SN1987A. A REVIEW*

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SN1987A, in the Large Magellanic cloud, was the closest supernova since the 1604 event observed by Kepler. It provided a unique opportunity to verify our theories and comfort our beliefs in quite a variety of domains: Astrophysics (Stellar evolution, conditions prevailing at the star's explosion), Nuclear Physics (Neutron star formation, Equation of state under extreme conditions, Nucleosynthesis) and Particle physics (Neutrino properties). All these observations strongly confirm our previous ideas on the physical conditions prevailing during the supernova explosions, although the SN1987A event was not exempt of surprises.

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Introduction

Historical supernovae stand as landmarks in our way of understanding the reality of our universe. The 1572 event observed by Tycho-Brahé and the 1604 supernova of Kepler forced the Western cultures to accept that the stars were not made once for ever, but were part of a changing world (the Eastern civilizations knew that thousand years before!). The 1885 explosion in the Andromeda Nebula was such a puzzle to the contemporary astronomers, that it inspired the view (Clerke 1890), very unorthodox at the epoch, that Andromeda could be an external galaxy. Clerke correctly estimated its distance 34 years before Hubble undoubtedly established its extragalactic nature. The two other close galaxies that are visible with the naked eye are the Magellanic clouds, where SN1987A occurred (Fig. 1), at a distance of 50kpc, comparable to the 30kpc diameter of our own Galaxy. Such close an event, at a time where all the modern techniques of observations are available brought a long series of new results and a growing list of unusual (but not unexpected) features belonging to quite different domains of Science. Astrophysics had undoubtedbly a large share: classification of the various supernova types since the SN1987A light curve

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was atypical, stellar evolution since for the first time the progenitor star had been observed before the explosion and was neither a white dwarf nor a red giant nucleosynthesis since the radioactive decay of ^{56}Co could be observed on-line. Particle physics, however, was as much — if not more — in honor: the observation for the first time of an intense neutrino emission due to SN1987A signs the formation of a neutron star and leads to several bounds on neutrino properties that are difficult to be obtained in terrestrial experiments: stability, number of species, mass, magnetic moment. Properties of other weakly interacting particles such as Axions can also be constrained. This neutrino emission is the signature of the formation of a neutron star. The emitted flux, the average neutrino energy, and more simply the occurrence of the event provide useful constraints on the Nuclear equation of state that prevails under these extreme conditions. In the future, the direct observation of the neutron star, especially the measurement of its surface redshift and temperature may provide clues for the possible existence of free quarks or any other condensed phase in its deep interior.

TABLE I

Salient properties of the various supernova types. Massive stars explode as the standard SNII does, but the progenitor as well as the light curve are different

Supernova type	SNI[a]	SNII[a]	Massive progenitors[b]	SN1987A
Initial mass ($M_\odot$)	<8	8–15	15–50?	15–20
Final mass ($M_\odot$)	1	8–10	10–20	10–12
Radius (cm)	10	14^{14}	10^{10}–10^{12}	$3 \cdot 10^{12}$
Nature	white dwarf	red giant	stripped star, Wolf Rayet	blue, stripped star
Cause of explosion	thermonuclear	gravitational collapse	gravitational collapse	gravitational collapse
Remnant	—	neutron star (neutrino emission)	neutron star (neutrino emission)	neutron star (neutrino emission)
Composition	no Hydrogen, Oxygen dominated	Hydrogen	little or no Hydrogen, Helium, Oxygen	Hydrogen, Helium, Oxygen
Energy source of light curve	Ni, Co decay	shock due to collapse	Ni, Co decay recombination of electrons	Ni, Co decay
Luminosity (erg s^{-1})	10^{44}–10^{43}	10^{43}–10^{42}	10^{42}–10^{41}	10^{42}
Photospheric temperature at maximum	hot (10000 K)	hot (10000 K)	cold (5000 K)	cold (5000 K)

[a] From V. Trimble (1982).
[b] From Schaeffer, Cassé and Cahen (1987).

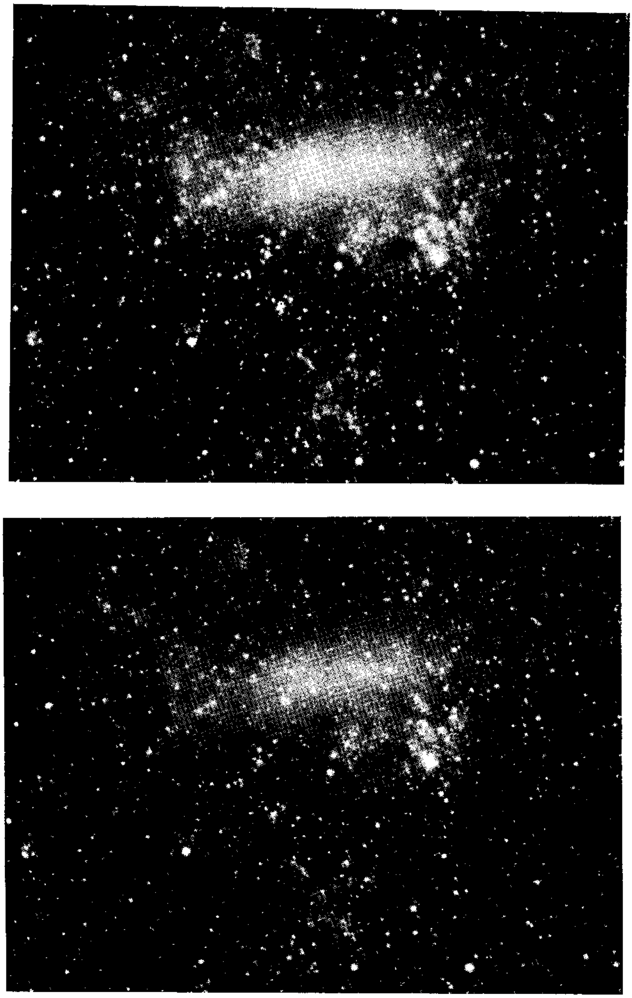

Fig. 1. Large Magellanic Cloud (ESO photograph) on February 22, 1987 (upper) and on February 24, 1987 (lower). Between the main part of the Cloud and Doradus (bottom right) one can distinctly see (black arrow) SN1987A, that is as luminous as the whole cloud

1. *Astrophysics*

1.1. The nature of supernovae

Type I supernovae originate from $M \leqslant 8M_\odot$ stars that eventually become $\sim 1M_\odot$ white dwarfs, some of which may undergo a thermonuclear explosion. Type II supernovae are due to the gravitational collapse of 8–10$M_\odot$ stars that leads to the formation of a $1M_\odot$ neutron star and to the shock ejection of the remaining envelope. It has been gradually realized that the more massive stars loose part of their envelope prior to explosion (Maeder 1981) and explode while they are blue stars, or even Wolf-Rayet stars (Maeder and Lequeux 1982). This leads to specific properties (Table 1) that makes this latter category

