THE AFTERMATH OF STELLAR DEATH: AN OUTLINE

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In this Lecture I shall outline the main observations and the present understanding of the phenomena taking place around stars which have terminated their normal life. These phenomena were almost completely unknown until the late '60's but have now become central in astronomy. In many cases they were discovered after the introduction of new observational techniques which made it possible to detect radiations different from optical light (radio waves, X-rays, gamma rays etc.). It is important to stress that many initial discoveries came with the use of new channels of information but, subsequently, a great wealth of information was gained through optical telescopes.

Roughly speaking, the classical view was that stars and galaxies evolve very slowly, with time-scales much longer than the typical age of man. The matter composing stars is, in general, in mechanical and thermodynamic equilibrium. Gravity and internal pressure are balanced. Typical temperatures have a broad range of values but, in most cases, correspond to a relatively small energy per particle (for the interior of a star like the Sun about one KeV). The occasional discovery of stars exploding with a large energy release (Supernovae) was not sufficient to shatter the view of a calm, slowly evolving Universe.

More important, at least in retrospect, was the discovery of cosmic rays. In the early '30's it was realized that these particles (nuclei and electrons moving close to the speed of light) are of cosmic origin. They were the first strong indication of the existence in the Universe of matter very far from equilibrium. Since then the connection between cosmic rays and astrophysics has become deeper and deeper and we presently know that, at least in part, it is related to the phenomena taking place at the end of stellar evolution.

FINAL STAGES OF STELLAR EVOLUTION

The present understanding, based upon observational evidence and theory, is that the evolution of stars, when there is no longer any significant production of nuclear energy, can lead to three alternative types of "corpses". The first type are the "white dwarfs", configurations where the mechanical equilibrium is guaranteed by the internal pressure of a degenerate electron gas. In this case equilibrium is possible only if the mass of the configuration is ≤ 1.5 solar masses. The typical radius of a white dwarf is 10^9 cm, corresponding to an average density around 10^6 gr cm^{-3}. From an observational point of view, white dwarfs were discovered already in the last century and they are the result of a relatively gentle evolution of stars like our Sun.

If the mass is larger than the limiting value for white dwarfs the gas pressure cannot substain anymore the pull of gravity. In a fraction of a second, the core collapses to densities so high that the matter becomes composed mostly of neutrons through inverse ß-decay. Neutron stars, originally studied theoretically by Landau, Oppenheimer and Volkoff, would have nuclear densities, a radius around 10 Km and a mass in the range 1-3 solar masses. The gravitational energy released by the collapse of the central core - about 10^{53} ergs - hits the outer layers and causes their violent explosion as a Supernovae, an hypothesis first suggested by Baade and Zwicky in the '30's. We shall see later that the early theoretical speculations about their existence were confirmed by the discovery of pulsars in 1968 and their identification with rapidly rotating, strongly magnetized neutron stars. Since neutron stars cannot have a mass larger than about 3 solar masses, more massive objects cannot be sustained by the pressure of the degenerate neutron gas and give rise to a third class of configurations, the so-called black holes. Also black holes are thought to originate with the explosion of Supernovae.

After this brief outline of the possibilities, it is of interest to evaluate the number of different types of corpses existing in a galaxy like our own. This is a somewhat difficult task since mass loss during stellar evolution introduces uncertainties in the correspondence between the mass of a star in the early phases and the mass of the final collapsed core. Additional uncertainties in stellar evolution are connected with the influence of rotation, magnetic field and exchanges of matter in those stars which are surrounded by a companion. Still, the combination of observational knowledge and theoretical understanding is now sufficiently advanced and it allows reasonable estimates.

It is known that the total number of stars in the galaxy is around 2×10^{11}. Observations indicate that the number of white dwarfs is of order 10^{10}. In the case of neutron stars, the total number should be of order 10^9. Indeed Supernovae explosions occur - in galaxies like our own - roughly once every 30 years. If we extrapolate back in time, in our Galaxy there should have been about 5×10^8 Supernovae. A somewhat higher frequency of events during the early galactic evolution is indicated by the chemical composition of the galactic matter (abundance of heavy elements) and therefore the number of past explosions and of the corresponding neutron stars in our Galaxy should be close to 10^9. This is consistent with the statistics of pulsars which are (or have been) active in the Galaxy.

