

LETTERS

An X-ray-emitting blast wave from the recurrent nova RS Ophiuchi

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Stellar explosions such as novae and supernovae produce most of the heavy elements in the Universe. The onset of a nova is well understood¹ as driven by runaway thermonuclear fusion reactions on the surface of a white dwarf in a binary star system; but the structure, dynamics and mass of the ejecta are not well known. In rare cases, the white dwarf is embedded in the wind nebula of a red-giant companion, and the explosion products plough through the nebula and produce X-ray emission. Here we report X-ray observations of such an event, from the eruption of the recurrent nova RS Ophiuchi^{2,3}. The hard X-ray emission from RS Ophiuchi early in the eruption emanates from behind a blast wave, or outward-moving shock wave, that expanded freely for less than 2 days and then decelerated owing to interaction with the nebula. The X-rays faded rapidly, suggesting that the blast wave deviates from the standard spherical shell structure^{4–6}. The early onset of deceleration indicates that the ejected shell had a low mass, the white dwarf has a high mass⁷, and that RS Ophiuchi is therefore a progenitor of the type of supernova (type Ia) integral to studies of the expansion of the Universe.

On 12 February 2006, RS Ophiuchi (RS Oph) was discovered in outburst near the historical maximum optical brightness of 4.4 mag (ref. 8)—more than four times brighter than the threshold for naked-eye visibility. The Rossi X-Ray Timing Explorer (RXTE) satellite⁹ first detected strong hard X-rays from RS Oph—the strongest ever observed from a white dwarf—at peak X-ray brightness on outburst day 2 with the All Sky Monitor camera. RXTE subsequently measured the X-ray spectrum with the Proportional Counter Array (PCA) on outburst days 3, 6, 10, 14, 17 and 21 (Fig. 1). During this time, the binary was in the phase of its orbit in which the white dwarf and red giant appear side-by-side from the perspective of the Earth^{10,11}.

During the first three weeks of the outburst, the total X-ray luminosity from the hottest X-ray-emitting gas fell from $\sim 300L_{\odot}$ to $\sim 30L_{\odot}$ (integrated from 0.5 to 20 keV, and taking a distance of 1.6 kpc (refs 12, 13); L_{\odot} is the solar luminosity). From day 6 onward, the X-ray emission from the hottest gas decreased as $t^{-5/3}$, where t is the time since the beginning of the outburst (Fig. 2a). After rising to maximum in about 2 days, the emission measure (n^2V , where n is the density of radiating electrons and V is the X-ray-emitting volume) remained roughly constant at $\sim 10^{58} \text{ cm}^{-3}$ until day 6, after which time it fell as $t^{-4/3}$. For comparison, the X-ray luminosity from hot gas in classical novae, where the white dwarf is not embedded in a dense nebula, is always below $30L_{\odot}$ (refs 14, 15), and the classical nova with the most comprehensive X-ray observations¹⁶ (V1974 Cyg) took more than 100 days to reach a maximum X-ray emission measure of a few times 10^{56} cm^{-3} . As the outburst progressed and the X-ray luminosity decreased, the bulk of the X-ray emission from RS Oph shifted to lower energies (Fig. 1). This shift corresponds to a

drop in the post-shock temperature. From the time of the first spectral observation on day 3, this temperature decreased as $t^{-2/3}$ (Fig. 2b).

If the X-rays are from circumstellar material heated by the blast wave produced in the nova explosion, we can associate the characteristic X-ray temperature with the blast-wave speed via the standard strong-shock relation. Optical emission-line widths directly measure the motion of either gas behind the blast-wave shock that has undergone charge exchange¹⁷ or the ejecta, and these line widths¹⁸ support the shock speeds that we derive. As $u \propto T^{1/2}$, where T is the post-shock plasma temperature and u is the blast-wave speed, the rate of temperature decrease indicates that the blast-wave speed decreased as $t^{-1/3}$. This direct measurement of the shock deceleration rate is, to our knowledge, the first for any nova. For an initial shock speed of $3,500 \text{ km s}^{-1}$ (refs 19, 20), and extrapolating backwards from our inferred shock speeds, we conclude that the deceleration began at approximately day 1.7. With the measured deceleration, we can obtain the blast-wave radius as a function of time. Comparing the blast-wave radius on days 21 and 27 to radio images of the expanding shock on those days (M. P. Rupen, A. J. Mioduszewski and J.L.S., manuscript in preparation), we confirm the 1.6 kpc distance to RS Oph.

