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The secondary supernova machine: Gravitational compression, stored Coulomb energy, and SNII displays

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ABSTRACT

Radioactive power for several delayed optical displays of core-collapse supernovae is commonly described as having been provided by decays of ^{56}Ni nuclei. This review analyses the provenance of that energy more deeply: the form in which that energy is stored; what mechanical work causes its storage; what conservation laws demand that it be stored; and why its release is fortuitously delayed for about 10^6 s into a greatly expanded supernova envelope. We call the unifying picture of those energy transfers the secondary supernova machine owing to its machine-like properties; namely, mechanical work forces storage of large increases of nuclear Coulomb energy, a positive energy component within new nuclei synthesized by the secondary machine. That positive-energy increase occurs despite the fusion decreasing negative total energy within nuclei. The excess of the Coulomb energy can later be radiated, accounting for the intense radioactivity in supernovae. Detailed familiarity with this machine is the focus of this review. The stored positive-energy component created by the machine will not be reduced until roughly 10^6 s later by radioactive emissions (EC and $\beta+$) owing to the slowness of weak decays. The delayed energy provided by the secondary supernova machine is a few $\times\ 10^{49}$ erg, much smaller than the one percent of the 10^{53} erg collapse that causes the prompt ejection of matter; however, that relatively small stored energy is vital for activation of the late displays. The conceptual basis of the secondary supernova machine provides a new framework for understanding the energy source for late SNII displays. We demonstrate the nuclear dynamics with nuclear network abundance calculations, with a model of sudden compression and reexpansion of the nuclear gas, and with nuclear energy decompositions of a nuclear-mass law. These tools identify excess Coulomb energy, a positive-energy component of the total negative nuclear energy, as the late activation energy. If the value of fundamental charge e were smaller, SNII would not be so profoundly radioactive. Excess Coulomb energy has been carried within nuclei radially for roughly 10^9 km before being radiated into greatly expanded supernova remnants. The Coulomb force claims heretofore unacknowledged significance for supernova physics.

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1. Introduction

A large volume of research has been published on diverse aspects of the core-collapse supernova phenomenon (e.g. Woosley and Weaver, 1986). The SNII events raise complex physical questions. We review one of those questions, the synthesis of radioactive nuclei by supernovae and their later decays causing displays of observable radiations. We describe this as a consequence of a new stimulating picture of what we call the *secondary supernova machine* owing to its machine-like properties. That machine has not been discussed previously. We focus on its clarifying physical picture of the manner in which energy is stored and released later into the supernova envelope, and we show that excess Coulomb energy within nuclei is the form of positive, releasable energy carried radially within particles from the first supernova second until it is released months later. This picture is not likely to alter how numerical computations are done, but it may enlarge the way in which SNII are thought of by physicists and astronomers.

A supernova machine is a device that makes use of prompt gravitational work to release energy to overlying SN regions where that energy is capable of causing observable phenomena. We distinguish immediately between two distinct SNII machines:

1. The *primary* SN machine converts gravitational work during core collapse into energy that is transported promptly by neutrinos or advection to the SN mantle. That energy causes its explosive ejection. This machine acts promptly, but it is not fully understood (e.g. Woosley and Weaver, 1986; Burrows, 2000). The primary machine does not store the energy responsible for the late supernova displays months after the collapse.
2. The *secondary* SN machine creates excess Coulomb energy within nuclei by gravitationally-caused compression of the Si presupernova shell resulting in larger $Z = N$ nuclei. This machine is our focus here. That excess energy is released only later after considerable expansion and thinning, and that delayed energy release emits non-thermal energy into the mantle. The release of excess Coulomb energy is delayed by long weak lifetimes for electron capture (EC) and β^+ decays, which renders that energy observable, producing phenomena that occur months after core collapse.

The following four observable displays of SNII are made visible by delayed weak emission of the excess Coulomb energy:

