Astrophysics and elementary particles

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Abstract. These are the lecture notes of an astroparticle course constructed from the local astrophysical environment out to the cosmological domain. The subjects reviewed are stellar physics, focusing on the standard solar model and the case of solar neutrinos; the Galactic interstellar medium and the origin of its cosmic rays; the more energetic extragalactic high energy cosmic rays, supernovae and neutrinos in the nearby universe; finally, a short digression is made into astroparticles at cosmological scales, regarding the nature of dark matter.

Introduction
The human perception of the Cosmos developed with the concepts of planets, stars and comets. Nebulae and galaxies entered the scenario together around the XIX century, later to be found to be distinct sort of objects. The interstellar medium (ISM) became an important and complex entity, composed not just by gas and dust but also by magnetic fields and relativistic elementary particles. The early notions of celestial objects were to extend to include more “exotic” objects like brown-dwarves, degenerate stars, black holes, quasars and the universe itself, permeated by cosmological radiation and -we believe- neutrino backgrounds.

The particle based perception of the universe started with protons, neutrons and electrons as the most obvious components of an universe dominated by baryons1. These were later complemented by heavy leptons, namely muons and neutrinos, and more exotic hadrons. Astrophysics and particle physics found common grounds in the study of stellar and primordial nucleosynthesis, cosmic rays, neutrinos, the early universe and, more recently in the study of the large-scale universe, which we now believe to be dominated by dark energy and formed primarily of non baryonic dark matter.

This text represents the notes of an Astroparticle course given during the XI Mexican School of Particles and Fields held in August 2004 in Xalapa, México, and organized by the Sociedad Mexicana de Física. This course was directed to postgraduated physics students with no astronomical background a priori and the level of these notes should reflect so. The course was constructed as a general astrophysics course, starting from the Sun, to the Galactic domain, the local universe and then into cosmological issues, with emphasis on elementary particles like neutrinos and cosmic rays. I will review these topics, at a general level and only superficially, and with unavoidable bias towards subjects I am familiar with, but with an effort to include updated information. These notes cover five sections: §1 reviews astrophysical information carriers; §2 presents basis of stellar models, the standard solar model and the problem of solar neutrinos;

1 as leptons barely contribute in terms of mass.
§3 presents the Galactic interstellar medium, with emphasis on cosmic rays; §4 builds on §2 to overview stellar explosions and their relation with high-energy cosmic rays; §6 makes a final digression into cosmology and the nature of dark matter.

1. Astrophysical information

Photons represent our main window to the universe, but certainly not the only one. Until little more than half a century ago this window was restricted to the narrow domain of visible light. Present day astronomical observatories exploit the whole electromagnetic spectrum, from radio-waves to the highest energy gamma rays, and scientists actively seek to expand into the era of neutrino and gravitational wave astronomy. Information about celestial particle accelerators has also been obtained through the study of cosmic rays, high energy charged elementary particles detected from altitude, space and ground. And although cosmic rays are deflected by cosmic magnetic fields and cannot provide direct information about the location of their source, their study has proven valuable for our understanding of high-energy astrophysical phenomena.

1.1. Photons

Photons are the carriers of the electromagnetic interaction. Their classical description is in terms of electromagnetic fields \( \{\vec{E}, \vec{B}\} \) of harmonic behaviour, like the solutions of Maxwell equations in vacuum:

\[
\vec{E}(\vec{r}, t) = E_0 \hat{\varepsilon} e^{\pm i(k \cdot \vec{r} - \omega t)},
\]

where \( |E_0|^2 = |B_0|^2 \) is the intensity of the electromagnetic field, \( \hat{\varepsilon} \) is an unitary imaginary vector describing the polarization of the (here assumed monocromatic) field. The dispersion relation resulting from Maxwell equations links the wavelength \( \lambda \) and frequency \( \nu \) through

\[
\nu \lambda = c,
\]

with \( c \) the speed of light, while the Planck equation,

\[
E = h \nu,
\]

defines the energy of an individual photon. The electromagnetic (EM) windows commonly used to describe astronomical observations are defined in terms of ranges of either \( \nu, \lambda \), or \( E \). Historically the discovery and generation of EM waves at different regions of the spectrum happened independently, leading to the present definition of the EM bands: radio, infrared, visible, ultraviolet, X rays and \( \gamma \) rays. Albeit the beginning and end of the EM spectrum are loosely defined, the optical window, corresponding to photons of two to three eV, is located roughly in the middle of the EM spectrum (Table 1).

