Suzaku Observations of Accreting White Dwarfs

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Abstract

Results from *Suzaku* observations on accreting white dwarfs are reviewed comprehensively. *Suzaku* identified the nova V458 Vul as an ONe-nova from X-ray spectroscopy with the XIS, which demonstrates *Suzaku* capability of understanding the nature of novae. Initial results on detection of a power-law component from the polar AM Her in its low state are reported. High spectral resolution and wide energy band of the XIS and the HXD enable us to determine the mass of white dwarfs in intermediate polars with unprecedented accuracy. Recently, some 80% of the galactic ridge X-ray emission is resolved into point sources. Based on luminosity distribution and space density, we consider non-magnetic CVs as the major contributor to the galactic ridge X-ray emission.

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

1. Novae

Nova eruption is triggered by thermonuclear flash at the bottom of accreted matter on a white dwarf. A nova shows a variety of X-ray emissions at different evolution stages. In the beginning, optically thin thermal emission above 1 keV is observed from ~10 days to a few hundred days, originating from shock-heated expanding ejecta shell. Later on, a photospheric soft X-ray emission from the white dwarf surface appears as the ejecta shell becomes less opaque as it expands. This phase is called the Super Soft Source (SSS) phase.

In observing novae in X-rays, a high resolution spectroscopy is favorable because the early phases of novae show a number of emission lines as well as absorption structures. However, current grating instruments onboard *Chandra* and *XMM-Newton* are useful only for bright novae due to limited effective area, and only RS Oph and V382 Vel have been observed so far with enough statistical quality (Ness et al. 2005, 2009a, Nelson et al. 2008). The XIS onboard *Suzaku*, on the other hand, has high S/N ratio and narrow line-spread function, providing moderate resolution spectroscopy for a larger number of novae in a reasonable exposure time. This enables us to diagnose temperature, abundances, and evolution of the expanding plasma shell. *Suzaku* so far observed the two novae V2491 Cyg (Takei et al. 2009) and V458 Vul (Tsujimoto et al. 2009), both as ToO observations. Of them, the result from V458 Vul are summarized here (see Takei et al. in this volume for V2491 Sgr).

V458 Vul was found turning into an outburst state on Aug 8, 2007 at $m_V = 9.5$ (Nakano et al. 2007), which is as ~1000 times as bright as pre-outburst phase. H/He emission lines show a P-Cygni profile with a velocity of ~2000 km s^{-1} on the next day (Buil & Fujii 2007), which is typical for nova outburst. The distance can be estimated by the decay time scale t_2, which results in 13 kpc (Downes & Duerbeck 2000). The *Swift* XRT has constantly monitored this source, and detected significant hard X-rays from the day 70 to 140 (Ness et al. 2009b). Responding to the alert of *Swift*, *Suzaku* pointed to V458 Vul as a ToO observation using DDT on November 4th, 2007 for 20ks (Tsujimoto et al. 2009).

The XIS spectra of V458 Vul is shown in Fig. 1. It has

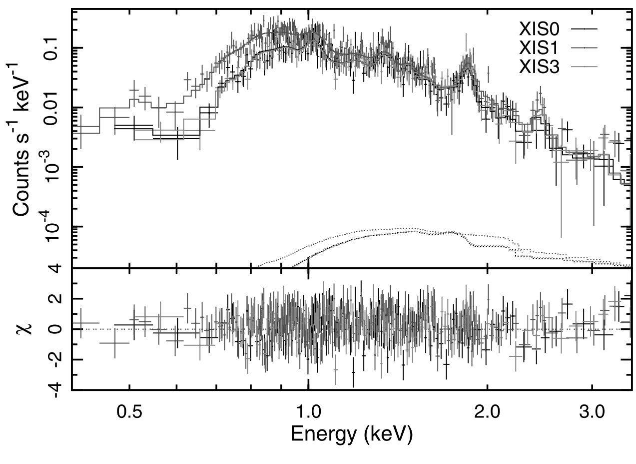

Fig. 1. The XIS spectra of the nova V458 Vul. From Tsujimoto et al. (2009)

