Recent Progress of Hard X-ray Studies of Classical Novae

Masahiro Tsujimoto[1] and Dai Takei[2]

[1] Japan Aerospace Exploration Agency, Institute of Space and Astronautical Science,
3-1-1 Yoshino-dai, Chuo-ku, Sagamihara, Kanagawa 252-5210
[2] Department of Physics, Rikkyo University,
3-34-1 Nishi-Ikebukuro, Toshima, Tokyo 171-8501
E-mail(MT): tsujimot@astro.isas.jaxa.jp

Abstract

Classical novae (CNe) are explosions caused by a nuclear runaway on the surface of a white dwarf (WD) when the critical mass is reached by the matter accreted from its companion star. The defining characteristic of CNe is a sudden increase in the optical brightness by ~10 mag, but CNe also show a variety of phenomena across wavelengths. In the X-rays, two types of emission after CNe have been known for decades: super-soft emission from the heated WD surface, and hard emission presumably caused in shocks by CN ejecta. Unlike the super-soft emission, the hard emission has not been observed in a systematic manner for its transient and faint nature. The start of a routine monitoring campaign by Swift for X-ray bright CNe drastically changed the situation, making timely pointing observations using X-ray observatories possible. Many new discoveries were reported in the hard X-ray regime and in the higher energy bands, including the detection of non-thermal emission, Fe fluorescence from rekindled accretion, altered chemical composition in the plasma, etc. In this article, we briefly summarize some of the topics in recent hard X-ray studies made with Suzaku and discuss utility of MAXI in this field.

Key words: stars: novae, cataclysmic variables — X-rays: stars

1. Historical Context

Classical novae are explosions that occur in binary systems consisting of a white dwarf (WD) and a late-type dwarf or giant star. When the accreted mass from the companion reaches the critical mass on the WD surface, thermo-nuclear runaway is ignited, leading to a classical nova explosions. They are characterized by a mass loss with an ejecta mass of 10^{-5} to 10^{-6} $M_{\odot}$, and ejecta velocities of 10^3 to 10^4 km s^{-1}. Roughly 10 classical novae are discovered every year by optical amateur astronomers.

It has long been known that a classical nova leaves soft X-ray emission below ~1 keV, which stems from the WD atmosphere heated to a temperature of ~1 MK, which is known as super soft source (SSS) emission. Some classical novae also leave hard X-ray emission. The hard X-ray light curve is completely different from the soft X-ray light curve, indicating different origins of the two.

Hard X-ray emission from CNe was first discovered by a ROSAT target-of-opportunity (ToO) observation conducted on day 5 of an explosion of V838 Her in 1991 (Lloyd et al. 1992). The spectrum is dominated by emission above 1 keV. The spectrum was unfortunately poor of only 194 counts and two completely different spectral fits were obtained by an optically-thin thermal plasma model of a temperature of 10 keV or 0.75 keV. Whichever the result is the case, however, it is distinctively different from the SSS emission in its early appearance and spectral hardness. The hard X-ray emission was immediately interpreted as X-rays from plasma created by shocks of ejecta running at velocities of a few 1000 km s^{-1}.

Such phenomena were interesting by themselves, but systematic studies (e.g., Orio et al. 2001) show that hard X-ray emission in the post nova phase is rare, indicating that they are faint and disappear quickly. This makes observations very risky. From the unpredictable nature of classical novae, we have to execute ToO observations, but it was very difficult to convince telescope managers to invest a fair amount of telescope time that would turn out to be nothing at a high probability.

Swift, which has been in operation since 2004, has changed the game completely. It routinely obtains X-ray snapshots for optically-discovered bright CNe at a very high cadence starting from as early as day 1. The results are released immediately to public. Therefore, observations by "observatory-type" satellites such as Chandra, XMM-Newton, and Suzaku, can be planned exactly at the time when they are most needed.

Take V2491 Cyg as an example (Page et al. 2010). At the onset of hard X-ray emission, we triggered Suzaku observations in search for Fe emission lines and super-hard power-law continuum (Takei et al. 2009). When the brightness in the soft-band increased by a factor of 100, ToO observations by XMM-Newton satellite were executed to take grating spectra of SSS emission (Ness 2010).

In doing so, data by advanced technologies including X-ray CCD & grating spectroscopy, high-resolution imaging, sensitive super-hard band detectors, were accumulated. This was absolutely impossible before the launch of Swift and there is no wonder why many new discoveries were made one after another in the last five years in this field.

