SUZAKU DETECTION OF SUPER-HARD X-RAY EMISSION FROM THE CLASSICAL NOVA V2491 CYGNI

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ABSTRACT

We report the detection of super-hard (>10 keV) X-ray emission extending up to 70 keV from the classical nova V2491 Cygni using the Suzaku satellite. We conducted two ~20 ks target-of-opportunity observations 9 and 29 days after the outburst on 2008 April 11, yielding wide energy range spectra by combining the X-ray Imaging Spectrometer and the Hard X-ray Detector. On day 9, a spectrum was obtained at 1.0–70 keV with the Fe XXV Kα line feature and a very flat continuum, which is explained by thermal plasma with a 3 keV temperature and power-law emission with a photon index of 0.1 attenuated by a heavy extinction of 1.4×10^{23} cm^{-2}. The 15–70 keV luminosity at 10.5 kpc is 6×10^{35} ergs s^{-1}. The super-hard emission was not present on day 29. This is the highest energy at which X-rays have been detected from a classical nova. We argue a non-thermal origin for the emission, which suggests the presence of accelerated charged particles in the nova explosion.

Subject headings: stars: individual (Nova Cygni 2008 number 2, V2491 Cygni) — stars: novae

1. INTRODUCTION

Classical nova explosions occur in accreting binaries with a white dwarf (WD) as the primary and a late-type dwarf or giant as the secondary. Hydrogen-rich accreted material is accumulated on the WD surface until a critical mass is reached that ignites a thermonuclear runaway (e.g., Starrfield et al. 2008). The released energy and mass propagate through the circumstellar matter and are expected to form a shock structure similar to, but in much smaller scales both in time and space than, those found in supernova remnants (SNRs). From the analogy to SNRs, we naturally expect both thermal and non-thermal emission in the X-ray band if we consider classical novae due mainly to the unusual behavior by a sudden release of magnetic energy. Successful detection of non-thermal X-rays will make classical novae another agent of cosmic particle acceleration. Also, because super-hard X-ray photons can penetrate through an extreme extinction of AV ~ 10^{4} mag, it will eventually give a tool to unveil the currently-inaccessible phenomena shielded by a thick ejecta material in the initial phase of classical nova explosions.

In this Letter, we report the result of the X-ray observations from the classical nova V2491 Cyg using the Suzaku satellite. We focus on the detection of super-hard emission extending up to 70 keV, the highest energy X-rays ever reported from classical novae. The results of the remaining data will be presented separately.

2. V2491 CYG

V2491 Cyg (Nakano et al. 2008, Samus 2008) was discovered on 2008 April 10.728 UT at a Galactic coordinate of (l, b) = (67.22874°, 4.35315°). We define the epoch of the discovery as the origin of time in this Letter. The evolution of the nova was extremely fast (Tomov et al. 2008a), declining at a rate of t_d ~ 4.6 d (Tomov et al. 2008b), where t_d is the time to fade by 2 mag from the optical maximum. Using an empirical relation between the maximum magnitude and the rate of decline among classical novae (Della Valle & Livio 1995), in which intrinsically brighter ones fade faster, a distance was estimated as ~10.5 kpc (Helton et al. 2008). The WD mass is considered to be on the higher end from the rapid development of the light curves (Hachisu & Kato 2009).

Intensive monitoring both by ground-based and space-based observations revealed some distinctive characteristics of this source. In general, classical novae continue to decline in the optical brightness, but V2491 Cyg exhibited a clear rebrightening followed by a sudden fading around day 15. A similar rebrightening was found only in two other cases: V1493 Aqr (Venturini et al. 2004) and V2362 Cyg (Kimeswenger et al. 2008, Lynch et al. 2008). Hachisu & Kato (2009) attempted to explain this unusual behavior by a sudden release of magnetic energy. V2491 Cyg is also one of the few examples with X-ray detection prior to the nova (Ibarra & Kunikers 2008, Ibarra et al. 2008, 2009) with possible spectral changes among several observations (Ibarra et al. 2009). The op-
tical rebrightening and the pre-nova X-ray activity suggest that V2491 Cyg might host a magnetic WD.