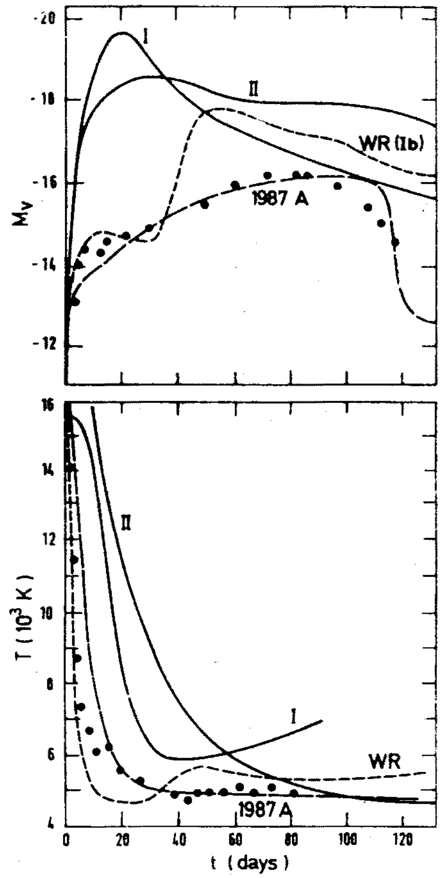

Fig. 2. From Schaeffer, Cassé, Mochkovich, Cahen (1987). Magnitude (a) and photospheric temperature (b) of SN1987A during the first days. SN1987A was typically fainter as ordinary SNI and SNII, and cooler. It is much closer to the light curve and temperature calculated before the occurence of SN1987A (Schaeffer, Cassé, Cahen 1987) for a stripped, massive, Wolf-Rayet star (dashed curve). At maximum, the WR curve is dominated by the decay of $0.3M_\odot$ of Ni. The SN1987A at maximum is also dominated by Ni decay, but the amount necessary to reproduce the observations is much smaller: $0.07M_\odot$ (Woosley 1987). As for WR stars, the progenitor of SN1987A is a compact massive star, that however contains still some hydrogen (whereas WR stars do not)

easily recognizable (Chevalier 1976, Schaeffer, Cassé and Cahen 1987), in particular these supernovae are dominated by ^{56}Ni decay although they explode via gravitational collapse as SNII do. They thus look like an SNI, and the subcategory SNIb (Wheeler and Levrault 1985, Schaeffer et al. 1987) could actually be due to these massive, but small, stripped stars. The identification of the progenitor, Sk-69-202, a compact and massive star, as well as the properties (Fig. 2) of the light curve (fainter, cooler than usual) makes SN1987A another member of this class (Arnett 1987, Schaeffer, Cassé, Mochkovich and Cahen 1987, Shigeyama et al. 1987, Woosley et al. 1987, Woosley 1988). It however still contains hydrogen, since it was not fully stripped. It has thus be classified as SNIIb. SN1987A is the first unambiguously established of this new type of supernovae due to compact and massive stars that all have common properties. The existence and the pecularities of the massive star explosions are now recognized.

1.2. Stellar evolution

The observation of the explosion of a blue compact star has obvious implications for stellar evolution (Maeder 1981, 1987). Moderately massive stars become red giants, but subsequently, due to mass loss, their radius decreases and they evolve towards the blue. Very massive stars may thus become blue supergiants and possibly Wolf-Rayet stars. There has been the alternate suggestion that, for the low metallicity prevailing in the LMC, massive stars evolve towards the blue and explode (Arnett 1987, Hillebrandt et al. 1987). This originally failed to explain in the LMC the proportion of red giants with luminosity comparable to Sk-69202. More recently, Saio et al. (1988) built models that comply with this constraint without requiring mass loss.

1.3. Galactic evolution

As had been realized for the SNIb (Wheeler and Levrault 1985, Schaeffer, Cassé and Cahen 1987), SN1987A is another example of the explosion of a massive star that does not look as a standard SNII. It is thus very likely that the explosion of massive stars had been misclassified, the red giant explosion representing not all the supernovae due to stars with $M > 8M_{\odot}$. This has implication on the yields of various elements and on the explosion frequency, and leads to revise the chemical history of our Galaxy (Rocca-Volmerange and Schaeffer 1989).

1.4. The γ-rays from Co decay

Needless to say, the observation (Matz et al. 1988) of the γ-ray lines due to the nuclear decay of ^{56}Co provides for the first time the proof that indeed the powering of the supernova light curve is the Ni → Co → Fe radioactivity. Both Co lines and hard X-ray emission (Dotani et al. 1987, Sunyaev et al. 1987) were observed by Ginga, Kvant and SMM much earlier than expected. Convective effects are needed (Itoh et al. 1987, Pinto and Woosley 1988) to explain these unexpected features.

1.5. The neutrino burst(s?) from SN1987A

Core-collapse supernovae are expected to form a neutron star, that emits its 10^{53} erg gravitational energy in the form of neutrinos as was suspected very early (Colgate and

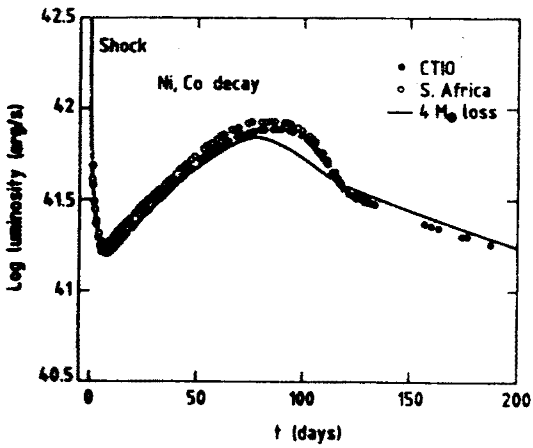

Fig. 3. Theoretical calculation (Woosley 1988) reproducing the observed bolometric light curve of SN1987A. From the observed luminosity of the progenitor, its main sequence mass can be estimated. In order to reproduce the data, a mass loss of about $4M_\odot$ (other models may lead to larger values) has to be assumed

