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# THE X-RAY EVOLUTION OF THE SYMBIOTIC STAR V407 CYG DURING ITS 2010 OUTBURST

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**Abstract.** We present a summary of *Swift* and *Suzaku* X-ray observations of the 2010 nova outburst of the symbiotic star, V407 Cyg. The *Suzaku* spectrum obtained on day 30 indicates the presence of the supersoft component from the white dwarf surface, as well as optically thin component from the shock between the nova ejecta and the Mira wind. The *Swift* observations then allow us to track the evolution of both components from day 4 to day 150. Most notable is the sudden brightening of the optically thin component around day 20. We identify this as the time when the blast wave reached the immediate vicinity of the photosphere of the Mira. We have developed a simpe model of the blast wave – wind interaction that can reproduce the gross features of the X-ray evolution of V407 Cyg. If the model is correct, the binary separation is likely to be larger than previously suggested and the mass-loss rate of the Mira is likely to be relatively low.

**Key words:** stars: symbiotic, white dwarfs – X-rays: stars

## 1. INTRODUCTION

The 2010 outburst of the little-studied symbiotic star, V407 Cygni, was detected on 2010 March 10. Subsequent optical photometry and spectroscopy (Munari et al. 2011; Shore et al. 2011) clearly establish this as a classical nova event with $t_2 = 5.9$ d and $t_3 = 24$ d, unlike the smaller amplitude events seen in 1936 and 1998. Thus, the closest analogue to the 2010 outburst of V407 Cyg is the 2006 outburst of the recurrent nova RS Ophiuchi. In the latter case, strong hard X-ray emission was almost immediately discovered and intensively monitored using *RXTE* and *Swift* (Sokoloski et al. 2006; Bode et al. 2006). In the subsequent months, RS Oph became a bright supersoft X-ray source; its evolution was followed with *Swift* and high resolution, high signal-to-noise spectra were obtained using *XMM-Newton* and *Chandra* grating instruments (e.g., Nelson et al. 2008; Ness et al. 2009; Osborne et al. 2011).

The X-ray emission of V407 Cyg evolved rather differently. Its hard X-ray emission developed more slowly and peaked at a much lower level than in RS Oph, and there was no obvious and bright supersoft phase, as was shown in the analysis of the *Swift* data (Shore et al. 2011). The likely reason for this is the different binary parameters. RS Oph is an S-type symbiotic with a normal red giant mass donor with an orbital period of 455.72 d (Zajczyk et al. 2007) and an orbital separation of $\sim 1$ AU; a 3 000 $\mathrm{km\,s^{-1}}$ nova blast wave would reach the vicinity of the red giant in half a day, get strongly shocked, and become a luminous hard X-ray source (see, e.g., Orlando et al. 2009). V407 Cyg, on the other hand, is a D-type symbiotic with a Mira type mass donor. Munari et al. (1990) noted dust obscuration events separated by 43 years and proposed that as the orbital period. While plausible, we do not consider this to be firmly established. Nevertheless, the current body of data on V407 Cyg indicates a substantially wider binary separation than for RS Oph, of at least 10 AU. Therefore, the nova blast wave propagates in a lower density environment, and it takes significantly longer to reach the Mira than was the case for RS Oph.

Most remarkably, V407 Cyg was detected as a transient GeV $\gamma$-ray source with *Fermi* LAT (Abdo et al. 2010). The first significant detection was obtained on 2010 March 10, the day of the optical discovery, and the last significant detection was on day 15 of the outburst (2010 March 25). As was already pointed out by Abdo et al. (2010), the fading of the $\gamma$-rays coincided with the rapid brightening of the X-rays. This provides additional motivation for our effort to understand the X-ray evolution of V407 Cyg.

## 2. SUMMARY OF X-RAY OBSERVATIONS AND RESULTS

X-ray observations of V407 Cyg were obtained with *Swift* XRT between day 3.8 and day 142 (34 visits, typical exposures of 1–5 ks). We also obtained a 42 ks *Suzaku* target-of-opportunity observation on day 30, near the peak of the X-ray emission. We have performed a detailed spectral analysis of the *Suzaku* data, and re-analyzed the *Swift* data in light of the *Suzaku* results. Full details are published elsewhere (Nelson et al. 2012). Here, we provide a summary of key findings, before exploring a range of parameters for the Mira, the binary, and the nova ejecta in the next section.

