THREE-DIMENSIONAL DOPPLER TOMOGRAPHY OF THE RS VULPECULAE INTERACTING BINARY

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ABSTRACT

Three-dimensional Doppler tomography has been used to study the \Halpha emission sources in the RS Vulpeculae (RS Vul) interacting binary. The two-dimensional tomogram of this binary suggested that most of the emission arises from the cool mass losing star with additional evidence of a gas stream flowing close to its predicted trajectory. However, the three-dimensional tomogram revealed surprising evidence that the gas stream has an average velocity of $-85$ km s\textsuperscript{-1} relative to the central velocity plane at $V_z = 0$ km s\textsuperscript{-1}, unlike U CrB in which the stream was prominent along this central plane. These unexpected $V_z$ motions may result from the interaction between magnetic activity on the cool star and the gravitationally induced Roche lobe overflow from that star. Evidence of a loop prominence on the cool star close to the L1 point has been found in the three-dimensional tomogram of RS Vul; hence, the magnetic field lines may have deflected the gas stream relative to the central plane. This result is consistent with earlier detections of RS Vul as both an X-ray and a radio source, and represents the first detection of a loop prominence in an interacting binary based on tomography. Moreover, recent radio images of $\beta$ Per, the prototype of the Algols, show that the magnetic field of the mass losing star is asymmetric and extends well beyond the orbital plane of the binary, so it is now plausible that the gas flow between the stars in RS Vul could be deflected in an asymmetric way by the magnetic field.

Key words: accretion, accretion disks – binaries: close – binaries: eclipsing – circumstellar matter – stars: imaging – stars: individual (RS Vulpeculae, U Coronae Borealis) – techniques: image processing

Online-only material: color figures

1. INTRODUCTION

Direct images of interacting binaries are difficult to create because the stars have separations in the milliarcsecond regime. Nevertheless, the CHARA and NPOI optical interferometers have produced the first resolved optical images of the $\beta$ Per (Algol) binary (Czismadia et al. 2009 and Zavala et al. 2010). Even with these advances, these direct images do not contain enough detail to isolate the gas flows between the stars. However, a global very long baseline radio interferometer array was recently used by Peterson et al. (2010) to create a resolved 15 GHz radio image of $\beta$ Per which displays asymmetric magnetic structures that are not confined to the orbital plane. Since $\beta$ Per is the prototype of the Algol-type eclipsing spectroscopic binaries, it is reasonable to expect that other members of that class may exhibit similar behavior. The three-dimensional (3D) structures of these binaries can now be examined more closely through indirect images provided by Doppler tomography (Agafonov et al. 2006, 2009).

Two-dimensional Doppler images can be created with the standard Filtered Back Projection (FBP) Method or with the Maximum Entropy Method (MEM) by projecting the sources of emission onto a single central $(V_x, V_y)$ velocity plane (e.g., Kaitchuck et al. 1994; Marsh & Horne 1988). This plane is expected to coincide with the orbital plane of the binary since this is where the gravitational forces dominate the gas flows. However, these sources may have non-zero velocities beyond the central two-dimensional (2D) plane since they are not geometrically thin and are not confined to the orbital plane. Instead, 3D images can be derived over a range of $V_z$ values transverse to the central plane. The resulting 3D maps are consistent with the 2D Doppler tomograms obtained with the MEM and FBP method and reveal substantial flow structures beyond the central velocity plane. Recent 2D tomography of cataclysmic variables and X-ray binaries (e.g., Elebert et al. 2009) has continued to demonstrate that this technique is a viable modeling tool, even though it is well known that the gas flows are not confined to the orbital plane. These analyses have provided reliable solutions to the observed spectra and the plausibility of the 2D solutions has gained a foothold in the literature.

The 3D reconstruction method applied in this work is the Radioastronomical Approach (RA) developed by Agafonov (2004a, 2004b) and Agafonov & Sharova (2005a, 2005b). A detailed discussion of the differences between this technique and the FBP method can be found in Agafonov et al. (2006, 2009). In particular, the RA method is especially useful when the number of projections is relatively small because it can achieve the same resolution as FBP while using fewer profiles (see Figure 1 of Agafonov et al. 2006). The effectiveness of the RA method has been examined by using initial 3D test models, calculating one-dimensional (1D) profiles from these models, and then performing the reconstruction. Sharova (2006) compared the computed and initial models and showed that the computed emission maxima coincided with the initial model and all details were reproduced. Hence, there was very good agreement between the initial test model and the reconstructed 3D tomogram. Additional tests of the plausibility of the solutions include comparisons between the observed and computed trailed spectrograms and the chi-square estimate of the quality of the fit between these spectra.

The two-dimensional Doppler tomograms of the Algol-type binaries (Richards et al. 1995; Albright & Richards 1996; Richards 2004) display a diverse range of circumstellar structures. These include a gas stream, accretion annulus, transient accretion disk, shock regions, and sometimes a chromospheric emission source in the short-period ($P < 5$ days) Algols, as well as a classical accretion disk in the long-period ($P \geq 5–6$ days).
Algols. Richards & Albright (1999) found that some systems, like U Coronae Borealis (U CrB) and U Sagittae (U Sge), alternate between streamlike and disklike states and display changes that can occur within a year, and sometimes overnight. They identified RS Vulpeculae (RS Vul) as a member of this group.

The first applications of the 3D procedure focused on the interacting Algol-type binary U CrB. The 2D tomograms constructed from Hα spectra of this binary collected in 1993 and 1994 displayed two distinct patterns: a transient accretion disk representing the disklike state (in epoch 1993) and a bright gas stream flowing along the predicted ballistic trajectory representing the streamlike state (in epoch 1994). The 3D tomograms of these emission sources were even more distinct than the 2D versions, and both states showed evidence of a prominent emission source associated with the mass gainer, resulting from the impact of the gas stream onto the photosphere of that star (Agafonov et al. 2006; Agafonov et al. 2009). Chromospheric emission from the mass loser was also visible especially when the binary was in the disklike state. The 3D image also showed distinct evidence of gas flows (like a jet) with high Vz velocities. These high-velocity flows were associated with three emission sources: (1) the impact/splash region where the gas stream strikes the mass gainer in the streamlike state (Vz ∼ −300 to +100 km s−1); (2) the interaction between the gas stream and accretion disk in the disklike state (Vz ∼ 300–400 km s−1); and (3) the Localized Region (LR) where the disk material interacts with the incoming gas stream after traveling around the mass gainer (Vz ∼ +200 to +500 km s−1). These high values are expected since the star-stream impact occurs at speeds of up to 500–600 km s−1, compared to the slower rotation of the mass gainer (Richards 1992; Blondin, Richards & Malinkowski 1995; Richards & Ratliff 1998). Moreover, the pattern of Vz velocities associated with the disk emission implies that the disk may be inclined to the orbital plane; which subsequently suggests that the rotation axis of the mass gainer could be precessing as a consequence of the star-stream impact. This result would not have been possible from 2D tomograms alone.

