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Observations of classical and recurrent novae with X-ray gratings[*]

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Abstract. X-ray grating spectra have opened a new window on nova physics. High signal-to-noise spectra have been obtained for 12 novae after the outburst in the last 13 years, with the *Chandra* and *XMM-Newton* gratings. They offer the only way to probe the temperature, effective gravity and chemical composition of the hydrogen burning white dwarf before it turns off. These spectra also allow an analysis of the ejecta, which can be photoionized by the hot white dwarf, but more often seem to undergo collisional ionization. The long observations required for the gratings have revealed semi-regular and irregular variability in X-ray flux and spectra. Large short term variability is especially evident in the first weeks after the ejecta have become transparent to the central supersoft X-ray source. Thanks to *Chandra* and *XMM-Newton*, we have discovered violent phenomena in the ejecta, discrete shell ejection, and clumpy emission regions. As expected, we have also unveiled the white dwarf characteristics. The peak white dwarf effective temperature in the targets of our samples varies between ≥400,000 K and over a million K, with most cases closer to the upper end, although for two novae only upper limits around 200,000 K were obtained. A combination of results from different X-ray satellites and instruments, including *Swift* and *ROSAT*, shows that the shorter is the supersoft X-ray phase, the lower is the white dwarf peak effective temperature, consistent with theoretical predictions. The peak temperature is also inversely correlated with t_2, the time for a decay by 2 mag in optical. I strongly advocate the use of white dwarf atmospheric models to obtain a coherent physical picture of the hydrogen burning process and of the surrounding ejecta.

Keywords : stars: novae, cataclysmic variables – stars: winds, outflows – X-rays: binaries

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1. Introduction

The evolutionary track of a post-nova white dwarf (WD) has been known since the pioneering work of Gallagher & Starrfield (1976), who discovered that the post-maximum decline in optical light during the outburst of a classical or recurrent nova is caused by a shift in the wavelength of maximum energy towards shorter wavelengths, during a constant bolometric luminosity phase, close to Eddington luminosity. This phase lasts from weeks to years as the white dwarf photosphere shrinks back to pre-outburst radius, while thermonuclear burning is still occurring near the surface.

I will describe the of X-ray grating observations of novae focusing first of all on a historical perspective. X-ray observations of *quiescent* novae were found interesting early on, as an excellent way to study the accretion process in nova close binaries (Becker & Marshall 1981). However, the central white dwarf burning hydrogen shortly before and after *outburst* in its hottest and most compact configuration (Shara et al. 1977; Fujimoto 1982), used to be described as an "extreme ultraviolet source" not as an X-ray source. The development of nova models showed that the white dwarf surface reaches temperatures above 200,000 K, and it became clear that not only the "Wien tail" of the black-body like spectral distribution, but even the peak can fall in the X-ray range (e.g. Prialnik & Kovetz 1992). A handful of luminous supersoft X-ray sources (SSS) were discovered with *Einstein*, and turned out to be white dwarf binaries, although they were not associated with nova eruptions (e.g. Long et al. 1981). Three post-outburst novae were detected as relatively luminous sources with *Exosat*, albeit almost without spectral resolution (Ögelman et al. 1984, 1987). *ROSAT*, the new imaging X-ray telescope after *Einstein*, had excellent sensitivity in the softest range, so in the late eighties and early nineties there was a sudden surge of excitement in the nova community, motivated by the possibility of detecting post-outburst novae as extremely luminous and soft sources after the nova ejecta became optically thin to X-rays.

Indeed, with *ROSAT* the *Exosat* source GQ Mus was observed as a luminous SSS more than 9 years after the outburst (Ögelman et al. 1993) although it was observed to turn off shortly thereafter (Shanley et al. 1995). Furthermore, Nova Cyg 1992 (V1974 Cyg) was the brightest X-ray source observed with *ROSAT* for a $\approx$ 8 months period starting more than a year after the outburst (Krautter et al. 1996; Balman et al. 1998). A third SSS *ROSAT* nova was detected as far away as the LMC, towards which the low interstellar absorption favors the detection of soft and luminous X-ray sources (Orio & Greiner 1999). The SSS phase seemed to be mostly short lived: in random, serendipitous observations only 3 out of 38 novae in the first 10 post-outburst years were caught in this phase, and none out of another 69 other novae observed between 10 and 100 years after the eruption (Orio et al. 2001). It also became clear that novae in outburst emit a slightly harder, less luminous flux that seemed to be associated with the ejected shell. This component of the X-ray flux has a different and independent evolution from the WD X-ray source (Krautter et al. 1996; Balman et al. 1998; Lloyd et al. 1992; Orio et al. 1996). The nebula ejected by a nova can be X-ray luminous for longer than a century (like the exceptional GK Per, see Balman & Ögelman 1999) although it mostly turns off within 2-3 years (Orio et al. 2001, 2009).

However, at this point in time in the nova scientific community the WD as SSS was the main object of attention, especially that of the theoreticians. Model predictions could be tested through these observations. The nova and pre-type Ia supernova models predict that the more massive the white dwarf, the less mass is accreted until degeneracy is lifted in an outburst. This happens because the material is more compressed on the smaller surface of a massive WD, so the pressure needed for the outburst is reached sooner. It is thus also reasonable to assume that mass loss ceases with less leftover envelope mass on massive white dwarfs, so the SSS duration must be shorter. There are also other important parameters in nova outbursts (mass accretion rate, WD initial atmospheric temperature at the onset of burning, chemical composition, degree of mixing with WD material), but the WD mass is fundamental in determining the length of the SSS phase.

Certainly not less interesting is the dependence of the highest WD atmospheric effective temperature T_{eff} reached *during* thermonuclear burning on the WD mass. The higher is the mass, the higher should be T_{eff}. Even if the *ROSAT* All-Sky-Survey proved that the supersoft X-ray source phase must be mostly short-lived, since no other SSS were detected in other exposures of Galactic novae (Orio et al. 2001), it became known that both symbiotic stars and other CV-like systems host at times a hot, hydrogen burning SSS WD for many years without apparent outburst, raising great interest for the identification of type Ia supernovae progenitors (e.g. van den Heuvel et al. 1992; Orio et al. 1994).