Since their invention in the early XVII century, optical telescopes have relied on focusing the light incident in their aperture into the smallest possible region, where a detector is placed. The human eye was superseeded as an astronomical light detector by photographic plates, photoelectric cells and optoelectronic devices (CCDs). The angular resolution of a telescope of aperture \( D \) observing at \( \lambda = 500 \) nm is limited by diffraction to an angular resolution \( \Delta \theta \approx 1.2 \lambda / D \approx 0.12 \) arcsec \( (D/m)^{-1} \). In practise Earth based telescopes are further limited by atmospheric perturbances producing a blurring of point images known as seeing, with a site dependent scale typically \( \lesssim 1 \) arcsec for good astronomical sites. And while optical space telescopes, like Hubble, have then an advantage in terms of angular resolution, modern technology ground-based telescopes have managed to partially compensate the effect of seeing through the use of active optics.

The development of radio astronomy began shortly after World War II, with radio telescopes taking the shape of either arrays of dipoles antenas or large single dishes relying on focusing
Table 1. The electromagnetic windows

| Window          | sub-window       | \( \nu \)  | \( \lambda \) | \( E \)      |
|-----------------|------------------|-------------|---------------|--------------|
| radio           | low frequency\(^{(1)}\) | 10 MHz      | 30 m          | 0.04 \( \mu \)eV |
|                 | microwaves       | 30 GHz      | 1 cm          | 0.12 meV    |
|                 | millimetric      | 300 GHz     | 1 mm          | 1.24 meV    |
| infrared (IR)   | far-IR           | 200 \( \mu \)m |              | 6.2 meV     |
|                 | mid-IR \(^{(2)}\) | 21 \( \mu \)m |              | 0.059 eV    |
|                 | near-IR \(^{(3)}\) | 2.2 \( \mu \)m |              | 0.56 eV     |
| optical         | red \(^{(4)}\)   | 700 nm      |              | 1.8 eV      |
|                 | visual           | 550 nm      |              | 2.3 eV      |
|                 | blue             | 440 nm      |              | 2.8 eV      |
| ultraviolet (UV)| near-UV          | 360 nm      |              | 3.4 eV      |
|                 | mid-UV \(^{(3)}\) | 91.1 nm     |              | 13.6 eV     |
|                 | far/extreme-UV   | 10 nm       |              | 124 eV      |
| X rays          | soft             | 4.1 nm      |              | 0.3 keV     |
|                 | medium           |              | 3 keV        |
|                 | hard             |              | 30 keV       |
| \( \gamma \) rays | soft \(^{(4)}\) |              | 0.511 MeV    |
|                 | medium           |              | 10 MeV       |
|                 | high-energy      |              | 1 GeV        |
|                 | very high-energy |              | 100 GeV      |
|                 | ultra high-energy|              | 100 TeV      |

\(^{(1)}\) approximately the ionospheric cut-off for low frequency radio-waves; \(^{(2)}\) optical, NIR and NUV defined in terms of the Johnson-Cousins photometric system; \(^{(3)}\) the ionization potential of the hydrogen ground level; \(^{(4)}\) the rest mass of the electron.

