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X-ray and γ-rays from stellar explosions: models, observations and challenges for the instrumentation

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Abstract

The importance of high-energy astrophysics for the understanding of the Cosmos is reviewed, with special emphasis on stellar explosions, which play a crucial role on the origin of the chemical elements in the Universe. The main properties of accreting white dwarfs, which are at the origin of nova and thermonuclear supernova explosions, are presented, as well as the main features of their X- and γ-ray emission. Main results from past and current observations, as well as prospects for detection with future instruments are summarized, together with a brief historical review of the satellites working in the X- and γ-ray domain. Some comments about recent advances and current challenges regarding instrumentation for high-energy astrophysics are also included.

1 Introduction

One of the most spectacular and nicest objects in the sky is the "Crab nebula" (see for instance the famous ESO picture at http://www.eso.org/public/images/eso9948f/). This nebula is in fact the remnant of a supernova explosion, discovered by chinese astronomers in 1054. It is at a distance of about 6000 light years, and hosts the well-observed Crab pulsar. At first glance, it is soon understood that the energy of the explosion that originated this nebula should have been enormous, strongly affecting the surrounding medium as expansion of the ejecta proceeded. Other more recent examples - e.g. Tycho, Kepler, Cas A and SN 1006 galactic supernova remnants - either from core collapse or thermonuclear supernovae again show us that such stellar explosions should have had a huge impact on their host galaxy, the Milky Way. They are crucial for the origin of the chemical elements, the trigger of star formation and the dynamics of the Galaxy.

The abundances of the chemical elements (in fact of all the isotopes) in the Solar System are known with very good precision. They can be well reproduced by taking into account the contribution of the Big Bang (H, He and a fraction of the light elements Li, Be and B), cosmic rays spallation reactions (the light elements) and nucleosynthesis in stars (all the other elements). Most of the elements come from stellar explosions, which eject huge quantities of matter into the interstellar medium. This material has been processed by nuclear reactions in stars, hydrostatic and/or explosively. Giant stars - when they evolve into white dwarfs - and massive stars - during phases with strong stellar winds - also contribute to the chemical enrichment of the Galaxy. As stated by Hubert Reeves several decades ago, we are made of "dust from the stars". Models of global chemodynamical evolution of the Galaxies reproduce quite well (although still with too many free parameters) the amount and distribution of chemical elements along our Galaxy.

The view of supernova remnants, and of the Universe in general, in X- and γ-rays traces the most energetic phenomena taking place there, such as the acceleration of particles up to GeV, TeV or larger energies (origin of cosmic rays) or the synthesis of radioactive elements. Acceleration of particles is the consequence of strong shocks between the ejecta and the circumstellar material, which are revealed through thermal and non-thermal emission of the heated plasma, in the X-ray energy range. On the other hand, fresh radioactive isotopes synthesized during stellar explosions decay producing γ-ray lines at characteristic energies, and also positrons which annihilate with electrons, producing γ-rays (line and continuum emission).

In fact, mass-accretion onto degenerate stars (white dwarfs, neutron stars, black holes) is at the origin of the emission of X and γ-rays through a variety of processes, e.g., bremmstrahlung, synchrotron, Compton and inverse Compton, nuclear and atomic transitions (the latter for heavy nuclei). In this review we mainly concentrate on stellar explosions of white dwarfs (classical and recurrent novae, thermonuclear - or type Ia - supernovae), with a particular emphasis on their emission of X-rays and "soft γ-rays", in the MeV range, i.e., corresponding to nuclear transitions and also to electron-positron annihilation.

