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The impact of Suzaku on the knowledge of cataclysmic variables

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Abstract. We review the observational results of cataclysmic variable stars using the Suzaku X-ray satellite. Many observations were conducted with Suzaku, yielding high signal-to-noise ratio light curves and spectra by combining the X-ray Imaging Spectrometer and the Hard X-ray Detector. The nature of cataclysmic variable stars in major subclasses (classical novae, dwarf novae, and magnetic cataclysmic variables) were discussed in three Ph. D. theses and 16 papers using the Suzaku data to date. Based on the results, we further discuss the impact on the knowledge of cataclysmic variable stars, focussing on the discovery of non-thermal X-ray emission from the classical nova V2491 Cygni.

Key words. Stars: novae, cataclysmic variables — Stars: white dwarfs — X-rays: stars

1. Introduction

Cataclysmic variables are binary systems composed of a white dwarf and a late-type dwarf or giant companion. Hydrogen-rich material is transferred from the companion star to the white dwarf via Roche lobe overflow or strong stellar winds. The mass transfer induces complex evolutionary tracks as well as rapid changes in their brightness. If these sources can continue to gain the mass of the white dwarf through accretion to reach the Chandrasekhar limit (e.g., Chandrasekhar 1931), the systems can also become the progenitor of Type Ia supernovae (e.g., Nomoto 1982). The study of cataclysmic variables has a wide range of astrophysical importance, including the understanding of white dwarfs, the evolution of binary systems, stellar population synthesis, physics of space plasma, etc. Extensive reviews of cataclysmic variables can be found in e.g., Warner (2003).

According to the mechanisms of the flux variabilities, cataclysmic variables are divided into several subclasses (e.g., Warner 2003): polars, intermediate polars, dwarf novae, and classical novae. Polars and intermediate polars are systems composed of magnetized white dwarfs (e.g., Cropper 1990; Patterson 1994). The stream of infalling material is governed by the magnetic field, thus an accretion funnel is formed along the magnetic field lines. Dwarf novae are caused by the instability of viscosity in the accretion disk (e.g., Warner 2003). When accreted material reaches a critical temperature, the sudden release of gravitational potential energy triggers a dwarf nova outburst. Classical novae are caused by sudden nuclear fusion on the white dwarf surface (e.g., Bode & Evans 2008). When the amount of accreted material reaches a critical mass, a

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large explosion occurs due to thermonuclear runaway (e.g., Starrfield et al. 2008).

Many essential characteristics in cataclysmic variables can be observed in X-rays: e.g., the nuclear reaction on the white dwarf surface, the geometry of accretion near the central star, and the diagnosis of shock-excited plasma within the accreting system or the ejected material (see, the contribution by S. Balman in the same journal). As X-ray photons can penetrate through the large attenuation, they also represent a tool to unveil currently-inaccessible phenomena directly through the interstellar or circumstellar matter along the line of sight. To make major progress in the study of cataclysmic variables, systematic X-ray observations are of significant importance.

For the purpose of studying high energy phenomena in cataclysmic variables, the Suzaku X-ray satellite has various advantages. The combination of two instruments aboard Suzaku covers a wide energy band in simultaneous observations (Mitsuda et al. 2007). Its medium-resolution CCD spectrometer yields a high signal-to-noise ratio spectrum for moderately bright X-ray sources in reasonable telescope time. It has sufficient spectral resolution to resolve emission lines from abundant elements. While we can only rely on global spectral models, the relative flux and energy of these lines enable us to conduct a temperature diagnosis, to study the plasma evolution, and to reveal elemental abundance patterns.

The purpose of this article is to review the X-ray studies of cataclysmic variables using the Suzaku satellite. In section 2, we briefly summarize the basic features of the spacecraft and the astronomical instruments onboard Suzaku. In section 3, we introduce the Suzaku results of magnetic cataclysmic variables, dwarf novae, and classical novae over six years since its launch. In section 4, we discuss the impact on the knowledge of cataclysmic variables with Suzaku, focussing on the X-ray emission of non-thermal origin from the classical nova V2491 Cygni (Takei et al. 2009). Finally, the major findings are summarized in section 5.

2. Suzaku X-ray satellite

The Suzaku satellite is a joint mission between Japan and the United States for X-ray astronomy. It was successfully launched on July 10, 2005 from the Uchinoura Space Center of the Japan Aerospace Exploration Agency. The weight and the length of the spacecraft are $\sim$1.7 tons and $\sim$6.5 m, respectively. The electric power is $\sim$1700 W and $\sim$660 W for total consumption and scientific instruments, respectively. The spacecraft orbits around the Earth once in ~96 minutes at ~570 km altitude with an inclination angle of $\sim$32°. The pointing accuracy is $\sim$0.2′. The fixed solar panels onboard the spacecraft constrain the pointing direction of the telescope to be 65–110° from the Sun. Most targets are occulted by the Earth once in an orbit during the observations. In addition, scientific observations are not possible during the South Atlantic Anomaly passages. Therefore, the average observing efficiency is $\sim$45%.

