EXPLOSIVE NUCLEOSYNTHESIS

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ABSTRACT

Many radioactive nuclei relevant for gamma-ray astrophysics are synthesized during explosive events, such as classical novae and supernovae. A review of recent results of explosive nucleosynthesis in these scenarios will be presented, with a special emphasis on the ensuing gamma-ray emission from individual nova and supernova explosions. The influence of the dynamic properties of the ejecta on the gamma-ray emission features, as well as the still remaining uncertainties in nova and supernova modelling will also be reviewed.

Key words: gamma rays: observations; novae; supernovae; nuclear reactions, nucleosynthesis, abundances.

1. INTRODUCTION

In this paper I will review the sites of explosive nucleosynthesis relevant for gamma-ray astronomy. Two main types of explosion are responsible for the emission of gamma-rays in the Galaxy: supernovae, both thermonuclear and gravitational (core-collapse) and classical novae.

Thermonuclear supernovae, or supernovae of type Ia, are exploding white dwarfs in close binary systems, which do not leave a remnant after the explosion. Core collapse supernovae (supernovae of type II, Ib/c) are exploding massive stars (M$\sim$ 10$M_\odot$), which leave as remnant either a black hole or a neutron star. Typical velocities of supernovae ejecta are some 10$^4$ km s$^{-1}$, energies involved 10$^{51}$ erg and ejected masses some M$_\odot$.

Classical novae are the result of the explosion of the external H-rich accreted shells of a white dwarf in a binary system. These explosions are recurrent phenomena (contrary to supernovae), since an explosion is expected every time the critical accreted mass on top of the white dwarf is reached. Typical velocities of novae ejecta are between some 10$^2$ and 10$^3$ km s$^{-1}$, energies involved 10$^{45}$ erg and ejected masses between 10$^{-3}$ and 10$^{-5}$ M$_\odot$.

The radioactive isotopes synthesized during explosive nucleosynthesis, either in novae or in supernovae, are summarized in table 1. 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), $\beta^+$ decays ($^{56}$Co $\rightarrow$ $^{56}$Fe, $^{44}$Sc $\rightarrow$ $^{44}$Ca, $^{26}$Al $\rightarrow$ $^{26}$Mg and $^{22}$Na $\rightarrow$ $^{22}$Ne) and $\beta^-$ decays ($^{60}$Fe $\rightarrow$ $^{60}$Co $\rightarrow$ $^{60}$Ni). The first six isotopes in the table ($^{56}$Ni, $^{56}$Co, $^{57}$Ni, $^{44}$Ti, $^{26}$Al and $^{60}$Fe) are produced in supernova explosions (although not exclusively, at least in the case of $^{26}$Al), whereas the last two are synthesized in classical novae. In sections 2 and 3 below, I will discuss how the synthesis of these radioactive nuclei proceeds in these scenarios. In the case of core-collapse supernovae, it is important to distinguish the nucleosynthesis during the pre-explosive stage of the massive star evolution from that in the explosive phases; it is crucial as well to know which part of the star will finally be ejected, since this quantity will determine the final enrichment of the Galaxy in radioactive (and other) elements. I won’t discuss the synthesis of radioactive isotopes in other (non-explosive) sites, like the AGB stars (see the contribution by Mowlavi, these proceedings) or the Wolf-Rayet stars (which can eject radioactive nuclei by strong stellar winds, during their hydrostatic evolution; see Arnould and Meynet 1997 and Meynet and Arnould, 1999 for recent reviews).

2. SYNTHESIS OF RADIOACTIVE ISOTOPES IN SUPERNOVA EXPLOSIONS

Two types of isotopes can be distinguished, depending on their lifetime (see Diehl and Timmes, 1998, for a recent 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. $^{56}$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 (provided that they
exist; see discussion of SNeIa types below). $^{60}$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 their source and mixed with those coming from other explosions (since the lifetime is longer than the typical period between two successive explosions in the Galaxy). For these isotopes, only the accumulated emission in the Galaxy can be observed and used as diagnostic of models and of the Galactic distribution of the sources. The same classification scheme applies to isotopes synthesized in novae; in this case, $^7$Be belongs to the short-lived group, whereas $^{22}$Na belongs to both of them (see section 3 below).

A very recent and interesting compilation of papers about astronomy with radioactivities can be found in Diehl and Hartmann (1999).

### 2.1. Observational clues

Gamma-ray astronomy provides an unique opportunity to detect radioactive isotopes in individual objects, giving a proof of ongoing nucleosynthesis in them. In the case of supernovae, another tool for the determination of the amount of radioactive nuclei in the ejecta is the bolometric light curve (UVOIR, from ultraviolet, optical and infrared). In addition to the well known fact that $^{56}$Co (daughter of $^{56}$Ni) powers the early evolution of the light curve ($^{56}$Ni mass can be determined from luminosity at maximum), $^{57}$Co is responsible for powering the light curve from around day 1000 after maximum. Later on $^{44}$Ti will provide a floor to the bolometric light curve and $^{22}$Na and $^{56}$Co could also play a minor role, depending on the supernova type and the specific yields of these radioactivities (see, e.g., Woosley, Pinto and Hartmann, 1989, Timmes et al. 1996, Diehl and Timmes 1998).