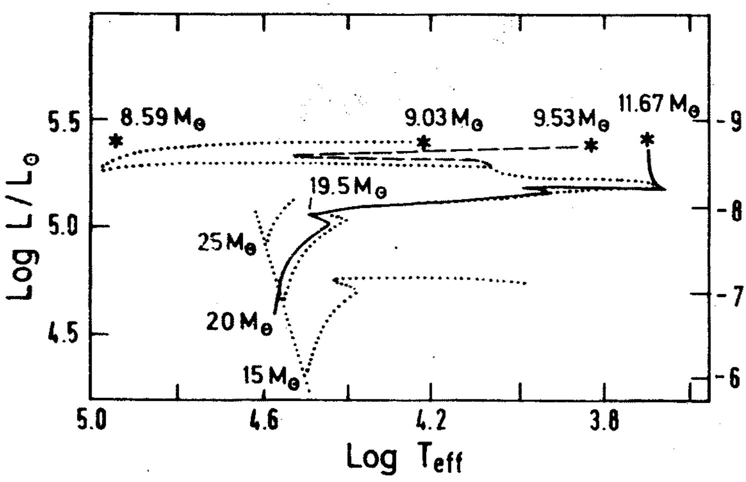

Fig. 4. Evolutionary tracks in the HR diagram (Maeder 1987). A massive ($\sim 20M_\odot$) star leaves the main sequence at the onset of He burning and becomes a red giant. For moderately small mass loss ($<8M_\odot$) it explodes in the latter stage. For a higher rate of mass loss ($\sim 10M_\odot$) its radius becomes so small that it explodes as a Blue Supergiant. For extremely strong mass loss ($>10M_\odot$) it ends its life as an $8M_\odot$ Wolf-Rayet star ($\log T_{eff} \sim 5.5$)

White 1960, Arnett 1966, 1967) and is now well recognized (Zeldovich et al. 1972, Mazurek 1976, Bethe et al. 1979, Nadëzhin and Ostroshenko 1980, Burrows and Mazurek 1983, Woosley et al. 1986, Mayle et al. 1987). Together with the announcement by Shelton, on February 24, of the appearance of a supernova in the LMC, the neutrino detector under the Mt Blanc was reported (Aglietta et al. 1987) to have seen a large neutrino flux on February 23 at 2 : 52. A few days later, the Kamioka (Hirata et al. 1987), the IMB (Bionta

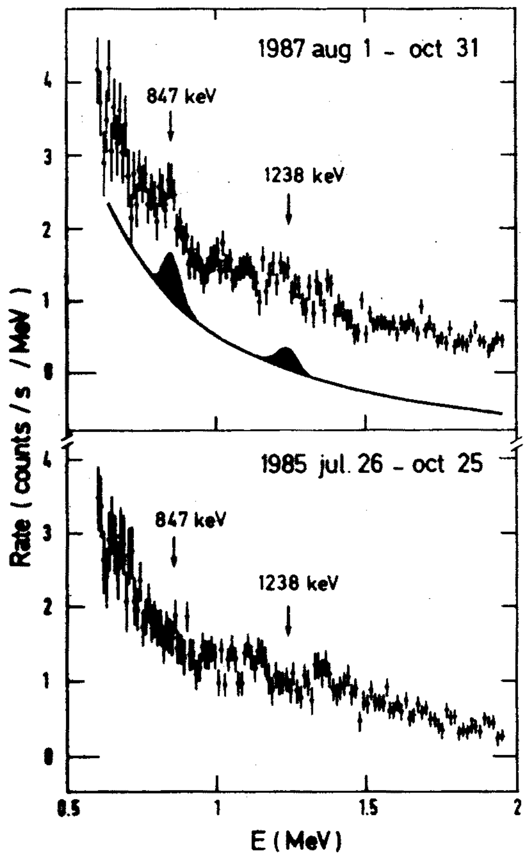

Fig. 5. Observation by the SMM mission (Matz et al. 1987) of the 847 keV and 1238 keV γ-ray lines due to Co decay in the SN1987A expanding remnant. These lines were absent in the observation of the same part of the sky in 1985

et al. 1987, 1988) as well as — possibly — the Baksan (Alexeyev et al. 1987, 1988) groups showed evidence for a neutrino detection on February 23, but at 7 : 35.

The Mt Blanc and Baksan detectors (Table II) are quire small ($\sim$100 t), and were optimized for a supernova in our Galaxy rather than in the LMC. Despite the rather efficient detection of the Mt Blanc, and the larger mass of the Baksan detector, one event was barely expected for a supernova at 50 kpc distance. The most efficient (large detector mass, and not too high at threshold) is obviously the Kamioka detector.

Although the uncertainty of the absolute arrival time was quite large in the beginning, they could now be traced back within ± 2 seconds for Kamioka and $^{+2}_{-54}$ s for Baksan (Alexeyev et al. 1988), and much less for the two other experiments. The relative times are known within miliseconds. At the time of the Mt Blanc detection, only one event is recorded by the Baksan detector (Fig. 7), consistently with the difference in detection threshold. A unique event of course could also be due to background. Three events are seen by Kamioka at a time close to, but different from the Mt Blanc events (De Rujula,

TABLE II

Main characteristics of the various detectors aiming at the observation of neutrinos due to supernovae: mass, 50% efficiency threshold, number of events expected from SN1987A and number seen in the burst observed on February 23, 1987

	M (ton)	E_{TH} (MeV)	Expected (Neutron star)	Reported
Mt Blanc	90	7	0.4	5
Baksan	200	11	1	5
Kamioka	2140	8	8	11
IMB	5000	30	8	9

1987). Taking into account the difference in efficiency, about 70 events are expected (Krauss, 1987) in this detector if the Mt Blanc detection is due to neutrinos from SN1987A. A much more optimistic analysis (De Rujula, 1987) claims the 5 events of the Mt Blanc and the 3 of Kamioka can be made consistent, but this requires an arbitrary modification of the detector efficiency parameters given by the Kamioka group. There is now a general agreement that the Mt Blanc and Kamioka detections at 2 : 52 are incompatible.

Let us now consider the 7 : 35 event. The Kamioka and IMB detections are consistent