In order to estimate the number of black holes we recall that it is generally believed that stars with mass in the range $8 < M < 40\text{-}60$ solar masses collapse into a neutron star. More massive stars (up to their maximum limit ~ 130 solar masses) become black holes. By using the empirical Salpeter's mass function a $\Psi(M) \propto M^{-2.5}$, one finds that the ratio between the number of neutron stars and the number of black holes should be in the range 10-50. The corresponding estimate for the number of black holes in the Galaxy is in the range 2×10^7 - 10^8 objects.

COSMIC RAYS IN THE GALAXY

Cosmic rays reach the Earth isotropically. Since they are electrically charged, the galactic magnetic field (10^{-5} - 10^{-6} gauss) causes continuous deviations of their motion and makes it impossible to identify the sources where they are produced. The nuclear composition reflects that of cosmic matter in general, with the notable exception of a higher abundance of Li, Be, B and of the heavy elements (iron and above). The overabundance of some light elements is due to spallation reactions in the interstellar medium. Quantitatively, one can deduce that cosmic rays, during their journey, travel through about 3 gr cm^{-2} of interstellar matter with a corresponding lifetime around $3x10^8$ years.

Cosmic rays cover a broad range of energies, from 10^8 eV up to more than 10^{20} eV. Their intensity distribution obeys a power law $I (> E) = K E^{-\gamma}$. The value of γ is 2.6 up to about 10^{15} eV, then becomes 3.1 up to 10^{18} eV and finally returns to 2.6 at still higher energies. The total energy density (about 1 eV cm^{-3}) is very close to the one existing in interstellar space in other forms (starlight, magnetic fields, gas turbulence...). Only 1% of this energy corresponds to the electronic component.

The total energy of cosmic rays in the Galaxy amounts to about 10^{56} ergs. A lifetime $3x10^8$ years and the assumption of a stationary state imply the existence of sources capable of providing approximately 10^{40} ergs s^{-1} in the form of relativistic particles, roughly one thousand of the energy released in the Galaxy as electromagnetic radiation.

The fact that most of the stellar matter has a typical energy of order $\sim$ KeV makes it impossible on thermodynamic grounds to think of ordinary stars as the main sources of cosmic rays. A good fraction of the hypothesis made about their origin has therefore involved peculiar astrophysical phenomena, in particular Supernovae.

In the 50's, the first evidence for a connection between cosmic rays and astrophysical objects came from the study of the Crab Nebula, the remnant of a star which exploded as Supernova in 1054. This nebula consists of a filamentary distribution of mass which radiates thermally and expands with a velocity around 1000 Km s^{-1}. The present physical size of the gaseous envelope expelled from the original star is about 3 light year, its mass a few solar masses.

Apart from the thermal emission from the filaments, the Crab Nebula emits also a strong, polarized continuum which has been detected over a broad range of wavelengths, from radiowaves up to gamma rays. This is due to synchrotron radiation from relativistic electrons with energy in the range 10^8 up to (at least) 10^{13}-10^{14} eV, moving in an ordered magnetic field around 3×10^{-3} gauss.

The energy density of these electrons and magnetic fields is about 10^6 times larger than the one present in the general interstellar medium, thus showing that the Crab Nebula is a region of space where cosmic rays are much more intense than elsewhere in the Galaxy. Similar phenomena have been observed in other remnants of Supernovae.

If one computes the lifetime of the relativistic electrons against radiation losses one finds a value which is much less than the age of the remnant itself. There can be no doubt that fresh relativistic particles are generated continuously, either by producing new ones or by re-energizing the old electrons. For instance, the total input into the Crab should match the energy radiated away, in total about 10^{38} ergs s^{-1}, about 100000 times the solar luminosity. Where does this energy come from? We shall see later how this mystery was solved with the discovery of pulsars and their identification with rotating neutron stars.

