HST imaging and ground-based spectroscopy of RS Ophiuchi: an example of the advantages of multi-institutional collaborations

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ABSTRACT

In this Poster we discuss the advantages of multi-institutional collaboration based on the example of a successful series of Hubble Space Telescope and ground-based observations. The purpose of this contribution is to encourage other observers to promote further collaborations of this nature. Hubble Space Telescope imaging, obtained 155 and 449 days after the 2006 outburst of the recurrent nova RS Ophiuchi, together with extensive ground-based spectroscopic observations, obtained from the Observatorio Astronómico Nacional en San Pedro Mártir, Baja California, México and at the Observatorio Astrofísico Guillermo Haro, at Cananea, Sonora, México, enabled us to model the outburst remnant into two distinct co-aligned bipolar components; a low-velocity, high-density innermost (hour glass) region and a more extended, high-velocity (dumbbell) structure. This overall structure is in agreement with that deduced from radio observations and optical interferometry at earlier epochs (see Valerio et al. 2009, for further details). The modeling was done with Shape; a code developed by one of the co-authors in this work from, Instituto de Astronomía, Universidad Nacional Autónoma de México, Ensenada, B.C., Mexico, and was originally designed to model bipolar Planetary Nebulae.

RS Ophiuchi Results

We observed RS Oph with HST/ACS imaging at 155 days after outburst using the F502N filter and combined these observations with ground-based spectroscopy in this multi-institutional programme. These observations were taken quasi simultaneously which would then allow us to model the system using the morpho-kinematical code Shape to replicate the observed images and spectrum and determine the remnant morphology.

Figure 1 show the results of this fitting. The best-fit structure was suggested to be that of an outer dumbbell with an inner hour-glass over density. Initial models using purely a simple dumbbell structure over-estimated the observed velocities in the spectrum. The structure described above was then varied in geometry, including inclination and the resultant synthetic spectrum compared to the observed spectrum by comparing the chi-squared parameter. We found that the best-fit inclination to be 39^{+1}_{-10} degrees (1 sigma errors) with a maximum velocity of the ejecta of 5100^{+1500}_{-100} km/s (the range in velocities is associated with the inclination errors). We applied a Doppler filter which replicated the filter profile in the ACS. Owing to the offset of the filter's effective wavelength from the [O III] rest wavelength, this produced the observed asymmetry in the HST image and we deduced from this that the west lobe was approaching the observer.

We also secured a later epoch HST/WFPC2 observation (WFPC2 used due to ACS failure, see Figure 2). This time we did not have contemporaneous spectroscopic observations and the results described below demonstrate spectroscopy is crucial for the interpretation of the observed images and thus our results here are open to over-interpretation. We evolved our first epoch model linearly to the second epoch, also applying the appropriate WFPC2 Doppler filter, and found that this did not replicate the image. Therefore, we allowed the outer dumbbell to evolve linearly (since at the time of the first epoch this had cleared the pre-existing red-giant wind) while the inner hour glass structure was kept the same size, consistent with deceleration. At the time of the first epoch this feature was still within the implied size of the pre-existing red-giant wind. These results suggest that remnant shaping is due to the interaction of the pre-existing material that is denser in the central regions.