These two types of observational approaches to the radioactive content in the ejecta had been possible for only one object so far: the supernova 1987A, which exploded 13 years ago in the LMC, only 55 kpc away from us. This was a type II supernova, which is not the most favorable case to look for gamma-ray emission, since its is much more opaque and has a smaller content of the most relevant radioactivities than SNeIa (see below); however, its very short distance allowed for detection of its gamma-ray emission and also for a follow-up until very late times of its light curve (through photometry in the UVBRIJHK bands).

Gamma-ray lines from $^{56}$Co decay, at 847 and 1238 keV, were detected in SN 1987A with the GRS instrument of the SMM satellite (Matz et al. 1988) and confirmed by several balloon-borne instruments (i.e., Teegarden et al. 1989, Mahoney et al. 1988, Sandie et al. 1988, Cook et al. 1988, Rester et al. 1989). One surprising fact was the appearance of these lines only 200 days after the explosion (Matz et al., 1988), much earlier than expected. This has been interpreted as a sign of some early extra mixing of $^{56}$Co in order to transport this isotope into regions of low gamma-ray optical depth (see, e.g., Pinto and Woosley, 1988, Leising 1988, Bussard, Burrows and The, 1989, Leising and Share, 1990). The line profiles observed with GRIS (Teegarden et al. 1989, Tueller et al. 1990) have also put constraints on theoretical models of supernova explosions, since sphericity and homogeneity of the ejecta were incompatible with the observed fluxes and widths of the $^{56}$Co lines.

Another crucial gamma-ray observation of short-lived isotopes in SN 1987A was the detection of gamma-ray radiation from $^{57}$Co decay (between 50 and 136 keV), with OSSE on the CGRO (Kurfess et al. 1992). The deduced $^{57}$Co content (for models with low gamma-ray optical depth, see Kurfess et al. 1992) was such that the original ratio $^{57}$Ni/$^{56}$Ni produced in the explosion should be about 1.5 times the solar $^{56}$Fe/$^{56}$Fe ratio. Observations up to now show the change of slope related to the sequence of $^{56}$Co-$^{57}$Co decays (see figure 3 in Timmes et al. 1996). Future UVOIR observations would possibly be able to show the light curve powering from $^{44}$Ti. The SPI instrument onboard INTEGRAL has some possibilities to detect the gamma-ray emission from this $^{44}$Ti, which would provide a unique proof of the nucleosynthesis in core collapse supernovae and an important link between the UVOIR and the gamma-ray observations. Coming back to $^{57}$Co it was first thought that the SN 1987A $^{57}$Co content deduced from OSSE observations was not enough to power the available bolometric light curve, since 5 times solar $^{57}$Fe/$^{56}$Fe ratio was required (Suntzeff et al. 1992) and alternative mechanisms to power the bolometric light curve were suggested (Clayton et al. 1992). However, more recent observations seem to require a smaller amount of $^{57}$Co-decay to power the light curve, in agreement with the $^{56}$Fe/$^{56}$Fe ratio deduced from OSSE observations (see figure 9 in Diehl and Timmes 1998).

The excitement induced by the above mentioned gamma-ray observations (together with many other observations at other wavelength ranges) has led the theorists to suggest different possibilities for mixing both during the explosion and the ejection phases (to quote only a few of the early works, see e.g., Arnett, Fryxell and Müller 1989, Benz and Thielemann 1990, Fryxell, Arnett and Müller 1991, Herant and Benz 1992, and also the general reviews of SN 1987A from Arnett et al. 1989 and McCray 1993 and references therein).

Another detection (tentative) of gamma-ray emission from a supernova, with COMPTEL on CGRO, was that of SN 1991T (which was an overluminous SNIIa), in NGC 4527 at around 17 Mpc distance. In that case, a marginal detection of the 847 keV line was reported (Morris et al. 1995, 1997), leading to a prediction of a quite large $^{56}$Ni mass, implying that all the white dwarf mass should have been incinerated, which is a rather unlikely scenario. All these observations confirm the importance of using gamma-rays in supernova studies, as they provide unique tools to test theoretical models and to constrain nucleosynthesis in supernovae.
ated to $^{56}\text{Ni}$ (in contradiction with current theoretical models). More recently, upper limits to the fluxes of the 847 and 1238 keV lines from $^{57}\text{Co}$-decay in the type Ia supernova 1998bu, in NGC 3368 at around 8 Mpc distance, have been deduced from COMPTEL observations (Georgii et al. 2000). Although no detection has been obtained, these limits are restrictive enough to constrain some of the available models of SNeIa nucleosynthesis (like a sub-Chandrasekhar mass model from Nomoto et al. 1997).

There is another important observation of gammaray lines related to short and medium-lived radioactivities in supernovae: the discovery of $^{44}\text{Ti}$ emission at 1157 keV in the Cas A supernova remnant (Iyudin et al. 1994; see reviews from Diehl and Timmes 1998 and Knödlseder, these proceedings). Again the observations in gamma-rays are in some way puzzling, because the amount of $^{44}\text{Ti}$ deduced from observations implies a $^{56}\text{Ni}$ content (according to theoretical models of supernovae nucleosynthesis) which should have originated a very bright supernova, in contrast with the absence of historical records (Timmes et al. 1996). Observations in gamma-rays push forward the theoretical models, in order to balance all the available possibilities and to consider new ones.