In this paper, we have continued our exploration of 3D tomography by studying the RS Vul system. Specifically, we have (1) identified the features in the 3D images and related them to those seen in the 2D tomograms; (2) compared the 3D tomogram of RS Vul with those of U CrB; and (3) provided a physical interpretation of these features. The system parameters and 2D results are described in Section 2, the 3D tomograms are described in Section 3, a model for RS Vul is given in Section 4, and the conclusions are outlined in Section 5.

2. 2D DOPPLER TOMOGRAPHY OF RS VUL

The Algol-type binary RS Vul is an interacting system in which the cooler G1 III secondary star is transferring mass to its B5 main-sequence companion (the primary) through Roche lobe overflow. RS Vul is a short-period Algol (Porb = 4.4776635 days; Holmgren 1989) with an orbital inclination of 78.7 ± 0.2 (Hutchings & Hill 1971). The properties of the system are M2 = 6.59 ± 0.15 M⊙, M1 = 1.76 ± 0.05 M⊙, R2 = 4.71 ± 0.48 R⊙, R1 = 5.84 ± 0.23 R⊙, systemic velocity Vr = −20.1 km s−1, velocity semi-amplitude K2 = 54.0 ± 1.0 km s−1, with a mass ratio, q = 0.27 (Holmgren 1989). Eighty-one Hα (6562.8 Å) spectra with a dispersion of 0.166 Å pixel−1 or 7.6 km s−1 were collected in 1993 with the KPNO 0.9 m Coudé Feed Telescope (see Richards & Albright 1999). The spectra were collected at closely spaced positions around the entire orbit of the binary. Since the observed spectra are dominated by the spectrum of the B5 mass gaining star, model atmosphere calculations were used to represent the photospheric contributions of the stars, and these stellar contributions were subtracted from the observed spectra to create difference spectra (see Richards & Albright 1999 for details). The difference spectra were used to calculate the tomograms.

The standard 2D Doppler tomogram of RS Vul 1993 is shown in Figure 1 along with the 2D tomogram of U CrB in the streamlike state (from Richards 2001). These 2D images were compared with the 3D Doppler tomograms based on the same data. In the tomograms, the solid trajectory is the gravitational free-fall path of the gas stream; and the circles along this trajectory are marked at intervals of a tenth of the distance from the L1 point to the distance of closest approach to the mass gainer. The largest solid circle and the smaller dashed circle mark the inner and outer edge of a Keplerian disk, respectively; the asterisk is the predicted location where the gas stream should strike the photosphere of the mass gainer; and the plus sign marks the center of mass of the binary. The RS Vul tomogram shows the presence of the gas stream, a circumprimary emission source, chromospheric emission, and a region dominated by absorption called the absorption zone (Richards 2001).
strongest emission source corresponds to chromospheric Hα emission from the donor star (Richards & Albright 1996).

3. 3D Doppler Tomography

The application of Doppler tomography to binary stars involves several important assumptions and constraints.

1. The main assumption is that the spectra are broadened only by Doppler motions, while other sources of the line broadening are neglected. Based on the agreement between the observed tomograms and theoretical calculations or hydrodynamic simulations of Algol-type binaries and cataclysmic variables, the assumption that Doppler motions dominate the observed spectra is a reasonable one.

2. The basic 2D reconstruction technique depends on the availability of spectra with high wavelength resolution as well as good sampling of these spectra around the orbit of the binary (called projections). Inadequate orbital coverage will produce streaks in the reconstructed image with the FBP method, but it has a much smaller influence on the image for the MEM or RA method which incorporate nonlinear reconstruction procedures.

3. An efficient method of processing the image is needed if there are only a few projections. The MEM and RA method are both very effective in creating 2D images under these more stringent conditions. However, only the RA method has been applied in the 3D case to date. The extension to 3D is much more complicated than the 2D situation because the 3D version incorporates the non-equidistant views in 3D space along the surface of a cone with an opening angle equal to the orbital inclination of the system.

4. Another assumption is that the technique can only be applied to emission line spectra, and yet many of the difference spectra of the Algols display absorption components. The tomography technique places these absorption sources at their corresponding velocities in the same way as done for the emission features. Doppler maps made from spectra that exclude these absorption features show the emission features in their identical locations in the tomogram, except that the absorption sources are missing.

5. The basic 2D tomography technique assumes that the gas is optically thin, and the same is true for the 3D calculation. Although we expect that some regions are optically thick, this assumption is reasonable to provide a first-order view of the binary. It is difficult to estimate the impact of high opacity gas until after the initial images have been obtained.

6. In the 2D formulation, it is assumed that there are no gas motions beyond the orbital plane. However, it is natural that the gas should possess all three velocity components (Vx, Vy, Vz).

7. The transformation of the emission intensity from velocity space to coordinate Cartesian space is very complicated and it has not yet been solved even for 2D images. The transformation from $I(V_x, V_y)$ space to $(x, y)$ for the 2D version and from $I(V_x, V_y, V_z)$ space to $(x, y, z)$ for the 3D version can only be solved if the velocity fields of the various emission sources are known. One approach is to use hydrodynamical simulations to estimate these velocity fields.

8. Finally, the 3D reconstruction is influenced by our fixed view of the binary against the plane of the sky. Specifically, the velocity resolution in the Vz-direction relative to those in the Vx- and Vy-directions depends on the orbital inclination. These velocity resolutions are equal only if the orbital inclination is 45°, however the resolution in Vz degrades as the inclination increases from 45° to 90°. Conversely, the resolution in the Vx- and Vy-directions improves from 0° to 90°. The consequence is that the 3D images appear stretched in the Vz-direction in accordance with the behavior of the 3D summarized point-spread function (SPSF) as the inclination angle increases. This effect is illustrated in Figure 2. A true test of the quality of the 3D image is obtained by comparing the observed profiles with those computed from the direct output of the RA method (including the stretching effect) since this represents the direct solution to the data.

