Hubble Space Telescope Imaging of the Expanding Nebular Remnant of the 2006 Outburst of RS Ophiuchi

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Abstract. We report Hubble Space Telescope imaging obtained 155 days and 449 days after the 2006 outburst of RS Ophiuchi. Both epochs show evidence of extended emission, consistent with that seen in earlier radio observations, and a maximum expansion rate of $3200 \pm 300$ km s$^{-1}$ (in the plane of the sky). The extended structure is consistent with the remnant having a bipolar morphology with an inclination similar to that determined for the binary.

1. Introduction

On 12.83 February 2006 the recurrent nova RS Ophiuchi was observed to be undergoing its sixth observed eruption (Narumi et al. 2006, $t = 0$). VLBI imaging at 6 and 18 cm began 13.8 days after outburst (O'Brien et al. 2006). These initial images showed a partial ring of non-thermal (synchrotron) emission, of radius 13.8 AU (assuming a distance of 1.6 kpc), consistent with emission from the forward shock. Extended lobes aligned in the east-west direction then gradually emerged, with the eastern lobe appearing first. This morphology is consistent with that derived from VLBI observations 77 days after the 1985 outburst (Taylor et al. 1989). O'Brien et al. (2006) proposed a simple geometrical model comprising an expanding double-lobed structure, with the major axis perpendicular to the proposed plane of the central binary orbit.

Here we briefly report Hubble Space Telescope (HST) observations of the expanding nebular remnant taken at $t = 155$ days (Epoch 1) and $t = 449$ days (Epoch 2), comparing both epochs to the structures seen earlier in the radio. Bode et al. (2007, hereafter Paper I) provide a much fuller discussion of the Epoch 1 HST observations.
2. HST Observations and Data Reduction

RS Oph was observed (prop. ID 11004) in Director’s Discretionary Time (DDT) 155 days after outburst on 17th July 2006 using the Advanced Camera for Surveys (ACS) on the HST. The 0.025′′pixel$^{-1}$ High-Resolution Channel (HRC) was used together with three narrow-band filters to isolate the H$\alpha$+N[sc ii] (filter F658N), [O iii] $\lambda$5007 Å (F502N) and [Ne v] $\lambda$3426 Å (F343N) nebular emission lines. One orbit was used to image RS Oph and the second to observe HD 166215, a bright nearby star of similar spectral type to be used as a PSF standard.

The Epoch 2 observations also took place in DDT, this time at 449 days after outburst on 7th May 2007, using the Wide Field Planetary Camera 2 (WFPC2, utilised due to the failure of the ACS). Three orbits of DDT were used to image RS Oph through the [O iii] $\lambda$5007 Å filter alone.

All data were processed using standard procedures outlined in the HST ACS Data Handbook and the Pydrizzle and Multidrizzle Handbooks, using optimal input parameters to maximise the signal-to-noise of each image. Using the profile of HD 166215 as the PSF, as well as profiles generated by TinyTim (Krist 2003), deconvolution using the Lucy-Richardson method was performed on each of the RS Oph images. Tests using both CLEAN and Maximum Entropy techniques produces similar results (see Paper I for a more detailed discussion of data reduction methodology).

As part of this study, a re-analysis was carried out of pre-outburst WFPC2 observations in the [O iii] $\lambda$5007 Å line on 12th June 2000. No extended emission was detectable, confirming the results of Brocksopp et al. (2003).

3. Results and Discussion

As can be seen in Figure 1, extended structure was clearly visible in the Epoch 1 [O iii] $\lambda$5007 Å PSF-subtracted image (and was indeed visible in the raw image). Deconvolution revealed more detailed structure in both [O iii] $\lambda$5007 Å and [Ne v] $\lambda$3426 Å. There was also a hint of possible extended emission close to the central source in the H$\alpha$ line, but this was not present at a significant level.

In the deconvolved [O iii] and [Ne v] Epoch 1 images, the most striking feature is an apparent double ring structure with major axis lying east-west and total (peak-to-peak) extent 360±30 mas (580±50 AU at $d = 1.6$ kpc). The most extended radio structures (the outer lobes; O’Brien et al. 2006) lie along this axis. Assuming ejection at $t = 0$ the expansion rate of the optically emitting gas along this axis is 1.2±0.1 mas day$^{-1}$ (equivalent to $v_{\text{exp}} = 3200\pm300$ km s$^{-1}$ in the plane of the sky). The optical emission is also detectable above background in the deconvolved images to a total extent of 520±50 mas, corresponding to an expansion rate of 1.7±0.2 mas day$^{-1}$. We compare this to 1.4±0.3 mas day$^{-1}$ for the east-west lobes seen in the radio, taken over four epochs from $t = 21.5$ to 62.7 days during the 2006 outburst (O’Brien et al., in preparation) and 1.3 mas day$^{-1}$ for the equivalent features derived from VLBI observations during the 1985 outburst (Taylor et al. 1989). Thus, there is evidence that the bipolar emission seen here and in the radio arises from the same regions of the remnant, if the expansion velocities are roughly constant.
Figure 1. *HST* ACS/HRC narrow-band Epoch 1 images of RS Oph. (a) PSF-subtracted [O\textsc{iii}] $\lambda5007$ Å image clearly showing extended emission at subarcsecond size scales particularly in the east-west direction; (b) results of deconvolution of the [O\textsc{iii}] $\lambda5007$ Å RS Oph PSF-subtracted image with the PSF star, showing a double ring structure; (c) same as (b), but for [Ne\textsc{v}] $\lambda3426$ Å and using a TinyTim PSF; (d) deeper, larger area view of (b), showing an arc-like feature to the east and a southern blob of emission.

O’Brien et al. 2006) proposed a simple bipolar model for the radio emission, where optical depth evolution led to a gradual “uncovering” of various features, most notably the outermost radio lobes. We have modeled the optical emission seen in our Epoch 1 *HST* images with a “peanut-shaped” bipolar structure using the code described by Harman & O’Brien (2003, see their Fig. 2). As can be seen in Figure 2 of Paper I, the model reproduces the morphology of the optical emission extremely well for an inclination $i = 35^\circ$, consistent with the major axis of the optical nebula lying normal to the binary plane. For
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\(d = 1.6 \pm 0.3\) kpc (Bode 1987) and such an inclination, the true expansion velocity, \(v = 5600 \pm 1100\), and \(v_{\text{rad}} = 4600 \pm 900\) km s\(^{-1}\) are implied for the material at the poles. Unless the ejection of material in the explosion is highly anisotropic, this result reinforces the notion that remnant shaping occurs due to the interaction of the ejecta with the pre-existing circumstellar environment (see Walder et al. 2008).

The Epoch 2 data are shown in Figure 2, and again extended structure is clearly visible in the deconvolved image. The peak-to-peak extent along the east-west axis after 449 days was 1.1″ (1,770 AU at \(d = 1.6\) kpc). This translates to an expansion rate along the east-west axis of 1.2 mas day\(^{-1}\).

Figure 2.  
\(HST\) WFPC2 narrow-band Epoch 2 images of RS Oph. (a) “Raw” [O \textsc{iii}] \(\lambda5007\) Å image; (b) results of deconvolution of the raw [O \textsc{iii}] image with a PSF star; a double ring structure is again visible. The NW spike is an artefact enhanced by image deconvolution.

It is clear that the current spherically symmetric hydrodynamic models used to describe the shock evolution in RS Oph need revision to account for the geometry revealed by these observations and those in the radio. Work currently underway includes the full analysis of the Epoch 2 data in conjunction with optical spectroscopy to explore more details of the remnant evolution.

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