A different kind of information is obtained from the observations of long-lived radioactivities ($^{26}\text{Al}$ and $^{60}\text{Fe}$). In this case, what is seen is not the ongoing nucleosynthesis in a particular object, but the integrated nucleosynthesis in the Galaxy. Up to now, this has been possible for the 1809 keV $^{26}\text{Al}$ emission. The $^{26}\text{Al}$ map obtained with the COMPTEL instrument onboard the Compton Gamma-Ray Observatory CGRO (Diehl et al. 1995, 1997, Oberlack et al. 1996, Knödlseder 1997, 1999, Plüschi et al. these proceedings) has posed interesting questions about the origin of the galactic $^{26}\text{Al}$ (see, e.g., review from Prantzos and Diehl, 1996). It provides a direct and unique insight on the integrated nucleosynthesis during the last $10^6$ years. Some regions of enhanced emission have been discovered (Cygnus, Carina, Vela), indicating the presumable link between $^{26}\text{Al}$ emission and massive star formation, as well as the relationship with spiral structure of the Galaxy (Diehl et al. 1996, Knödleseder et al. 1996a,b, Diehl et al. 1999, Knödlseder, these proceedings). For $^{60}\text{Fe}$, a similar map should be observed by INTEGRAL, because the sources of this isotope are the same as those of $^{26}\text{Al}$, being the yields smaller by some factor (Timmes et al. 1995, Diehl et al., 1997).

It is worth mentioning that the integrated nucleosynthesis of $^{44}\text{Ti}$ and $^{22}\text{Na}$ may also be seen, if instruments are sensitive enough. The future $^{44}\text{Ti}$ and $^{22}\text{Na}$ maps will provide a precious information about their sources, i.e., supernovae (mainly core collapse ones) and novae, respectively.

2.2. Thermonuclear supernovae (SNeIa)

The defining characteristic of SNeIa is the lack of hydrogen in their spectra, as well as the presence of a P Cygni feature related to SiII, $\lambda_{6335}$, at maximum light (Wheeler and Harkness 1990); in general, intermediate-mass elements (O, Mg, Si, S, Ar, Ca) appear in the spectrum near maximum light with high velocities (8000-30000 km s$^{-1}$). SNeIa are quite homogeneous from the observational point of view (i.e., $\sim$90% of all SNeIa have similar spectra, light curves and peak absolute magnitudes), although some differences exist (i.e., subluminous explosions, like SN1991bg and SN1992K, and overluminous ones, like SN1991T). SNeIa appear in both elliptical and spiral galaxies and, therefore, their progenitors should be long-lived. These facts altogether suggest that the thermonuclear disruption of mass-accreting carbon-oxygen (CO) white dwarfs is responsible for these explosions. Already in the sixties, Hoyle and Fowler (1960) suggested that thermonuclear burning in an electron-degenerate stellar core might be responsible for type I supernova (there was no subclassification at the epoch) explosions, with the explosion energy coming from the thermonuclear burning of CO into higher mass elements (see also, e.g., the pioneering works by Arnett 1969, Hansen and Wheeler 1969). It was also suggested at the epoch that the early supernova luminosity might have its origin on the radioactive decay of $^{56}\text{Ni}$ (Colgate and McKee 1969), which was already known to be a product of supernova nucleosynthesis, and that gamma-ray lines should be emitted from those explosions (Clayton, Colgate and Fishman, 1969). But the particular scenario where the explosion occurs (see, e.g., Livio 1999) and the physics of the flame itself (see, e.g., Hillebrandt and Niemeyer 2000) are far from being understood.

Two types of progenitors have been suggested so far, concerning the mass of the exploding CO white dwarf: Chandrasekhar and sub-Chandrasekhar mass models. In the Chandrasekhar mass models, a CO white dwarf explodes when reaching that mass, with central carbon ignition propagating outwards being responsible for the explosion. The main problems related to this model are the uncertainties concerning burning propagation (deflagration, detonation, delayed detonation, see below), but also the scenario is unclear. Either a double degenerate (merging of two CO white dwarfs) or a single degenerate scenario is possible. In all cases, the growth to the Chandrasekhar mass is problematic, because both mass loss (through nova episodes, for instance) and accretion induced collapse (if the initial mass is high enough and/or the white dwarf is made of oxygen and neon) should be avoided (see, e.g., Canal, Isern and Labay 1990, 1992, Canal et al. 1990, Isern, Canal and Labay 1991, Nomoto and Kondo 1991, Bravo and García-Senz 1999). In addition, for the double degenerate scenario there is a problem of statistics: there are not enough double white dwarf systems with sufficiently short period and total mass in excess of the Chandrasekhar mass able to explode.
in less than the Hubble time and to explain the galactic SNeIa rate. In fact there wasn’t any observed system fulfilling these conditions until the very recent discovery of KPD 1939+2752 (Maxted, Marsh and North, 2000), which is the first SNIa progenitor candidate observed.