The adjustment for this stretching effect, specifically a general deconvolution of the image along the Vz-direction, presents a significant constraint on the full reconstruction of the 3D image. The solution is simple only if the emission features are compact or point sources since the image would then consist of the sum of SPSFs with their different resolutions along the three velocity directions. An adequate adjustment for the stretching effect can then be made along the Vz-direction in this case. However, the situation is more complicated if the reconstructed image consists of both extended and compact features. Once again, an exact...
adjustment can be made for the compact sources but only an approximate adjustment can be made for the extended features. For these reasons, it is more accurate to display the direct output from the RA procedure without any adjustment for the stretching effect since we expect the image to consist of both compact and extended features.

Based on these assumptions and constraints, the RA method creates 3D velocity maps of the gas intensity, without making any prior adjustment for the stretching effect of the point spread function. The emission features identified in earlier published 2D tomograms have been used as a basis for identification of similar features in the 3D tomogram.

Further details of the application of the RA method can be found in Agafonov et al. (2006) and Agafonov et al. (2009). It has been possible to obtain a first view of the 3D structure of accretion flows by (1) creating a procedure for constructing the 3D Doppler tomogram from the 1D projections, (2) constructing the 3D tomograms and identifying the optimum way to display these tomograms, (3) identifying the features in the 3D images and relating them to those seen in the 2D tomograms, and (4) providing an initial physical interpretation of these features. We will also (5) examine these interpretations by constructing synthetic spectra and comparing the Doppler tomograms generated from the observed and synthetic spectra as done in the case of TT Hya with 2D tomograms (Miller et al. 2007). The most challenging part is in the interpretation of the results; hence, any initial interpretations of the emission features will be examined further to provide confirmation of the model.

### 3.1. The 3D Tomogram of RS Vul

For the reconstruction of the 3D Doppler tomograms, we analyzed the same set of Hα line profiles that were used by Richards (2001) to construct the standard 2D Doppler tomogram of RS Vul. The 3D Doppler tomogram was calculated as a set of numerical values in the cells of a cube, with dimensions ($V_x$, $V_y$, $V_z$) having values ranging from $-700$ to $+700$ km s$^{-1}$. The maximum of this function was normalized to the unit to permit a comparison between slices taken from any direction. The appearance of the images has been simplified by displaying the ($V_x$,$V_y$) slices in the horizontal plane to be consistent with the direction of the orbital plane of the binary, while the slices containing the $V_z$-axis are in the vertical direction.

The velocity resolution of the reconstructed 3D image depends on the number of projections (i.e., number of spectra) and their distribution in orbital phase; and the orbital inclination influences the ratio of the resolutions in the $V_x$, $V_y$, and $V_z$-directions. The dispersion of the spectra is 7.6 km s$^{-1}$, which is already sufficiently small to allow for an optimal resolution since it plays a smaller role in setting the resolution of the image compared to the constraints set by the orbital inclination. Since the orbital inclination of RS Vul is high ($i = 78.7$), the velocity resolutions in the $V_x$- and $V_y$-directions will be better than the resolution in the $V_z$-direction. Consequently, the 3D tomogram was restored with a resolution of 30 km s$^{-1}$ in the $V_x$- and $V_y$-directions and 105 km s$^{-1}$ in the $V_z$-direction, corresponding to an SPFS half power beam width of 30 × 30 × 105 in units of km s$^{-1}$. As explained earlier, the lower resolution in the $V_z$-direction is a direct consequence of the high inclination angle.

The quality of the reconstructed 3D image of RS Vul produced by the RA method was examined by comparing the observed spectra with those computed from the reconstructed 3D tomograms. Figure 3 shows the trailed spectrograms in which the radial velocity, $V_r$, is plotted versus orbital phase, with a resolution of 30 km s$^{-1}$. The observed spectra are displayed in the left frames and the spectra computed from the 3D tomograms are displayed in the middle frames. Two S-wave patterns are noticeable in the observed and computed spectra corresponding to the motions of the two stars. The overall agreement between the observed and computed spectra is very good. The quality of the fit is shown in the right frame of Figure 3, which displays the relative chi-square statistic, $\chi^2/\chi_c^2$, versus orbital phase. Here, $\chi^2$ is normalized to the critical value of $\chi_c^2$, which corresponds to the largest acceptable value of $\chi^2$ at the 99% confidence level and demonstrates the quality of the calculated values of $\chi^2$ (e.g., Skilling & Bryan 1984). Figure 3 shows that $\chi^2$ was less than 20% of the critical value at most orbital phases and it was only as high as 65% of the critical value over a narrow phase range from 0.47 to 0.49, perhaps because the 3D code assumes that the gas is optically thin when it might be optically thick at these phases. So, in all cases, $\chi^2$ was much lower than the critical value which confirms that the 3D reconstruction has produced a model reconstruction for RS Vul that describes the data well.

Figure 4 displays 18 slices in the ($V_x$,$V_y$) plane for values of $V_z$ ranging from $V_z = -480$ km s$^{-1}$ to $+480$ km s$^{-1}$. The

**Figure 3.** Comparison between the original data (left frame) and the spectra computed from the reconstructed 3D Doppler map of RS Vul (middle frame) in terms of the radial velocity, $V_r$ vs. orbital phase. The right frame displays the orbital phase variation of the relative chi-square statistic, $\chi^2/\chi_c^2$, where $\chi_c^2$ is the critical value corresponding to the 99% confidence level. The agreement between the observed and computed spectra is very good.

(A color version of this figure is available in the online journal.)
Figure 4. Visualization of the \((V_x, V_y)\) 2D slices in the 3D Doppler tomogram of RS Vul (1993) displayed symmetrically from \(V_z = -480\) km s\(^{-1}\) to \(V_z = +480\) km s\(^{-1}\). The images are shown for intensity levels: +0.01, 0.05, 0.1, 0.3, 0.5, 0.7, 0.9 (red) and −0.01, −0.05, −0.1, −0.3 (blue). The main features are (1) circumprimary emission, (2) emission from active magnetic regions associated with the donor star, (3) gas stream, (4) star-stream impact site (the asterisk \(*\)), (5) the predicted locus of accretion disk, (6) localized region (LR) between stars, (7) other LR, and (8) high-velocity flow moving away from the donor star. The absorption zone is found in the lower half of the slices (in yellow).

(A color version of this figure is available in the online journal.)
superposition of the color or gray-scale images with the contour images allows us to emphasize the main features in each $V_z$ slice of the 3D image. Since RS Vul and U CrB have similar geometries and components, the corresponding figure for U CrB in the streamlike state is displayed in Figure 5 for comparison.

