ASCA OBSERVATIONS OF
WHITE DWARFS, NEUTRON STARS AND BLACK HOLES

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1. Introduction

ASCA, the fourth Japanese X-ray astronomy satellite, was launched by the Institute of Space and Astronautical Science (ISAS) on 1993 February 20. ASCA is designed to be a high-capability X-ray observatory (Tanaka *et al.* 1994). It is equipped with nested thin-foil mirrors which provide a large effective area over a wide energy range from 0.5 to 10 keV. Two different types of detectors, CCD cameras (SIS) and imaging gas scintillation proportional counters (GIS) are employed as the focal plane instruments.

The ASCA instruments cover the most important energy band for plasma diagnostics, because the K lines and the K absorption edges from oxygen through iron (and also the L lines of iron) at various ionization stages all lie within this band. On the other hand, the previous high-sensitivity imaging missions, the EINSTEIN Observatory and ROSAT, are limited to narrower energy bands than ASCA: the EINSTEIN Observatory is limited to <4 keV, and ROSAT to <2 keV. The ASCA SIS can individually resolve all major lines (except the L line complex around 1 keV). Motion of plasma of the order or greater than 1000 km s^{-1} can be measured significantly from Doppler shift of the line energies. Also, ASCA has a much larger effective area, hence a much larger photon collection power, than the EINSTEIN Observatory and ROSAT, which is an advantage for detailed line spectroscopy requiring large enough numbers of photons for meaningful statistics. These capabilities of ASCA allow diagnostics of accreting matter around compact objects through studies of emission and absorption features. This review shows some recent ASCA results on studies of accreting matter around white dwarfs, neutron stars and black holes.

J. van Paradijs et al., (eds.), Compact Stars in Binaries, 321–331.

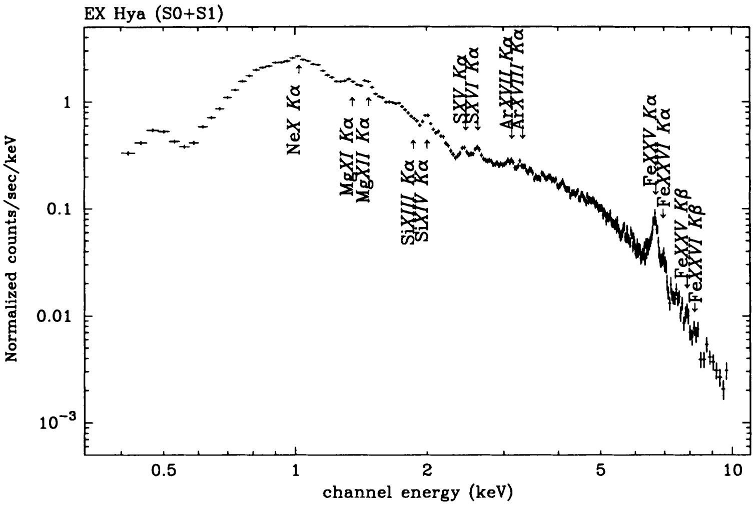

Figure 1. **The spectrum of EX Hya obtained with the ASCA SIS. Helium-like and hydrogen-like Kα lines of Mg, Si, S, Ar, and Fe are clearly seen (Ishida *et al.* 1994).**

2. Emission Lines from EX Hydra

EX Hydra is one of the brightest intermediate polars and shows two periodicities in its light curve: one is the orbital period of 98.3 min and the other is the rotational period of the white dwarf of 67.0 min.

ASCA observed this source on July 16, 1993 (Ishida *et al.* 1994). Fig. 1 shows the ASCA SIS spectrum averaged over the observational period. In this figure, helium-like and hydrogen-like Kα lines of various elements are clearly seen. If the plasma emitting these lines is in ionization equilibrium, the ratio of the intensity of the H-like line to that of the He-like line of a particular element indicates the temperature of the plasma responsible for the line emission from the element. Fig. 2 shows the theoretical ratio of the line intensities for Mg, Si, S, Ar and Fe as a function of the temperature and the allowable range of the temperature from the observation is shown for each of the elements. Clearly, if ionization equilibrium holds, then a multi-temperature plasma is needed.