Suzaku has mirror assemblies and three scientific instruments for X-ray observations (Mitsuda et al. 2007): the X-Ray Spectrometer (XRS; Kelley et al. 2007), the X-ray Imaging Spectrometer (XIS; Koyama et al. 2007), and the Hard X-ray Detector (HXD; Takahashi et al. 2007; Kokubun et al. 2007). The XRS became unoperational due to a thermal short between helium and neon tanks one month after the launch, while the XIS and the HXD provide simultaneous observations in a broad energy band with a high signal-to-noise ratio, a medium energy resolution, and a low background level.

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 sensitive in a 0.4–12 keV energy range. The remaining one (XIS1) is a back-illuminated (BI) CCD sensitive at 0.2–12 keV. The absolute energy scale is typically accurate to $\lesssim$10 eV. The energy resolution is $\sim$130–220 eV (FWHM) at 6 keV, where the spaced-row charge injection technique (Nakajima et al. 2008) were employed for the XIS to rejuvenate its spectral resolution by filling the charge traps with artificially injected electrons through CCD readouts (Uchiyama et al. 2009). The effective areas of the FI and BI chips are respectively 150 and 100 cm^2 at 8 keV. Each XIS has a format of 1024×1024 pixels and covers a $18' \times 18'$ field of view with an energy-independent half-power diameter of $1\overset{\prime}{.}8$–$2\overset{\prime}{.}3$. XIS2 and a part of XIS0 have not been functional since 2006 November and June 2009, respectively.

The HXD is a non-imaging collimated instrument sensitive in the 10–600 keV energy range. The sensor consists of 16 well-type main units and 20 surrounding scintillators for active anti-coincidence shielding. Thanks to the active anti-coincidence shields, a narrow field of view, and stable as well as low background environment in a low Earth orbit, unprecedented sensitivity is achieved in the hard X-ray band. Each well-type unit consists of two independent sensors: the gadolinium silicate / bismuth germanate phoswich counters and the PIN silicon diodes. The PIN has sensitivity in the 10–70 keV energy range, and gradually becomes transparent to higher energy photons. The transparent photons are detected with the gadolinium silicate scintillators located in the middle layer, which has sensitivity in the 40–600 keV energy range. More details of Suzaku can be found in e.g., the Suzaku Technical Description, the Suzaku First Step Guide, and the official web page[1].

3. Summary of the Suzaku results

3.1. Magnetic cataclysmic variables

Magnetic cataclysmic variables are composed of a magnetized white dwarf, and divide into two major subclasses called polars and intermediate polars. The magnetic field strengths of the white dwarf is estimated to be $\gtrsim 10^7$ and $\sim 10^6$ gauss in polars and intermediate polars, respectively. The strength of the magnetic field mainly affects the form of mass accretion (figure 1). For polars, the motion of infalling material is governed by their strong magnetic field, thus instead of a disk an accretion funnel is formed along the magnetic field lines (e.g., Cropper 1990). For intermediate polars, the accretion disk is truncated at the Alfvén radius where the magnetic and the ram pressures are equal to each other, from which matter accretes along the field lines (e.g., Patterson 1994). The accretion funnel in both systems forms strong shocks, and the resultant hot plasma produces X-rays. For extensive reviews of magnetic cataclysmic variables, readers can refer to e.g., Warner (2003).

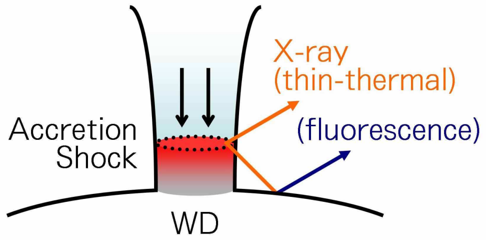

Fig. 1. Schematic view of the mass accretion process on a magnetized white dwarf in a cataclysmic variable. X-rays are considered to be caused by shock-excited plasma at the base of an accretion funnel. Fluorescence also occurs at the white dwarf surface.