The *Suzaku* spectra (one for the two units of XIS with front illuminated CCDs combined, and one for the XIS unit with a back illuminated chip) on Day 30 (Figure 1) consist of a soft component, dominant below $\sim 0.9$ keV, and a hard component. The hard component is optically thin with $kT$ of order 3 keV, and exhibits prominent lines of He-like Fe, S, Si and Mg. While the He-like Fe line is expected in a $\sim 3$ keV thermal plasma in collisional ionization equilibrium (CIE), the other lines are not. They are expected of 3 keV plasmas on their way toward

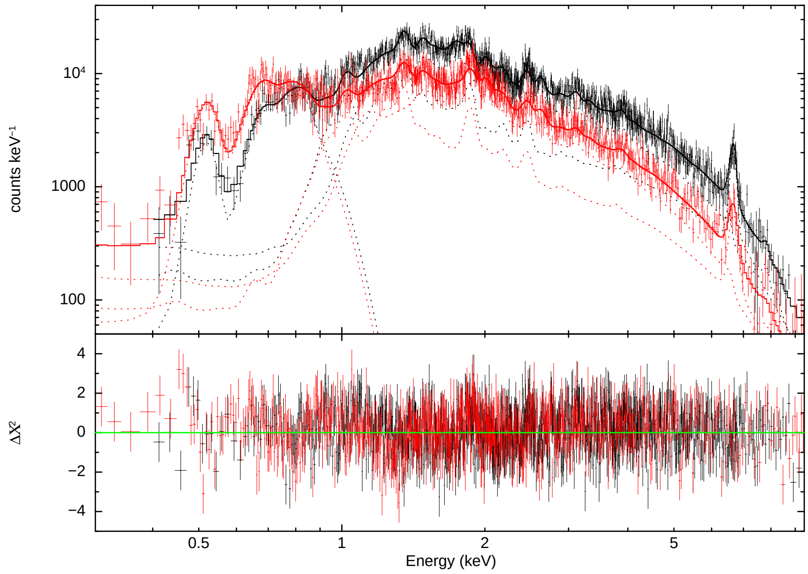


**Fig. 1.** The *Suzaku* X-ray spectra (black: XIS0+XIS3; red: XIS1) of V407 Cyg obtained on day 30, fitted with a two component (one in collisional ionization equilibrium and the other not) plasma model plus a supersoft blackbody.

ionization equilibrium (Smith & Hughes 2010). Nelson et al. (2012) were able to obtain a satisfactory fit above 1 keV by using a mixture of CIE and non-ionization equilibrium (NIE) plasmas, and interpreted this as being due to the shock near the Mira (higher density environment) and the shock away from the Mira (lower density, and hence did not have the time to reach ionization equilibrium).

The shape of the soft component is poorly constrained by the data. However, fits using optically thin plasma models require an unrealistically high emission measure; therefore, we discard this possibility as implausible. We do achieve a reasonable fit using a blackbody to represent the soft component, with a best-fit luminosity of $8.4\times10^{39}$ erg s$^{-1}$. We interpret this as the supersoft emission from the surface of the nuclear burning white dwarf, whose luminosity is overestimated due to the use of the blackbody model.

Individual *Swift* XRT spectra have far fewer counts than the *Suzaku* data, even though we analyzed sliding sums of 3 neighboring pointings. We therefore used a simple spectral model, consisting of an absorbed blackbody and a single APEC optically thin, CIE, plasma model. By applying the same model consistently to all the *Swift* data, we were able to infer the evolution of spectral parameters throughout the outburst. We show the X-ray flux of the soft and hard components in Figure 2.

The blackbody component is detected only during days 20–50. The rapid evolution of the supersoft emission and the relatively high temperature ($kT$ = 40–60 eV) both suggest that V407 Cyg contains a massive white dwarf. It was not seen to make a dominant contribution to the observed X-ray flux during any period because of high intrinsic absorption in the Mira wind.

