Gamma-ray emission from novae related to positron annihilation: constraints on its observability posed by new experimental nuclear data

Margarita Hernanz

Institut d’Estudis Espacials de Catalunya/CSIC, Edifici Nexus-201, C/Gran Capità 2-4, E-08034 Barcelona, SPAIN

Jordi José

Departament de Física i Enginyeria Nuclear (UPC), Avinguda Víctor Balaguer, s/n, E-08800 Vilanova i la Geltrú (Barcelona), SPAIN

and

Institut d’Estudis Espacials de Catalunya, Edifici Nexus-201, C/Gran Capità 2-4, E-08034 Barcelona, SPAIN

Alain Coc

Centre de Spectrométrie Nucléaire et de Spectrométrie de Masse, IN2P3-CNRS, Université Paris Sud, Bât.104, F-91405 Orsay Campus, FRANCE

Jordi Gómez-Gomar

Institut d’Estudis Espacials de Catalunya, Edifici Nexus-201, C/ Gran Capità 2-4, E-08034 Barcelona, SPAIN

and

Jordi Isern

Institut d’Estudis Espacials de Catalunya/CSIC, Edifici Nexus-201, C/Gran Capità 2-4, E-08034 Barcelona, SPAIN

ABSTRACT

Classical novae emit γ-ray radiation at 511 keV and below, with a cut-off at around (20-30) keV, related to positron annihilation and its Comptonization in the expanding envelope. This emission has been elusive up to now, because it occurs at epochs well before the maximum in optical luminosity, but it could be detected by some sensitive instrument on board a satellite, provided that the nova is close enough and that it is observed at the right moment. The detection of this emission, which is a challenge for
the now available and for the future $\gamma$-ray instruments, would shed light into the physical processes occurring in the early phases of the explosion, which are invisible in other lower energy ranges. A good prediction of the emitted fluxes and of the corresponding detectability distances with different instruments relies critically on a good knowledge of reaction rates relevant to $^{18}$F destruction, which have been subject to a strong revision after recent nuclear spectroscopy measurements. With respect to previous results, smaller ejected masses of $^{18}$F are predicted, leading to smaller emitted fluxes in the (20-511) keV range and shorter detectability distances.

Subject headings: gamma-rays: observations — novae, cataclysmic variables — nuclear reactions, nucleosynthesis, abundances

1. Introduction

The role of novae as potential gamma-ray emitters has been mentioned long ago (Clayton & Hoyle 1974, Clayton 1981, Leising & Clayton 1987), and analyzed in detail on the basis of theoretical models just recently (Gómez-Gomar et al. 1998). In many of the historical studies, more attention has been paid to the long lasting emission, related to the decay of some medium-lived isotopes, such as $^7$Be ($\tau=77$days), $^{22}$Na ($\tau=3.75$yr), and to the possible contribution of novae to the Galactic content of $^{26}$Al ($\tau = 1.04 \times 10^6$ yr). Up to now, no positive detection neither of the 478 keV emission (Harris et al. 1991), related to $^7$Be decay, nor of the 1275 keV one (Iyudin et al. 1995), related to $^{22}$Na decay, has been obtained. The 1809 keV line associated with the galactic $^{26}$Al was detected some years ago by the HEAO3, High Energy Astrophysics Observatory (Mahoney et al. 1982), but observations made with the COMPTEL (Compton Telescope) instrument on board the CGRO satellite (Compton Gamma-Ray Observatory) seem to indicate that the $^{26}$Al emission is more related to a young population of massive stars, although a nova contribution cannot be ruled out yet (Diehl et al. 1995, Prantzos & Diehl, 1996). The most powerful emission in gamma-rays from classical novae is not the one related to the 478, 1275 or 1809 keV lines, but that at 511 keV and below (down to $\sim$(20-30) keV), which originates from electron-positron annihilation (Hernanz et al. 1997a, b, Gómez-Gomar et al. 1998), and consists of a line at 511 keV and a continuum below it. The 511 keV line comes from the direct annihilation of positrons and from the positronium (in singlet state) emission, whereas the continuum comes from both the positronium continuum (triplet state positronium) and the Comptonization of photons emitted in the 511 keV line. The main contributors to positrons in nova envelopes are the short-lived $^{13}$N ($\tau=862$s) and $^{18}$F ($\tau=158$ min), besides the long-lived $^{22}$Na (this one only in oxygen-neon novae). The problem with this emission is its very short duration, making its detection very difficult. Furthermore, because of the short lifetimes of $^{13}$N and $^{18}$F, its maximum happens well before the maximum in visual light, which still enhances the difficulty of detection. When $^{13}$N decays, the nova envelope is still too opaque; therefore, $^{18}$F plays the most important role, since it decays appreciably when the envelope begins to be transparent enough to allow for the gamma-ray photons to be transported through
the whole envelope, and then be emitted into space.