2. Why X-ray gratings?

The so called supersoft X-rays offer a short-lasting, but precious window to observe the "naked" hydrogen burning white dwarf. The WD burns accreted hydrogen in a shell with only a thin layer on top, and the atmosphere that becomes extremely hot when the CNO cycle is in full swing. The nova outburst models indicate temperatures of up a million K. By fitting the continuum and absorption features of the hot WD with detailed atmospheric models, in principle we should be able to derive the WD effective temperature, radius, and effective gravity (which indicates the WD mass if the distance to the nova is known). The independent correlation of WD effective temperature and mass offers, another way to check whether the derived mass is reasonable.

The more recent nova models indicate that in most CN the WD mass does not grow after each outburst, but rather all accreted mass is ejected and even some WD original material is eroded. However, this may not be true for some recurrent novae (RN).

With the advent of *Chandra* and *XMM-Newton* and their X-ray gratings, capable of resolving spectral lines in the soft X-rays range, the nova community hoped that by observing a number of classical and recurrent novae with high spectral resolution, a number of important issues would be solved. They can be summarized as follows:

1. Are Neon-Oxygen WD common in accreting and hydrogen burning close binaries? The ejecta composition of several novae shows overabundant oxygen, neon and magnesium (the latter is an enhanced element in NeO WD). The final destiny of NeO WD binaries may be an accretion induced collapse, not a type Ia supernova.

2. Can we distinguish between these three possibilities: a) Typical abundances of "fresh" CNO ashes (very rich in nitrogen and depleted in carbon), b) Freshly accreted material (similar in composition to the envelope of the secondary), or c) chemical composition indicating erosion of the WD core? This is crucial to understand whether the WD mass of CN or RN can increase over the secular evolution, despite the mass ejection in nova outbursts.

3. Is the range of peak $T_{\rm eff}$ consistent with the models, and is the temperature inversely proportional to the duration of the SSS phase? This question can be answered thanks to correlation with early *ROSAT* observations and especially, with the more recent *Swift* monitoring of novae. With short snapshot broad-band observations, even twice a day, the *Swift* X-ray telescope measures the exact SSS duration (see Schwarz et al. 2011). Such monitoring could not be scheduled before *Swift*.

4. Does the WD return to the "cold WD" radius, or is it significant bloated?

5. Does mass loss cease completely when the nova fades in optical and UV, or do the X-rays indicate a residual wind?

These five questions are central for the nova theory, and also for any realistic pre-supernova type Ia model from a single degenerate binary system.

3. A comprehensive summary until 2012 August

I will not review here the precise characteristics of the X-ray gratings on board *Chandra* and *XMM-Newton*, well explained in the papers I quote. Suffice to say that *XMM-Newton* is equipped with independent X-ray telescopes for each instruments, and has two Reflection Grating Spectrometers (RGS) able to resolve lines in the 0.33-2.5 keV energy range, with varying spectral resolution. The effective area peaks around 15 Å. *Chandra* is equipped with a low energy transmission grating (LETG) providing resolving power ($E/\Delta E > 1000$) at energy 0.07-0.15 keV (80-175 Å) and moderate resolving power at higher energies (up to 4.13 keV). The HRC camera has always been used with the LETG in the observations of novae. The HETG (high energy transmission gratings) consists of two sets of gratings, each with different period. One set, the Medium Energy Grating (MEG), works in the 0.4-5 keV range and the High Energy Gratings (HEG) in the 0.8-10 keV energy range. The HETG have been used only once for the recurrent nova RS Oph. Nova Mon 2012 has also been observed with the HETG while this article was in press.

Table 1 presents a comprehensive list and summary of characteristics of 12 novae observed with X-ray gratings. Table 2 presents the data on the Large Magellanic Cloud novae (only two yielded grating spectra), but *EPIC* data were useful also for the other two objects. Before the launch of *Swift* in November of 2004, we had to rely on preliminary short observations done with the *Chandra* ACIS camera or with XMM-Newton (which uses all detectors - gratings included - simultaneously). However, Target of Opportunity (TOO) observations are not practical or easy to schedule with these satellites. Without preliminary measurements, a long exposure of nova

V1187 Sco was scheduled with the *Chandra* LETG, but turned out to produce no usable results. A TOO mission like *Swift* was needed to proceed to ensure the targets are bright enough for a long (> 3 hours) grating exposure. Today, after *XMM-Newton* and *Chandra* have worked together with *Swift* for several years, we have learned with precision when the SSS became observable in many novae, and an important sample were observed around peak luminosity in long exposures with the gratings. There often is a correlation between supersoft X-ray phase and Fe [X] forbidden line at 6375 Å in the optical spectra (Schwarz et al. 2011), but this was not known 13 years ago. In fact, even this optical emission line is not an absolute index, since it can also be due to shocked ejecta, so it is not a completely reliable diagnostic of the SSS observability. In short, having a systematic X-ray monitoring has revolutionized the scheduling of grating observations, making them really efficient because they were done at or around peak luminosity. Since a nova can increase in X-ray luminosity by a factor of 10,000 within few days, it is important to observe it at the right time. Fast recurrent novae (RN) are very X-ray luminous for only few weeks, as the Tables indicate.

For the sake of completeness I have also listed short *XMM-Newton* exposures of V598 Pup, and of Novae LMC 1995 and 2000, although no usable RGS spectra were collected, because the aim was to use the *EPIC* cameras, the RGS gratings would have detected exceptionally bright emission lines if they were emitted. Therefore we can rule out at least very prominent and broad emission lines in this set of novae observed at the given post-outburst time.