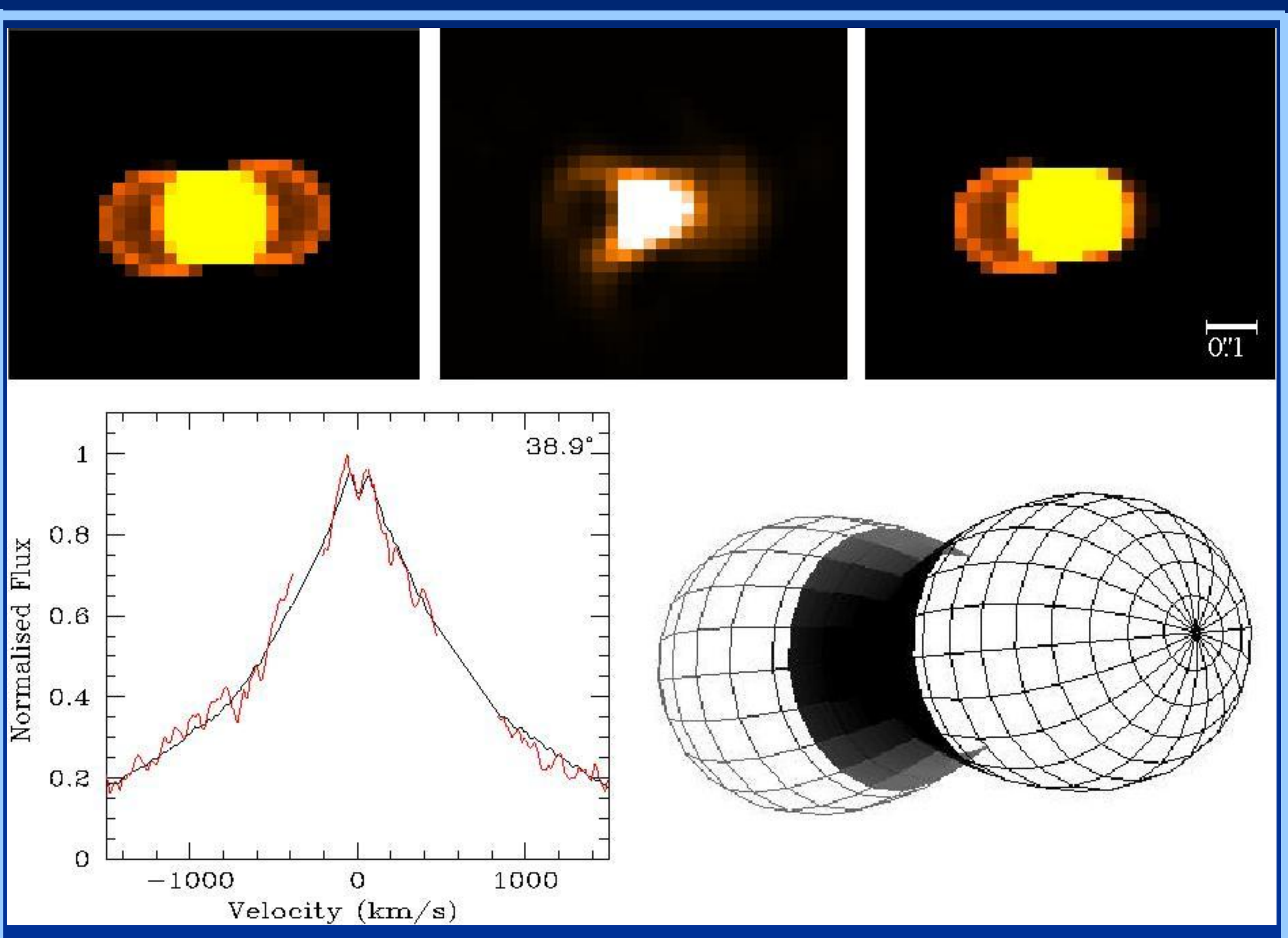


Figure 1. Top – synthetic image without the HST narrowband filter profile applied (left); observed HST image at 155 days after outburst (middle); and synthetic image with the HST narrowband filter applied (right). Bottom – best-fit synthetic spectrum (black) to the observed spectrum (red), with emission lines attributed to be due to the wind removed (left); and model structure used to replicate the observed images and spectrum.