Figure 6 displays several cross sections of the flow in the $(V_x, V_y)$ plane along with cross sections that have been adjusted for the stretching effect by means of an approximate deconvolution of the slices (see Section 3). A uniform scaling of the images by a factor of 3.5, corresponding to the ratio of the velocity resolutions in the $V_z$-direction compared to the other directions, provides a rough first approximation to the complex deconvolution. This uniform adjustment is useful in illustrating the locations of the emission sources in 3D (see Figure 7). The adjusted $V_z$ values are given in the last column of Table 1.

3.2. Description and Interpretation of Emission Features

Algol-type binaries display 2D tomograms that contain a variety of emission sources including a gas stream, classical accretion disk or transient accretion disk, shock regions, and emission sources associated with both stars (Richards et al. 1995; Albright & Richards 1996; Richards 2004). In addition, the tomograms of “Alternating Algols,” like U CrB and U Sge, can vary between streamlike and disklike states; and RS Vul was identified as a member of this group (Richards & Albright 1999).

RS Vul and U CrB were expected to exhibit similar gas dynamics because their stellar components are almost identical: RS Vul contains a B5V + G1 III-IV binary in a 4.48 day orbit, while U CrB has B6V and G0 III-IV components in a 3.45 day orbit. In addition, the synchronous velocity of the mass gainer in RS Vul is 62 km s$^{-1}$ compared to 44 km s$^{-1}$ for U CrB. Both systems are direct impact Algols in which the gas stream is expected to strike the surface of the mass gainer, create shock regions and a splash of gas at the impact site. The main difference is that the mass gainer in RS Vul has a larger radius relative to the binary separation than in U CrB; hence, the gas stream in RS Vul has relatively less room to travel before impact with the mass gaining star. At impact, the gas stream can reach velocities of 500–800 km s$^{-1}$ (Lubow & Shu 1975; Olson 1980) in the orbital plane, depending on the mass transfer rate. Hence, the impact is expected to spin up the mass gaining star well beyond the much lower 40–65 km s$^{-1}$ photospheric values. Moreover, the gas stream is expected to have a circular cross section perpendicular to the direction of the flow (thickness $\sim 0.3 R_\odot$; Lubow & Shu 1976); hence, it should have a non-zero $V_z$ velocity even when gravitational forces alone can influence the gas dynamics.

Both binaries contain a late-type donor star that is expected to have a strong magnetic field accompanied by flares, prominences, and coronal mass ejections (CMEs). The effect of the magnetic field on the gravitational flow from the donor star is unknown. In the case of U CrB, the 3D tomogram showed that the gas flows had velocities close to the central velocity plane; hence, the magnetic field strength may be small relative to the gravitational forces in that system. The same may not be true in RS Vul since the emission sources in its 3D tomogram have higher $V_z$ velocities than found in U CrB (see Figures 4 and 5). In this binary, the gas stream could achieve high $V_z$ velocities if its path is tilted away from the central plane by the magnetic field of the donor star.

Observational similarities between U CrB and RS Vul were identified in their 2D tomograms, which showed intense emission associated with the velocity of the mass gaining star (called “circumprimary emission”), as well as emission associated with the donor star, and emission from a gas stream (Richards et al. 1995). Similarities were also found in the individual 2D slices of the 3D tomograms of both systems (Figures 4 and 5), except that the gas flows in RS Vul are prominent at velocities well beyond the central plane. When the 3D tomograms are displayed in true 3D format (as in Figure 7), there is a difference between the $V_z$ distributions in RS Vul and U CrB. However, these differences reflect the intriguing variety and range of emission structures found in the direct impact Algols.

The 3D reconstruction of U CrB in both its streamlike and disklike states revealed a strong resemblance between the emission features seen in the 2D $(V_x, V_y)$ tomograms and the separate 2D slices of the 3D tomograms. The 2D slices of the 3D tomograms of both states of U CrB display the following features (Agafonov et al. 2009): (1) circumprimary emission (centered on the velocity of the mass gainer in the 2D tomogram) and an accretion annulus (a circular region of low velocity); (2) emission from active magnetic regions associated with the cool donor star; (3) the gas stream flowing along its predicted ballistic trajectory; (4) the star-stream impact region, where the gas stream strikes the stellar surface; (5) emission within the predicted locus of the accretion disk; (6) a localized region between the stars where the gas stream strikes material that has circled the mass gainer; (7) a second localized region where the gas stream makes impact with the outer edge of the accretion disk; (8) a high-velocity flow moving away from the cool donor star; and (9) a high-velocity flow (jet) extending in the $V_z$-direction beyond the stream-star impact region. The first seven of these features were also found in the 2D tomograms of U CrB. Moreover, the gas flows in U CrB were usually evenly distributed about the central velocity plane, with the adjusted $V_z$ velocities within 30 km s$^{-1}$ of that plane.

Similar features were identified in the individual 2D slices of the 3D tomogram of RS Vul (see Figure 4) except that there is almost no emission from an accretion disk and little evidence of the star-stream impact region. Figure 4 also shows that the strongest emission sources are associated with both the cool donor star and the mass gaining star. In addition, the gas flows in RS Vul are prominent at $V_z$ velocities well beyond the central plane (adjusted $V_z$ velocities within $\pm 150$ km s$^{-1}$) so the features in RS Vul are not as straightforward to interpret as those listed for U CrB. Gravitational forces alone cannot explain the observed out-of-plane motions in RS Vul; therefore, the structure of the magnetic field of the donor star or CMEs may play a stronger role in RS Vul than in U CrB.

In this section, we describe the emission features of RS Vul that were identified in the 2D slices of the 3D tomograms shown in Figures 4 and 6. In the tomograms, the light (yellow) areas with blue contours represent absorption while the dark (deep pink) areas with red contours represent emission. The emission sources are listed in Table 1 along with their typical $V_z$, $V_x$, and $V_y$ velocity ranges based on the original reconstructed tomogram (see Columns 3–5), as well as the $V_z$ velocities adjusted by a factor of 3.5 for the stretching effect of the SPSF ($V_z(adj) = V_z/3.5$; see Column 6). Note that the $V_z$ velocities shown in Figure 4 have not been adjusted for this stretching effect. In the descriptions below, we refer to the adjusted $V_z$ velocities of the various sources. For consistency, we have retained the names of the first seven emission features based on their locations in the 2D tomograms.
Figure 5. Visualization of the seven most interesting \((V_x, V_y)\) slices in the 3D Doppler tomogram of U CrB (1994) in the streamlike state displayed symmetrically. The main features are (1) circumprimary emission, (2) emission from active magnetic regions associated with the donor star, (3) gas stream, (10) a high-velocity flow (jet) in the \(V_z\)-direction (see Agafonov et al. 2006, 2009).

