Title of your IAU Symposium
Proceedings IAU Symposium No. 281, 2011
A.C. Editor, B.D. Editor & C.E. Editor, eds.

DOI: 00.0000/X000000000000000X

The White Dwarf Mass and the Accretion Rate of Recurrent Novae: an X-ray Perspective

Koji Mukai[1,2], Jennifer L. Sokoloski[3], Thomas Nelson[4], and Gerardo J. M. Luna[5]

[1]CRESST and X-ray Astrophysics Laboratory, NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA
email: Koji.Mukai@nasa.gov

[2]Also Department of Physics, University of Maryland Baltimore County, 1000 Hilltop Circle, Baltimore, MD 21250, USA

[3]Columbia Astrophysics Laboratory, 550 W. 120th St., 1027 Pupin Hall, Columbia University, New York, NY 10027, USA

[4]School of Physics and Astronomy, University of Minnesota, 115 Church St. SE, Minneapolis, MN 55455, USA

[5]Instituto de Ciencias Astronómicas, de la Tierra y del Espacio (ICATE/FCEFyN), Av. España Sur 1512, J5402DSP, San Juan, Argentina

Abstract. We present recent results of quiescent X-ray observations of recurrent novae (RNe) and related objects. Several RNe are luminous hard X-ray sources in quiescence, consistent with accretion onto a near Chandrasekhar mass white dwarf. Detection of similar hard X-ray emissions in old novae and other cataclysmic variables may lead to identification of additional RN candidates. On the other hand, other RNe are found to be comparatively hard X-ray faint. We present several scenarios that may explain this dichotomy, which should be explored further.

1. Introduction

By definition, a recurrent nova (RN) has been seen to undergo multiple episodes of thermonuclear runaway within the last century or so. For the hydrogen-rich envelope to reach the high temperature and density required for a runaway in such a short period, the white dwarf must be massive and its accretion rate must be high. Although only ten Galactic RNe are currently known, the true number of RNe is likely to be much larger, considering the low discovery probability of nova outbursts (Schaefer 2009). Two important goals for RN observers in the context of Type Ia progenitors therefore are (i) observational determination of white dwarf mass and accretion rate; and (ii) search for hitherto undiscovered or unrecognized RNe.

In non magnetic cataclysmic variables (CVs) and symbiotic stars, X-rays are emitted in the boundary layer between the disk and the white dwarf. Optically thin boundary layers predominantly emit hard X-rays; even optically thick boundary layers are seen to retain some hard X-ray flux, presumably because the surface layer remains optically thin (Patterson & Raymond 1985). These hard X-rays are multi-temperature plasma emission whose maximum temperature is strongly constrained by the depth of the gravitational potential, i.e., the white dwarf mass. Thus, hard X-ray observations may be a viable alternative method to optical and UV spectroscopy in our study of white dwarf masses, particularly in cases of high interstellar extinction.

If the Keplerian flow just above the white dwarf surface is strongly shocked, then the shock temperature is half of the free-fall case, well known in the studies of magnetic CVs.

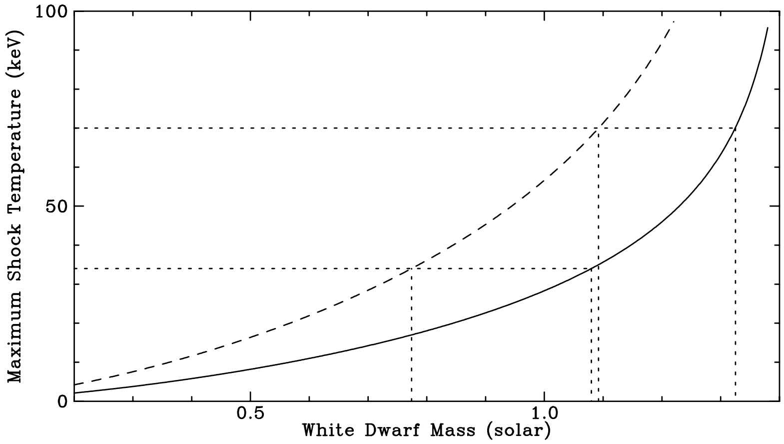

Figure 1. The expected maximum temperature of the optically thin X-rays for the magnetic (dashed line) and non-magnetic (solid) cases. The lower limit of 34 keV for V2487 Oph corresponds to 0.77 $M_\odot$ (magnetic) or 1.08 $M_\odot$ (non-magnetic) white dwarf. The best-fit temperature of 70 keV corresponds to 1.01 $M_\odot$ and 1.33 $M_\odot$, respectively.

Multiple groups have used X-ray spectroscopy to infer the white dwarf mass in magnetic CVs; the study of quiescent X-rays from dwarf novae (Byckling *et al.* 2010) suggests that this is also possible for non-magnetic CVs. One complication is that the hard X-ray emission of a dwarf nova usually becomes fainter and softer during outburst when a part of the boundary layer becomes optically thick (see below for a possible reason). Even so, the maximum temperature derived for the hard component sets a firm lower limit for the white dwarf mass.