The second column in the Table reports the outburst date and the third the type (Classical nova, CN, versus RN). Because we want to correlate the X-ray data with other wavelengths, especially the optical, the fourth column groups together three parameters used to measure and evaluate the optical light curve: t_2 and t_3, the time for a decay by 2 and 3 magnitudes respectively, and a quality parameter defined by Strope et al. (2010): S for a smooth light curve, F for a flat-topped one (with a plateau), J for "jitter", O for the characteristic oscillations of some novae, and C for "cusp", or light curves with a secondary maximum. We do not have any J-type nova in our sample. t_2 and t_3 were obtained from Strope et al. (2010) for the Galactic novae, from Subramanian & Anupama (2002) for the LMC novae, or from AAVSO light curves for more recent novae. Columns 6, 7, 8 and 9 report the date and exposure times with *Chandra* and *XMM-Newton*, respectively. For Chandra, an L or an H in front of the exposure date indicate either the LETG or the HETG gratings. As we can see, all but one *Chandra* observations were done with the LETG, the low energy transmission grating (as opposed to the HETG, or high energy transmission gratings). The 10th column indicates the SSS turn off time if it could be measured with *ROSAT* or more often, with *Swift*. Finally, we indicate the effective temperature $T_{\rm eff}$ measured by fitting atmospheric models in column 11. The measured $T_{\rm eff}$ in the grating spectra is mostly high, in the 650,000 - one million K range. This is mostly because of a selection effect. *Swift* is essentially a TOO mission, and TOO observations are easier to obtain and to schedule when they are done in the same month and for an object that immediately proves to be very luminous (and/or very variable). In fact, for the relatively cool and slow N LMC 1995 we have only broad band data, and the only "less hot" nova with a peak $T_{\rm eff}$ measurement is GQ Mus, observed in the *ROSAT* time.

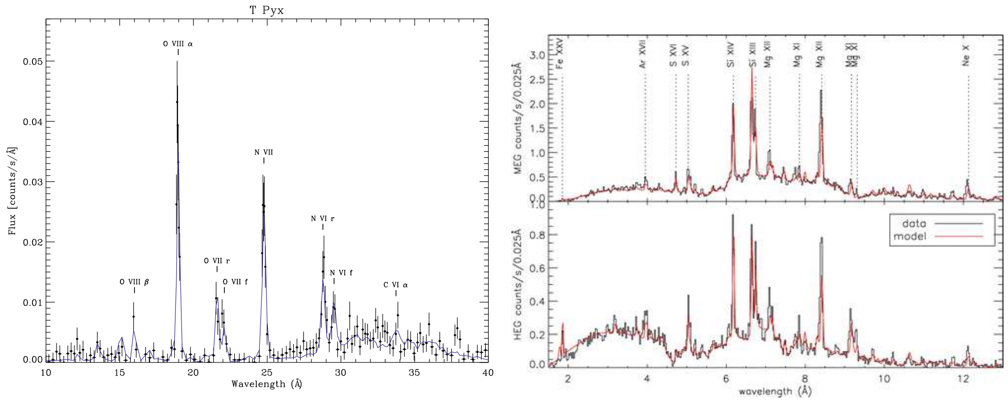

Figure 1. Novae spectra dominated by emission-lines (*e* type in the Table) : LETG spectrum of T Pyx in October of 2011 (2a, left) and HEG and MEG spectra of RS Oph in February of 2006 (2b, right), with collisional ionization models. RS Oph was observed with the LETG in April of the same year and a luminous atmosphere was detected, with only few residual emission lines in the soft range.

Quality parameter for the X-ray light curve and one for the spectrum are presented in the last two columns. For the X-ray light curve (XLC), “f” indicates that flares were observed, “p” and “sp” periodic and semi periodic oscillations, and “o” an obscuration or sudden dimming of the source.

I would like to start the next Section referring to the very last column (12) in the Table, XRS indicates the attribute given to the X-ray spectrum. A broad classification shows that there are three classes of X-ray spectra, those in which the continuum and absorption features of the WD are dominant (“b” for bright), those in which broad and strong emission lines in the ejecta are dominant and the continuum is hardly measurable with the gratings (“e” for emission), and the hybrid ones “b” where the two components appear equally important. If no parameter is listed in this column, no usable grating spectrum was obtained. In some cases, the same nova transitions between these states during the outburst (e.g. RS Oph, N LMC 2009).

4. The unexpected emission lines

Although the X-ray emission in the ejecta seemed to be known as a fact by the time the X-ray grating observations started in May of 1999, the spectra obtained for the first two novae, V382 Vel and V1494 Aql, of the “e” type, were quite surprising. It became suddenly clear that the so-defined “thermal bremsstrahlung” continuum in other novae (e.g. Orio et al. 1995; Balman et al. 1998) was not a continuum, but there were many unresolved strong and broad emission lines.

Orio et al. had already obtained broad band spectra of V382 Vel with *BeppoSAX*, (published in 2002), probably shortly after the SSS maximum. Although the nova was a luminous SSS, it was obvious that the continuum departed so much from atmospheric models that other components were present and even emitted conspicuous flux. In two and a half months intervening until the first *Chandra* LETG grating observation could be scheduled, this emission "component" was dominating. The WD was much less luminous as an SSS, having started to turn off, with $T_{\rm eff} <$ 300,000 K. It displayed many emission lines, due to hydrogen-like and helium-like transitions of Si, Mg, Ne, O, N and C in the 6-50 Å range. Iron lines were completely missing. All the lines had broad profiles with full width at half maximum corresponding to about 2900 km s^{-1}, and a few had a complex structure, to be fitted with at least two Gaussians (Ness et al. 2005). Altogether, all this is rather typical of other novae, as well (see Fig. 1).

In observations of V1494 Aql seven months later, the emission lines were very dominant again, although there was a non-negligible continuum level. A complete analysis for this nova appeared only later, in a paper by Rohrbach et al. in 2009. Emission lines were observed this time in the 16-34 Å range, and although the authors could fit a comprehensive model, they noted that at least the O VII Lyman-alpha line can only be explained with collisional ionization, because an upper limit to the temperature of the central WD is around 200,000 K. The authors favored however a combination of collisional and photo-ionization to explain the rest of the spectrum.

It was not until the 2003 observations of V4743 Sgr that the luminous SSS WD could really be studied in great detail. For this nova however, a sudden obscuration of the WD during the first observation revealed a low level emission line spectrum that was superimposed on the WD atmosphere. Emission lines thus always exist in the X-range for novae. Some grating spectra (HV Cet, V5156 Sgr, U Sco) that we classify as "be" show a measurable continuum and at the same time very strong emission lines, making the fit with composite models accounting for both the WD atmosphere and the ejecta quite challenging. For U Sco, collisional ionization in a dense and clumpy medium has been invoked to explain the line ratios of the observed triplets (Orio et al. 2012a). The emission lines seem to be produced in condensations of very dense material.