(A color version of this figure is available in the online journal.)
Figure 6. Cross sections of the RS Vul 3D Doppler tomogram in the \((V_x, V_y)\) plane for \(V_x = -200, -120, -20, 0, 20, 120, 200 \text{ km s}^{-1}\) with intensity levels of \(\pm 0.01, 0.05, 0.10, 0.30, 0.50, 0.70, \) and \(0.90\), respectively. The numbered features correspond to those in Figure 4. The seven frames on the left correspond to the original reconstructed images, while the frames on the right show the same cross sections after an approximate deconvolution to minimize the artificial stretching effect of the SPSF in the \(V_z\)-direction.

(A color version of this figure is available in the online journal.)

1. The **circumprimary emission** in RS Vul is labeled (1) in Figure 4. This name originates from photometric studies that suggested the presence of an equatorial bulge with a velocity higher than that of the mass gaining star (Olson 1980). The structure is believed to have formed as a result of the impact of the gas stream onto the stellar surface in direct impact Algols, and hence it is expected to have a \(V_z\) velocity component that represents the state of the star after impact. In the 2D tomograms, the circumprimary emission is usually centered on the \((V_x, V_y)\) orbital velocity of the mass gainer, and hence it is associated with that star. In RS Vul, this feature is the strongest source of emission in the 3D image, its central velocity in the \(V_z\) slices is located at \((V_x, V_y) = (0, -60)\), which is nearly identical to that of the mass gainer (at \((V_x, V_y) = (0, -54) \text{ km s}^{-1}\)); hence, it is almost centered on the velocity of the star in these slices. Figures 4 and 6 show that this gas has \(V_z(\text{adj})\) velocities of 0 to \(-90 \text{ km s}^{-1}\) with the peak at about \(-45 \text{ km s}^{-1}\) (Table 1); therefore, it is not symmetric about the central plane, as found for U CrB. However, this adjusted \(V_z\) velocity could be produced if the gas stream strikes the star at an angle to the \((V_x, V_y)\) plane.

2. **Emission from active magnetic regions** associated with the cool mass losing star is labeled Feature (2). This
feature is comparable in strength to the circumprimary emission. The Hα tomograms may include contributions from emission sources linked to the cool star such as the chromosphere, bright plages around starspots, dark filaments, and prominences above the limb of the star. In RS Vul, this emission source is roughly centered in 3D on the donor star. In the $(V_x, V_y)$ plane it slices, it has nearly the same velocity as the donor star, and it can be seen over a range of $V_y(adj)$ velocities from $-150$ to $+155$ km s$^{-1}$, with some gaps on the positive $V_x$ side (see Figures 4 and 6, and Table 1). This 305 km s$^{-1}$ range in $V_y(adj)$ resembles a loop prominence along which gas is rising and falling since the footprint in the $(V_x, V_y)$ plane stays the same while the $V_y$ velocity changes. Skelly et al. (2008) found similar behavior in a T Tauri star based on Hα spectra and linked even higher velocity ranges to slingshot prominences on that star. This may be the first detection of a loop prominence in an interacting binary based on tomography.

3. The gas stream is Feature (3). In RS Vul, this emission source flows close to the predicted ballistic trajectory from the L1 point toward the mass gaining star with speeds up to 450 km s$^{-1}$ in the $(V_x, V_y)$ plane. Beyond the central plane, the gas stream was detected over a range of $V_y(adj)$ velocities from $-140$ to $+50$ km s$^{-1}$, and was most extended at $V_y(adj) = -85$ km s$^{-1}$ (Table 1). This behavior was unexpected because gravitational forces should have confined the flow to the central plane, as found for U CrB in its streamlike state (see Figure 5). However, it is noteworthy that the gas stream emission in RS Vul peaks at the same $V_y(adj)$ velocity as the emission from the magnetic regions on its donor star (Feature 2); this correspondence suggests a link between the gas stream flow and magnetic activity on the donor star.

4. The predicted location of the star-stream impact region is found at (4). This is the velocity at which the gas stream strikes the stellar surface, and it is found close to the intersection of the gas stream trajectory with the inner part of the disk. In RS Vul, no emission was detected at this location so the gas stream never reached this predicted velocity even in its most extended state at $V_y(adj) = -85$ km s$^{-1}$.

5. There is very little evidence of any emission within the predicted locus of the accretion disk (Feature 5) in the RS Vul images, although some clumping is seen within this region. This feature was much stronger in U CrB, and there is slightly more space around the mass gainer in U CrB to form a disk. Nevertheless, gas may have traveled around the mass gainer in RS Vul and created the localized regions (described below) when the interaction with the stream slowed this gas flow.

6. A Localized Region between the stars labeled (6) was found near the center of the tomogram where the flow around the mass gainer is expected to strike the inner edge of incoming gas stream. The braking effect associated with the LR was first used to explain the Hα spectra of the Algol-type binary β Per (Richards 1992), and its existence was confirmed by hydrodynamic simulations of Algol binaries (Blondin, Richards & Malinkowski 1995; Richards & Ratliff 1998) and cataclysmic variables (Kuznetsov et al. 2001; Bisikalo et al. 2000a, 2000b). Cartesian models of this region have been developed for β Per (Richards 1992, 1993), RW Tau (Vesper & Honeycutt 1993), and other direct-impact systems. In the 3D tomogram of RS Vul, the LR was detected along the $V_x = 0$ km s$^{-1}$ line at $V_y = +50$ km s$^{-1}$; hence, it is located between the stars. However, the LR has positive $V_y(adj)$ velocities from $+15$ to $+85$ km s$^{-1}$ (Figure 4), and could extend to $+120$ km s$^{-1}$ if the emission source at the L1 point in the $(V_x, V_y)$ plane is also part of the LR. In Figure 6, Feature 6 can be seen in the $V_z$ slices from $-20$ to $+20$ km s$^{-1}$. In the $(V_x, V_y)$ plane, the LR has a $V_y(adj)$ velocity that is diametrically opposite to that of Feature 1, as though the gas flowed along a tilted path below the mass gainer and back above and beyond the central velocity plane. Therefore, Feature 6 is not in the central velocity plane but its $V_y(adj)$ velocity is consistent with the $V_y(adj)$ velocity of the circumprimary emission (Feature 1).