2 Recent and current X- and γ-ray satellites

The last 20 years correspond to the so-called "Golden Age" of X and γ-ray astronomy, with a number of powerful satellites, some of them still in orbit. In the γ-ray domain, the "Compton Gamma-Ray Observatory", CGRO, from NASA (1991-2000) flew four instruments: OSSE, COMPTEL, EGRET and BATSE, which made important discoveries. One of the most important CGRO hits was the discovery with BATSE of more than 2700 gamma-ray bursts (GRBs), with an isotropic distribution in the sky (not following at all the galactic plane or any other galactic population tracer); this showed that those phenomena should occur at cosmological distances, and thus their energetic output was the largest ever observed. The COMPTEL instrument also provided new interesting data, specially the galactic map of the radioactive isotope ^{26}Al, showing some hot spots corresponding to regions of massive stars with ongoing star formation, instead of the expected diffuse emission tracing the whole galactic plane [8]. It was also important its discovery of ^{44}Ti in the Cas A supernova remnant [25]. Since ten years ago (2002), the INTEGRAL satellite is in orbit, providing new and interesting results, in the hard X-ray range (with the IBIS instrument) and in the MeV γ-ray range, with SPI. For instance, the 511 keV line galactic map (and also the positronium continuum emission map), show a puzzling bulge dominated distribution, with a lower than expected emission in the galactic plane (see for instance [27]). Regarding the ^{26}Al line at 1.8 MeV, it has been seen with unprecedented energy resolution - thanks to INTEGRAL/SPI - along the Galaxy, with blue and redshifts correlated with the rotation of the Galaxy. Therefore, the ^{26}Al sources corotate with the Galaxy and ^{26}Al is spread along it, with massive stars and core collapse supernovae being the main producers [9]

No individual nova or supernova has been detected, except the exceptional SN1987A in the LMC, which was observed by several instruments on balloon flights and also by CGRO/OSSE. The MeV range is in fact extremely challenging observationally (see Sect. 5 about the future of instrumentation).

In the X-ray energy range, progress in the last 20 years has been paramount. The improvement in the mirror building techniques, together with the much better performance of detectors and the advent of gratings have led to much larger sensitivities, and much better spectral and angular resolutions. For instance, powerful instruments like those onboard XMM-Newton from ESA (1999-) and Chandra (1999-) from NASA, have allowed for the detection of very faint sources (XMM-Newton) and to get exceptional resolving power in crowded regions like the galactic center (Chandra). XMM-Newton has a large effective area, with its three co-aligned instruments including many concentric mirrors, whereas Chandra has less effective area but with better mirrors able to provide better spatial resolution. Therefore, both satellites complement each other. Grating instruments onboard XMM-Newton and Chandra also allow for unprecedented energy resolution. Other current important satellites also working in the X-ray range are the japanese Suzaku, launched in 2005 (reaching higher energies - 600 keV - than XMM-Newton and Chandra, 10 keV), and Swift from NASA (2004-), with its XRT instrument, 10 times less sensitive than XMM-Newton, but with a companion instrument (Swift/BAT) allowing for the detection of higher energy sources, like GRBs.

The recently turned-off RXTE satellite (1995-2012) has been an exceptional and long-lived X-ray observatory, providing a continuous coverage of the sky in X-rays, discovering many new transient sources and their timing properties. It was essential to trigger observations of new and old transient phenomena with XMM-Newton and Chandra.

3 Explosions of accreting white dwarfs

White dwarfs are the final stages of the evolution of stars with masses smaller than 8–11 $M_\odot$. The final fate of isolated white dwarfs is just cooling down to invisibility. However, when they are in interacting binary systems, more exciting phenomena can happen, like nova explosions and supernovae of the thermonuclear class, i.e., type Ia supernova explosions. Accretion of matter from the companion star is responsible for such interesting phenomena, but the path from the onset of accretion up to the final explosion can be rather complicated.

3.1 Thermonuclear supernovae (SNIa)

It is known that thermonuclear supernovae (or Type Ia supernovae) are the result of the explosion of a carbon-oxygen (CO) white dwarf, once it reaches the critical density for carbon ignition; this occurs either at the center of the star or off-center, always in strongly degenerate conditions. Therefore, it is expected that the properties of such explosions are quite uniform, in agreement with the observations, allowing for their use as standard candles for cosmological purposes. In contrast, core collapse supernovae come from the explosion of a massive star, and gravitational collapse is the driver of the explosion; therefore, such supernovae show a wide range of observational properties, since the range of masses of the progenitor stars is extremely large.

Type Ia supernovae are very important cosmological tools, which have shown the accelerating expansion of the Universe; they are also crucial contributors to the chemical and dynamical evolution of the Galaxy, and they act as well as the triggering mechanism for star formation; however, their exact scenario is still unknown.