Although it is clear that Supernovae Remnants produce relativistic particles, the origin of cosmic rays cannot be understood only by involving them. Indeed, it is now known that some properties of the Crab Nebula do not fully reflect those of cosmic rays. For instance the relative energy content in nuclei and electrons inside the Crab is, at most, of order 1 while the corresponding value in interstellar space is about 100. The addition of other types of sources is required. In this context we note that relativistic particles are produced also in the nuclei of some galaxies (active galactic nuclei). The collision of gas clouds in space, also probably stirred by the explosion of Supernovae, could be another mechanism produces high energy particles, a suggestion initially made by Enrico Fermi. The origin of cosmic rays is therefore not yet fully understood and it is probably the result of a variety of processes.

RESURRECTIONS

We turn next to the issues of "resurrections" i.e. to the phenomena which have been discovered around neutron stars or black holes.

The first fundamental discovery, made in 1968 by Hewish, Bell and coworkers was that of radio pulsars. Observations did then show the existence in the sky of sources emitting very intense regular radio pulses, with periods of order of 1 second or much less. At present, more than 600 pulsars have been discovered in our Galaxy. To make a long story short, it was soon understood that these pulses are a lighthouse effect associated with the rotation of a celestial body. Only neutron stars can have the extremely stable rotational periods in the observed range. The (small) observed secular increase of periods is easily understood as the gradual loss of rotational energy due to the presence of a strong magnetic field at the stellar surface, giving rise to an electromagnetic torque. Rotation periods in the range 1ms up to seconds and magnetic fields around 10^{12} gauss were indeed expected by theorists because of conservation of angular momentum and magnetic flux in the collapsing stellar core.

Shortly after the discovery of the first pulsars, one of them was found to lie close to the center of the Crab Nebula. Its period is 33 msec and its slowing down corresponds to an energy loss of 10^{38} ergs sec^{-1}, exactly what is required to energize the surrounding nebula. Pulsars are very efficient accelerators of high energy particles. This is not surprising from the point of view of general principles: unlike normal "thermal" stars, pulsars store their energy just in one degree of freedom (rotation) and there is no thermodynamic problem in transferring this energy into relativistic particles.

Most pulsars have periods in the range 100 ms - 1s and magnetic fields of order 10^{12} gauss. Their ages can be estimated from the ratio between period and period's derivative and are up to 10^6 - 10^7 years. It is thought that this is the typical value for the lifetime of pulsars. Some interesting exceptions to the rule were found more than 10 years ago with the discovery of sources with periods in the millisecond range, much weaker magnetic fields (10^8 - 10^9 gauss), ages up to 10^9 years or so. Unlike the normal pulsars which are (almost) always isolated, millisecond pulsars are in most cases associated with binary systems. We now know of the existence of more than twenty millisecond pulsars and we shall return to their nature and origin later.

Various mechansims have been proposed in order to explain how pulsars work. If one connects the pole to the equator of a magnetized rotating sphere through a nonrotating circuit, an electromotive force arises and the circuit is traversed by a current (Faraday experiment). In a laboratory experiment (say with a sphere of size ~ 10 cm, field ~ 10^4 gauss, spinning frequency ~ 10^3 s^{-1}) the difference of potential between poles and equator is just a few volts. In the case of neutron stars (size ~ 10^6 cm, field ~ 10^{12} gauss, spinning frequency ~ 1000 times a second) the difference of potential exceeds 10^{16} volts.

Around the neutron star the resulting electric field is about 10^{10} volts cm^{-1} and the electric force on a charge largely exceeds the gravitational pull. The outer parts of the stellar surface cannot be in equilibrium and the particles are shot out along the magnetic field lines. In other words, a neutron star cannot be surrounded by a vacuum.

