SUPERNOVA 1987A - TEN YEARS AFTER

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Abstract

Supernova 1987A became a milestone in physics and astronomy. The most important things that have been learned from it, the most important problems yet to be solved and the prospects for learning important new physics from future observations of nearby supernova explosions are shortly summarized.
1 Introduction

SN1987A, the supernova explosion on February 23, 1987 in the nearby Large Magellanic Cloud only about 50 kpc away, was the brightest supernova seen since the invention of the telescope. It is the first supernova which has been visible to the unaided eye since Kepler saw SN1604, the last Supernova seen in our Milky Way galaxy. It has offered a unique opportunity to observe for the first time a supernova explosion from a relatively close distance within the range of various detection techniques. The first signals that were recorded on Earth were neutrino signals in the Mont Blanc (Aglietta et al. 1987), Kamiokande (Hirata et al. 1987), IMB (Bionta et al. 1987) and Baksan (Alexeyev et al. 1988) underground detectors and an unconfirmed gravitational wave signal in the Rome detector (Amaldi et al. 1987). They were followed by a spectacular optical flash that began a few hours later, but was the first signal from 1987A that had been noticed (McNaught 1987). Observations of SN1987A have continued since then, from the ground (optical telescopes, radio telescopes, gravitational wave antennas, high energy γ-ray Cerenkov telescopes and extensive air shower arrays) from underground (neutrino telescopes), from high in the air (detectors aboard high altitude planes and balloons) and from space (Hubble Space Telescope, X-ray telescopes and γ-ray telescopes). They have yielded rich information which is of fundamental importance for astrophysics as well as for other branches of physics and which is documented in hundreds of papers and many excellent reviews that have been published in the scientific literature. I will not attempt to review this vast literature but rather focus on what I think are the most important consequences of SN1987A, the most important things that we have learned from it, the most important problems yet to be solved and the prospects for learning important new physics from future observations of nearby supernova explosions.

2 The Birth of Extrasolar Neutrino Astronomy

Perhaps the most important consequence of SN1987A is the birth of extrasolar neutrino astronomy: When the first large underground water Cerenkov detectors, IMB and Kamiokande, were constructed for looking for proton decays, it was suggested that they can also perform as neutrino telescopes (e.g., Dar 1983 and references therein) which may detect neutrino bursts from galactic supernova explosions and the diffuse cosmological neutrino background from stellar evolution and past supernovae (e.g., Dar 1985). This was dramatically demonstrated when the Kamiokande and IMB telescopes detected the
neutrino burst from SN1987A. This monumental success has probably convinced physicists and funding agencies that galactic and extragalactic neutrino astronomy are not just a dream but are important achievable scientific goals. This has already resulted in the construction of Superkamiokande, an amazing galactic and near galactic neutrino telescope. Together with the pioneering studies of the DUMAND project, SN1987A perhaps also led to the construction of the AMANDA experiment under the south pole, the Baikal experiment under lake Baikal and to the planned NESTOR and ANTARES deep sea projects in the Mediterranean sea offshore Pylos in Greece and offshore France, respectively. The Universe is opaque to very high energy gamma rays because of electron-positron pair production on intergalactic background photons. It is, however, transparent to neutrinos. It is anticipated that when the above experiments will be scaled up to a $1 \, \text{km}^3$, they may detect very high energy neutrinos from Active Galactic Nuclei at cosmological distances, from the mysterious Gamma Ray Bursters and from other unexpected sources. They also may point at the nature and identity of the cosmic accelerators and help solve the 85 years mystery of the origin of high energy cosmic rays. These, to my mind, may be the most important consequences of SN1987A ...

3 Supernova Theory

Already before SN1987A, the theory of type II supernova explosions (SNeII) was able to explain many of the observed properties of SNeII that occur at cosmological distances at a rate of about 1 per second per Universe, but was not able to explain the exact explosion mechanism (see, e.g., Shapiro and Teukolsky 1983 and references therein, Bruenn 1987 and references therein). This has not been changed by SN1987A in spite of continuous theoretical progress, impressive numerical efforts and many important refinements in the theory of SNeII as a result of the detailed observations of both SN1987A and other nearby SNeII. It is now generally believed that spherical symmetric one-dimensional (1-D) codes with the best available physics (improved progenitor profiles, improved equation of state, improved opacities and neutrino transport and general relativistic effects) cannot reproduce SNeII.