a plenty of emission lines from N, Ne, Mg and especially strong Si and S lines. Thanks to a moderate spectral resolution of the XIS, the plasma, with a temperature of 0.64keV is found to be in collisional ionization equilibrium. Abundances of mid-Z elements are about 0.5⊙. Depletion of O and enhancement of N with respect to these mid-Z elements strongly indicate that V458 Vul is an ONe-nova rather than CO-nova. This observation demonstrates that the XIS observation is useful to unveil the nature of novae.

2. Magnetic White Dwarfs as a cosmic-ray accelerator

The origin of the cosmic ray (CR) has been a long-standing matter for ~100 years since its discovery. It is established that particle acceleration of up to the knee energy ($= 10^{15.5}$ eV) surely takes place in rotation-powered pulsars (RPPs) and SNRs (Koyama et al. 1995), although it has been a matter of debate whether the total energy density can be explained by them or not. CRs above the knee energy are likely to emanate from extra galactic sources.

As in RPPs, a magnetized white dwarf can achieve rotation-induced voltage as

$$\begin{aligned} V &= \int (\boldsymbol{v} \times \boldsymbol{B}) \cdot d\boldsymbol{r} \sim \left(\frac{2\pi}{P}\right) BR^2 \\ &= 6 \times 10^{15} \left(\frac{P}{10^3\mathrm{s}}\right)^{-1} \left(\frac{B}{10^6\mathrm{G}}\right) \left(\frac{R}{10^9\mathrm{cm}}\right)^2 \ [\mathrm{V}]. \end{aligned}$$

Since it is as high as 10^{15} volts, and the white dwarf population is large, we consider a magnetized white dwarf as a potential candidate of the cosmic ray accelerator.

As a matter of fact, we discovered a non-thermal pulsating emission from the IP AE Aqr whose white dwarf has the shortest spin period of 33 sec among the known magnetic CVs. AE Aqr is known to have a sinusoidal pulse profile in soft X-ray band, which is of thermal plasma origin. *Suzaku* discovered a different pulsating component above ~4 keV, whose pulse profile is spiky like RPPs, and it is detected also with the HXD PIN (Fig. 2). We considered various possibilities to generate such hard component, like inverse Compton scattering, curvature radiation along the B field, non-thermal bremsstrahlung, and finally concluded that synchrotron radiation from electrons accelerated at least up to GeV is the only possible interpretation. The synchrotron emission is highly inhomogeneous which can easily explain the spiky pulse profile.

As another example shown in Fig. 3 is the XIS spectra of AM Her in a low accretion state observed during October 29 through November 1, 2007. During this period $m_V \simeq 16$ whereas $m_V \simeq 13$ in a normal high accretion state. The spectra are successfully explained by a ~1 keV optically thin thermal emission plus a power law with $\Gamma \simeq 2.2$. From light curves folded at the rotational period of the white dwarf (≃11139 s) is found no evidence of pulsation. These results suggest that particle

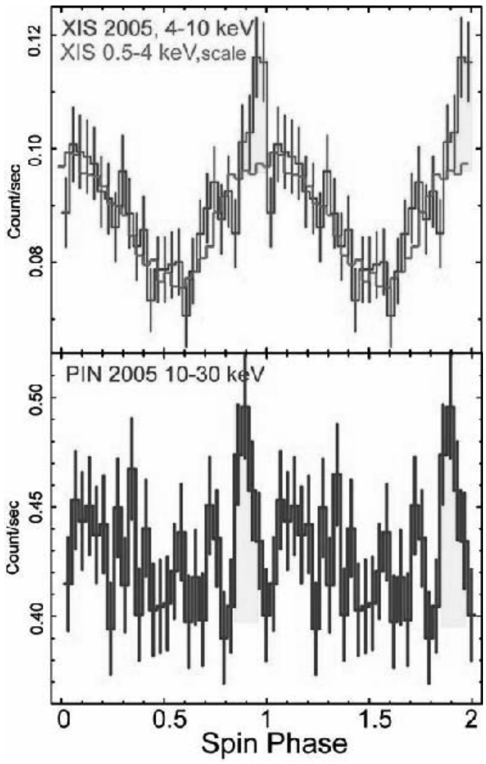

Fig. 2. Light curves from the XIS and the HXD PIN of AE Aqr folded at the spin period of 33 s. From Terada et al. (2008)