7. A second Localized Region is labeled (7). It is distinct from Feature 6 because its location in the $(V_x, V_y)$ plane is farther from the line between the stars, and the two features have positive $V_y$ velocities over different velocity ranges. Feature 7 has positive $V_y(adj)$ velocities from $+45$ to $+100$ km s$^{-1}$ and is located on the $V_y = 0$ km s$^{-1}$ line (see Figure 4). In Figure 6, it can be seen in the $V_y = -120$ km s$^{-1}$ frame, with an average $V_y(adj)$ velocity of $+70$ km s$^{-1}$. This feature may later merge with the other LR that runs along the line of centers between the stars, so both Features 6 and 7 may be part of the same structure.

8. The feature labeled (8) is a high-velocity flow moving away from the donor star with positive velocities in two directions. This feature is not centered on the donor star but its velocity in the $(V_x, V_y)$ plane is near that of the donor star. Feature 8 moves from $V_x = +100$ to $+300$ km s$^{-1}$ at a nearly constant $V_y$ velocity of $+200$ km s$^{-1}$ (comparable

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Table 1

| Number | Emission Feature | Location: central velocity or velocity range (km s$^{-1}$) |
|--------|-----------------|--------------------------------------------------------|
| 1      | Circumpri... | $V_x (−60 \text{ to } +60)$ | $V_y (−60 \text{ to } −120)$ | $V_z (−160 \text{ to } −320)$ | $V_y (−160 \text{ to } −320)$ |
| 2      | Emission from... | $V_x (−120 \text{ to } +120)$ | $V_y (210 \text{ to } 360)$ | $V_z (−300 \text{ to } +540)$ | $V_y (−85 \text{ to } +155)$ |
| 3      | Gas stream... | $V_x (−520 \text{ to } 0^a)$ | $V_y (100 \text{ to } 300^a)$ | $V_z (−300 \text{ to } +480)$ | $V_y (−85 \text{ to } +155)$ |
| 4      | Star-stream impact region | No source found |
| 5      | Locus of the accretion disk | Very weak |
| 6      | Localized Region (LR) – Part 1 | $V_x (0)$ | $V_y (+50 \text{ to } 100)$ | $V_z (180 \text{ to } 500)$ | $V_y (50 \text{ to } 150)$ |
| 7      | Localized Region – Part 2 | $V_x (100)$ | $V_y (−25 \text{ to } −80)$ | $V_z (240 \text{ to } 350)$ | $V_y (70 \text{ to } 100)$ |
| 8      | High velocity flow near donor | $V_x (200 \text{ to } 300)$ | $V_y (−200)$ | $V_z (360 \text{ to } 540)$ | $V_y (100 \text{ to } 150)$ |
| 9      | Absorption zone | $V_x (80 \text{ to } 30)$ | $V_y (60 \text{ to } 90)$ | $V_z (70 \text{ to } 30)$ | $V_y (50 \text{ to } 150)$ |

Note. $^a$ Corresponds to the predicted ballistic trajectory of the gas stream.
to that of the donor), while moving at a $V_z$ (adj) velocity of $+50$ to $+150$ km s$^{-1}$ (see Figures 4 and 6). Moreover, the velocities in the $V_x$- and $V_z$-directions are higher than that of the other features, except for Feature 2 which is directly associated with the donor star. Hence, the high velocities associated with Feature 8 are suggestive of a CME which is moving away from the star, as opposed to a loop prominence which would display both positive and negative velocities.

9. The absorption feature in RS Vul seen in the lower left and right quadrants of Figure 4 from $V_z$ (adj) $= -35$ to $+155$ km s$^{-1}$ was called the absorption zone by Richards (2001, 2004), and is associated with the locus where the gas temperature becomes too high to emit at H$\alpha$. A structure at a similar location was identified in the ultraviolet tomogram of U Sge by Kempner & Richards (1999) and in the H$\alpha$ tomogram of U CrB by Agafonov et al. (2009).

The 3D tomograms also reveal an interesting symmetry in the emission sources found in the $V_z$ slices. A strong source near the mass losing star (in velocity space) is detected with intensities of 0.852 and 0.955 in symmetrical locations at $V_z$ (adj) $= -85$ and $+85$ km s$^{-1}$ ($V_z = -300$ and $+300$ km s$^{-1}$), respectively (see Figure 4). A similar symmetric intensity pattern ($I = 0.343$ and 0.333) is seen at $V_z$ (adj) $= -135$ and $+135$ km s$^{-1}$ ($V_z = -480$ and $+480$ km s$^{-1}$). In the case of the mass gaining star, another symmetric pattern is revealed. The most intense emission feature in the $V_z$ (adj) $= +50$ km s$^{-1}$ frame in Figure 4, with $I = 0.612$, is located along the $V_z$ $= 0$ km s$^{-1}$ line at $V_z = +80$ km s$^{-1}$, in the opposite $V_z$-direction from the circumprimary emission. These symmetries may be purely coincidental or perhaps we can see the same feature with motions on both sides relative to the central velocity plane, with a $-V_z$ component in the $-z$-direction and with a $+V_z$ component in the $+z$-direction as though they belong to a tilted structure relative to the central velocity plane (see Figure 6, $V_z = 0$ frames) as viewed from opposite parts of the orbit.

Features 6, 7, and 8 also emphasize the resemblance between the 3D tomograms of RS Vul and U CrB (1993, disk state) since these three features have nearly the same $V_x$, $V_y$, and $V_z$ velocities in both systems (see Figure 4 of Agafonov et al. 2009). Moreover, these features are all associated with high positive $V_z$ (adj) velocities of $+55$ to $+115$ km s$^{-1}$. In U CrB (1993), Feature 6 is located at roughly opposite $V_z$ velocities from that of Feature 1, which has been identified as being associated with the mass gaining star. This diagonal symmetry described earlier suggests that Features 1, 6, 7, and 8 may be created by the same process or they could be part of the same physical structure.

4. A MODEL FOR RS VUL

An examination of the emission sources in the 3D tomogram of RS Vul has confirmed the presence of several features: (1) circumprimary emission that is centered on the mass gainer in the ($V_x, V_y$) plane and offset from the central velocity plane in the negative $V_z$-direction; (2) an emission source resembling a loop prominence that is associated with the donor star in the ($V_x, V_y$) plane, displays a 305 km s$^{-1}$ range in the $V_z$-direction, and is roughly equally distributed in velocities relative to the central plane; (3) a gas stream that is offset in the negative $V_z$-direction like the circumprimary emission; (4) two localized regions between the stars that are offset in the positive $V_z$-direction; (5) a high-velocity flow moving away from the donor star with positive $V_z$ and $V_y$ velocities resembling a CME; and (6) an absorption zone near the mass gainer corresponding to a region of hotter gas. There was no emission from the star-stream impact site or within the predicted locus of the accretion disk. These features are similar to those found in the 2D slices of the 3D tomogram of U CrB, except in the direction away from the central velocity plane.