Let me first summarize the SNeII theory prior to SN1987A, its spectacular success and its serious problems.

Standard stellar evolution theory predicts that massive stars $8\,M_\odot \leq M \leq 20\,M_\odot$ evolve for $\sim 10^7 \, \text{y}$ by the thermonuclear burning of heavier and heavier fuels and terminate in anion like red supergiant with a white dwarf like central core consisting primarily
of iron group nuclei and supported primarily by electron degeneracy pressure. When
the core mass exceeds the Chandrasekhar mass of about $1.4M_\odot$, gravity overcomes the
degeneracy pressure and collapse begins (e.g., Arnett 1977; Barkat 1977). The central
density of the core increases quickly and reaches a value where electrons from the top
of the Fermi sea can be captured and convert protons, free and in bound nuclei, into
neutrons via $e^- + p \rightarrow n + \nu_e$. The capture of electrons results in a short neutronization
burst (ms) which stops because of Pauli blocking by neutrinos which are trapped in the
core (because of neutral current elastic scattering from nuclei). Electron capture from
the top of the Fermi sea by free protons and iron group nuclei reduces degeneracy pressure
and accelerates the collapse. The collapse becomes essentially a free fall with a time
scale $t \sim 1/\sqrt{G\rho} \sim 50 \text{ ms}$. When the central density of the core reaches supranuclear
density the repulsive QCD forces between nucleon constituents (quarks and gluons) of the
same color stop the collapse, the core bounces and drives a strong shock wave that climbs
outside through the infalling layers. The strong shock supported by energy transport
through convection and neutrinos is believed somehow to reverse the infall velocity of
the layers, to overcome their gravitational binding and to propel them to the observed
expansion velocities of more than 10000 km s$^{-1}$ which amounts to a total kinetic energy
of about $10^{51}$ erg. The shock is believed to produce the spectacular light display of SNeII
(Grassberg, Imshennik and Nadyozhin 1971): With a velocity which is a considerable
fraction of the velocity of light it takes the shock a few hours to reach the atmosphere of the
supergiant (typical radius of about $10^{13}$ cm). When it reaches the atmosphere it heats it
up to a high temperature which produces a UV flash. However, the integrated luminosity
of SNeII ($\sim 10^{49}$ erg) and the total kinetic energy of the ejected shell ($10^{51}$ erg) are only
a tiny fraction of the released energy. Most of the gravitational binding energy of the
collapsed core ($\sim GM^2/R \sim$ a few $10^{53}$ erg) which is released in the collapse is converted
into thermal energy of a protoneutron star, which cools slowly ($\sim$ 10 s) by radiating
neutrinos from its surface (Colgate and White 1966; Wilson et al. 1986 and references
therein, Mayle et al 1987 and references therein). The protoneutron star is essentially
opaque to neutrinos which are thermally produced mainly via $e^+e^- \rightarrow \nu\bar{\nu}$ in the hot core
(central temperature $\sim 30$ MeV) and diffuse slowly to the surface of last scattering (the
“neutrinosphere”) where they are emitted with a much smaller temperature, typically
$3 - 4$ MeV for electron neutrinos and $7 - 8$ MeV for $\mu$ and $\tau$ neutrinos, which can be
predicted from quite general considerations (e.g., Dar 1987).