Radio waves into appropriate detectors, presently heterodyne receivers or bolometers. Following the diffraction limit expression one can see that the angular resolution of a single dish is mostly dependent on the frequency, ranging from just below one degree for neutral hydrogen 21-cm observations, \( \Delta \theta \simeq 43 \text{arcmin} \left( \lambda/21 \text{cm} \right) \left( D/20 \text{m} \right)^{-1} \), to \( \simeq 5 \text{arcsec} \left( \lambda/1 \text{mm} \right) \left( D/50 \text{m} \right)^{-1} \) for the Large Millimeter Telescope (LMT), in Sierra Negra, México. Radio and millimeter single dish telescopes have poorer angular resolution than optical telescopes. Still, radio astronomy has attained the highest spatial resolutions through the use of interferometry. Combining the phase information of radio waves simultaneously observed by telescopes separated by a distance \( D \), interferometers can reach \( \Delta \theta \simeq 0.004 \text{arcsec} \left( \lambda/21 \text{cm} \right) \left( D/10000 \text{km} \right)^{-1} \) for the HI line.

As illustrated in Figure 1, far infrared (FIR), X rays and \( \gamma \) rays are absorbed by Earth’s atmosphere and astronomical observations in these bands require telescopes to be placed either in balloons, rockets, or spacecrafts. Like optical and radio telescopes, FIR and low energy X ray telescopes also rely on focusing light into the smallest region. The spatial resolution of the state-of-the-art *Spitzer Space IR Telescope Facility* is limited by diffraction from 1.5" at 3.6 \( \mu \)m to 1 arcmin at 160 \( \mu \)m. Focusing of X rays, up to energies of a few keV, is ingeniously achieved by the principle of grazing incidence optics invented by Wolter in the early 1950s ([93]). The resolution is limited by the precision to which metallic paraboloids and hyperboloids nested to form each imaging X ray telescope can be manufactured. The *Chandra X ray Observatory*, in orbit since 1999, is a remarkably powerful instrument, able of sub-arcsecond spatial resolution.
Beyond photon energies $\gtrsim 10$ keV focusing telescopes have not been possible to construct. High energy telescopes detect photons without focusing, i.e. through the direct incidence of photons in the detector. Three basic physical principles allow to construct such high energy telescopes:

- **the photoelectric effect**: hard X rays can be detected through visible or UV light produced in a crystal undergoing a photoelectric absorption. This basic principle has recently been combined with the use of coded-masks to produce telescopes with angular resolutions of a few arcmin, like BeppoSAX able to study photons up to 300 keV.
- **the Compton effect**: at energies of some 100s of keV the Compton scattering cross section overtakes that of photoelectric absorption. COMPTEL on-board Compton Gamma-Ray Observatory (CGRO) was the first Compton telescope ever in orbit. It was designed with a two level structure with its detection principle relying on a Compton scattering occuring in the upper level and the detection of the scattered photon in the lower level. The measurement of the direction of the scattered photon and the energy deposits in the two levels allows to estimate the original photon energy and scattering angle. COMPTEL made the first sky survey in the 0.7-30 MeV spectral window ([72]), but its inherent azimuthal
uncertainty in locating photons and the high cosmic ray induced photon background at those energies make this an extremely difficult and challenging spectral range to study.

- **pair production**: telescopes rely on converting \( \gamma \) rays into \( e^\pm \) pairs, tracking their trajectories within the telescope and measuring their energies in a calorimeter. The Energetic Gamma-Ray Experiment Telescope (EGRET), also on-board CGRO, detected 271 sources of photons with energies above 100 MeV. The GLAST telescope, scheduled for launch in 2007, will have a detection area ten times larger over a larger field-of-view and is eagerly expected to expand on the discoveries made by EGRET during the 1990s.

The highest energy gamma rays produce particle cascades in Earth’s atmosphere which can be directly detected from ground or observed through the Čerenkov radiation emitted by relativistic charged particles in the cascade. The effective use of the atmospheric Čerenkov technique requires imaging the distribution of light arriving at the ground to statistically differentiate photon events from the larger background of cosmic ray events ([90]). A new generation of Čerenkov telescopes, composed either of arrays of a few Čerenkov telescopes like HESS or of large aperture efficient single telescopes like MAGIC, is now coming online. These instruments have the potential to observe photons with energies below 100 GeV, overlapping with the energy range of GLAST and closing one of the remaining gaps in the astronomical EM windows.

