1 Supernovae and Supernova Remnants: The Big Picture in Low Resolution

Athem W. Alsabti and Paul Murdin

Abstract

A supernova is a star ending its life in a powerful explosion, nearly always leaving behind an expanding gaseous remnant, which has an influence on the surrounding circumstellar and interstellar medium, and possibly a compact stellar remnant. Multiple supernovae events, collectively, can have a strong influence on local galactic regions, the entire parent Galaxy, and the intergalactic medium. On average, supernovae occur at a rate of $\sim$2 per century per galaxy. The observational phenomena generated in and after each event show a rich variety of scientific properties. These are both photometric and spectroscopic (and covering the entire electromagnetic spectrum), but also include newer areas of observational astronomy, such as neutrino physics, cosmic rays and gravitational waves.

Supernovae are the result of either of two distinct explosive mechanisms. Type Ia supernovae are explosions of white dwarfs pushed over the Chandrasekhar limit, typically with a peak luminosity $\sim 2 \times 10^{43}$ erg s^{-1}. They leave no stellar remnant. Type II, Type Ib and Type Ic supernovae are the results of the collapse of the core in supergiant progenitor stars of mass $M > 8$ solar masses, with a peak luminosity typically $\sim 10^{42}$ erg s^{-1}. They leave a neutron star or black hole stellar remnant (or possibly none).

Supernovae play an essential role in the synthesis of many elements in the periodic table, apart from the lightest (H, He and tiny amount of Be, B and Li, produced in the Big Bang). They distribute into the interstellar medium the

A.W. Alsabti (✉)
University College London Observatory, University College London, London, UK
e-mail: a.alsabti@ucl.ac.uk

P. Murdin
Institute of Astronomy, University of Cambridge, Cambridge, UK
e-mail: murdin@ast.cam.ac.uk

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elements that they make and the elements made in, on and near to their progenitor stars by other processes. All these elements are injected into molecular clouds and provide the raw material from which stars and planetary systems form. Supernova explosions close to the Sun, say within $\sim$100 pc, continue to be an influence on the solar system, depositing identifiable isotopes like Fe^{60} on the Earth and Moon. Cosmic rays produced within the shells of supernova remnants influence climate and probably caused lasting effects on the evolution of life. Neutrinos produced by supernovae have an indirect effect on the chirality of amino acids.

Contents

1 Introduction

The study of supernovae connects us with almost all fields of research in astronomy and many in physics. No objects studied in astronomy have covered so many multidisciplinary topics as supernovae, as is shown by the scope and size of *The Handbook of Supernovae*, edited by the present authors (Springer 2016). The development of supernovae and their remnants takes place over a long time, and the association of historical supernovae, like the "Guest Star" of AD 1054, recorded by a number of oriental civilizations, and connected with explosive astrophysical objects now studied in great detail, such as the Crab Nebula, provides observational material to make connected studies of the evolution of supernovae over a millennium. The observations ongoing of recent supernovae, like SN 1987A in the Large Magellanic Cloud, repeatedly restart these studies, studied on timescales of decades.

The investigation into the theoretical science of supernovae started on a path parallel to observational science in the 1930s. The observational path led to our understanding of brightness, light curves and spectra, as well as improving the methodology of their discovery on an industrial scale! On the other hand, the theoretical path taught us how stars advanced on their evolution to late stages of stellar structure and the ways in which they explode, resulting in different types and classes of supernovae. The interrelationships among all these observational data and theoretical possibilities are complex topics which remain matters for discussion up to the present day. The physics of the explosions remains at the cutting edge of research, in particular the way that the explosion in a supernova drives off the outer layers of its progenitor star and produces various remnants such as neutron stars and black holes.

In the course of the explosion, new elements are formed by nucleosynthesis and the explosion scatters into interstellar space these elements and the other elements generated by nuclear burning and other processes in, on, and near the progenitor star. The role of remnants of supernovae as expanding shells pushing into the interstellar medium is also important, and the input of energy into the interstellar medium that supernovae generate affects the evolution of galaxies and the space around them. Beyond individual galaxies, intergalactic space can be measured using supernovae as standard candles.

Coming back closer to home, the solar system can now be investigated from the point of view of the role of supernovae in creating its initial constituents and the formation from these constituents by supernova shocks of our Sun and its planetary system. The residue from the multiple supernovae explosions in the neighborhood of the Sun can be identified in interplanetary dust and on the Moon. In recent years, the planetary climate and space weather have also been found to have been affected by galactic cosmic rays originating from the expanding shells of supernova remnants. It has also been suggested that neutrinos originating from explosions of supernovae could have affected the molecular structure of amino acids in the solar system, thus affecting the emergence of life on Earth.

The importance of supernovae in astrophysics can be judged by the list of Nobel Prizes awarded to scientists who have made significant advances in areas connected with supernova research:

2011: Saul Perlmutter, Brian P. Schmidt and Adam G. Riess "for the discovery of the accelerating expansion of the Universe through observations of distant supernovae."

2002: Riccardo Giacconi "for pioneering contributions to astrophysics, which have led to the discovery of cosmic X-ray sources."

1993: Russell A. Hulse and Joseph H. Taylor Jr. "for the discovery of a new type of pulsar, a discovery that has opened up new possibilities for the study of gravitation."

1983: Subrahmanyan Chandrasekhar "for his theoretical studies of the physical processes of importance to the structure and evolution of the stars."

1983: William Alfred Fowler "for his theoretical and experimental studies of the nuclear reactions of importance in the formation of the chemical elements in the universe."

1974: Antony Hewish "for his decisive role in the discovery of pulsars."

2 The Foundations of Supernova Astrophysics

The word "nova" in astronomy (plural "novae") is an abbreviation of the Latin phrase "nova stella," meaning "new star," i.e., a bright star appears for a period of time at a place in the sky where there was no such bright star before. The occurrence of two such novae, in 1572 and 1604, was widely discussed in Europe because they were exhaustively studied by many influential astronomers, notably Tycho Brahe and Johannes Kepler, respectively. In that these two events focused attention on the intrinsic properties of stars, as distinct from their positions and motions, the two new stars can be said to have started astrophysics. In the early 1930s, following work by Knut Lundmark on the range of luminosities of novae in galaxies, Walter Baade and Fritz Zwicky identified a class of novae that were 10,000 times more powerful than others and gave currency to Lundmark's word "supernova" (SN, plural SNe) to describe them.

Large numbers of novae and supernovae have been discovered and observed over the centuries. Evidence has been uncovered of some novae and supernovae observed historically, prior to the time of modern science and recorded in contemporary accounts, usually with an astrological context. Historical evidence has been usually been correlated with the discovery of a "supernova remnant" (SNR), i.e., an expanding shell of material resulting from a supernova explosion, which draws attention to a locality in the sky and an epoch where a supernova has occurred. SN 1006, SN 1054 (the Crab Nebula), SN 1181 (3C58), Tycho's SN 1572, and Kepler's SN 1604 are examples of SNe/SNRs where the complete history over 500–1000 years as well as a precise age is available to help us understand the astrophysics of these objects. In total, taking account of historical supernovae recorded with varying degrees of certainty over the last 2000 years, the number of supernovae that have been seen in our own Galaxy is a mere handful – fewer than 10. Most supernovae – hundreds and thousands of them – have been seen in external galaxies, such as M31, the Andromeda Galaxy, and the large numbers of galaxies at great distances, visible to us because the explosions are so powerful.