Various aspects of X-ray emission have been studied from magnetic cataclysmic variables, illustrating their typical and unique behaviors. Yuasa, T. (2011) performed a systematic study of intermediate polars using deep X-ray spectra of Suzaku, in which the masses of white dwarfs were estimated from 17 sources with the statistical fitting errors of 0.2 $M_\odot$ (see, the contribution by T. Yuasa in the same journal). The highlights of the Suzaku results also have been published in seven papers as follows: (1) The hard X-ray pulsations were discovered from the intermediate polar AE Aquarii for the first time (Terada et al. 2008). Significant periodic signals were detected with the HXD in the 10–30 keV energy band. The spectrum has a signature of a power-law tail in the hard X-ray band, thus Terada et al. (2008) argued a non-thermal origin in accelerated particles from a rotating white dwarf. (2) Broadband properties were discussed in two intermediate polars IGR J00234+6141 and 1RXS J213344.1+510725 using INTEGRAL, XMM-

[1] http://www.astro.isas.jaxa.jp/suzaku/

Newton, and Suzaku data (Anzolin et al. 2009). (3) Plasma diagnostic with iron emission lines was performed in the intermediate polar SAX J1748.2−2808 (Nobukawa et al. 2009). (4) X-ray studies of the polar AM Herculis in a very low state were conducted by Terada et al. (2010). (5) Hard X-ray properties of magnetic cataclysmic variables were summarized by Scaringi et al. (2010) using INTEGRAL, Swift, and Suzaku data. (6) The masses of white dwarfs were estimated from 17 intermediate polars with broad-band X-ray spectra of Suzaku (Yuasa et al. 2010). (7) Deep X-ray spectroscopy of the intermediate polar V1223 Sagittarii was conducted by Hayashi et al. (2011).

3.2. Dwarf novae

Dwarf novae are a subclass of cataclysmic variables, which include a non-magnetic or weakly magnetized white dwarf. Accreted material forms a disk structure around the white dwarf (figure 2). Dwarf novae are characterized by quasi-periodic outbursts, which are caused by a thermal instability in the accretion disk (e.g., Osaki 1974; Hōshi 1979). When accreted material reaches a critical temperature, the sudden release of gravitational potential energy is triggered by the change of viscosity in the accretion disk. An outburst is characterized by an increase in the optical brightness, and by a decrease in the X-ray brightness. The innermost part of the accreting system, called a boundary layer, is considered to produce X-ray emission in the quiescent phase. For extensive reviews of dwarf novae, readers can refer to e.g., Warner (2003).

Various aspects of X-ray emission have been revealed in dwarf novae with the Suzaku satellite. Okada, S. (2008) performed intensive studies of the dwarf nova SS Cygni, in which the geometries of X-ray emitting regions were discussed in both outburst and quiescent phases using high signal-to-noise X-ray spectra (see, the contribution by M. Ishida in the same journal). The nature of dwarf novae were also discussed in three papers as follows: (1) An X-ray luminosity function of dwarf novae was derived from parallax-based distance measurements based on Suzaku, XMM-Newton, and ASCA data (Byckling et al. 2010). (2) A partial X-ray eclipse was discovered from the dwarf nova V893 Scorpii for the first time (Mukai et al. 2009). (3) Phase-induced X-ray spectroscopy of the dwarf nova SS Cygni was conducted by Ishida et al. (2009).

3.3. Classical novae

Classical novae occur in binary systems consisting of a white dwarf and a late-type or giant companion (see, the contribution by M. Kato in the same journal). Hydrogen-rich material filling the Roche-lobe around the companion accretes onto the white dwarf. When the amount of accreted material reaches a critical mass, hydrogen fusion is ignited explosively, causing a thermonuclear runaway on the white dwarf surface (e.g., Starrfield et al. 2008). The sudden increase in radiation pressure leads to the ejection of accreted material, and a rapid and large rise in the optical brightness is observed as a classical nova. For extensive reviews of classical novae, readers can refer to e.g., Warner (2003) and Bode & Evans (2008).

X-rays are also emitted at various stages in the post-burst evolution with different mechanisms (figure 3). In the early stages, hard X-rays are considered to be emitted from shocks in the expanding ejecta (e.g., Mukai & Ishida 2001; the contribution by M. Hernanz in the same journal). After the ejecta shell expands

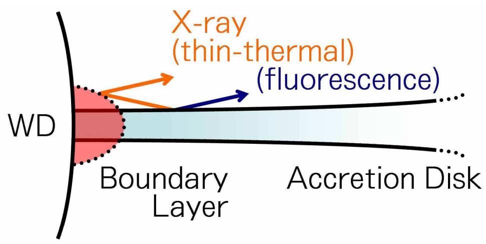

Fig. 2. Schematic view of the mass accretion process in a quiescent phase of a dwarf nova. X-rays are considered to be caused by hot plasma at the optically-thin boundary layer. Fluorescence also occurs at the white dwarf surface and the accretion disk.