The faint, hard emission observed during the first two weeks is consistent with a $\sim$6 keV plasma with high ($>10^{23}$ cm$^{-2}$) absorption. Between days 20 and 50, the

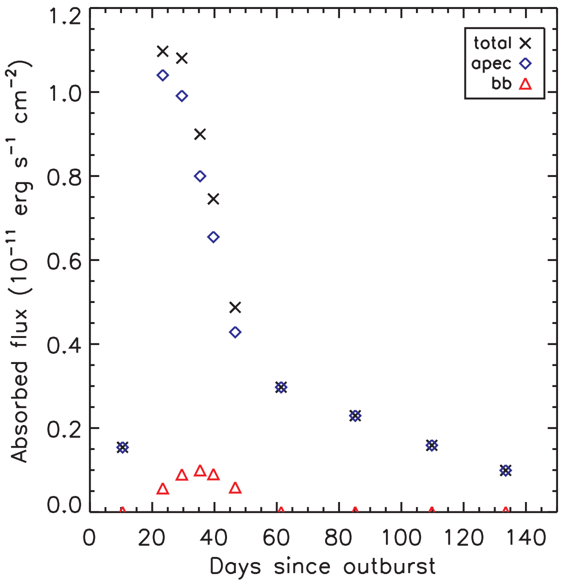


**Fig. 2.** The X-ray flux evolution of the hard (APEC) and soft (blackbody) components of V407 Cyg, as inferred from *Swift* XRT data.

emission measure, $kT$, and $N_H$ all declined sharply, and thereafter they declined at a much reduced rate.

## 3. EXPLORATION OF PARAMETER SPACE

The most likely origin of the hard component of the X-ray spectrum of V407 Cyg is the forward shock driven into the Mira wind by the nova blast wave. We have therefore developed a simple model of this interaction. The model tracks the sweeping up of the Mira wind by the ejecta as they travel outwards from the white dwarf, and estimates the global properties of the resulting X-ray emission. We assume that the Mira wind follows an $r^{-2}$ density profile, and adopt a photospheric radius of 500 $R_\odot$ and a wind velocity of 30 km s$^{-1}$. The wind mass-loss rate is a key parameter and is poorly constrained in V407 Cyg: we therefore compare the results for three assumed values, $10^{-7}$, $10^{-6}$ and $10^{-5}$ $M_\odot$ yr$^{-1}$.

The white dwarf is significantly offset from the center of the Mira wind, by the orbital separation $a$ that is also unknown. We explore the effects of different binary separations by running models for $a$ = 10, 20 and 50 $R_\odot$. Based on the full width at zero intensity of the Balmer lines (Munari et al. 2011; Shore et al 2011), we adopt the initial ejecta velocity of 3200 km s$^{-1}$. If the blast wave is undecelerated, it would take 4, 10 and 25 days to reach the surface of the Mira for these three values of $a$, respectively, after subtracting the red giant radius of 500 $R_\odot$ ($\sim$2.3 AU).

Given this situation, the evolution of the shock is strongly asymmetric. Ejecta traveling towards the Mira encounter an increasingly high density and evolve quickly, until they reach the photosphere. Ejecta traveling away from the Mira encounter progressively lower density and evolve much more slowly. Our model

