Introduction to astroparticle physics and astrophysics

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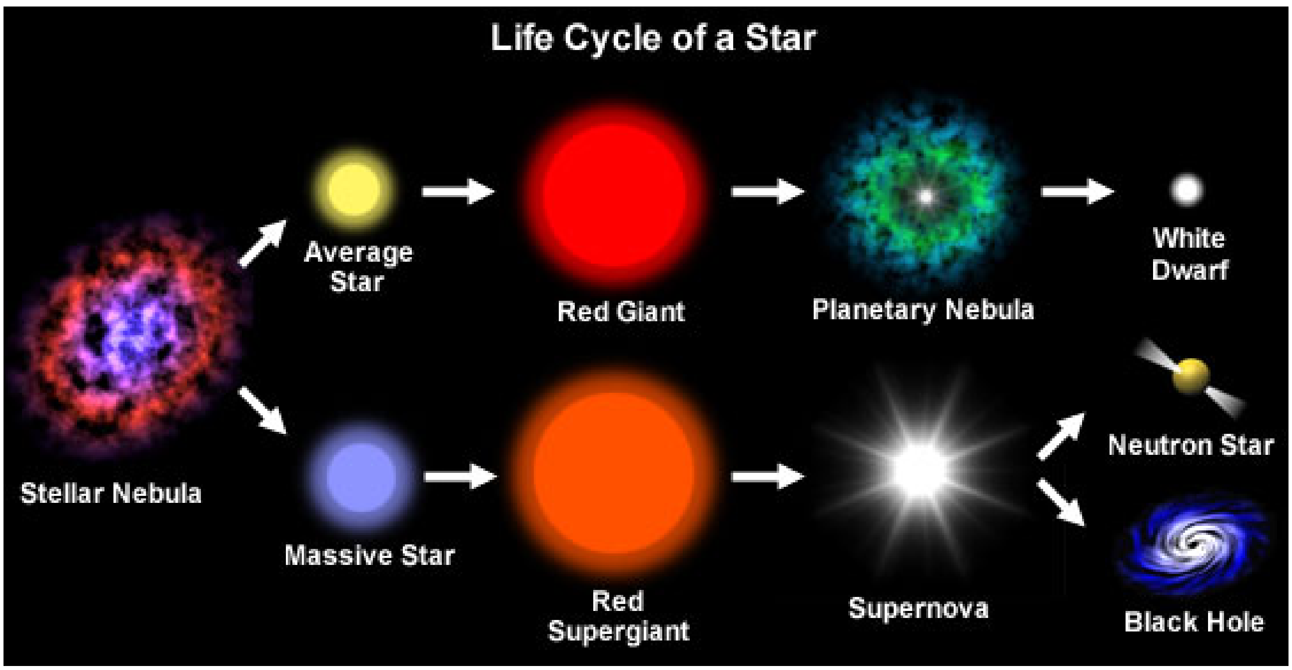

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Chapter 1

Nuclear and particle astrophysics

In this chapter we try to describe, rather briefly, few aspects of astrophysics that have some direct connection with particle physics.

1.1 The first few seconds of the early universe

In 1929 Hubble observed that the well–known lines in the spectrum of gases from stars in galaxies were shifted towards red. Hubble was able to show that the more distant the galaxies were located the larger this redshift was. This shift is due to the fact that galaxies are moving away from us and further galaxies are flying with higher speeds. The universe is expanding and any two points in the universe separated by distance r are moving away from each other at a speed given by

$$v = H_0 r, \tag{1.1.1}$$

where $H_0 \approx 70$ km/s/Mparsec is called the Hubble constant, with 1 Mparsec $\approx 3.1 \times 10^{19}$ km. Observations of supernovae have yielded evidence that the constant is not actually a constant and that the universe's expansion is accelerating.

As the universe expands its temperature is reduced. This implies that the early universe must have been significantly hotter. According to the presently accepted "standard model" of the evolution of the early universe, everything got initiated by a singularity (or in some theories it could have emerged through vacuum fluctuations) with a enormous internal energy. The primordial fireball expanded rapidly and its temperature dropped with time during this expansion process. The current understanding is that the age of the universe is around 14 billion years and has evolved through a set of defined periods and phases separated by phase transitions. These phases are given, together with some indicative numbers in Table **??**.

Age	Temperature (K)	Energy (eV)	Type of transition	Era
0			vacuum to matter	-
10^{-43} sec	10^{32}	$\approx 10^{28}$	All forces unify	Planck scale (BSM)
10^{-33} sec	10^{28}	$\approx 10^{24}$	Inflation (?)	Inflation
10^{-10} sec	10^{15}	$\approx 10^{11}$	Weak and E/M forces unify	Electroweak
10^{-6} sec	10^{12}	$\approx 10^{8}$	Quarks	Quark
3 min	10^{9}	$\approx 10^{5}$	Nucleosynthesis	Particle
4×10^{5} years	3×10^{3}	$\approx 10^{-1}$	Plasma to atoms	Photon
1.4×10^{10} years	2.7	$\approx 10^{-4}$	-	Present

Table 1.1: The basic phase transitions in the evolution of the universe, given with indicative numbers.