The standard blast-wave theory presupposes that the shock structure is self-similar, or that the density and temperature as a function of fractional distance from the white dwarf to the shock front are similar to these functions at later times. In the initial ejecta-dominated phase, the ejecta expand freely and produce a shock moving at constant velocity. After the expanding blast wave has swept up a few times the ejecta mass, it begins to decelerate and enters the Sedov-Taylor phase. After the 1985 outburst of RS Oph, standard supernova blast-wave theory was adapted to explain the late X-ray emission⁶. Models for RS Oph must also account for the fact that the nova explosion takes place within a stellar wind whose density far from the binary decreases as the inverse of the distance from the binary squared ($n \propto 1/r^2$, where r is the distance from the wind-producing red giant). Whereas the early hard X-ray emission from classical novae is thought to arise in the ejecta that has been heated by a reverse shock²¹, the early hard X-ray emission from RS Oph comes predominantly from circumstellar material heated by the forward-moving blast wave.

Our observations indicate that the standard self-similar blast-wave model does not explain the ejection of material from this nova. Although our discovery that $u \propto t^{-1/3}$ agrees with the theoretical prediction for a blast wave moving into a stellar wind and the general expansion law for a shock wave resulting from a point explosion^{4–6}, the observed rate of X-ray fading disagrees with predictions. In the current outburst, the initial X-ray flux was almost 100 times brighter than expected on the basis of observations and modelling of the

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late-time X-ray emission in the 1985 outburst^{6,22}. The total X-ray flux for thermal bremsstrahlung emission from a fully ionized gas is proportional to $T^{1/2}n^2V$, where T is temperature. If the volume of the post-shock emitting region increases as the radius of the blast wave cubed (as in the standard similarity solutions for supernova shells), the X-rays should decrease as t^{-1} . The X-ray emission from RS Oph in the Sedov-Taylor phase decayed instead as $t^{-5/3}$.

The X-ray flux evolution reflects the environment of the binary and suggests how the nova explosion deviates from a spherically symmetric, self-similar blast wave. The fast X-ray rise of RS Oph compared to classical novae is due to the higher circumstellar density and the faster initial shock speed. The observed peak emission measure can be attained in 2 days if the material swept up by the blast wave produces thermal bremsstrahlung emission at the immediate post-shock density and temperature. The observed X-ray decay rate from day 6 onward is consistent with emission from a hot post-shock region whose volume increases roughly as the square of the blast-wave radius. Such an emitting-volume evolution could be produced by radiative cooling, which has little impact on the early-time shock velocity, but a significant impact on the post-

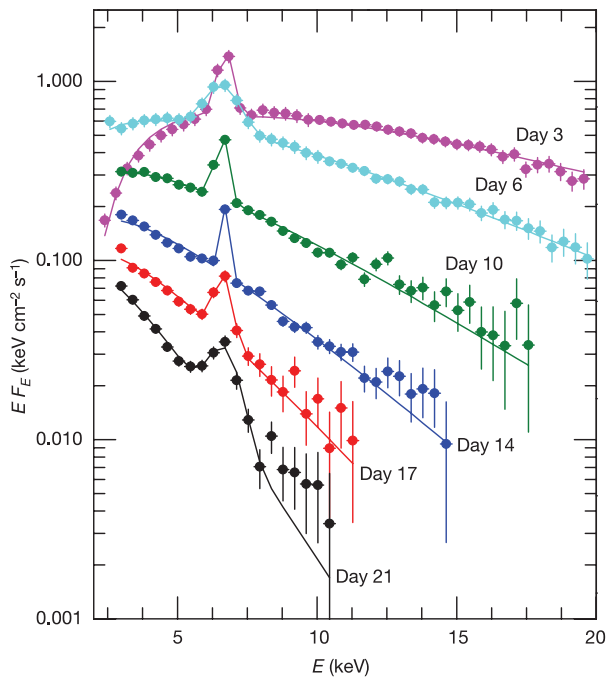


Figure 1 | X-ray spectra from the first 3 weeks of the 2006 outburst of RS Oph. These six spectra were taken with the PCA instrument on board the RXTE satellite. The abscissa is the energy, E , of the detected X-rays. The quantity EF_E is the photon energy times the energy flux density, and it provides a measure of the relative amount of energy being emitted across the spectrum. The usable energy range for the PCA is approximately 2–25 keV. The spectra were reduced using standard RXTE data reduction software (the FTOOLS package) and the standard RXTE background models. The presence of a blended emission line near 6.6 keV from H-like and He-like Fe indicates that the X-ray emission is optically thin thermal plasma emission; the spectra can all be reasonably well fitted (reduced χ^2 ranging from 0.4 to 1.7 for the six observations) with a single-temperature thermal bremsstrahlung model plus line emission from Fe and absorption by intervening material. Although RXTE is not very sensitive to absorption, which preferentially affects photons with energies less than around 2 keV, the absorption was high enough on day 3 ($N_H = (5.5 \pm 1.1) \times 10^{22} \text{ cm}^{-2}$, where N_H is the column density of neutral hydrogen) to have a significant impact on the low-energy end of the spectrum. The absorption lessened in the subsequent observations as the blast wave moved outward and the amount of neutral intervening wind decreased. After day 10, we fixed the absorption parameter in our fits to the interstellar value^{13,22,30} of $N_H = 4 \times 10^{21} \text{ cm}^{-2}$. Error bars represent 1 standard deviation.