For some objects, fortunately, the emission lines are less strong and the continuum more luminous, so the WD can be better studied. T Pyx, observed in an eruption at the end of 2011 (see Fig. 1, left panel), is another nova for which strong emission lines were detected, and only an upper limit can be given for the T_e of the central source, about 200,000 K (Tofflemire et al. 2012). There never was very luminous period during the complete *Swift* coverage of T Pyx, and a large part of the SSS flux seems to have always been in line emission. The T Pyx gratings spectra are consistent with the "low" effective temperature of a small mass WD, and (mostly) with a collisional ionization mechanism of emission line formation. Yet, T Pyx is a RN, where high mass and effective temperature are expected, since the envelope pressure for an outburst is frequently reached.

The most surprising emission line spectrum ever observed is the one of RS Oph shortly after the outburst, when also the *Chandra* HETG gratings were used (Fig. 1, right panel, from Nelson et al., 2008), in addition to the RGS. For this nova the emission lines were in a very hard range in the first month after the outburst. It was already known that the nova ejecta collide with the circumstellar material of the red giant wind in the RS Oph binary system, yet this hard spectrum, certainly a proof of violent shocks, was surprising. This spectrum evolved and disappeared

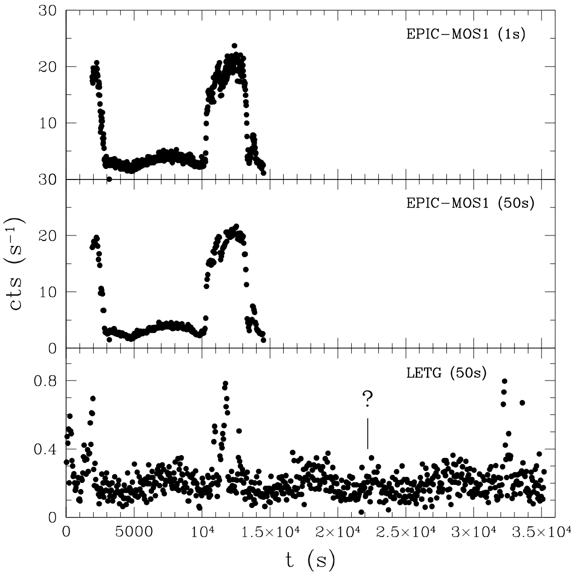

Figure 2. The upper and middle panel show the EPIC-MOS-1 light curve observed for V5116 Sgr plotted with bins of 1 and 50 s, respectively. This observation was described by Sala et al. (2008). The bottom panel shows the *Chandra* + HRC-S detector and LETG grating light curve, done 5 and a half months later. This observation was longer and covered four orbital cycles. In three out of four orbital cycles the flaring behavior was clearly observed. Note that the amplitude of the flare, however, significantly decreased in the *Chandra* observations (plot from Bianchini & Orio 2012b, in preparation).

quickly. Four months later, after the SSS had became bright and turned off, the RS Oph spectrum was similar to the one of T Pyx (Fig. 1, left).

5. Wild variability after the outburst

Before proceeding with the analysis of what has been learn thanks to the SSS spectra, it is important to review the short term variability of the post-nova SSS. The exceptional variability of post-novae WD was apparent already after the second X-ray observation done with a grating. Exposure times with previous satellites were of the order of 1-3 hours for pointed observations with CCD-type detectors, and exposures were only a few minutes long during the *ROSAT* All-Sky-Survey. The need to expose for longer than previously done with broad band detectors, in order to obtain a reasonable signal-to-noise with the X-ray gratings, implies also that variability phenomena are easier to detect. Generally, the variability seems more common in the first weeks after the SSS turns on, and it is quite clear that it has several different root causes. The observed phenomena are periodic, quasi-periodic and periodic, on time scales from tens of seconds to many hours. I will attempt to classify these phenomena as follows:

1. *Orbital variability*. Modulations of the soft X-ray flux with the orbital period were already observed with *ROSAT* for GQ Mus (Kahabka 1996) and possibly N LMC 1995 (Orio et al. 2003). they have been more recently measured in X-ray gratings exposures for V4743 Sgr (Leibowitz et al. 2006), U Sco (Ness et al. 2012; Orio et al. 2012a) and T Pyx (Tofflemire et al. 2012). The modulation is associated with the central source for U Sco (the emission lines were unvaried), but there is also modulation of the emission lines in T Pyx. Another SSS nova, HV Cet, was observed with *Swift* to have a 1.77 days orbital modulation (Beardmore et al. 2010; this orbital period was too long to be observed with the *Chandra* exposure).

2. *Periodic or quasi-periodic variability* with a period (or quasi-period) in the range of seconds and tens of minutes. The fastest oscillations were observed for RS Oph and KT Eri (≃35 s in both cases). For RS Oph the period was not stable and changed from day to day, but the last long *Chandra* observation and *Swift* observations during the plateau of the SSS phase show that the period became stable over several days before disappearing (Leibowitz et al. 2012, unpublished). Leibowitz et al. (a project in which the author is involved) are proposing that this is the rotation period of the WD in RS Oph, and that the initially apparently "unstable" period is due to the collimated outflows (observed at radio wavelength, Eyres et al. 2009): the jet may have been precessing as it left the WD polar caps' surface and was hot, still emitting super-soft X-rays. This precession scenario fits the data quite well. Some of our colleagues have criticized this explanation as too speculative, but other explanations are difficult to devise, unless the oscillation is still associated with the WD spin. Indeed, theoretical predictions by Yoon & Langer (e.g 2005 paper) foresee a rapidly rotating, with periods of order of a minute for a WD spun up by high accretion rate (as is the case for KT Eri and RS Oph).