SN1987A provided a dramatic confirmation of these predictions of the theory of SNeII.
SN1987A was caused by the violent death of a massive star ($\sim 20M_\odot$). The integrated
light emission ($\sim 10^{49}$ erg) and the kinetic energy of the expanding shell ($\sim 10^{51}$ erg)
consisted only of a tiny fraction of the energy released by SN1987A. Most of the energy (a few $10^{53}$ erg) was radiated in neutrinos, which indeed were detected by the Mont Blanc, Kamiokande, IMB and Baksan underground detectors. As expected, neutrino emission preceded the first UV light flash by a few hours. The average energy of the $\bar{\nu}_e$'s was $\sim 13$ MeV (temperature of about 4 MeV) and the duration of the neutrino burst was $\sim 10$ s. This energy is consistent with the gravitational binding energy released in the formation of a neutron star in stellar core collapse. The UV flash and its spectral evolution was well fitted by a shock wave reaching the surface of the supergiant star and heating it. The detection of $\gamma$-ray lines and infrared emission lines confirmed that the exponential decay of the supernova light curve was because the remnant was being heated by radioactivity from isotopes made in the explosion, $0.07 M_\odot$ of $^{56}$Co and $0.003 M_\odot$ of $^{57}$Co.

However, some major predictions of SNeII theory were not very successful and many puzzles remain. They include:

a. Why was the progenitor of SN1987A a blue supergiant and not a red supergiant?
b. How were the triple rings around the remnant of SN1987A (Fig 1.) formed?
c. Why was the explosion aspherical, as evident from the debris of SN1987A?
d. What is the explosion mechanism of SNeII?
e. Did SN1987A produce a neutron star and when will it become visible?
f. Did SN1987A produce a black hole?
g. Did SN1987A bang twice?
h. Did SN1987A emit significant gravitational radiation?

**a. The Progenitor:** For the first time the progenitor of a SNeII has been clearly identified. After the fading of the optical flash from SN1987A, careful measurements have shown that a type B3 blue supergiant, entry number 202 in the declination band 69° south of the equator in a catalog of LMC giants compiled by N. Sanduleak, which was at the exact position of SN1987A, disappeared in the explosion, whereas its two blue neighbor stars (Star 1 and Star 2 at respectively 2.90 and 1.66 arcseconds away) survived the explosion. Astronomers were astonished to find that the progenitor of SN1987A was a blue supergiant and not a red supergiant as thought to be the case for most SNeII. Two alternative explanations have been proposed: Perhaps a $\sim 20 M_\odot$ blue star on the main sequence swelled up to become a red supergiant, lost mass through a stellar wind then contracted and reheated to become a blue supergiant. Another explanation that leads to a blue supergiant is that the progenitor formed from the merger of two stars in a binary system. The prior history of Sanduleak -69° 202 is probably imprinted in the
circumstellar nebulae around SN1987A and will be able to test the two models.

**b. The Rings:** The gas surrounding SN1987A was expected to be illuminated by EUV and X-rays (Chevalier 1988) emitted when the explosion shock wave reached the envelope of the pre-supernova star. Early images taken by the Hubble Space Telescope, which was launched in April 1990, unexpectedly have shown (Wampler et al 1990; Jakobsen et al 1991) that the light emission from the circumstellar gas around the remnant of SN1987A is localized in three ring like forms along a common axis which passes through the remnant of SN1987A (see Fig. 1) and is tilted at roughly 45°. The inner ring is centered on the remnant, has an approximate radius of $R \approx 6.1 \times 10^{17} \text{cm} \ (0.65 \text{ly})$, a mass about 0.2 to 0.4 $M_\odot$ and a radial velocity $v_r \approx 10 \text{ km s}^{-1}$. The ring is also extraordinarily symmetric and highly localized in both space ($\delta R/R \approx 10\%$) and velocity. VLB radio observations and recent HST observations have shown that the radius of the glowing debris from SN1987A is now about 0.1 arcseconds (about 15% of the distance to the ring) and the expansion speed has been nearly constant, over the past 10 year history, i.e., $\approx 0.01 \text{ arcsecond per year or } v_r \approx 2500 \text{ km s}^{-1}$. This is much slower than the speediest material observed back in 1987, which reached 30000 km s$^{-1}$, but probably was of a small mass which was slowed down by the circumstellar gas. Thus, it seems that the rings were there before SN1987A. Various models have been proposed for the origin of the rings. The same basic structure is seen with HST in the Hourglass Nebula, suggesting that some common aspects of mass loss were at work both in this planetary nebula and in SN1987A. Consequently, it was suggested that the SN1987A rings formed by the illumination of a pre-supernova red giant wind that was much thicker at the waist than the poles resulting in an expected hour-glass shape (Luo and McCray 1991; Wang and Mazzali 1992; Blondin and Lunqvist 1993; Martin and Arnett 1995). It was suggested that the glow of the rings is formed by recombination of electrons and atoms that were ionized by the EUV and X-ray flash from SN1987A in the case of the inner ring, and by the EUV and X-ray emissions from a relativistic conical jets in the case of the external rings. Other models assume that the inner ring is a relic from an accretion disk (McCay and Lin 1994) or from an excretion disk from which the presupernova star was born (Chen and Colgate 1996). It is also possible that the inner and outer rings are thin flash ionized layers at the inner surfaces of much greater mass of circumstellar as yet unseen.

