STELLA NOVAE: PAST AND FUTURE DECADES
ASP Conference Series, Vol. 490
P. A. Woudt and V. A. R. M. Ribeiro, eds

Morpho-kinematic Modeling of Nova Ejecta

Valério A. R. M. Ribeiro

Astrophysics, Cosmology and Gravity Centre, Department of Astronomy, University of Cape Town, Private Bag X3, Rondebosch, 7701, South Africa; vribeiro@ast.uct.ac.za

Abstract. Morpho-kinematic modeling allows us to disentangle the morphology and kinematics of an object. The technique has been applied to a number of novae where resolved imaging, or lack of, and spectroscopic line profile fitting, show how we may retrieve important parameters of the system, such as the maximum expansion velocity, inclination angle and the morphology of the ejected shell. Furthermore, this technique may be used as a predictor for searches of eclipses which will then provide us further information on the system parameters, such as the orbital period and the white dwarf mass.

1. Introduction

Nova ejecta have been resolved in the optical with a myriad of structures (Hutchings 1972; Solf 1983; Slavin, O'Brien, & Dunlop 1995; Gill & O'Brien 2000; Harman & O'Brien 2003). The most widely accepted mechanism for the formation of these structures is that of a common envelope phase where the ejecta engulfs the secondary star within a matter of minutes. The secondary then transfers energy and angular momentum to the ejecta (for a recent review see O'Brien & Bode 2008). However, a new mechanism has been put forward where the mass loss from the secondary, during quiescence, is highly concentrated in the orbital plane producing naturally the bipolar structures of the ejecta, with possibly an equatorial waist (Mohamed & Podsiadlowski 2012; Mohamed, Booth, & Podsiadlowski 2013).

Morpho-kinematic modeling[1] involves disentangling the morphology and kinematics of an object providing information on the expansion velocity ($V_{\rm exp}$), inclination angle and the morphology of the ejected shell following a nova outburst. In this proceeding, some examples are shown of the potential of this technique in retrieving these key parameters. In Section 2, the potential of applying this technique to both resolved imaging and ground-based spectroscopic observations is demonstrated and in Section 3 a particular case where only the optical spectroscopic emission line profile were available is presented. Finally, in Section 4 a discussion of the implications of these results are presented.

[1]Using SHAPE (Steffen et al. 2011), available from `http://bufadora.astrosen.unam.mx/shape/`

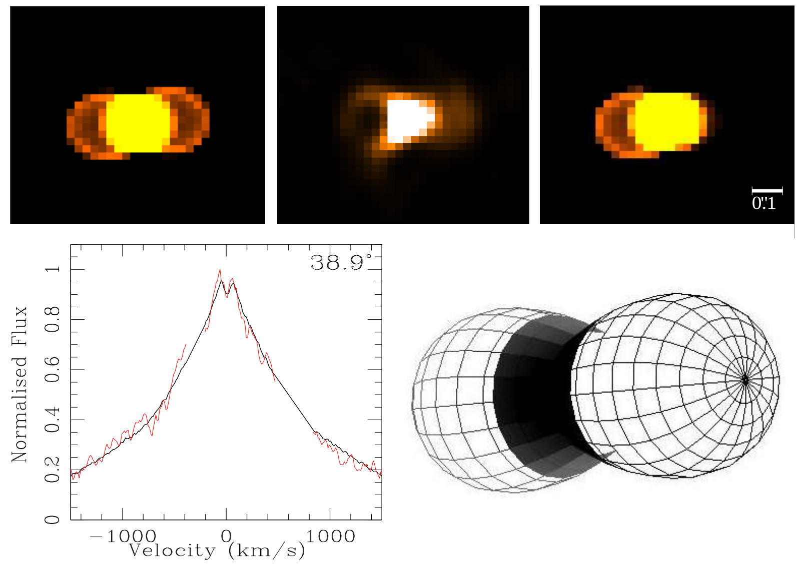

Figure 1. Top: synthetic image without the *HST* F502N ACS/HRC filter profile applied (left), enlarged ACS/HRC image at $t = 155$ days after outburst (middle) and synthetic image with the ACS/HRC F502N filter profile applied (right). Bottom: best fit synthetic spectrum (black) overlaid with the observed spectrum (red). To the right is the model structure for RS Oph (outer dumbbell and inner hour glass). Images reproduced from Ribeiro et al. (2009).

