The prompt gamma-ray emission of novae

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Abstract

Classical novae are potential gamma-ray emitters, because of the disintegration of some radioactive nuclei synthesized during the explosion. Some short-lived isotopes (such as $^{13}$N and $^{18}$F), as well as the medium-lived $^{22}$Na, decay emitting positrons, which annihilate with electrons and thus are responsible for the prompt emission of gamma-rays from novae. This emission consists of a 511 keV line plus a continuum between 20 and 511 keV, and is released before the maximum in visual luminosity, i.e., before the discovery of the nova. The main characteristics of this prompt emission, together with the related uncertainties (both of nuclear and hydrodynamical origin, with a particular emphasis on the influence of the envelope properties) and prospects for detectability are analyzed in this paper.

Key words: Gamma-ray astronomy, gamma-ray lines, nucleosynthesis, novae, cataclysmic variables

1 Introduction and models

The explosive phenomenon of classical novae occurs on the surface of accreting white dwarfs, in close binary systems of the cataclysmic variable type, whenever certain initial conditions of white dwarf mass and luminosity and mass-accretion rate are met. The hydrogen-rich accreted matter, mixed with matter from the underlying white dwarf core, burns in degenerate conditions, leading to a thermonuclear runaway and the ensuing explosion. An important
increase in visual luminosity and the ejection of a fraction of the accreted envelope are some of the consequences of the explosion. The outburst is accompanied by the release of gamma-rays, with different time scales.

The prompt $\gamma$-ray emission from classical novae has its origin in $e^+-e^-$ annihilation, with the positrons coming mainly from $^{13}$N and $^{18}$F decays (see the pioneering work from Leising & Clayton (1987)). The positrons emitted by $^{22}$Na decay also contribute to the prompt emission, but with a much lower flux than those from $^{13}$N and $^{18}$F, because of its much longer decay time. In general, the released positrons annihilate and produce a line at 511 keV and a continuum below it. The continuum is produced both by the positronium emission (when it is formed in triplet state) and by the Comptonization of the photons emitted in the line; it has a cut-off at around 20-30 keV, because of photoelectric absorption (this mechanism has larger cross-sections than Compton scattering at low energies). The isotopes $^{13}$N and $^{18}$F have relatively short lifetimes, which makes the corresponding emission of short duration and tightly related to the conditions in the expanding envelope (opacity to gamma-rays). The prompt gamma-rays from novae are emitted very early in the explosive phase, i.e., before the maximum in visual luminosity and, therefore, before optical discovery for the majority of novae.

There is another type of gamma-ray emission, related to line emission from the decay of medium-lived radioactive nuclei (such as 478 keV from $^7$Be and 1275 keV from $^{22}$Na), lasting for months and years after the explosion, which has not been detected in any nova up to now (Harris et al., 1991, 1996; Leising et al., 1988; Iyudin et al., 1995), but its study is out of the scope of this paper (see for instance the pioneering papers from Clayton (1981), Clayton & Hoyle (1974), and the recent ones from Gómez-Gomar et al. (1998), Hernanz et al. (1999a) and references therein).

Complete evolution of various nova models (both of the CO and ONe type, depending on the chemical composition of the underlying white dwarf, which, in turn, depends on its core mass) from the accretion phase up to the ejection one, has been computed, with a hydrodynamical code (see José & Hernanz (1998), for details about the code). It is important to stress that some nuclear reaction rates play a very important role on the synthesis of the most relevant radioactivities in nova explosions. In particular, $^{18}$F synthesis is affected mainly by $^{18}$F+p reactions ($^{18}$F(p,$\gamma$) and $^{18}$F(p,α), which are still quite uncertain (see Hernanz et al. (1999b) and Coc et al. (2000)). Therefore, the final amount of $^{18}$F, which almost directly translates into the flux of positron annihilation gamma rays emitted promptly, will be as close to reality as the measured nuclear cross sections are. It is also important to treat accurately the initial composition of the underlying white dwarf core, specially for the case of the ONe novae, as well as the amount of mixing between accreted and white dwarf matter (see discussion in José & Hernanz (1998)). In table 1 we
show the radioactivities, relevant for the positron annihilation gamma rays, for a handful of computed nova models. One important result is that similar amounts of $^{18}$F are produced in both nova types, contrary to what happens with other longer lived radioactivities (i.e., $^7$Be, mainly produced in CO novae, and $^{22}$Na, mainly produced in ONe novae).

The main properties of the emission of positron annihilation gamma rays from novae are displayed in figure 1, where the time axis origin is at peak temperature (which occurs before visual luminosity maximum). First we show (figure 1 left) the light curve of the 511 keV line, for the four models from table 1. Although the amount of ejected $^{18}$F is similar in all the models, the less massive CO nova (0.8 $M_\odot$) emits a smaller flux than the other ones; that’s because its outer expanding shells move at smaller velocities and, therefore, are more opaque to gamma-rays. It is important to notice that there is also an initial peak in the light curves, related to $^{13}$N decay, of even shorter duration than that produced by $^{18}$F decay (because of the shorter lifetime of $^{13}$N as compared with $^{18}$F). Another interesting aspect is that in ONe novae the 511 keV line has a longer duration, because of the contribution of the positrons from $^{22}$Na-decay: a low-level “plateau” becomes visible at the tail of the light curve (see figure 1). However, when the envelopes finally become transparent (one or two weeks after $T_{\text{peak}}$) $e^+$ escape without annihilating. A similar behavior is displayed by the continuum light curves (see figure 1 right); here one can see that there is much more flux in the continuum than in the 511 keV line (which has widths FWHM between 3 and 8 keV).