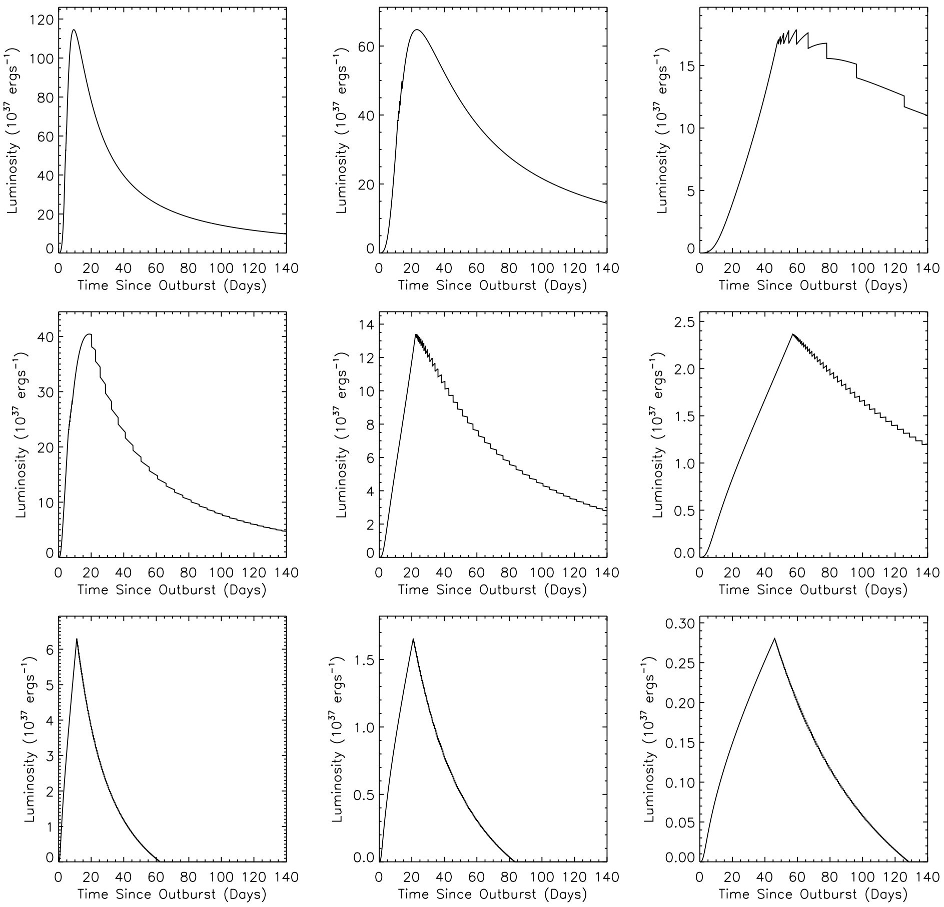


**Fig. 3.** Luminosity evolution over the first 140 days predicted by our simple model for an assumed Mira mass-loss rate of $10^{-5}$ $M_{\odot}$ yr$^{-1}$. The top, middle and bottom rows are the results for nova ejecta masses of $10^{-5}$, $10^{-6}$ and $10^{-7}$ $M_{\odot}$, respectively, and the left, middle and right columns are for binary separation of 10, 20 and 50 $R_{\odot}$. The steplike features in some of the plots are artefacts of our simple model – if the post-shock temperature of a given region is less than $10^6$ K, we assume it no longer emits X-rays. Therefore, discontinuities in the luminosity arise as material is strongly decelerated.

divides the ejecta into many azimuthal bins, and tracks the interaction with the environment separately for each bin.

The final unknown is the total ejecta mass, for which we adopted $10^{-7}$, $10^{-6}$ and $10^{-5}$ $M_{\odot}$. We show the predicted luminosity evolution for these 3×3×3 cases in Figures 3–5.

We first note that this model can reproduce the shape of the observed X-ray light curve using certain combinations of the parameters (e.g., a binary separation of 50 AU, ejecta mass of $10^{-5}$ $M_{\odot}$, and Mira wind mass-loss rate of $10^{-7}$ $M_{\odot}$ yr$^{-1}$). That is, our model predicts an initial phase of low flux, a sudden increase in luminosity, and a decline with a changing slope.