2. Selected Recent Topics

2.1. Plasma chemistry

X-ray spectroscopy brings information about the chemical composition of abundant metals including N, O, Ne, Mg, Si, S, Ar, and Fe relative to H in the unit of solar metal abundance under the assumption that the He abundance relative to H is solar.

The plasma abundance reflects WD core composition and nuclear products, and therefore an indicator of WD mass. WDs are divided into two in their chemical composition, which depends on their initial mass. When the initial mass is smaller than about $\sim 1.1\ M_{\odot}$, the core is dominated by C and O, and thus they are called CO-type. When the initial mass is larger than $\sim 1.1\ M_{\odot}$, the core is dominated by O and Ne, thus they are called ONe-type. Three processes can alter the chemical composition. The first is accretion from the companion, which is rich in H and He. The second is mixing between WD material and accreted material. The third is synthesizing in the thermonuclear process.

The surface gravity is much larger for more massive WDs for the reasons that (a) they are more massive and (b) their radius is smaller; the radius depends negatively on mass for the mass-radius relation of WDs. Therefore, the temperature during the thermonuclear runaway can reach much higher for heavier WDs, Major nuclear reaction in CO novae does not go beyond elements heavier than O, while that in ONe novae reaches up to Si and S (e.g., Jose et al. 1998). Based on the X-ray spectroscopy, we speculated that V458 Vul is an ONe-type nova (Tsujimoto et al. 2009), but it was confirmed as CO-type by optical spectroscopy. We clearly need some adjustments in our diagnosis.

Another interesting feature is Fe deficiency. For unknown reasons, the Fe abundance in the X-ray plasma is very small with being consistent with virtually none for all classical novae with measured Fe abundance. One of the most extreme cases is V382 Vel taken by ASCA (Mukai & Ishida 2001). At a plasma temperature of 5–10 keV, which explains the continuum emission very well, we would naturally expect a prominent pair of emission lines from Fe XXV and Fe XXVI in this energy range. However, these lines are always weak or none in the shocked plasma, which remains a mystery. Possible ideas for the cause include non-equilibrium ionization, dust condensation, and sinking deep into WD core before explosions.

2.2. Rekindled accretion

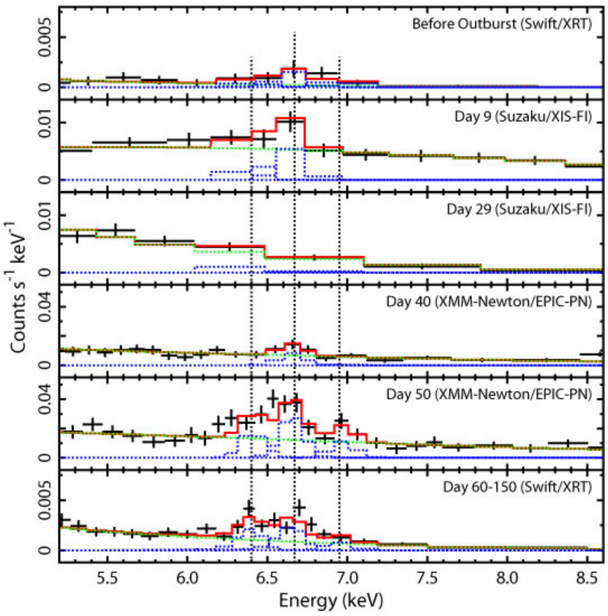

Fig. 1. Evolution of Fe emission of V2491 Cyg (Takei et al. 2011). The emission lines of Fe I (6.4 keV), Fe XXV (6.7 keV), and Fe XXVI (7.0 keV) are shown with dotted lines.

The accretion process from the secondary to the WD is considered to be suspended after a nova explosion. Some authors even argue that CN explosions destroy accretion disks. Then, how early does the accretion resume? The answer to the question is vital to understand the post-nova evolution and the eventual fate of the binary system.

We can conduct such a measurement for CNe occurring in systems containing magnetized WDs. To date, about a handful of classical novae occurred in moderately magnetized WDs called intermediate polars, and one classical nova occurred in strongly magnetized WDs called polars. Intermediate polars, in particular, are characterized by strong Fe emission lines both from neutral and highly ionized spices. For magnetic WDs, the accreting matter goes along the magnetic field lines from the Alfven radius, making a plasma by accretion shocks at magnetic poles. The temperature can reach as high as $\sim$10 keV, producing emission lines from Fe XXV and XXVI, whereas reprocessed emission at the WD surface produces neutral iron line as fluorescence. These lines are defining characteristics of the accretion process in intermediate polars. We can use these lines to probe reestablished accretion after a CN explosion.