c. **Aspherical Explosion ? Jets?** Recent high resolution VLB radio images (Gaensler et al 1997) and HST optical images (Pun 1997) of SN1987A and its inner ring show that the glowing debris of the supernova itself is elongated along the axis of the rings. It was pointed out that a a merger of two stars in a binary system (Podsiadlowski 1992) leads to a blue supergiant progenitor and can explain an equatorial outflow of several solar masses
of gas during a merger of the two stars some 20,000 years before the explosion. Such a merger would probably yield a progenitor that is highly flattened by rotation. If so, the explosion would naturally blow out preferentially along the polar axis, perhaps even jetting the ejecta. Although such a model may be plausible, it is not yet well developed, certainly not universally accepted. If supernovae explode aspherically it is imprinted upon the ejecta and has additional signatures such as significant gravitational radiation (Mönchmeyer et al. 1991), natal kicks to nascent neutron stars (Burrows and Hayes 1996; Woosley 1987), mixing of iron-peak and r-process nucleosynthetic products, generation of pulsar magnetic fields and perhaps jetting of the debris.

**d. The explosion Mechanism?** In spite of impressive theoretical and numerical efforts during the past ten years, we still do not know how type II supernovae explode and convert $\sim 1\%$ of their gravitational energy release into kinetic energy of debris. Since the neutrino observations of SN1987A provided strong support for the basic picture of SNeII it is widely believed that neutrinos coupled with convection transport sufficient energy from the core to the mantle to blow it off. Because the observed kinetic energy in SNeII is so steady, many investigators have hoped (and some still do) that improvements in the input microscopic and macroscopic physics in one-dimensional (1-D) spherical symmetric calculations will lead to the solution. The improvements in microphysics included the use of improved neutrino opacities at high densities, the inclusion of the neutrino annihilation $\nu\bar{\nu} \rightarrow e^+e^-$ mechanism (Goodman, Dar and Nussinov 1987) and neutrino bremsstrahlung $nn \rightarrow nn + \nu\bar{\nu}$ (Suzuki 1993) in energy transport and the use of improved equation of state at high densities. The important improvements in macrophysics and numerics included the use of improved progenitor structure, the inclusion of convection, the use of improved neutrino transport algorithm (multi-group, flux limited, full transport, diffusion) and the inclusion of general relativistic effects. Other authors believe that the correct explosion mechanism can only be demonstrated through multidimensional (2-D or a full 3-D) calculations. In fact, the recent VLB radio observations and HST observations of SN1987A suggest that SN1987A and perhaps many SNeII explode aspherically and perhaps with jetting of their debris. The natal kicks to new born neutron stars may also be a result of aspherical explosion. Numerical calculations of such aspherical explosions require multi-D codes. Although such multi-D codes have been developed and applied to study core collapse SNeII (e.g., Herant et al. 1994; Burrows, Hayes and Fryxell 1995; Mezzacappa et al. 1996; Janka and Müller 1996), they still do not include all the relevant physics: None is a full 3-D, none incorporates general relativity, none has correctly treated all known neutrino processes in the core, none adequately handles transport in either the angular or radial direction.
Neutrinos alone, in 1-D codes, do not seem to be able to revive the stalled shock. A variety of hydrodynamic instabilities have been invoked by theorists over the years to help explode supernovae. Neutrino driven instabilities between the neutrinospheres and the stalled shock are generic feature of core-collapse supernovae (Bethe 1990; Herant, Benz and Colgate 1992; Herant et al. 1994; Burrows, Hayes, and Fryxell 1995; Janka and Müller 1996; Mezzacappa et al 1996). Though it is generally accepted that pre-explosion cores of massive stars are hydrodynamically unstable, the role of convective motions in driving supernova explosions is not yet clear.