The universe is believed to have begun either from a singularity or from vacuum fluctuations. It is impossible at this stage to consider times less than $\hbar c^{-2}\sqrt{G/(\hbar c)} \approx 10^{-43}$ sec, what is usually referred to as Planck time, since conventional concepts of space and time break down. We would need a theory that combines gravity and quantum mechanics to describe a system at that early times. After the first phase transition, gravity became weaker than the other three forces and was no longer unified. The universe is then believed to have entered the grand unified theory (GUT) era in which the electroweak and the strong forces were still unified. At about 10^{-10} sec when the temperature has dropped to about 10^{15} K, a temperature that corresponds to about 100 GeV, the electromagnetic and weak forces separated. The weak force became short–ranged, as opposed to long–ranged which was before that, since particles were all massless. The ratio of the number of baryons to photons acquired around that time its close to final value of 6×10^{-10}. After a short period where the quarks and gluons were able to move freely, a state of matter called the Quark Gluon Plasma (QGP), the QCD phase transition took place. The quarks and gluons started combining, forming hadrons with their present masses.

When the temperature fell to about 3×10^{11} K ($kT \approx 10^7$ eV) protons and neutrons remained in equilibrium because the reactions $\overline{\nu}\mathrm{p} \to e^+\nu$ and $\nu n \to e\mathrm{p}$ can proceed with ease in both directions. The rate of a reaction is governed by the available energy or temperature. For example for energies larger than $2mc^2$ particle–antiparticle pair production can occur. When the production rate of a particle decreases and becomes negligible compared to the expansion rate, then we say that the particle has decoupled. When the temperature fell to about 10^{10} K ($kT \approx 10^6$ eV), at about 1 sec, the weak interactions were sufficiently weak that neutrinos decoupled and became free to roam the universe. The previous reactions became negligible and the ratio of proton over neutron increased to 3 : 1 since the mass difference between the two nucleons was comparable to kT. As the temperature dropped even further, electron-positron pair creation became negligible while annihilation to photons continued to occur. The reaction $e^+e^- \to \nu\overline{\nu}$ was much slower compared to the annihilation to photons and consequently photons gained energy and heated up compared to neutrinos. As a result, ”relic” neutrinos are expected to have one third of temperature of the corresponding ”relic” photons.

After about three minutes nucleosynthesis began and ceased at about 30 minutes, when the temperature had dropped to about 10^8 K ($kT \approx 10^4$ eV). The first hydrogen atoms started forming after about 4×10^5 years, when the temperature had dropped to about 3000 K ($kT \approx 1/4$ eV). At this time the universe became transparent to light and this is as far as we can see by just looking at photons. The photons were consequently emitted with a blackbody radiation distribution with a characteristic temperature of ≈ 3000 K. However, due to the expansion of the universe the radiation has now a characteristic temperature of ≈ 2.7 K. This radiation is now called the cosmic microwave background (CMB) and was first observed by Penzias and Wilson.

1.1.1 Some pitfalls

The evolution of the early universe as discussed so far had a number of pitfalls that will be described below. The solution to these pitfalls has been given at a theoretical level although all of them lack at this stage an experimental verification.

- **Inflation**: let us start with the CMB. The temperature of the CMB is now known to a rather impressive accuracy from the latest measurements of the WMAP mission. This temperature is estimated to be 2.725 ± 0.001 K from where we infer that the age of the universe is $(1.37 \pm 0.02) \times 10^{10}$ years. However, the problem rises from the fact that the temperature is pretty uniform in all directions with very subtle fluctuation patterns (to be discussed further below). The radiation observed from opposite directions was emitted when the sources were separated by more than 90 times the distance that the light could have travelled since the beginning of the universe. The sources were then causally disconnected and this apparent isotropy is very hard to understand.

  Another problem rises from the flatness of the universe. Out of the various solutions of the equations of Einstein i.e. convex, concave or flat universe, the latter is favoured by data. The ratio Ω of the density of the universe to the critical density at which the geometry is precisely flat is estimated to be $0.97 \geq \Omega \geq 1.12$. Any deviation from unity is increasing with time, which means that when the temperature of the early universe was 10^{28} K, Ω could not have been different from unity by more than 10^{-50}. This fine tuning is also hard to comprehend.

  A solution to these problems is given by the so–called inflationary scenario. The basic idea is that the potential energy of a scalar field (like the Higgs field discussed in a previous chapter) dominated the energy density of the early universe. This condition led to the acceleration of the expansion of the universe while the energy density remained the same. The expansion was exponential, with the radius doubling in about 10^{-34} sec. This inflation continued until 10^{-32} sec. Eventually the scalar field returned to the minimum of its potential and inflation terminated. By that time the radius of the early universe had increased by a factor of 10^{50}. The ratio Ω, discussed just before, was brought to unity since the surface becomes flatter as it expands (like a balloon). This means that the curvature becomes insignificant and remained like this until today. In this scenario, the universe begins from a much smaller ($\approx 10^{-50}$) region than without inflation and the two previous problems are solved.

Fortunately, temperature seems to have distinct fluctuation patters across the sky. The WMAP mission has measured in quite some detail and mapped the temperature differences across the whole sky and revealed non-uniformities at the level of 1 part in 10^5. These temperature non-uniformities originate from density non-uniformities in the early universe matter distribution. In the inflation scenario these non-uniformities were quantum fluctuations that were amplified by the rapid, exponential expansion.