The two basic scenarios for the progenitors of type Ia supernova explosions are the single degenerate scenario, where the white dwarf is accreting matter from a main sequence or a red giant star companion, and the double degenerate scenario, where the merging of two white dwarfs occurs. In the first case, accreted matter is hydrogen-rich, except when the companion is a helium star [31] and pure He is accreted. In the double degenerate scenario, accreted matter can be either pure He or a mixture of carbon and oxygen, depending on the type of white dwarf companion.

Accretion of H-rich material - in the single degenerate scenario - poses some problems, since hydrogen is not seen in the spectra of type Ia supernovae (absence of hydrogen is one of the defining properties of the type I -and in particular Ia- class). However, according to models, some hydrogen should be stripped from the secondary star during the explosion and, therefore, some hydrogen should exist in the ejecta [32, 33]. This hydrogen is predicted to move with small velocities (lower than $\sim$ 10000 km/s), and its detection is hard at the stages where bulk material expands at larger speeds. In the last years, there have been serious attempts to search for hydrogen in the spectra of type Ia supernovae, and upper limits have been obtained which do not completely contradict the single degenerate scenario (see for instance [30] and references therein). In fact, there has been detection of circumstellar material, indicative of a red giant companion (i.e., single degenerate scenario) in a few cases [21, 38].

Another important issue is to know the mass and chemical composition of the accreting white dwarf, which are strongly related. Three compositions are possible for white dwarfs: helium, carbon-oxygen (CO) and oxygen-neon (ONe). The mass range over which the white dwarf progenitor star undergoes either the AGB (Asymptotic Giant Branch) phase, without carbon ignition and leaving a CO core, or the super-AGB phase, which burns carbon and leaves an ONe core, is still controversial. The mass of the progenitor star for which an ONe white dwarf can form ranges between $\sim$ 8 and 10 $M_\odot$, depending on the treatement of convection (and specially on the inclusion or not of overshooting) and mass-loss during the previous binary evolution and during the thermal pulses themselves [39, 11]. Only CO white dwarfs are expected to explode as type Ia supernovae, since they are carbon-rich. On the contrary, ONe white dwarfs are expected to collapse, because of the effect of electron captures on ^{24}Mg (see for instance [35, 36, 3, 20] and references therein).

Anyway, the single degenerate scenario seems not to be "on fashion" nowadays, because some deep observations of the regions around supernova explosions have not succeeded to find the companion, which should have survived the explosion (see for instance [16], where it is shown that there's not a surviving companion of the remnant of SN1006).

Two possibilities exist, regarding the mass of the white dwarf: Chandrasekhar and sub-Chandrasekhar. The standard scenario is based on the explosion of a Chandrasekhar mass CO white dwarf, but it has been claimed that relatively low-mass CO white dwarfs could also explode. In this case, helium detonation on top of the white dwarf would drive the final central or off-center carbon ignition responsible for the explosion (see for instance [45]). The propagation of the outward carbon burning through material at a lower density (than in a Chandrasekhar mass white dwarf) alleviates the problem of the absence of intermediate-mass elements (such as Si and S, for instance) of the old pure carbon detonation models of Chandrasekhar mass white dwarfs (e.g., [34]). But other problems arise in the sub-Chandrasekhar scenario, because it does not reproduce the observed velocities of the intermediate-mass elements; however, this scenario has not been completely ruled out, and a lot of multidimensional works have been dedicated to study it (e.g., [13, 12] and references therein).

As a summary, there are not yet successful simulations of the explosion (see the review by [23]), although important progress has been made, specially regarding multidimensional simulations.

3.2 Novae

Classical novae are explosions occurring on top of white dwarfs in close binary systems with a solar-like star companion, i.e., in cataclysmic variables. Transfer of hydrogen-rich matter onto the white dwarf is the driver of the explosion, provided that the white dwarf is massive enough and that the mass accretion rate is low enough. Matter accumulates on top of the white dwarf until it reaches hydrogen ignition conditions, with a pressure such that there is electron degeneracy. This leads to a thermonuclear runaway, because once nuclear burning starts self adjustment of the envelope through expansion is not possible.

Explosive hydrogen burning synthesizes some β^+-unstable nuclei of short lifetimes (e.g. ^{13}N, ^{14}O, ^{15}O, ^{17}F, with τ=862, 102, 176, and 93s respectively) which are transported by convection to the outer envelope, where they are preserved from destruction and where they decay later on. These decays lead to a huge energy release in the outer envelope, which causes the nova outburst, with a large visual luminosity increase accompanied by mass ejection with velocities typically in the range $10^2 - 10^3$ km/s.