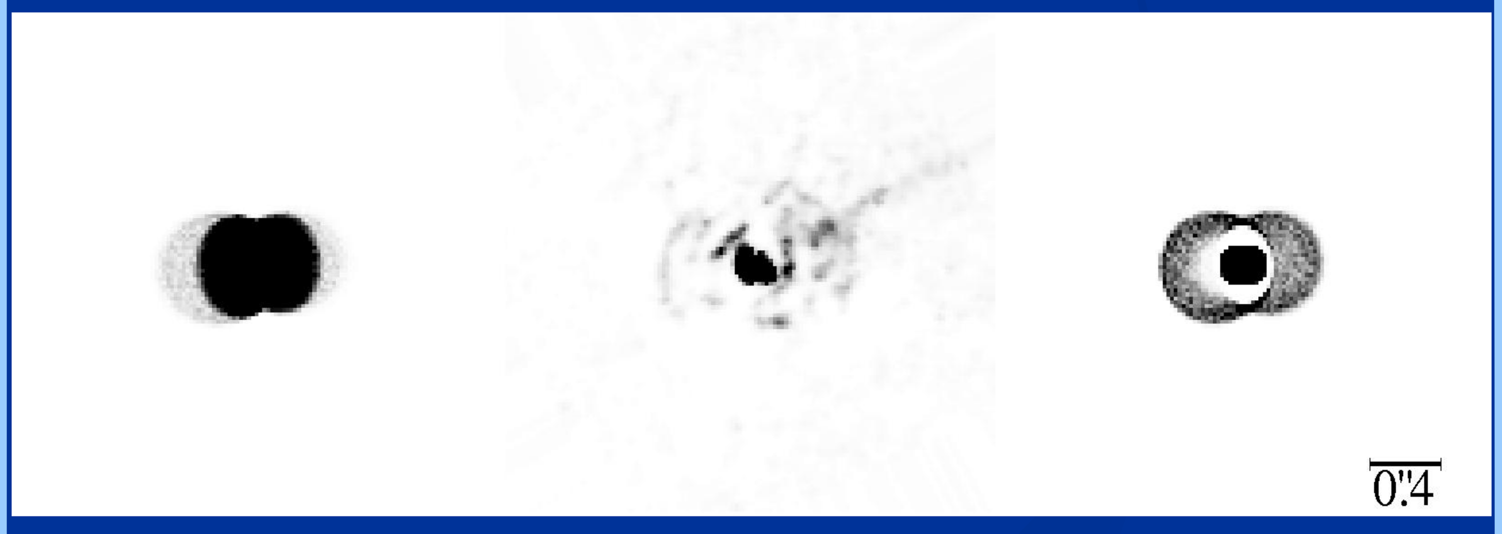
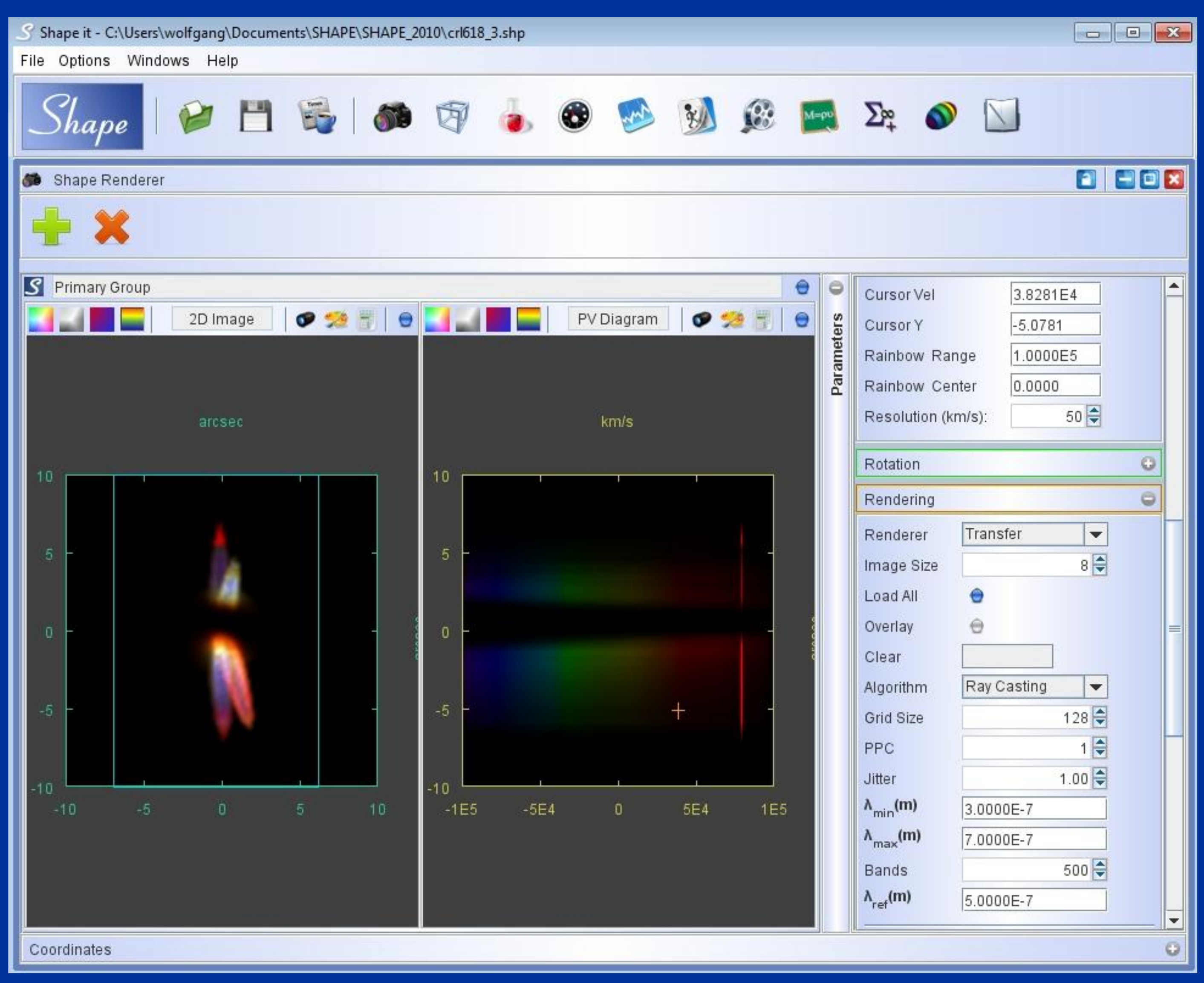