A cooling flow along an accretion column onto a magnetized white dwarf could be the origin of the multi-temperature plasma. The temperature and the density structure of the accretion column behind the shock have been analytically solved by Aizu (1973). A rough estimate assures that ionization equilibrium holds in the accretion column of EX Hydra. Then, the line ratio can be calculated for each of the elements as a function of the shock temperature and we can obtain the shock temperature by comparing the

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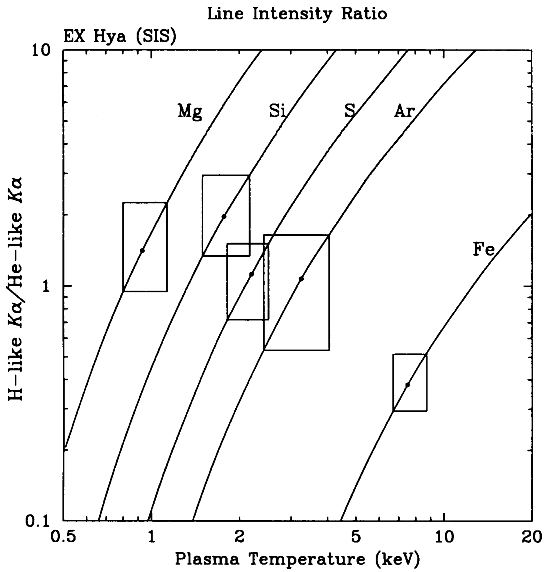

Figure 2. The allowable temperature ranges obtained from the intensity ratios of H-like to He-like $K\alpha$ lines for Mg, Si, S, Ar and Fe, observed in the EX Hya spectrum. Solid curves are the theoretical intensity ratios for these elements as a function of the plasma temperature.

observed line ratios with the theoretical curves as shown in Fig. 3 (Fujimoto *et al.* 1994).

Since the height of the shock above the white-dwarf surface is considered to be small compared to the radius of the white dwarf, the shock temperature is proportional to the ratio of the mass to the radius of the white dwarf. As a result, the mass of the white dwarf is estimated to be $0.5 \pm 0.2\,M_{\odot}$ if we assume the theoretical mass-radius relation of white dwarfs.

The above discussion suggests that matter in the accretion column cools from above 10 keV just behind the shock to below 1 keV along the flow, since emission lines from such light elements as Mg or Si should come from a plasma with a temperature of about 1 keV. Most of the gravitational energy seems to be radiated away from the optically thin accretion column in this case, which is currently considered to be carried into the optically thick atmosphere of the white dwarf in AM Her stars (see, e.g., Frank *et al.* 1985). We need further X-ray spectroscopic studies of the polar-type sources.

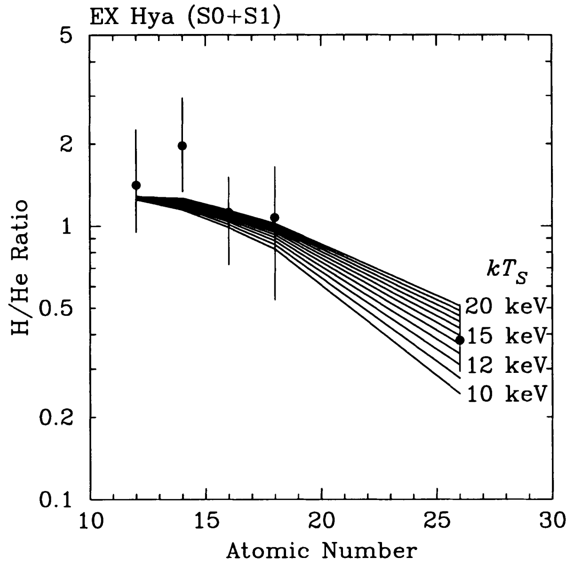

Figure 3. **The line intensity ratios expected from the post-shock accretion flow together with the observed ratios. The temperature and the density profiles have been taken from Aizu (1973).**

3. Very Dim Phase of 1608–52 and Cen X-4

The low-mass X-ray binaries 1608–52 and Cen X-4 are known to be recurrent transients [see, e.g., Tsunemi (1991) for 1608–52; Matsuoka *et al.* (1980) for Cen X-4). Both sources are also X-ray bursters (e.g., Nakamura *et al.* 1989; Matsuoka *et al.* 1980), which strongly suggests that these sources harbour weakly magnetized neutron stars in their centers of activity.