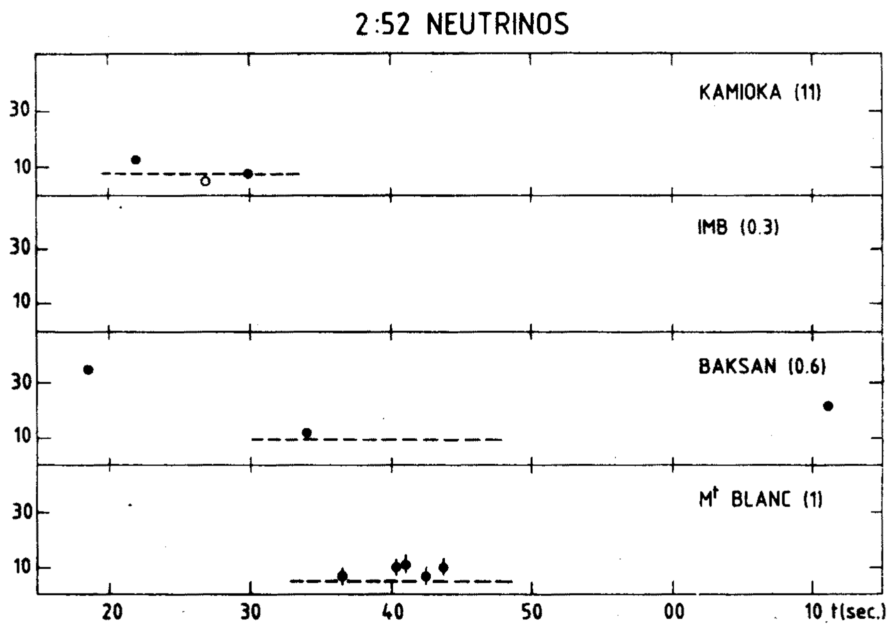

Fig. 6. Neutrinos observed on February 23 at 2 : 52 by the large underground particle detectors. The times are expected to have been traced back within ±2s (except for the Baksan detector). The numbers in brackets are sensitivity factors (a black-body spectrum integrated over the detector efficiency and multiplied by the detector mass) indicating in which proportions the various detectors should be sensitive to a $T = 3$ MeV flux. For 5 events observed by the Mt Blanc more than 50 should be seen by Kamioka

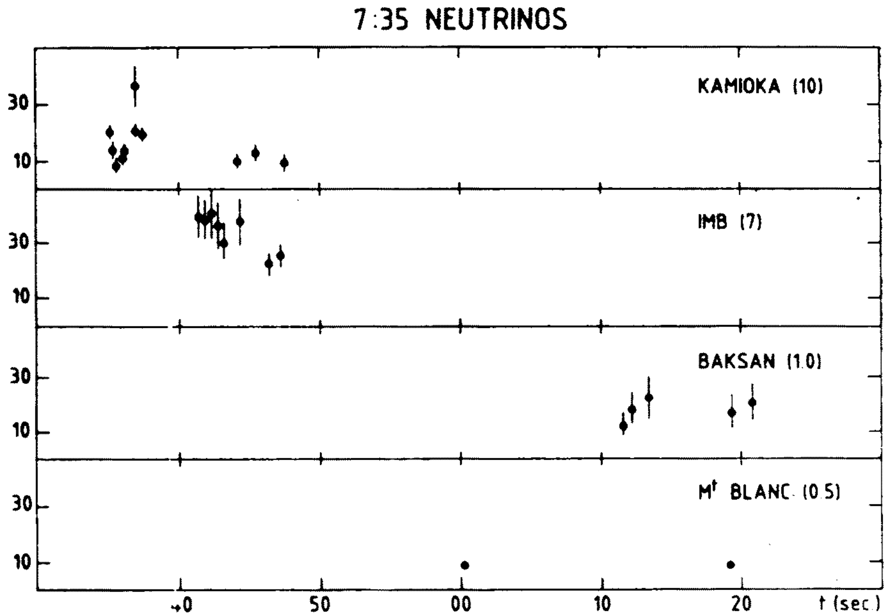

Fig. 7. Neutrinos observed on February 23, 1987 at 7 : 35 by the large underground particle detectors. The time measurements of Kamioka and Baksan are not very accurate. The former could trace back the observation time within ± 2s, the latter give an error of $^{+\ 2}_{-54}$ s. The numbers in brackets are sensitivity factors (a black-body spectrum integrated over the detector efficiency and multiplied by the detector mass) indicating in which proportions the various detectors should be sensitive to a $T = 4$ MeV flux

within one standard derivation (Bahcall et al. 1987, Ellis and Olive 1987, Kahana et al. 1987; Krauss 1987, Lattimer and Yahil 1987, Schaeffer, Declais and Jullian 1987). From their observed flux, $L_{\bar{\nu}_e} \sim 6 \times 10^{52}$ erg, about one event is expected in the Baksan detector. However, including the 5 events seen in the latter raises the observed neutrino flux up to the larger value $L_{\bar{\nu}_e} \sim 8 \times 10^{52}$ erg (Piran and Spergal 1988) leading to an expected number of 1.6 plus 0.6 for background, making the Baksan detection marginally (with a 7% chance) consistent with the observed 5 events.

The most likely conclusion thus is that the Kamioka and IMB events were true detections of the neutrino from SN1987A, with a possible but marginal detection by Baksan. The Mt Blanc event having not been seen by the more sensitive Kamioka detector may not be due to SN1987A.

This neutrino emission by SN1987 can be considered as a proof of the formation of a neutron star. No other astrophysical object is expected to emit such a signal.

1.6. Timing of the optical and neutrino signals

Only one, short, neutrino signal is expected at the formation of a neutron star. If the latter is to hold, one of the detections must not correspond to SN1987A.

Optical records of the LMC on February 23 were carefully examined. A satellite traking camera in Australia found SN1987A had a magnitude ~6 on February 23, 10 : 30.

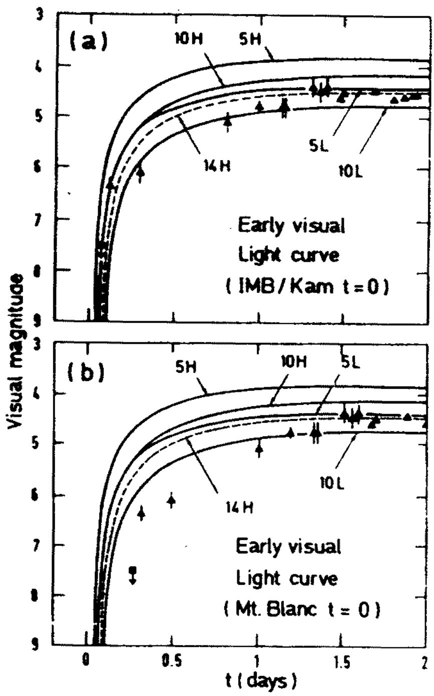

Fig. 8. SN1987A light curve during the first few days. (Woosley 1988) compared to various theoretical calculations using an exagerately large range of parameters, and assuming that either the IMB/Kamioka/ /Baksan detections trace the time of collapse (a), or that the Mt Blanc observation is at the time of collapse (b). Only the former is seen to provide consistency between the optical and neutrino timing, despite the short delay (2 hours) this implies

This is the earliest known optical signal. A. Jones who was observing this area obtained only an upper limit of ~7.5 magnitudes at 9 : 30 the same day. This sets rather stringent limits on the collapse time. Arnett (1988) and Woosley (1988) who made an extensive study of the timing problem find that the collapse could only have taken place at 7 : 35. The time of the Mt Blanc detection (2 : 52) is too remote (Fig. 8).

