Classical nova explosions

Margarita Hernanz

Institut d’Estudis Espacials de Catalunya (CSIC), Campus Universitat Autònoma de Barcelona, Facultat de Ciències, Torre C5-parell, 2ª planta. E-08193 Bellaterra (Barcelona), Spain

Abstract. A review of the present status of nova modeling is made, with a special emphasis on some specific aspects. What are the main nucleosynthetic products of the explosion and how do they depend on the white dwarf properties (e.g. mass, chemical composition: CO or ONe)? What’s the imprint of nova nucleosynthesis on meteoritic presolar grains? How can gamma rays, if observed with present or future instruments onboard satellites, constrain nova models through their nucleosynthesis? What have we learned about the turnoff of classical novae from observation with past and present X-ray observatories? And last but not least, what are the most critical issues concerning nova modeling (e.g. ejected masses, mixing mechanism between core and envelope)?

1. Introduction

Classical novae are explosions occurring on top of white dwarfs in close binary systems of the cataclysmic variable type. Transfer of hydrogen-rich matter from the main sequence star to the white dwarf is the driver of the explosion, provided that the white dwarf is massive enough and that the mass accretion rate is sufficiently low. In these conditions, matter accumulates on top of the white dwarf until it reaches hydrogen ignition conditions, with a pressure such that matter is degenerate. This leads to a thermonuclear runaway because self adjustment of the envelope once nuclear burning starts is not possible.

The general scenario for nova explosions thus seems quite well understood, but there are still many open issues concerning the initial conditions leading to the explosion (e.g. need of mixing between core and envelope material) and some observed properties of the outburst (e.g. amount of mass ejected or velocity distribution in the ejecta).

In this paper some of the basic observational properties of novae are first reviewed. Then the general scenario for nova explosions based on hydrogen thermonuclear runaway is outlined, paying special attention to the influence of the properties of the underlying white dwarf (e.g. mass and chemical composition). The relevance of nucleosynthesis in classical novae (e.g. chemical evolution of the Galaxy, understanding of isotopic ratios in some meteoritic presolar grains) is then analyzed, as well as the potential of gamma-rays to reveal the nuclear processes taking place during nova outbursts. A snapshot of the link between the nova outburst and its cataclysmic variable host as revealed by recent X-ray observations of novae is finally presented, followed by a (partial) list of the still open issues in nova modeling.
2. Basic observational properties of novae

Classical novae are in general discovered by amateur astronomers, looking at the sky to search for variabilities in stars. An histogram of the number of nova discoveries in the last century (period 1900-1995) is displayed in figure 1 based on data from [Shafter (1997)], with a zoom of the most recent data, 1991-1995 (histograms versus apparent visual magnitude at maximum and distance are also shown in figures 2 and 3). Even if the dataset is not absolutely complete, it can be seen that at most 5 novae are discovered every year in our Galaxy. This number is far from the total number of novae estimated to explode in the Milky Way, based either on extrapolation from galactic data ([Hatano et al. 1997; Shafter 1997]) or scalings from extragalactic nova surveys ([Della Valle & Livio 1994; Shafter, Ciardullo, & Pritchet 2000]): rates based on extrapolations, 15-24 yr⁻¹ or 27±8 yr⁻¹, tend to be smaller than those based on galactic data, 35±11 yr⁻¹ or 41±20 yr⁻¹ (a recent review of the Galactic nova rate can be found in [Shafter 2002]).

The optical light curves of classical novae show that there is an increase in luminosity which corresponds to a decrease of $m_V$ (apparent visual magnitude) of more than 9 magnitudes occurring in a few days, with a pre-maximum halt, 2 magnitudes before maximum, in some cases (see [Warner 1995], and references therein). Nova light curves are classified according to their speed class, defined from either $t_2$ or $t_3$, which is the time needed to decay by 2 or 3 visual magnitudes after maximum. Speed classes range from very fast ($t_2 < 10$ days) and fast ($t_2 \sim 11 - 25$ days) to very slow ($t_2 \sim 151 - 250$ days) ([Payne-Gaposchkin 1957]). Some examples are the fast nova N Cyg 1992, which had $t_2 \sim 12$ days, the even faster nova N Her 1991 ($t_2 \sim 2$ days), and the slow nova N Cas 1993, which had $t_2 \sim 100$ days.
Here I would like to emphasize the essential role played in the compilation of nova light curves by amateur astronomers and, particularly, the AAVSO, under the enthusiastic and extremely competent leadership of the late Janet Mattei, to whom this cataclysmic variable conference has been dedicated.