Mixing between the accreted envelope (roughly with solar composition) and the underlying white dwarf (CO or ONe) is a necessary condition both to power the explosion and to get the large over solar metallicities observed in several nova ejecta [14]. 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. Recent efforts with multidimensional codes have not yet succeeded completely in reproducing the necessary mixing needed to power the explosion (see a review in [15] and some multidimensional results in [2] and references therein). Recent simulations have shown that Kelvin-Helmholtz instabilities are the source of inhomogeneous mixing in nova explosions [4]

Classical nova explosions are recurrent phenomena, since only the outer envelope is ejected (contrary to type Ia supernova explosions, where the whole white dwarf is disrupted). Typical recurrence times are of the order of $10^4 - 10^5$ years. The orbital periods of the hosting CVs range between hours and days, with average separations of $\sim 10^{10}$cm. A galactic nova rate of $\sim$(20-40)/yr is expected in our Galaxy [42]

In a few cases, the companion of the white dwarf is a red giant star instead of a main sequence star, losing mass via its stellar wind; the host system of the nova explosion is then a symbiotic binary instead of a cataclysmic variable. The larger mass transfer rate drives more frequent outbursts, and then more than one nova outburst can be recorded in human lifetime. These are called "recurrent novae" (although, as said above, all novae are recurrent). Orbital periods in symbiotic recurrent novae are much larger than in classical novae, i.e., a few 100 days, as well as average separations $\sim 10^{13} - 10^{14}$cm. There are about 10 recurrent novae known in the Galaxy, although there could be more that have been probably missed [41].

4 X-rays and γ-rays from stellar explosions

The production of γ-rays in nova and supernova explosions is related to the synthesis of radioactive isotopes (see the list of the most relevant isotopes in Tables 1 and 2). Three types of decay chains can occur: electron captures (^{56}Ni $\rightarrow$ ^{56}Co, ^{57}Ni $\rightarrow$ ^{57}Co $\rightarrow$ ^{57}Fe, ^{44}Ti $\rightarrow$ ^{44}Sc and ^{7}Be $\rightarrow$ ^{7}Li), β^+ decays (^{56}Co $\rightarrow$ ^{56}Fe, ^{44}Sc $\rightarrow$ ^{44}Ca, ^{26}Al $\rightarrow$ ^{26}Mg and ^{22}Na $\rightarrow$ ^{22}Ne) and β^- decays (^{60}Fe $\rightarrow$ ^{60}Co $\rightarrow$ ^{60}Ni). The isotopes listed in Table 1 (^{56}Ni, ^{56}Co, ^{57}Ni, ^{44}Ti, ^{26}Al and ^{60}Fe) are synthesized in supernova explosions (although not exclusively in the case of ^{26}Al), whereas those listed in Table 2 are synthesized in classical novae (plus ^{26}Al). It is important to distinguish the nucleosynthesis during the pre-explosive stage (especially for the massive stars in core collapse supernovae) from that in the explosive phases; it is crucial as well to know which part of the star will finally be ejected, since this will determine the final enrichment of the Galaxy in radioactive (and other) elements. For thermonuclear supernovae, the whole star (white dwarf) is disrupted.

Two types of isotopes can be distinguished, depending on their lifetime (see [10] for a review). Short-lived isotopes, such as ^{56}Ni, ^{57}Ni (and their daughters ^{56}Co and ^{57}Co), ^{44}Ti and ^{60}Co, have lifetimes short enough (see Table 1) to make them detectable in individual objects (see Sect. 4.1). ^{56}Ni and ^{57}Ni are produced in all types of supernovae; ^{44}Ti is mainly produced in core-collapse supernovae, but it can also be synthesized in thermonuclear supernovae of the sub-Chandrasekhar type. ^{60}Co is produced directly and from ^{60}Fe decay, with ^{60}Fe belonging to the long-lived isotopes group.