ASCA observed 1608–52 and Cen X-4 on August 12, 1993, and Feb. 27, 1994, respectively, and both sources were very dim.

The flux from 1608–52 was 7 $10^{-13}\,\mathrm{erg\,cm^{-2}\,s^{-1}}$ (0.5–10 keV) and its luminosity was estimated to be $10^{33}\,\mathrm{erg\,s^{-1}}$, assuming a distance of 3.6 kpc (Nakamura *et al.* 1989). The X-ray spectrum was very soft and can be reproduced with either a single power law model, an optically thin thermal emission model, a thermal bremsstrahlung or a blackbody with a photoelectric absorption. The best-fit temperature is $\sim$0.5 keV for a thermal bremsstrahlung model, and $\sim$0.2 keV for a blackbody.

The flux from Cen X-4 was 1.4 $10^{-12}\,\mathrm{erg\,cm^{-2}\,s^{-1}}$ (0.5–10 keV) and the luminosity was estimated to be 2 $10^{32}\,\mathrm{erg\,s^{-1}}$ on the assumption that the distance is 1.2 kpc (McClintock & Remillard 1990). The X-ray spectrum can again be reproduced with either a single power law, an optically thin thermal emission model, thermal bremsstrahlung or a blackbody. The best-fit temperature is $\sim$0.7 keV for thermal bremsstrahlung and $\sim$0.3 keV for a blackbody.

ROSAT observations of the transient low-mass X-ray binary Aql X-1 revealed that its quiescent luminosity is also as low as several times 10^{32} erg s^{-1}, with a spectrum that could be described by a blackbody of temperature $\sim$0.3 keV (Verbunt *et al.* 1994).

An important question is where the X-rays come from in the very dim phase of weakly magnetized neutron star sources. These sources commonly exhibit luminosities as low as 10^{32-33} erg s^{-1} and very soft spectra which can be reproduced typically with a blackbody of temperature 0.2–0.3 keV.

One possibility is that mass overflow from the companion star completely ceases in this dim phase and the X-rays come from the coronal activity of the companion star. However, the mass of the companion star is thought to be less than a solar mass and hence the stellar luminosity from the nuclear burning at its center should be less than 10^{33} erg s^{-1}. Since the energy release rate in coronal activity should be a small fraction of the nuclear energy generation rate, coronal activity with a luminosity of 10^{32-33} erg s^{-1} seems to be too large.

A second possibility is that mass overflow from the companion star takes place but the accretion disk does not extend to the neutron star surface due to the very low efficiency of angular momentum transfer. In this case, gravitational energy release at the outer side of the disk is expected to produce the X-rays. The luminosity can be explained by the gravitational energy release of matter with an accretion rate of 10^{16-17} g s^{-1} at a distance of 10^{10} cm from the neutron star. However, if the emission is optically thick, the temperature should be of the order of 10^4 K; if the emission is optically thin, a temperature of the order of 10^6 K seems to be too low compared to the temperature corresponding to the gravitational potential at that distance from the neutron star.

It should also be noted that radio pulsar activity is expected in the above two cases but no radio emission has been detected (Kulkarni *et al.* 1992; see also the poster contribution to this symposium by Kulkarni *et al.*).

A third possibility is that matter is accreted by the neutron star at a rate of 10^{12-13} g s^{-1}. In this case, a significant fraction of the radiation will heat the surface of the neutron star, irrespectively of how the gravitational energy is converted to radiation, and will be re-radiated as blackbody emission from the neutron star surface. If we estimate the surface area responsible for the blackbody emission from the observed luminosity and the temperature with the help of the Stefan-Boltzmann constant, the result is roughly consistent with emission from a fraction of the neutron star surface.