Ordinary novae are relatively mild explosions on the surface of a white dwarf star. Baade and Zwicky's brighter class of "supernovae" are, by contrast, disruptive explosions that result in the gravitational collapse of the progenitor star to a compact object such as a neutron star or black hole or even disrupt the entire progenitor. The material that does not end up in a compact stellar remnant is dispersed into the surrounding space, where it becomes a supernova remnant. The release of the gravitational binding energy of the core of the original star into kinetic energy amounts to approximately 10^{51} ergs; this is roughly 100 times the energy radiated by the Sun in its lifetime. The large amount of energy accounts for the powerful effects of a supernova and as a unit has been informally given the name FOE, some of the initials of words in the phrase "ten to the fifty-one ergs." Most energy is released as neutrinos: 10^{53} ergs. The energy that is released heats the material of the collapsing core to temperatures of order 10^{10} K. The core collapses almost in free fall, in less than a second, so the energy release has a luminosity of 10^{54} erg s^{-1}, roughly the same luminosity as the visible universe.

The energy produced by a supernova explosion is spread into various forms including radiant energy, such as neutrinos, gravitational waves and the entire range of electromagnetic radiation, as well as the kinetic energy of outflowing material, high-energy cosmic rays, and nuclear energy. Radiant energy from the supernova phenomenon heats the body of the progenitor star, which shows as a photosphere with spectral lines of characteristic elements depending on the material's composition and shapes depending on the distribution and motion of the material. The "new star" phenomenon is the manifestation of this large, hot, expanding photosphere. It starts abruptly, rising in brightness over a matter of hours, and is at its maximum brightness for a matter of days or weeks. Its brightness fades and its temperature falls with time so that the supernova becomes invisible over a matter of perhaps years, depending on the star's distance. The rise and fall of the light output and temperature of the supernova constitute its light curve and its spectral evolution. These observational characteristics have properties that have been grouped into empirical classifications. As observed in SN 1987A and others, the shock waves produced by the supernova propagate into the circumstellar and interstellar medium surrounding the supernova and create effects and features within the parent galaxy.

Supernovae take place only in certain kinds of stars at a particular stage of their lives, but, other than a general indication that a supernova is possible, there is little or no visible sign in the outer parts of the progenitor star that an explosion is imminent. Thus, supernovae are unannounced. Over most of astronomical history, supernovae have been discovered by chance, after one has happened and is noticed. They average around two per Galaxy per century, so it is necessary to scan at least hundreds, and better millions, of galaxies to find supernovae at a rate at which they can be studied at all intensively. The first systematic searches were by Fritz Zwicky, using the wide-field Schmidt telescopes of the Palomar Observatory. He repeatedly surveyed large numbers of galaxies, looking by eye on photographs for "new stars." Follow-up observations were delayed by the time that the discovery process took, perhaps not made at all if it was not possible to change telescope schedules from their planned work and, if made, were made with an arbitrary set of equipment deployed for some unconnected purpose on whatever telescope was available. In the current era, a number of well-focused and coordinated supernova surveys are being executed, relying on automated gathering of large amounts of observational information, rapid computer processing of the blocs of "big data" to find candidate supernovae in a very short time, and follow-up observations that are prescheduled and appropriately equipped for well-targeted investigations in the certain knowledge that a number of supernovae would have been identified by the prior survey. These surveys have found hundreds of supernovae and made it possible to use them in statistically meaningful studies in cosmology and to provide large enough samples to discover rare types of supernova.

It is worth mentioning that amateur astronomers carry out searches for supernovae, concentrating on the brighter galaxies distributed over the whole sky and thus providing early alerts to the nearer supernovae, which might be overlooked by professional searches that are concentrated in limited areas of the sky but which are material for potentially detailed study.

The energy that is released by a supernova produces astronomical phenomena whose details depend on the kind of star that exploded, in particular its evolutionary state at the moment of explosion, and the star's circumstellar and interstellar environment, including whether it has a binary companion or not. The range of circumstances of the explosions, the rapidity of the development of the explosions, the challenging physics, and the variety of significant dimensional scales in the various parts of the star all make the theoretical solution of the explosion difficult. It is even becoming clear that the simplifying assumption of spherical symmetry has to be abandoned because some supernovae are essentially asymmetric and some phenomena are the results of that. The drive to understand these explosions is strong because their consequences are far-reaching: supernovae have effects on the history of galaxies and planets, including the development of life on Earth.

3 Progenitor Stars

3.1 White Dwarfs

White dwarfs are stars whose hydrostatic equilibrium is supported by electron-degeneracy pressure. In 1930, Subrahmanyan Chandrasekhar showed that such a configuration was possible only if the star was less than a certain mass, up to what has become known as the Chandrasekhar limit, approximately 1.4 solar masses. Beyond this limit, a white dwarf star will collapse and appear as a supernova. The cause of the collapse is either the gradual accretion of matter from a nearby star, i.e., a companion in a binary system, or the merger of two white dwarf stars to produce a white dwarf star that is over the limit. This triggers a runaway thermonuclear explosion, with a subsonic ("deflagration") flame that propagates through the body of the white dwarf. The composition of the white dwarf is commonly carbon and oxygen, possibly also silicon. Fusion of these nuclei releases energy and raises the temperature of the star's material. Degeneracy pressure is independent of temperature, and a runaway thermonuclear reaction results, detonating the star. No compact remnant is left. The thermonuclear fusion process produced heavy elements in the iron group, like Co^{56} and Ni^{56}, whose radioactive decay powers the light curve of the supernova.

The progenitor white dwarf star is the outcome of the evolution of a star, initially of up to 8 solar masses, in which its original hydrogen has been converted to heavier elements or lost into space in a stellar wind, so no hydrogen is visible in the supernova's spectrum. Such a supernova spectrum is described as being of Type Ia.

Super-chandra supernovae are rare Type Ia SNe that are particularly bright, conjectured to arise from white dwarfs that are up to twice the usual Chandrasekhar mass limit. The progenitor of such a supernova may result from the abrupt merger of two Chandrasekhar limit white dwarfs, or it may have been a single white dwarf partially supported by rapid rotation in addition to electron-degeneracy pressure.

3.2 Core-Collapse Supernovae

The evolution of most massive stars in general results in a core of heavy elements, typically iron but possibly, for the least massive stars in this range, a mixture of oxygen, neon, magnesium and silicon, O/Ne/Mg/Si. The core is electron-degenerate, essentially a white dwarf, but surrounded by an envelope of material that may well contain hydrogen but which has at least in part been nuclear-processed to elements heavier than hydrogen. The precise structure of the envelope depends on the initial mass of the progenitor star and its mass-loss history, which in turn depends on its metallicity and whether it is in a binary star system, and if so how close and massive was its companion during its evolution.

Such a star, of initial mass above 8 solar masses but below 140 solar masses, produces a core-collapse supernova (CCSN). Often the spectrum of a CCSN shows hydrogen spectral lines, arising from residual hydrogen in the progenitor's envelope, in which case it is designated through observations as a Type II. But if the pre-explosion evolutionary history of the progenitor (stellar winds, mass transfer in a binary system) has dispersed the hydrogen of its outer envelope into the circumstellar region and the core collapses inside an envelope primarily of helium, carbon, oxygen and silicon, no hydrogen is visible in the supernova's spectrum, certainly not at first. The CCSN is then said to be of Type I, with suffixes in the classification label which identify compositional specifics such as the presence of helium or not (Type Ib or Type Ic, respectively), which make it different from a Type Ia.

Other suffixes identify features of the light curve, such as a decline in brightness after maximum that is linear when expressed in astronomical magnitudes or is characterized by a standstill or plateau (Type II-L or Type II-P, respectively). Differences in the light curves are caused by differences in the density and compositional structure of the progenitors' envelopes, and therefore the progression of opacity as the photospheres of the supernova material passes through the exploding body of their parent stars.

The present supernova classification system is complex (Fig. 1) and grew incrementally. Many astronomers think that it is not fit for purpose and needs overhauling in the light of modern research.

The energy released by a CCSN depends on the mass and structure of the progenitor star. Thus the luminosity of CCSNe is quite variable, because stars with masses >8 solar masses in an advanced evolutionary state have a variety of structures. Some extreme Type II-P supernovae are termed "ultra-faint SNe." Some Type Ic SNe are "super-luminous (SL SNe)," while others are "broad-lined" (meaning high velocity of the ejecta) or "hyper-novae." They may also be high-energy supernovae which are the origin of long-duration gamma-ray bursts.