There is a relationship between the absolute magnitude at maximum $M_V$ and the speed class of novae: brighter novae have shorter decay times ($t_2$ or $t_3$). The theoretical explanation of this relationship (Livio 1992) is based on the widely accepted model of nova explosions, which states that novae reach a maximum luminosity close to the Eddington luminosity and that they should eject roughly all their envelope in a time similar to $t_3$. Therefore, it can be established that $L_{\text{max}}$ is an increasing function of $M_{\text{wd}}$ and that $t_3$ is a decreasing function of $M_{\text{wd}}$. From these two relationships an expression relating $M_V$ at maximum and $t_3$ is deduced. This empirical relation, valid both in the $V$ and $B$ photometric bands, is very often used to determine distances to novae, once visual extinction is known (see figure 4). Different calibrations of the maximum magnitude-rate of decline relationship (MMRD) exist, with that from Della Valle & Livio (1995) being the most usual one (see also Shafter 1997).

Astronomical satellites like IUE (International Ultraviolet Explorer), allowed for an extension of the light curves to further energy ranges besides the optical. It was discovered from IUE observations that the luminosity in the ultraviolet band increased when the optical one started to decline: the reason is that the energy distribution shifts to higher energies, since deeper and hotter regions of the expanding envelope are seen (the photosphere recedes as a consequence of the decreasing opacity when temperature falls below $10^4$K, the hydrogen recombination temperature). Infrared observations (when available, i.e. for novae which form dust) indicate an increase in luminosity once the ultraviolet luminosity starts to decline, which is interpreted as the resulting re-
radiation (in the infrared) by dust grains of the ultraviolet energy they have absorbed. In summary, the bolometric luminosity of classical novae is constant for quite a long period of time, being the duration of this constant $L_{\text{bol}}$ phase dependent on the remaining envelope mass of the nova. The phase of constant $L_{\text{bol}}$ corresponds to hydrostatic hydrogen burning in the remaining envelope of the nova, accompanied by continuous mass-loss, probably due to an optically thick wind [Kato & Hachisu 1994]. Since the bolometric luminosity deduced from observations is close to or even larger than the Eddington luminosity, radiation pressure is probably the main responsible for ejection of nova envelopes. An additional observational proof of this phase has come from the observations in the soft X-ray range ([Krautter et al. 1996; Balman, Krautter, & Ögelman 1998; Orio, Covington, & Ögelman 2001]), which directly reveal the remaining nuclear burning shell on top of the white dwarf after its nova explosion.

Coming back to the problem of the galactic nova rate, it is worth reminding that it cannot be disentangled from the fact that there are two distinct nova populations: disk novae, which are in general fast and bright ($M_V(\text{max}) \approx -8$), and bulge novae, slower and dimmer ($M_V(\text{max}) \approx -7$). This was first suggested by Della Valle et al. [1992] and later corroborated by the classification of novae in two classes according to their early post-outburst spectra [Williams 1992] and based on the stronger group of emission lines they display (either Fe II lines or He and N lines); FeII-type novae evolve more slowly and have a lower level of ionization, whereas He/N-type novae have larger expansion velocities and a higher level of ionization. It has been deduced that the faster and brighter He/N novae are concentrated closer to the galactic plane than the slower and dimmer Fe-II ones, which would preferentially belong to the bulge (Della Valle & Livio 1998; see Della Valle 2002 for a recent review).
In fact, nova spectra are rather complicated and not well understood from the theoretical point of view. A recent paper by Cassatella et al. (2004) makes an excellent analysis of IUE archival high resolution spectra of nova Cygni 1992. The complex behavior of the various lines at different epochs after the outburst requires a complex interpretation. We summarize the results of Cassatella et al. (2004) here just to show that the complexity of the observed features leads to an empirical model based on various mass loss phases, which is not yet well accounted for in the thermonuclear runaway nova models described below; so observations are still far ahead from models in this case. In the earliest days there is an optically thick high velocity wind with decreasing mass loss rate as time elapses (then the photosphere recedes, leading to an increasing degree of ionization which manifests in the strengthening of higher excitation emission lines); emission comes from successively deeper shells with smaller velocities and therefore the emission lines get narrower. The absorption lines superimposed on the emission lines are formed in two different shells which should have been ejected with some time interval; the inner shell (ejected later) has larger velocity and catches up the outer shell. The model in Cassatella et al. (2004) is in agreement with the optically thick wind models from Kato & Hachisu (1994), already addressed by Friedjung (1966). Another independent view of the spec-
tral evolution of Nova Cyg 1992 (and other objects) can be found in the recent review by Shore (2002).