Long-lived radioactive isotopes, such as ^{26}Al and ^{60}Fe, have lifetimes long enough to make them undetectable in individual sources, because the nuclei can be quite far away from

Table 1: Main radioactive isotopes synthesized in explosive events

Isotope	Decay chain	Lifetime	Line energy (keV)
^{56}Ni	^{56}Ni $\rightarrow$ ^{56}Co	8.8d	158, 812, 750, 480
^{56}Co	^{56}Co $\rightarrow$ ^{56}Fe	111d	847, 1238
^{57}Ni	^{57}Ni $\rightarrow$ ^{57}Co $\rightarrow$ ^{57}Fe	(52h) 390d	122, 136
^{44}Ti	^{44}Ti $\rightarrow$ ^{44}Sc $\rightarrow$ ^{44}Ca	89yr (5.4h)	78, 68, 1157
^{26}Al	^{26}Al $\rightarrow$ ^{26}Mg	1.0x10^{6}yr	1809
^{60}Fe	^{60}Fe $\rightarrow$ ^{60}Co $\rightarrow$ ^{60}Ni	2.0x10^{6}yr (7.6yr)	1173, 1332

Table 2: Main radioactivities in nova ejecta

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

their source and mixed with those coming from other explosions (since their lifetime is longer than the typical period between two successive explosions in the Galaxy). For these isotopes, the accumulated emission in the Galaxy can be observed and used as diagnostic of models and of the Galactic distribution of the sources (see comments about galactic ^{26}Al emission in Sect. 2). The same classification scheme applies to isotopes synthesized in novae; in this case, ^{7}Be belongs to the short-lived group, potentially detectable in individual novae, whereas ^{22}Na belongs to both of them.

Supernova and nova explosions are also important emitters of X-rays, which have a completely different origin. There are various mechanisms for X-ray production in such explosions. There is optically thin emission in the hot ejecta of novae and supernovae; there is also optically thick emission of the hot white dwarf photosphere after nova explosions, whenever residual hydrogen burning remains active on the white dwarf surface before the nova turns-off.

4.1 Supernovae and their remnants

In a thermonuclear supernova (SNIa), degenerate ignition of ^{12}C in a CO white dwarf transforms all the ^{12}C and ^{16}O into the so-called "intermediate-mass" elements (Si, S, Ca) and

Ni (^{56}Ni and ^{57}Ni), mainly (see Sect. 3.1). It is worth reminding that all the Galactic iron comes from the radioactive niquel synthesized in SNIa [7], through the chain ^{56}Ni $\rightarrow$ ^{56}Co $\rightarrow$ ^{56}Fe, with the lifetimes indicated in Table 1. In fact the lifetimes of ^{56}Ni and ^{56}Co dictate the visual light curve evolution (half-lifes of 6 days and 77 days, determine its two successive slopes), because the visual energy output is driven by the radioactive isotopes ^{56}Ni and ^{56}Co. It is also important because of the γ-rays released (see Table 1). The radioactive chain ^{57}Ni $\rightarrow$ ^{57}Co $\rightarrow$ ^{57}Fe, also plays an important role for the γ-ray emission, with a bit longer lifetimes.

The γ-ray spectral evolution of SNIa with different assumptions for the burning propagation of carbon were shown in [17]. The cases considered corresponded to detonation (supersonic flame), delayed detonation, deflagration (subsonic flame) and the sub-Chandrasekhar case (see Sect. 3.1). It was shown that γ-rays are a powerful tool to discriminate models of SNIa, but unfortunately they are very difficult to detect. SNIa are more intense γ-ray emitters than core collapse supernovae, since γ-rays can escape very fast and all the ^{56}Ni can be observed; on the contrary, in core collapse supernovae γ-rays should go through a huge amount of mass before escaping, so that they are partially absorbed and the γ-ray luminosity is smaller. However, the only supernova that has been clearly detected up to now in γ-rays was SN1987A, in the LMC. This was not a SNIa, but its proximity made it detectable. Both the 847 keV line of ^{56}Co and the 122 kev line of ^{57}Ni line were detected [28].

There was a recent nearby SNIa, SN2011fe, in the Pinwheel Galaxy (Messier 101), at 6.4 Mpc [37]. It has been observed by INTEGRAL, but unfortunately not detected [26]. As already anticipated 15 years ago in [17], the SNIa γ-ray lines are expected to be broad, which makes their detection really challenging with current instruments, even at short distances.

