Gamma-Rays from Classical Novae: Expectations from Present and Future Missions

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Abstract

A review of the main features of the gamma-ray emission of individual classical novae is presented. We concentrate on the theoretical predictions of both the long lasting emission, produced by electron captures on ^{7}Be and β^{+}-decay of ^{22}Na, and the prompt emission, produced by electron-positron annihilation (with positrons coming from ^{13}N and ^{18}F β^{+}-decays). Special attention is payed to the observability of novae with the current INTEGRAL observatory and with future missions, like EXIST.

Key words: Gamma-ray astronomy; gamma-ray lines; nucleosynthesis; novae; cataclysmic variables
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1 Introduction

The potential role of classical novae as gamma-ray emitters has been pointed out long ago (Clayton & Hoyle, 1974; Clayton, 1981; Leising & Clayton, 1987) and fully consistent theoretical models have been developed already more than 5 years ago (Gómez-Gomar et al., 1998; Hernanz et al., 1999). However, their detection has not been possible yet (Harris et al., 1991, 1996, 1999, 2001; Leising et al., 1988; Iyudin et al., 1995; Hernanz et al., 2000). The gamma-rays emitted by classical novae originate in the disintegration of the unstable

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Table 1
Radioactive isotopes synthesized in novae relevant for gamma-ray emission

Isotope	Lifetime	Type of emission	Main disintegration process	Nova type
^{13}N	862 s	511 keV line & continuum	β^+-decay	CO and ONe
^{18}F	158 min	511 keV line & continuum	β^+-decay	CO and ONe
^{7}Be	77 days	478 keV line	e^--capture	CO
^{22}Na	3.75 years	1275 keV & 511 keV lines	β^+-decay	ONe
^{26}Al	10^6 years	1809 keV & 511 keV lines	β^+-decay	ONe

radioactive isotopes produced during the explosion, which occurs as a consequence of a thermonuclear runaway on top of an accreting white dwarf in a binary system of the cataclysmic variable type. Complete evolution with full nucleosynthesis has been followed by means of a spherically symmetric, implicit, one-dimensional hydrodynamical code (José & Hernanz, 1998), whereas the ensuing production and propagation of the gamma-rays in the expanding envelope is handled with a Monte Carlo code (Gómez-Gomar et al., 1998).

We assume that there is mixing between matter from the underlying white dwarf (CO or ONe) and the solar-like material from the donor star, during accretion (a mixing ratio of 50% has been adopted in the models presented in this paper). This approach is justified because there is not any known self-consistent mechanism of mixing in novae, explaining the large enrichment of metals found in many of them, in spite of the continuing efforts of multidimensional studies (Rosner et al., 2001). The exact composition of the top layers of the underlying white dwarf is of crucial importance for the final yields of radioactive nuclei (specially ^{7}Be, ^{22}Na and ^{26}Al) in novae. This composition depends mainly on that of the underlying white dwarf's core (see however José et al. 2003, where the chemical stratification of the white dwarf - i.e., presence of a thick CO-buffer on top of the ONe rich core - has been taken into account).

Carbon-oxygen (CO) novae are best suited for ^{7}Be synthesis, because of their rapid rise time to temperatures around 10^8K, where ^{7}Be destruction is prevented by ^{8}B photodisintegration (Hernanz et al., 1996). On the other hand, novae occurring on oxygen-neon (ONe) white dwarfs are the only producers of ^{22}Na and ^{26}Al, since the synthesis of these intermediate-mass isotopes requires the previous existence of some seed nuclei, only available from the mixing with an underlying ONe white dwarf, together with large enough temperatures, only obtainable in massive (i.e. ONe) white dwarfs. (José & Hernanz, 1998; José et al., 1999). The lifetimes and the associated gamma-ray emission of these medium and long-lived isotopes are detailed in table 1 (see Hernanz, 2002, for a recent review). The short-lived isotopes ^{13}N and ^{18}F are almost equally produced in CO and in ONe novae.