acceleration takes place in AM Her, and the acceleration site locates far enough above the white surface not to be eclipsed by the white dwarf due to its rotation. See Terada et al. in this volume for more detail.

3. Intermediate Polars

An intermediate polar (IP) is a semi-detached binary composed of a magnetized ($B = 0.1$–10 MG) white dwarf and a Roche-lobe-filling secondary star. The accreting matter from the secondary star forms an accretion disc around the white dwarf, and starts to be funneled to the two accretion poles at the Alfvén radius. The accreting matter then forms a steady shock wave close to the surface of the white dwarf, and finally settles down to the white dwarf via radiative cooling.

Suzaku has observed ~20 IPs for various scientific purposes such as comparison with the galactic ridge emission spectra, obtaining mass functions of IP white dwarfs, and investigating shock geometry. Among them, significant progress has been made in mass measurement of the white dwarfs with *Suzaku* X-ray spectroscopy.

Since the shock wave stands very close to the white dwarf surface (the shock height is believed to be < 5% of the white dwarf radius, Aizu 1973), the shock temperature T_{S}, which can be directly measured from X-ray spectra above ~10 keV, is related to the gravitational

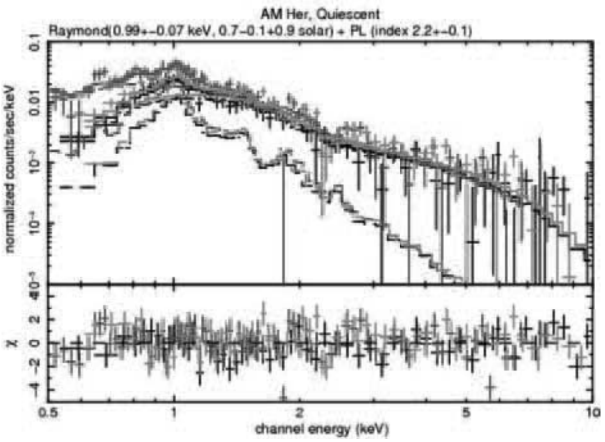

Fig. 3. The XIS spectra of AM Her in low accretion state. See Terada et al. in this volume

potential depth of the white dwarf $M_{\rm WD}/R_{\rm WD}$ as

$$\begin{aligned} kT_{\rm S} &= \frac{3GM_{\rm WD}}{8R_{\rm WD}}\mu m_{\rm H} \\ &= 16\left(\frac{M_{\rm WD}}{0.5M_\odot}\right)\left(\frac{R_{\rm WD}}{10^9{\rm cm}}\right)^{-1} \ ({\rm keV}) \end{aligned} \tag{1}$$

With the aid of a mass-radius relationship of the white dwarf (Nauenberg 1972, for example), we can obtain the mass and the radius of the white dwarf from this equation.

In Fig. 4 shown are the spectra of the XIS and the HXD-PIN of the IP V1223 Sgr. The spectrum of IPs in