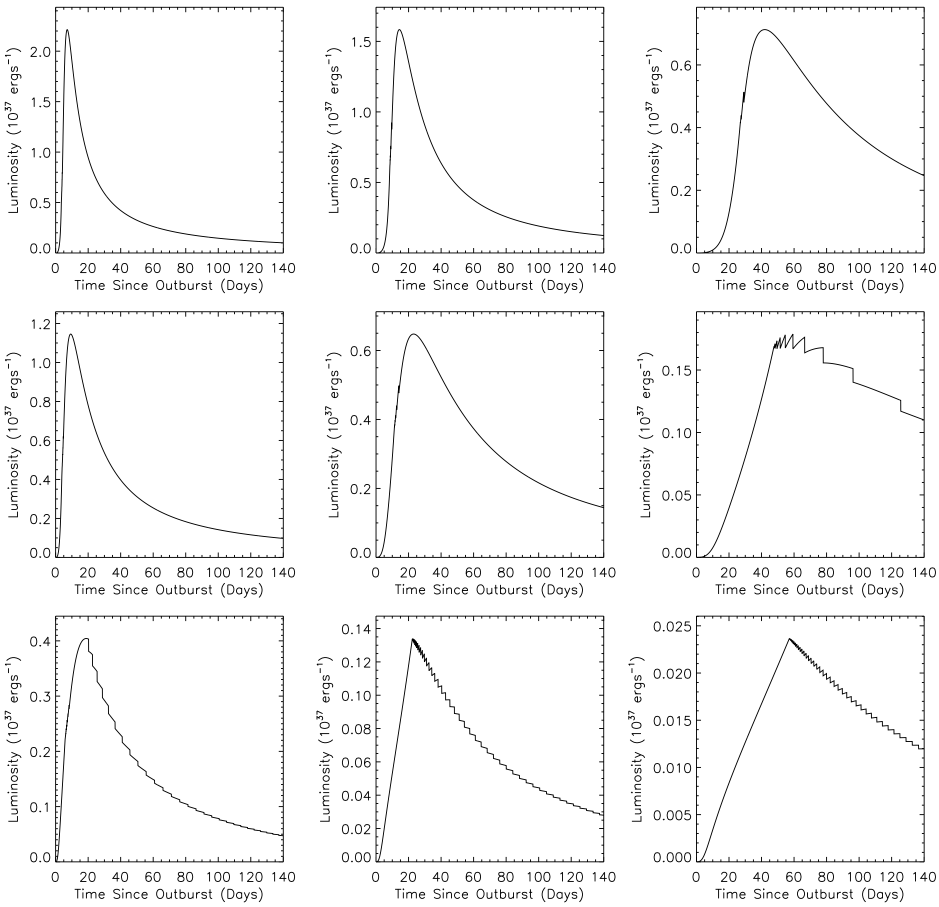


**Fig. 4.** Same as Figure 3, but with a Mira mass-loss rate of $10^{-6}$ $M_\odot\,\mathrm{yr}^{-1}$.

Based on this success, we identify the sudden brightening observed around day 20 with the time when the blast wave reached the immediate vicinity of the Mira. To first order, this implies a binary separation of 40 AU for an ejecta velocity of 3200 $\mathrm{km\,s^{-1}}$. The real separation is smaller by an amount dependent on the degree of deceleration during this period. However, significant deceleration necessarily implies significant interaction, which results in increased X-ray emission well before the ejecta reach the Mira surface. Thus, parameter combinations that have low ejecta mass and/or high wind mass-loss rates result in a gradual increase in X-ray luminosity, compared to the sudden increase that is observed.

Thus, our model results suggest a large binary separation and a modest mass-loss rate for the Mira in V407 Cyg. However, it should be kept in mind that ours is a simple model. A full physical model of the ejecta – wind interaction might result in a somewhat different conclusion. We also suggest that a careful modeling of the existing body of optical spectra during the first 20 days should be performed to infer the degree of deceleration towards of the ejecta traveling towards the Mira. This could provide the best measurement of the binary separation, assuming our

