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Supernovae and supernova remnants

1 GENERAL INTRODUCTION TO SUPERNOVAE AND SUPERNOVA REMNANTS

A supernova explosion is among the most dramatic events that can be seen. The term '*supernova*' is somewhat misleading, as such an event represents not a new star (that is, a '*nova*'), but instead the end of a star's life. Nuclear fusion, the energy source of the stars, creates heavier elements from lighter elements. In this way, almost all of the elements that make up the universe, with the exception of hydrogen and helium, are created inside a star through this process. These elements accumulate inside a star over its lifetime and are dispersed into space through a supernova explosion. We may therefore say that all of the material of the Earth (excepting hydrogen and helium) were probably created inside some star many eons ago, and that they were ejected by a supernova, soon to become the primordial material of the Earth. Nuclear fusion inside a star can generate heavy elements ranging from helium up to the most stable nucleus, iron. It may therefore be said that the iron that plays such a vital role in the hemoglobin of our blood must have been generated inside a massive star that soon went supernova. This must have happened at least five billion years ago, since this is the age of our solar system.

Based on the statistical study of the occurrence rate of supernovae in other galaxies, we believe that a supernova should occur every few tens of years in our Galaxy. Further, the energy released by a supernova is of the order of 10^{53} erg, which is two orders of magnitude larger than the energy radiated by our Sun over its entire 10-billion-year lifetime. Although 99% of this energy is carried away by neutrinos that go nearly completely undetected, the remaining 1% still represents an enormous amount of energy released over a very short time. The maximum absolute magnitude of the supernova is about -19^M. This means that if a supernova occurred at a distance of 10 parsecs (pc: $1\,\mathrm{pc} = 3.1\times 10^{18}\,\mathrm{cm}$) from the Earth, it would appear to be about 1,000 times as bright as a full moon. If it were to appear at the outer edge of the Galaxy, it would be as bright as Venus, if it did not suffer from extinction due to interstellar matter. The Galaxy, however, does contain a great deal of diffuse matter so that there is a great deal of extinction, particularly at optical wavelengths. This is especially true in the Galactic plane. Since most of the stars of the Galaxy are in the Galactic plane, only those supernovae that occur nearby are visible. On the contrary, supernovae appearing in external galaxies lying outside of the Galactic plane can be easily seen. We can therefore study the supernova rates in these galaxies.

The appearance of several supernovae has been documented over the past 2,000 years. Most of these were recorded in the Eastern as opposed to the Western world, for reasons that appear to be socio-political. In the Western worldview, God created the universe perfect and forever fixed. It is thus likely that the appearance of a '*new star*', a phenomenon at variance with a perfect, unchanging universe, would go unrecorded. Such a '*mistake*' could not be accepted. On the contrary, in the Eastern worldview, changes in the celestial sphere could result from God's 'mistake', a forecast for an impending disaster. In China, in fact, it became an important concern for the emperor to be able to predict a drought, a flood, or other such disasters. It was thus a regular job for astronomers to search the sky for any omens of such events. Furthermore, a nearby supernova would be bright enough to be easily visible even during the

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day, thus not only professional astronomers, but even common people would have been able to observe such events.

During a supernova explosion, the heavy elements synthesized inside the star expand at very high velocity, up to 10,000 km sec^{-1}. Afterwards the supernova slowly fades through adiabatic expansion. The major heat source during this phase comes from the following series of radioactive decays: ^{56}Ni (7 days) → ^{56}Co (77 days) → ^{56}Fe. This decay series will keep the supernova bright for several months. The ejecta, rich in heavier elements, will eventually form another generation of stars and planets. The ejecta first expand at high velocity with no deceleration. Eventually, it will sweep up enough interstellar material so that deceleration becomes effective. The deceleration will heat up both the ejecta and the interstellar material and the temperatures will become high enough so that the majority of the radiation will be not in the visible but in the X-ray regime. The swept-up material will form a shell-like structure, leaving a low density, high temperature interior.