In the sub-Chandrasekhar mass models, a CO white dwarf of low-mass (0.6-0.8 M⊙) accretes helium (\(\Delta M_{\text{He}} \sim 0.1-0.2\ M_{\odot}\)), reaching a final mass smaller than the Chandrasekhar mass. Provided the accretion rate is moderate (around \(10^{-8}\ M_{\odot}\ \text{yr}^{-1}\)), there is He ignition on the top of the CO core. This ignition causes an outward propagating He-detonation wave (basically transforming He into Ni at high velocity) and an inward propagating pressure wave. The last one finally provokes a carbon ignition (central or off-center), which leads to an outward carbon-detonation incinerating all the white dwarf, and synthesizing intermediate-mass elements, in addition to Ni (see, e.g., Livne 1990, Livne and Glassner 1991, Woosley and Weaver 1994). Therefore, in this model (called “indirect double detonation”, IDD, or “edge lit detonation”, ELD) there is an outer layer of high-velocity Ni and He above the intermediate-mass elements, which does not exist in the Chandrasekhar-mass models. Sub-Chandrasekhar mass models are not considered as good SNeIa progenitors nowadays, because of both observational and theoretical problems; observational: the high velocity Ni above intermediate mass elements is not seen in the spectra; theoretical: the He-driven carbon detonation is very model dependent (see for instance the 3D models from García-Senz, Bravo and Woosley 1999). But it is still a possibility that sub-Chandrasekhar mass models explain some subluminous SNeIa, like SN1991bg (see, e.g., Ruiz-Lapuente, Canal and Burkert 1997).

In summary, the bulk of normal SNeIa are assumed to be exploding Chandrasekhar-mass CO white dwarfs, but there is still room for the sub-Chandrasekhar mass models to explain some peculiar objects. Therefore, whether SNeIa come from single or double-degenerate scenarios and whether they come from carbon or helium plus carbon ignition are not closed issues (see, e.g., the recent paper from Branch 2000).

The main problems still remaining on the modeling of SNeIa affect the ignition process and the flame propagation. Different possibilities exist: deflagration (subsonic flame speed), detonation (supersonic) and a combination of both (delayed detonation). A detonation with densities larger than ~10^7 g cm^{-3} is not a viable mechanism, since all the star would be incinerated to Ni, without synthesis of intermediate-mass elements. On the contrary, if the density is lower, intermediate-mass elements are synthesized, in agreement with the observations. Concerning deflagrations, they produce nucleosynthesis at velocities in general agreement with the observed spectra, but some neutronized isotopes (such as ^{54}Fe, ^{54}Cr and ^{58}Ni) are overproduced in amounts incompatible with the chemical evolution of the Galaxy. To overcome this problem, delayed detonations were suggested (Khokhlov 1991a). There are two situations in which a deflagration to detonation transition (DDT) could occur in supernovae (see, e.g., Khokhlov, Oran and Wheeler, 1997): DDT could occur directly or as a result of a previous expansion. For instance, in the pulsation delayed detonation, a first slow deflagration is quenched because of the expansion of the white dwarf, which subsequently pulses and recontracts, causing a detonation upon recollapse (Khokhlov 1991b). The propagation of the detonation wave through the pre-expanded star produces the required intermediate mass elements in the outer layers at densities lower than ~10^7 g cm^{-3} (which are not synthesized in detonations at larger densities). In these models, the problem of overproduction of highly-neutronized nuclei is alleviated but not solved (Khokhlov 1991a, b). Models of delayed detonations in 2D, both of the first deflagration phase and of the subsequent detonation phase, have been performed by Arnett and Livne (1994a, b); they show that the first slow deflagration is insufficient to unbind the star, that a pulsation of large amplitude is generated and that reignition occurs after the first contraction phase.

In summary, there is a general consensus about the fact that, in order to explain spectroscopic observations, burning should proceed subsonically (deflagration) in the inner core (where densities are large, i.e., \(\rho > 10^8\ g\ cm^{-3}\)), whereas burning becomes supersonic (detonation) in the outer lower density zones (see examples of models in Bravo et al. 1993, Höflich and Khokhlov 1996, Bravo et al. 1996, Woosley 1997). But the way in which the deflagration to detonation transition (DDT) occurs is not yet clear, (see, e.g., discussions in recent papers by Niemeyer and Woosley 1997, Niemeyer 1999, Lisewski, Hillebrandt and Woosley 2000, and in the review by Hillebrandt and Niemeyer 2000). There is also ample debate about the way in which the initial burning occurs: flame instabilities, flame-turbulence interactions (see review about turbulence and thermonuclear burning by Hillebrandt and Niemeyer 1997, and references therein).