1. Gamma-ray lines emitted from the supernova surface after interior release of them by radioactive decays: These were predicted long ago (Clayton et al., 1969) and first detected emerging from SN 1987A (Gehrels and Share, 1988).
2. Continuous spectrum of X-rays (Clayton and The, 1991) leaving the SN surface: these were also discovered first from SN1987A by Russian and Japanese X-ray satellites (Sunyaev et al., 1987; Dotani et al., 1987).
3. Non-thermal species made visible in the SN atmosphere, primarily He^+ ions and free C atoms: He^+ would not normally exist thermally near 4000 K but was observed in SN 1987A (Graham, 1988). Likewise, free carbon would not normally exist abundantly because that portion of C inside the He-burning shell would have been oxidized by the larger oxygen abundance as ambient temperature fell through 3500 K (Yu et al., 2013). But Compton electrons from propagating gamma rays restore free C by dissociation of CO molecules.
4. The supernova light curve after the first month: adiabatic expansion would so cool supernova ejecta that they would be dark without radioactive heating (Colgate and McKee, 1969) to maintain hot supernova photospheres. In SN1987A the exponential light curve radiated 10^{49} ergs from 0.07 $M_\odot$ of ^{56}Ni nuclei (Arnett et al., 1989).

These four displays allude to a significant portion of supernova research, and the energy machine that makes them observable is clearly important for astrophysics. We present a new way of visualizing the action of that machine in core-collapse SN. Its essential feature is the establishment by gravitational work of excess Coulomb energy in large alpha-particle ($Z = N$) nuclei such as ^{56}Ni followed by a lengthy delay of the return of that excess Coulomb energy to the greatly expanded supernova envelope. Without considerable delay, returned energy from nuclei would simply be absorbed into the opaque thermal density of the supernova interior, so that the four activations would not be observable.

2. Gravitational work and Coulomb energy

How does gravitational work upon the Si shell of core-collapse supernovae create excess Coulomb energy within its nuclei? That idea needs focus as it is central to the secondary SN machine. A crucial feature of the Si-rich shell is its compositional domination by a very abundant Z = N nucleus; namely, ^{28}Si. Dominant ^{28}Si can be either virtually pure ^{28}Si (a state reached naturally by nuclear evolution) or ^{28}Si accompanied by a less abundant cohort of ^{32}S, ^{36}Ar and ^{40}Ca (e.g. Woosley et al., 1973) that is compressed to higher temperature. The compression occurs either by simple gravitational contraction or by the shock wave that rebounds when matter supersonically falls onto the neutron star. The resulting shock wave is launched by gravitational collapse, so the compression and heating of overlying mantle by that shock wave is also a “gravitationally caused compression”. These gravitationally caused compressions most often occur sequentially in core-collapse supernovae (SNII), and they store Coulomb energy in nuclei. Consider first the mechanisms of compression and storage of Coulomb energy independent of the supernova setting.

2.1. Rapid compression of a ^{28}Si gas stores Coulomb energy in nuclei

Key workings of the secondary supernova machine can best be grasped apart from the complexities of core-collapse supernovae. The storage of increased Coulomb energy owing to compressional work can be seen by the compression of gas in an adiabatic cylinder. Consider a gas of pure ^{28}Si nuclei at, say, $T = 3.14 \times 10^9$ K ($T_9 = 3.14$) and a density of $\rho = 5 \times 10^6$ g/cc. This composition dominated by ^{28}Si nuclei is realistic within one shell of the presupernova star, as is the temperature and density. Imagine the gas in that cylinder adiabatically compressed by a piston to half its initial volume V. Adiabatic compression of an ideal gas follows $TV^{2/3} =$ constant. Consequently, $\rho = 5 \times 10^6$ g/cc is compressed to $\rho = 10^7$ g/cc and $T_9 = 3.14$ is compressed to $T_9 = 5$ by the adiabatic halving of the volume. Suppose further that the compression of the piston is followed by its rapid expansion (on a density e-folding timescale of 0.2 s) until nuclear reactions, which occur at a furious pace at the compression temperature of $T_9 = 5$, “freeze out” near $T_9 = 4$. The compression stroke causes thermal decomposition of ^{28}Si nuclei (Bodansky et al., 1968; Woosley et al., 1973), sometimes called “^{28}Si melting” instead of ^{28}Si burning; but those liberated nucleons are quickly recaptured by other remaining ^{28}Si nuclei because the strength of the nuclear force rebinds them. It is well known that the flurry of nuclear reactions generates an approximately quasiequilibrium abundance distribution between silicon and nickel (Bodansky et al., 1968; Woosley et al., 1973; Meyer et al., 1998). Suppose further that this compression and expansion both happen too quickly for weak decays of nuclei to occur. If, as in a supernova shock wave, the compression and its expansion occurs in less than a second, the bulk nuclei must then maintain $Z = N$ by charge conservation. The transition from ^{28}Si to a QSE (quasiequilibrium) distribution of alpha-particle nuclei is accompanied by significant increase of Coulomb energy contained within that