The unexpected behavior of the gas flow in the $V_z$-direction is consistent with the presence of an active magnetic field on RS Vul. The general characteristics of the gas flows suggest that magnetic activity of the donor star in RS Vul may have deflected the gas at the L1 point, tilted the gas stream flow relative to the orbital plane (toward negative $V_z$ velocities), created the circumprimary emission source after impact (on the same side of the central plane as the gas stream), and caused the gas to move from one side of the central plane to the other side (hence, the LRs are offset toward positive $V_z$ velocities).

The representation of the 3D tomogram as a set of 2D slices along the $V_z$-direction (as in Figure 4) makes it challenging to visualize the true 3D distribution of the gas flows. Figure 7 displays a more realistic 3D view of the gas flows which incorporates the adjusted $V_z$ velocities. The top frames of Figure 7 illustrate a tilted view of the velocity distribution of the gas beyond the central plane in both U CrB (stream-like state, Figure 5) and RS Vul. The other 3D views are shown in order of orbital phase starting with $\phi = 0.0$ (second row), $\phi = 0.25$ (third row), $\phi = 0.5$ (fourth row), and $\phi = 0.75$ (last row) for each binary. Although the 3D gas velocities in U CrB and RS Vul are not identical, they both display gas flowing well beyond the central velocity plane. In addition, Figure 7 shows that there are more emission sources associated with the donor star in RS Vul than in U CrB, which confirms that the differences between the two binaries are related to the characteristics of the donor star.

While the image reconstruction process can now produce 3D velocity images, we are still unable to create the desired 2D or 3D Cartesian images because the various emission features have different velocity fields. However, an estimate of the gas stream flow can be made from information provided in Figure 1 (e.g., Richards et al. 2000). Based on the point where the gas stream is truncated, we can produce a Cartesian model to show the dominant emission sources in RS Vul. The distance from the L1 point to the center of the primary star has been divided into 10 equal segments in the center frame of Figure 1, and the similar small circles on the Doppler tomograms are marked at velocity intervals corresponding to those distance intervals. Comparing the center and right frames of Figure 1, we see that the gas stream flow is truncated after traveling seven small circles on the gas stream trajectory, which is equivalent to 70% of the distance from the L1 point to the center of the primary star. The star-stream interaction occurs along the path of the gas stream right where the gas stream ends (at 70% of the distance from the L1 point). Figure 4 shows that the gas flow reaches the stellar surface corresponding to the solid circle in the tomogram, which corresponds to the Keplerian velocity at the surface of the mass gainer. Beyond this point, there is no evidence of any significant disk in this binary at this epoch.

The detection of the offset in the $V_z$ velocity of the gas stream is interesting. It is already well known that circumstellar gas in Algol binaries is distributed well above and below the orbital plane of the binary based on studies of ultraviolet resonance lines and the H$\alpha$ line (e.g., Peters & Polidan 1984; Richards 1993). This gas can reach heights comparable to the radius of the mass gaining star. Nevertheless, semi-analytical ballistic studies (e.g., Lubow & Shu 1975, 1976) or hydrodynamic simulations
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Figure 7. 3D representations of the velocity distribution of emission sources relative to the $V_z$-axis for U CrB (stream-like state) and RS Vul. The top frames illustrate a tilted view of the velocity distribution of the gas beyond the central velocity plane of each binary. The other 3D views are shown in order of orbital phase starting with $\phi = 0.0$ (second row), $\phi = 0.25$ (third row), $\phi = 0.5$ (fourth row), and $\phi = 0.75$ (last row). The emission sources in the image have been scaled according to intensity, with the brightest sources shown as large red points and the fainter sources as small green points. (A color version of this figure is available in the online journal.)

of the mass transfer process (e.g., Richards & Ratliff 1998) assume that the gas should be found very close to the orbital plane, if magnetic fields are not involved. In addition, the gravitationally induced Roche lobe overflow mechanism alone cannot explain the large motions beyond the central plane in the 3D tomograms. Since the cool donor star is expected to display enhanced magnetic activity associated with its rapid rotation relative to the Sun, the unexpected high gas motions beyond the central plane could be powered by magnetic activity on this star. Moreover, this activity could lead to deviations from the steady state and variability in the gas flows. Such temporal variability has been associated with RS Vul since it has been classified as an Alternating Algol in which the emission sources are variable over timescales of months (Richards & Albright 1999).

Stern et al. (1992) suggested that CMEs could account for more than 10% of the mass transfer expected solely from Roche lobe flow by gravitational processes alone. If the solar coronal behavior can be scaled to the enhanced levels seen in many Algol binaries, then radio and X-ray flares detected from these systems can be interpreted as the periodic reconnection of the coronal field (Stern et al. 1992). Evidence of magnetic activity on RS Vul was found by White & Marshall (1983) when they detected it as an X-ray source with a luminosity, $L_x = 2.0 \times 10^{30} \text{ erg s}^{-1}$, which is about half of the X-ray luminosity of $\beta$ Per. Radio emission from RS Vul was also detected by Umana et al. (1998) with a flux density of 0.26 mJy and radio luminosity, $L_{\text{radio}} = 3.7 \times 10^{16} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ Hz}^{-1}$, compared to 0.30 mJy and $9.1 \times 10^{16} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ Hz}^{-1}$ for U CrB. So, the magnetic fields of the active stars in RS Vul and U CrB should be comparable.

The long-term radio flare survey of the prototype Algol system $\beta$ Per by Richards et al. (2003) demonstrated that major flares (up to 1 Jy) occur regularly and predictably every 48.9 $\pm$ 1.7 days (or 17 orbital cycles); thus, the flaring rate is at least 7.5 yr$^{-1}$ and could be as high as 100 yr$^{-1}$ (for weaker flares every orbit). Mass ejections from X-ray flares observed with EXOSAT and Ginga are estimated to be $\approx 5$–50 $\times 10^{-15} M_\odot$ (Stern et al. 1992), and a total mass ejection rate of $\approx 3.75$–37.5 $\times 10^{-12} M_\odot \text{ yr}^{-1}$ would correspond to the detected flaring rate of 7.5 yr$^{-1}$ for $\beta$ Per. These arguments suggest that CMEs may influence the transfer of gas between stars and even the angle at which the flow is directed. The differences between the gas distributions in RS Vul and U CrB cannot be readily explained by differences in magnetic activity based on their X-ray and radio luminosities. However, it is
The ultimate test of the plausibility of the tomography results is a comparison with direct images of the gas flows. However, the recent resolved 15 GHz radio image of β Per obtained by Peterson et al. (2010) from a global very long baseline radio interferometer array has illustrated that the magnetic structures in that binary are not symmetric and not confined to the orbital plane. In fact, the distribution of the radio image seen at phase 0.5 in Figure 2 of that paper is very similar to the tilted gas distribution found in the 3D tomogram of RS Vul at the same orbital phase. This agreement strengthens our suggestion that the gas flows in RS Vul could be deflected in an asymmetric way by the magnetic field of the donor star.