2. Modeling with Resolved Imaging and Spectroscopic Observations

Hubble Space Telescope (*HST*) ACS/HRC narrow band (F502N filter) imaging and ground-based spectroscopic observations of the recurrent nova RS Ophiuch at 155 days after outburst allowed Ribeiro et al. (2009) to model the ejecta as a bipolar composed of an outer dumbbell and inner hour glass structures (Figure 1). The inner hour glass was required as an over-density in order to replicate the observed [O III] 5007Å line profile. The apparent asymmetry of the ejecta in the *HST* image was shown to be an observational effect due to the finite width and offset of the central wavelength from the line centre of the F502N filter. From detailed kinematic modeling, the inclination of the system was determined as 39^{+1}_{-9} degrees and maximum expansion velocity 5100^{+1500}_{-100} km s^{-1} (the range in velocity arises from the 1σ errors on the inclination, Figure 1). This asymmetry was proposed to be due to interaction of the ejecta with a pre-existing red-giant wind (Bode et al. 2007; Ribeiro et al. 2009).

The model was then evolved to 449 days after outburst, to match the second *HST* observations. However, in this case, due to the lack of simultaneous ground-based spectroscopy the model was harder to constrain. Ribeiro et al. (2009) suggested that at this time the outer dumbbell structure expanded linearly while the inner hour glass structure showed some evidence for deceleration. It was not until Ribeiro, Bode, & Williams (2013b) performed archival searches of ground based facilities that they found spectroscopic data on day 415 which suggest the interpretation by Ribeiro et al. (2009) may not be far from the truth (see also Ribeiro, Bode, & Williams 2014, for an update).

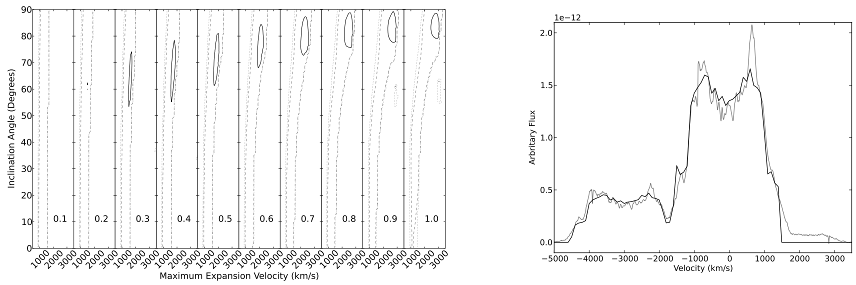

Figure 2. Nova Mon 2012 best fit models. *Top* – probability density function results for different degrees of bipolarity (black contour represents PDF = 1σ, gray dashed = 0.05 and dotted = 0.01). *Bottom* – best fit model (black) to the observed day 130 after outburst (gray) for a bipolar structure with a pinch of 0.8, derived as one minus the ratio of the semi-major to the semi-minor axis of the ejected shell. Images from Ribeiro et al. (2013d).

3. Line Profile Fitting

Unfortunately, nature does not always provide such good quality data as described above. In subsequent work, only novae with spectroscopic observations were available. In most cases for example, V2672 Oph (Munari et al. 2011), V2491 Cyg (Ribeiro et al. 2011) and KT Eri (Ribeiro 2011; Ribeiro et al. 2013a) only the Hα emission line was reproduced, due to lack the of forbidden lines. Nova Mon 2012 showed forbidden lines and fitting these lines suggested a bipolar morphology with an inclination angle of 82±6 degrees and $V_{\rm exp} = 2400^{+300}_{-200}$ km s^{-1} (Figure 2, Ribeiro, Munari, & Valisa 2013d). A 7.1 hr periodicity was found in the X-rays (Page et al. 2013) and shown to be near sinusoidal in shape with a weak secondary minimum (Munari et al. 2013).

4. Discussion

Ideally to constrain a model, the interplay between resolved imaging and ground based spectroscopic observations play a great role. However, this is not always the case. Applying different models based on observations of novae can aid in constraining the best morphology and hence, the inclination angle and maximum expansion velocity.

The success of modeling RS Oph, suggested the existence of an extra component that was required to determine the observed low velocity of the emission line profile while the imaging showed much higher velocity material. This extra component has been suggested to be material that survives the outburst (Evans et al. 2007; Ribeiro et al. 2013b). Further study is required here.