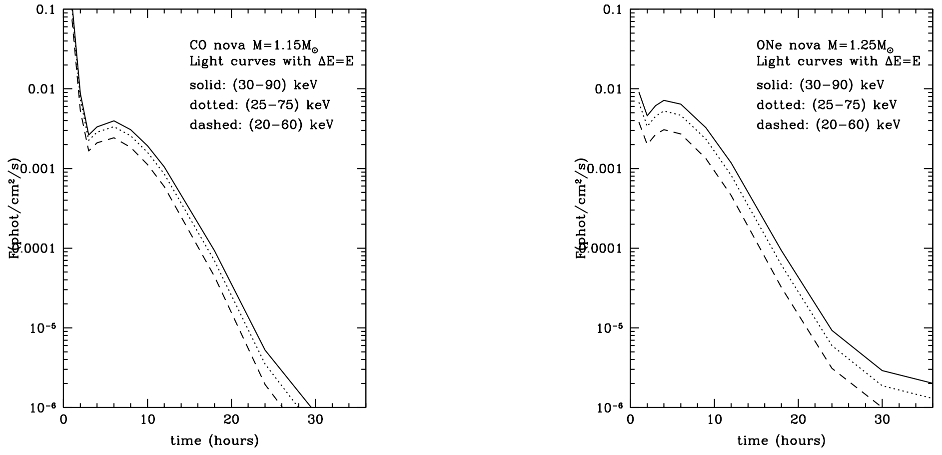

Fig. 1. (Left) Light curves of the emission in three γ-ray continuum bands for a CO nova of 1.15 M$_\odot$. (Right) Same for an ONe nova of 1.25 M$_\odot$. Distance is 1 kpc.

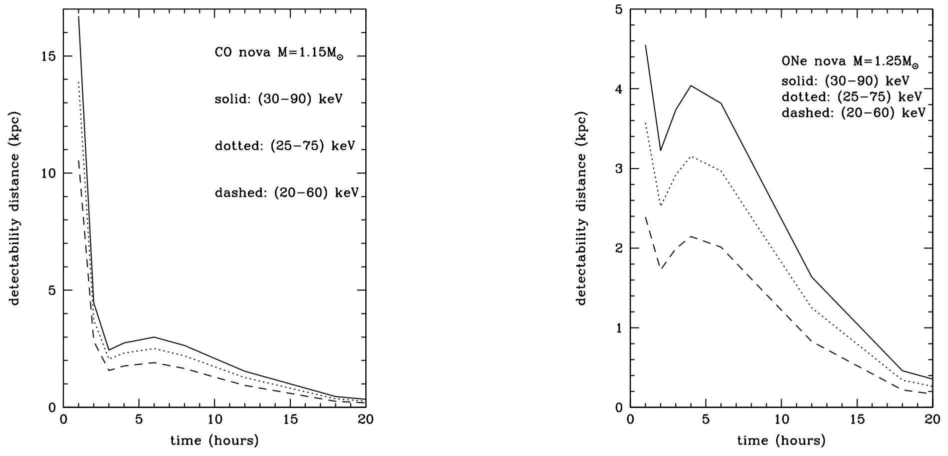

Fig. 2. (Left) Detectability distance with the future EXIST mission of a CO nova of 1.15 M$_\odot$, in different γ-ray continuum bands, versus the observation starting time. (Right) Same for an ONe nova of 1.25 M$_\odot$.

2 Line emission at 478 and 1275 keV

The best candidates for the detection of gamma rays from classical novae are lines, when high resolution spectrometers, like SPI onboard INTEGRAL, are used. The same will be true for the future gamma-ray focusing mission MAX (see von Ballmoos contribution in this same volume), or other future missions based on the Compton Telescope technique (i.e., Xenon Compton Telescope, MEGA, ...; see for instance, Aprile, Kanbach, Kurfess contributions in this same volume). On the other hand, other instruments like IBIS onboard INTEGRAL or the future EXIST mission are best suited for continuum detection.

The 478 keV and 1275 keV lines are emitted by classical novae of the CO and ONe type, respectively. The rise phase of the 478 keV light curve lasts between 5 days and two weeks, depending on the mass of the underlying CO white dwarf (a larger mass leads to a smaller envelope mass, a faster expansion and a shorter rise phase). The fluxes at maximum are around $1-2\times10^{-6}$ phot/cm^2/s (for distance d=1kpc) and the duration of the emission is some weeks (since there is an exponential decline with timescale 77 days); the line width (FWHM) is around 8 keV. With these main characteristics, the ^{7}Be line at 478 keV can be detected with SPI/INTEGRAL only for novae at distances shorter than 0.2 kpc (with an observation time of 10^6s), according to the new sensitivities measured for SPI and published for the AO2 INTEGRAL call for proposals. With pre-launch estimated sensitivities (those published for AO1 call for proposals), which were around a factor of 4 better, the distances were larger by around a factor of 2. A promising mission for the detection of the 478 keV line from novae will be MAX, based on the gamma-ray focusing concept. With the predicted sensitivity at 478 keV, more than 100 times better than that of SPI (for the "MAX XL" configuration), novae at distances $\sim$ 2kpc would be detected through the ^{7}Be line.