A few hours delay between the collapse and the onset of the optical signal is astonishingly short as compared to the one that is believed to hold for usual type II

TABLE III

SN1987A prior to its discovery by Shelton. There was an optical signal from the SN on Feb. 23 at 10.30, but none at 9.20. The Kamioka-IMB-Baksan neutrino burst was observed at 7.35

Feb. 24.23	(5.30)	Shelton discovers SN	SN seen
Feb. 23.44	(10.30)	Mc Naugh observation	SN seen
Feb. 23.39	(9.20)	Jones' upper limit	not seen
Feb. 23.32	(7.35)	Kamioka, IMB, (Baksan)	ν signal
Feb. 23.12	(2.52)	Mt Blanc	ν signal

supernovae in external galaxies, where, although not observed, this delay is believed to be of a few days. It is however consistent with the outcome of the sophisticated numerical simulations and corresponds to the time needed for the shock to reach the star's surface. Simply from the difference in radii (Table I) which are in a ratio 10^{14} cm/3×10^{12} cm ~ 30, the naive expectation of the propagation time in this compact star is reduced by the same factor, and of the order of a few hours rather than days.

Ad hoc models have been devised to account for the Mt Blanc signal. They involve a two step formation of a black hole (De Rujula 1987, Hillebrandt et al. 1987). Such an explanation, however, implies that the onset of the explosion is at the Mt Blanc time. This seems rather difficult to reconcile with Kamioka as well as with the optical observations.

1.7. The pulsar

Nearly two years after the occurrence of the supernova, the discovery of the expected pulsar has been announced (Middleditch et al. 1989, Kristian et al. 1989). During 7 hours on January 18 a strong optical signal of an astonishingly short period, 0.508 ms, at an extremely high significance level (10 to 40 standard deviations) has been detected. Unfortunately, none of the numerous subsequent observations made by the same team as well as by several other groups from January to June was successful again. The disappearance of the signal is unexpected, and must be explained by dust obscuration due to the still quite turbulent surroundings of the pulsar. We have thus to live with one unique observation.

The short pulsar period makes it the fastest known pulsar. Indeed, since the energy of the emitted pulses is taken from the rotation energy, young pulsars are expected to be rapid rotators. The expected period of newly born pulsars, however, was barely below a tenth of a second. The fastest known pulsars are found in (former) binary systems and are fairly old: their rotation is due to angular momentum transfer from orbital motion caused by accretion during a long time interval. Their periods are typically above 1 ms: 1.56 ms for PSR 1937+214 (Baker et al. 1982) and 1.61 ms for PSR 1957+20 (Fruchter et al. 1988). A young pulsar rotating even faster thus is a real surprise. Its radius must be below 24 km to prevent its surface to move at the velocity of light and it is very likely to be neutron star (the other possibility, a black hole, being excluded by the interpretation of the observed neutrino signal). To radiate energy at the (fairly low) rate that was observed, its magnetic field must be abnormalously low.

The high frequency signal was pulsed with an additional 8 hours period. After having been corrected for the motion of the Earth, the pulsation was a nearly perfect sinusoid. It may be due to small ($\delta I/I \sim 10^{-6}$) but periodic and quite regular changes of the moment of inertia. Typical oscillations of neutron stars, however, have periods from seconds down to a miliseconds. So, one must find another process that is much slower such as oscillations of the star's crust (Kristian et al. 1989). Another explanation for this 8 hour period is a companion that must be fairly close to the neutron star and thus made during the explosion. In this case, again, we see a rapidly rotating neutron star in a binary system.

2. *Nuclear physics*

2.1. Energy balance in SN explosions

The assumption that massive stars explode via core-collapse and neutron star formation leads to a severe energy balance problem. The observed neutron stars are rather cold, and have a binding energy of $\sim 3 \times 10^{53}$ erg. The star before collapse, in these units, has a negligible binding. The energy used up in the luminous emission and in the kinetic energy of the ejected matter is barely above 10^{51} erg. The energy in gravitational waves is not expected to be much larger. The bulk of the available energy, indeed, is emitted in the form of neutrinos of all known species (e, μ, τ). So, if a neutron star is formed, the observed neutrinos should make up for nearly all the available energy. It is remarkable — as for instance emphasized in the context of SN1987A by Schaeffer (1987) and Schaeffer, Declais and Jullian (1987) — how the spread of the theoretical estimates for this energy is narrow. Unless extreme equations of state are used, these estimates range between 2.5 and 3.5×10^{53} erg for a $1.4 M_\odot$ star, with a maximum of 6×10^{53} erg for stars having the largest possible mass, at the edge of gravitational instability. This is due to the fact that nuclear matter is rather incompressible, leading to similar star radii whatever equation of state

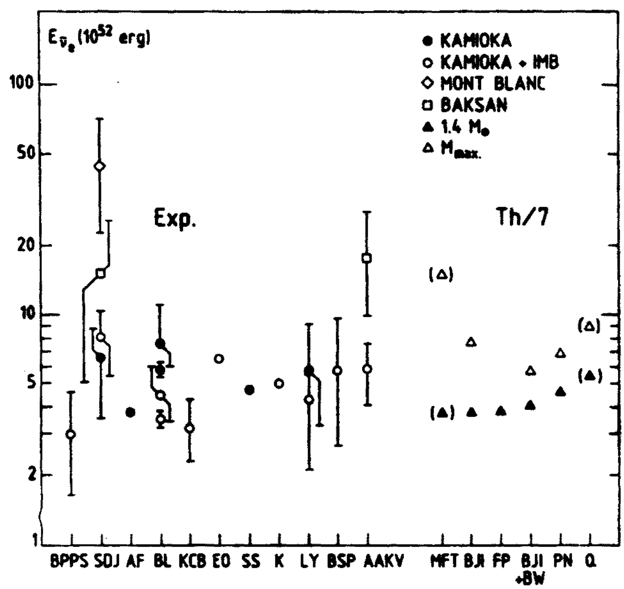

Fig. 9. Energy of the emitted $\bar{\nu}_e$ flux, as obtained from the observations by various authors. There is a general agreement that the Kamioka and IMB detections are consistent at the 1σ level, whereas the Baksan detection implies an appreciably larger flux, and the Mt Blanc signal, if due to SN1987A, would necessite excessive energy requirements. The bars denote 1σ errors, whereas the double bars corresponds to a 95% confidence limit (2.5σ). The predicted energies (Haensel 1988) for a $1.4 M_\odot$ neutron stars or for the maximum possible mass are given for various equation of state: MFT, BJI, BJI+BW, PN (Haensel and Proszynski 1982), FP (Haensel and Schaeffer 1982) and Q (Haensel, Zdunik and Schaeffer 1986). The brackets indicate extreme equation of state that do not reproduce all the properties of nuclei