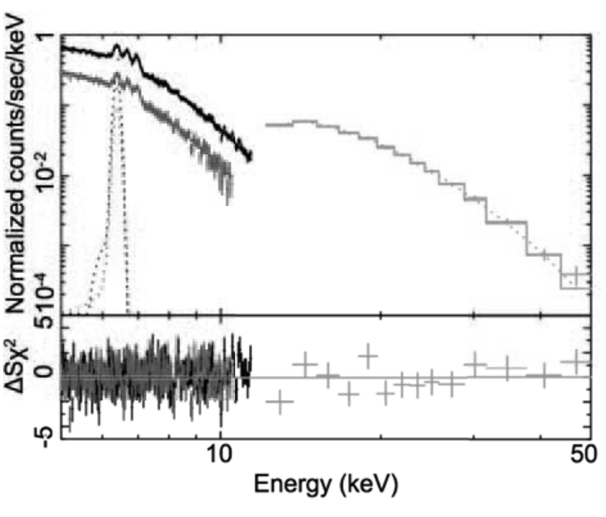

Fig. 4. The XIS and HXD-PIN spectra of V1223 Sgr. See Hayashi et al. in this volume

general comprises of a multi-temperature plasma emission in the post-shock accretion column, its reflection from the white dwarf surface as it manifests itself by a 6.4keV emission line, and a partial-covering absorption with $N_{\rm H} \sim 10^{23}{\rm cm}^{-2}$ associated with the pre-shock accreting matter. Moderate resolution spectroscopy of the XIS and high sensitivity of the HXD-PIN above ∼10keV are a good combination for disentangling these complexity for bright IPs (>1 mC). From the spectra shown in Fig. 4, Hayashi & Ishida (2009) measured the shock temperature to be $kT_{\rm S} = 33.5^{+7.1}_{-5.4}$ keV, thereby obtaining $M_{\rm WD} = 0.76^{+0.08}_{-0.07}M_\odot$. Yuasa et al. (2009) compiled data of 15 IPs observed with *Suzaku* and evaluated the mass of the white dwarf in these IPs. This X-ray method of mass determination is advantageous in that it only requires an X-ray spectrum, and hence, it is free from uncertainty of the orbital inclination on which optical measurement depends.

4. Contribution of Accreting White Dwarfs to GRXE

The origin of the Galactic Ridge X-ray Emission (GRXE) has been a matter of debate since its discovery some 25 years ago. Even until recently, two competing interpretations exist. One is proposed by Ebisawa and his colleagues claiming that most of GRXE is truly a diffuse source, and only 10% of GRXE is attributed to point sources with a flux down to 3×10^{-15} erg cm^{-2}s^{-1} (Ebisawa et al. 2005). The other one is given by Revnivtsev and his collaborators saying it is ensemble of point sources, because surface brightness distribution of GRXE is quite similar to that in near-infrared, which represents the Galactic stellar distribution (Revnivtsev et al. 2006).

Recently, Revnivtsev et al. (2009) reported that more than 80% of GRXE at $(\ell,\, b) \simeq (0.1^\circ,\, -1.4^\circ)$ is resolved into discrete point sources in the 6–7 keV band. If so, accreting white dwarfs are probably the major contributor to GRXE, because a 6.4keV emission line with an EW of ∼100 eV observed in the spectra of GRXE is typical for CVs in general. The other potential candidate, coronally active stars, have no 6.4keV line. Among CVs, however, an IP is excluded, because the intermediate polars generally emit H-like iron Kα line as strong as He-like line, whereas the GRXE spectrum is dominated by a He-like line.

On the other hand, non-magnetic CV spectra show close similarity to those of GRXE. A spectrum of GRXE and that of the non-magnetic CV SS Cyg in outburst are shown in Fig. 5 for comparison. They both show a series of emission lines from oxygen to iron, indicating multi-temperature plasma, negligibly weak H-like line of Fe, comparable intensities of He-like and H-like lines for Mg, Si, S, sign of He-like line for Ar, Ca. Note that GRXE continuum seems harder, but this can be interpreted as multiple source contribution to GRXE, each with different distance (= different Galactic absorption).