Figure 2. Model image applying a linear expansion (left). Observed HST/WFPC2 image at 449 days after outburst (middle). Model image with the outer dumbbell structure allowed to expand linearly while the inner hour glass was kept the same size (right).

What is Shape?

Shape is a morpho-kinematic modeling tool for astrophysical nebulae. Its design purpose is the analysis of the 3D structure and kinematics of astrophysical objects in a way that can be compared directly with observations. It is particularly suited to model expanding nebulae-like planetary nebulae and other structures with clear kinematical signatures such as accretion disks and other streaming flows that can be studied using the Doppler-effect. Starting from a 3D structure with a model velocity field, Shape generates 2D images, position-velocity(PV-) diagrams, channel maps, light echo maps and one-dimensional spectral line profiles for comparison with actual observations (Steffen, et al., 2010). Shape provides visual interactive model building with highly customizable geometry and physics. Model rendering that mimics observations allows direct comparison with Telescope data. It is easy and fast to learn and handle, so one can quickly get results and play with them before an inspiration evaporates. Shape uses modern, interactive 3D modeling techniques to "construct" the object in three dimensions. Following the lead of several commercial 3D drawing programs such as 3D Studio Max, Shape uses simple mesh shapes and modifiers to manipulate those shapes. Within this modifier framework one can create as complex a shape as needed. Additionally, modifiers can affect velocity and properties like density, thereby creating complex velocity fields and density distributions.