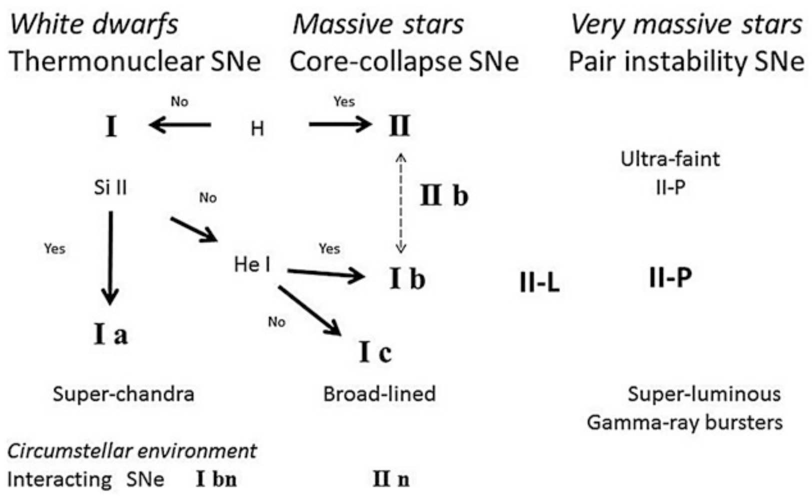

Fig. 1 A taxonomic map showing the classifications and interrelationships between supernova types (Figure supplied by Cosimo Inserra (Queen's University Belfast))

3.3 Pair-Instability Supernovae

At the present time, now that the history of the universe has progressed via the elements generated and distributed by supernovae, and other processes, to produce an interstellar medium of approximately solar composition, the maximum mass of a star in hydrostatic equilibrium is about 120 solar masses. Otherwise the star exceeds the Eddington limit of luminosity at which radiation pressure overcomes gravitational attraction and disperses the star. The mass limit can be pushed to 150 solar masses or more for low metallicities, because the opacity of the stellar material is reduced. Even more massive stars may exist if they are not in equilibrium. Very massive stars of low metallicity, above 140 solar masses at the outset, do not get to form a stable iron core at the end of their evolution. Their central regions enter into an electron-positron pair-instability state during the oxygen burning stage. Collisions between nuclei and gamma rays in the core result in pair production, which reduces the thermal pressure in the oxygen core. The core collapses dynamically. This is a pair-instability supernova (PISN). The star is completely disrupted, leaving no stellar remnant behind. They may be manifested as SL SNe and/or SNe with abnormally long-duration light curves.

4 What Happens in a Typical Core-Collapse Supernova

The core of a CCSN collapses in less than 1 s to a compact stellar object, i.e., a neutron star if the initial mass of the progenitor is less than about 40 solar masses (there is a metallicity dependence; see Fig. 5) or black hole if more massive.

The collapse heats the infalling material to a high temperature and releases most of the collapse energy in the form of neutrinos. The neutrinos also heat the envelope material and begin to launch it outwards to become supernova ejecta. Other neutrinos travel quickly out of the progenitor and radiate as the promptest indication to the outside universe that the core has collapsed and the supernova phenomenon is under way. It is possible in a nonspherical collapse that significant energy could be lost in the form of gravitational waves, and these also travel, undelayed, directly from the core and are equally prompt in announcing core collapse. At a later stage of the explosion, asphericity may result in detectable spectroscopic and polarization anomalies.

If the collapse forms a neutron star, infalling material bounces on its hard surface, generating a shock wave that travels to the surface of the progenitor, taking about an hour. The shock heats the surrounding material, adding to breakouts from the surface, and heats it to a temperature of a million degrees. The sudden heating and brightening of the surface of the progenitor star and consequent ultraviolet photons, emitted in a flash lasting a few minutes, are the second signal to the outside universe that a supernova has occurred. The outer layers of the progenitor star start to expand, increasing its size by perhaps a factor of 10 or more in one day and its brightness by about a factor of 1000. It is in this third phase, about a day after the collapse of the core, that the star starts to exhibit to the rest of the universe the defining characteristic of a “new star.” It is an observational challenge to astronomy that the opportunity to study the onset of the supernova phenomenon is heralded by gravitational waves and neutrinos, the detection of which is intrinsically difficult so that detection techniques are in the early stages of development from their infancy, although the recent (2016) detection of gravitational waves from a binary black hole is an observational triumph that is encouraging.

The calculation of the physics of the collapse is a complex problem involving thermodynamics, hydrodynamics, electromagnetism and gravitational theory, and atomic, nuclear, and particle physics. Numerical methods are challenging, with high-resolution steps required in both space and time. Additionally, the geometric model within which the calculation takes place may contain complicating factors such as rotation and asymmetry; indeed asphericity is a necessary complication to address some issues.

The supernova continues to expand indefinitely, but its outer layers become more rarefied, and its photosphere eventually starts to contract, after a matter of weeks. It has reached its maximum brightness and begins to fade.

If the collapse forms a black hole, there is no hard surface on which any infalling material can bounce. This means there is no outward shock. This reduces the energy deposited in the envelope. This can weaken the supernova, which is thus fainter than typical; it may weaken the supernova phenomenon so drastically that all the progenitor star’s material is swallowed by the black hole and no remnant is left at all. It is even possible that some supernovae take place by a sudden collapse of the entire star without any significant outflow at all, so that the star suddenly disappears.

In the core collapse, the stellar material is heated to high temperatures and compressed to high densities. Nuclear reactions generate nickel-56, Ni^{56}, which with a half-life of 6 days decays to cobalt-56, Co^{56}, which itself is radioactive with a half-life of 77 days and decays to iron-56, Fe^{56}, which is stable. The Co^{56} decay emits a spectrum of gamma rays, including one with an energy of 847 MeV, as observed in SN 1987A. Expansion of the supernova material, especially since the material becomes lumpy, with transparent tunnels, allows gamma rays to exit from the supernova from a few weeks after the core collapse.

5 Nucleosynthesis

In an epoch-making paper in 1957, known by the initials of its authors as B^2FH, Margaret Burbidge, Geoffrey Burbidge, William Fowler and Fred Hoyle laid the foundation for the theory of the origin of the elements. The form of the study was to list a small number of nuclear processes that would produce the entire range of isotopes within the periodic table and calculate from principles of nuclear physics the cosmic abundances of the chemical elements. B^2FH also sought to identify astronomical sites where the processes occur. The nuclear physics led the astronomy.

The nuclear processes that provide the energy to power stars are processes that build heavier elements from hydrogen. Supernova explosions distribute these elements into the interstellar medium (Figs. 2 and 3). In addition, the explosions themselves are nuclear processes that make further new elements (Fig. 4).

One process on the B^2FH list was labeled the r-process. Its fundamental idea of nuclear physics was a succession of rapid neutron captures (hence the name r-process) by a heavy seed nucleus. The sites where this process occurred were identified as supernova explosions. B^2FH founded the physics of the origin of the elements, but the details of nucleosynthesis are more complex than they originally identified, with the astronomical circumstances playing a major role, as well as the nuclear physics. In present methodology, the yields of nuclides from supernova explosions are calculated starting from the astronomy. The calculation starts with a model for the supernova progenitor, models the SN explosion, and calculates the results of the explosive nucleosynthesis with laboratory-based nuclear reaction networks. The broad outcome is that supernovae are responsible for the creation of approximately half of the neutron-rich atomic nuclei heavier than iron, almost everything heavier than tin and everything heavier than lead.