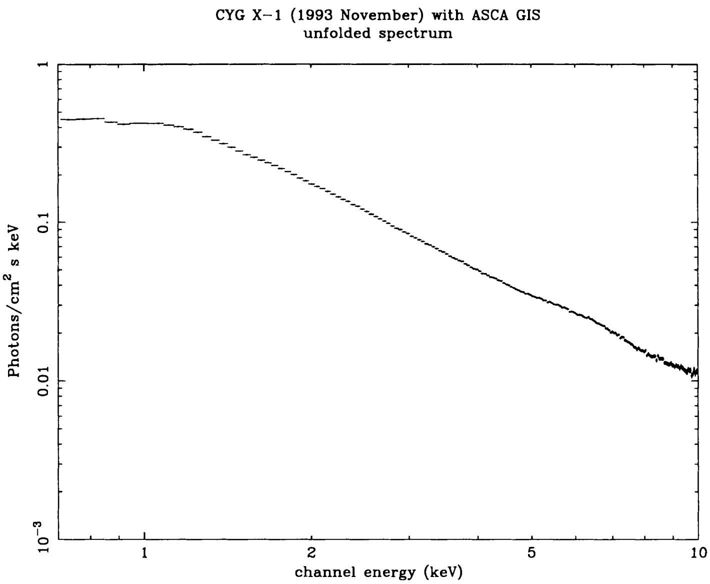

Figure 4. **The unfolded photon spectrum of Cyg X-1 obtained with the ASCA GIS.**

However, the allowable range in the relation between the strength of the magnetic field at the surface of the neutron star and its rotational period is very limited in this case. In order for mass accretion to take place at the Alfvén radius, the gravitational force should be stronger than the centrifugal force at the Alfvén radius. This condition can be written as

$$P > 63\ (B/10^8\,\mathrm{G})^{6/7}(\dot{M}/10^{13}\,\mathrm{g\,s^{-1}})^{-3/7}(M/\mathrm{M}_\odot)^{-5/7}(R/10^6\,\mathrm{cm})^{18/7}\,\mathrm{ms}, \tag{1}$$

where P, B, M, R and $\dot{M}$ are the rotational period, the surface magnetic field, the mass and the radius of the neutron star, and the accretion rate onto the neutron star, respectively. As seen from this equation, very weakly magnetized or very slowly rotating neutron stars are necessary in this case. If this possibility holds true, these sources cannot be progenitors of millisecond pulsars.

4. Iron Lines from Black-Hole Candidates

It is widely known that black-hole candidates generally have two states, the soft (high) state and hard (low) state (see, e.g., Inoue 1993).

The spectrum of Cyg X-1 in the hard state obtained with ASCA GIS is shown in Fig. 4. No prominent emission lines characteristic of thin thermal

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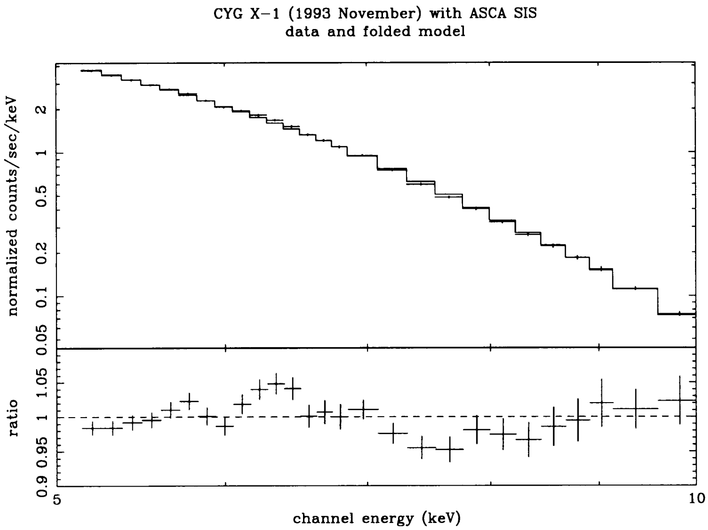

Figure 5. The Cyg X-1 spectrum obtained with the ASCA SIS (crosses) and the best-fit power law spectrum (histograms) (upper panel); the ratio of the observed to the model spectrum (lower panel).

emission are seen. However, we find a slight but significant excess over a single power law around 5–7 keV as seen in Fig. 4. This broad excess can be interpreted in terms of a reflection component superposed on the power-law component (Tanaka 1989). If the reflection component really exists in the spectrum, it must be accompanied by a fluorescent iron line. In fact, if we fit a single power law to the SIS spectrum in the 5–10 keV range, the ratio of the observed spectrum to the power law model shows a clear line feature around 6.3–6.4 keV as seen in Fig. 5. By fitting a Gaussian profile to this emission line feature, it is found that the line is consistent with a fluorescent iron line at 6.4 keV and the line width is less than 200 eV. Hence, this line does not seem to come from a relativistic region near the central object. However, the equivalent width of this narrow line is about 10 eV and this value is much weaker than expected from the intensity of the reflection component. A significant fraction of the broad excess around 5–7 keV might be due to a broad emission line from the relativistic region (Fabian *et al.* 1989).

