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X-ray observations of classical novae Theoretical implications

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Abstract. Crucial information about the explosion mechanism of classical and recurrent novae is obtained from the study of their X-ray emission in outburst. The white dwarf photosphere is extremely hot, while hydrogen (H) nuclear burning remains active on top of the white dwarf core; soft X-rays reveal such hot photosphere, once the ejecta becomes transparent, and give direct information about the amount of H-rich envelope mass remaining after the explosion. In addition, post outburst X-ray emission reveals both the shocked ejecta and/or the accretion flow, once mass transfer onto the white dwarf resumes. Therefore, properties of the host binary system (a cataclysmic variable for classical novae and a symbiotic binary in some recurrent novae) can be traced through the analysis of this post-outburst X-ray emission. A review of X-ray observations of classical novae, together with the main nova properties derived from them is presented.

Key words. Stars: novae, cataclysmic variables, white dwarfs – X-rays: binaries

1. Introduction

A classical nova explosion occurs in a carbon-oxygen (CO) or in an oxygen-neon (ONe) white dwarf (WD), which accretes H-rich matter from a main sequence star companion in a close binary system (of the cataclysmic variable - CV - type). Mass transfer occurs because the companion star overflows its Roche lobe. Mass transferred accumulates on top of the white dwarf until degenerate conditions are reached; then H-ignition occurs, leading to a thermonuclear runaway. Explosive burning of hydrogen synthesizes some β^+-unstable nuclei with short lifetimes (e.g. ^{13}N, ^{14}O, ^{15}O, ^{17}F, with τ = 862, 102, 176, and 93s respectively); these isotopes are transported by convection to the outer envelope, where they are preserved from destruction. Their decays lead to a huge energy release in the outer shells which causes the nova outburst, with a visual luminosity increase accompanied by mass ejection ($M_{\rm eject} \sim 10^{-4} - 10^{-5} M_\odot$) with typical velocities of a few $10^2 - 10^3$ km/s (Prialnik & Kovetz 1995; Starrfield et al. 1998; José & Hernanz 1998). Luminosities at visual maximum reach $10^4 - 10^5 L_\odot$, close to the Eddington limit.

Classical nova explosions are recurrent phenomena, because only the outer envelope is expelled (contrary to type Ia supernova explosions, where the whole white dwarf is disrupted). Typical recurrence times are of the order of 10^4 – 10^5 years. The orbital periods of the hosting CVs range between hours and days, with average separations of a$\sim$ 10^{10}cm. A galactic nova rate of $\sim$35/yr is expected in our Galaxy (Shafter 1997).

In a few cases, the companion of the white dwarf is a red giant star, losing mass via its stellar wind, and the host system of the nova explosion is a symbiotic binary; the larger mass transfer rate can lead to more frequent outburst, so that more than one nova outburst can be recorded; these are called "recurrent novae" (although, as said above, all novae are recurrent). Orbital periods in symbiotic recurrent novae are much larger than in classical novae, i.e., a few 100 days, as well as average separations a$\sim$ 10^{13} – 10^{14}cm. There are about 10 recurrent novae, of any type, known in the Galaxy, although there are some that have been probably missed (Schaefer et al. 2009).

It is important to remind that some mixing between the accreted envelope (with solar composition, as corresponds to the outer envelope of the companion main sequence star) and the white dwarf core (composed of either CO or ONe) is required, both to power the explosion and to explain the overabundances, with respect to solar, observed in several novae ejecta (Gehrz et al. 1998).

2. Origin of X-ray emission

After a nova explosion, a fraction of the accreted envelope - or even the whole envelope including some material dredged-up from the core of the underlying white dwarf - is ejected. Steady nuclear burning is expected to take place on the (potential) remaining H-rich envelope on top of the white dwarf. As shown through multi wavelength observations of novae, after optical maximum there's a decline in the visual luminosity, in parallel with an increasing luminosity in the ultraviolet (UV); the reason is that the radius of the photosphere decreases (since the photosphere recedes as the envelope mass is depleted), and thus the effective temperature increases and the spectrum hardens from visual to UV and to soft X-rays. In fact, the bolometric luminosity remains quasi constant during such phase, in agreement with theoretical predictions (Starrfield 1989; MacDonald 1996; Krautter 2002). Supersoft X-rays reveal the hot white dwarf photosphere, with typical effective temperatures of several 10^5K (up to 10^6K); they can be observed once the expanding ejecta becomes transparent enough to such radiation. Typical luminosities are close to the Eddington limit, i.e., $\sim 10^{38}$erg/s. The duration of the supersoft X-ray emission phase is directly related to the amount of H-rich matter remaining on top of the white dwarf after the nova explosion; it indicates the length of the turn-off phase of the nova (Sala & Hernanz 2005).