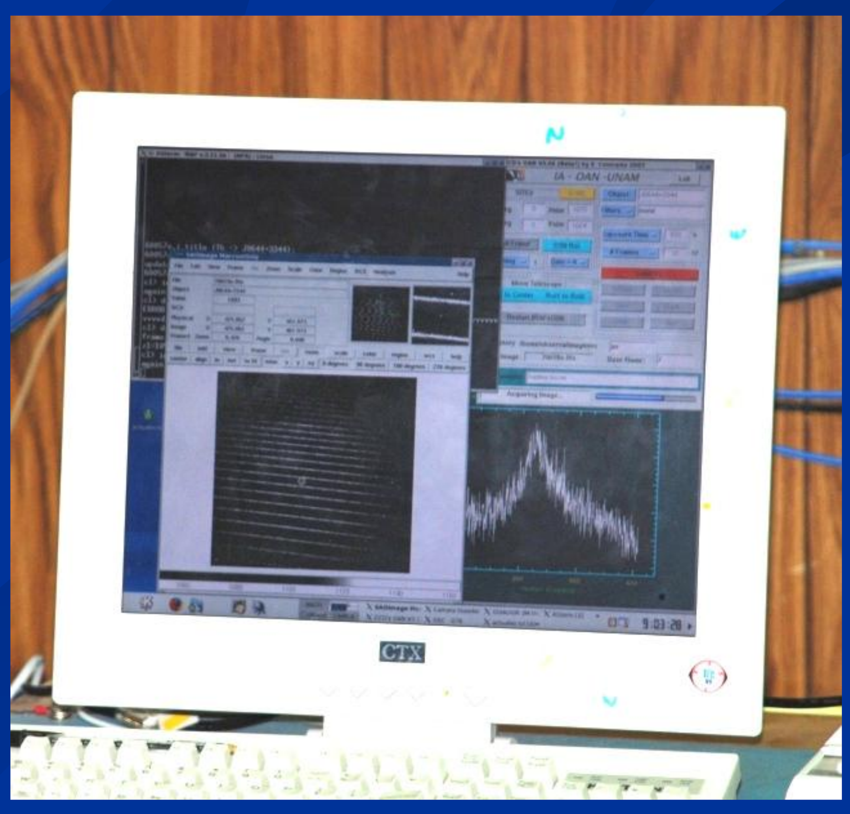


For the work on RS Ophiuchi we have added a new category of tools to Shape, which act on the final rendering information, similar to filters on a telescope. *The narrowband ACS/HRC filter profile was offset to the red side from the effective wavelength of the [O III] 5007 rest wavelength, which due to the fast expansion of RS Ophiuchi meant that this produced an asymmetry on the blue side.* To include this into the synthetic information a new customizable filter tool was introduced in Shape. Similar filter tools for related purposes were added later.

The advantages of ground-based collaborations

Most of the spectral observations were carried out over several epochs from 10 days (2006 February 22) to 168 days (2006 July 30) after outburst, at the Observatorio Astronómico Nacional in San Pedro Mártir, Baja California, México, using the 2.1 m telescope with the *echelle* spectrograph (left), which has a maximum resolution of about *R = 18,000 at 5000 Å*. More than 500 spectrum shows the presence of broad emission lines of Hβ, Hγ, Hδ, He I (λ4471, 4713, 4922, 5016, 5048 and 5411), Fe II (multiplets 27, 28, 42, 48, 49), NIII λ4640, and [Si II] λ5041, and many other lines. The acquisition system (right) show one of the multiple order echelle images, the exposure control icon and an extraction of the Hβ line.

The advantage of combining a high technology facility like the HST with a modest ground-based observatory, which has the advantage of acquiring hundreds of spectra or direct images for a large period of time is fairly obvious. In this case, we also profited with the use of Shape, a code developed at Ensenada for astrophysical nebulae and modified at Liverpool for the use of Recurrent Nova ejecta. We encourage future HST observers to contact us for future collaborations.



References

Steffen et al. 2010. arXich1003.2012S
Valerio et. Al 2009. ApJ. 703, 1955.

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