All 1D models (which were the unique ones available up to the nineties and still are the only ones to include complete nucleosynthesis) rely on prescriptions based on some parametrization of the flame speed and, in the case of delayed detonations, of the deflagration-detonation transition -DDT- densities. Different groups work in models of thermonuclear SNeIa and their nucleosynthesis, including the radioactivities. It is out of the scope of this paper to mention even a small fraction of them, but a small sample can be useful to show the main results and the main caveats still remaining (see the recent books Thermonuclear Supernovae, edited by Ruiz-Lapuente, Canal and Isern, 1997, and Type Ia Supernovae: Theory and Cosmology, edited by Niemeyer and Truran, 2000). Nomoto and coworkers have computed detailed nucleosynthesis in carbon deflagration supernovae (Nomoto, Thielemann and Yokoi, 1984, Thielemann, Nomoto and Yokoi, 1986),
and also in other types of explosive carbon burning (such as delayed detonations, with parametrized ignition densities and deflagration-detonation transition –DDT- densities, see Iwamoto et al. 1999). The yields of radioactive isotopes are mainly affected by the DDT density (i.e., synthesized mass of $^{56}\text{Ni}$ ranges from 0.55 to 0.77 M$_\odot$, and $^{57}\text{Ni}$ from 9.6x10$^{-3}$ to 1.98x10$^{-2}$ M$_\odot$, in Iwamoto et al.’s models). These yields are larger than those from core collapse supernovae (see below) and distributed in less opaque zones, since there isn’t much mass above them. This makes type Ia supernovae better targets for INTEGRAL than SNeII (but see section 2.1 for observational results). In the context of gamma-ray astronomy, it is important to stress that sub-Chandrasekhar mass models synthesize larger amounts of $^{44}\text{Ti}$ than Chandrasekhar mass ones (see, e.g., Woosley and Weaver, 1994).

Gamma-ray spectra of SNeIa for the different models provide important signatures of the explosion mechanism, although unfortunately there isn’t much observational data to compare with (see previous section). Prospects for SNeIa explosion mechanism identification with gamma-rays have been analyzed recently by Gómez-Gomar et al. (1998a), with a special emphasis on detectability with the instruments that will be onboard INTEGRAL (see also Burrows and The 1990, Höflich, Khokhlov and Müller 1994, Kumagai and Nomoto 1997, Höflich, Wheeler and Khokhlov 1998).

Lines from $^{56}\text{Ni}$-decay ($158$, $750$, $812$ keV) are prominent during the first days after the explosion, but they disappear very fast, because of the short $^{56}\text{Ni}$-lifetime. Lines from $^{56}\text{Co}$ ($847$, $1238$ keV) and $^{57}\text{Co}$ ($122$, $136$ keV) appear later and have longer durations. The most intense lines are those at $847$, $1238$, $812$ and $158$ keV, in addition to the annihilation line at $511$ keV. The strongest line is always the $847$ keV one (detectable up to 11-16 Mpc with SPI on INTEGRAL), whereas the $158$ keV line (from $^{56}\text{Ni}$-decay) is the most interesting to discriminate between models. The $158$ keV line is narrower and, therefore, detectable at longer distances with SPI, than another $^{56}\text{Ni}$-line (at $812$ keV), despite being fainter. It is almost undetectable in pure deflagration models, whereas it is even stronger than the $1238$ line in detonation models. Another interesting signature of the models is the ratio between the $847$ keV and the $158$ keV line fluxes (200 days after maximum and at maximum, respectively), because it provides information about the ratio between total $^{56}\text{Ni}$ in the ejecta and $^{56}\text{Ni}$ in the external layers: the late emission at $847$ keV comes from $^{56}\text{Co}$-decay (coming from $^{56}\text{Ni}$-decay), while only the $^{56}\text{Ni}$ present in the outermost shells is responsible for the $158$ keV line flux (see Gómez-Gomar et al. 1998a for details). Finally, line profiles will also provide important information allowing for discrimination between the models, for explosions at distances short enough (see again Gómez-Gomar et al. 1998a).

2.3. Core-collapse supernovae

All supernova types except type Ia’s (i.e., type II, Ib/c) are explained by the explosion of massive stars. Stars with initial masses ($M > 10$ M$_\odot$) don’t end their lives as white dwarfs. Successive phases of thermonuclear burning ($\text{C}$, $\text{Ne}$, $\text{O}$, $\text{Si}$) give as a result a star with an “onion-skin” structure, where a central iron core is surrounded by shells made of elements of progressively lower atomic mass. The chemical composition along the star is the following (see, e.g., figure 10.8, corresponding to a $25$ M$_\odot$ star, in Arnett 1996): $\text{Fe}$ core, $\text{Si}$-burning zone (made mainly of elements from Si to Ni, without $\text{O}$), $\text{O}$-burning zone ($\text{O}$, $\text{Si}$-$\text{Ca}$), Ne-burning zone ($\text{Ne}$, $\text{Mg}$ and $\text{O}$, no $\text{C}$), C-burning zone ($\text{C}$ and $\text{O}$, Ne and Mg), radiative He-burning zone ($\text{He}$, $\text{C}$ and $\text{O}$), convective He zone, inert part of old He core (interior to H-burning shell), material above the H-burning shell (plus some inert zones associated with the $\text{Si}$, $\text{O}$ and C-burning zones and just outside them). Once the Fe-core reaches the Chandrasekhar mass, it becomes unstable and collapses to form a neutron star. The gravitational energy released ($\sim 10^{54}$ erg) during core collapse is responsible for the ensuing supernova explosion, but it is not yet completely understood how the conversion of this potential energy into kinetic energy proceeds (only 0.1% of the available potential energy is needed).