Several attempts are being carried out to detect the annihilation gamma-ray emission from novae, with instruments like BATSE (Burst and Transient Source Experiment) on board the CGRO, or TGRS (Transient Gamma Ray Spectrometer), on board the WIND satellite. SPI, the future spectrometer for INTEGRAL (International Gamma-Ray Laboratory), could in favorable conditions detect that emission. The detectability distances for these instruments, or for any future ones, rely on the detailed properties of novae expanding envelopes and, in particular, on their $^{18}$F content, which strongly depends on the rates of the nuclear reactions involved in its synthesis. A good knowledge of the gamma-ray output of novae is needed to elucidate the possibilities of detection and to put constraints on the theoretical models from the observations.

2. Gamma-ray emission of novae and $^{18}$F synthesis

The flux emitted by a classical nova in the gamma-ray range below 511 keV depends on the amount of $^{18}$F at the epoch where the envelope begins to be transparent to gamma-rays. Therefore, profiles of $^{18}$F along the expanding envelope at different times are needed to compute the spectrum at different epochs after the outburst (or in an equivalent way, the light curves for different gamma-ray bands at and below 511 keV). Of course, the whole spectrum depends also on the abundances of the other isotopes and on the density and velocity profiles; these quantities determine the number of interactions of photons with the ejecta through Compton scattering, photoelectric absorption and pair production. Theoretical models of the gamma-ray emission from individual classical novae, based on the nucleosynthetic yields obtained from a hydrodynamical code that follows the explosive phase and the related nucleosynthesis (José & Hernanz 1998), predict an intense line emission at 511 keV plus a continuum below (Gómez-Gomar et al. 1998). The emission appears between 5 and 6 hours after maximum temperature, i.e., some days before the maximum in visual luminosity. The continuum displays always a cut-off at low energies, which is related to photoelectric absorption, which has larger cross sections than Compton scattering at low energy, acting as a sink of the Comptonized photons. The cut-off is located at ~20 keV, for the carbon-oxygen (CO) and ~30 keV for the oxygen-neon (ONe) rich envelopes typical of nova models.

The main nuclear path leading to $^{18}$F synthesis in novae belongs to the hot CNO (carbon-nitrogen-oxygen) cycles. Since in both CO and ONe novae the initial abundance of $^{16}$O is large, $^{16}$O is the main source for $^{18}$F formation, through two possible chains of reactions: $^{16}$O (p,$\gamma$)$^{17}$F (p,$\gamma$)$^{18}$Ne($\beta^+$)$^{18}$F and $^{16}$O (p,$\gamma$)$^{17}$F ($\beta^+$)$^{17}$O(p,$\gamma$)$^{18}$F. However, $^{18}$F yields are severely constrained by its destruction mode, whatever the production channel is. During the thermonuclear runaway, $^{18}$F destruction by beta decays can be neglected when compared to its destruction by proton captures. Because of the low alpha emission threshold, $^{18}$F (p,$\alpha$)$^{15}$O is faster than $^{18}$F (p,$\gamma$)$^{19}$Ne, and hence it is the main destruction channel of $^{18}$F (see Figure 1). The rates for $^{18}$F (p,$\gamma$) and $^{18}$F (p,$\alpha$) generally adopted in nova models are those from Wiescher & Kettner (1982), which were estimated at a time where the relevant experimental data were scarce (i.e., very limited spectroscopic
data was available for $^{19}$Ne). Thanks to recent measurements, in particular to those of Graulich et al. (1997), Utku et al. (1998), and references therein, it is possible now to use updated rates. Two resonance strengths have been measured directly (Coszach et al. 1995, Graulich et al. 1997) in $^{18}$F ($p,\alpha$) using a radioactive $^{18}$F beam. Of these two, the one lying at higher energy is so broad that its tail alone gives a contribution larger than the Wiescher & Kettner (1982) rate at nova temperatures. Nuclear spectroscopic studies performed by Utku et al. (1998) have led to the localisation of several new $^{19}$Ne levels to which should correspond new resonances in $^{18}$F +p. They have calculated updated $^{18}$F ($p,\gamma$) and $^{18}$F ($p,\alpha$) rates including the two directly measured resonances plus the contribution of the expected ones. To calculate this last contribution, they used information about $^{19}$F analog levels supplemented with estimated quantities. A comparison of the new rates with those of Wiescher and Kettner is shown in Figure 1; in the range of temperatures relevant to nova explosions, the new rates are quite larger than the older ones. Although the uncertainties associated with the rates of $^{18}$F destruction, $^{18}$F ($p,\gamma$) and $^{18}$F ($p,\alpha$), are far from being settled in the nova temperature range, it seems clear that the rates that had been used up to now (Wiescher & Kettner, 1982) were underestimated.