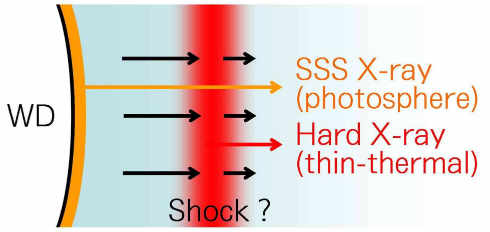

Fig. 3. Schematic view of a classical nova explosion. Several processes are involved in producing X-rays. One is photospheric emission from a hot layer of the white dwarf surface fueled by residual nuclear burning after the explosion. Another is considered to be caused by thin-thermal plasma due to internal shocks in the nova ejecta.

and becomes less opaque, soft X-rays emerge from the pseudo photosphere, in which the spectrum is characterized by soft blackbody-like emission as the class of super-soft X-ray sources (e.g., Kahabka & van den Heuvel 1997; the contribution by I. Hachisu in the same journal). X-ray spectroscopy is a powerful tool to unveil the nature of high energy phenomena in classical novae. However, observations were difficult because of their faint, variable, and transient behaviors.

In collaboration with worldwide amateur astronomers as well as current X-ray satellites (i.e., Swift, Chandra, XMM-Newton, and Suzaku), we established an effective observing system of classical novae despite their observational difficulties (Takei, D. 2011). As a result, Suzaku successfully observed X-ray emission from five classical novae to date (Suzaku J0105-72, V458 Vulpeculae, V2491 Cygni, V2672 Ophiuchi, and U Scorpii 2010). Various aspects of X-ray emission have been studied, including their typical behavior and the diagnostics that they bring. The highlights of the Suzaku results are summarized as follows: (1) Super-hard X-ray emission above 10 keV was discovered in the initial phase of the classical nova V2491 Cygni for the first time (Takei et al. 2009). (2) The reestablished accretion process was confirmed in the post-outburst evolution from V2491 Cygni (Takei et al. 2011). (3) The chemical composition of the ejected material was constrained from the classical nova V458 Vulpeculae (Tsujimoto et al. 2009). (4) Plasma diagnostics of photospheric emission from Suzaku J0105-72 and V2491 Cygni were performed with Suzaku (Takei et al. 2008; Takei & Ness 2010). (5) High energy phenomena in past classical novae were classified into five types (Takei, D. 2011).

4. Discovery of non-thermal X-rays

In this section, we focus on the first discovery of the super-hard X-ray emission from the classical nova V2491 Cygni (Takei et al. 2009), in which the Suzaku data makes a great impact on the knowledge of cataclysmic variables. The classical nova V2491 Cygni (Nakano et al. 2008; Samus 2008) was discovered on 2008 April 10.728 UT (54566.73 d in modified Julian date) in the constellation Cygnus at (RA, Dec) = ($19^h43^m01.96^s$, $+32°19'13.8''$) in the equinox J2000.0. Subsequent follow-up observations were also made by ground-based telescopes (Nakano et al. 2008; Lynch et al. 2008; Ashok et al. 2008; Tomov et al. 2008b,a; Rudy et al. 2008; Helton et al. 2008). V2491 Cygni is an extremely fast nova (Tomov et al. 2008b), declining at a rate of $t_2 \sim 4.6$ d (Tomov et al. 2008a) and $t_3 \sim 16.8$ d, where t_2 and t_3 are the durations to fade by 2 and 3 mag respectively from the optical maximum. The distance was estimated as ~10.5 kpc (Helton et al. 2008) using an empirical relation between the maximum magnitude and the rate of optical decline among classical novae (della Valle & Livio 1995).

The discovery of V2491 Cygni also triggered an intense monitoring campaign with space-based observatories (see, the contribution by K. Page in the same journal). The Swift satellite continued observations for more than half a year (Kuulkers et al. 2008; Osborne et al. 2008; Page et al. 2008, 2010). The XMM-Newton satellite provided high-resolution X-ray spectroscopy of V2491 Cygni in the later phase of the outburst (Ness et al. 2008a,b; Ness 2010; Ness et al. 2011). We also conducted a target-of-opportunity observation of V2491 Cygni 9 days after the outburst using Suzaku, and successfully detected super-hard

X-ray emission up to 70 keV (Takei et al. 2009). The spectrum cannot be explained by a bremsstrahlung model with any reasonable temperature, and a power-law model is necessary to describe the high energy emission (see figure 2 in Takei et al. 2009). The power-law emission with a very flat slope and the photon index of 0.1 poses a challenge to understand the emission mechanism. Based on the result, Takei, D. (2011) discussed several ideas to explain the phenomena, and we introduce two of them in the following subsections.