- **Dark matter and energy**: One of the biggest mysteries that cosmology and particle physics face is the apparent small percentage of matter that baryonic matter (i.e. less than 4%) constitutes, required by the condition $\Omega = 1$. It turns out that the remaining matter if split to about 22% which is dark matter and 74% which is dark energy. The evidence for dark matter comes from the distribution of galaxies and clusters of galaxies together with their motions, from the study of stars and from the expansion of the universe. Dark matter is believed to make itself felt through gravitational effects but remains practically invisible to other probes. Weakly interacting massive particles (WIMPs) and axions (a hypothetical particle proposed to solve the strong CP problem i.e. the apparent negligible CP–breaking in strong interactions) are candidates to solve the problem. There are two important scenarios that speak of ”hot dark matter” which assumes that dark matter has velocities close to the speed of light and ”cold dark matter” that assumes rather low velocities. Presently the latter is the preferred hypothesis, promoted by models that include cold dark matter that are able to fit the CMB data.

  On the other hand, dark energy is a possible explanation for the unanticipated accelerating expansion of the universe. This accelerating expansion is confirmed by at least two independent groups that studied distant supernovae.

- **Matter–antimatter asymmetry**: There is an obvious asymmetry between matter and antimatter in our universe. This asymmetry must have been introduced at the initial stages of the evolution of the early universe, when all forces were unified. Theories which unify the strong with the electroweak forces predict baryonic decays which together with CP and time reversal violation constitute a possible scenario that explains the particle over antiparticle excess and the ratio of baryons over photons. The conditions for creating an excess of baryons over antibaryons were stated by Sakharov:

  - CP non–conservation
  - baryon non–conservation
  - non–equilibrium condition

  As an example, one of the theories that explains this asymmetry predicts the existence of a particle X of mass $\approx 10^{14}$ GeV/c^2. If baryon and lepton numbers are not conserved exactly (please note that this is a theory beyond the Standard Model), X may decay into a quark and an electron, while $\overline{X}$ decays into an antiquark and a positron. Above energies of the mass of X, the decay rate of X and $\overline{X}$ are in equilibrium. As the temperature fell, an excess of quarks over antiquarks is developed if CP invariance does not hold and the partial decay rate of X to a quark is slightly faster than the corresponding decay rate of $\overline{X}$ to an antiquark. An excess of quarks over antiquarks at this age of the order of $\approx 6 \times 10^{-10}$ is sufficient to account for our present universe.

1.2 Nucleosynthesis

Primordial nucleosynthesis did not start until the universe was more than several tenths second old and had cooled through expansion to a temperature of about 10^9 K. At this temperature deuterons formed in the capture reaction of np $\rightarrow$ dγ remained stable. Further neutron and proton capture by deuterons led to the creation of the first ^{3}H and ^{3}He. The ^{3}H β–decays to ^{3}He which in turns can capture a neutron and form ^{4}He but this process is rather slow compared to the formation of ^{4}He through the reaction d^{3}He $\rightarrow$ p^{4}He. Capture of ^{3}H and ^{3}He by ^{4}He leads to the formation of ^{7}Li and ^{7}Be. The amounts of all these nuclides produced primordially are sensitive to the density of baryons or the baryon over photon ratio as well as the rate of expansion or cooling. The primordial creation of heavier elements is stymied by the inability of neutron capture on ^{4}He to lead to stable nuclei and by how slow the other reactions are.

Primordial nucleosynthesis ceased at about 30 minutes after the birth of the universe, when the temperature had dropped to about 10^8 K. The abundances of the elements formed were frozen so that the the presently observed abundances of light elements such as d, ^{3}He, ^{4}He and ^{7}Li still reflect this stage.

1.3 Life of stars

The production of energy in the sun via fusion reactions is well understood. The sun is a huge object with a radius of about 7×10^8 m, with an outside temperature of about 6000 K and a temperature at its centre of about 1.6×10^7 K. Fusion reactions proceed at a much lower rate than that needed for terrestrial reactors. However the total released energy is large since the volume is huge.

The first reaction sequence proposed and is applicable for hot stars (not the sun) was the one of the carbon or CNO cycle that proceeds as follows:

$$^{12}\mathrm{C} + \mathrm{p} \rightarrow ^{13}\mathrm{N} + \gamma$$

$$^{13}\mathrm{N} \rightarrow ^{13}\mathrm{C} + e^+ + \nu$$

$$^{13}\mathrm{C} + \mathrm{p} \rightarrow ^{14}\mathrm{N} + \gamma$$

$$^{14}\mathrm{N} + \mathrm{p} \rightarrow ^{15}\mathrm{O} + \gamma$$

$$^{15}\mathrm{O} + \rightarrow ^{15}\mathrm{N} e^+ + \nu$$

$$^{15}\mathrm{N} + \mathrm{p} \rightarrow ^{12}\mathrm{C} + ^{4}\mathrm{He}$$

In the whole chain ^{12}C acts as a catalyst, it undergoes changes but it is not used up since it appears also in the final state. Thus the overall reaction can be written as:

$$4\mathrm{p} \rightarrow ^{4}\mathrm{He} + 2e^+ + 2\nu + 3\gamma$$

The total energy release, considering the known masses, is found to be

$$Q(4\mathrm{p} \rightarrow ^{4}\mathrm{He}) = 26.7 \text{ MeV}$$

Out of this amount, around 25 MeV is used to heat up the star and the rest is carried off by the neutrinos.

