Supernova 1987A: Ten years after

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Supernovae are gigantic explosions of stars in which millions of tons of hot gas and debris are released. Such an event at its maximum brightness may outshine the entire galaxy in which it appears, and can be one of the most spectacular sights in the sky. Most supernovae appear faint because of enormous distances separating them from us. However, if one erupts in our galaxy or a nearby galaxy, it may be possible to see it with the naked eye. Five naked-eye supernovae were recorded between AD 1006 and 1604. After a long gap of 383 years since the last one, a supernova event that could be seen with the naked eye took place a decade ago. It was first observed by Ian Shelton from Las Campanas in Chile on 24 February 1987, and was located at a distance of 17,000 light years in the Large Megallinic Clouds in the southern sky. The Large Megallinic Clouds are a bunch of small, irregular galaxies that are companions to our own Milky Way galaxy. Photographs of the sky area where the eruption took place, taken some years previously, revealed a star at the location of the supernova. Catalogued as Sanduleak-69°202, it was a very hot, blue supergiant star about fifteen times more massive than the sun and about fifty times larger in diameter.

How does a star like Sanduleak-69°202 get to become a supernova? According to the standard theory of stellar evolution, the initial stages of energy production in stars is due to thermonuclear reactions that fuse hydrogen nuclei into nuclei of helium with atomic number four. In these reactions, there is a net mass loss which reappears as an enormous amount of energy as per the famous mass–energy conversion rule given by Albert Einstein. Enormous amounts of light and heat can be manufactured by this process. The nuclear reactions that convert hydrogen to helium can occur in two ways. One process, the proton–proton chain, is a set of three reactions that are efficient at temperatures below about 16 million degrees Kelvin. The other, more efficient at temperatures higher than this, is a more complex set of six different nuclear reactions called the CNO cycle involving carbon, nitrogen and oxygen. In the interior of the sun where the temperature is about 15 million degrees Kelvin, the proton–proton chain produces ninety per cent of the energy and the rest is due to the CNO cycle. As the supply of hydrogen as fuel gets diminished, there is no longer enough pressure that was generated by the heat of the reactions to counter the inward pressure of gravitation. As a result, the core of the star will collapse under its own weight. This process will heat the core and its overlying layers. Hydrogen will then burn in a shell surrounding the core and another round of thermonuclear reactions, that fuse the helium nuclei into the nuclei of carbon and oxygen, will be triggered in the core. If the star is a massive one, like Sanduleak-69°202, then after the helium burning is over the weight of the outer layers can be sufficient to force the core consisting of carbon and oxygen to contract. Once again, this will lead to a heating of the core and the overlying layers. Now the scenario will be as follows. Helium burning will commence in a shell surrounding the carbon–oxygen core, and beyond this shell there will be another shell in which hydrogen conversion to helium takes place. The carbon–oxygen core will continue to contract till it becomes hot enough to trigger the next round of thermonuclear reactions that will fuse the carbon nuclei into the nuclei of neon, oxygen, sodium and magnesium.

This kind of process can repeat, with the ashes of one set of fusion reaction cycle serving as fuel for the next round of reactions which will produce heavier nuclei. However, after the production of iron nuclei, this repetitive process must come to a halt. This is because iron nuclei are extremely tightly bound by nuclear forces, and also because by the time there is a large abundance of iron nuclei the Coulomb electric repulsive forces among them will act to prevent them from coming too close to each other.