Another radioactive isotope that has been detected in supernovae is ^{44}Ti - in supernova remnants, in fact, since it has a medium lifetime which leads to its accumulation after decades. The first γ-ray detection of the ^{44}Ti 1.16 MeV line was in the SNR Cas A with the Comptel instrument onboard the CGRO (see Sect. 2). ^{44}Ti was also detected in hard X-rays (68 and 78 keV lines) with the BeppoSAX X-ray satellite. Very recently, the ^{44}Ti lines at 68 and 78 keV have been also detected in SN1987A, with the IBIS/ISGRI instrument onboard INTEGRAL [19].

Supernova remnants are important emitters of X-rays, which provide impressive views of their structure and composition. A nice example is the remnant of the Tycho Brahe supernova (which exploded in 1572) as seen by the Chandra X-ray satellite. The plasma heated by shock waves and the effect of particle acceleration are clearly seen in those images (see image and comments in http://chandra.harvard.edu/photo/2011/tycho2/).

4.2 Classical and recurrent novae

Crucial information about the explosion mechanism of classical and recurrent novae is obtained from the study of their X-ray emission in outburst. After the explosion, a fraction of the accreted envelope - or even the whole envelope with some material dredged-up from the core of the underlying white dwarf - is ejected. Steady nuclear burning is expected to take place on the (potential) remaining H-rich envelope on top of the white dwarf. As shown through nova multi wavelength observations, the decline in the visual luminosity after optical maximum, happens in parallel with an increasing luminosity in the ultraviolet. The reason is that the radius of the photosphere decreases (because the photosphere recedes as the envelope mass is depleted), and consequently the effective temperature increases. Therefore, the spectrum hardens from visual to UV and to soft X-rays. In fact, the bolometric luminosity remains quasi constant during such phase. Supersoft X-rays reveal the hot white dwarf photosphere, with typical effective temperatures of several 10^5K (up to 10^6K); they can be observed once the expanding ejecta becomes transparent enough to such radiation. Typical soft X-ray luminosities are close to the white dwarf Eddington limit, i.e., $\sim 10^{38}$erg/s. The duration of the supersoft X-ray emission phase is directly related to the amount of H-rich matter remaining on top of the white dwarf after the nova explosion; it indicates the length of the turn-off phase of the nova [40].

Internal and external shocks, within the ejecta and between the ejecta and the surrounding medium, are another cause of X-ray emission from classical novae. These shocks heat the plasma which then emits as an optically thin medium, mainly through thermal bremsstrahlung, with a spectrum harder than the supersoft one corresponding to the photosphere. In the particular case of symbiotic recurrent novae, where the companion is a red giant, there's a strong interaction between the nova ejecta and the red giant wind, which is responsible for the emission of very hard X-rays, or even very energetic gamma-rays (see below), as in V407 Cyg and RS Oph [43, 1, 24].

Finally, the nova emits as a cataclysmic variable once accretion is reestablished [22]. Both soft and hard X-rays are expected. The spectral characteristics depend on the magnetic field of the white dwarf: the cataclysmic variable can be magnetic (either a polar - direct accretion onto the magnetic poles of the WD - or an intermediate polar - with a truncated disk) or non magnetic (with a standard accretion disk). Intermediate polars are expected to emit harder X-rays than polars, since the plasma is hotter because cyclotron cooling is less effective.

Regarding γ-rays, a detailed view of the radioactive isotopes synthesized in novae is displayed in Table 2. In addition to ^{7}Be (mainly synthesized in CO novae) and ^{22}Na (in ONe novae mainly, as well as ^{26}Al shown only in Table 1), we include in Table 2 the very short-lived ^{13}N and ^{18}F (see Sect. 3.2). These are β^+-unstable nuclei, which emit positrons when they decay. The annihilation of these positrons with ambient electrons produces line emission, at 511 keV, and a continuum below this energy.

The shape an intensity of the γ-ray output of novae, related to the radioactive decay of the unstable isotopes synthesized during the explosion, as well as its temporal evolution does not depend only on the amount of γ-ray photons produced, but also on how they propagate through the expanding envelope and ejecta ([29, 18]). Several interaction processes affect the propagation of photons, i.e. Compton scattering, e$^-$–e$^+$ pairs production and photoelectric absorption (see details in [18]).