In cooler stars the so–called pp–cycle is dominant. Its basic steps are summarised below:

$$\mathrm{p} + \mathrm{p} \rightarrow \mathrm{d} + e^+ + \nu$$

or

$$\mathrm{p} + \mathrm{p} + e^- \rightarrow \mathrm{d} + \nu$$

leading to

$$\mathrm{d} + \mathrm{p} \rightarrow ^{3}\mathrm{He} + \gamma$$

$$^{3}\mathrm{He} + ^{3}\mathrm{He} \rightarrow ^{4}\mathrm{He} + 2\mathrm{p}$$

$$^{3}\text{He} + ^{4}\text{He} \rightarrow ^{7}\text{Be} + \gamma$$

The first part of the above reaction is summarised by $4\text{p} \rightarrow ^{4}\text{He} + 2e^{+} + 2\nu$ while the second part produces a ^{7}Be. The latter leads to ^{4}He through a series of reactions:

$$^{7}\text{Be} + e^{-} \rightarrow ^{7}\text{Li} + \nu$$

$$^{7}\text{Li} + \text{p} \rightarrow 2\ ^{4}\text{He}$$

or

$$^{7}\text{Be} + \text{p} \rightarrow ^{8}\text{B} + \gamma$$

$$^{8}\text{B} \rightarrow ^{8}\text{Be}^{*} + e^{+} + \nu$$

$$^{8}\text{Be}^{*} \rightarrow 2\ ^{4}\text{He}$$

In a star pressure induced by gravity tends to decrease the star's volume. On the other hand, the pressure from the hot gas in the core tends to counteracts this reduction. Under these extreme conditions of pressure and temperature (e.g. in the centre of the sun the pressure is about 2×10^{10} bar and the temperature is about 16MK) atoms will be almost completely ionised, resulting in a mixture of free electrons and bare nuclei. This mixture is the gas mentioned above. The internal pressure is maintained by the nuclear reactions that provide the energy for the star's radiation. As long as these reactions proceed, the internal pressure will balance the pressure from gravity and the star will be in equilibrium. However, when the fuel is used e.g. when the pp–cycle in the sun ends, the star will contract gravitationally and the central pressure and temperature will increase. At higher temperatures new reactions will start, a new equilibrium will be reached and new elements will be formed.

After the formation of ^{4}He the next step is the creation of ^{12}C. This is facilitated by the α–capture process of a ^{8}Be (significant amount of unstable ^{8}Be exists in the core of the star through the process $^{4}\text{He} + ^{4}\text{He} \rightarrow ^{8}\text{Be}^{*} \rightarrow ^{4}\text{He} + ^{4}\text{He}$):

$$^{4}\text{He} + ^{8}\text{Be}^{*} \rightarrow ^{12}\text{C}$$

Then, the formation of ^{16}O proceeds via helium burning:

$$^{4}\text{He} + ^{12}\text{C} \rightarrow ^{16}\text{O} + \gamma$$

This sequence can be repeated up the ladder of elements. When α–burning becomes insufficient the star compresses due to the gravitational pull and heats up until carbon burning occurs:

$$^{12}\text{C} + ^{12}\text{C} \rightarrow ^{20}\text{Ne} + \alpha \rightarrow ^{23}\text{Na} + \text{p} \rightarrow ^{23}\text{Mg} + \text{n}$$

These reactions need a temperature of higher than 10^{9} K and they can occur only in massive, heavy stars. The exact path of stellar nucleosynthesis depends on the initial conditions and on whether there can be additional fresh hydrogen e.g. coming from a young, companion star. In general the production proceeds towards the more stable nuclei, ending up in Fe.

As the formation of elements reaches iron a new aspect appears: the binding energy per nucleon reaches a maximum at the iron group. Beyond these elements the binding energy per nucleon decreases. Hence the iron group cannot serve as a fuel and burning ceases once iron is formed. This feature also explains why elements centred around Fe are more abundant than others.

Most elements beyond the iron group are formed mainly through neutron capture reactions. There are two main processes involved: a slow one called s and rapid one called r. The capture processes depend critically on the neutron flux. With the

β decays of unstable nuclei, the proton number Z increases by one. In the s–process that takes place in stars like red giants, neutron capture processes are not very frequent because the neutron fluxes are low. So once the capture occurs, there is plenty of time for the β decay to happen before another neutron can be captured. Thus the s–process follows a path close to the stable nuclei and this path is determined by the relative β decay half lives. On the other had, if the neutron flux is high, as in the interior of a supernova, the r–process can take place. Neutron capture is much faster than the β decay and determines the path of the stellar nucleosynthesis. The nuclei formed are very neutron reach and thus very far from the valley of stability. As before, the slow process determines the rate of stellar nucleosynthesis. When a β decay occurs a neutron changes into a proton opening a hole in the neutron shell that can be quickly filled by another neutron capture process. In this way, through the succession of β decays followed by a quick neutron capture, nuclei like uranium or even heavier can be formed. There is no s–process path through stable nuclei to uranium.

Equivalently to neutron there are also proton capture processes that take place in proton–rich environments. Explosive proton burning, usually referred to as rp–process (see fig. 1.1) can take place when an old star (hot but without any hydrogen) can combine in a binary system with a younger star full of hydrogen. Novae and x–ray bursts are probably generated like this.