A very important result deduced from nova observations (optical, ultraviolet and infrared) is that their ejecta are very often enriched in carbon, nitrogen and oxygen, as well as in neon in many objects (around 1/3 of the total); the global metallicities in nova ejecta are well above solar metallicities (see Gehrz et al. 1998, for a recent review). This observational fact has been one of the main drivers of the theoretical models and, of course, should be explained by them. The general assumption made long ago (see for instance Starrfield, Truran, & Sparks 1978; and Prialnik, Shara, & Shaviv 1978) is that some enrichment of the accreted matter (which is in principle assumed to be of solar composition) with matter from the underlying white dwarf core (of the CO, carbon-oxygen, or ONe, oxygen-neon, type) is necessary, both to power the nova explosion and to explain the observed enhanced (with respect to solar) abundances.

3. Scenario

3.1. Thermonuclear runaway

There is a general agreement on the scenario of classical nova explosions: a low luminosity white dwarf accretes hydrogen-rich matter in a cataclysmic binary system, as a result of Roche lobe overflow of its main sequence companion. For accretion rates low enough, e.g. \( \dot{M} \sim 10^{-9} - 10^{-10} \, M_\odot \, \text{yr}^{-1} \), accreted hydrogen is compressed up to degenerate conditions until ignition, thus leading to thermonuclear burning without control (thermonuclear runaway, TNR). Explosive hydrogen burning synthesizes some \( \beta^+ \)-unstable nuclei of short lifetimes (e.g. \( ^{13}\text{N}, \, ^{14}\text{O}, \, ^{15}\text{O}, \, ^{17}\text{F} \), with \( \tau = 862, \, 102, \, 176, \, \text{and} \, 93\text{s} \) respectively) which are transported by convection to the outer envelope, where they are preserved from destruction. These decays lead to a huge energy release in the outer shells which causes the nova outburst, i.e. a visual luminosity increase accompanied by mass ejection with typical velocities \( 10^2 - 10^3 \, \text{km/s} \).

The mechanism for nova explosions is better understood after evaluating some relevant timescales (see Starrfield 1988, for a review): the accretion timescale, defined as \( \tau_{\text{acc}} \sim \frac{M_{\text{acc}}}{\dot{M}} \) (which is of the order of \( 10^4 - 10^5 \, \text{yr} \), depending on the accretion rate \( \dot{M} \) and accreted mass \( M_{\text{acc}} \)), the nuclear timescale \( \tau_{\text{nuc}} \sim \frac{C_p T}{\epsilon_{\text{nuc}}} \) (which is as small as a few seconds at peak burning; \( C_p \) is the specific heat and \( \epsilon_{\text{nuc}} \) the rate of nuclear energy generation), and the dynamical timescale \( (\tau_{\text{dyn}} \sim \frac{H_p}{c_s} \sim (1/g)\sqrt{P/\rho}; \, H_p \) is the pressure scale height and \( c_s \) the local sound speed). During the accretion phase, \( \tau_{\text{acc}} \leq \tau_{\text{nuc}} \), accretion proceeds and the envelope mass increases. When degenerate ignition conditions are reached, degeneracy prevents envelope expansion and the TNR occurs. As temperature increases, degeneracy would be lifted (since \( T \) would become larger than \( T_{\text{Fermi}} \)) and expansion would turn-off the explosion, but this is not the case because \( \tau_{\text{nuc}} \ll \tau_{\text{dyn}} \) (specially if the envelope is enriched in CNO elements, thus enhancing the contribution of the CNO cycle to hydrogen burning). Therefore, since the envelope can not readjust itself through expansion, temperature and nuclear energy generation rate continue to increase without control. The value
of the nuclear timescale is crucial for the development of the TNR and its final fate. In fact there are mainly two types of nuclear timescales: those related to $\beta^+$-decays, $\tau_{\beta^+}$, and those related to proton capture reactions, $\tau_{(p,\gamma)}$. In the early evolution towards the TNR, $\tau_{\beta^+} < \tau_{(p,\gamma)}$ and the CNO cycle operates in equilibrium. But as temperature increases up to $\sim 10^8$ K, the reverse situation is true ($\tau_{\beta^+} \gtrsim \tau_{(p,\gamma)}$), and thus the CNO cycle is $\beta$-limited (see figure 5). In addition, since the large energetic output produced by nuclear reactions can not be evacuated only by radiation, convection sets in and transports the $\beta^+$-unstable nuclei to the outer cooler regions where they are preserved from destruction and where they will decay later on ($\tau_{\text{conv}} \lesssim \tau_{\beta^+}$), leading to envelope expansion, luminosity increase and mass ejection if the attained velocities are larger than escape velocity. Another important effect of convection is that it transports fresh unburned material to the burning shell. In summary, non-equilibrium burning occurs and the resulting nucleosynthesis will be far from that of hydrostatic hydrogen burning.