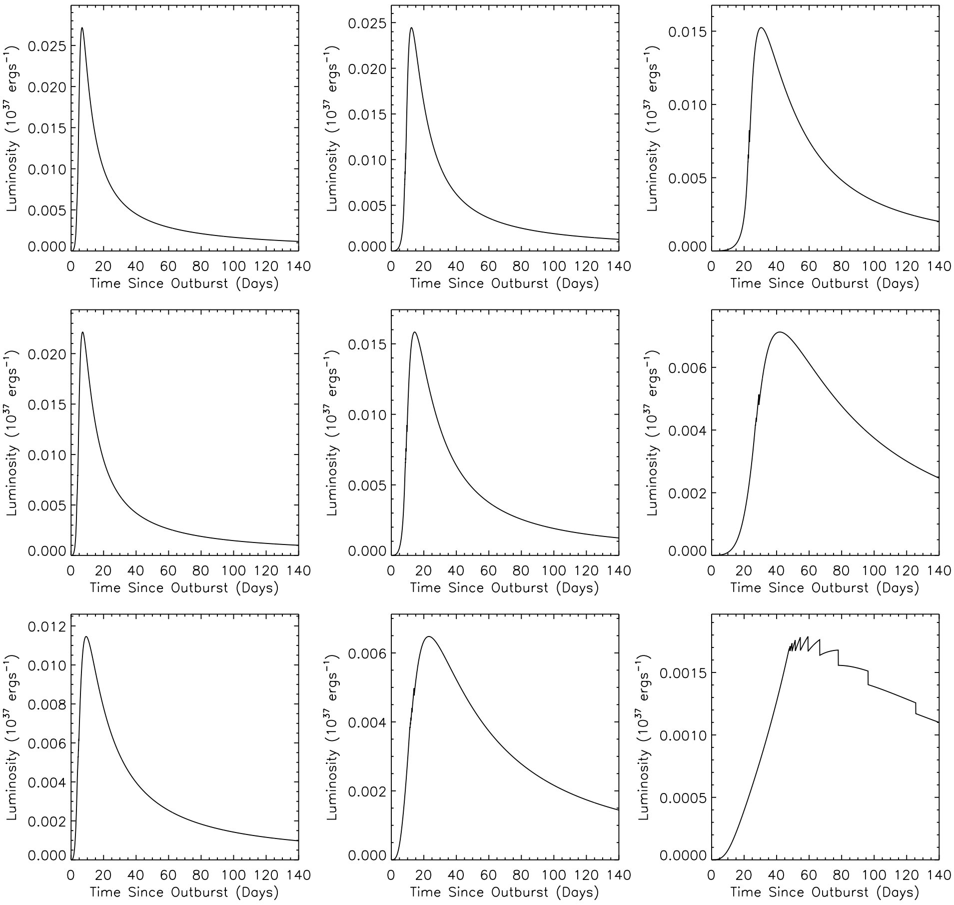


**Fig. 5.** Same as Figure 3, but with a Mira mass-loss rate of $10^{-7}$ $M_\odot\,\mathrm{yr}^{-1}$.

interpretation of the sudden X-ray brightening is correct.

## 4. CONCLUSIONS

Our analysis suggests that V407 Cyg harbors a massive white dwarf in a wide binary, much wider than RS Oph. The blast wave initially encounters a relatively low density ($< 10^6$ cm$^{-3}$) stellar wind. The subsequent evolution is highly asymmetric; in one direction, the wind density sharply increases around day 20 as the ejecta approach the Mira surface. This leads to the sudden increase in the X-ray emission. In the opposite direction, the wind density decreases. This asymmetry results in an X-ray spectrum that can be modeled using our CIE+NIE, two-component model.

The GeV $\gamma$-ray emission detected with *Fermi*/LAT (Abdo et al. 2010) requires both particle acceleration and a secondary process that generates the $\gamma$-rays. The latter may either be accelerated protons hitting the Mira, producing pions, or the infrared photons of the Mira inverse-Compton scattering off relativistic electrons.

In the direction away from the Mira, both the number of accelerated particles and that of the target particles continue to decrease with time. In the direction towards the Mira, the deceleration caused by the high density environment leads to a sharp decrease in the maximum energy that the particles can be accelerated to, even though the density of seed and target particles both increase. This, in our view, is the cause of the drop in $\gamma$-ray intensity at the time of X-ray flux increase.

The exploration of parameter space of our simple model suggests that the binary separation is larger ($>20$ AU) than the proposed orbital period of 43 years would imply. It also suggests a modest wind mass-loss rate (not much more than $10^{-7}\ M_{\odot}\,\mathrm{yr}^{-1}$ ) for the Mira. These tentative results should be checked with additional observations.

V407 Cyg joins a small group of symbiotic stars that have exhibited a fast nova outburst. Other four are all known recurrent novae, and V407 Cyg may yet prove to be one. The short duration of the supersoft phase suggests that its white dwarf may be massive enough to have a short recurrence time. It is quite possible, therefore, that V407 Cyg in quiescence is a luminous, hard X-ray source similar to T CrB and several other symbiotic stars (Kennea et al. 2009). On the other hand, RS Oph in quiescence is significantly fainter than T CrB (Nelson et al. 2011). We believe that a quiescent X-ray observation should be attempted as a matter of priority.

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