There are differences in the yields of the elements produced by CCSN and thermonuclear supernovae. The thermonuclear runaway in a carbon-oxygen white dwarf that produces a Type Ia supernova results in the explosive synthesis of iron-group elements, plus some others. SNe Ia are the main producer of iron in the universe. Type II/Ib/Ic core-collapse supernovae occur in evolved massive stars with a layered structure of alpha elements and result in the explosive nucleosynthesis of heavy elements near the core, with the outer layers expelled. Nuclear processing as the supernova shock wave propagates through the star produces "α-products." Carbon burning produces O, Ne, Mg, etc.; neon burning produces O, Mg, etc.; oxygen burning produces Si, S, Ar, Ca, etc.; and silicon burning produces Fe, Si, S, Ca, etc.

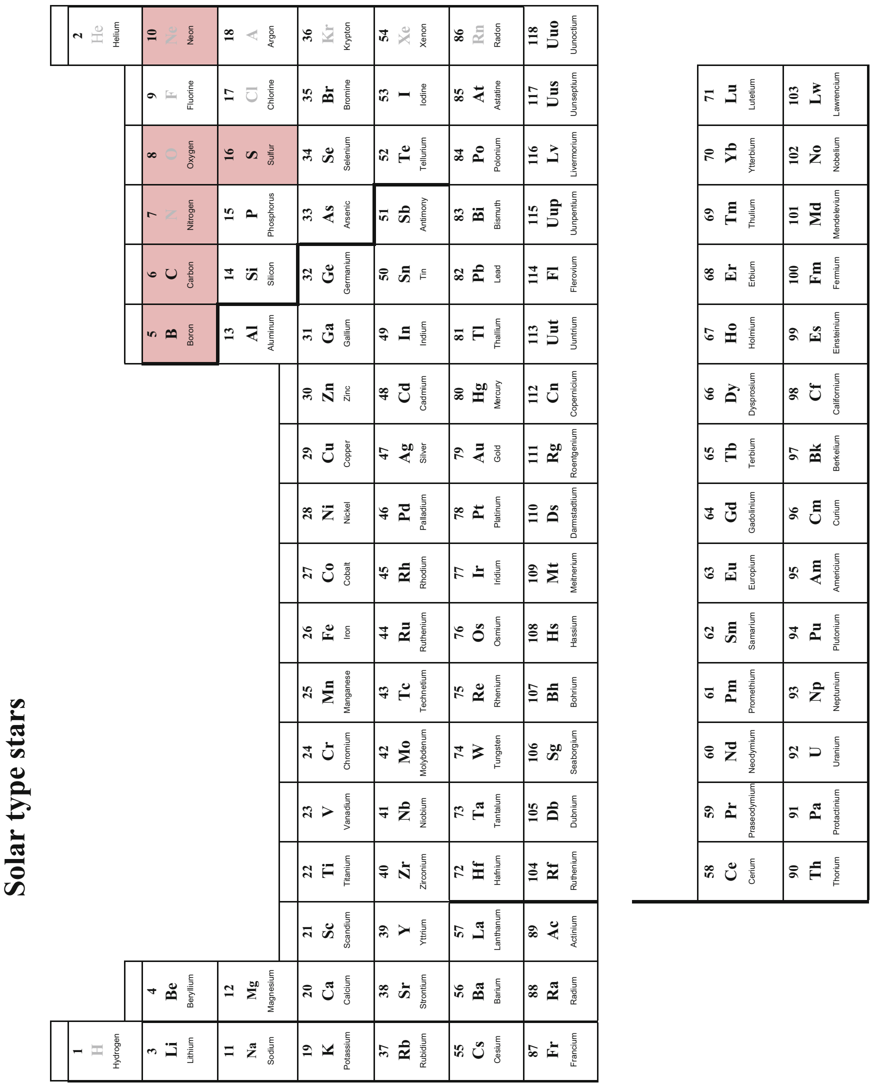

Fig. 2 Elements made in less massive stars that are distributed into the interstellar medium principally by Type Ia supernova explosions (Heger et al. 2003)

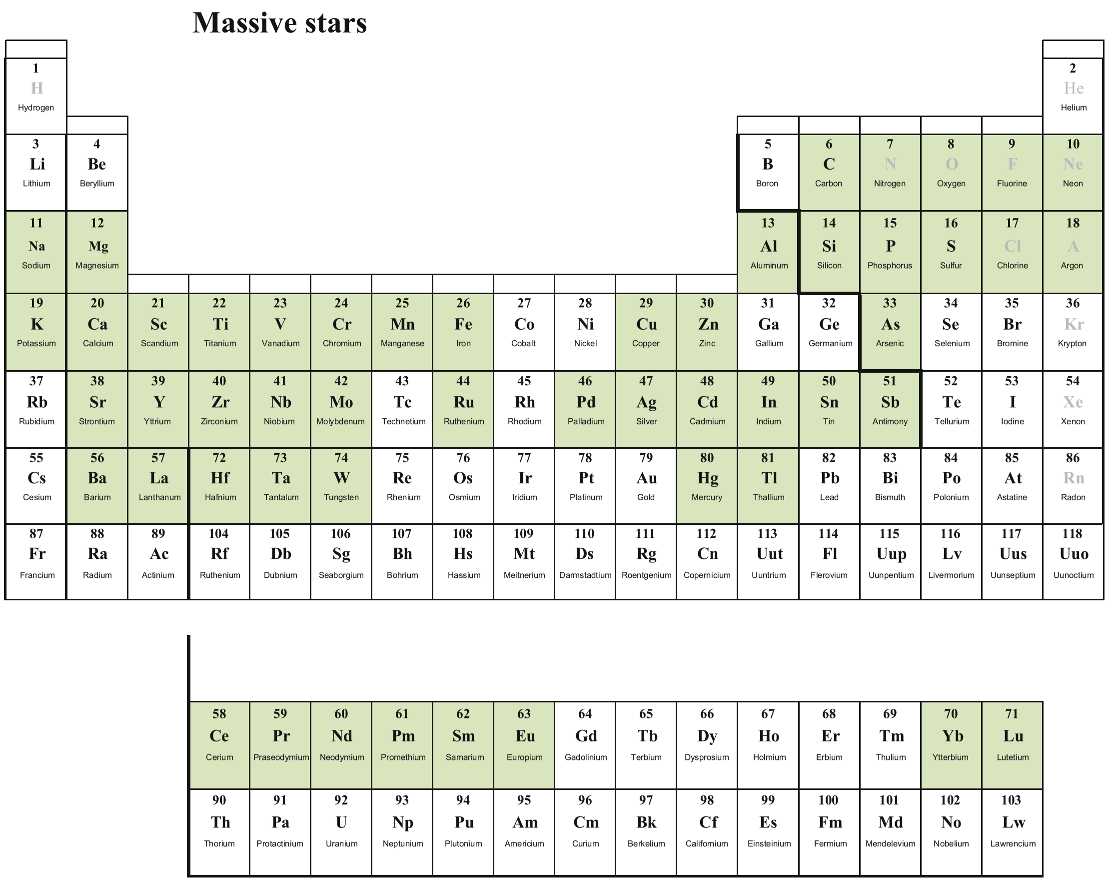

Fig. 3 Elements made in massive stars that are distributed into the interstellar medium by CCSN explosions

Fig. 4 Elements in the periodic table that are made in supernovae

Because the progenitors of the white dwarfs have long life times, compared to the more massive stars which become core-collapse supernovae, iron-group elements and alpha-elements in stars of different ages trace different components of the history of our Galaxy.

6 Circumstellar Material and Stellar Companions

Some supernovae show narrow hydrogen emission lines in their spectra and are given a suffix to indicate the narrow lines, e.g., Type IIn. The underlying supernova may be of Type Ia or Type II, and the type may change as the supernova progresses through its various stages. Other rare supernovae show narrow helium emission lines, classified as Type Ibn. The hydrogen or helium emission probably arises from circumstellar material, which is swept up in the progressive expansion of the supernova.

Ultraviolet light emitted by the supernova ionizes any circumstellar material, which in the case of a nearby supernova may then be visible as it recombines, to show a circumstellar nebula, as in the case of SN 1987A. When at a later time the material ejected from the supernova reaches the circumstellar material, it will be collisionally ionized.