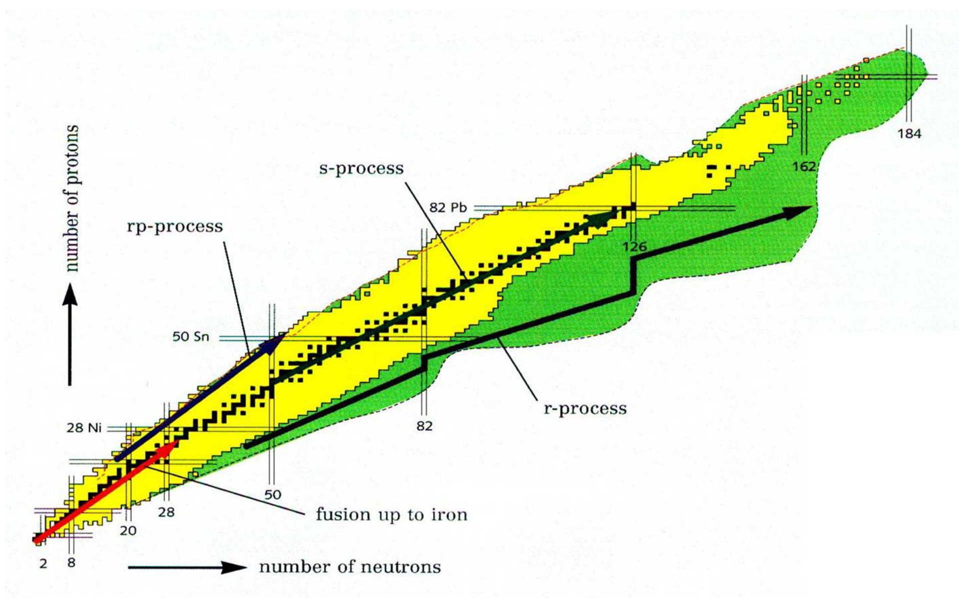

Fig. 1.1: The correlation between number of protons (y-axis) and number of neutrons (x-axis) for various nuclides. The different processes, namely s–process, r–process and rp–process are also shown.

1.4 Death of stars

In the previous section we briefly reviewed the burning processes in stars. These processes are obviously responsible for burning down the fuel of such stellar objects. When all the fuel is gone we say that the star dies and ends up in one of the following three categories:

- white dwarf,
- neutron star,
- black hole.

The ultimate fate of the star is mainly determined by its initial mass.

1.4.1 White dwarfs

White dwarfs are thought to represent the end point of stellar evolution for main-sequence stars with masses from about 0.07 to $10M_{sun}$. This would include the sun and over 97% of the other stars in the Milky Way. The composition of the white dwarf produced will depend on the initial mass of the star. After the hydrogen-fusing period of a main-sequence star of low or medium mass ends, such a star will expand to a red giant during which it fuses helium to carbon and oxygen in its core by the triple-alpha process. If a red giant has insufficient mass to generate the core temperatures, around 1 billion K, required to fuse carbon, an inert mass of carbon and oxygen will build up at its centre. After such a star sheds its outer layers and forms a planetary nebula, it will leave behind a core, which is the remnant white dwarf. Usually, white dwarfs are composed of carbon and oxygen. If the mass of the progenitor is between 8 and 10.5 solar masses, the core temperature will be sufficient to fuse carbon but not neon, in which case an oxygen?neon?magnesium white dwarf may form. Stars of very low mass will not be able to fuse helium, hence, a helium white dwarf may form by mass loss in binary systems.

The material in a white dwarf no longer undergoes fusion reactions, so the star has no source of energy. As a result, it cannot support itself by the heat generated by fusion against gravitational collapse, but is supported only by electron degeneracy pressure, causing it to be extremely dense. The physics of degeneracy yields a maximum mass for a non-rotating white dwarf, the Chandrasekhar limit (approximately 1.44 times of M_{sun}) beyond which it cannot be supported by electron degeneracy pressure. A carbon-oxygen white dwarf that approaches this mass limit, typically by mass transfer from a companion star, may explode as a type IA supernova via a process known as carbon detonation.

A white dwarf is very hot when it forms, but because it has no source of energy, it will gradually radiate its energy and cool. This means that its radiation, which initially has a high colour temperature, will lessen and redden with time. Over a very long time, a white dwarf will cool and its material will begin to crystallise (starting with the core). The oldest white dwarfs still radiate at temperatures of a few thousand kelvins.

1.4.2 Neutron stars

A neutron star is the collapsed core of a large star which before collapse had a total of between 10 and 29 solar masses. Neutron stars are the smallest and densest stars known to exist. Though neutron stars typically have a radius on the order of 10 kilometres, they can have masses of about twice that of the sun. They result from the supernova explosion of a massive star, combined with gravitational collapse, that compresses the core past the white dwarf star density to that of atomic nuclei. Once formed, they no longer actively generate heat, and cool over time. However, they may still evolve further through collision or accretion. Most of the basic models for these objects imply that neutron stars are composed almost entirely of neutrons. Neutron stars are supported against further collapse by neutron degeneracy pressure, a phenomenon described by the Pauli exclusion principle, just as white dwarfs are supported against collapse by the electron degeneracy pressure.

Neutron stars that can be observed are very hot and typically have a surface temperature of around 6×10^5 K. Their magnetic fields are between 10^8 and 10^{15} times as strong as that of the Earth. The gravitational field at the neutron star's surface is about 2×10^{11} times that of the Earth.

As the star's core collapses, its rotation rate increases as a result of conservation of angular momentum, hence newly formed neutron stars rotate at up to several hundred times per second. Some neutron stars emit beams of electromagnetic radiation that make them detectable as pulsars. The radiation from pulsars is thought to be primarily emitted from regions near their magnetic poles. If the magnetic poles do not coincide with the rotational axis of the neutron star, the emission beam will sweep the sky, and when seen from a distance, if the observer is somewhere in the path of the beam, it will appear as pulses of radiation coming from a fixed point in space (the so-called "lighthouse effect"). The fastest-spinning neutron star known is rotating at a rate of 716 times a second.