Figure 1 shows the evolution of Fe features. We see significant changes in the intensities of the three Fe lines. We interpret this as follows. In the pre-nova phase, the plasma by accretion shocks produces hard X-ray emission with noticeable Fe lines. When a CN explosion occurred, the hard X-ray emission was replaced by the plasma by ejecta shocks with Fe deficiency. The accretion shocked plasma disappeared as the accretion was suspended due to increased radiation pressure. When the radiation pressure decreased and the accretion resumed (day 50 and thereafter), the Fe features due to accretion shocks reemerged.

2.3. Non-thermal emission

From an analogy to the supernova explosions and their remnants, it is expected that CN explosions to be an agent of particle acceleration. Such phenomena can be observed with non-thermal emission in the hard X-rays, yet no such evidence was presented.

We observed V2491 Cyg with Suzaku on day 9 in response to a report by Swift that the source showed unusually hard spectrum. Figure 2 shows the result of the Suzaku spectrum, in which we clearly detected a hard X-ray continuum extending up to 70 keV. This was explained by a power-law model, and not by a thermal model with physical temperature values. We thus concluded that this is the non-thermal emission in the hard X-rays. The emission mechanism as well as the acceleration mechanism of charged particles responsible for the emission are still unknown.

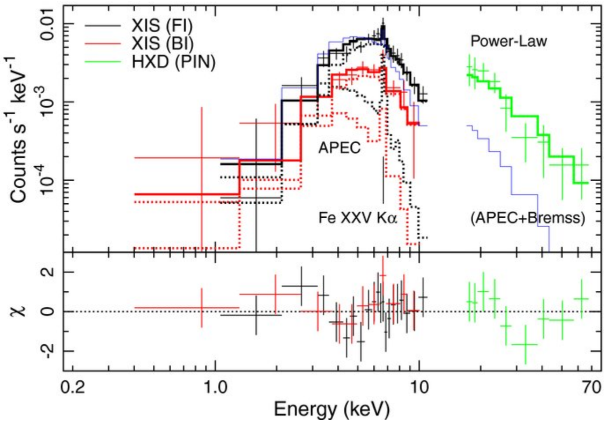

Fig. 2. X-ray spectrum of V2491 Cyg taken on day 9 by Suzaku (Takei et al. 2009).

3. Future Prospects

Hard X-rays have unique capabilities to address challenges regarding CNe. It has a penetrating power through the Galactic plane and is suitable for unbiased surveys if it has sufficient sensitivity. It has a coverage of both thermal and non-thermal features. It also enables diagnoses of WD mass, though it still remains immature at this point.

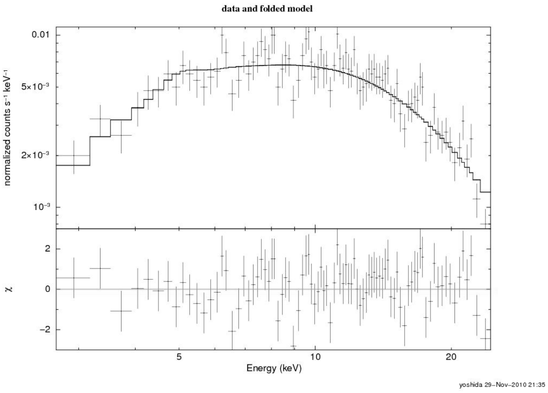

Fig. 3. MAXI GSC simulated spectrum of one-day integration, assuming a spectrum of RS Oph. Courtesy: T. Yoshida at Tokyo University of Science.

Below is our personal prospective for the problems regarding X-ray emission from CNe that are to be addressed in the next five to ten years.

- Abundance pattern in X-ray plasma to distinguish CO-type or ONe-type WDs.
- Mass distribution of Galactic CNe in collaboration with other wavelengths.
- Post-nova evolution of non-thermal emission.
- Differences in hard X-ray features between non-magnetic and magnetic WDs.
- Cause for the mysterious Fe deficiency in the ejecta shock plasma.

MAXI has a role to play in this future outlook. It can be used to study the evolution of non-thermal emission. Existing data cannot address this issue because such emission was detected only once from only one source (Takei et al. 2009). Even at the sensitivity of MAXI, the brightest among classical novae, such as RS Oph (Sokoloski et al. 2006), can be observed as shown in figure 3.

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