What happens next to the iron core produced this way? Since the progenitor of the iron core was a massive star, the core is expected to possess a mass in excess of the Chandrasekhar limit. This implies that the iron core will not be able to stay as a stable configuration, but will start to collapse when the electrons in the core become degenerate (that is, lose their thermal kinetic energy). At this point, the collapse is expected to proceed at a very rapid rate (fractions of a second) to ever-increasing densities and temperatures. The squeezed nuclei and electrons can react with each other via the process of inverse beta decay to produce neutrinos and (progressively more) neutron-rich nuclei. Eventually, a stage will be reached, when the densities are pretty high, namely of the order of 10^{14} g cm^{-3}, that the highly neutron-rich nuclei will almost touch each other, and lose their individual identity. The composition then will be a more or less homogeneous sea of neutron matter, with small admixtures of protons and electrons. This is an enormously large value of density, possible only in centres of heavy nuclei such as lead or uranium. Because of the large density, the electron gas will attain a high value of the fermi momentum. That leaves little phase space for any more new electrons to join the club of these electrons. So, the neutrons that are formed will have to resist their otherwise natural tendency to decay into protons, electrons and neutrinos, and remain stable. A qualitatively new thing is now possible. Because the interaction potential between any pair of nucleons (nucleon is a collective term for either a neutron or a proton) is strongly repulsive with a rapid build-up at short inter-particle separations (of the order of a fermi), a system of such high density neutron matter will have a net repulsive force (which is a sum of nuclear repulsive force and the repulsive force of degeneracy) sufficient to balance the inward gravitational crunch, and halt the core collapse. A new stable stellar configuration, made up of mostly neutrons, forms. Such an object is called a neutron star. The abrupt halt of the core collapse is expected to produce powerful shock waves which will throw out the overlying shells of matter and radiation, resulting in a supernova eruption. Numerical computations suggest that typically a neutron star will have a radius of about ten kilometres but have the similar mass as that of the sun. In a sense, a neutron star is giant nucleus, with an atomic number of the order of 10^{57}.

The large number of neutrinos that are produced in the collapsing core do not stay there. Neutrinos are sub-atomic elementary particles that have zero or very small rest mass and no electric charge and are very elusive in the sense that these hardly interact at all with normal matter. Therefore, once produced, the neutrinos will rapidly escape. In fact, they are expected to get out of the star's confines hours before the shock wave from the interior blows the star to pieces. Two detectors, the Kamiokande detector in Japan and the IMB detector in the USA, both large water Cerenkov detectors, recorded a burst of neutrinos, during a 12-second interval, passing through the earth on 23 February 1987, about 18 h before the supernova was seen in the sky. This was strongly suggestive that the exploding Sanduleak-69°202 must have gotten to the stage of a neutron star formation.

Neutron stars born this way usually possess the right amounts of spin and surface magnetic field so as to give themselves away as pulsars. A pulsar emits beeps of radio frequency pulses at regular intervals of time that can be picked up by radio telescopes on earth. The funny thing about the Sanduleak supernova, designated SN 1987A, is that in the ten years since the event took place, no neutron star has been detected in that region of the sky. This is a mystery. Now two well-known nuclear physicists Gerry Brown and Hans Bethe have come up with an explanation of this mystery of the missing neutron star[1]. Their idea is a novel one, and, if true, it may change our thinking on neutron star formation.

The stellar collapse sequence described earlier is valid for stars whose masses are about ten to hundred times as much as the mass of the sun. For stars with initial mass much in excess of this, the nuclear repulsive forces are not sufficient to measure up to gravity. The collapse process in such cases is then a one-way traffic, namely collapse all the way whose end result is the formation of a black hole – a situation of extreme gravity from where no radiation or matter (the elusive neutrinos included) can make good their escape. This is the classic route to formation of a black hole. Sanduleak-69°202 was an ordinary star of about fifteen solar masses. This is not enough initial mass for this star to end up as a black hole as per the above classic description. The detection of the neutrino burst is a clear indication that a black hole could not have formed there at that time right away. More likely, a neutron star was formed. So then, where is the neutron star? Alternatively, if a black hole formed, then no neutrinos should have been detected.

Brown and Bethe believe that no pulsar could be detected in SN 1987A because no stable neutron star formed there. Instead, they have come up with a clever idea that there is a black hole at the centre of SN 1987A – a small one formed in a fundamentally different way than the classical theory suggests. Now it only remains to explain why neutrinos would be produced, if there is a black hole. The basic premise of the Brown–Bethe explanation is that high density neutron star matter will behave like a soft rubber ball. Such a system will not stand up to squeezing by external pressure, and so can follow a path to a final black hole state. Because short range nuclear forces are very repulsive, this cannot happen if neutron star matter is all or mostly neutrons. Brown and Bethe suggest that after a neutron star is formed, the composition of its interior will undergo a spontaneous change whereby a new set of particles, called K mesons or kaons, will appear in substantial numbers.