A much longer oscillation lasting ≃41.7 min was observed in V1494 Aql with *Chandra*, several periods of tens of minutes were measured for V4743 Sgr, and a 37.2 min period for V2491 Cyg (Ness et al. 2011). These may be better explained with non-radial g-mode pulsations of the hot WD. However, there is no theoretical model for these pulsations. They may be associated with iron ionization, but not with ionization of other elements as in "cold", non-accreting WD. A number of side-frequencies observed in V1494 Aql and V4743 Sgr seems to support this explanation. Things are a little more complex however, since one of the periods of V4743 Sgr is observed until and during quiescence and at optical wavelengths, and seems to be the spin period of the WD (Leibowitz et al. 2006; Dobrotka & Ness 2010). V1494 Cyg, V4743 Sgr, and V2491 Cyg are all thought to be intermediate polars (IP) also for other, independent reasons.

On the other hand, U Sco is not an IP and it and a semi-regular oscillation with a period of about half an hour in the first *XMM-Newton* exposure is explained by Ness et al. (2012) with dense clumps of material that fall in the newly re-established accretion disk. We have suggested that this could be the disk rotation period (Orio et al. 2012a).

3. *A sudden dimming or obscuration of the WD*. The most dramatic case is V4743 Sgr in the first *Chandra* observation, in which after several hours of observations of the SSS, the central source suddenly disappeared within few hours. Two weeks later, when *XMM-Newton* pointed at the nova, the SSS was luminous again and there was not any new obscuration in this

and several successive observations. This phenomenon may be explained with a sudden shell of material that leaves the WD surface and is optically thick to supersoft X-rays. If this is the correct interpretation, the nova outflow is not always smooth and continuous, but rather episodic.

4. *A large and sudden flare* lasting for about 1000 s was observed for V1494 Aql (Drake et al. 2003). A very similar, *periodic* flare almost at each orbital period was observed for V5116 Sgr with *XMM-Newton* (Sala et al. 2008) and months later with *Chandra* by the PI, albeit with much lower amplitude (see Fig. 2). Although Sala et al. have proposed an explanation in terms of a warped, truncated disk, it is difficult to imagine how such a disk could have been stable for months, and why the rise occurs within only few minutes. I suggest that the root cause may be a non completely thermalized atmosphere in a magnetic system, an intermediate polar or polar nova where the polar caps were much hotter than the rest of the surface at the time of the outburst. This does not rule out that the thermonuclear flash propagated evenly in the bottom layers of the envelope.

6. The WD spectrum

In most novae, we have observed a very strong continuum and at least resonance absorption lines of the two highest ionization stages of C, N, and O. Fitting and interpreting the WD spectrum is clearly hindered by the superimposed emission lines, which in some cases make it difficult to trace the continuum shape. The "wild variability" described above is another problem. Good quality time resolved spectra over the variability time scales can only be obtained at times, especially of repeated cycles were observed. The ≃35 s oscillations of RS Oph and KT Eri are too short to extract a spectrum, at the peak of oscillations, for instance. For U Sco, phase resolved spectra could be extracted, demonstrating significant variation of the emission lines over the orbital period or along the oscillations of the second observations (Ness et al. 2012; Orio et al. 2012a). Ideally, long grating exposures are desirable, especially at the onset of the SSS phase, when it is almost certain that some type of variability will be observed.

Another interesting complication is the possibility, especially at high inclination, that the WD is actually not observed because the accretion disk has already been rebuilt. In U Sco, for instance, optical observations indicate a disk already two weeks after the outburst. However, a Thomson scattering corona makes a "reflected" continuum observable. In these cases, like for Cal 87 (Orio et al. 2003), the total bolometric luminosity phase is only a small fraction of the near Eddington luminosity of objects like RS Oph or V4743 Sgr, and is clearly not consistent with $T_{\rm eff}$, if this can be derived, and with the radius obtained from the effective gravity g. For U Sco, only about 30% of the WD continuum was observed to be eclipsed by the secondary. The rest of the SSS flux comes from a more extended area than the orbital separation. Initially the broad absorption features were not embedded in the extremely broad emission lines. It was concluded by two different groups (Ness et al. 2012, Orio et al. 2012a) that about 70% of the flux is emitted by a surface with a large radius, a Thomson scattering corona. Although Thomson scattering is not wavelength dependent, it may smear the absorption features, depending on the geometry of the system. Model fitting may thus become more difficult and less reliable.

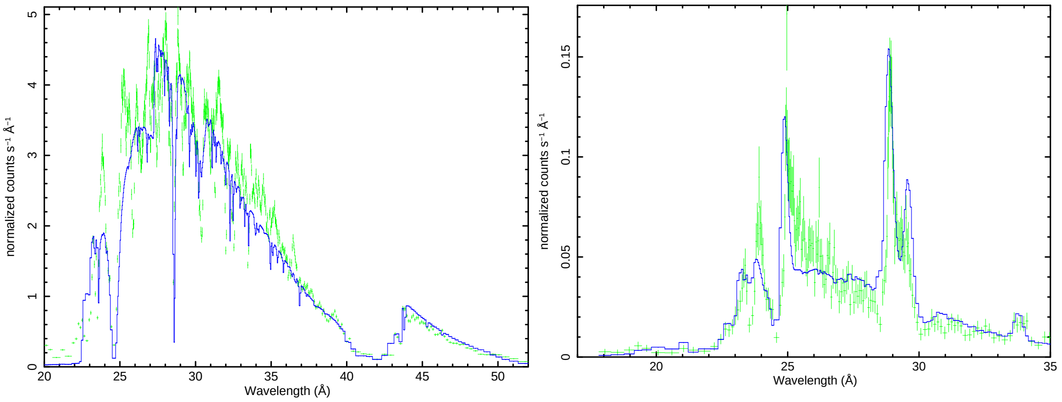

Figure 3. *Chandra* LETG grating spectra of novae in the luminous WD phase: V4743 Sgr ("b" type) in March of 2003 (left panel), and U Sco ("be" type) in February of 2010 (right panel). The U Sco spectrum is in green, the fit with a model in blue. We show an atmospheric model at 700,000 K for V 4743 Sgr, and an atmospheric model+collisional ionization for U Sco. Note the different strength of the emission lines relative to the continuum in the two novae, and that some emission lines are still unidentified.