4.1. Fermi acceleration model

In order to explain the spectra, we first discuss the possible presence of a population of accelerated charged particles with the non-thermal energy distribution. Non-thermal emission is speculated as the interaction between the accelerated particles with a magnetic field, photons, or protons. Here, the photon flux of power-law emission is described as

$$I(E) \propto AE^{-\Gamma}[\text{photons s}^{-1}\ \text{cm}^{-2}], \tag{1}$$

where A is a constant factor, Γ is a photon index, and E is a photon energy. This can be converted to the energy flux as

$$F(E) \propto AE^{-\alpha}[\text{erg s}^{-1}\ \text{cm}^{-2}], \tag{2}$$

using the spectral index of $\alpha = (\Gamma - 1)$. For example, when we assume the synchrotron radiation due to accelerated electrons with a power-law energy distribution of index P, the spectral index (e.g., Rybicki & Lightman 1985) is described as

$$\alpha = \frac{P-1}{2}. \tag{3}$$

Assuming the mechanism of first-order Fermi acceleration, the index of the electron energy distribution is larger than ~2 (e.g., Blandford & Ostriker 1980). Using these relations, we tested the spectra with a combination of the first-order Fermi acceleration model and typical radiation mechanisms (i.e., inverse Compton, synchrotron, and bremsstrahlung emission). However, the extremely flat photon index (Γ = 0.1) of the power-law radiation is ruled out for these models. To explain the extremely flat spectrum, other explanations would be necessary: e.g., particle acceleration mechanisms including multiple shocks, turbulence, and magnetic reconnection (e.g., Pittard & Dougherty 2006).

4.2. Annihilation line model

Non-thermal emission above 10 keV has been expected from classical novae in previous theoretical studies (e.g., Clayton & Hoyle 1974; Livio et al. 1992; Gomez-Gomar et al. 1998; Hernanz 2008). X-ray emission is expected as the Compton degradation of γ-ray emission lines produced by radioactive decays. When the proton-rich nucleus ^{22}Na causes a β^{+}-decay to a stable isotope ^{22}Ne, a positron and a 1275 keV photon are produced with high probability. The positrons additionally produce 511 keV photons in annihilation with electrons. Suzuki & Shigeyama (2010) argued that the Compton down-scattering process of these two γ-ray emission lines can explain the Suzaku spectra and its time-scale. This model was a first step to explain the Suzaku data, while a discrepancy still remains in explaining the required amount of ^{22}Na (~3×10^{-5} $M_{\odot}$). The total mass of the ejecta in a typical classical nova is expected to be ~10^{-5} $M_{\odot}$ (e.g., Bode & Evans 2008), indicating that extremely abundant Na would be necessary for the model by Suzuki & Shigeyama (2010). In order to investigate nature of this phenomenon, it should be examined by instruments with improved sensitivity on the future X-ray observatories such as ASTRO-H (Takahashi et al. 2008).

5. Summary and future works

We briefly reviewed the Suzaku results of cataclysmic variables. Many observations were conducted with Suzaku, yielding high signal-to-noise ratio light curves and spectra by combining the XIS and the HXD. The nature of cataclysmic variables in major subclasses (classical novae, dwarf novae, and magnetic cataclysmic variables) were discussed in three Ph. D. theses and 16 papers using the Suzaku data to date. Among them, the first discovery of non-thermal X-ray emission from the classical nova V2491 Cygni made a great impact on the knowledge of cataclysmic variables. Including the result of V2491 Cygni, the signatures of high energy phenomena from cataclysmic variables have been discovered one after another in recent years (e.g., Terada et al. 2008; Abdo et al. 2010). In order to better understand their nature, systematic studies with more samples should be examined by future studies.

6. Discussion

MARGARITA HERNANZ : Hard X-rays from V2491 Cygni detected ~6 days post visual maximum by Suzaku cannot come from the comptonization of the 511 keV annihilation line, because such emission occurs before nova is discovered optically. The positrons come from ^{13}N and ^{18}F (lifetimes very short, <1 day), and not from ^{22}Na (larger lifetime but more than 10^4 times less abundant).

MARGARITA HERNANZ : Predictions for ASTRO-H based on Suzuki and Shigeyama paper are ”wrong”, because such paper makes non-realistic models and takes non-realistic initial conditions. Novae would have been already detected by CGRO and INTEGRAL and Swift/BAT, if such predictions were true, but this has not been the case.

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