The expanding shell contains a mixture of interstellar matter and the heavy elements from the supernova progenitor and the supernova itself. Once the temperature becomes high enough to ionize most of the elements, the shell barely cools down. The dominant emission mechanism is thermal bremsstrahlung (also referred to as free-free emission), which results from free electrons colliding with the nuclei within the shell, losing energy by emitting radiation. The result is an X-ray continuum spectrum. When the temperature has cooled enough so that some heavier atoms, such as iron, capture electrons, much more efficient cooling processes take over. When an iron nucleus, for example, captures a free electron, free-bound radiation is emitted. When a free electron collides with a bound electron, the bound electron is excited to a higher energy level. Almost immediately, this electron returns to its ground state, emitting a photon in a bound-bound transition (line emission). Once the matter cools down to the line-emitting temperature, the cooling process accelerates. The lower the temperature, the more efficient the cooling process. The temperature range for which the iron family (the most abundant species among the heavy elements) captures electrons is thermally unstable. When the temperature reduces further, the more abundant light elements such as oxygen begin to capture electrons that again accelerate the cooling process. The cooling region is compressed by its surroundings and further increases in density, further accelerating the cooling process. Sheets that are visible in the optical are formed as a result of the thermal instability. Figure 1 shows a portion of the Veil nebula in the Cygnus Loop, that results from the radiative instability of the hot gas.

The supernova leaves behind a high-temperature low-density cavity a few tens of pc in diameter. It can survive for a few million years due to its low density. Taking into account the occurrence rate of supernovae, we find that the hot gas, with temperatures of a few million degrees and only visible in X-rays, potentially occupies a large volume of our Galaxy.

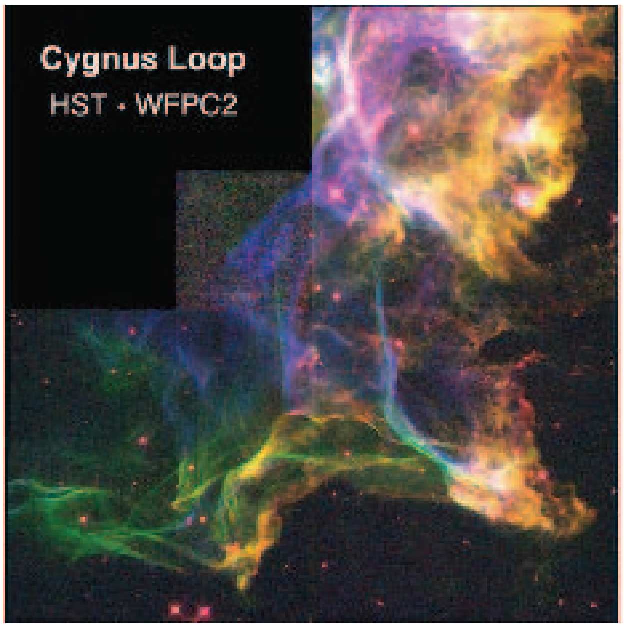

Figure 1 Close up of the Veil Nebula (the Cygnus Loop) obtained by the HST (see http://oposite.stsci.edu/pubinfo/gif/CygnusLoop.gif) (courtesy of J. Hester, Arizona State Univ. and NASA). A high density region forms a filamentary structure.

The fraction of heavy elements in our Galaxy is gradually increasing. Moreover, apart from this in-flux of material, there is also a flow of thermal and kinetic energy. The heavy elements are generated inside the stars as a by-product of the nucleosynthesis in the stars. The energy released by this nucleosynthesis is continuously radiated away by the stars as visible and ultraviolet light, while the heavy elements continue to accumulate within the star. When the star becomes a supernova, a large amount of the star's gravitational energy is released along with the heavy elements. These elements then disperse through the Galaxy and form the building blocks for the next generation of stars. The supernovae and supernova remnants (SNRs) provide the most dramatic examples of this cycle of life-and-death in the Galaxy.

A star, such as the Sun, is a large sphere of hot plasma with nucleosynthesis taking place only in its innermost regions. The energy is transported away from the center via emission and, in the outer layers, by convection. The photons emitted from the center (excluding the neutrinos) are scattered, absorbed and re-emitted by the surrounding material. Therefore, photons that are created in the center of the star cannot be directly detected. The photons that we detect from stars come from only a very shallow layer near to the star's surface. This region is known as the photosphere.

The supernova remnant (SNR) is a blow-up of the star, where the matter is at very low density. Because of this, we may directly detect emission from any portion of the plasma. That is, we do not need to worry so much about intervening material in the remnant absorbing photons. Such a plasma is referred to as being optically thin. In this circumstance, we can measure directly the abundances of the heavy elements in the remnant. Because of the remnant's great size and low density, self-absorption and scattering do not play an important role in the radiation process. We can therefore directly see emission from the heavy elements irrespective of their position in the remnant. When heavy elements such as O, Ne, Mg, Si, S, A, Ca, and Fe emit photons at their characteristic energies (line emission) the photons will reach us undisturbed (thermal broadening of the lines is very small, in practice). Thus we are provided with a unique opportunity to directly see these heavy elements before they redistribute themselves through the Galaxy. Further, the morphology of the remnants is also intricate, making them interesting in their own right.