Given the much higher X-ray flux measured for the other novae in the SSS phase, it seems that cases like Cal 87 or U Sco are relatively rare. However, it has been argued that the main complication in understanding nova spectra is the large blue shift of the absorption features observed in some spectra, most notably V4743 Sgr (Rauch et al. 2010), V2491 Cyg (Ness et al. 2011) and U Sco (Orio et al. 2012a). The group of Ness et al. (e.g., 2011 paper) has repeatedly argued that no hydrostatic atmospheric models can give reliable results because a wind is still flowing from the the central SSS. Their reasoning is that this SSS cannot be the WD itself. My objection is that: a) The "moving lines" were observed to be extremely similar (except for the blue-shift) to other cases in which the absorption lines were instead observed at zero velocity, e.g. RS Oph. This seems to demonstrate that the wind must really be at the base of the atmosphere, still reflecting its characteristics, and b) Both blackbody or atmospheric model yields such high temperature that the SSS must be extremely compact, or else it would be much above Eddington luminosity. Not surprisingly, atmospheric models often yield a log(g)=9 and masses above 1.2 $M_{\odot}$.

It turns out that the observed novae were mostly chosen as targets because *Swift* had discovered the SSS phase. This is extremely helpful, but it also carries a strong bias towards fast novae. Not even *Swift* will keep on monitoring a nova every week, if not every day, for many years. A nova on a non-massive WD, whose ejecta are also more massive, becomes optically thin to the SSS after years, possibly only shortly before the SSS turns off, and will be missed. Not surprisingly, we mostly derived very high $T_{\rm eff}$ novae in our sample in Tables 1 and 2, which thus is clearly biased.

Atmospheric models for the hottest, hydrogen burning WD have long been known to yield fits with higher $T_{\rm eff}$ and lower luminosity than blackbodies, because a realistic atmosphere always departs from a simple blackbody approximation (Heise et al. 1994). After initial work by

Table 1. Galactic novae in outburst observed with X-ray gratings, including XLC=observed optical maximum date, the type (classical or recurrent), optical light curve parameters t_2, t_3 and Strope quality parameter (see text), time of Chandra or XMM-Newton observation with exposure time in kiloseconds, time for the SSS turn-off, WD effective temperature, XLC or X-ray variability parameter (f for flare, o for occultation, p for periodic, sp for semi-periodic, po=periodic with orbital period), and XRS, type of X-ray spectrum (e=emission lines, b= dominated by very bright white dwarf, be=hybrid, no=no results. The atmospheric fits were done by the author (see also references).

1 Nova	2 Max. (date)	3 Type	4 LC	5 Chandra (date)	6 exp. ksec	7 XMM-Newton (date)	8 exp. ksec	9 t.off months	10 T 10^3 K	11 XLC	12 XRS
V382 Vel (1,2)	5-22-99	CN	6,13,S	L 3-2-01	24.5			7±1	≥400	o	e
V1494 Aql (3,4)	12-3-99	CN	8,16,O	L 9-28-00	8.1			19.17±7.05		f	e
				L 10-1-01	18.2						e
				L 11-28-01	25.8						no
V4743 Sgr(5,6,7)	9-20-02	CN	6,12,S	L 3-19-03	25			20.5±3.5	740±70	o,p	b
						4-4-03	35.6				b
				L 3-24-06	10					sp	b
						4-7-06	18.6			sp	b
				L 7-18-03	12					sp	b
				L 9-25-03	12					sp	b
						9-30-03	22.5			sp	b
				L 2-28-04	10					sp	b
V5116 Sgr (8,9)	7-4-05	CN	12,26,S			3-5-07	13	34.5±3.5	700±100	f,p	b
				L 8-24-07	12					f,p	b
RS Oph (10,11)	2-12-06	RN	7,20,S	H 2-26-06	10	2-26-06	23.8	3.25±0.25	800±50		e
						3-10-06	11			f,sp	be
				L 3-24-06	10					o, sp	b
						4-7-06	18.6			sp	b

Table 1. Continued.

1	2	3	4	5	6	7	8	9	10	11	12
Nova	Max.	Type	LC	Chandra	exp.	XMM-Newton	exp.	t.off	T	XLC	XRS
	(date)			(date)	ksec	(date)	ksec	months	10^3 K		
				L 4-20-06	9					p	b
				L 6-4-06	20						e
						9-7-06	10				e
				L 9-7-06	40						e
				L 10-9-06	40						e
						10-9-06	48.7				
V598 Pup (12)	6-4-07	CN				10-29-07	5.1				
V2491 (13) Cyg	4-10-08	RN?	4,16,C			5-20-08	39.3	1.47	1000±100	o,p	b
						5-30-08	30				b
HV Cet (14,15)	10-7-08	CN		L 12-18-08	35			3.5±1	750±100		be
KT Eri	11-14-09	CN	15,28,S	01-23-10	15			9.5	650±150	sp	b
				01-31-10	5.2						
				02-26-10	5.2						
				04-21-10	5.2						
U Sco (16.17)	1-28-10	RN	1.2,2.6,S	L 2-14-10	23		7	1.67	950±100		be
						2-19-10	64			po,sp	be
						3-13-10	63			po	be
T Pyx (18)	4-14-11	RN	32,62,P	L 3-11-11	40					p	e
						11-28-11	30			p	e

1. Orio et al. 2002, 2. Ness et al. 2005, 3. Drake et al. 2003, 4. Rohrbach et al. 2009, 5. Ness et al. 2003, 6. Leibowitz et al. 2006, 7. Rauch et al. 2010, 8. Sala et al. 2008, 9. Nelson & Orio 2009, 10. Nelson et al. 2008, 11. Ness et al. 2007, 12. Page et al. 2009 13. Ness et al. 2011, 14. Sala et al. 2006, 15. Nelson & Orio 2007, 16. Orio et al. 2012a, 17. Ness et al. 2012, 18. Tofflemire et al. 2012