There are thought to be around 100 million neutron stars in the Milky Way, a figure obtained by estimating the number of stars that have undergone supernova explosions. However, most are old and cold, and neutron stars can only be easily detected in certain instances, such as if they are a pulsar or part of a binary system.

1.4.3 Black holes

A black hole is a region of spacetime exhibiting such strong gravitational effects that nothing, not even particles and electromagnetic radiation such as light, can escape from inside it. The theory of general relativity predicts that a sufficiently compact mass can deform spacetime to form a black hole. The boundary of the region from which no escape is possible is called the event horizon. Although the event horizon has an enormous effect on the fate and circumstances of an object crossing it, no locally detectable features appear to be observed. In many ways a black hole acts like an ideal black body, as it reflects no light.

In 1974, Hawking predicted that black holes are not entirely black but emit small amounts of thermal radiation. This effect has become known as Hawking radiation. By applying quantum field theory to a static black hole background, he determined that a black hole should emit particles that display a perfect black body spectrum. If Hawking's theory of black hole radiation is correct, then black holes are expected to shrink and evaporate over time as they lose mass by the emission of photons and other particles. The temperature of this thermal spectrum (Hawking temperature) is proportional to the surface gravity of the black hole, which is inversely proportional to the mass. Hence, large black holes emit less radiation than small black holes. A stellar black hole of $1M_{\mathrm{sun}}$ has a Hawking temperature of about 100 nanokelvins. This is far less than the 2.7 K temperature of the cosmic microwave background radiation. Stellar-mass or larger black holes receive more mass from the cosmic microwave background than they emit through Hawking radiation and thus will grow instead of shrink. To have a Hawking temperature larger than 2.7 K (and be able to evaporate), a black hole would need a mass less than the moon. Such a black hole would have a diameter of less than a tenth of a millimetre.

Black holes of stellar mass are expected to form when very massive stars collapse at the end of their life cycle. After a black hole has formed, it can continue to grow by absorbing mass from its surroundings. By absorbing other stars and merging with other black holes, supermassive black holes of millions of solar masses may form. There is general consensus that supermassive black holes exist in the centres of most galaxies.

Despite its invisible interior, the presence of a black hole can be inferred through its interaction with other matter and with electromagnetic radiation such as visible light. Matter that falls onto a black hole can form an external accretion disk heated by friction, forming some of the brightest objects in the universe. If there are other stars orbiting a black hole, their orbits can be used to determine the black hole's mass and location. Such observations can be used to exclude possible alternatives such as neutron stars. In this way, astronomers have identified numerous stellar black hole candidates in binary systems, and established that the radio source known as Sagittarius A^*, at the core of our own Milky Way galaxy, contains a supermassive black hole of about 4.3 million solar masses.

1.5 Cosmic rays

We are constantly bombarded by energetic particles from outer space e.g. around 1 charged particle/sec passes through ever cm^2 of the Earth's surface. These particles are dubbed cosmic rays and their existence was discovered in 1912. Since then there have been many theories about their origin and many experiments have tried to get a better insight on this aspect and study them in detail. Cosmic rays are one of the main components of our galaxy. They have been observed and studied at various altitudes, in deep underground caverns, in mountaintop laboratories, with balloons, with rockets and satellites.

The radiation that reaches the atmosphere of the Earth consists of nuclei, electrons, positrons, photons and neutrinos. Out of these, cosmic rays are called only the charged component. Let us first consider the fate of an energetic proton that hits Earth's atmosphere: this proton interacts with an oxygen or nitrogen nucleus and a cascade process is initiated. These interactions will create a large number of hadrons, pions predominantly but also antinucleons, kaons, hyperons. These hadrons can again interact further with nuclei in the atmosphere and produce more particles. Unstable particle will decay and result in producing electrons, muons, neutrinos and photons. The photons produce electron-positron pairs, the muons decay but due to time dilation they are able to reach the Earth's surface. In general, an energetic cosmic ray particle can create a very large number of particles and the shower can be extended up to an area of many Km^2 on the Earth's surface. A schematic view of the development of such cosmic ray shower is given in fig. 1.2.

The composition of the nuclear component of the primary cosmic ray presents similarities but also significant differences when compared to the universal distribution of the elements observed in the solar atmosphere and the meteorites. One of the important differences is that the elements Li, Be and B are about 10^5 times more abundant in cosmic rays than