Baade and Zwicky (1934) were the first to suggest that the gravitational energy released during the formation of a neutron star could produce a supernova explosion. Colgate and White (1966) built a supernova model, considering that the transfer of energy takes place by the emission and deposition of neutrinos; Wilson (1971) showed that the electron capture neutrino burst was not strong enough to eject material. The Weinberg-Salam model of electroweak interactions opened new possibilities of neutrino interactions with matter (neutral currents). In 1974, Freedman noticed the importance of neutral currents in the physics of core collapse supernovae; as a result of the increased cross section of core material to neutrinos, these particles are trapped during the collapse. It was shown by Bethe et al. in 1979 that one of the consequences of neutrino trapping is that the entropy of the core changes little during collapse (it remains low), leaving the collapse continue up to nuclear densities. Further compression is prevented by the repulsive component of the strong interaction (stiffness of nuclear matter), leading to the core bounce. A shock wave is generated at its boundary and propagates outwards. But it has been shown that the energy of this shock is mainly invested in the photodisintegration of heavy nuclei and in neutrino losses; therefore, the shock stalls and the explosion via the so called “prompt mechanism” is unsuccessful. In the “delayed mechanism”, there is a revival of the stalled shock because of neutrino heating behind the shock (Bethe and Wilson 1985). However, the explosion energy does not reach easily the necessary $10^{51}$ erg. Further works introduced the effect of convective instabilities, caused by a negative
entropy gradient, in order to deliver energy to the shock (see, e.g., Bethe, 1990, Herant, Benz and Colgate 1992, Herant et al. 1994, Bethe 1995, Janka and Müller, 1995, Burrows, Hayes and Fryxell, 1995, to quote only a few of the papers dealing with this topic). Convection aids the explosion because it increases the efficiency at which neutrino energy is deposited (material that rises cools and converts energy from neutrino deposition into kinetic energy, instead of re-radiating it as neutrinos) and also reduces the energy required to launch the explosion (by reducing the pressure at the accretion shock) (see recent reviews by Fryer, 2000, Burrows 2000, and references therein). The handling of this process is very model dependent: treatment of neutrino transport, multidimensional aspects. Also the structure of the stellar core before collapse (i.e., the presupernova model) are important for the final outcome of the explosion.

Fortunately, nucleosynthesis during core collapse supernova explosions can be computed without a complete knowledge of the explosion mechanism itself. As in the case of thermonuclear supernovae, all the details of the physics involved in the explosion are not required to have an approximate, but quite good when compared with the observations, idea of which are the main nucleosynthetic yields of core collapse supernovae. Two steps are needed to compute SNIa (and Ib/c) yields: nucleosynthesis during the massive star evolution (i.e., pre-supernova phase) and explosive burning when a shock wave crosses the mantle surrounding the collapsing core.

There are different ways to simulate the explosion artificially. One is by means of a “thermal bomb”, i.e., injecting thermal energy inside the Fe core, in a way such that the ejecta attains the desired kinetic energy, \( \sim 10^{51} \text{erg} \) (see, e.g., Thielemann, Nomoto and Hashimoto, 1996). Another alternative is the injection of momentum, through a piston, inward-moving during the infall previous to the explosion, and outward-moving during the explosion, with a velocity such that the desired kinetic energy of the ejecta is obtained (see, e.g., Woosley and Weaver, 1995). The mass cut between the collapsing core and the ejecta determines the amount of mass ejected (and that of \(^{56}\text{Ni}\) and other radioactive isotopes, in particular). In the “thermal bomb” method, they adjust it taking into account the relationship between supernova progenitor masses and \(^{56}\text{Ni}\) masses ejected deduced from some observations. In the piston approach, the mass cut is obtained from the choice of piston position and energy; a mass cut located outside the piston is often obtained (for a discussion of the differences between both models, including an analysis of the influence of the nuclear reaction rates, see Hoffman et al., 1999). In summary, both groups have performed calculations of detailed nucleosynthesis by inducing the core-collapse supernova explosion on massive stars (previously evolved following all the nucleosynthesis phases). Other groups have performed studies of massive star evolution, but there is no room in this short review to mention all of them.

The masses studied by Thielemann et al. (1996) range between 13 and 25 \(M_\odot\), with initial metallicities, \(Z\), equal to solar (see Nakamura et al. 1999 for the effect of low \(Z\)). Woosley and Weaver (1995) studied the range 11-40 \(M_\odot\), for \(Z=0\) and \(Z\) between \(10^{-4}\) and \(Z_\odot\). Si, O, Ne and C explosive burning occurs when the shock wave crosses the corresponding zones in the pre-supernova (see above for the description of its structure). A brief description of the results concerning the synthesis of radioactive isotopes follows.