shock temperature structure²³. Alternatively, or in conjunction with radiative cooling, a non-spherical ejecta geometry such as that inferred from radio observations^{24,25}, or a contribution to the X-ray luminosity from ejecta heated by a reverse shock, could also steepen the X-ray decline.

Finally, because the transition to the Sedov-Taylor phase occurs when a few times the ejecta mass have been swept up, the timing of the onset of deceleration constrains the ejected shell mass independently of all previous estimates. Taking a density inside the binary of 10^9 cm^{-3} from observational constraints on the red-giant mass-loss rate¹⁰ and assuming that the density fall-off does not begin until outside the binary, on about day 2 the shock had swept up only a few times $10^{-7}M_\odot$ of material (M_\odot is the solar mass). Thus, the ejecta mass could not have been much more than $10^{-7}M_\odot$. Theoretical models of nova explosions with recurrence times of 20 years, as in RS Oph, have been constructed for white dwarfs with masses of $1.25M_\odot$ and $1.40M_\odot$ (ref. 7). Whereas the $1.25M_\odot$ models require an ejecta mass of $\sim 10^{-6}M_\odot$, the $1.40M_\odot$ models eject material with a total mass of $2 \times 10^{-7}M_\odot$. The ejected shell mass of $\sim 10^{-7}M_\odot$ from RS Oph is thus more consistent with the $1.4M_\odot$ model.

The mass accumulation efficiency of white dwarfs in recurrent novae is controversial^{7,26}. Our conclusion that the white dwarf in RS Oph must be extremely close to the maximum mass shows that significant mass accumulation is possible, and that some recurrent novae will explode as type Ia supernovae. If recurrent novae lead to type Ia supernovae such as the one recently discovered to contain hydrogen in its spectrum²⁷, sweeping up of the red-giant wind by the nova blast wave could explain the cavity surrounding this supernova^{28,29}. Our results also have bearing on studies of type II supernovae. The early days of the 2006 outburst of RS Oph show the first two phases of blast-wave evolution, the analogue of which can take hundreds of years for a supernova remnant. These data also provide the blast-wave deceleration law, which is difficult to measure directly in supernovae. Our results should motivate modelling that will lead to better understanding of cooling mechanisms as

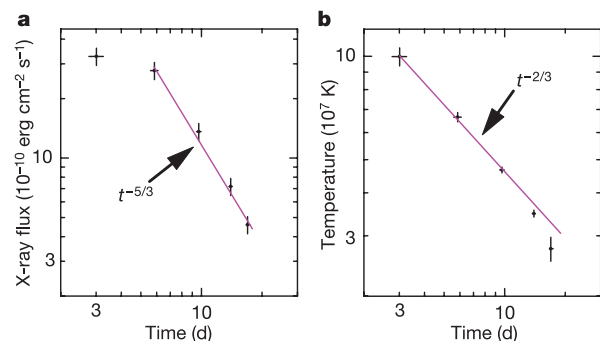


Figure 2 | X-ray flux and post-shock plasma temperature as a function of time. We measure the time, t , from the start of the outburst, which we take to be February 12.6 UT. **a**, X-ray flux in energy range 0.5–20 keV from the hottest plasma, obtained by integrating the best-fit thermal bremsstrahlung model, corrected for the effects of absorption by intervening material. This energy range was chosen to match typical observing ranges and to include most of the emission from the hot plasma. The uncertainty was taken to be 5%, and comes primarily from uncertainty in the model parameters, especially interstellar absorption. **b**, The characteristic X-ray plasma temperature determined from fitting the X-ray spectra with thermal bremsstrahlung models, as a function of time. Error bars represent 1 standard deviation. The temperature decays as expected for material that has been shock-heated by a decelerating Sedov-Taylor blast wave moving into a $n \propto 1/r^2$ stellar wind. As RXTE is sensitive to X-rays with energies greater than 2 keV, we obtain the best determination of the parameters from the first several observations, when the post-shock plasma is hottest. By the sixth observation, the error bars have become too large for these data to be useful (Fig. 1), so the data from the final observation are not included on the plots.

well as post-shock and ejecta structure of novae and other stellar explosions.

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