Core overturn driven by negative entropy and lepton gradients during the deleptonization and cooling of the protoneutron star may boost the driving neutrino luminosities (Burrows 1987; Keil, Janka and Müller 1996). Only after a full neutrino transport will be incorporated in multi-dimensional calculations it will become clear whether neutrinos can drive supernova explosions.

e. Is There a Neutron Star? The 12 seconds neutrino burst from SN1987A suggests the formation of a neutron star, at least transiently. Besides the neutrino burst there is no other evidence that the SN1987A remnant contains a central neutron star. Independent observations have failed to confirm reported observation (Middleditch) of a 2.1 ms optical pulsar. At present, the emission observed from SN1987A is completely accounted for by radioactive energy sources (mainly $^{44}$Ti with half life of 78 years) in the debris, so the energy input from a pulsar or any other source must be small. To have escaped detection, the central compact object must have a luminosity less than a few hundred times that of the sun and far less than that of the 943 years old pulsar in the Crab Nebula. However, the average column density of the expanding shell (assuming spherical symmetry) is $\approx 20M_\odot/4\pi R^2 \approx 0.5 \text{ g cm}^{-2}$ for an average expansion velocity around 2500 km s$^{-1}$. The debris now is quite cold throughout (a few hundred K only) and probably blocks the light from the central source for decades, or longer if the debris are clumped and the source happens to lie behind a cloud. However, the expanding shell is not opaque to energetic gamma rays.

f.g. A Central Black Hole? Double Bang? It was suggested that late time accretion (Brown, Bruenn and Wheeler 1992) may have induced collapse of the nascent neutron star into a black hole. Such a scenario may lead to two neutrino bursts (“double bang”) well separated in time, and may explain the Mont Blanc early signal (Aglietta et al 1987). But the Mont blanc early signal implies unrealistically large binding energy release in the first bang which has not been detected by the Kamiokande, IMB and Baksan detectors. The fingerprint of a central stellar black hole are difficult to detect. There is a chance to
“detect” the central black hole only if it is orbitted by a close companion which survived the explosion.

h. Natal Kick and Gravitational Radiation Pulsar locations (e.g., Taylor and Cordes 1993) and proper motion data (e.g., Harrison, Lyne and Anderson 1993) imply that radio pulsars are a high-speed population. Mean three-dimensional galactic speeds of 450±90 km s⁻¹ have been estimated (Lyne and Lorimer 1994), with measured transverse speeds of individual pulsars reaching up to ∼1500 km s⁻¹. Impulsive mass loss in a spherical supernova explosion that occurs in a binary can impart to the nascent neutron star a substantial kick (Gott, Gunn, and Ostriker 1970). However, theoretical studies of binary evolution through the supernova phase have difficulty reproducing the observed velocity distributions (Fryer, Burrows and Benz 1997). This implies that neutron stars receive an extra kick at birth. Anisotropic neutrino radiation (Chugai 1984; Woosley 1987) have been invoked to accelerate neutron stars. A 1% dipole asymmetry in the neutrino radiation of a neutron star’s binding energy is sufficient to accelerate it to ∼300 km s⁻¹. Jetting of the ejecta along the polar axis and imbalance between the momenta of the two opposite jets can also be the origin of the natal kick. Aspherical explosion, perhaps even jetting of the debris are already evident in the high resolution VLB radio images (Gaensler et al 1997) and in the recent HST images (Pun et al 1997). Merger scenarios and non axisymmetric collapse can lead to very significant gravitational wave emission at typical frequencies of ∼ c/2πR ∼ a few kilo Hertz. However a reliable estimate of the gravitational wave signal (wave form and light curve) probably will have to wait until the explosion mechanism becomes clearer. Perhaps the Caltech-MIT Laser Interferometric Gravitational Wave Observatory (LIGO) will detect gravitational wave signals from SNeII, before reliable theoretical estimates become possible?

