Feeding Compact Objects: Accretion on All Scales
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Explorations into 3D Doppler Tomography of Interacting Binaries

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Abstract. Over the past twenty-five years, the technique of Doppler tomography has produced many 2D images of the accretion structures and other gas flows in a range of systems containing compact and non-compact stars, including cataclysmic variables, polars, Algols, x-ray, and gamma-ray binaries. Recent 3D images derived from the Radio astronomical Approach (RA) have revealed prominent gas motions beyond the central plane, and display the usual characteristics found in 2D images, as well as new evidence of tilted or precessing accretion disks around the mass gainer, and magnetic loop prominences and coronal mass ejections associated with the donor star. In this work, we have compared new 3D images derived from the back projection tomography technique with those derived from the RA method. In general, back projection produces sharper and more distinctive images than the RA method, thereby permitting a more detailed study of the physical properties of the accretion sources.

Keywords. Accretion, accretion disks, (stars:) binaries techniques: image processing, X-rays: binaries, gamma rays: observations, stars: individual (β Per, U CrB, RS Vul, Cyg X-1)

1. Introduction

Tomography has revolutionized the study of interacting binaries by creating indirect images of the gas motions in each system. Images are reconstructed from spectra of eclipsing systems observed at multiple orbital phases, from which projections or slices of the image can be viewed. Two-dimensional Doppler tomograms of Algols, CVs, polars, x-ray and gamma- ray binaries show visual evidence of the gas stream from the donor star; symmetric and asymmetric accretion disks; shock regions where the stream and disk interact; regions where the gas slows down after circling the mass gainer in direct-impact systems; magnetic structures associated with the donor star; and gas flowing along magnetic field lines on the mass gainer.

The basic technique for computing tomograms was described by Radon (1917) in terms of the projections of an object. Three-dimensional Doppler tomograms have been reconstructed from these projections using the Radioastronomical Approach (RA; Agafonov & Sharova 2005a,b) and the Back Projection (BP) technique (Marsh & Horne 1988; Radon 1917; Richards 2004, 2012). The main differences are that the RA technique is faster and can be used with a limited number of projections, while the BP technique produces sharper and more distinctive images (Agafonov, Richards & Sharova 2006).

The *3D Radioastronomical Approach* solves the convolution equation: $g(x, y, z) = f(x, y, z) *** h(x, y, z) + n(x, y, z)$, where $g(x, y, z)$ is the summarized image or "dirty map", $f(x, y, z)$ is the brightness distribution of the unknown object, $h(x, y, z)$ is the summarized point spread function, and $n(x, y, z)$ is the noise. The extension to 3D has also been achieved with the *3D Back Projection* technique (e.g., Bracewell & Riddle 1967). Here, $f(v_x, v_y, v_z)$ is the 3D velocity image; $p(v_r, \phi, i)$ is the intensity of the line profile, with Doppler shift v_r at each orbital phase ϕ and orbital inclination i;

$v = \gamma - v_x \cos\phi \sin i + v_y \sin\phi \sin i + v_z \cos i$; and γ is the systemic velocity of the binary. In the case of 2D tomography, set $v_z = 0$ and $i = 90°$.

$$f(v_x, v_y, v_z) = \int_0^{2\pi} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} p(v_r, \phi, i)\ |\omega|\ e^{2\pi i\omega(v-v_r)}\ dv_x dv_y dv_z\ d\omega\ d\phi$$

2. New Results from 3D Tomography

To date, 3D Doppler tomography with the Radioastronomical Approach has been applied to four binaries: U CrB (Agafonov *et al.* 2006, 2009), RS Vul (Richards *et al.* 2010), β Per (Richards *et al.* 2012), and Cyg X-1 (Sharova *et al.* 2012). This 3D technique has produced significant results that could not be derived from 2D Doppler tomography: (1) Prominent gas flows exist beyond the central plane (in the z-direction) of each binary. (2) The 3D images are consistent with the images derived from 2D tomography for $V_z = 0$. (3) A precessing and/or tilted accretion disk exists in at least one system (e.g. U CrB). (4) Loop prominences and coronal mass ejections (CMEs) associated with the cool donor star were found in two systems: RS Vul and β Per. (5) The 3D images confirm evidence of the superhump phenomenon: that the gas stream and annulus are threaded with the donor's magnetic field (e.g. β Per). (6) The gas stream can be deflected beyond the central plane by the magnetic field of the mass loser (e.g. RS Vul). Finally, (7) the 3D results derived from back projection are consistent with those derived from the RA method.

Recent applications to compact mass gainers include the 2D ultraviolet tomogram of the nova-like binary V3885 Sgr based on the S IV λ1063 and λ1073 doublet (Prinja *et al.* 2012), and the 3D tomogram of Cyg X-1 based on Hα lines (Sharova *et al.* 2012). The 2D tomogram of the gamma-ray binary LS I +61 303 displays a prominent Keplerian accretion disk (Richards, McSwain, & Cocking 2012); while a new 3D tomogram of the BD+46°442 binary (neutron star with AGB companion) suggests the presence of a jet (Richards, Gorlova, & Cocking 2012).

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