2. X-ray Bright RNe

In recent years, four symbiotic stars have been detected as luminous hard X-ray sources in the *Swift* BAT and *INTEGRAL* surveys Kennea *et al.* (2009). One of the four is T CrB, with a 15–150 keV luminosity of $7\times10^{33} \times [d/1kpc]^2$ erg s^{-1}. The current generation of hard X-ray all-sky surveys have a detection limit of order $\sim 10^{-11}$ ergs cm^{-2}s^{-1}, or $\sim 10^{33}$ erg s^{-1} at 1 kpc, below which many more hard X-ray bright symbiotics are likely to exist. In fact, Luna *et al.* (2010) have significantly increased the number of known hard X-ray sources among symbiotic stars through pointed observations with *Swift* XRT.

Kennea *et al.* (2009) made the case that T CrB contains a near Chandrasekhar mass, non-magnetic white dwarf using a Bremsstrahlung fit to the BAT spectrum available at the time. We have updated their argument as follows. We fit the BAT spectrum below 100 keV from the *Swift* BAT 58-month survey with a cooling flow model, and obtain the maximum temperature of kT_{max} = 46±6 keV. If the emission is from an optically thin boundary layer, it implies a white dwarf mass of M_{wd}=1.2 $M_\odot$. More likely, a significant portion of the boundary layer in T CrB is optically thick, given that the high UV luminosity (Selvelli *et al.* 1992). If this has resulted in the reduction of kT_{max} by a factor of 1.7, as it does in SS Cyg in outburst, then M_{wd}=1.35 $M_\odot$ in T CrB.

V2487 Oph is the first nova for with a pre-outburst X-ray detection (Hernanz & Sala 2002). It is also a hard X-ray source detected in the *INTEGRAL* and *Swift* BAT surveys. Although this is a CV and not a symbiotic system (the mass donor in V2487 Oph is not a red giant), its X-ray spectrum can be compared to that of T CrB. Using the BAT 58-

month survey data and a cooling flow model, the best fit kT_{max} is 70 keV; the 90% lower limit is 34 keV, while the upper limit cannot be constrained due primarily to the limited grid of plasma models available within the cooling flow model. For a distance of 12 kpc (Schaefer 2010), its 2–10 keV luminosity is close to 10^{35} $\mathrm{ergs\,s^{-1}}$. In contrast, intermediate polars (IPs), the most hard X-ray luminous subclass of magnetic CVs, usually do not exceed 10^{34} $\mathrm{ergs\,s^{-1}}$. V2487 Oph was established as an RN by Pagnotta *et al.* (2009), who discovered its 1900 outburst in photographic plates.

V2487 Oph is often considered a candidate IP, based on its X-ray appearances. However, the signature of a spin period, a key defining characteristic of IPs, has never been seen in this object. Moreover, the hardness of its X-ray spectrum can be explained by two scenarios: it may be a magnetic CV with a moderately massive white dwarf, or it may be a non-magnetic CV with a near Chandrasekhar mass white dwarf (Figure 1). Also considering the fact that V2487 Oph is a RN, the latter interpretation is very attractive.

V2491 Cyg has several similarity with V2487 Oph, including a pre-nova X-ray detection (Ibarra *et al.* 2009) and the strong post-nova X-ray emission (Takei *et al.* 2011). These X-ray characteristics alone make it a candidate RN, which seems to be corroborated by several RN-like characteristics in the optical.

We also find several other CVs that are not known to be a nova, let alone RNe, and have not been firmly established to be magnetic, in the BAT 58-month survey catalog: AH Men, V426 Oph, TW Pic, and V1082 Sgr (two dwarf novae, SS Cyg and RU Peg, are also detected by BAT but their accretion rates are presumably too low to be of interest in this context). These 4 systems may deserve further attention.

3. X-ray Faint RNe

However, it is now clear that not all RNe are X-ray bright. RS Oph is significantly fainter in X-rays (2×10^{33} $\mathrm{ergs\,s^{-1}}$, 0.3–10 keV on day 538) and significantly softer (kT_{max} $\sim$ 5 keV in a cooling flow fit) than T CrB (Nelson *et al.* 2011). T Pyx in quiescence is also a faint (and not supersoft) X-ray source. The central binary has a luminosity of $\sim 10^{32}$ $\mathrm{ergs\,s^{-1}}$ for a distance of d=3.5 kpc (cf. Balman 2010).

We have observed 3 additional Galactic RNe, V394 CrA, CI Aql, and and IM Nor with *XMM-Newton*. For IM Nor, there is a source at RA=15:39:27.6, Dec=−52:18:55.1, roughly 30" from the cataloged position of this RN, at about 4.2×10^{-3} $\mathrm{c\,s^{-1}}$ with a poorly constrained spectrum. If this X-ray source is the RN, its luminosity is roughly 5 $\times10^{30}[d/2kpc]^2$ $\mathrm{ergs\,s^{-1}}$ (2–10 keV). V394 CrA and CI Aql are undetected with 2–10 keV upper limits of 5 $\times10^{31}[d/5kpc]^2$ $\mathrm{ergs\,s^{-1}}$ and 5 $\times10^{30}[d/2kpc]^2$ $\mathrm{ergs\,s^{-1}}$, respectively. We note that IM Nor and CI Aql are known to be eclipsing. If the inclination angles are high enough, or the disks thick enough, it is possible that the white dwarf is always hidden from our view, in which case the observations do not necessarily reflect the true X-ray luminosity of these systems.