Another origin of the X-rays emitted by classical novae are the internal and external shocks, within the ejecta and between the ejecta and the surrounding medium, respectively. Such shocks heat the plasma which then emits as an optically thin medium, mainly through thermal bremsstrahlung, with a spectrum harder than the supersoft one corresponding to the very hot photosphere. In the particular case of symbiotic recurrent novae, where the companion is a red giant, there's a strong interaction between the nova ejecta and the red giant wind, which is responsible for the ejection of very hard X-rays, or even very energetic gamma-rays, as in V407 Cyg and RS Oph (Tatischeff & Hernanz 2007; Abdo et al. 2011; Hernanz & Tatischeff 2011).

Finally, once accretion is reestablished, the nova emits as a cataclysmic variable (see, e.g., M. Mouchet's contribution in this volume). Both soft and hard X-rays are expected. The spectral characteristics depend on the magnetic field of the white dwarf, which determines if the cataclysmic variable is magnetic (either a polar - direct accretion onto the magnetic poles of the WD - or an intermediate polar - with a truncated disk) or non magnetic (with a standard accretion disk). Intermediate polars are, in general, expected to emit harder X-rays than polars, since cyclotron cooling is less effective in them and thus the plasma is hotter.

It has also been suggested that the Comptonization of the gamma-rays produced in ^{22}Na nuclear decay could be responsible of prompt hard X-rays emitted by novae (Livio et al. 1992); but this has been ruled out after detailed modeling of the gamma-ray spectra of classical novae: Compton down-scattered photons are harder (energies larger than 20-30 keV, because of photoelectric absorption) and emitted earlier than the observed hard X-rays.

In fact, emission of Comptonized gamma-rays has very short duration (less than 2 days) and occurs before the nova is discovered optically (Gómez-Gomar et al. 1998; Hernanz et al. 1999). The outburst of the recurrent nova RS Oph in 2006 was a good example of an early hard X-ray emission, detected with Swift/BAT and RXTE (Bode et al. 2006; Sokoloski et al. 2006), non attributable to such Comptonization of gamma-rays (Hernanz & José 2008).

3. Observations

3.1. Novae as supersoft X-ray sources

The first nova detections in soft X-rays were done with the EXOSAT and ROSAT satellites. GQ Mus (1983) was discovered with EXOSAT (Ögelman et al. 1984) and later detected with ROSAT (Röntgen satellite); it is one of the novae with the longest duration supersoft X-ray emission phases, about 9 years (Ögelman et al. 1993; Shanley et al. 1995; Orio et al. 2001; Balman & Krautter 2001). It is worth reminding that only 3 novae (V1974 Cyg 1992, GQ Mus 1983 and N LMC 1995) were found emitting soft X-rays, from a sample of 30 galactic and 9 LMC novae observed up to 10 years after their explosion, both during the ROSAT All Sky Survey and in pointed observations (Orio et al. 2001). V1974 Cyg 1992 was a very bright nova, observed at all wavelengths; a complete soft X-ray light curve was obtained with ROSAT, from the early rise phase to the plateau and the decline, lasting 1.5 years (Krautter et al. 1996; Balman et al. 1998). The third nova discovered in soft X-rays with ROSAT was N LMC 1995 (Orio & Greiner 1999), later observed with XMM-Newton (Orio et al. 2003), with a whole duration of the supersoft source phase of about 8 years.

Further observations with enhanced energy resolution were performed with BeppoSAX, which detected V382 Vel (1999), with turn-off time of 7-9 months and showing emission lines superimposed to the hot WD photospheric emission (Orio et al. 2002). These emission lines were also detected with the grating instruments of the Chandra satellite (Burwitz et al. 2002; Ness et al. 2005). Other examples of Chandra and XMM-Newton observations of the supersoft X-ray phase of novae in outburst are V1494 Aql (1999) and V4743 Sgr (2002), both displaying puzzling temporal behaviors (Drake et al. 2003; Ness et al. 2003; Rauch et al. 2010); see S. Balman's contribution in this volume. Two more examples of novae detected as active supersoft X-ray emitters are V5115 Sgr (2005a) and V5116 Sgr (2005b), both discovered by Hernanz & Sala with XMM-Newton, 18 months and 20 months after outburst, respectively. V5116 Sgr was particularly interesting (Sala et al. 2008), since it exhibited abrupt increases and decreases of its flux, by a factor of $\sim$ 8, with a tentative period consistent with the optical period found (Dobrotka et al. 2008). The turn-off took place between 2 and 3 years after outburst (as deduced from later observations, with Swift/XRT and with XMM-Newton, when the nova had already turned off).