In Table 1 we show the most relevant properties of some nova models computed by means of the hydrodynamic code described in José & Hernanz (1998), with the nuclear reaction network described in José et al. (1999) (recommended rates) and the new Utku’s rates for $^{18}$F ($p,\gamma$) and $^{18}$F ($p,\alpha$) reactions. We have chosen models representative of the two nova types, CO and ONe, and with masses 1.15 $M_\odot$ in the CO case and 1.15 and 1.25 $M_\odot$ in the ONe case, in order to analyze the influence of the composition and mass of the underlying white dwarf on $^{18}$F synthesis. The accretion rate in all the cases is $2 \times 10^{-10}$ $M_\odot$yr$^{-1}$ and the degree of mixing with the core is 50% (see José & Hernanz 1998 for a discussion of the initial mixing effect). Similar ejected masses of $^{13}$N and $^{18}$F are obtained in all the models, which is not the case for other radioactive nuclei relevant to $\gamma$-ray emission with longer timescales, such as $^7$Be (mainly produced in CO novae) and $^{22}$Na and $^{26}$Al (mainly synthesized in ONe novae). When compared with results with the old rates for $^{18}$F +p reactions, a general reduction, by a factor between 10 and 20, of $^{18}$F yields is present, whereas the maximum temperature and the mean kinetic energy are almost unchanged, since the $^{18}$F +p reactions do not affect the energetics of the nova explosion. Concerning the general nucleosynthesis, the changes are not very relevant, except for $^{18}$F, which is reduced typically by a factor of 10.

The gamma-ray spectrum 12 hours after peak temperature is shown in Figure 2, for a CO nova of 1.15 $M_\odot$ and an ONe nova of 1.25 $M_\odot$ at a distance of 1 kpc. The 511 keV line from our models is slightly blueshifted (with a maximum energy of 517 keV) during the first phases, and has a moderate width (from $\sim 5$ to $\sim 8$ keV, FWHM, depending on the model and on the epoch). Light curves in the 20-511 keV band and in the 511 keV line alone have been computed. A summary of their fluxes at different epochs after peak temperature, for a distance of 1 kpc, is shown in Table 2. There is an early maximum at around 1 hour, which is related to $^{13}$N decay. This maximum has very short duration and is very dependent on the distribution of $^{13}$N in the outer layers of the envelope (which are the only ones seen at these early epochs). A larger abundance of $^{13}$N in the
outer layers of the CO nova with respect to the ONe one leads to the larger flux in the CO case (see Table 2). The flux reaches its second and broader maximum, related to $^{18}$F decay, at around 6 hours after peak temperature. It is important to notice that the flux emitted in the continuum, with a maximum around 50 keV, is larger than that in the line at all times. Also, the clear cut-off at $\sim$20 keV, together with the short duration of the whole emission and its early appearance before maximum visual luminosity, rules out the interpretation of the early hard X-ray emission observations of Nova Herculis 1991 (Lloyd et al. 1992), and of the recent Nova Velorum 1999 (Orio et al. 1999, Mukai & Ishida 1999), as a Comptonization of the gamma-ray emission (Livio et al. 1992, Starrfield et al. 1992). For the purpose of comparison, the gamma-ray spectrum of the CO nova model, but computed with the old $^{18}$F +p rates, is also shown in Figure 2. A reduction by a factor of $\sim$10 at all the energies in the relevant range is obtained in the new models, since the fluxes are smaller than the previous ones by the same factors than $^{18}$F ejected masses (between 10 and 20). This difference appears during the first 24 hours, when $^{18}$F is the main source of positrons; but later on, when only $^{22}$Na remains as a positron source, the new and the old fluxes are quite similar, being much smaller in CO novae because they are almost devoid of $^{22}$Na.