The charges drawn off the surface form around the star a magnetosphere which can be divided into two regions. The first (corotating magnetosphere) contains the field lines which close before a critical distance $r_c = c/\Omega$. In this region the particles slide along the rigidly rotating field lines. This corotating magnetosphere cannot extend beyond the critical distance because otherwise the velocity Ωr would exceed the speed of light. The lines of force which pass beyond this distance define the so-called open magnetosphere: in this region there cannot be pure corotation and the plasma escapes freely under the influence of the electromagnetic field. The potential difference in the magnetosphere is available for an electrostatic acceleration up to very high energies.

An alternative possibility involves a neutron star rotating about an axis different from the magnetic axis. This system radiates low frequency waves at the basic rotation frequency Ω . The near-zone is similar to the one discussed for an aligned rotator, with the extra complication of time dependency. At $r >> c/\Omega$ the electromagnetic field becomes a wave field. The energy loss is given by the flux of the Poynting's vector

$$I\Omega\Omega \approx B_c^2 \, c \, r_c^2$$

where B_c is the field strength at r_c (it would be easy to see that, in a dipole geometry, this gives the classical formula for the radiation of a rotating dipole!)

Low frequency electromagnetic waves with $f \equiv eB/mc\Omega >> 1$ accelerate particles very efficiently. Since the gyrofrequency eB/mc is much larger than the wave frequency Ω, the particles move in a strong, nearly static, crossed electric and magnetic field. In a very short time ($<< \Omega^{-1}$) they reach relativistic velocities along the direction of propagation and then they ride the wave at constant phase. In the case of a plane wave, a particle exposed to it acquires a Lorentz factor $\gamma = f^{2/3}$. In the Crab Nebula, at the beginning of the wave zone, $f \sim 10^{11}$ and the electrons could acquire an energy $\sim 10^{13}$ eV. A young pulsar could accelerate particles almost up to the highest energies found in cosmic rays.

The detailed mechanism for emitting the pulses is still poorly understood and poses two different problems. On one hand, the very short duty cycle (pulsars are "on" during a time of order a few percent of the period) implies the existence of a very sharp lighthouse, associated with the emission from a directional beam of relativistic particles. The second problem is the very high specific brightness which entails coherence, like in the case of radio antennas or of masers. The prevailing view is that particles are distributed in bunches (size L) which move relativistically along curved field lines (above the magnetic poles?) and radiate coherently at all wavelengths $\lambda > L$.

Also worth of note is the fact that only very few pulsars have been detected at shorter wavelengths, in the optical, X-ray and γ-ray range. This emission could be due to incoherent process in the neutron star magnetosphere.

After 10^7 years or so the second life of stars ends: isolated pulsars become undetectable and they are probably lost forever. However a second resurrection occurs in the case of objects surrounded by a less evolved, normal star.

Indeed the launch of the UHURU X-ray satellite in 1969 did show the existence in the sky of many point-line X-ray sources and the following optical studies indicated that these are associated with binary systems. The most important feature of these X-ray sources is that their emission comes a very hot gas which is being accreted by a collapsed body. We note that accretion can be effective around neutron stars as well as around black holes and indeed the mass determination for the collapsed companion has, in some cases, indicated the presence of an obscure companion with $M > 3\ M_{sun}$, the likely signature of a the black hole.

Matter falling from the normal star into the neutron star or into a black hole releases gravitational energy and a not-negligible fraction of the rest energy is available for internal heating (around 5% i.e. five times the maximum efficiency of nuclear energy sources). If the rate of accretion is sufficiently high, the mechanism is self-regulatory. Indeed the heated gas radiates and in this way it exerts a pressure on the surrounding matter (Thomson scattering on the electrons). It would be easy to see that this leads to a critical luminosity (named after Eddington) which depends only upon the mass of the collapsed body $L \sim 10^{38}\ M/M_{sun}$ ergs s^{-1}. A good fraction of the stellar X-ray sources are observed to be close to this limit. The radiation should come out in the X-ray range: if we take an emitting surface with a radius of order 10^7 cm, a luminosity ~ 10^{38} ergs s^{-1} and we assume a black body spectrum, the temperature should be $T \sim 10^7$ °K. This corresponds to a peak of emission around 1 KeV.