The most prominent features of the spectra are the annihilation line at 511 keV and the continuum at energies between 20-30 keV and 511 keV (in both nova types), the ^{7}Be line at 478 keV in CO novae, and the ^{22}Na line at 1275 keV in ONe novae. There's a sharp cut-off at energies around 20–30 keV, caused by photoelectric absorption. A few hours after the outburst, when transparency increases, the back-scattering of the 511 keV photons produces a feature at 170 keV. The main differences between spectra of CO and ONe novae are, as expected, the long-lived lines: 478 keV in CO novae as compared with 1275 keV in ONe novae, which directly reflect the different chemical composition of the expanding envelope (^{7}Be-rich in CO novae and ^{22}Na-rich in ONe ones).

The 511 keV line and the continuum below this energy are the most intense emissions, but they appear very soon (even before the nova is dicovered optically), and disappear very fast (because of the short lifetimes of ^{13}N and ^{18}F, the isotopes releasing positrons). Therefore, this prompt and intense emission can only be detected with wide field-of-view instruments, monitoring the whole sky very often.

A second mechanism of γ-ray production in novae is related to acceleration of particles in shock waves, expected to be relevant only when the nova ejecta collides with the wind of the red giant companion, i.e., only in the case of recurrent novae in symbiotic binaries. A good example is the symbiotic recurrent nova RS Oph, which had its two last eruptions in 1985 and 2006. Once the nova explodes, an expanding shock wave forms which sweeps the red giant wind: the system behaves as a "miniature" supernova remnant, evolving much faster and being much dimmer. It was predicted that this nova could accelerate cosmic rays ([43, 24]), with the ensuing emission of γ-rays with energies larger than 100 MeV coming mainly from neutral pion, π^0, production. Such emission from RS Oph would have been detected by the Fermi satellite, but it was not in orbit yet in 2006. A more recent object, V407 Cyg (another nova occurring in a symbiotic binary with a red giant companion) has been detected by Fermi ([1]), thus confirming our previous theoretical predictions for RS Oph. Two more novae, this time not belonging to symbiotic binaries, have been detected: Nova Sco 2012 and Nova Mon 2012 [5, 6]. It is still a mystery why such novae have produced very high-energy γ-rays. They probably had a dense environment, but not related to a red giant companion star.

5 Future instrumentation

Gamma-ray astronomy in the MeV range, which is the most interesting for observations of nucleosynthesis products of stellar explosions, has always faced important challenges from the instrumental point of view. In addition to the general difficulties of γ-ray detection (few signal photons have to be extracted from a very intense background), the MeV range is specially difficult, since it corresponds to the energy range where Compton scattering - with small cross sections and harder to handle than photoelectric absorption or pair formation, at lower and larger energies respectively - is dominant. Past and current γ-ray instruments in the MeV range make use of geometrical optics - shadowcasting in modulating aperture systems - or quantum optics - Compton scattering. This kind of instruments have the problem that *bigger does not necessarily mean better*. The reason for this apparent contradiction is that the collection area in traditional γ-ray telescopes should be roughly equal to the detection area. Therefore, the larger the collection area, the larger the detection volume and thus the higher the instrumental background. Significative improvements in sensitivity thus need huge instruments, not suitable for space missions.

An innovative concept for detecting γ-rays in the MeV range, which would overcome this problem and allow for unprecedented sensitivities, consists of focusing the γ-rays from a large collection area onto a small detector. This *γ-ray lens* concept is based on the diffraction of the incident radiation of a particular energy onto a common focal spot where the detector is placed [44]. Laue diffraction lenses have demonstrated their potential in laboratory measurements (see [44] and references therein). In addition, a balloon flight of a Laue lens prototype (CLAIRE) and a ground test of it, a collaboration between CESR, Toulouse, and ICE (CSIC-IEEC), have successfully demonstrated the lens principle. However, there's not yet an approved space mission based on the γ-ray lens.

Regarding X-rays, there's a mission called LOFT (Large Observatory for X-ray Timing) which has been approved by ESA as an M3 mission (medium class) candidate, in the framework of the Cosmic Vision Programme 2015-2025. This is mainly a timing mission, aimed to understand the behavior of matter under extreme conditions (neutron stars, black holes), as well as to continue the study of the transient universe so successfully studied by the recently turned-off RXTE satellite. Our Institute ICE (CSIC-IEEC) participates actively in LOFT (see http://www.isdc.unige.ch/loft/ for details). Another very interesting and challenging X-ray mission proposal is IXO, of the ESA's large class (see http://sci.esa.int/science-e/www/area/index.cfm?fareaid=103). It is of the major importance for X-ray astronomy to have a successor of the very successful missions in orbit nowadays, which won't be available anymore in a not very distant future.