3. OBSERVATIONS AND REDUCTION

The onset of the nova triggered an X-ray monitoring campaign using the Swift satellite (Kuulkers et al. 2008; Osborne et al. 2008; Page et al. 2008, 2009). No emission was found on day 1, but X-rays emerged clearly on day 5 with extremely hard continuum emission (Kuulkers et al. 2008) as well as a line-like feature near 6.7 keV attributable to Fe XXV Kα in our quick look. These X-ray features are quite rare in classical nova explosions, yet are important for understanding their high-energy behavior. We therefore requested a ∼20 ks target-of-opportunity observation by Suzaku and obtained a well-exposed spectrum on 2008 April 19–20 (day 9.1 in the middle of the observation). In order to follow the spectral evolution, we requested another ∼20 ks time on May 9 (day 28.9). The data were processed with the pipeline version 2.2.

Suzaku has two instruments in operation (Mitsuda et al. 2007): the X-ray Imaging Spectrometer (XIS; Koyama et al. 2007) sensitive at 0.2–12 keV and the Hard X-ray Detector (HXD; Takahashi et al. 2007; Kokubun et al. 2007) above 10 keV. The utility of the unique combination of detectors covering a wide energy range is illustrated by previous Suzaku studies of classical novae (Takei et al. 2008; Tsujimoto et al. 2009).

The XIS is equipped with four X-ray CCDs at the foci of four X-ray telescope modules (Serlemitsos et al. 2007). Three of them (XIS0, 2, and 3) are front-illuminated (FI) CCDs and the remaining one (XIS1) is back-illuminated (BI). The absolute energy scale is accurate to ≤5 eV and the energy resolution is 160–190 eV (FWHM) at 5.9 keV. Each XIS covers a 18′×18′ field of view (FoV) with an energy-independent half power diameter of 1.8′–23′. The XIS2 is not functional, thus we used the remaining three CCDs. The XIS was operated in the normal clocking mode with a frame time of 8 s.

The HXD is a non-imaging X-ray detector consisting of several components sensitive at different energy ranges. We focus on the PIN detector operating at 10–70 keV with an energy resolution of ∼3.0 keV. Passive fine collimators restrict the FoV to 34′×34′ (FWHM). Thanks to the surrounding anti-coincidence scintillators, the narrow FoV, and the stable and low background environment in a low earth orbit, the PIN achieves unprecedented sensitivity in the super-hard X-ray band.

4. ANALYSIS

4.1. XIS Image and Spectrum

Figure 1 shows the XIS image on day 9. V2491 Cyg is clearly detected as a very hard source at the center with a total count rate of 4.5×10^−2 s^−1 (0.2–12 keV) along with other softer sources. We constructed a background-subtracted spectrum on day 9 (red and black symbols in Fig. 2), which is characterized by a hard flat continuum extending beyond 10 keV and a Fe Kα line presumably from Fe I at 6.4 keV, Fe XXV at 6.7 keV, or Fe XXVI at 7.0 keV between 6 and 7 keV. No emission in the soft band is visible. On day 29, the spectrum became much softer, and the hard continuum and the Fe Kα line emission disappeared. The detailed results of the second spectrum are presented in Takei et al. in prep.

![Image](image-url)

**Fig. 1.**—XIS image on day 9 coded with yellow (0.2–2.0 keV), magenta (2.0–5.0 keV), and cyan (7.0–12.0 keV). The source and background photons for V2491 Cyg are accumulated respectively from the solid and dashed regions in order to avoid contamination from other sources in the view.

![Image](image-url)

**Fig. 2.**—Background-subtracted XIS and PIN spectra on day 9 and the models. The two XIS FI spectra with nearly identical responses were merged, while the BI spectrum was treated separately. The best-fit model (APEC + power-law) is shown with thick lines (solid for total and dashed for each component) for FI, BI and PIN in different colors. The alternative unsuccessful model (APEC + 100 keV bremsstrahlung) is shown with thin blue lines for FI and PIN. The lower panel shows the residual from the best-fit.

4.2. PIN Spectrum

We see a high prospect of PIN detection on day 9, in which the XIS spectrum shows very flat continuum emission extending beyond 10 keV. We examine the signal against the background, which is a combination of the instrumental non-X-ray background (NXB) and the X-ray background. The X-ray background consists of the Cosmic X-ray background (CXB) emission and the Galactic ridge X-ray emission (GRXE). The majority of the background is the NXB: the CXB is ∼2 orders smaller than the NXB, and the GRXE is totally negligible with ≥1 order smaller than the CXB toward V2491 Cyg (Revnivtsev et al. 2004).