4 Limits On Particle Properties and Interactions

Astrophysics and cosmology provide test grounds for the standard model of particle physics and extensions of the model over distances, time scales and other conditions not accessible to laboratory experiments. Limits on neutrino properties from SNeII (lifetime, mixing, decay modes magnetic moments) were derived long before SN1987A. SN1987A provided a new test ground which attracted the attention of many more physicists. New limits were derived not only for standard particles and minimal extensions of the standard model, but for all kinds of hypothetical particles and interactions. Here, I will limit my summary to standard particles and well motivated minimal extensions of the standard
model of particle physics. I will quote only limits which were derived from observations and general considerations and either do not depend on, or are insensitive to the detailed modeling of SNeII. I will focus mainly on improvements since 1988 of the limits on neutrino properties which were included in Table 1 of my talk at La Thuile one year after SN 1987A (Dar 1988). Table I, to my judgement, summarizes the most important limits.

Mass Limits On Standard Neutrinos. The travel time of relativistic neutrinos of mass $m_\nu$ and energy $E_\nu$ from a distance $D$ to Earth is given approximately by

$$t = (D/c)[1 + (1/2)(m_\nu c^2/E_\nu)^2].$$

The observed energies and the dispersion in arrival times of the neutrinos from SN1987A were used to estimate upper limits on the mass of the $\nu_e$. Although the limits are model dependent, they are not very sensitive to the models. A limit of about $m_{\nu_e} < 15$ eV was obtained both from simple models and from more “sophisticated” models (which are not necessarily more reliable). The particle data group (Barnett et al. 1966) do not quote a laboratory limit since “unexplained effects have resulted in significantly negative $m_{\nu_e}^2$ in the new precise tritium beta decay experiments”. The cosmological bound (e.g., Cowsik 1977), $\Sigma m_\nu < 94\Omega h^2$ eV, yields $m_\nu < 15$ eV for stable neutrinos, for the currently best measured values of the cosmological parameters, $\Omega \leq 0.3$ and $h \approx 0.7$. This limit on $m_{\nu_e}$ may be improved by one order of magnitude by the more sensitive detectors like Superkamiokande and SNO if they will detect a thermal neutrino burst from a more distant SNeII or a neutronization burst from a galactic SNeII (e.g., Dar 1988).

If neutrinos are Dirac particles with nonzero mass they can flip their helicity in collisions with neutrons in the protoneutron star. Right (left) handed neutrinos (antineutrinos) which have no standard electroweak interactions escape immediately and cool the hot protoneutron star (PNS). Since the neutrino helicity flip cross section is proportional to $m_\nu^2$ (standard electroweak $Z^0$ exchange yields $\sigma_{\text{flip}} \approx G_F^2 m_\nu^2/\pi$), the observed cooling rate of SN1987A was used to obtain the limit $m_\nu < 15$ keV for Dirac neutrinos (Raffelt and Seckel 1988; Griffols and Masso 1990; Dar 1990). This limit is much weaker than the cosmological limit, but applies also to unstable neutrinos with $\tau > R_{\text{PNS}}/\gamma c > 10^{-7}$ s! It is much stronger than the laboratory limits, $m_{\nu_\mu} < 170$ keV and $m_{\nu_\tau} < 24$ MeV.

The Supernova mass limits on muon and tau neutrinos may be improved by about two to three orders of magnitude by future measurements of the time structure of the neutrino bursts from galactic SNeII with neutrino telescopes like SNO, Superkamiokande and HELLAZ which are sensitive to all neutrino flavors (e.g., Dar 1988).