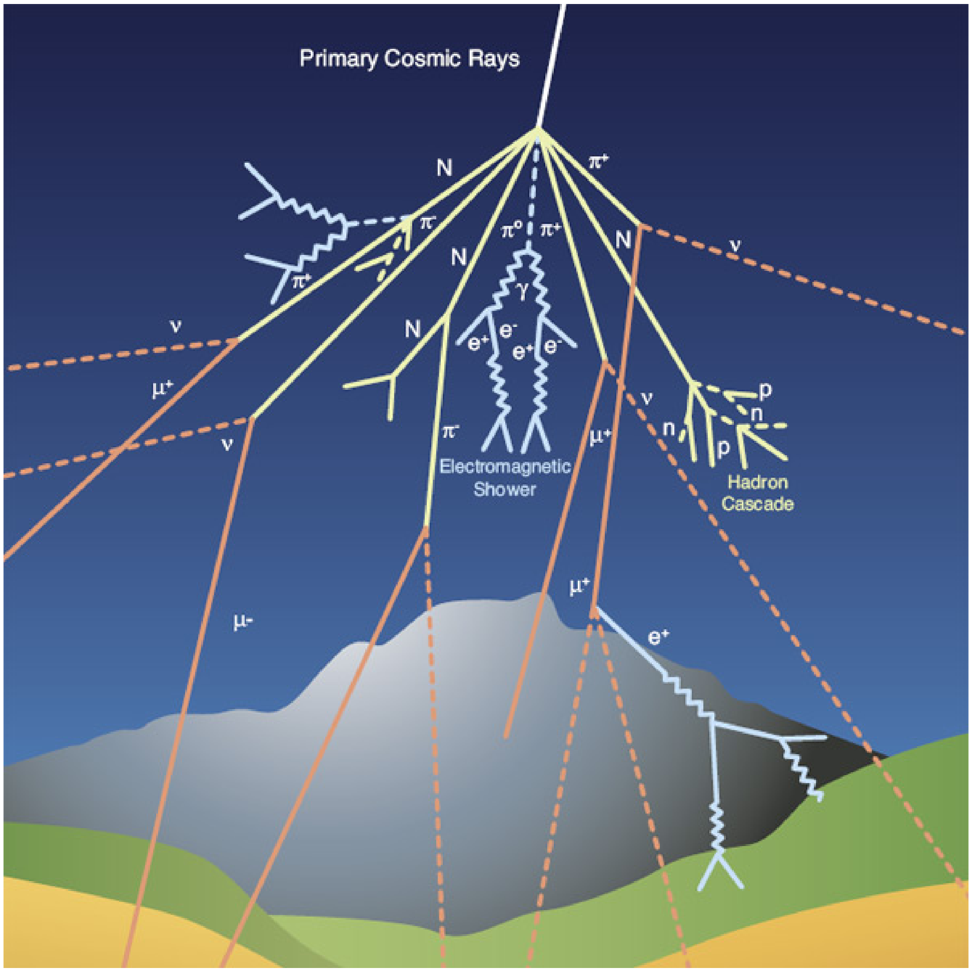

Fig. 1.2: A schematic view of the development of a cosmic ray shower.

universally. In addition, the ratio $^3He/^4He$ is about 300 times larger in cosmic rays. Finally, heavy nuclei are more abundant in cosmic rays. The first two observations can be explained by assuming that cosmic rays have traversed about several g/cm^2 of matter between their source and the top of Earth's atmosphere. Since the interstellar density is of the order of 10^{-25}g/cm^3, the cosmic rays must have wandered around for $10^6 - 10^7$ years. A couple of additional facts may provide crucial information about the origin of these cosmic rays: so far no antihadrons have been observed in primary cosmic rays and electrons are 1% as abundant as nuclei in the same energy interval.

The energy spectrum, the number of primary particles as a function of energy, has been the topic of many studies and has been investigated over an enormous range. The cosmic ray flux is presented in fig. 1.3. Measurements exist for energies even higher than 5×10^{20} eV, about 40 million times the energy of particles accelerated by the Large Hadron Collider. The energy spectrum is not thermal but exhibits a power-law satisfying the relation $I(E) \approx E^{-2.7}$ for $E < 10^{15}$ eV. At about $E \approx 5 \times 10^{15}$ eV, there is (what is referred to as) a knee in the spectrum. The cause of this feature is still under debate, but the two most prominent explanations are related to either propagation effects or a new accelerating mechanism. Above this energy and up to about 10^{18} eV the fit is more like $I(E) \approx E^{-3}$. Above this energy the slope changes again. It is usually assumed that cosmic rays with energy above 10^{18} eV are extragalactic since no galactic acceleration mechanism for these ultra-high-energy cosmic rays has been found. There is an expected theoretical cutoff at about 6×10^{19} eV, known as the Greisen-Zatsepin-Kuzmin limit (GZK cutoff), due to interactions of cosmic rays with the cosmic microwave background producing pions, so that the energy is degrading. However, there are measurements from many experiments carried out all over the world that show that the energy spectrum of the primary cosmic rays is now known to extend beyond 10^{20} eV. A huge air shower experiment called the Auger Project is currently operated at a site on the pampas of Argentina by an international consortium of physicists. Their aim is to explore the properties and arrival directions of the very highest-energy primary cosmic rays.