Next, the luminosity distribution of non-magnetic CVs are considered to see if they can really explain the

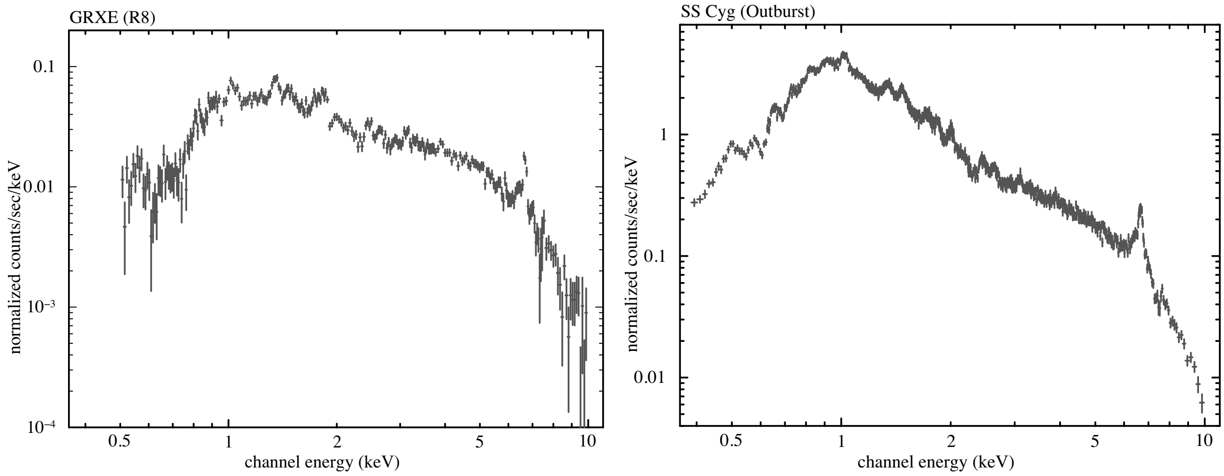

Fig. 5. The XIS spectrum of GRXE at $(\ell,\, b) \simeq (28.5^{\circ},\, -0.2^{\circ})$ and that of the dwarf nova SS Cyg in outburst.

GRXE consistently. From the *Chandra* 1 Ms observation, the resolved point sources comprise of CVs with $L_{2-10\mathrm{keV}} \simeq 10^{31-32}$erg s^{-1} and coronally active stars with $L_{2-10\mathrm{keV}} < 10^{31}$ erg s^{-1}. Based on the *ROSAT* all-sky survey, on the other hand, Verbunt et al. (1997) derived that the luminosities of DNe and Nova likes distribute below 10^{32} erg s^{-1}. The luminosities of 29 non-magnetic CVs observed with *ASCA* also distribute below 10^{32} erg s^{-1} (Baskill et al. 2005). Thus, the luminosity range of known non-magnetic CVs matches the point sources resolved by Chandra 1 Ms observation.

Finally, the space density of non-magnetic CVs is considered. The *Chandra* 1 Ms observation resolved $\sim$430 galactic sources in the region with $r < 2.56$ arcmin. The emission enhancement of the galactic ridge exists within 30 degrees in the galactic longitude, corresponding to the 4 kpc arm. If all $\sim$430 sources distribute within the 4 kpc arm uniformly, the space density becomes 4.5×10^{-4} pc^{-3}, although this is likely to include coronally active stars. According to Yamauchi et al. (2009), on the other hand, the iron 6.7 keV line intensity at $(\ell, b) \simeq (28.5^{\circ}, -0.2^{\circ})$ requires a CV space density of 2.6–21$\times 10^{-5}$ pc^{-3}, if the luminosity of each source is 10^{32} erg s^{-1}. Now that the luminosity of the *Chandra* resolved sources is typically less than 10^{32} erg s^{-1}, the space density estimated from the 6.7 keV line is roughly consistent with that estimated from the *Chandra* resolved sources. Note that, current best estimate of CV space density is 3×10^{-5} pc^{-3} at the solar neighborhood (Schwope et al. 2002). Hence, there is an order of magnitude difference between the space densities of the galactic ridge and of the solar neighborhood. But this may be attributable to density enhancement within the 4 kpc arm. In conclusion, major contributor to GRXE is probably non-magnetic CVs.

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