Kaon is a collective name given to a set of four elementary particles, all of which have a rest mass of about 495 MeV. One of these is positively charged (designated K^+), another negatively charged (designated K^-), and the other two have zero electric charge (designated K^0 and $\overline{K}^0$). The existence of such particles has been known for quite some time now from high energy particle physics experiments. It is also known that these are unstable particles (with several distinct decay channels) with a half life of the order of 8×10^{-9} sec. The possibility of spontaneous deposition of kaons inside neutron stars was first suggested by David Kaplan and Ann Nelson[2] in 1986. A feature of strongly interacting sub-atomic elementary particles, which goes by the name of chiral symmetry, stipulates that kaons have a net attractive interaction with neutrons and protons that is proportional to the baryon number density. This interaction is equivalent to a density-dependent mass of the kaon, and is such that it effectively lowers the energy of the kaon in the matter. Once the K^- meson energy comes down to the electron chemical potential, which increases with increasing density, the electrons change into K^- mesons and neutrinos through the reaction $e^- \rightarrow K^- + \nu$. This is estimated to occur at a density $\rho_c \sim 3\rho_0$, where ρ_0 is the equilibrium nuclear matter density whose value is about 2.8×10^{14} g cm^{-3}. Above the density ρ_c, the K^- mesons condense into a zero momentum state. Although kaons made on earth in particle accelerators are very short-lived, kaons in neutron stars would be stable by virtue of their attraction to nucleons. Roughly as many protons as neutrons will be present because the charge carried by the former can be neutralized by the negatively charged kaons. As a result, the collapse remnant will resemble nuclear matter, that is, it will be a 'nucleon' star rather than a neutron star. Nuclear matter is more compressible that neutron matter. Besides, kaons are particles that obey the Bose statistics, and so can co-exist occupying the lowest energy level without exerting any resistance against infalling matter. These two phenomena, taken together, imply that a neutron star with a kaon condensate will have a softer equation of state than a neutron star without it. Such a neutron star, travelling the path of gravitational collapse can slide into the path of formation of a black hole if the kaon condensate is sufficient. This delayed formation scenario of a black hole, induced by kaon condensation, is the key element of the Brown–Bethe hypothesis as it allows for time for the neutrinos formed earlier during the collapse to escape from the star. Had it been a straight, classic route to black hole, these neutrinos would have been gobbled up by the black hole, and could in no way pass through the earth. It so happens that ten seconds is about the time delay that Brown and Bethe compute for the gravitational collapse to black hole via kaon condensation. The neutrino burst detected on 23 February 1987 lasted for an interval of twelve seconds. It is interesting that the two time spans are so close to each other. It is worth mentioning here that a completely different explanation of this time-spread is possible. For example, Cowsik[3] has attributed this to a finite rest mass of the neutrinos which will cause lower energy neutrinos to arrive later. By analysing the neutrino-induced events on the time–energy plane he finds that masses 4 eV and 22 eV fit the data best. In any case his analysis provides an upper bound of about 25 eV on the rest mass of the neutrino.

The idea of Brown and Bethe of a delayed onset of a black hole starting with an intermediate neutron star stage with substantial kaon condensation is a clever one, that is able to explain the mystery of the missing neutron star in SN 1987A as well as the neutrino observation. However, the idea is a model assumption that looks promising, and is yet to find a general acceptance among all astrophysicists. For one thing, kaon condensation is not the only mechanism for a delayed collapse of a nascent neutron star into a black hole. A delayed formation of a black hole can possibly also happen due to other evolutionary changes in the neutron star core, such as a phase transition due to the formation of additional hadronic degrees of freedom besides neutrons and protons. The passage to black hole can also be triggered by a substantial late fallback of the ejected matter onto the neutron star. Numerical estimates of the critical threshold density for kaons to make their appearance in neutron star interiors are beset with uncertainties. The values mentioned earlier are imprecise. The reason for this is that the exact value of the chiral symmetry term is not known from particle physics theory. The possibility exists that the value of ρ_c may be estimated in future from heavy-ion collision experiments. Whatever may be the case, the SN 1987A has undoubtedly triggered a renewed interest in research on the equation of state of neutron star interiors.

1. Brown, G. E. and Bethe, H. A., *Astrophys. J.*, 1994, **423**, 659–670.
2. Kaplan, D. B. and Nelson, A. E., *Phys. Lett. B.*, 1986, **175**, 57–63.
3. Cowsik, R., *Phys. Rev. D.*, 1988, **37**, 1685–1687.

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