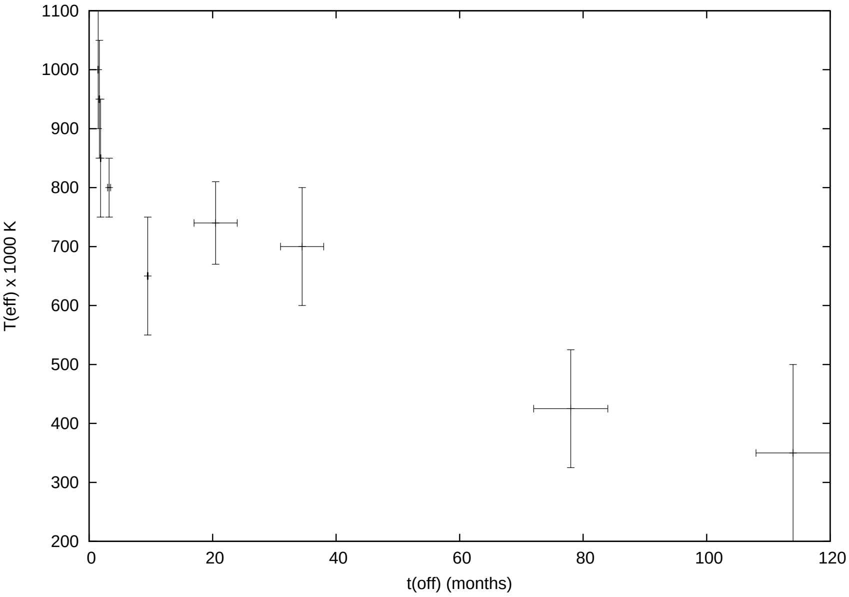

Figure 4. Turn off time versus peak effective temperature *measured with atmospheric models*. The two last data points on the right indicate measurements made with broad band detectors.

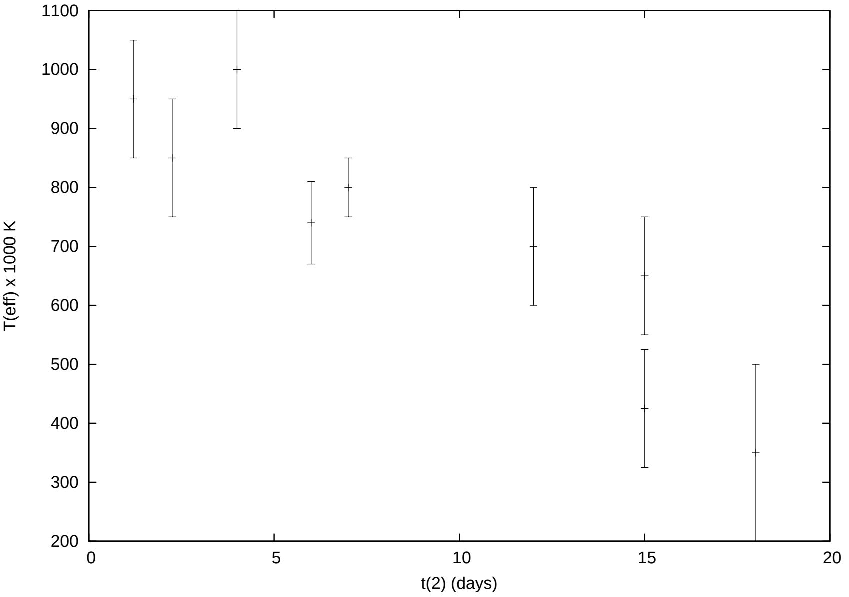

Figure 5. Optically measured t_2 versus peak effective temperature *measured with atmospheric models*. The two last data points on the right indicate measurements made with broad band detectors.

Table 2. Magellanic Clouds novae observed with X-ray gratings, including OLC observed optical maximum date, type (classical or recurrent), optical light curve parameters t_2, t_3 and Strope quality parameter (see text), time of Chandra or XMM-Newton observation with exposure time in kiloseconds, time for the SSS turn-off, WD effective temperature, XLC or X-ray variability parameter (f for flare, o for occultation, p for periodic, sp for semi-periodic, po for periodic with orbital period), and XLS or type of X-ray spectrum.

1	2	3	4	5	6	7	8	9	10	11	12
Nova	Max.	Type	LC	Chandra	exp.	XMM-Newton	exp.	t.off	T	XLC	XRS
	date			date	ksec	date	ksec	months	10^3 K		
N LMC 1995 (19,20)		CN	15,23					78±6	425±100	p?	
N LMC 2000 (21)		CN	(),17					9.8±4			
N LMC 2009	2-5-09	RN				5-6p-09	37.6	10			be
						7-20-09	58				b
						8-20-09	32				b
						9-23-09	51				b
N LMC 2012	3-26-12	RN	2.25, 4.15	L 4-26-12	20.2			1.87	850±80		b

19. Orio et al. 1998, 20. Orio et al. 2005, 21. Greiner et al. 2004

Hartmann (e.g. Orio et al. 2003 and references therein), remarkably complex non-LTE models have been calculated by Lanz et al. (2005) and by Rauch et al. (2010). Rauch has made his models publicly available, and even Ness et al. (2011), despite their objections to a non-dynamical mode, remark that the fit to the V2491 Cyg spectrum is really quite good. I argue that non-LTE model atmospheres give a physically significant qualitative agreement with the observed spectra even when a velocity field is present, and should be used. Rauch et al. employ plane-parallel, static models calculated with the TMAP10 code (Werner et al. 2003). Opacities of elements H, He, C, N, O, Ne, Mg, Si, S, and Ca-Ni are included. The grid of available models has been studied for V4743 Sgr and U Sco (see eg. Fig. 3), and in principle new models should be developed for each nova to really obtain a good fit, even if it is a heavy "numerical task".

A recent attempt to explain the V2491 Cyg absorption spectrum has been done by Pinto et al. (2012). The authors adopt a blackbody for the continuum, and assume that its spectrum is absorbed by three different ionized absorbing shells. The absorption includes dust and is different for every shell. Even if it is worth exploring how mass ejection may have been discrete, and it is important also to implement realistic opacities, it seems almost a wasted effort because the extremely luminous central source is modeled with a blackbody, neglecting the deep and strong absorption features of the central source itself. Whatever absorption lines may be produced in the ejecta, must be superimposed on the WD ones. Altogether, Pinto et al. (2012) present an interesting model, but there are many ad hoc assumption. A weak point is this: Why are no emission features observed in V2491 Cyg that correspond to the absorption ones? Red-shifted emission causing a P Cyg profile is observed in the optical spectra of novae and lasts always longer than the absorption, coming from a larger volume; in other novae X-ray emission lines attributed to collisional ionization are observed, but not in V2491 Cyg. The ejecta of V2491 had reached a distance that was overwhelmingly large compared with the WD radius when the observations were made, more than a month after the eruption - it seems difficult not to observe the corresponding emission. The authors hypothesize a possible large asymmetry in the shell. In short, in addition to not giving a better spectral fit than model atmospheres, the model by Pinto et al. (2012) is not self consistent yet and makes many assumptions. We cannot rule out that some absorption features may be formed in a thin shell in the ejecta as in the model, but certainly they would not appear as broad as in U Sco, for instance.