5. CONCLUSIONS

Three-dimensional Doppler tomography has been used to study the Hα emission sources in the RS Vul interacting binary and has led once again to the discovery of gas flows with significant \( V_z \) velocities. The 2D tomogram of this binary suggested that most of the emission arises from the cool donor star with additional evidence of a gas stream flowing close to its predicted trajectory. However, the 3D tomogram revealed surprising evidence that the most prominent gas stream flow was not found in the central velocity plane \( (V_z = 0 \text{ km s}^{-1}) \) as in the U CrB binary, but at \( V_z(\text{adj}) \) velocities of −140 to +50 km s\(^{-1}\). These unexpected \( V_z \) motions may result from the interaction between magnetic activity on the cool star and the gravitationally induced Roche lobe overflow from that star. The detection of a loop prominence on the cool star close to the L1 point in the 3D tomogram of RS Vul suggests that the magnetic field lines may have deflected the gas stream relative to the central plane. This result is consistent with earlier detections of RS Vul as both an X-ray and a radio source, and represents the first time that a loop prominence has been found in an interacting binary using tomography. Moreover, the agreement between the 3D tomogram of RS Vul and the new radio image of the prototype of the Algol binaries is encouraging. Exploration of the 3D velocity structures of other binary systems should improve our understanding of these out-of-plane gas motions.

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REFERENCES

Agafonov, M. I. 2004a, Astron. Nachr., 325, 259
Agafonov, M. I. 2004b, Astron. Nachr., 325, 263
Agafonov, M. I., Richards, M. T., & Sharova, O. I. 2006, ApJ, 652, 1547
Agafonov, M. I., & Sharova, O. I. 2005a, Astron. Nachr., 326, 143
Agafonov, M. I., & Sharova, O. I. 2005b, Radiophys. Quantum Electron., 48, 329
Agafonov, M. I., Sharova, O. I., & Richards, M. T. 2009, ApJ, 690, 1730
Albright, G. E., & Richards, M. T. 1996, ApJ, 459, L99
Bisikalo, D. V., Boyarchuk, A. A., Kuznetsov, O. A., & Chechetkin, V. M. 2000a, Astron. Rep., 44, 26
Bisikalo, D. V., Harmanec, P., Boyarchuk, A. A., Kuznetsov, O. A., & Hadrava, P. 2000b, A&A, 353, 1009
Blondin, J. M., Richards, M. T., & Malinkowski, M. 1995, ApJ, 445, 939
Csizmadia, S., et al. 2009, ApJ, 705, 436
Elebert, P., Callanan, P. J., Torres, M. A. P., & Garcia, M. R. 2009, MNRAS, 395, 2029
Holmgren, D. 1989, Space Sci. Rev., 50, 347
Hutchings, J. B., & Hill, G. 1971, ApJ, 166, 373
Kaitchuck, R. H., Schlegel, E. M., Honeycutt, R. K., Horne, K., Marsh, T. R., White, J. C., & Mansperger, C. S. 1994, ApJS, 93, 519
Kempner, J. C., & Richards, M. T. 1999, ApJ, 512, 345
Kuznetsov, O. A., Bisikalo, D. V., Boyarchuk, A. A., Khruzina, T. S., & Cherepashchuk, A. M. 2001, Astron. Rep., 45, 872
Lubow, S. H., & Sha, F. H. 1975, ApJ, 198, 383
Lubow, S. H., & Sha, F. H. 1976, ApJ, 207, L53
Marsh, T. R., & Horne, K. 1988, MNRAS, 235, 269
Miller, B., Budaj, J., Richards, M. T., Koubsky, P., & Peters, G. J. 2007, ApJ, 656, 1075
Olson, E. C. 1980, ApJ, 241, 257
Peters, G. J., & Polidan, R. S. 1984, ApJ, 283, 745
Peterson, W. M., Mutel, R. L., Gudel, M., & Goss, W. M. 2010, Nature, 463, 467
Richards, M. T. 1992, ApJ, 395, 2029
Richards, M. T., & Albright, G. E. 1996, in Stellar Surface Structure, ed. K. Strassmeier & J. Linsky (Dordrecht: Kluwer), 493
Richards, M. T., & Albright, G. E. 1999, ApJS, 123, 537
Richards, M. T., Albright, G. E., & Bowles, L. M. 1995, ApJ, 438, L103
Richards, M. T., Koubsky, P., Simon, V., Peters, G. J., Hirata, R., Skoda, P., & Masuda, S. 2000, ApJ, 531, 1003
Richards, M. T., & Ratliff, M. A. 1998, ApJ, 493, 326
Richards, M. T., Waltham, E. B., Ghigo, F., & Richards, D. St. P. 2003, ApJS, 147, 337
Sharova, O. I. 2006, in IAU Symp. 234, Planetary Nebulae in our Galaxy and Beyond, ed. M. J. Barlow & R. H. Méndez (Cambridge: Cambridge Univ. Press), 507
Skelly, M. B., Unruh, Y. C., Collier Cameron, A., Barnes, J. R., Donati, J.-F., Lawson, W. A., & Carter, B. D. 2008, MNRAS, 385, 708
Skilling, J., & Bryan, R. K. 1984, MNRAS, 211, 111
Stern, R. A., Uchida, Y., Tsuneta, S., & Nagase, F. 1992, ApJ, 400, 321
Umana, G., Trigilio, C., & Catalano, S. 1998, A&A, 329, 1010
Vesper, D. N., & Honeycutt, R. K. 1993, PASP, 105, 731
White, N. E., & Marshall, F. E. 1983, ApJ, 268, L117
Zavala, R. T., Hummel, C. A., Boboltz, D. A., Ojha, R., Shaffer, D. B., Tycner, C., Richards, M. T., & Hutter, D. J. 2010, ApJ, 715, L49