The ^{22}Na line at 1275 keV is more promising, both for SPI/INTEGRAL and for future missions. This line, emitted only in novae with an underlying ONe white dwarf, reaches fluxes around 2×10^{-5} phot/cm^2/s (d=1kpc), with a duration of some months (exponential decline with lifetime 3.75 years); the line width (FWHM) is around 20 keV. The corresponding detectability distances, for an observation time of 10^6s, with SPI/INTEGRAL are 0.5 kpc. The same comment about sensitivities applies to this case: they are reduced by around a factor of 3.4 with respect to pre-launch estimates. MAX will not detect 1275 keV photons, with its current configuration. Other future instruments (like an Advanced Compton Telescope) would be able to detect novae up to the galactic center, i.e., the majority of them, provided that they reach sensitivities of $\sim3\times10^{-7}$ phot/cm^2/s, for a 1275 keV broad (20 keV FWHM) line. Some nuclear uncertainties still affect the synthesis of ^{22}Na in novae. However, those relative to the ^{21}Na(p,γ)^{22}Mg nuclear reaction rate have been reduced recently (Bishop et al., 2003; Davids et al., 2003).

3 Continuum and 511 keV line emission

The radioactive nuclei ^{13}N and ^{18}F are responsible for a prompt emission of gamma-rays (511 keV line and a continuum between 20 and 511 keV), as a consequence of electron-positron annihilation in the expanding nova envelopes[1]. The continuum emission is produced by the Comptonization of the 511 keV line photons and also by the positronium continuum. The cutoff at low energies is a consequence of photoelectric absorption in the expanding envelope, and its exact location (between 20 and 30 keV) depends on the chemical composition of the medium. The annihilation emission has a very short duration and occurs well before the maximum in visual luminosity and, therefore, before the nova is discovered (see Hernanz et al. 2002 for a recent review). As an immediate consequence, pointed observations of novae are unable to detect this type of emission, since the alert should come from optical discovery. Only wide field of view instruments, monitoring the sky in the hard X-ray/soft gamma-ray range, are suited for such a detection. Some examples of appropriate instruments were TGRS/WIND and BATSE/CGRO; attempts to detect the 511 keV line with these instruments have been unsuccessful, because of limited sensitivity (Harris et al., 1999; Hernanz et al., 2000).

A promising future mission will be EXIST (Energetic X-ray Imaging Survey), planned to do a deep hard X-ray (from 4 to 600 keV) imaging survey (see Hartmann's contribution in this same volume). We have computed light curves in three continuum bands for which EXIST will be very sensitive, centered at energies 40, 50 and 60 keV and with $\Delta E = E$; these curves are shown in figure 1 for CO and ONe novae. The flux at very early epochs, related with ^{13}N decay, is larger in CO novae because they have larger quantities of ^{13}N in the outer envelope. Adopting the continuum sensitivities per orbit (period around 90 minutes) from Grindlay et al. (2002), we obtain a preliminary estimation of the detectability distances of the annihilation continuum. These distances depend largely on the moment after the outburst when the nova is observed, because of the rapidly decaying light curves (see figure 1). The effective EXIST's sensitivity could be better, because a nova event could be detected during more than one orbit. The results shown in figure 2 correspond to a CO nova of 1.15 $M_\odot$ and an ONe nova of mass 1.25 $M_\odot$. More detailed estimations, also including the 511 keV line (and the long-lasting 478 keV line) are in progress.

The number of potentially detectable novae with EXIST is quite large, if we adopt the continuum detectability distances mentioned above. Between 1 and

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[1] The synthesis of ^{18}F in novae is affected by some nuclear uncertainties, mainly in the ^{18}F(p,α)^{15}O rate. Fortunately, recent measurements have reduced these uncertainties (Séréville et al., 2003)

2 ONe novae and between 3 and all the CO novae exploding every year could be detected. With a mission of this kind, a considerable fraction of the Galactic novae could be detected in gamma rays, giving a very valuable information about their Galactic distribution. This is in contrast with optical observations, which are able to detect only 3 to 5 (of the 35 predicted theoretically) novae per year, because visual extinction by interstellar dust prevents the detection of these objects in the center and in other obscured regions of the Galaxy. The spatial distribution of novae in the Milky Way, as well as their rate of occurrence would be for the first time obtained from observations in the Milky Way itself.

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