Nevertheless, it is clear that not all RNe are luminous hard X-ray sources like T CrB and V2487 Oph. These X-ray faint RNe may nevertheless harbor massive white dwarfs accreting at high rates. The X-ray luminosity can be reduced if the boundary layer is completely optically thick, if the white dwarf is rotating at near break-up spin, or if the optically thin part of the boundary layer is Compton-cooled.

When Bremsstrahlung is the primary cooling mechanism of the post-shock plasma, the cooling time is inversely proportional to the square of the density; the plasma cools and becomes denser, which increases the cooling efficiency, and the cycle repeats. However, if there is a strong external field of soft photons, Compton cooling may be more efficient than Bremsstrahlung in parts of the boundary layer. Nelson *et al.* (2011) explored the possibility of Compton cooling for RS Oph, and Fertig *et al.* (2011) applied the same idea to dwarf novae in outburst. Compton cooling dominates over Bremsstrahlung only in the less dense, which is also the hotter, regions of the boundary layer. Therefore, Compton cooling lowers both the temperature and the luminosity of the observed hard X-ray emission. This is indeed seen in dwarf novae in outburst, in which the seed photons are supplied by the optically thick part of the boundary layer. If, in RS Oph, the entire white dwarf is still hot and luminous ($\sim 10^{35}$ ergs s^{-1}), this can provide a copious amount of seed photons. Therefore, the potential difference in the white dwarf temperature can explain the different X-ray properties of RS Oph and T CrB in principle.

The luminosity of the white dwarf in RNe is likely to depend on the time since last outburst, somewhat longer-term history of recent outbursts, and other factors. If our Compton cooling model is correct, then RNe with luminous white dwarf are X-ray faint. While this interpretation is not firmly established, it offers a plausible explanation for the diverse X-ray characteristics of quiescent RNe without invoking a low mass white dwarf or a low accretion rate.

4. Conclusions

We have learned that some quiescent RNe are luminous, hard X-ray sources. Although the fraction of such systems among RNe is unknown, this offers a new method for discovering RNe candidates. A sensitive hard X-ray all-sky survey, such as expected using the *e-ROSITA* mission, will be very useful in this regard.

The X-ray spectra of T CrB and V2487 Oph are consistent with what one would expect for an optically thin, or partially optically thick, boundary layer around a massive non-magnetic white dwarf. With the current level of knowledge, we cannot measure the white dwarf mass accurately, although high temperature X-ray emission requires high M_{wd}. The X-ray luminosity is a direct measure of the accretion rate onto the white dwarf if and only if the boundary layer is completely optically thin; in the partially optically thick case, we can only provide a lower limit for the accretion rate.

The existence of X-ray faint RNe requires an explanation. We offer Compton cooling as a possibility. In addition to more quantitative exploration of this process, we must understand the evolution of the white dwarf luminosity appropriate in the RN regime.

References

Balman, S. 2010, *MNRAS*, 404, L26

Byckling, K., Mukai, K., Thorstensen, J.R., & Osborne, J.P. 2010, *MNRAS*, 408, 2298

Fertig, D., Mukai, K., Nelson, T., & Cannizzo, J. 2011, *PASP*, in press

Hernanz, M., & Sala, G. 2002, *Science*, 298, 383

Ibarra, A., Kuulkers, E., Osborne, J.P., Page, K., Ness, J.U., Saxton, R.D., Baumgartner, W., Beckmann, V., Bode, M.F., Hernanz, M., Mukai, K., Orio, M., Sala, G., Starrfield, S., & Wynn, G.A. 2009, *A&A*, 497, L5

Kennea, J.A., Mukai, K., Sokoloski, J.L., Luna, G.J.M., Tueller, J., Markwardt, C.B., & Burrows, D.N. 2009, *ApJ*, 701, 1992

Luna, G.J.M., Sokoloski, J., Mukai, K., & Nelson, T., 2010, *ATel*, 3053

Nelson, T., Mukai, K., Orio, M., Luna, G.J.M., & Sokoloski, J.L. 2011, *ApJ*, 737, A7

Pagnotta, A., Schaefer, B.E., Xiao, L., Collazzi, A.C., & Kroll, P. 2009, *AJ*, 138, 1230

Patterson, J., & Raymond, J.C. 1985, *ApJ*, 292, 535

Schaefer, B.E. 2010, *ApJSupp*, 187, 275

Selvelli, P.L., Casatella, A., & Gilmozzi, R. 1992, *ApJ*, 393, 289

Takei, D., Ness, J.U., Tsujimoto, M., Kitamoto, S., Drake, J.J., Osborne, J.P., Takahashi, H., & Kinugasa, K. 2011, *PASJ*, in press