Binarity plays a role in the evolutionary build-up to the explosion of some supernovae. It is an essential feature of the double-degenerate model for Type Ia supernovae, which envisages the merger of two white dwarf stars, either gradually by a mass transfer process or more suddenly by wholesale merger.

A companion star will stand in the way of a supernova explosion from the other star in its binary system. The sudden burst of radiated energy from the supernova will produce an X-ray and optical flash lasting minutes to days, and this affects the external layers of the companion star, with consequent spectral indications – which however are transient and easily overlooked.

In some circumstances of proximity and mass ratios, a companion star may be liberated from its binary system and be ejected, essentially because the gravitational pull of the supernova progenitor has been switched off as the supernova material passes beyond the companion and there is no effective gravitational pull to hold the companion in orbit. The companion star continues at its orbital speed in a straight line and becomes a high-velocity star, moving at speed ($>100\,\mathrm{km\,s^{-1}}$), through the other stars of the Galaxy. Such stars are called "runaway stars." In the intermediate case, the system survives intact but with an eccentric orbit, later circularized through tidal interactions. Supernovae that occur in star clusters may, to a small extent, affect the amount of gas that they contain.

In the event that a Type II supernova occurs in a binary system, does not disrupt it, and leaves a stellar remnant (neutron star or black hole), the binary system may well evolve to show further interesting phenomena. X-ray binaries are pairs of stars in which the X-rays are generated as the companion star deposits material on the neutron star or black hole. The properties of such binary stars depend not only on the nature of the compact remnant and the separation of the stars but also the nature of the companion star, broadly whether it is a high-mass star (making a high-mass X-ray binary, HMXB) or low mass (LMXB). Associated phenomena include the mass transfer process, such as accretion disks, and outflows such as winds and jets (as in the star SS433). X-ray binaries may evolve further through a second supernova explosion to be a binary neutron star or a neutron star-white dwarf binary. The spin period of the first neutron star may be speeded up, and it may be released as a lone millisecond pulsar.

7 Supernova Remnants

The ejecta from a supernova are formed of the material of the progenitor star, including elements that have been processed in the course of the star's evolution up to the moment of the supernova explosion and elements made from those elements by processing in the explosion itself. The ejecta are accelerated in the explosion to speed up to 30,000 km s^{-1}. The outflow is spherical and homogeneous only to first order; there may be considerable irregularity and anisotropy not only because of the properties of the explosion but also because of proximate circumstellar material. Outside the circumstellar environment, after perhaps 10 years, the supernova blast wave encounters the interstellar medium, heating it to X-ray-emitting temperatures, manifest as a line-dominated spectrum with a bremsstrahlung continuum, and signaling the transition from SN to SNR. Nonthermal electrons produce synchrotron radiation: this is detected as radio emission from the SNR. A reverse shock propagates inward, reheating the ejecta. For hundreds to thousands of years, the expanding shell of material is in this "ejecta-driven" stage, during which the ejecta themselves can be identified as a hollow shell of outwardly moving filaments with abundances typical of the evolved progenitor star. A well-studied example is Cas A, the SNR from a supernova that exploded in about 1681.

The energy radiated is small compared to the kinetic energy of the ejecta and the evolution of the supernova remnant is adiabatic, with the material cooled by expansion and progressively decelerated by interstellar material that is swept up. In an idealized formulation, there is an exact solution to the evolution of this phase formulated in the 1950s by Geoffrey Taylor and Leonid Sedov in the context of military explosions. The Taylor-Sedov phase of a supernova remnant lasts for perhaps 20,000 years. In some SNRs like the Crab Nebula, there is a central neutron star, which, if it is a pulsar, inflates a bubble of relativistic particles and a magnetic field to form a pulsar wind nebula (PWN) within the SNR, but the pulsar's energy output does not usually alter the overall evolution of the SNR.

The SNR expands and cools adiabatically until it reaches a temperature of about 1 million K. The ionized atoms of the SNR material capture free electrons and lose energy by radiation. Adiabatic expansion ceases, and the SNR enters the "radiative phase" or "snow plough phase" with more and more interstellar gas being swept up until it dominates over the ejected stellar material. This phase lasts perhaps 100,000 years, the shell breaking up and dispersing into the interstellar medium.

The nuclear-processed material of the ejecta feed into the interstellar medium, enriching it with so-called metals, i.e., elements heavier than hydrogen or helium.

As the supernova remnant cools, its gaseous elements progressively combine from ions to atoms to molecules and to solid grains. Infrared photometry and spectroscopy can be used to investigate the properties of the cooler stages. The first galaxies formed in the universe were under-abundant in heavy metals and thus generated lots of massive so-called Population III stars. They exploded as supernovae within a few million years and generated large amounts of carbon in the interstellar medium which condensed to dust. The "Dark Ages" is the period after the formation of the first galaxies during which dust obscures the visible light from the remaining stars in these galaxies and the abundant supernovae which they generate. Their visible-band radiant energy is absorbed and reradiated as infrared and millimeter wave radiation. The galaxies constitute high-redshift ultra-luminous infrared galaxies. Molecules in the ejecta of present-day supernovae feed into molecular clouds, with the dust, and the inorganic and organic molecules becoming the seed material of newly formed stars and planetary systems.

8 Neutron Stars and Black Holes

As the O/Ne/Mg core or iron core collapses in a CCSN, its temperature passes through 5×10^9 K. The iron nuclei photodisintegrate into alpha particles as a result of interaction with high-energy gamma rays and then protons and neutrons. At yet higher temperatures, the protons combine with electrons to form neutrons through the process of electron capture. At a density of 4×10^{26} g.cm^{-3}, neutron degeneracy pressure halts the contraction, creating a neutron star, of mass around 2 solar masses. The mass distribution of neutron stars is tightly peaked but bimodal, representing possible formation mechanisms via two channels.

If, in the course of its formation in a core-collapse supernova, the putative neutron star is more massive than the upper limit for such objects (as degeneracy-pressure-supported objects, neutron stars have maximum masses like white dwarfs), or if, depending on metallicity, it accretes material which, having begun to eject in the supernova explosion, stalls and falls back, the neutron star collapses further to a black hole (Fig. 5). A scheme that relates this underlying astrophysics to the observational types and classes of supernovae is shown in Fig. 6.

The collapse of the core of a CCSN preserves to some extent its angular momentum, which is $Mk^2\Omega$ (ignoring geometric and other factors of order 1), with the radius of gyration, k, decreasing by a factor of 100, so that its rotation frequency, Ω, increases by a factor of 10^4. If the core rotated with a period of 1 day (as might be typical for a star), the neutron star now rotates with a period of about 1 s. The highly conductive material of the collapsing core traps magnetic field lines and throttles them into a smaller cross-sectional area, increasing the magnetic field strength by the same factor of 10^4. The rapidly rotating neutron star becomes a pulsar, radiating in the radio region but perhaps over the entire electromagnetic spectrum.