In Figure 3, we compare the observed signal against the model background. The NXB model was simulated by taking account of the cut-off-rigidity history and the elapsed time from South Atlantic anomaly passages during the observation. The 1 σ reproducibility of the NXB
is $\lesssim 1.8$ % in flux (Fukazawa et al. 2009). The CXB model was constructed by convolving the detector responses with the CXB model derived by HEAO-1 observations (Boldt 1987). A significant signal up to 70 keV was detected at a $\gtrsim 3\sigma$ level on day 9. The detection is also significant even when subtracting the maximum allowable NXB model. The detection is further confirmed by subtracting another NXB model constructed differently by accumulating the PIN data of our own observation during the earth occultation. In contrast, no significant PIN emission was detected on day 29.

We attribute the PIN emission on day 9 to V2491 Cyg for the following reasons: (1) the flux of the PIN emission is consistent with the extrapolated flux of the flat hard continuum in the hard end of the XIS spectrum (Fig. 2), (2) no other X-ray source with a comparable hardness was found in the XIS image (Fig. 1). (3) no super-hard X-ray source is known within the PIN FoV by the INTEGRAL (Ebisawa et al. 2003) and the quick-look data by the All-Sky Monitor in the Rossi X-ray Timing Explorer (RXTE), and (4) the absence of the PIN emission on day 29 is consistent with the fact that the extrapolated XIS emission is too weak for any PIN detection.

4.3. Spectral Fitting

We now fit the resultant background-subtracted XIS and PIN spectra on day 9 simultaneously. We start with the Fe Kα feature between 6 and 7 keV. We fitted the feature locally with a Gaussian line and obtained the best-fit energy and equivalent width of 6.6\textpm 0.1 keV and 120 eV, respectively. The detection of the line was found significant at a 3σ level both by the F-test and a Monte Carlo simulation (Protassov et al. 2002). We attribute the feature to the Fe XXV Kα emission line at 6.7 keV. We further examined the presence of possible accompanying lines at 6.4 keV by Fe I Kα and at 7.0 keV by Fe XXVI Kα, but these lines were found insignificant.

The presence of the Fe XXV Kα line and the absence of the Fe XXVI Kα line indicate a thermal origin of the emission by plasma with a temperature of \lesssim 10 keV. The plasma at this temperature is incapable of producing the flat super-hard continuum, so an additional harder spectral component is required. We fitted the entire spectrum with two different combinations of models. The first one is optically-thin thermal plasma (APEC; Smith et al. 2001) plus a power-law model, which is respectively for the thermal features in the hard band and the flat continuum across both bands. The second combination employs a bremsstrahlung model in place of the power-law model. These models are attenuated by an interstellar extinction model (TBabs; Wilms et al. 2000). The Fe abundance relative to H in the plasma model was not constrained well by the data, and we therefore fixed it at solar (Anders & Grevesse 1989).

We obtained a statistically acceptable fit for the first combination. The best-fit parameter values are compiled in Table 1 for the amount of extinction ($N_H$), the thermal plasma temperature and flux ($k_B T$ and $F_X^{(\text{th})}$), and the power-law photon index and flux ($\Gamma$ and $F_X^{(\text{pl})}$). The extinction-corrected luminosity at 10.5 kpc was also derived for each component ($L_X^{(\text{th})}$ and $L_X^{(\text{pl})}$). The second combination of models, the electron temperature of the bremsstrahlung emission is constrained to be $> 100$ keV, which is much higher than the post shock temperature in a strong shock by the ejecta propagating at $\sim 4000$ km s$^{-1}$ (e.g., Tomov et al. 2008a,b). We therefore conclude that the spectrum on day 9 is better explained by a combination of 3 keV thermal plasma and power-law emission with a photon index of 0.1 attenuated by a heavy extinction. The systematic uncertainty in the NXB reproducibility for the PIN brings little change in the result by about $\pm 0.3$ keV in $k_B T$, $\pm 0.08$ in $\Gamma$, and $\pm 15\%$ both in $F_X^{(\text{th})}$ and $F_X^{(\text{pl})}$.