### 3.2. Underlying white dwarf: CO or ONe

As mentioned above, mixing between the accreted envelope (with solar composition) and the underlying white dwarf is a necessary condition both to power the explosion and to interpret the large over solar metallicities observed in nova ejecta. There have been many suggested mechanisms to explain this process, either occurring prior or during the thermonuclear runaway, but none of them is
complete satisfactory up to now (see Livio 1994, for an extensive review). One example is diffusion induced convection, first discussed by Prialnik & Kovetz (1984) and Kovetz & Prialnik (1985), which can explain moderate enrichments but has difficulties to account for some large enrichments observed (Prialnik & Kovetz 1997). Other possibilities are shear mixing, convection induced shear mixing and convective overshooting induced flame propagation. Recent efforts with multidimensional codes have not yet succeeded completely in reproducing the necessary mixing needed to power the explosion (see a recent review in Glasner & Livne (2002) and a recent multidimensional result in Alexakis et al. (2004)).

It is clear that once a mechanism for mixing is adopted, even if not well physically founded yet, the following step is to take some composition of the underlying white dwarf core to mix with the solar (in principle) composition of accreted matter; core composition will play a crucial role in the subsequent evolution. It is important to distinguish between novae occurring on CO and ONe white dwarfs: stars originally less massive than \( \sim 10 - 12 \, M_\odot \) end their life as white dwarfs, made of helium, carbon and oxygen or oxygen and neon. The exact mass interval leading a particular white dwarf type is not completely well determined, since it depends on details of stellar evolution and, especially, on the single or binary nature of the progenitor. The most common white dwarf case is CO, whereas for massive progenitors with masses around 10 \( M_\odot \), non-degenerate carbon ignition leads to the formation of a degenerate core mainly made of oxygen and neon, with traces of magnesium and sodium. These cores were thought to be made of oxygen, neon and magnesium (the so-called ONeMg white dwarfs) some years ago, when parametrized calculations of hydrostatic carbon burning were adopted (Arnett & Truran 1969) before self-consistent models of AGB (asymptotic giant branch stars) following the thermally pulsing phase were available (Domínguez, Tornambé, & Isern 1993; Ritossa, García-Berro, & Iben 1996). The minimum mass at the zero age main sequence leading to extensive carbon burning is \( \sim 9.3 \, M_\odot \) and the resulting ONe mass is \( \sim 1.1 \, M_\odot \), if the evolution occurs in a binary system (Gil-Pons et al. 2003). It is important to notice that the ONe white dwarf has a thick CO buffer on top of its ONe core, which would prevent the mixing of accreted matter with the underlying ONe core (at least until a number of previous outbursts would have eroded that buffer). Then, strange explosions could occur where there would be, for instance, a lack of neon in the ejecta of a nova occurring on top of an ONe core (see José et al. 2003, for details).

4. Relevance of nucleosynthesis in novae

The main goal of theoretical models of nucleosynthesis in novae is to reproduce the observed abundances in novae ejecta. Although both from the observational and theoretical side some uncertainties exist, a rather good fit is obtained in many cases (e.g. see table 5 in José & Hernanz 1998).

Novae are not important contributors to the abundances observed in the interstellar medium, in contrast with supernovae. However, they can contribute to Galactic abundances of some particular isotopes, whenever the overproduction factors with respect to solar abundances are larger than around \( 10^3 \) (see José & Hernanz 1998; and Gehrz et al. 1998). In figure 6 the overproduction
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Factors relative to solar versus mass number are shown for two typical novae: a CO and an ONe nova, with mass 1.15 M\(_\odot\), 50% of mixing with core material and accretion rate 2 \(\times 10^{-10}\) M\(_\odot\) yr\(^{-1}\). In this figure some general features are distinguishable: both in CO and in ONe novae, the largest yields correspond to elements of the CNO group, whether in CO novae \(^7\)Li is also largely overproduced. In the case of more massive ONe novae (see figure 7 corresponding to mass 1.35 M\(_\odot\)), intermediate-mass elements such as Ne, Na, Mg, S, Cl are also overproduced (José & Hernanz 1998).