Of particular interest to Nova Mon 2012, besides its γ–ray origin, is the e-VLBI observations of two components which may be associated with the ejecta (O'Brien et al. 2012). Furthermore, resolved VLBA imaging showed what appeared to be a bipolar morphology of Nova Mon 2012 (M. Rupen, private communication). The derived inclination angle suggest eclipses should be observed. In fact, at least in Nova Mon 2012, a orbital period of 7.1 hr has been observed which was suggested to be due to partial eclipse from extended emission by an accretion disk rim (Page et al. 2013). Munari et al. (2013) showed the light curve to have a near sinusoidal shape with a weak secondary minima at phase 0.5. This was interpreted as arising from the super-imposed ellipsoidal distortion of the K3 V Roche lobe filling secondary and irradiation of its side facing the WD. All these results agree well with the high inclination and bipolar morphology derived by Ribeiro et al. (2013d).

It is not always that we have great success with deriving the best-fit model. In some cases the model is not as simple as just bipolar. For example, in V2491 Cyg the best-fit model structure was that of polar blobs and an equatorial ring. The model was allowed to evolve from the early outburst phase to later stages. This evolution reproduced well the observed spectra, in particular when [N II], in either side of the Hα line, also modeled (Ribeiro et al. 2011).

Acknowledgments. The author is grateful to long term collaborators, Mike Bode, Matt Darnley, Dan Harman and Ulisse Munari for insightful discussions over the years and Wolfgang Steffen and Nico Koning for valuable discussion and continued development of SHAPE. The author acknowledges the South African SKA Project for funding the postdoctoral fellowship at the University of Cape Town.

References

Bode, M. F., Harman, D. J., O'Brien, T. J., et al. 2007, ApJ, 665, L63
Evans, A., Woodward, C. E., Helton, L. A., et al. 2007, ApJ, 671, L157
Gill, C. D., & O'Brien, T. J. 2000, MNRAS, 314, 175
Harman, D. J., & O'Brien, T. J. 2003, MNRAS, 344, 1219
Hutchings, J. B. 1972, MNRAS, 158, 177
Mohamed, S., Booth, R., & Podsiadlowski, P. 2013, in Binary Paths to Type Ia Supernovae Explosions, edited by R. di Stefano, M. Orio, & M. Moe (Cambridge: Cambridge Univ. Press), vol. 281 of the IAU Symposium, 195
Mohamed, S., & Podsiadlowski, P. 2012, Baltic Astronomy, 21, 88
Munari, U., Dallaporta, S., Castellani, F., Valisa, P., Frigo, A., Chomiuk, L., & Ribeiro, V. A. R. M. 2013, MNRAS, 435, 771
Munari, U., Ribeiro, V. A. R. M., Bode, M. F., & Saguner, T. 2011, MNRAS, 410, 525
O'Brien, T. J., & Bode, M. F. 2008, in Classical Novae, edited by M. F. Bode, & A. Evans (2nd ed. Cambridge: Cambridge Univ. Press), 285
O'Brien, T. J., Yang, J., Paragi, Z., et al. 2012, The Astronomer's Telegram, 4408
Page, K. L., Osborne, J. P., Wagner, R. M., Beardmore, A. P., Shore, S. N., Starrfield, S., & Woodward, C. E. 2013, ApJ, 768, L26
Ribeiro, V. A. R. M. 2011, Ph.D. thesis, Liverpool John Moores University
Ribeiro, V. A. R. M., Bode, M. F., Darnley, M. J., Barnsley, R. M., Munari, U., & Harman, D. J. 2013a, MNRAS, 433, 1991
Ribeiro, V. A. R. M., Bode, M. F., Darnley, M. J., et al. 2009, ApJ, 703, 1955
Ribeiro, V. A. R. M., Bode, M. F., & Williams, R. 2014, in Stella Novae: Past and Future Decades, edited by P. A. Woudt & V. A. R. M. Ribeiro, (San Francisco: Astron. Soc. Pac.), vol. 490 of the ASP Conf. Series, these proceedings
— 2013b, in Feeding Compact Objects: Accretion on All Scales, edited by C. M. Zhang, T. Belloni, M. Méndez & S. N. Zhang, (Cambridge: Cambridge Univ. Press), vol. 290 of the IAU Symposium, 137
Ribeiro, V. A. R. M., Darnley, M. J., Bode, M. F., Munari, U., Harman, D. J., Steele, I. A., & Meaburn, J. 2011, MNRAS, 412, 1701
Ribeiro, V. A. R. M., Munari, U., & Valisa, P. 2013d, ApJ, 768, 49
Slavin, A. J., O'Brien, T. J., & Dunlop, J. S. 1995, MNRAS, 276, 353
Solf, J. 1983, ApJ, 273, 647
Steffen, W., Koning, N., Wenger, S., Morisset, C., & Magnor, M. 2011, IEEE Transactions on Visualization and Computer Graphics, 17, 454, arXiv:1003.2012