5. DISCUSSION

We have found the super-hard X-ray emission extending up to 70 keV from V2491 Cyg on day 9. The spectrum cannot be explained by a simple bremsstrahlung model with a reasonable temperature. The best-fit power-law model is very flat with a photon index of $0.1\pm 0.2$. The emission was absent on day 29 in an observation with the same exposure. The 15–70 keV flux decreased from $4.8 \times 10^{-11}$ ergs s$^{-1}$ cm$^{-2}$ on day 9 to $\lesssim 1.5 \times 10^{-11}$ ergs s$^{-1}$ cm$^{-2}$ on day 29 (a 90% confidence upper limit assuming the same spectral shape). The rapid decay rules out the possibility of Comptonization of nuclear $\gamma$-ray lines from radioactive species such as $^{22}$Na (Livio et al. 1992) or rekindled accretion (Hernanz & Sala 2002).

Super-hard X-ray emission was studied in two other classical novae to date: V382 Vel by BeppoSAX (Orio et al. 2001), and RS Oph by RXTE (Sokoloski et al. 2000) and Swift (Bode et al. 2006). Similarly to V2491 Cyg, these observations were conducted a short time after the outburst (days 3 and 15.

Fig. 3.— Comparison of the observed signal (red) against the model background (green) of the PIN data on days 9 (left) and 29 (right). The background includes both the NXB and the CXB. The background-subtracted spectrum is shown in black. The dotted band indicates the uncertainty stemming from the inaccuracy of the reproducibility in the NXB model. On day 29, the data are not used below 20 keV due to high detector temperatures.

![Graph showing comparison of observed signal against model background.](image-url)
for RS Oph and V382 Vel, respectively). However, neither of the two other cases shows clear evidence of non-thermal signature of the emission. In RS Oph, RXTE detected photons only below ∼20 keV, which is attributable to thermal plasma with a reasonable temperature of ≤10 keV (Sokoloski et al. 2006). Swift reported weak 25–50 keV detection but no spectrum was obtained in the super-hard X-ray band (Bode et al. 2006). In V382 Vel, BeppoSAX only constrained a 2 σ upper limit in the 15–60 keV band (Orio et al. 2001). On the contrary, in V2491 Cyg, the spectrum is clearly seen up to 70 keV, which is not explained by a simple bremsstrahlung model with a reasonable temperature but by an extremely flat power-law model.

The power-law emission from V2491 Cyg suggests the presence of an accelerated population of electrons with non-thermal energy distribution. Non-thermal particles in classical nova explosions are suggested in some radio observations and theoretical studies of RS Oph. Rupen et al. (2008) found evidence of synchrotron emission in a high-resolution radio interferometer observation. Tatischeff & Hernanz (2007) argued for the presence of diffusive shock acceleration based on the fact that the blast wave decelerated at a much faster rate than that predicted by the standard adiabatic shock model. Our result is the first to claim a non-thermal signature from classical nova explosions in the X-ray band.

The extremely flat photon index of 0.1±0.2 in the power-law radiation poses a challenge to understand the radiation mechanism as well as the acceleration mechanism of electrons to produce the radiation. If the dominant radiation is inverse Compton or synchrotron emission and the electrons lose energy radiatively, the electron population has a number index from −0.8 to −1.8 in the power-law energy distribution at injection. If bremsstrahlung emission is the dominant radiation and the non-relativistic electrons lose energy via ionization losses with ambient matter, the injected electrons have a number index from −0.4 to 1.1. These values are too hard for standard diffusive shock acceleration, in which a number index of 2.0 is expected (Blandford & Ostriker 1980). Additional explanations, such as multiple scattering in the inverse Compton process or the acceleration by magnetic reconnections, would be necessary.

Alternative interpretations to the non-thermal model for the super-hard emission include a multiple temperature hot (≥10 keV) plasma with an extreme extinction (>10^25 cm^{-2}) and Comptonized blackbody emission (Nishimura et al. 1986). The former is unlikely due to the lack of reprocessed emission (e.g., Fe I Kα) and the fact that such a large extinction cannot be realized by the typical amount of ejecta (∼10^{-5} M_{⊙}; e.g., Pietsch et al. 2007). The latter requires blackbody emission of ∼5 keV, which is too hot for the WD surface emission.

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