Because so many remnants have already been observed, it is impossible to review all of them. In this chapter, we will discuss a sample of SNRs, ranging from young remnants to old remnants. This will help us to understand how the heavy elements and the energy of the supernova are distributed throughout the Galaxy.

1.1 Nuclear fusion inside a star

Atomic nuclei consist primarily of baryons (protons and neutrons) which determine the mass of the nucleus. Figure 2 shows the average baryon mass inside the atomic nucleus as a function of mass number, A. The figure gives the energy level of each nucleus: the lower the energy level, the more stable the nucleus. The isolated proton, hydrogen (^{1}H, A=1) has the highest energy level among the various nuclei. The baryons inside the helium atom (^{4}He, A=4) form a local minimum in Figure 2, being lower than lithium (^{6}Li, ^{7}Li), beryllium (^{9}Be) and boron (^{10}B, ^{11}B) that follow it. ^{12}C becomes lower than ^{4}He. Beyond this, the data points fluctuate up and down. Generally, however, the energy level gradually decreases with increasing mass number until ^{56}Fe is reached. This nucleus (A=56) has the lowest energy level among all nuclei and is therefore the most stable atomic nucleus. Beyond this nucleus, the energy level of nuclei increases. This is a fundamental result of nuclear mass measurements.

After the Big Bang, the matter of the universe consisted mostly of hydrogen along with a little helium. Because of the gap between helium and lithium seen in Figure 2, very little high-Z elements (i.e. elements beyond helium, where Z is the atomic number) existed. This energy gap hindered the creation of elements beyond helium in the first 3-minute after the Big Bang. In contrast, the universe today is abundant in high-Z elements. In the first epoch of the universe, matter was partly clustered and formed into stars. Once the stars began to form, the nuclear fusion of hydrogen into helium began in their cores. This phase of a star's life is called the 'main sequence phase', and it is the most stable phase of a star's life. The Sun, for example, has been in the main sequence phase for the last five billion years and will remain in this phase for another five billion years.

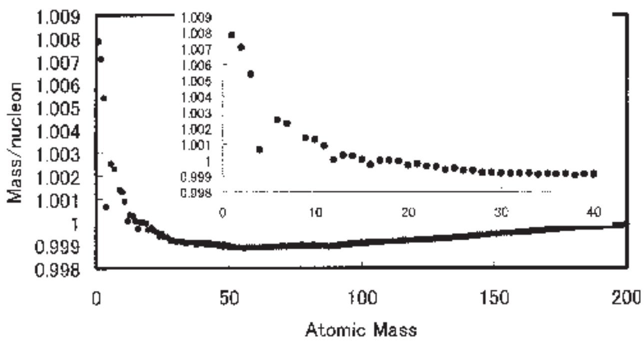

Figure 2 Atomic mass per nucleon as a function of mass number. Hydrogen has the highest mass per nucleon while the nucleons in ^{56}Fe have the lowest ones.

Once the star has exhausted the hydrogen in its core, the main sequence phase ends, and the star intermittently expands and contracts. During this phase, a new class of fusion processes proceeds, creating heavier elements such as C, N, O, Ne, etc. Each element is created by a process that occurs at its own particular temperature. In general, the higher the temperature, the heavier the element created. Because the temperature increases as one goes deeper into the star and because the temperature in the core of a star is slowly increasing during this phase, an '*onion-skin structure*' results. That is, the elements are created in layers so that, as one proceeds from the outer layers to the core of the star, different layers of elements are passed through. Elements with higher Z are found deeper in the star. Elements with a lower energy level are more stable, so that the fusion of two or more lighter nuclei into a heavier one creates a nucleus with a lower energy level, that is, a more stable nucleus. The most stable nucleus is ^{56}Fe. It therefore represents a barrier beyond which nuclei cannot be easily created through the fusion process. Since a certain minimum temperature is required for fusion and since the temperature in the core of a star depends primarily on its mass, iron is created only in the most massive stars. It may thus be said that iron represents the ashes of the nuclear burning that took place in the star. Through this process the high Z elements are created and accumulate in a massive star.

Meanwhile, the energy released in this process is ultimately released through the star's surface, making the star shine.