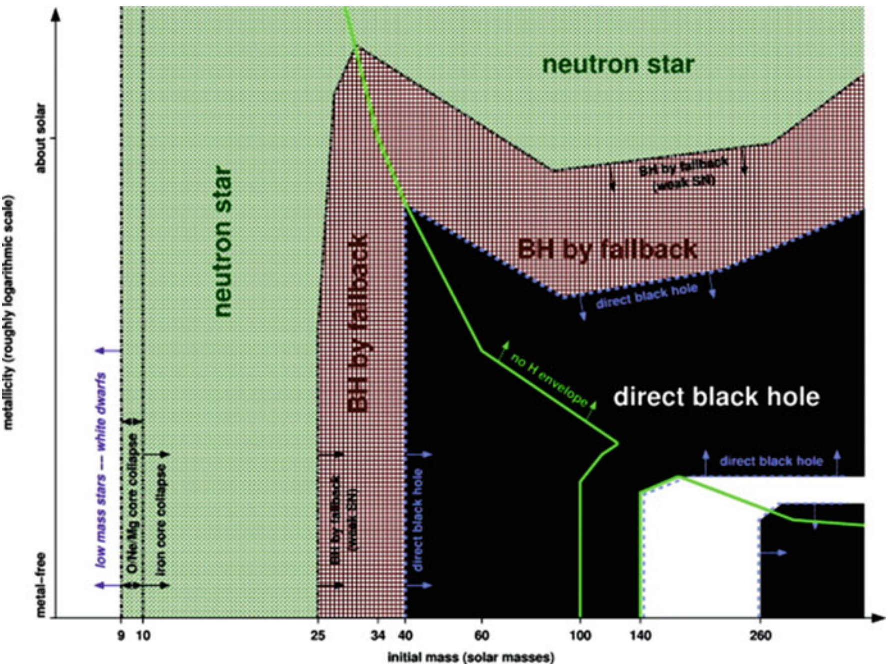

Fig. 5 Remnants of massive single stars as a function of initial metallicity (y-axis) and initial mass (x-axis). At low masses, the cores do not collapse, white dwarfs are made and supernovae do not occur (white strip at the very left). The *thick green line* separates the regimes where the stars keep their hydrogen envelope (left and lower right) from those where the hydrogen envelope is lost. The *dashed blue line* indicates the border of the regime of direct black hole formation (*black*). This domain is interrupted by a strip of pair-instability supernovae that leave no remnant (*white*). Outside the direct black hole regime, at lower mass and higher metallicity, follows the regime of BH formation by fallback (*red cross-hatching* and bordered by a *black dot-dashed line*). Outside of this, *green cross-hatching* indicates the formation of neutron stars. The lowest mass neutron stars may be made by O/Ne/Mg core collapse instead of iron core collapse (*vertical dot-dashed lines* at the left) (Figure from Fig. 1 of Heger et al. (2003), © American Astronomical Society, reproduced by permission)

Neutron stars with much higher than usual magnetic fields (giga-tesla) are called magnetars. A magnetar embedded within a supernova may generate sufficient power that the supernova is super-luminous.

9 Supernovae and the Environment of the Solar System

The local interstellar medium is a region that surrounds the solar system out to a few hundred parsecs. This region contains several structures. Among the largest is Gould's Belt, a flat, young, massive, elliptical star system about $350 \times 250 \times 50$ pc in

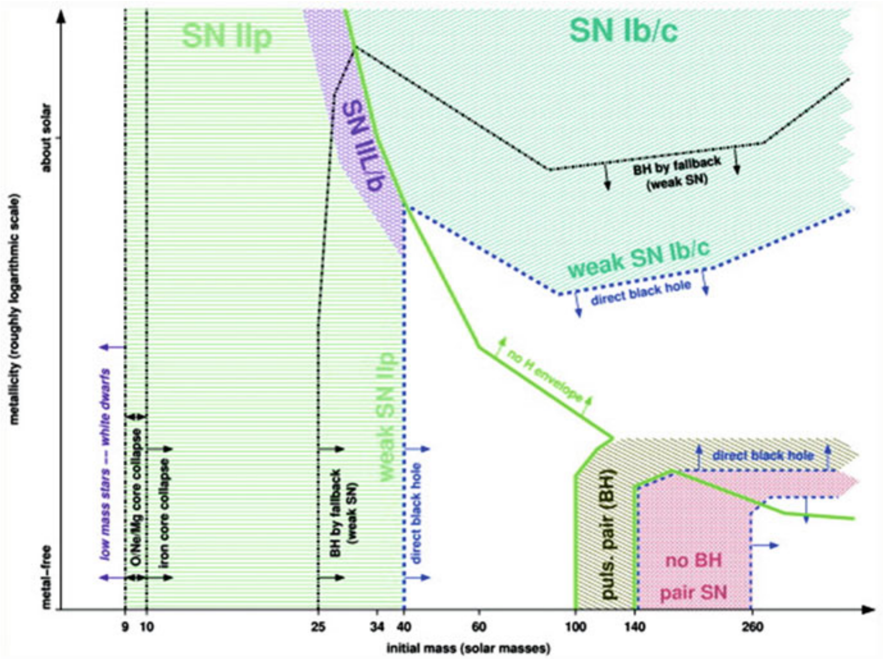

Fig. 6 Supernovae types of nonrotating massive single stars. The diagram is divided in the same way as Fig. 5. *Green horizontal hatching* indicates the domain where Type II-P supernovae occur. At the upper right-hand edge of the SN Type II regime, close to the *green line* across which the hydrogen envelope is lost, Type II-L/b supernovae are made (*purple cross-hatching*). In the upper right-hand quarter of the figure, above both the lines of hydrogen envelope loss and direct black hole formation, Type Ib/c supernovae occur. In the direct black hole regime, no "normal" supernovae occur since no SN shock is launched. Pair-instability supernovae (*red cross-hatching*) make no remnant, except very high-mass supernovae that launch their ejection before the core collapses (lower right-hand corner; *brown diagonal hatching*) (Figure from Fig. 2 of Heger et al. (2003), © American Astronomical Society, reproduced by permission)

dimension (Fig. 7). It consists of OB stars, molecular clouds, and neutral hydrogen as well as high-temperature coronal gas and dust.

Gould's Belt contains many young stellar associations, the bright stars in many constellations including (in order going more or less eastward) Cepheus, Lacerta, Perseus, Orion, Canis Major, Puppis, Vela, Carina, Crux (the Southern Cross), Centaurus, Lupus, and Scorpius (including the Scorpius-Centaurus Association). Many of these stars will explode as core-collapse supernovae and some of their sisters already have. These supernovae have left their mark on the local structures. For example, a supernova that exploded near the Orion Nebula in the Orion Association about 2 million years ago created a set of runaway stars, namely, AE Aurigae, 53 Arietis, and μ Columbae. ζ Ophiuchi is a similar example, running away from a location in the Scorpius-Centaurus Association (Sco-Cen). Gould's Belt also contains interstellar clouds and has been long associated with an expanding

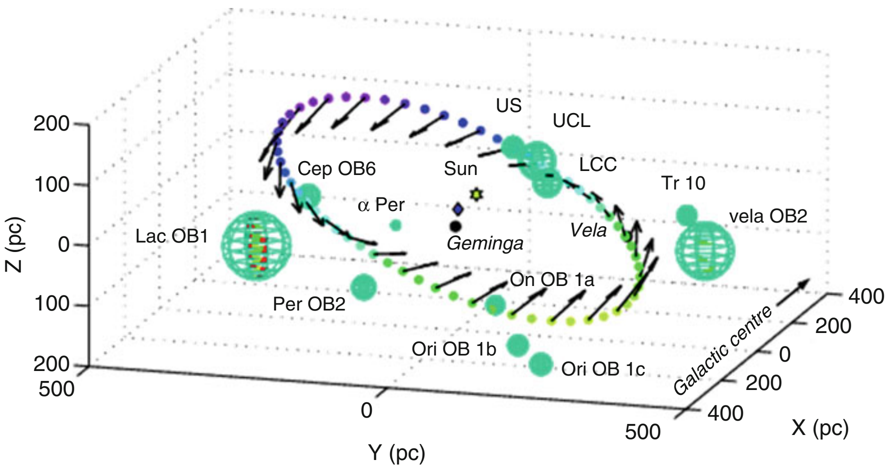

Fig. 7 3D view of the present Gould's Belt and its velocity field with respect to the local standard of rest. The local OB associations are marked as spheres. The diamond notes the location of the Belt center and the star that of the Sun. Local associations include the Scorpius-Centaurus Association thought to be the major source of supernovae in the neighborhood of the Sun (Figure by I.A.Grenier.)

HI Ring 28. The fact that dark clouds participate to the expansion was recognized 20 years. H_2 complexes, such as Orion, Ophiuchus, and Lupus, have long been related to the Belt, but more recently mapped complexes, such as Aquila Rift, Cepheus, Cassiopeia, Perseus, and Vela, appear to be part of the expanding shell as well (Fig. 8).