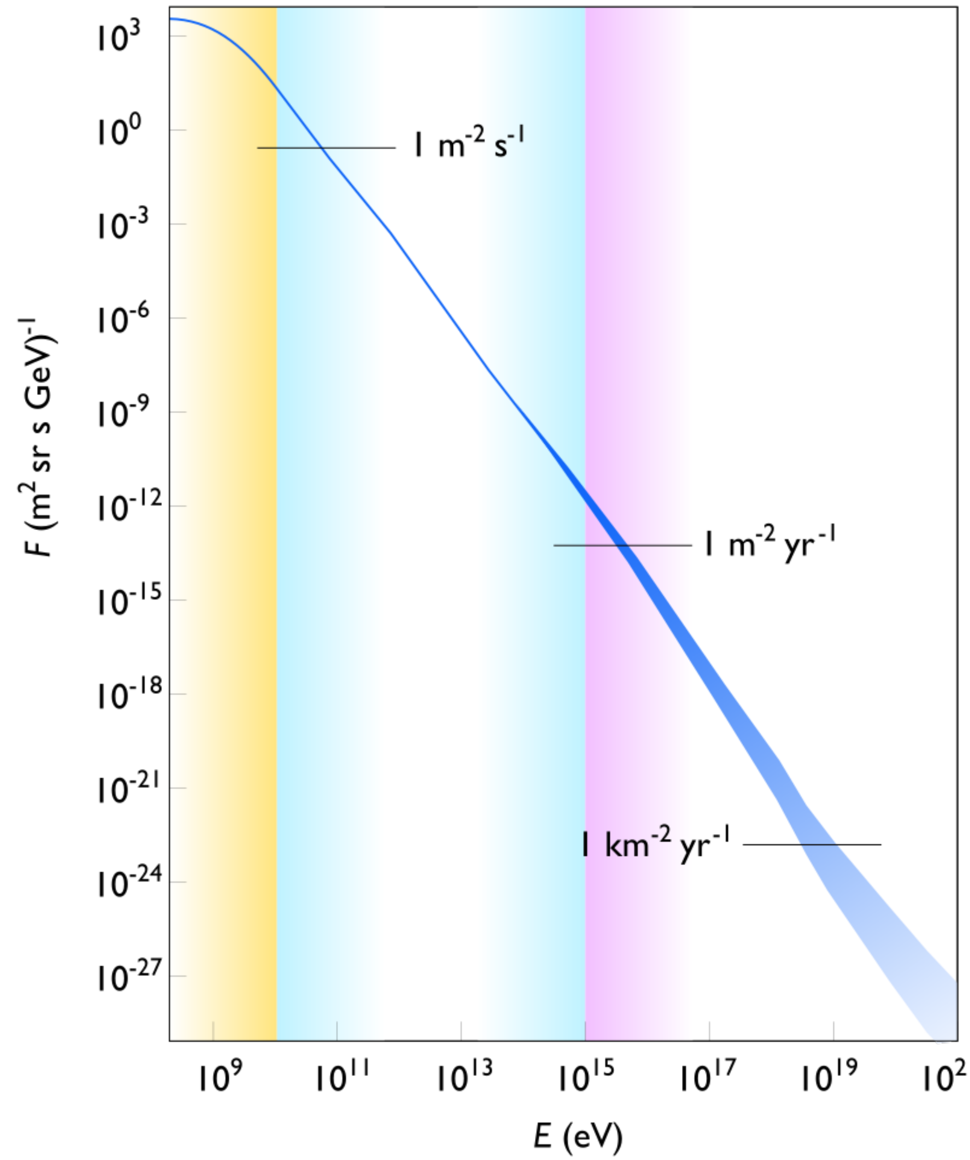

Fig. 1.3: The cosmic ray flux as a function of the energy of particles.

For the origin of the energetic cosmic rays there are two other aspects of particular interest:

- measurements in outer space indicate that the cosmic ray flux is essentially isotropic for $E \leq 10^{15}$ eV,
- the time dependence of the intensity, studied over long periods of time at the abundances of different nuclides created in moon or meteorite samples, is constant over a period of about 10^9 years.

All the points above imply that there are several sources of cosmic rays that contribute collectively to the energy spectrum. At this point of time the majority of people are convinced that cosmic rays with energies $E \leq 10^{15}$ eV are of galactic origin. These cosmic rays can be produced in the inner radiation disk of the Milky Way or in the galactic halo. However for energies above this limit things are not that clear. A favoured hypothesis for the energy of ultra-energetic cosmic rays with $E \geq 10^{18}$ eV is the explosion of supernovae as well as neutron stars (e.g. pulsars).

1.6 Neutrino astronomy

Classical astronomy is restricted in the narrow band of the visible light, from 400 to 800 μm. This window has been significantly enlarged by including information from radio and infrared astronomy from one side and from X– and γ–ray astronomy on the other side. Cosmic rays i.e. charged particles), as discussed in the previous section, provide yet another extension. However all these observations do not provide much information about the interior of stars since radiation is usually absorbed in a relatively small amount of matter. To have an idea of the dimensions, a photon needs $10^4 - 10^5$ years to come out from the centre of the sun. However, there is one particle that barely interacts with matter, the neutrino.

As seen before, the absorption of neutrinos in matter is very small. The absorption cross-section is given by

$$\sigma(\mathrm{cm}^2) = 2.3 \times 10^{-44} \frac{p_e}{m_e c} \frac{E_e}{m_e c^2}$$

where p_e and E_e are the momentum and energy of the final electron in the reaction $\nu N \rightarrow eN'$. It is then found that the mean free path of an 1 MeV electron neutrino in water is 10^{21} cm i.e. exceeding the linear dimensions of stars.

In addition, neutrinos and antineutrinos can be detected through their interactions with water. Although the neutrino luminosity at the surface of our planet is dominated by the flux from the sun, it is believed that the origin of primary galactic neutrinos are supernovae and their remnants. In the cooling process of supernovae, neutrino-antineutrino pairs of all flavours are emitted through neutral current reactions such as $e^+e^- \rightarrow \nu\bar{\nu}$. In addition, electron neutrinos and antineutrinos are generated through charged current reactions in nuclei e.g. $e^-\mathrm{p} \rightarrow \mathrm{n}\nu_e$.

Finally, neutrinos can be used to probe dark matter. In particular if WIMPs exist, one of their decay channels is into neutrinos. These neutrinos can be observed in earth by dedicated detectors, thus providing stringent constrains for the corresponding theories.