We will not review here with the many beautiful observational results and theoretical understanding but we stress that both pulsars and X-ray sources are basically machines which release gravitational energy, unlike normal stars which exploit the nuclear binding energy. Pulsars do it in a highly non-thermal way through a combination of fast rotation and large scale electromagnetic fields. On the other hand, the X-ray sources result from the presence of a very hot gas, although some observed features indicate that non-thermal phenomena also play some role in determining the detailed properties.

Accretion can only last as long as the companion is in the appropriate evolutionary stage. When matter is not supplied any longer, the X-ray sources disappear and the third life terminates. What's left behind? The answer is simple: a rejuvinated neutron star, spinning very rapidly. Indeed accretion from the orbiting companion transfers angular momentum into the collapsed object and, at the end of the process, the neutron star will have acquired once more a very fast rotation. It is the current view that the previously mentioned millisecond pulsars are born in this way and represent the final outcome of this evolutionary sequence. At this stage the magnetic field has probably decayed to the observed, relatively small, values and the rate of release of rotational energy is also small. This resurrection can therefore last for a very long time, almost comparable with the age of Galaxy .

GAMMA-RAY BURSTS

Gamma-ray bursts were discovered more than 20 years ago but our knowledge about their properties has greatly increased in recent years, when the recently launched Gamma-Ray Observatory (GRO) started to report an impressive number of events, in total around 1200 (roughly, one per day). These are transient phenomena, evidencing a very short time structure (milliseconds up to - in some cases - several minutes). The typical energy range is between 10 KeV and 10 MeV. No associated emission has been detected at other wavelengths.

The short time-scale Δt suggests that they originate from very small sources, although relativistic motions in the source can modify the quantitative requirement that their size should be less than $c\ \Delta t$. This had originally led to the suggestion by Ruderman and myself that gamma-ray bursts could be the result of sudden readjustments of the magnetosphere of old, dead neutron stars. This scenario could be compatible with the measured fluxes only if the sources were rather close to us (say, 10 parsecs or so). We would then expect an isotropic distribution of bursts since the typical distance from us would be much less than the thickness of the galactic plane. This is indeed confirmed by the much wider statistics resulting from GRO but - at the same time - it is now clear that the observations contradict the expected distribution of events $N (> L) \alpha L^{-3/2}$. Weak bursts are more rare than expected, something which can result from cosmological effects and suggests much larger distances.

At this point the theory of gamma ray bursts is in a very lively, excited stage. The observed distribution of luminosities can actually be accomodated either in a model where bursts originate in the halo of the Galaxy (at a distance 100-300 Kiloparsecs) or at much larger cosmological distances (about 10^{28} cm, the Hubble radius). In the first case, each event would correspond to a total energy release about 10^{41} ergs; in the second it must involve at least 10^{50}-10^{51} ergs. In both cases, the very high intrinsic luminosity entails the initial presence of a compact "fireball", with a huge density of gamma rays, electrons and positrons. The evolution is dominated by expansion and it results also in the production of a large number of neutrinos (if the bursts originate at cosmological distance the expected signal is far too small for detection).

Most of the present speculations/theories about the nature of gamma ray bursts involve neutron stars or other collapsed objects. One suggestion is that the bursts result from the coalescence of a very close binary system consisting of two neutron stars, following the emission of gravitational waves and the consequent shrinking of the orbit. The expected frequency of these mergings in a typical galaxy is about one every 10^6 years, of the right order of magnitude to account for the observed rate of events if we integrate over the entire Universe. It is however not yet clear whether the detailed theoretical analysis of what goes on during a merging will really support the idea that gamma-ray bursts are the latest addition to the large number of high energy phenomena taking place around stellar corpses, after a long sequence of deaths and resurrections. It is probably too early to reach firm conclusions. Gamma-ray bursts still remain an enigma which will perhaps be solved only with the help of observations at other electromagnetic wavelengths or through completely different channels of information (gravitational waves?).