The large overproduction of \(^7\)Li in CO novae is an important result, since the origin of Galactic lithium is still not well understood (Hernanz et al. 1996). It is widely accepted that there is some primordial lithium produced during the big bang and that spallation reactions by cosmic rays in the interstellar medium or in stellar flares also produce it. But some extra stellar source of \(^7\)Li (without generating \(^6\)Li) has to be invoked to explain the steep rise of the observed lithium abundance between the formation of the solar system and the present time (Romano et al. 1999). Concerning the CNO group isotopes, novae largely overproduce \(^{13}\)C, \(^{15}\)N and \(^{17}\)O: Galactic \(^{17}\)O is most probably almost entirely of novae origin (José & Hernanz 1998), whereas for \(^{13}\)C and \(^{15}\)N other sources are probably required.

Another important piece of information relative to nova nucleosynthesis comes from the measurement of isotopic ratios in presolar grains. Five SiC (silicon carbide) and one graphite grain isolated from the Murchison carbonaceous meteorite have been discovered with low \(^{12}\)C/\(^{13}\)C and \(^{14}\)N/\(^{15}\)N ratios, large excesses in \(^{30}\)Si and high \(^{26}\)Al/\(^{27}\)Al ratios. These isotopic signatures are close to those predicted theoretically for ONe ejecta and can not be matched by any other stellar source (Amari et al. 2001). Recent more detailed theoretical estimates will help to properly identify nova grains in primitive meteorites with nova origin (José et al. 2004). The formation of grains in novae is fully justified, since infrared observations clearly indicate that some novae form dust (Gehrz et al. 1998).
5. High energy emission from novae

5.1. Gamma-rays

An important property of nova ejecta is the presence of radioactive nuclei (the role of novae as potential γ-ray emitters was mentioned long ago by Clayton & Hoyle (1974); Clayton (1981); Leising & Clayton (1987)). In addition to the very short-lived isotopes responsible for the nova explosion, other longer-lived nuclei are synthesized which have some relevance to the radioactivity of the Galaxy and to the γ-ray emission of individual novae.

Short-lived nuclei $^{13}$N and $^{18}$F ($\tau=862$ s and 158 min) are produced in similar quantities in all nova types, whereas $^{7}$Be ($\tau=77$ days) is mainly produced in CO novae and $^{22}$Na ($\tau=3.75$ yrs) and $^{26}$Al ($\tau = 10^6$ yrs) are produced in appreciable amounts only in ONe novae. The reason is that in nova explosions the temperatures reached (around $2 - 3 \times 10^8$ K) are not high enough to break the CNO cycle; therefore, only if some seed nuclei (like $^{20}$Ne, $^{23}$Na, $^{24,25}$Mg) are present in the envelope material, can the NeNa-MgAl cycles operate and synthesize those radioactive nuclei (and other intermediate-mass isotopes). As CO white dwarfs are devoid of these nuclei, it is almost impossible for them to produce large amounts of radioactive $^{22}$Na and $^{26}$Al.

Radioactive nuclei ejected by novae play a role in the radioactivity of the Galaxy which depends on their lifetimes. The short-lived nuclei (i.e., $^{13}$N
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Figure 8. Left panel: Gamma-ray light curves of the three possible lines as compared with visual light curve (the latter in arbitrary units). Right panel: Early temporal evolution of the gamma-ray spectra of a CO (dotted) and an ONe (solid) nova, at a distance of 1 kpc.

and \(^{18}\text{F}\) produce an intense burst of \(\gamma\)-ray emission, with duration of some hours, which is emitted before the nova visual maximum (see figure S and Gómez-Gomar et al. (1998; Hernanz et al. (1999) for details). This emission is related to positron annihilation, which consists of a line at 511 keV and a continuum at energies between 20 and 511 keV, related to the positronium continuum plus the comptonization of the photons emitted in the line. In figure S the spectral evolution of a CO and an ONe nova at different epochs after peak temperature is shown. The emission related to medium-lived nuclei, \(^{7}\text{Be}\) and \(^{22}\text{Na}\), appears later and is different in CO and ONe novae, because of their different nucleosynthesis: CO novae display a line at 478 keV related to \(^{7}\text{Be}\) decay, whereas ONe novae show a line at 1275 keV related to \(^{22}\text{Na}\) decay.