Even if Lanz et al. (2005) note that the perfect atmospheric model for a hot, hydrogen burning WD cannot be calculated yet for deficiencies in the atomic data, I already see a remarkable strength of the model atmospheres: their agreement with the observed spectra, and their test of the theoretical models. This test can be seen in Figs 4 and 5. The correlation of WD $T_{\rm eff}$ with SSS turn-off time and with t_2, a parameter obtained form the nova speed class and is also correlated with $m_{\rm WD}$, are quite good. These plots clearly demonstrate the theory's predictions, that the fastest novae are also the most massive, if we assume that $T_{\rm eff}$ is a proxy for the WD mass $M_{\rm WD}$. Of course, a spread is expected in this relationship, due to the other important parameters in determining the post-outburst evolution: mass transfer rate $\dot{m}$, initial $T_{\rm eff}$ of the WD and its chemical composition, the first being often the most dominant. Note that in the figures, I added the *ROSAT* source GQ Mus at the low temperature end (in 1993 it was fitted with an early, less complete model atmosphere, courtesy of J. Mac Donald). I would like to point out that here the definition of the SSS and its turn-off is different from Schwarz's et al. (2011). My definition is based on spectral fits of objects having $T_{\rm eff}$>200,000 K; it is more rigorous and physics based than definition based on hardness ratio. Schwarz et al. include many more low luminosity objects, where there are no statistics or spectral resolution to rule out that we are observing an emission line spectrum and no SSS at all. The luminosity of some of these novae appears too low to be due to the central WD.

7. Conclusions: What are we learning?

Cecilia Payne Gaposchkin presented and reviewed optical light curves and spectra of classical and recurrent novae in her book "The Galactic Novae", which is still fascinating to read for the nova expert. X-ray light curves and spectra are revealing a similar wealth of complex phenomena, and it is taking years to analyse them. For each X-ray grating observations, more than one paper has appeared, and mostly these papers have taken a while to complete, they were not immediately published.

The emission lines spectra of novae are demonstrating the complex physics of the mass outflows. Collisional ionization seems common in nova shells, and the ejecta are far from being homogeneous, they are rather clumpy. Mass seems be lost at times in "parcels" or discrete shells. There are still several unidentified emission lines. Most of them are listed by Ness et al. (2011) and are common to more than one nova.

The X-ray light curves tell us about the resuming of accretion, the WD pulsations and underlying phenomena, the WD rotation, inhomogeneities in the atmosphere, and sometimes about mass loss itself.

The WD spectra were the most awaited, and they are challenging to analyse for the difficulties underlined in the previous section. However, Figs 4 and 5 clearly show that we have come a long way. The theories can be tested by assuming that $T_{\rm eff}$ is basically a proxy for $m_{\rm WD}$, and the correlation of $m_{\rm WD}$ with optical speed class and turn-off time (as indication of the accreted envelope mass) is exactly as expected.

I would like to conclude with an analysis of how we have started to answer the questions in Section 2.

1. So far, X-ray gratings' absorption spectra have shown signatures of a NeO WD only for V2491 Cyg (Pinto et al. 2012). The possibility of detecting these signatures is very interesting, because enhanced Ne, O or Mg in the ejecta may be due to mixing with traces of these elements in the WD superior layers, or with the secondary. The ejecta composition is not necessarily the same as the underlying WD core, although mixing with the core occurs. It is important to probe the WD abundances directly. There is another interesting possibility to indirectly explore the WD composition, namely through nucleosynthesis of peculiar elements. Only mixing with Ne and Mg can produce side reactions of the CNO cycle that synthesize Ar and Cl. Traces of these elements

have been found in the optical spectra of some novae, and we detected transient Ar and Cl lines in a small soft flare that RS Oph showed at the very beginning of the SSS phase, in the *XMM-Newton* observation of March 10 of 2006 (Orio et al. 2012b, in preparation). Unfortunately, exact Ar and Cl overabundances in NeO novae depend on the uncertain 30P(p,g) reaction (Iliadis et al. 1995). It would be important, after many years, to determine this reaction rate accurately (this is our special request from the nuclear physicists.

2. For RS Oph and V4843 Sgr, the WD analysis through spectral elements shows a very large N/C ratio, typical of CNO ashes (Nelson et al. 2008, Rauch et al. 2010). This high ratio cannot be obtained if the nova is newly accreting or if its burning eroded WD material, so this is a proof of mass accretion over the secular evolution, despite the mass loss in the nova eruptions.

3. The measured $T_{\rm eff}$ is consistent with the models' predictions, and Figs 4 and 5 prove that the basic trends predicted by the models are verified. However, it would be important to explore a larger parameters' space, with more moderately slow and slow novae. Once a statistically significant number of novae are observed, the spread in linear $T_{\rm eff}$ versus turn-off and $T_{\rm eff}$ versus t_2 relationships will indicate the range of variations of $\dot{m}$ and WD temperature and chemical composition at the onset of burning. Thus, completing these plots is essential for the theories, and CCD-type instruments do not measure the absorption features, important for an accurate $T_{\rm eff}$ estimate.

4. The hottest WD that we have observed with the gratings thanks to *Swift* monitoring, must be very compact, with log(g) around 9, or else the luminosity would be above the Eddington level.

5. The emission line spectrum observed for RS Oph after other signatures of mass loss ceased, in June and September of 2006, seems to indicate is a residual wind for some time after the main eruption.

I would like to conclude with the predictions that acquiring more high resolution spectra of novae in outburst will not only improve the statistics, but also throw new light on the data we already have.

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