ASCA obtained a typical soft-state spectrum from GRS 1009–45. This source was first detected with the GRANAT/WATCH experiment (Lapshov *et al.* 1993; Harmon *et al.* 1993). Following the first detection, ASCA observed this source on Nov. 10, 1993 (Tanaka *et al.* 1993). Fig. 6 shows

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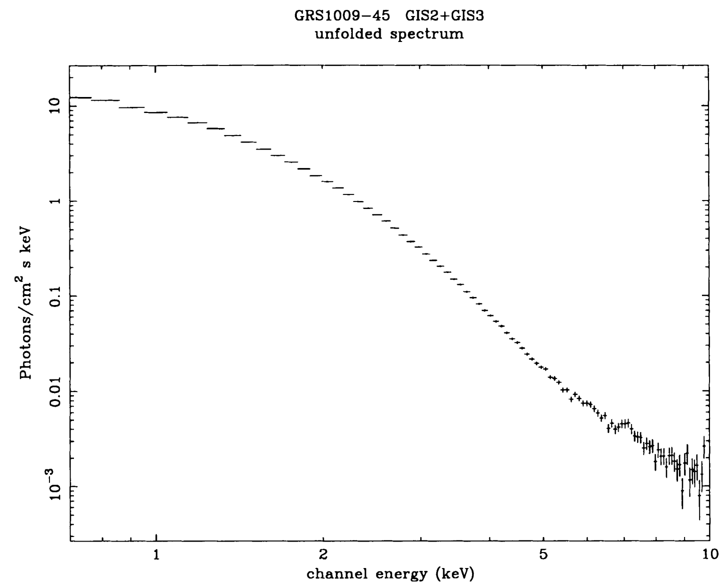

Figure 6. **The unfolded photon spectrum of GRS 1009–45 obtained with the ASCA GIS.**

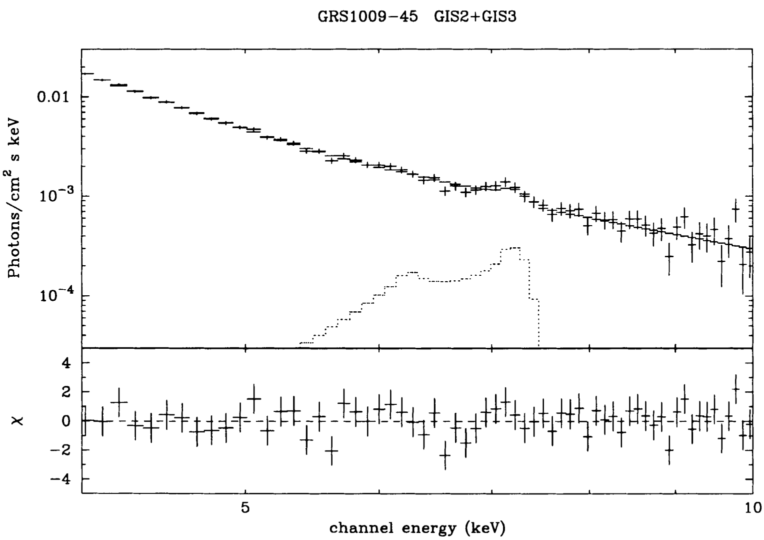

Figure 7. **The GIS spectrum of GRS 1009–45 fitted with a line profile from a relativistic accretion disk (dashed line). The detector response has been unfolded. The best-fit line energy is determined with other parameters fixed: $r_{\rm in} = 10\,r_s$, $r_o = 100\,r_s$, $q = -2$, $i = 40°$ (for definitions, see Fabian *et al.* 1989). (Tanaka 1994).**