The long-lived isotope \(^{26}\text{Al}\) is also produced by novae. The Galactic \(\gamma\)-ray emission observed at 1809 keV (Mahoney et al. (1984) with the HEAO 3 satellite; Diehl et al. (1993) with the CGRO/COMPTEL) corresponds to the decay of \(^{26}\text{Al}\). Its distribution seems to correspond better to that of a young population and the contribution of novae is not the dominant one (see Prantzos & Diehl 1996; José, Hernanz & Cod 1997).

In summary, classical novae explosions produce \(\gamma\)-rays, being the signature of CO and ONe novae different. The detectability distances for the lines at 478 and 1275 keV with the INTEGRAL/SPI instrument ranges between 0.2 and 0.5 kpc (Hernanz & José 2004); the width of the lines (\(\sim 7\) keV for the 478 keV line and \(\sim 20\) keV for the 1275 keV line), which is non negligible and largely degrades the sensitivity of the instrument, has been taken into account to compute these distances. The continuum and the 511 keV line are the most intense emissions, but their appearance before visual maximum and their very short duration requires “a posteriori” analyses, with large field-of-view instruments monitoring
the whole sky at the appropriate energies (some hundred keVs). With future instruments of these characteristics, novae would be detectable more easily in $\gamma$-rays than visually, because of the lack of extinction. So future instrumentation in the $\gamma$ and hard X-ray domain will give crucial insights on the nova theory allowing for a direct confirmation of the nucleosynthesis in these explosions, but also providing unique information about the Galactic distribution of novae and their rates.

5.2. X-rays

X-rays provide an important piece of information about nova outbursts, specially concerning their turnoff. The EXOSAT satellite detected the nova GQ Mus (N Mus 1983) as a soft X-ray emitter (in the interval 0.04-2 keV), 460 days after optical maximum (Ogelman, Beuermann, & Krautter 1984). ROSAT detected again that source (0.1-2.4 keV), even 9 years after the explosion (Ogelman et al. 1993). Nova Cyg 1992 was also detected by ROSAT as a bright soft X-ray source, but its emission lasted only for 18 months (Krautter et al. 1996). The soft X-ray emission is interpreted as the photospheric emission of the hot white dwarf, hosting a remaining hydrogen-burning shell, which becomes visible when the expanding envelope is transparent enough. The luminosity in soft X-rays is close to $L_{\text{Edd}}$, thus indicating again the constancy of $L_{\text{bol}}$ and the hardening of the spectra. The turn-off times of novae deduced from soft X-ray and ultraviolet observations, range between 1 and 5 yr (González-Riestra, Orio, & Gallagher 1998), except for N Mus 1983 (9-10 yr). This is much shorter than expected from the nuclear burning timescale of the generally accepted mass of the remaining envelope (see Sala & Hernanz, this volume); therefore, some extra and unknown mechanism should remove mass after or during the nova outburst (see as well the papers by Orio, Balman and Hernanz in this same volume, for recent results from X-ray observations of novae – and nova remnants – with XMM-Newton and Chandra).

In addition to soft X-rays, novae can also emit harder X-rays, as observed with ROSAT (Lloyd et al. 1992; Orio et al. 2001; Krautter 2002) and more recently with XMM-Newton and Chandra. We would just like to mention that observations of Nova Oph 1998 with XMM-Newton, have clearly revealed that accretion had been reestablished as soon as 2.7 years after explosion, which indeed is a very short recovery time (Hernanz & Sala 2002), perhaps indicating that accretion disks (or in general accretion streams, if the system is magnetic) are not completely destroyed by the explosion.

6. Discussion

A number of open problems concerning classical novae that still remain unsolved were outlined in the discussion session of the conference:

- Accretion rates: variability and relationship with the hibernation scenario.
- Ejected mass: can theory be reconciled with observations?
- High metallicity ejecta: how to explain it? How does the required mixing occur?
• How long is the decline from maximum bolometric luminosity to pre-outburst luminosity?

• Super Eddington luminosities in white dwarfs.

• Long-term evolution of white dwarfs in novae: does the white dwarf grow in mass? Possible scenario of type Ia supernovae.

These topics have been since long in the list of open and unsolved questions and they remain there, in spite of the observational and theoretical efforts of the last years. Hopefully some of them will be better understood when the next meeting takes place.

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