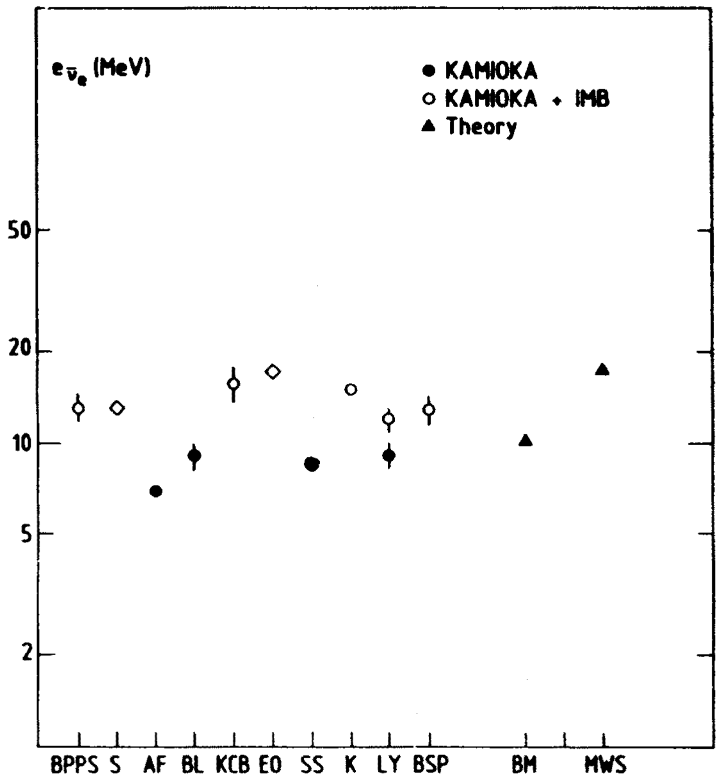

Fig. 10. Average energy of the neutrinos emitted by SN1987A. The inclusion of the IMB counts is seen to increase systematically this energy, that is in the 10–15 MeV range. The triangles are the theoretical predictions made before the event

is used. The binding energy $\sim GM^2/R$ being of gravitational origin is then rather model independent.

Many groups calculated the energy implied by the observed $\bar{\nu}_e$ neutrinos, that are expected (Mayle et al. 1987), because there are 3 species (6 different neutrinos), to represent about 1/7 of the total emitted energy (the ν_e flux contains a somewhat larger fraction of the total energy because of the initial ν_e excess due to the $e^- + p \rightarrow n + \nu_e$ neutronization). Their findings are compiled in Fig. 10. The Kamioka and IMB observations give consistent results, and lead to energies that are just in the range needed, $L_{\bar{\nu}_e} \sim 6 \times 10^{52}$ erg, to insure the energy balance. They, however, are not precise enough to constrain the theoretical models. The Baksan measurement predicts an energy that is larger by about a factor of 4 (when the neutrino black-body temperature of Kamioka and Baksan are taken to be the same). When added to the Kamioka and IMB signal, it raises the observed luminosity significantly, so that $E_{\bar{\nu}_e} > 4.4 \times 10^{52}$ erg at the 95% significance level. This would exclude all of the realistic equations of state for neutron stars (Fig. 10) unless one is willing to question the energy equipartition found in the realistic (Mayle et al. 1987) calculations of the neutrino emission. This simply reflects the early statement (Schaeffer 1987, Schaeffer et al. 1987) on the very large energy that would be required to account for the Baksan observation.

The Mt Blanc signal, if real, also implies an uncomfortably large energy flux emitted in the form of $\bar{\nu}_e$'s, $L_{\bar{\nu}_e} \sim 6 \times 10^{53}$ erg, that by no means can be provided by a neutron star.

2.2. Neutrino energy and cooling time

The average neutrino energy and cooling time depend on the detailed energy transport in the neutron star. The neutrino mean free path in the interior determines the emitted energy flux. The weak interactions involved are well-known, but the degree at which nuclear matter can be excited is also an important parameter.

Realistic calculations give $E_\nu \sim 10$ MeV, $\tau \sim 10$ s (Burrows and Mazurek 1983), $E_\nu = 18$ MeV, $\tau = 10$–20 s (Mayle et al. 1987). The temperature and duration are difficult to extract from IMB measurement since only the very high (>20 MeV) energy events were recorded. The interpretation of the Kamioka results differs among various authors which obtain average energies that vary from 7 to 19 MeV (8 to 14 if we retain the most careful analysis), with a duration of ~10 s.

Interesting indications on the nature of the neutrino-emitting object can be obtained from these observations. Indeed, the total emitted energy

$$E_{\rm tot} = \int dt 4\pi R^2 \sigma T^4 \sim 4\pi R^2 \sigma \langle T \rangle^4 \tau$$

and the average neutrino energy $\langle E_\nu \rangle = 3.15 \langle T \rangle$ together with the duration of the signal can be used to estimate the radius R. From the Kamioka + IMB analysis one obtains

$$R \simeq \left(\frac{E_{\rm tot}}{4\pi\sigma \langle T \rangle^4 \tau} \right)^{1/2} \sim 12 \pm^{6}_{3} \text{ km}.$$

This is a typical neutron star radius. Also, from the estimate that an e-folding time for the energy is about $\tau/4$ since $\langle T \rangle$ drops from its maximum to the observational threshold within τ, we get from a simple random walk argument the effective neutrino mean free path within the emitting object

$$\lambda \sim \frac{4R^2}{c\tau} \sim 40 \text{ cm}.$$

Again, such values, typically, are only encountered within hot neutron stars, just after their formation.

2.3. Nuclear incompressibility

Bethe et al. (1979) and Brown et al. (1981) proposed a mechanism, the iron core collapse and shock ejection of the envelope (the "prompt" mechanism) as the explanation for the SNII explosion of $\sim 8 M_\odot$ stars. Subsequent numerical simulations showed that these ideas were qualitatively correct, but run into quantitative problems since the outgoing shock was not energetic enough to expell the outer layers, the problem becoming worse for increasing mass. Explosion could finally be achieved (Baron et al. 1985) by using better calculations of the progenitor composition and by a modification of the nuclear incompressibility down to $K = 140$ MeV and of the adiabatic index down to $\gamma = 2$. This compressibility is rather low as compared to the value obtained by Blaizot (1980) from nuclei, $K_N = 210 \pm 30$ MeV, even once the latter is corrected to $K = 160 \pm 20$ MeV because of the different proton to neutron ratio in nuclei and supernovae. The adiabatic index of realistic equations of state for nuclear matter, with the charge per nucleon ~ 0.3 to be used for supernovae, is rather close to 3 at the relevant densities that is twice the nuclear matter density. The gradient of the pressure under these conditions used for supernovae thus is lower by a factor of 2 than what is implied by realistic equations of state that reproduce all the properties of nuclei. The whole procedure, thus, has been criticized (Glendenning 1986), especially on the basis of other determinations of $K_N \sim 240$ from pion emission in nuclear collision (Stock et al. 1982). In the latter determination, however, important corrections were left out (Bertsch et al. 1984, Kapusta 1984). This is very likely also the case of the interpretation of the particle distribution (Molitoris and Stöcker 1985) in nuclear collision that lead to even larger values of $K(\sim 400)$. Also, the new data (Sharma et al. 1988) on the frequency of the vibration modes in some nuclei that from a simplified interpretation seemed to call for a large compressibility ($K \sim 300$ MeV) are finally found (Blaizot 1989) to be consistent with the original 210 MeV value. On the other hand, values of the order of $K = 100$ have been obtained using sum rules (Brown and Osnes 1985), and would support the equation of state employed for supernova explosions. Such values, however, are exagerately low (Pines et al. 1988). As a conclusion of this discussion on the compressibility of nuclear matter, we find there is no strong evidence that the original value (210 MeV) should be modified. After correction for the N/Z dependence, this value is consistent with the one used in current supernova calculations. This, however, leaves unsettled the problem of the low adiabatic index needed to make the explosion successful.