A star is stable when the gravity of the star, which tends toward collapsing the star, is balanced by the pressure in the star's interior, which tends toward expanding the star. This outward pressure is maintained by the thermal energy of the star which is in turn regulated by the nuclear reactions. Therefore, once the star has exhausted its source of nuclear energy, it can no longer support itself against its own gravity. If the star has less than a certain mass, another source of pressure will ultimately halt the collapse. However, for stars beyond this lower mass, the collapse cannot be stopped and a supernova will result. This supernova will shine as brightly as the entire Galaxy. During the explosion, more nucleosynthesis takes place, creating more high-Z elements. In some supernova, the entire star is detonated while in others a compact object – a black hole or a neutron star – is left behind.

The metal abundance in the universe is referred to as the '*cosmic abundance*', which is essentially the same as the abundances of the elements within our solar system. These abundances are determined through studies of the sun as well as of meteorites (Anders and Grevesse 1989). There are many elements above iron. The Earth, for example, has Ni, Cu, Ag, Au, Pt, U, etc., although their abundances are relatively small. These higher-Z elements (elements beyond Fe) are created by a variety of processes. One of these processes, known as the rapid-process, occurs only in the presence of a large flux of neutrons. A supernova has the necessary high flux so that this rapid-process occurs during a supernova explosion. The process is able to operate because neutrons do not carry an electric charge, so that the Coulomb barrier in a nucleus is ignored by them. The elements thus created have large numbers of neutrons, some of which migrate to higher-Z elements via β–decay. In this way, the high-Z elements up to uranium are created. These high-Z elements have a higher energy level than iron, as is seen in Figure 2. Therefore, excess energy can be released when they are split into two or more lower-Z elements. This process is called nuclear fission. We extract energy from these nuclei via the fission process in nuclear power stations and in nuclear weapons.

1.2 The supernova explosion

When the supernova occurs, the high-temperature plasma, the ejecta, expands outward and mixes with the interstellar matter, giving rise to an increase in its metal abundance. Early in the explosion, the ejecta expand adiabatically and cool very rapidly. In general, there are two types of supernova: Type I and Type II supernovae. The supernova type is phenomenological, depending on whether or not the H–β absorption line (in the visible region) is seen in its spectrum near the maximum brightness. If the line is present, the progenitor must have had a hydrogen envelope, an indication of a massive star. The internal structure of the supernova depends on the mass of the progenitor star.

If the mass of the progenitor star is less than a certain critical mass, a few times $M_\odot$ ($M_\odot$ represents the mass of the sun, 2×10^{33} g), it will not become a supernova. It will evolve instead into a white dwarf. Our sun will therefore not explode after it has exhausted its hydrogen about five billion years in future. A star whose mass is over the critical mass accumulates high-Z elements in its center forming an onion-skin structure. In the deepest layer of the star, we will see that the matter consists mainly of elements from the iron family (Fe, Ni, etc.), which represent the ashes of the nuclear fusion. Above this layer, lighter elements form layers one by one. The outermost layer consists of hydrogen, if the star has not lost its hydrogen envelope. Otherwise, it consists primarily of relatively low-Z elements such as carbon, oxygen etc.

If the mass of the progenitor star is in some range (up to several times $M_\odot$), it is believed that the entire star will be detonated in a supernova. All of the nucleo-synthesized matter is ejected, creating the building blocks for the next generation of stars. If the mass is greater than this critical mass, some inner region of the star is not ejected in the explosion but instead forms a compact object, i.e. a neutron star or a black hole. Whether a neutron star or a black hole is left behind thus depends on the mass of the progenitor. In this way, we can say that a Type I supernova supplies a large amount of iron since the entire star is blown up, whereas a Type II supernova leaves a compact source behind: a neutron star or a black hole.

1.3 The supernova remnant

The supernova releases both an enormous amount of energy and a large mass of high-Z elements into space. The effects of these two components are long-lasting and are seen as a supernova remnant (SNR).

As the ejecta expand into the interstellar medium, they sweep up the surrounding interstellar matter. As long as the material swept up is less than the mass of the ejecta, the expansion is considered to be a free expansion. This phase lasts for a few hundred years, depending on the density of the interstellar matter around the supernova. As the ejecta expand into the interstellar matter, a violent collision occurs between the ejecta and the interstellar matter. The former is expanding at a velocity of a few thousand km sec^{-1} while the latter is stationary. At the boundary of the collision, a shock front is formed, resulting in shock heating of the matter up to tens of million degree. The shock front represents a boundary at which physical conditions, such as temperature and density, are discontinuous. After the collision, the ejecta and the interstellar matter gradually mix.

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