\(^{56}\text{Ni}\) and \(^{57}\text{Ni}\) are produced when either oxygen or silicon-rich layers with low neutron excess \((Y_e \gtrsim 0.498)\) are heated to temperatures above \(4 \times 10^9\) K (explosive O- and Si-burning). They are produced whether the material ejected is alpha-rich or not, although \(^{57}\text{Ni}\) synthesis is favored in alpha-rich freeze-out; this happens when material, initially in nuclear statistical equilibrium (NSE) at relatively low density, is cooled so rapidly that the free alpha particles do not have time to merge via the \(3\alpha\) reaction and, therefore, matter cools down in the presence of a large concentration of \(\alpha\)-particles, which modify the final composition (with respect to the normal freeze-out). \(^{44}\text{Ti}\) is also produced during a-rich freeze-out from NSE in the hottest and deepest layers ejected during the explosion. Therefore, the yields of these radioactive isotopes are very sensitive to the mass-cut location (Woosley and Hoffman 1991, Hoffman et al. 1995, Woosley and Weaver, 1995, Timmes et al. 1996). For example, stars with masses larger than 30 \(M_\odot\) don’t eject any \(^{56}\text{Ni}\) (nor \(^{57}\text{Ni}\) and \(^{44}\text{Ti}\)) if the kinetic energy (at infinity) is around \(1.2 \times 10^{51}\) erg. If this energy is enhanced, the mass-cut is lowered and some \(^{56}\text{Ni}\) (and \(^{57}\text{Ni}\) and \(^{44}\text{Ti}\)) are ejected. Ejected masses of \(^{56}\text{Ni}\) are around 0.1 \(M_\odot\) and those of \(^{44}\text{Ti}\) between \(\sim 10^{-5}\) and \(10^{-4}\) \(M_\odot\). Similar results are obtained by Thielemann et al. (1996), except for the larger amounts of \(^{44}\text{Ti}\), probably because of the different way of simulating the explosion, which possibly injects larger entropy in the inner shells and favors a larger ejected mass and an enhanced \(\alpha\)-rich freeze-out (see, e.g., Aufderheide, Baron and Thielemann 1991 and Hoffman et al. 1999).

\(^{26}\text{Al}\) is another important radioactive isotope which is produced in core collapse supernovae (and in other scenarios) through the \(^{25}\text{Mg}(p,\gamma)\) reaction. \(^{26}\text{Al}\) yields depend on pre-supernova evolution (H- and O-Ne burning shells) and on the explosion. Two factors enhance \(^{26}\text{Al}\) production during the explosion: explosive burning in O-Ne shells and \(\nu\)-spallation reactions on \(^{20}\text{Ne}\), \(^{16}\text{O}\), \(^{23}\text{Na}\), \(^{24}\text{Mg}\), which liberate protons that are captured by \(^{25}\text{Mg}\). It is important to stress that another important long-lived radioisotope, \(^{56}\text{Fe}\), is coproduced with \(^{26}\text{Al}\) in the same regions within SNIa (this isotope is synthesized by neutron captures on \(^{56},^{58}\text{Fe}\) in the O-Ne burning shell and in the base of the He-burning shell, both pre-explosively and explosively). Therefore, these nuclei should have similar spatial distributions in the ejecta (Timmes et al. 1995). The \(^{26}\text{Al}/^{56}\text{Fe}\) ratio depends on the mass of the pre supernova: \(^{26}\text{Al}/^{56}\text{Fe}\) is larger than 1 for \(M\) larger than 25 \(M_\odot\) and similar to 1 for smaller masses. The typical yields of \(^{26}\text{Al}\) are \(10^{-4}\)
The final yields depend on three aspects: presupernova evolution, explosion energy and details of the explosion mechanism (see Diehl and Timmes, 1998 and Thielemann 1999 for recent analyses). The main issues concerning presupernova evolution are those affecting general stellar evolution of low-mass stars, plus some specific ones relative to massive stars. For instance, the treatment of convection affects nucleosynthesis; in particular, convective burning in the O-shell of massive stars. Models with M=20 M⊙ have deserved a particular attention for the theorists, since they are crucial to understand the mixing of radioactive (and other) isotopes, like 56Ni, in supernova ejecta, which has been deduced from the observations of SN1987A (see section 2.1 above). 2D models of O-burning (Bazan and Arnett 1994) obtain significant mixing beyond the boundaries defined by mixing-length convection. What they obtain are perturbations in density in the oxygen shell that are sufficiently large to “seed” hydrodynamic instabilities, which will mix the “onion-skin” composition of the presupernova (Bazan and Arnett 1998). This occurs in precisely the region in which 56Ni is explosively produced by oxygen burning behind the explosion shock. This result poses some problems to the models of explosive nucleosynthesis based on 1D presupernova evolution. Rotation can also have some effect (see, e.g., works by Meynet and Maeder 1997, Heger, Langer and Woosley 2000), as well as mass-loss during the presupernova evolution, in the final yields of radioactive elements. Concerning the energy of the explosion and the details of the explosion mechanism, one of the main problems is the location of the mass-cut, which determines how much mass falls back into the collapsing core (and therefore whether it will be a neutron star or a black hole) and how much mass is ejected and with which composition (the profile of some isotopes is steep around the mass-cut location and, therefore, the yield is affected by it). Therefore, the mass-cut determines crucially the final yields of radioactive elements, specially for those produced in the inner regions of the supernova (56Ni, 57Ni and 44Ti). As mentioned above, the explosion energy, and the corresponding entropy in the inner shells, crucially affect the degree of α-rich freeze-out and, therefore, the yields of the Fe-group nuclei and of 44Ti.