Recently the problem of getting a successful explosion has been seriously aggravated since the inclusion of the scattering by electrons of the neutrinos emitted during the collapse makes the explosion by the prompt mechanism considerably more difficult (Myra and Bludman 1989; Cooperstein and Baron 1989) even by softening the equations of state.

Another possibility, the late revival of the energy-deficient shock by the emitted neutrinos has been shown (Bethe and Wilson 1985) to lead to successful explosions. The shock energy implied by the SN1987A light curve is of the order of $1 \cdot 10^{51}$ erg or slightly above (Arnett 1987, Schaeffer et al. 1987, Shigeyama et al. 1987, Woosley et al. 1987, Woosley et al. 1988), on the very upper edge of the possible energies that can be obtained by this mechanism.

This long history of the difficulties in getting supernovae to explode and the (often bitter) discussions it generated led to the feeling that supernova theory was not in a good shape, and that may be a totally different explosion mechanism is to be invented. It is thus gratifying to note that a neutron star was very likely made in this event and that the bolometric light curve (Fig. 3) shows unambiguous evidence for the emergence of a shock at the onset of the optical emission, comforting our ideas in the matter: neutron star formation and shock heating of the envelope is seen to exist.

2.4. The neutron star

The discovery of the SN1987A pulsar and its fast rotation has, if confirmed, important consequences on the nuclear equation of state.

The condition for the centrifugal force to be balanced by gravity naively gives

$$v_{rot}^2 < GM/R$$

and shows there is a lower limit to the rotation period t_{rot}:

$$t_{tot} > \left(\frac{R}{15\ \mathrm{km}}\right)^{3/2} \left(\frac{M}{1.4\, M_\odot}\right)^{-1/2} \mathrm{ms}$$

which is actually a condition ($t > 1/\sqrt{G\varrho}$) on the average density of the star. Calculations including general relativity and realistic equations of state lead to a condition that can accurately be reproduced by the above formula with a numerical coefficient very close to unity. Shapiro et al. (1983) thus conclude that the discovery of a single pulsar with period $\leqslant 0.5$ ms would require exceedingly large neutron stars equilibrium densities and rule out all current equations of state. This indeed is the case of the SN1987A pulsar (Friedman et al. 1989, Haensel and Zdunik 1989), with very marginal exceptions (stars being just at the disruption limit due to rotation and at the same time at the collapse limit due to general relativity). It has been suggested (Glendenning 1989, Krivoruchenko 1989) that strange quark stars (Whitten 1984, Haensel et al. 1986, Alcock et al. 1986) could be acceptable candidates. Even this explanation is not free of difficulties (Haensel and Zdunik 1989). To allow for fast enough rotation, one has to take an equation of state that leads to compact enough stars. This can in principle be achieved by choosing parameters that lead to dense quark matter. This process however has a limit since the quark matter binding energy decreases with increasing density. When parameters are pushed too far, nuclear matter gets more and more favoured at low density and eventually the star radius starts to increase again because of the appearance of a sizeable nuclear matter envelope, preventing the desired compactness to be achieved. So, even the possibility of having compact quark stars that agree with the constraint of rapid rotation is fairly marginal since, if it exists, it can only be in a narrow range of parameters.

A new equation of state very likely is needed to comply with the rotation constraint. It should lead to $\sim 1.4\, M_\odot$ stars with fairly small radii, 4 to 8 km instead of the more usual 15 km. An example of a possible equaion of state is proposed by Haensel and Zdunik (1989). This equation satisfies all constraints but may be too stiff to give successful supernova explosions.

In case of non-uniform rotation, however, none of the above constraints would hold.

3. *Particle physics*

Most of the constraints obtained from SN1987A are relative to neutrinos, and more specifically to the electron-antineutrino. Some constraints can be derived for other weak interacting particles. The fact that the two first events observed by Kamioka were forward-

-peaked led some authors to assume they were due to ν_e-e scattering. Even if, on the average, one such event is expected, this assumption is too strong to lead to neutrino properties that could be safely used. Also, properties that involve the time structure (three separate bursts) of the Kamioka observations are unreliable since this structure is quite consistent with fluctuations due to small number statistics.

It has been known for many years that the observation of the neutrino emission of a supernova would lead to a limit on the neutrino lifetime and on its mass (Zatsepin 1968).

Also, various physical processes were proposed, that could prevent the solar neutrinos to come to earth still in the state of ν_e's. The fact that the $\bar{\nu}_e'$s from the LMC were seen can be used to eliminate, or at least to put some constraints on these processes.

3.1. Neutrino lifetime

In case neutrino has zero mass, it is stable. With finite mass, its lifetime (using $D > 44$ kpc) is constrained by

$$\tau_{\nu_e} > 1.5\ 10^5\, E_\nu/m_\nu \text{ years.}$$

Assuming this lifetime holds also for the electron-neutrino eliminates a possible ν_e decay as the explanation of the solar neutrino problem (Schramm 1987).

3.2. Neutrino mass

Finite mass particles have different travel times according to their energy:

$$\Delta t = 2.6\left(\frac{m_\nu}{10\text{ eV}}\right)^2\left(\frac{10\text{ MeV}}{E_\nu}\right)^2\frac{D}{50\text{ kpc}}\text{ s.}$$

The larger the mass, the larger the dispersion of the signal. So, from the width of the observed neutrino signal, one gets an upper limit on the neutrino mass. From the requirement that the dispersion due to possible finite mass of the neutrino is smaller than the 12s duration of the signal, one gets the conservative limit

$$m_\nu < 30\text{ eV.}$$

Schramm (1987) and Kolb et al. (1987) argue that this is the only sensible value to be extracted from the data. More specific assumptions on the initial structure of the emission may lead to lower limits, ranging from 11 eV (Bahcall and Glashow 1987) up to the value given above. This is to be compared to the 95% limit (Fritshi et al. 1986)

$$m_\nu < \ \ 0\text{ eV}$$

obtained from accelerator experiments.