3. Discussion and conclusions

The potential detection of the electron-positron annihilation emission from classical novae is faced with various challenging problems: besides of the relatively small fluxes, the short duration and the early appearance of the emission make its detection quite hard. Large field of view instruments, like BATSE, are the more appropriate to detect this type of emission. Its capability to observe all the sky, together with its high sensitivity in the low-energy range make BATSE an ideal instrument to detect this emission, although the new fluxes presented here restrict the detectability distances to less than 3 kpc. There is an ongoing project of analysis of BATSE background data for nearby novae that have exploded since CGRO launch.

Another instrument which could be able to detect the annihilation gamma-ray emission from novae, because of both its wide field of view and its high spectral resolution, is the Transient Gamma Ray Spectrometer (TGRS) on board the WIND satellite (Teegarden et al. 1996). Very recently, Harris et al. (1999) have tried to detect the annihilation line emission at 511 keV from the five known Galactic novae in the instrument field of view, during the time interval 1995-1997. No definite detections were made, but the method applied was shown to be sensitive enough to detect novae out to about 2.5 kpc. Since the conclusions of that paper were based on models in Gómez-Gomar et al. (1998), they should be revised and the corresponding distances should be reduced by a factor $\sim \sqrt{10}$.

Finally, we should mention the future spectrometer for INTEGRAL, SPI, which could be able to detect the 511 keV line up to 3 kpc with the fluxes we obtain now. A similar detectability distance is predicted for the continuum. It is worth noticing that both TGRS and SPI have very good spectral resolution, because of their germanium detectors; this of course is favorable for the
detection of the 511 keV line (although its non negligible width worsens the sensitivity appreciably) but not so interesting for the continuum, where novae emit a larger flux.

The detection by some present or future instrument of the positron annihilation emission from novae would help to understand the mechanism of the explosion and the dynamics of the early expansion stage.

This research has been partially supported by the CICYT-P.N.I.E. (ESP98-1348), by the DG-ICYT (PB97-0983-C03-02; PB97-0983-C03-03), by the CIRIT (GRQ94-8001) and by the PICS 319.

REFERENCES


Mukai, K. & Ishida, M. 1999, IAU Circular 7205

Orio, M, Torroni, V. & Ricci, R. 1999, IAU Circulars 7196, 7197


Fig. 1.— Comparison between the Utku et al. (1998) rates and those from Wiescher & Kettner (1982), as well as comparison between $^{18}$F (p,α) and $^{18}$F (p,γ) rates, for a wide temperature range.

Fig. 2.— Gamma-ray spectrum at $t=12$ h after peak temperature, for a CO nova of $1.15 \, M_\odot$ (solid line) and an ONe nova (dashed line). The old spectrum from Gómez-Gomar et al. (1998) for the CO nova model is also shown for comparison (dotted line).
Table 1: Main properties of the ejecta 1 hour after peak temperature. $T_{\text{max}}$ is the peak temperature, $<E_{\text{kin}}>$ the mean kinetic energy, in units of $10^{45}$ ergs. The ejected masses of $^{13}$N and $^{18}$F are in $M_\odot$.

<table>
<thead>
<tr>
<th>Nova type</th>
<th>$M_{\text{wd}}$ ($M_\odot$)</th>
<th>$T_{\text{max}}$ (K)</th>
<th>$&lt;E_{\text{kin}}&gt;$</th>
<th>$M_{\text{ej}} (^{13}\text{N})$</th>
<th>$M_{\text{ej}} (^{18}\text{F})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO</td>
<td>1.15</td>
<td>2.05 x 10$^8$</td>
<td>1.1</td>
<td>2.3 x 10$^{-8}$</td>
<td>2.6 x 10$^{-9}$</td>
</tr>
<tr>
<td>ONe</td>
<td>1.15</td>
<td>2.31 x 10$^8$</td>
<td>1.5</td>
<td>2.9 x 10$^{-8}$</td>
<td>5.9 x 10$^{-9}$</td>
</tr>
<tr>
<td>ONe</td>
<td>1.25</td>
<td>2.51 x 10$^8$</td>
<td>1.5</td>
<td>3.8 x 10$^{-8}$</td>
<td>4.5 x 10$^{-9}$</td>
</tr>
</tbody>
</table>