3. CLASSICAL NOVAE

Classical novae explosions are the most common explosions in the Galaxy. The cause of the explosion is a thermonuclear runaway (TNR) on top of a white dwarf, ensuing the degenerate burning of the accreted hydrogen (Starrfield 1989, Hernanz & José 2000). The synthesis of radioactive isotopes in classical nova is important for two reasons. First, some of the isotopes produced are crucial for the explosion mechanism itself (i.e., 14O, 15O, 17F with lifetimes 102, 176 and 93s, respectively). The reason is that these isotopes are transported by convection to the outer layers of the envelope, during the run-away, where they subsequently decay (τ_{conv} < τ_{decay}) and cause the expansion of the envelope and the increase in visual luminosity. Second, the decay of the unstable nuclei generates gamma-ray emission, because of either direct emission of gamma-ray photons or positrons (for β+-unstable nuclei), which annihilate with electrons. The photons emitted (511 keV, positronium continuum, 478 and 1275 keV, see table 1) experience Comptonization in the nova expanding envelope. Therefore, the emission from novae consists of lines plus a continuum (see Gómez-Gomar et al. 1998b, Hernanz et al. 1999, Hernanz et al. these proceedings and references therein). The potential role of classical novae as gamma-ray emitters had been already pointed out many years ago (Clayton and Hoyle 1974, Clayton 1981, Leising and Clayton 1987).

The first available hydrodynamic models of nova explosions (Starrfield et al. 1978 and Prialnik et al. 1978) realized that there was a need of an initial enrichment in CNO isotopes both to power the explosion and to explain some observed abundances. Two and three dimensional simulations of the thermonuclear runaway of a CO white dwarf, valid when the accreted envelope has been already built up, are the only available up to now (Glasner et al., 1997, Kercek et al. 1998, 1999). They predict that enrichment proceeds too slowly if the accreted gas has nearly solar CNO abundances at the onset of the thermonuclear runaway, and conclude that fast nova outbursts require huge enrichments of C and O. The mechanism which leads to such enhancements must operate prior to the outburst and has not been modeled up to now. Therefore, it is known that some mixing with core material (either CO or ONe) during the accretion phase prior to the runaway should occur, but this process has not been modeled yet in a self-consistent way. Another approach to the problem of initial enrichment comes from the multicycle 1D models (of CO novae only, up to now), from Prialnik and Kovetz (Prialnik and Kovetz 1995, Kovetz and Prialnik, 1997); diffusion is responsible for the enrichment, which becomes larger after a number of flashes. However, the large metallicities and neon abundances observed in some novae are not well reproduced. Another approach is based on 1D models with an initial (parametrized) enrichment, such that the general properties of observed novae (mainly abundances) are well modeled (see for instance Starrfield et al. 1998, José and Hernanz 1998). Classical novae synthesize many radioactive isotopes, which vary depending on the nova type (which in turn depends on the type -CO or ONe- of the underlying white dwarf). CO novae produce mainly 7Be, whereas ONe produce 22Na and 26Al. Other radioactive activities with shorter lifetimes, such as 13N and 18F (τ = 862s and 158min, respectively) are produced in similar amounts in CO and ONe novae (see José and Hernanz, 1998, José, Coc and Hernanz, 1999, Hernanz et al. 1999 and Hernanz et al., these proceedings for details). Typically, 10^{-7} - 10^{-8}M⊙ of 13N, 22Na, 26Al and 18F are produced.
10^{-9} M\odot of 18F are ejected in both CO and ONe explosions. CO novae also eject 10^{-9} M\odot of 7Be, and ONe novae 10^{-9} M\odot of 22Na and 10^{-8} M\odot of 26Al. The reason of the different explosive nucleosynthesis results in CO and ONe nova types is that some seed nuclei (such as 20Ne, 22Ne, 24,26Mg) are necessary to synthesize 22Na and 26Al. That’s because temperatures attained at the peak of the nova outburst are not high enough to break the CNO cycle towards NeNa-MgAl cycles.

The two short-lived isotopes 13N and 18F are crucial for the prompt gamma-ray emission of novae, which is the most intense emission (10^{-3} photon cm^{-2} s^{-1}), but of very short duration (a few days) and appearing before optical detection. The medium-lived isotopes (7Be and 22Na) produce fluxes of around 10^{-6} and 10^{-5} photon cm^{-2} s^{-1}, for distances of 1 kpc. The prospects for detectability with the SPI instrument onboard INTEGRAL are analyzed in Hernanz et al. (these proceedings, and references therein). It is important to remind that, in addition to the 7Be and 22Na emission from individual novae, the cumulative emission from all the galactic novae can give important information about the distribution of the sources, specially if there is only one dominant source for that particular isotope. For 22Na, novae are the main individual contributors. Therefore, the detection of galactic 22Na emission, and the corresponding 1275 keV emission map (see Jean et al., 1999, 2000), would be a very valuable tool to study the distribution of novae in the Galaxy, which is very poorly known from optical-UV and IR observations because of interstellar extinction. Finally, 26Al is produced in ONe novae in such an amount that makes it quite improbable that novae contribute largely to the 26Al content of the Galaxy, as observed through its emission at 1809 keV.

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Table 1. 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 | $1.0\times10^6$yr | 1809 |
| $^{60}$Fe | $^{60}$Fe $\rightarrow$ $^{60}$Co $\rightarrow$ $^{60}$Ni | $2.0\times10^6$yr (7.6yr) | 1173, 1332 |
| $^{7}$Be | $^{7}$Be $\rightarrow$ $^{7}$Li | 77d | 478 |
| $^{22}$Na | $^{22}$Na $\rightarrow$ $^{22}$Ne | 3.8yr | 1275 |

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