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References

[1] Abdo, A.A. et al. 2010, Science, 329, 817

[2] Alexakis, A. 2004, ApJ, 602, 931

[3] Canal, R., Isern, J., & Labay, J. 1992, ApJ, 398, L49

[4] Casanova, J., José, J., García-Berro, E., Shore S.N., & Calder, A. 2011, Nature, 478, 490

[5] Cheung, T. et al. 2012, #ATel 4284

[6] Cheung, T. et al. 2012, #ATel 4310

[7] Clayton, D.D. 1999, Met. & Plan. Sci., 34, A145

[8] Diehl, R. et al. 1995, A&A, 298, 445

[9] Diehl, R. et al. 2006, Nature, 439, 45

[10] Diehl, R. & Timmes F.X. 1998, PASP 110, 637

[11] Eldridge, E.E., & Tout, C.A. 2004, Mem. S.A. It., 75, 694

[12] Fink, M., Hillebrandt, W., & Röpke, F.K. 2007, A&A, 476, 1133

[13] García-Senz, D., Bravo, E., & Woosley, S.E. 1999, A&A, 349, 177

[14] Gehrz R.D., Truran, J.W., Williams, R.E., & Starrfield, S.E. 1998, PASP, 110, 3

[15] Glasner, S.A., Livne, E., & Truran, J.W. 2007, ApJ, 625, 347

[16] González Hernández, J.I., Ruiz-Lapuente, P., Tabernero, H.M., et al. 2012, Nature, 489, 533

[17] Gómez-Gomar, J., Isern, J., & Jean, P. 1998, MNRAS, 295,1

[18] Gómez-Gomar, Hernanz, J.M., José, J., & Isern, J. 1998, MNRAS, 296, 913

[19] Grebenev, S.A., Lutovinov, A.A., Tsygankov, S.S., & Winkler, C. 2012, Nature 490, 373

[20] Gutiérrez, J., García-Berro, E., Iben Jr., I., et al. 2006, ApJ, 459, 701

[21] Hamuy, M., et al. 2003, Nature, 424, 651

[22] Hernanz, M. & Sala, G. 2002, Science, 298, 393

[23] Hillebrandt, W., & Niemeyer, J.C. 2000, ARA&A, 38 191

[24] Hernanz, M., & Tatischeff, V. 2012, Baltic Astronomy, 21, 62 (arXiv:1111.4129)

[25] Iyudin, A., et al. 1994, A&A, 284, L1

[26] Isern, J., et al. 2011, ATel #3683

[27] Knödlseder, J., et al. 2005, A&A, 441, 513

[28] Leising, M.D. 1988, Nature, 332, 516

[29] Leising, M.D. & Clayton, D.D. 1981, ApJ, 323, 159

[30] Leonard, D.C. 2007, ApJ, 670, 1275

[31] Limongi, M. & Tornambe, A. 1991, ApJ, 371, 317

[32] Marietta, E., Burrows, A., & Fryxell, B. 2000, ApJS, 128, 615

[33] Meng, X., Chen, X., & Han, Z. 2007, PASJ, 59, 835

[34] Nomoto, K. 1982, ApJ, 257, 780

[35] Nomoto, K. 1987, ApJ, 322, 206

[36] Nomoto, K. & Kondo, Y. 1991, ApJ, 367, L1

[37] Nugent, P., et al. 2011, Nature, 480, 34

[38] Patat, F., et al. 2007, Science, 317, 924

[39] Ritossa, C., García-Berro, E., & Iben Jr., I. 1996, ApJ, 460, 48

[40] Sala, G. & Hernanz, M. 2005, A&A, 439, 1061

[41] Schäfer, B.E. 2010, ApJS, 187, 275

[42] Shafter, A.W. 1997, ApJ, 487, 226

[43] Tatischeff, V. & Hernanz, M. 2007, ApJ, 663, L101

[44] von Ballmoos, P., et al. 2004, New Astronomy Reviews, 48, 243

[45] Woosley S.E. & Weaver, T.A 1994, ApJ, 423, 37