Table 2: Fluxes, in photons.s$^{-1}$.cm$^{-2}$, at different times after peak temperature, in two energy bands in the continuum and in the 511 keV line (FWHM=8 keV), for a CO nova of 1.15 $M_\odot$ and an ONe nova of 1.25 $M_\odot$, at a distance of 1 kpc. The fraction of escaping energy in gamma-ray photons is displayed in the last column.

<table>
<thead>
<tr>
<th>t(hours)</th>
<th>Model</th>
<th>$F_{(20-250)\text{keV}}$</th>
<th>$F_{(250-511)\text{keV}}$</th>
<th>$F_{511\text{keV line}}$</th>
<th>fraction escaping (in %)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>CO</td>
<td>2.5 x 10$^{-1}$</td>
<td>9.6 x 10$^{-2}$</td>
<td>2.2 x 10$^{-2}$</td>
<td>0.4</td>
</tr>
<tr>
<td></td>
<td>ONe</td>
<td>2.2 x 10$^{-2}$</td>
<td>9.3 x 10$^{-3}$</td>
<td>1.8 x 10$^{-3}$</td>
<td>0.02</td>
</tr>
<tr>
<td>3</td>
<td>CO</td>
<td>5.3 x 10$^{-3}$</td>
<td>1.8 x 10$^{-3}$</td>
<td>3.6 x 10$^{-4}$</td>
<td>1.9</td>
</tr>
<tr>
<td></td>
<td>ONe</td>
<td>1.6 x 10$^{-2}$</td>
<td>7.2 x 10$^{-3}$</td>
<td>1.6 x 10$^{-3}$</td>
<td>4.2</td>
</tr>
<tr>
<td>6</td>
<td>CO</td>
<td>8.1 x 10$^{-3}$</td>
<td>2.9 x 10$^{-3}$</td>
<td>6.0 x 10$^{-4}$</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>ONe</td>
<td>1.7 x 10$^{-2}$</td>
<td>8.8 x 10$^{-3}$</td>
<td>1.9 x 10$^{-3}$</td>
<td>17</td>
</tr>
<tr>
<td>12</td>
<td>CO</td>
<td>2.5 x 10$^{-3}$</td>
<td>1.2 x 10$^{-3}$</td>
<td>3.0 x 10$^{-4}$</td>
<td>39</td>
</tr>
<tr>
<td></td>
<td>ONe</td>
<td>3.8 x 10$^{-3}$</td>
<td>2.6 x 10$^{-3}$</td>
<td>6.7 x 10$^{-4}$</td>
<td>47</td>
</tr>
<tr>
<td>24</td>
<td>CO</td>
<td>2.5 x 10$^{-5}$</td>
<td>3.0 x 10$^{-5}$</td>
<td>8.4 x 10$^{-6}$</td>
<td>77</td>
</tr>
<tr>
<td></td>
<td>ONe</td>
<td>5.2 x 10$^{-5}$</td>
<td>7.4 x 10$^{-5}$</td>
<td>2.0 x 10$^{-5}$</td>
<td>80</td>
</tr>
<tr>
<td>48</td>
<td>CO</td>
<td>1.5 x 10$^{-7}$</td>
<td>2.3 x 10$^{-6}$</td>
<td>2.0 x 10$^{-8}$</td>
<td>95</td>
</tr>
<tr>
<td></td>
<td>ONe</td>
<td>1.1 x 10$^{-5}$</td>
<td>2.7 x 10$^{-5}$</td>
<td>8.2 x 10$^{-6}$</td>
<td>94</td>
</tr>
</tbody>
</table>
\[ \frac{^{18}F(p,\alpha)^{15}O}{^{18}F(p,\gamma)^{19}Ne}, \text{Utku et al.} \]

\[ ^{18}F(p,\alpha)^{15}O, \text{Utku et al. / WK82} \]

\[ ^{18}F(p,\gamma)^{19}Ne, \text{Utku et al. / WK82} \]