Finally, much stronger neutrino mass limits can be obtained from SNeII neutrino bursts if neutrinos are mixed and oscillate.
Neutrino Oscillations. The number of events which were detected by Kamiokande and IMB, their angular distribution, and their energy distribution and the maximal binding energy release in gravitational core collapse suggest that they are mostly $\bar{\nu}_e p \to n e^+$ events. However, if the $\bar{\nu}_e$ were obtained by neutrino oscillation from $\bar{\nu}_\mu$'s or $\bar{\nu}_\tau$'s into $\bar{\nu}_e$'s in vacuum with a large mixing angle, their temperature should have been much higher, $T \sim 7$ MeV. The observed temperature $T \leq 4$ MeV of the Kamiokande and IMB 19 events practically excludes the large angle vacuum oscillation solution to the solar neutrino problem.

Neutrino Lifetime. If the neutrinos which were detected are those that were emitted by SN1987A (no mixings, no “conspiracy schemes”), then their mean life time must satisfy $\gamma \tau(\nu_e) > D/c \approx 5 \times 10^{12}$s, since they arrived with the expected number (see, e.g., Bahcall, Dar and Piran 1987).

Axion Mass. Various extensions of the standard model predict the existence of light neutral pseudoscalars, like the axion proposed by Peccei and Quinn (PQ) in order to solve the problem of CP conservation in strong interactions. The original axion associated with the breaking of the PQ symmetry at the weak scale ($f_w$) is excluded experimentally, but not the invisible axion if the breaking scale is much larger ($f_a \gg f_w$ $m_a \sim f_a$). The axion lifetime is very long but a strong magnetic field can enhance its decay via $a \to \gamma \gamma$. Limits on the mass of the invisible axion were derived from laboratory experiments, astrophysics and cosmology. The absence of a $\gamma$ ray signal from SN1987A has limited its mass to the narrow window $10^{-6}$eV $\leq m_a \leq 10^{-3}$eV (e.g., Raffelt 1990).

What to Expect? Detectors like Superkamiokande and SNO will allow for the first time good energy, time and flavor spectroscopy of both the neutronization burst and the thermal burst from galactic SNeII. In particular, the early phase of core collapse that precedes SNeII is better understood than the explosion. Neutrinos from this phase are emitted mainly due to $e^-$ captures on free protons and iron group nuclei. Up to core densities of $\sim 3 \times 10^{11}$ g cm$^{-3}$ (neutrino trapping density) these $\nu_e$ escape freely from the overlying stellar matter without any interaction that changes their energy. The total number of neutrinos emitted from a 1.4 $M_\odot$ stellar core as it evolves from a initial density of $\sim 4 \times 10^9$ g cm$^{-3}$ to a neutrino-trapping density of $\sim 3 \times 10^{11}$ g cm$^{-3}$ is $\approx 10^{56}$. The duration of this $\nu_e$ burst is a few ms. The charge-current and neutral-current reactions, $\nu_e D \to ppe^-$ and $\nu_x D \to pn\nu_x$, respectively, on deuterium nuclei in SNO and the $\nu_x e \to \nu_x e'$ scattering in the more massive Superkamiokande water detector, can be used to detect the neutronization burst from galactic SNeII, to identify its flavor content and measure the neutrino energies. These may yield new important information on the physical and
the nuclear configuration of the collapsing stellar core and on neutrino properties, in particular on neutrino masses, flavor mixing and matter oscillations (Dar 1988).

5 More To Expect

The story of SN1987A is not over yet. For astrophysicists perhaps the most exciting future developments will be the collision of the debris with the circumstellar gas and rings which will shed more light on the nature of the explosion and on the history of the progenitor before its supernova phase, the emergence of a neutron star and the birth of a pulsar:

**Future Fireworks.** The blast wave from SN1987A will strike the inner ring some six to ten years from now (Chevalier and Dwarkadas 1995; Borkowski, Blondin and McCray 1997) and the ring is predicted to brighten by a factor $\sim 10^3$ in all bands of the electromagnetic spectrum. Shock acceleration will probably begin to produce relativistic particles and $\gamma$ ray emission from the inner ring.