Sco-Cen is believed to be the cradle of several young massive OB stars that exploded in the past 15 million years creating a high-temperature low-density cavity in a network of expanding gas called a super-bubble. Part of this structure is the local bubble, believed to be a result of shock waves caused by multiple supernova explosions in the local interstellar medium. Its electron density is 0.07 atoms cm^{-3}, which is about one order of magnitude less dense than the local interstellar medium. This region is $\sim$200 pc in diameter, and its age is $\sim$10 million years. The solar system is only 10–20 pc from the edge of the local bubble.

The local bubble is not a perfect structure but has also got small structures that seem out of place. These include parsec-sized clouds of temperature $\sim$8000 K, with other smaller clouds in the neighborhood of the solar system (very local interstellar medium). The Sun appears to be located in such local cloud with a relative velocity $\sim$19 km s^{-1}. The flow comes from direction of gas and dust where an SNR (Loop 1) merges with the local bubble.

Supernovae in the neighborhood of the Sun have influence on scales of the order $\sim$100 pc. The influence on the heliosphere of the solar system is very evident. Such influence includes the formation of structures at the heliosphere's boundary with the interstellar medium such as filaments.

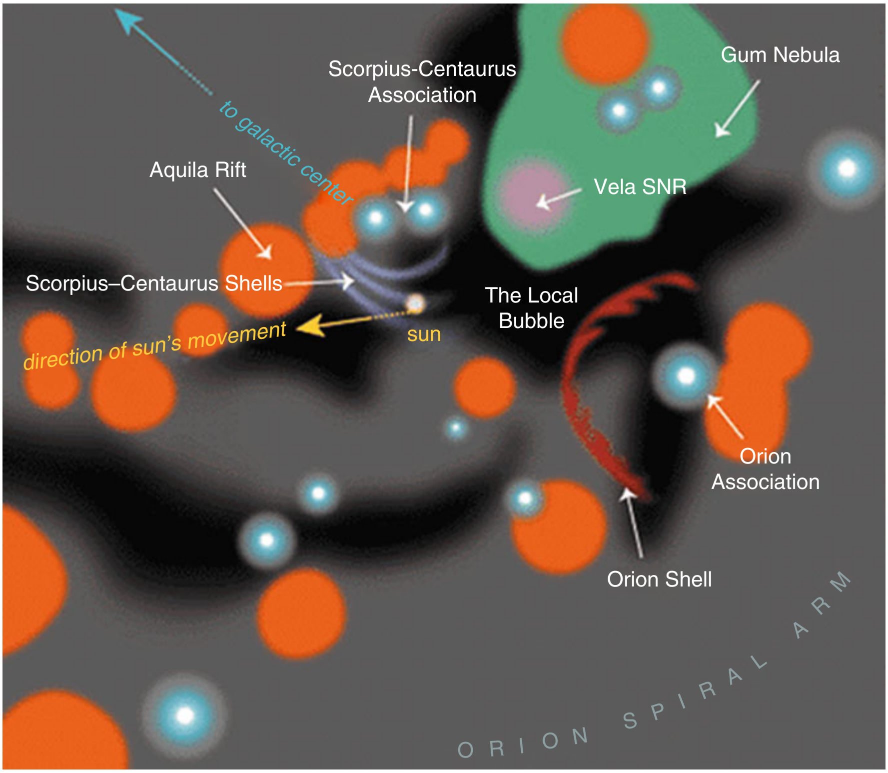

Fig. 8 Local interstellar medium in solar neighborhood, showing the Sun's position with respect to the Scorpius-Centaurus Association, where nearby supernovae are thought to have originated (Figure by P. Frisch.)

External influences on the solar system include supernovae, supernova remnants and galactic cosmic rays, as well as cosmic dust and the interstellar medium, including neutral atoms and ions. The region dominated by solar influences extends for around $\sim$100 AU is created by the solar wind and is called the heliosphere (Fig. 9). Separating the two regions, where the influences balance, is the termination shock.

In the inner heliosphere, solar cosmic rays (SCR) with MeV to GeV energies are a major concern. However, galactic cosmic rays (GCR) (MeV to TeV) and anomalous cosmic rays (ACR) ($<$100 MeV) are also important (as observed by the Voyager spacecraft). The flux at Earth of galactic cosmic rays (originating from supernova remnants) is modulated by the solar activity levels in sunspot cycles but also by the effects of close ($<$10 parsecs) supernovae and the passage of the solar system through supernovae remnants.

The nature of the effects was discussed by I. Shklovsky in the 1960s, and by others, with attempts to identify possible evidence for such explosions in the past.

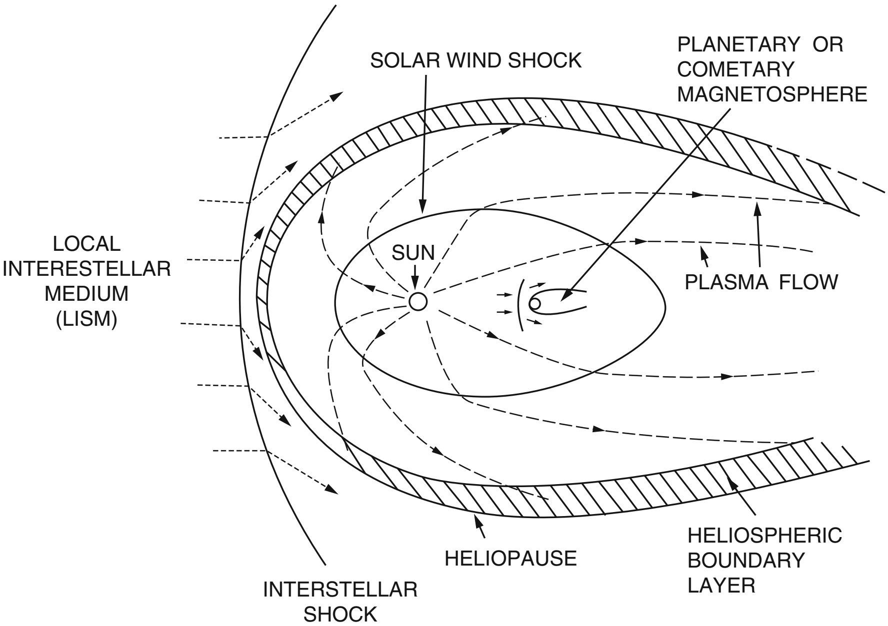

Fig. 9 The interaction of the heliosphere and local interstellar medium. The shape is resulting from heliosphere's interaction with the surrounding plasma (Figure by Timothy Eastman.)

In recent years, evidence has accumulated for such effects including a range of influences from climate change to mass extinctions. Such influences include the influence of cosmic rays from supernovae on the Earth's upper atmosphere, with resulting changes in the chemistry and thus structure as a result. Extreme ionization radiation from beyond the solar system would result in dissociation of N atoms and creation of NOx. This in turn would possibly result in catalytic destruction of the ozone layer, NO_2 shading of visible insolation, post-perturbation oxidation of NOx and atmospheric excitation and re-emission. The environmental results would be a direct radiological hazard, enhanced solar UV penetration, global cooling, nitric acid rainout, nitrate fertilization, and UV flash.

It is estimated that the critical distance for a supernova explosion to have a lethal radiation effect on life on Earth is 10 pc. Supernovae at larger distances produce biological but non-lethal consequences. Earth and its Moon have been subjected to several nearby supernova events that have left their traces.

The expected frequency of supernovae occurring close to the Earth ranges from 1 per 75 Myr to 1 per 150 Myr. Supernovae occur at random at a rate of $\sim$0.02 SN/year in a typical region of the Galaxy. If we assume the galactic disk has a radius of $\sim$15 kpc, and that the Sun orbits within the plane of the Galaxy, we expect one supernova within 10 pc every $\sim$112 Myr. However, vertical oscillation of the Sun about that orbit crosses regions of higher star density, including star-rich spiral arms and OB associations where frequent young stars explode as supernovae. The frequency of nearby supernovae (at distances of less than 10 pc) can vary from 1 in ~75 Myrs in dense regions to 1 in 150 Myrs in empty stellar spaces!

