. Roche Tomography of LTT 560 from Tappert et al. (2011).

Although the Roche Tomography in Cataclysmic Variables is a powerful tool to study the secondary stars, it has the disadvantage, compared to isolated or detached binary stars, that the accretion disc masks the signature of the absorption lines and therefore, only large orbital period systems can be observed. For example, based on the Roche Tomography method by Rutten & Dhillon (1994) and the LSD analysis, Tappert et al. (2011) have found, in the detached post-common envelope binary LTT 560, that a large area of the secondary star on its leading side is covered by star spots, as shown in Fig. 12.

2.5. Modulated and 3-dimensional tomography

New applications of Doppler Tomography have been developed. Among them, time modulated as well as three-dimensional (3D) Doppler Tomography. Steeghs (2003) has extended the classical tomography to a modulated emission line tomography by relaxing the requirement that the material is visible at all times and allowing the mapping of time-dependent emission sources. He has applied a new code to IP Peg during outburst and finds (see Fig. 13) that the asymmetric two-arm disc modulates strongly in terms of its sine and cosine amplitudes.

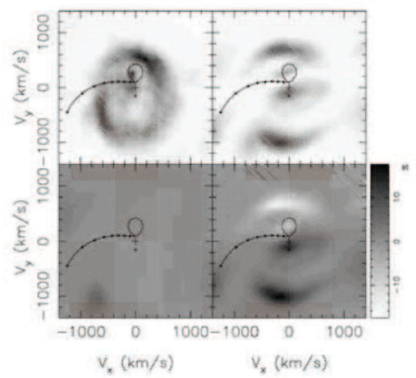

Fig. 13. Modulated Tomography of IP Peg from Steeghs (2003).

Agafonov et al. (2006) have also developed a three-dimensional (3D) tomography by relaxing, this time, the requirement that all the material is all in the orbital plane, thus exploring the z-axial dependance. They find a high velocity stream across the orbital plane for the Algol-type system U CrB which has a well know high inclination angle. Richards et al. (2010) have also found evidence of out of the plane flow for the system RS Vul.

3. Conclusions

We have reviewed, Doppler Tomography in Cataclysmic Variables, making a special emphasis on the Doppler Effect as a tool in general in astrophysics, a discovery made more that a century and a half years ago. Combined with another important tool, the tomography, devised for medical purposes during de middle of the last century, Doppler Tomography has been devised for Cataclysmic Variables recently. A discussion was made, starting from the first trailed spectra to the establishment of a 2D velocity profiling of the accretion discs and unto other techniques, which involve Roche Tomography of the secondary stars, time modulated and 3D imaging tomography of the discs.

4. Discussion

Dmitry Kononov

As you state, I understand that the bright spot increase during the outburst due to the increase mass transfer rate. But don't you suppose that it may happen due to the redistribution of the intensity when the almost destroyed disc becomes fainter and most of the contribution to the tomogram is from the shocks.

Echevarría

It is the case in WZ Sge that a well formed disc still remains near the peak of the outburst, nearly 10 days after maximum as shown in Fig. 7. This tomogram was constructed from spectra taken on 2001, 1-3 of July and three days later, on July 6, the system still shows a spiral structure as shown in Fig. 6.

Dmitry Bisikalo

Could you comment on the perspectives of 3D tomography?

Echevarría

The method has proved to be effective for very well know high inclinations systems. It has yet to be seen if it can be applied other systems as well. The adjustment of a stretching effect, specifically a general deconvolution of the image along the z-direction, presents a significant constraint on the full reconstruction of the 3D image.

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