The Swift satellite has contributed very significantly to the study of the X-ray emission from novae, through its campaign of novae monitoring with the XRT telescope and the UVOT monitor (Ness et al. 2007; Schwarz et al. 2011); it has also served as a trigger for ToO observations with XMM-Newton and Chandra. There is a nova observed by Swift which is very interesting, regarding the length of the supersoft X-ray emission: V723 Cas (N Cas 1995). This nova was still bright in supersoft X-rays, when observed with Swift in 2006-2007, thus having the longest duration of supersoft X-ray emission phase (Ness et al. 2008). However, V723 Cas was quite dim and its Swift/XRT spectra had poor spectral resolution, so that the observations were not compelling and it was not 100% clear that the origin of the emission was residual H-nuclear burning on top of the white dwarf. Interestingly enough, this nova has been again detected as being "on" in 2010 (with XMM-Newton) and with Swift/XRT again in 2011; therefore, it has the longest ever supersoft source (SSS) phase, 12 years. Several other novae have been detected by Swift as SSS. According to Osborne (Osborne 2009), 35 novae had been observed, earlier than 4000 days post outburst, with Swift (March 2009 data; see update Schwarz et al.

2011); 19 were detected in X-rays, out of which 9 (including RS Oph 2006 outburst) were SSS. So ROSAT's (plus Beppo-SAX, XMM-Newton and Chandra) statistics have really improved thanks to Swift. The duration of the supersoft X-ray emitting phase, however, is still quite short: at most 3.5 years (V574 Pup 2004) for all novae detected as SSS except the above mentioned V723 Cas (N Cas 1995), with 12 years up to now.

3.2. Post-outburst novae

Observations of novae where H nuclear burning has turned off reveal ejecta emission and/or the recovery of accretion. In the last case, they trace the properties of the CV system hosting the nova explosion. An interesting post-outburst nova, observed with XMM-Newton, is V2487 Oph (Nova Oph 1998). It was detected at five epochs: 2.7, 3.2, 3.7, 4.3 and also 8.8 years after outburst. Already in the first observation, 2.7 years after outburst, it became clear that accretion was reestablished, because the fluorescent Fe Kα emission line at 6.4 keV was detected; this indicated that there was reflection of hard X-rays on cold neutral matter - either in the accretion stream or on the WD surface (Hernanz & Sala 2002). In addition to the neutral Fe line at 6.4 keV, the He-like Fe line at 6.68 keV and the H-like Fe line at 6.97 keV were also present.

Furthermore, the spectral shape (flat slope) and the high X-ray luminosity ($\sim 10^{34}$ erg/s) presumably indicated that the CV hosting the post-nova is an intermediate polar; additional indications of the magnetic character of the WD come from the optical observations performed with the NOT telescope in the ORM in La Palma (C. Ferri's PhD Thesis, unpublished), which showed the HeII line. But we can't confirm the CV type yet because we don't know well P_{orb} and P_{spin}.

V2487 Oph 1998 was also detected by INTEGRAL/IBIS, in the 20-100 keV range (Barlow et al. 2006). All the observations in X-rays, plus the shape of the optical curve seem to indicate that the WD in this nova is quite massive. This is in agreement with the discovery that Nova Oph 1998 is a recurrent nova, with a previous eruption in 1900 (Pagnotta et al. 2009); only novae with very massive WDs can erupt as frequently as recurrent novae (which have recurrence periods smaller than $\sim$ 100 years, i.e., more than one recorded outburst). Another recent case of a presumably recurrent nova, thus also hosting a massive white dwarf, is V2491 Cyg (2008), detected in hard X-rays with Suzaku (see D. Takei's contribution to this volume).

4. Conclusions

X-ray observations of novae give a huge information about the properties of the WD, the turn-off of the explosion and also about the CV hosting the nova. A recent discovery has been the presumed existence of very massive WDs in some nova explosions (e.g., recurrent novae), which is very important to disentangle the scenario of type Ia supernova explosions. Such massive WDs would increase their mass instead of decreasing it, after each explosion (Hernanz & José 2008), and therefore they could finally reach the Chandrasekhar mass and explode as SNIa. However, massive WDs are expected to be made of ONe, instead of CO, and then they would finally collapse instead of explode, since they are devoid of carbon. Thus, for this and other reasons the scenario(s) of SNIa is far from being understood.

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