2 Influence of the ejecta properties in the annihilation emission

Other important factors, beyond the critical nuclear reaction rates mentioned above, concern aspects of the envelope. As an illustrative example, the low mass CO nova (0.8 $M_\odot$) emits a flux in the 511 keV line, which is smaller than that emitted by other more massive novae by a factor larger than their ratio of $^{18}$F yields (see figure 1 left and table 1). In order to study these factors, we varied ejected masses and velocity profiles in some of our models, leaving the abundances of radioactive material unchanged. These models are interesting for illustrative purposes, although they are not self consistent. An additional interest comes from the fact that all current theoretical nova models still fail to reproduce some observed ejected masses (observed larger than theoretical).

The effect of ejected mass is shown in figure 2 for a CO (left) and an ONe (right) nova. In both cases, the effect of ejected mass at early epochs is opposite to that at later times. At early times, the larger the ejected mass the larger the opacity of the envelope to gamma-rays; therefore, novae with larger ejected masses emit smaller fluxes. On the contrary, at later times (after $\sim$1 day, see figure 2), the envelope is more transparent and the fluxes almost directly reflect the amount of $^{18}$F (i.e., the larger the ejected mass the larger the flux).
In the ONe novae, the fluxes emitted in the “plateau” phase directly reflect the amount of $^{22}$Na (thus the ratio of fluxes equals the ratio of ejected masses).

The influence of the velocity of the ejecta is displayed in figure 3. At early epochs, the gamma-ray flux increases with envelope velocities because of increased transparency. Later on (around 1 day after peak temperature), ONe novae differ from CO novae, because of their much larger $^{22}$Na content: the decline of the gamma-ray flux in ONe novae is delayed by $^{22}$Na positrons annihilating in the envelope, until the moment when the envelope becomes transparent to positrons and also these annihilations fade away. This happens some weeks later, the exact figure depending on the transparency of the envelope; therefore, the smaller the velocity, the smaller the transparency at a given time and the longer the duration of this phase (see figure 3 right).

3 Discussion and prospects for detectability

We have shown that the continuum (20-511 keV) and 511 keV line light curves provide a direct insight into the dynamics of the expanding envelope, as well as information about the nova type and its $^{18}$F (CO and ONe novae) and $^{22}$Na (ONe novae) content. The fluxes in various continuum bands and in the 511 keV line are more intense than those in the 478 keV line and 1275 keV lines, but their short duration and early appearance makes them impossible to detect with standard pointed observations. Only all-sky monitors, able to do surveys in the range from 20 to 600 keV, are suited for such type of detection. Attempts have been made with the TGRS instrument onboard the WIND satellite ([Harris et al., 1999]), the BATSE onboard the Compton Gamma-Ray Observatory ([Fishman et al., 1991; Hernanz et al., 2000]). The negative results obtained up to now are consistent with our predicted fluxes. Therefore, we have to wait for more sensitive instruments (EXIST, Advanced COMPON Telescope), or hopefully the shield of the future INTEGRAL spectrometer SPI ([Jean et al., 1999]), to confirm the theoretical predictions and to extract all the crucial information about the nova phenomenon that only the gamma-rays can provide.

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Table 1
Radioactivities in novae ejecta relevant for prompt emission ($^{13}$N and $^{18}$F at 1h after $T_{\text{max}}$)

| Nova | $M_{\text{wd}}$ ($M_\odot$) | $M_{\text{ejec}}$ ($M_\odot$) | $^{13}$N ($M_\odot$) | $^{18}$F ($M_\odot$) | $^{22}$Na ($M_\odot$) |
|------|----------------------------|-----------------|----------------|--------------------|------------------|
| CO   | 0.8                        | 6.2x10$^{-5}$   | 1.5x10$^{-7}$ | 1.8x10$^{-9}$      | 7.4x10$^{-11}$  |
| CO   | 1.15                       | 1.3x10$^{-5}$   | 2.3x10$^{-8}$ | 2.6x10$^{-9}$      | 1.1x10$^{-11}$  |
| ONe  | 1.15                       | 2.6x10$^{-5}$   | 2.9x10$^{-8}$ | 5.9x10$^{-9}$      | 6.4x10$^{-9}$   |
| ONe  | 1.25                       | 1.8x10$^{-5}$   | 3.8x10$^{-8}$ | 4.5x10$^{-9}$      | 5.9x10$^{-9}$   |

Fig. 1. (Left) Light curves for the 511 keV line of the 4 nova models shown in table 1, placed at a distance of 1 kpc. (Right) Continuum light curves for the ONe nova of 1.15 $M_\odot$ at the same distance.

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Fig. 2. (Left) Light curves for the 511 keV line for a CO nova of 1.15 $M_\odot$, for a range of ejected masses. (Right) Same for an ONe nova of 1.15 $M_\odot$. Distance is 1 kpc.

Fig. 3. (Left) Light curves for the 511 keV line for a CO nova of 1.15 $M_\odot$, for a range of parametrized velocities of the ejecta. The value indicated corresponds to the outermost shell. (Right) Same for an ONe nova of 1.15 $M_\odot$. Distance is 1 kpc.