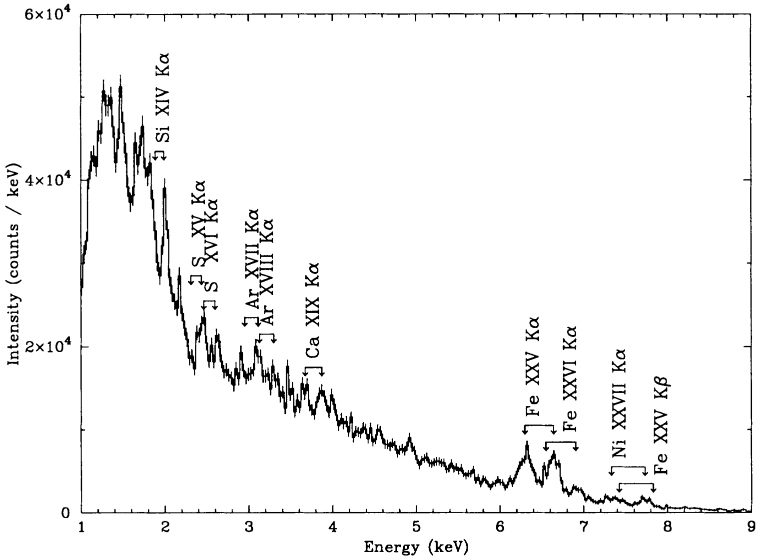

Figure 8. **The X-ray count spectrum of SS 433 obtained with the ASCA SIS on 1993 April 23. The candidates for emission lines and possible identifications are shown by arrows. (Kotani *et al.* 1994).**

the ASCA GIS spectrum of GRS 1009–45. It is clearly ultrasoft, and accompanied by a hard tail. A remarkable finding is a line feature near 7 keV. If we fit a Gaussian profile to the feature, the best fit line center energy is 7.1 keV, which does not correspond to any atomic lines without a Doppler effect. The rotational motion in the accretion disk may be the origin of the Doppler effect. In fact, a line profile from a relativistic accretion disk can reproduce the line feature as shown in Fig. 7 (Tanaka 1994).

5. Various Emission Lines from SS 433

SS 433 is a well-known X-ray binary system ejecting bipolar jets. The jets have an ejection velocity of about a quarter of the light velocity and precess with a period of 163 days.

Fig. 8 shows the ASCA SIS spectrum of SS 433 on April 23, 1993, and the presence of various emission lines is obvious (Kotani *et al.* 1994). These lines can be identified with pairs of emission lines from silicon to iron and all the lines are consistent with coming from either of the two jets. If we compare the degrees of the Doppler shift of the two jets best reproducing the various line energies with the simultaneously obtained Doppler shift

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at the optical band, we will be able to see whether or not the velocity of the X-ray emission region is the same as the optical emission region. This analysis is in progress.

Coexistence of He-like and H-like Kα lines from silicon to iron suggests the presence of temperature structure in the X-ray emission region as discussed earlier for EX Hydra. The ratios of the intensity of He-like to H-like lines of various elements are again the best indicator of the temperature structure. If we assume that all the physical parameters can be expressed as a power of the radial distance, the line intensity can be obtained by integrating $T^{\alpha}\Lambda(T)$ over T from 0 to $T_{\rm max}$, where $\Lambda(T)$ is emissivity at temperature T. Then, the line intensity ratio can be calculated for various elements in terms of the power-index α and compared with the observation. If we assume that v = const., $S \propto r^2$ and $P \propto \rho^{5/3}$, we find $\alpha = -0.25$. (Here, v, S, P and ρ are the velocity, cross-section, pressure and density of matter in a jet, respectively.) This preliminary result shows that the observed line intensity ratios of silicon, sulphur and iron are significantly smaller than those for the adiabatic flow. This may suggest the importance of radiative cooling in the X-ray emitting region of jets.

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Discussion

P. Charles: In your explanation for the quiescent X-ray emission from the neutron star transients 4U 1608–52 and Cen X-4 you dismissed the possibilities of coronal emission from the companion star, because it is too weak. I would like to point out that, since almost all these transients appear to have approximately K0 secondaries, they are analogous with the X-ray active RS CVn systems. Admittedly, typical RS CVn luminosities are still below those observed in the transients, but their binary periods are shorter and so the coronal activities could be higher, making it a significant contribution. This could be tested by future higher sensitivities observations by searching for coronal X-ray line emission.