The inferred statistic of occurrence of supernovae in the past in the neighborhood of the Sun is disputed, although it seems accepted that there was one relatively nearby supernova perhaps 2.5 Myr ago at a distance of a few to ~50 pc. At that time the Sco-Cen association, which at present is 150 pc away, was much closer, 50–100 pc away and the supernova may have been a massive star from that association. The supernova caused the observed ^{60}Fe excess found in deep ocean and lunar samples laid down at that time and the dust which penetrated within the inner solar system with minerals of SiC, Si_3N_4, graphite, oxides, and silicates.

Future candidates for supernova explosions which are less than 300 pc from the Sun are IK Pegasi, Betelgeuse, and WRII at distances 46 pc, 197 pc, and 260 pc, producing SN Type Ia, SN Type II, and SN Type Ic, respectively.

Supernovae not only produced the chemical elements that make up the planets and the resultant biochemistry. The evolution of life is constantly being driven by genetic mutations caused by cosmic rays from supernovae, which bombard the solar system with varying intensity depending in part on the solar activity. But there may have been one further fundamental connection between supernovae and the origins of life on Earth. The chirality of amino acids could be established in the magnetic field of a nascent neutron star from a core-collapse supernova via processing by emitted neutrinos. Thus one can truly say that supernovae are the cause of change and of death but also of life, on our planet and perhaps others.

10 Supernova Cosmology

Tycho Brahe observed the supernova in 1572 with pre-telescopic instruments and established its lack of parallax, which set the distance of the "new star" as beyond the Moon, more typical of stars than objects in the Earth's atmosphere, like meteors. This disproved the prevailing view that the heavens never changed. Supernovae also figured in the discussion about the nature of galaxies during the Great Debate of the 1920s, about whether the so-called nebulae were all within the Milky Way. The issue revolved around the question of the luminosities of novae that appeared near or in nebulae and others that appeared in the Milky Way and the distances of the nebulae that were thus indicated. Knut Lundmark recognized that there was a discrepancy in the brightness of some bright novae and others that were more run-of-the-mill. S Andromedae, a nova that appeared in 1885, was 10 magnitudes brighter than other novae that had appeared in the Andromeda Nebula. With this clarification, the nature of the nebulae as galaxies external to the Milky Way was strongly indicated.

Since this time, the use has been pursued of supernovae as extragalactic distance indicators. At first the situation was confused by the non-uniformity of supernovae. However, astronomers gradually recognized subtypes which were more homogeneous. In particular, Type Ia supernovae offered the hope that they would be standard candles for distance measurements, although their light curves varied in the rate at which they developed. A calibration became possible through the correlation between light curve shape and peak luminosity, especially when infrared measurements of the light curve were taken into account. Not only are the infrared measurements less sensitive to errors induced by interstellar reddening, but the light curves of Type Ia supernovae are more uniform in the infrared. The physics that underpins the existence of the calibration is connected with the amount of Ni^{56} which is produced in the Type Ia supernova explosion and which powers the light curve. There are some extreme cases, which are of great interest because they hint at the details of the physics of the explosions; with exceptions like these, the absolute magnitude of a Type Ia supernova at peak can now be established with a precision of about 0.1 magnitudes. There is greater diversity among CCSN, but they too are becoming useful as standard candles.

It is interesting to compare Type Ia supernovae as standard candles with Cepheid variable stars. Both have a feature, namely, variability, which makes them recognizable. Both are well understood empirically as standard candles, with both requiring a calibration process (the brightness of Cepheid variable stars depends on their period). Both types of stars are bright and can be seen at great distances, but Type Ia supernovae are brighter and can therefore be seen from greater distances than Cepheids. They have both been used as cosmological distance indicators, to determine the scale of the universe through measurement of the local value of the Hubble constant. But Type Ia SNe probe beyond the range of the Cepheids, to distances characterized by a redshift $z > 1$. Cepheids have been used to measure the rate of expansion of the universe; Type Ia SNe have resulted in the identification its acceleration, the phenomenon known as "dark energy" and in the future will provide some of its characteristic properties.

11 Cross-References

- ▶ Close Binary Stellar Evolution and Supernovae
- ▶ Confirming Cosmic Acceleration in the Decade That Followed from SNe Ia at $z > 1$
- ▶ Cosmology with Type IIP Supernovae
- ▶ Detecting Gravitational Waves from Supernovae with Advanced LIGO
- ▶ Determining Amino Acid Chirality in the Supernova Neutrino Processing Model
- ▶ Discovery of Cosmic Acceleration
- ▶ Discovery, Confirmation, and Designation of Supernovae
- ▶ Dust and Molecular Formation in Supernovae
- ▶ Dynamical Evolution and Radiative Processes of Supernova Remnants
- ▶ Dynamical Mergers
- ▶ Effect of Supernovae on the Local Interstellar Material
- ▶ Electron Capture Supernovae from Super Asymptotic Giant Branch Stars
- ▶ Evolution of Accreting White Dwarfs to the Thermonuclear Runaway
- ▶ Evolution of the Magnetic Field of Neutron Stars

▶ Stardust from Supernovae and Its Isotopes
▶ Strange Quark Matter Inside Neutron Stars
▶ Structures in the Interstellar Medium Caused by Supernovae: The Local Bubble
▶ Superluminous Supernovae
▶ Supernova 1604, Kepler's Supernova, and its Remnant
▶ Supernova Cosmology in the Big Data Era
▶ Supernova of 1006 (G327.6+14.6)
▶ Supernova of 1054 and its Remnant, the Crab Nebula
▶ Supernova of AD 1181 and its Remnant: 3C 58
▶ Supernova Progenitors Observed with *HST*
▶ Supernova Remnant Cassiopeia A
▶ Supernova Remnants as Clues to Their Progenitors
▶ Supernovae and the Chemical Evolution of Galaxies
▶ Supernovae and the Evolution of Close Binary Systems
▶ Supernovae and the Formation of Planetary Systems
▶ Supernovae from Massive Stars
▶ Supernovae from Rotating Stars
▶ Supernovae, Our Solar System, and Life on Earth
▶ The Core-Collapse Supernova-Black Hole Connection
▶ The Effects of Supernovae on the Dynamical Evolution of Binary Stars and Star Clusters
▶ The Extremes of Thermonuclear Supernovae
▶ The Hubble Constant from Supernovae
▶ The Infrared Hubble Diagram of Type Ia Supernovae
▶ The Masses of Neutron Stars
▶ The Multidimensional Character of Nucleosynthesis in Core-Collapse Supernovae
▶ The Peak Luminosity-Decline Rate Relationship for Type Ia Supernovae
▶ The Physics of Supernova 1987A
▶ The Progenitor of SN 1987A
▶ The Supernova – Supernova Remnant Connection
▶ Thermal and Non-thermal Emission from Circumstellar Interaction
▶ Thermal Evolution of Neutron Stars
▶ Thermonuclear Explosions of Chandrasekhar Mass White Dwarfs
▶ Type Iax Supernovae
▶ Ultraviolet and Optical Insights into Supernova Remnant Shocks
▶ Unusual Supernovae and Alternative Power Sources
▶ Very Massive and Supermassive Stars: Evolution and Fate
▶ Violent Mergers
▶ X-ray Binaries
▶ X-ray Emission Properties of Supernova Remnants
▶ X-ray Pulsars
▶ Young Neutron Stars with Soft Gamma Ray Emission and Anomalous X-ray Pulsars

References

Heger A, Fryer CL, Woosley SE, Langer N, Hartmann DH (2003) How Massive Single Stars End Their Life. The Astrophysical Journal v.591, No.1, pp. 288–300