**Shining the Past.** When the blast wave will continue to propagate into the interstellar medium it will lit more rings and shells which may have been ejected by the progenitor in its presupernova phase.

**Neutron Star Emergence and Pulsar Birth.** The debris will first become transparent to $\gamma$-rays and X-rays. If the hot neutron star is there, it will glow in thermal X-rays. If it has begun pulsed emission over the whole electromagnetic spectrum and if we happen to lie within the pulsar beaming cones, we will start to see pulsed emission of radio waves, X-rays, and perhaps $\gamma$ rays. It will take much longer (half a century or more) before the debris will become transparent to optical photons.

6 Concluding Remarks

Perhaps the most important consequences of SN1987A are the birth of extrasolar neutrino astronomy, the construction of galactic and extragalactic neutrino telescopes and the push to the construction of gravitational wave detectors. All these will help solve some of the most interesting puzzles in astronomy and test interactions and particle properties over physical domains not accessible to laboratory experiments.

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Table I: Expected limits on neutrino properties from nearby SNeII compared with the corresponding limits from terrestrial experiments, from SN 1987A and from cosmology.

| Property                           | Terrestrial Exp | SN1987A          | Nearby SNeII (Expected) | Cosmology |
|------------------------------------|-----------------|------------------|-------------------------|-----------|
| Masses                             |                 |                  |                         |           |
| $m_{\nu_e}$                        | -               | <15 eV           | <1 eV                   | <15 eV    |
| $m_{\nu_\mu}$                      | 170 keV         | <15 keV (if Dirac)| <100 eV                | <15 eV    |
| $m_{\nu_\tau}$                     | 24 MeV          | <15 keV (if Dirac)| <100 eV                | <15 eV    |
| Lifetime                           |                 |                  |                         |           |
| $\gamma\tau(\nu_e)$               | (Atmospheric $\nu$'s) | > 5 x 10^{-12} s | > 10^{14} s             | > 10^{3} s |
| $\gamma\tau(\nu_\mu)$             | > 4 x 10^{-2} s  | -                | > 10^{12} s             | > 10^{3} s |
| $\gamma\tau(\nu_\tau)$            | -               | -                | > 10^{12} s             | > 10^{3} s |
| Mixing                             | Excluded Region | Large Angle Mixing Excluded | Small Angles Also Excluded? |
| $<\nu_\mu|\nu_x>$                   | $\Delta m^2 > 0.1 eV^2$ | $\sin^2 2\theta > 0.01$ | $\sin^2 2\theta > 0.01$ |
| Electric Charge                    |                 |                  |                         |           |
| $q(\nu_e)$                         | < 10^{-13} e    | < 2 x 10^{17} e  | < 1 x 10^{-18} e        |           |
| $q(\nu_\mu)$                       | < 10^{-6} e     | -                | < 2 x 10^{-17} e        |           |
| $q(\nu_\tau)$                      | < 10^{-2} e     | -                | < 2 x 10^{-17} e        |           |
| Magnetic Moment                    |                 |                  |                         |           |
| $\mu(\nu_e)$                       | $1.8 \times 10^{-10} \mu_B$ | < 10^{-12} $\mu_B$   | < 10^{-14} $\mu_B$      |           |
| $\mu(\nu_\mu)$                     | $7.4 \times 10^{-10} \mu_B$ | < 10^{-12} $\mu_B$   | < 10^{-14} $\mu_B$      |           |
| $\mu(\nu_\tau)$                    | $5.4 \times 10^{-7} \mu_B$ | < 10^{-14} $\mu_B$   | < 10^{-14} $\mu_B$      |           |
| Radiative Decay                    |                 |                  |                         |           |
| $B^{-1}_\gamma \tau_\nu/m_\nu$    | > 20 s/eV       | > 2 x 10^{16} s/eV | > 10^{17} s/eV          |           |
| $\nu$ Flavors                      | 3               | ≤ 5              | 3                       | 3         |

Fig.1: An image of the triple ring structure around the remnant of SN1987A taken in early 1997 by the Wide Field and Planetary Camera 2 of the Hubble Space Telescope.
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