3.3. Number of flavors

It is quite clear that the observed ν_e flux is just consistent with the binding energy of a standard $1.4 M_\odot$ star. Would there be more than three species of low mass (<10 MeV) neutrinos, the necessity of sharing the energy among $2N_\nu$ different types of particles would rapidly lead to severe energy problems. Due to the small number of events that were observed, the error bars are fairly large and although $N_\nu \sim 3$ is the most likely value to be retained, upper bounds at the 95% level, once derived under similar assumption all give $N_\nu \leqslant 5$ or 6 (Schamm 1987, Ellis and Olive 1987, Schaeffer, Declais, Jullian 1987), with the assumption of equipartition of energy, and of a neutron star that has no more than 3.5×10^{53} erg binding energy. This limit is comparable to the one obtained from accelerator experiments but less severe than the limit $N_\nu \leqslant 4$ from primordial nucleosynthesis (Yang et al. 1983).

A similar limit can be obtained by requiring for any kind of particles not to take out of the star more than the neutron star binding energy. For instance limits (Ellis and Olive 1987, Turner 1987, Mayle et al. 1987) on the axion coupling constant can be obtained this way.

3.4. Neutrino oscillations

Neutrino oscillations, either in vacuum, or in the presence of matter (Mikheyev, Smirnov 1986, Wolfenstein 1978) have also been invoked to solve the solar neutrino problem.

Vacuum oscillations result in the transformation of ν_e into ν_μ and ν_τ. Provided the oscillations length is short enough, only $\sim 1/3$ of the original ν_e's are left at arrival on earth. Little is to be expected from SN1987A since all species are emitted in about equal proportions. Mutual transformation would not alter the $\bar{\nu}_e$ flux. It would slightly increase its energy, since the $\bar{\nu}_\mu$ and $\bar{\nu}_\tau$ are more energetic, but this is unobservable.

The MSW effect has received somewhat more attention (Lagage et al. 1987, Walker and Schramm 1987). The solution of the solar neutrino problem, however, requires that the ν_e, $\nu_\mu(\nu_\tau)$ mix. Then the $\bar{\nu}$'s don't. Since we refrain from using the conclusions based on the too risky assumption that the two first Kamioka events are due to ν_e's, there is no connection between the solar neutrino problem and the MSW effect. Considering a possible mixing between antineutrinos alters the $\bar{\nu}_e$ energy distribution. Again, this was not observable for SN1987A.

3.5. Neutrino magnetic moment

In case the neutrino would have a magnetic moment, its helicity could flip in the sun's magnetic field, and the left-handed ν_e's produced in the sun could partly arrive at earth as being right-handed, and not interact with ^{37}Cl. Thus for $\mu \sim 10^{-11}$–10^{-10} μ_B, where μ_B is the Bohr magneton, the solar neutrino problem would be solved (Okin et al. 1986). Theoretical predictions (Cisnero 1971) from standard weak interaction theory are much lower: $\mu \sim 3 \times 10^{-18}$ $(m_\nu/10\ \text{eV})$ μ_B and the present experimental limits are $\mu < 4 \times 10^{-10}$ μ_B. A limit can be obtained from the fact that the SN1987A observation implies that most, if not all, of the emitted $\bar{\nu}_e$'s arrived at earth being left-handed. Magnetic fields being larger in neutron stars than in the sun, the limits are lower. They are $\mu < 10^{-14}$ μ_B (Nussinov and Raphaeli 1987) or $\mu < 10^{-12}$ μ_B (Lattimer and Cooperstein 1987), the difference being in the assumed magnetic field. Both limits rule out a moment large enough to account for the solar neutrino problem.

3.6. Tests of relativity

Photons and neutrinos are very different particles, they have different spins and different internal quantum numbers.

The weak equivalence principle states that any uncharged body will follow the same geodesic independently of its internal structure. The fact that the time-delay between the neutrino and optical signal was only a few hours, provides for a test of this principle.

In empty space, the velocity c of light and the velocity c_ν of neutrinos emitted by SN1987A was identical to (Longo 1987)

$$\left|\frac{c_\nu - c}{c}\right| \leqslant 2 \cdot 10^{-9}.$$

Previous accelerator test (Kalbfleish et al. 1979) gave a much less stringent limit: $4 \cdot 10^{-5}$.

Also, there is a ~6 month time delay in the signal due to the gravitational field of our galaxy, half due to the modification of the geodesics, half to gravitational redshift. The short delay between the two signals thus provides also a test of the weak equivalence principle in the gravitational field of our galaxy (Longo 1987, Krauss and Tremaine 1987), since the time delay for both particles was the same within a fraction of a percent.

3.7. Future physics from 1987A

Most of the new physical bounds obtained from SN1987A rely on the existence of a neutron star with the standard binding energy. The direct observation of the neutron star properties would obviously be of tremendous value, and confirm nearly all of the conclusions drawn previously.

The surface redshift $z \sim GM/Rc^2$, that could be measured from the e^+e^- annihilation line, is a sensitive function of the star binding energy. The energy equipartition among neutrinos, the emission of any other kind of particles may be constrained this way. The surface temperature could also be measured soon after the star's birth. The cooling rate a year or more after formation is very sensitive to the equation of state at ultra-high densities: quark matter, or other possible new phases of nuclear matter, would alter significantly the cooling rate. This may possibly bring some evidence for the existence of quark matter that is searched so actively in accelerator experiments.

4. *Conclusion*

A wealth of new results have been obtained from SN1987A about supernovae, stellar evolution, neutrino and neutron star physics.

For the first time, the progenitor of the supernova had been observed befoıe the explosion. Photometric measurements provide evidence for a shock in the outer layers of the star and the associated UV flash and pin down its arrival at the surface of the star with an accuracy of an hour. The neutrino emission detected by Kamioka and IMB has been seen for the first time, providing a signature for the formation of a neutron star and a check of the core-collapse + shock ejection mechanism of a SNII explosion. The direct detection of the neutron star is still to be confirmed.

The SN1987A event sheds some new light on explosion scenarii that before were considered as marginal possibilities: SN1987A was optically dominated by ^{56}Ni decay, exploded by forming a neutron star, and had a blue progenitor! Unorthodox possibilities have been put forward by several authors, and maybe in our obscurantism are we still missing major facts that would oblige us to totally revise our beliefs. For the moment, however, the gratifying surprises provided to us by SN1987A can be incorporated into our standard views, and should be considered as backing our previous ideas on the matter.

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