### 1.2. Astrophysical Neutrinos

Neutrinos are elemental particles of spin \( \pm \hbar/2 \) produced or absorbed through the weak nuclear interaction. Prototypical are \( \beta \)-decay reactions, like spontaneous neutron decay

\[
  n \longrightarrow p + e^- + \bar{\nu}_e .
\]  

(4)

These reactions, permitting neutrons to produce protons and vice versa, are fundamental for the fusion of hydrogen to helium occurring in stellar interiors. Consequently, stars must be astrophysical neutrino sources. Observational evidence is provided by the observation of solar neutrinos. Neutrinos must be produced also during the collapse of a massive star core, when protons and electrons merge to produce neutrons. It is believed that in fact most of the energy of the collapse goes into neutrinos and that these drive the expansion of the outer layers of the star, producing in this way the supernova explosion observed. The direct detection of neutrinos from SN 1987A is the first evidence that neutron stars are indeed produced in supernova.

Neutrinos come in three flavors, related to the three leptons: electron (\( \nu_e \)), muon (\( \nu_\mu \)) and tauon (\( \nu_\tau \)). As such, muon decay produces \( \mu \)-neutrinos: \( \mu \rightarrow e + \bar{\nu}_e + \nu_\mu \). The first neutrino detectors were sensitive to electron neutrinos only; more recent neutrino detectors incorporate flavor-sensitivity. The small cross-section of the weak interaction results in the need of massive and voluminous neutrino detectors. A short review of experiments and results is given by [60]. The basic neutrino detector principles result in instruments like:

- the Davis solar neutrino observatory in the Homestake Gold mine, South Dakota, contains 100,000 gallons of \( C_2 Cl_4 \), chlorine atoms being susceptible to the weak reaction

\[
  ^{37}_{17}Cl + \nu_e \rightarrow ^{37}_{18}Ar + e^- ,
\]  

(5)

which has a threshold energy of 0.814 MeV. The neutrino flux is estimated through counting the numbers of argon atoms produced, with typical rates of about one argon atom produced every two or three days. The rate is translated to a solar neutrino flux measured in Solar Neutrinos Units, with 1 SNU = 10\(^{-36}\) reactions per target per atom per second. The standard solar model predicts 7.9 SNU while the measured rate is 2.23 ± 0.26 SNU. The accepted solution to the solar neutrino problem is the existence of neutrino oscillations, as it will be mentioned later.
a second type of chemical neutrino detectors are Gallium detectors, like the Gallex and SAGE experiments. The weak reaction involved is

$$^7_{31}\text{Ga} + \nu_e \rightarrow ^7_{32}\text{Ge} + e^-,$$  \hspace{1cm} (6)

with the overall working principle being similar to that of the chlorine detectors. One of the most important features of Ga detectors is the low threshold of the reaction, at 0.233 MeV.

• Neutrino Čerenkov detectors, like the Kamiokande and Super-Kamiokande experiments, rely on detecting the Čerenkov emission from electrons scattered by high-energy neutrinos. They have a higher energy threshold than chemical detectors, \(\gtrsim 5\) MeV, and are therefore sensitive to solar neutrinos produced in \(^8\text{B}\) reactions. The rate of solar neutrinos measured by Kamiokande II is consistent with the Homestake gold mine experiment. Kamiokande II detected also neutrinos from SN 1987A, the first direct observational evidence of a core collapse during a supernova explosion.

• the Sudbury Neutrino Observatory (SNO) is a heavy-water (D\(_2\)O) flavor-sensitive neutrino detector in Ontario ([60]). Electron neutrinos participate in charged current weak interactions, while all sorts of neutrinos participate in neutral current interactions and neutrino - electron scattering,

\[
\begin{align*}
\nu_e + d & \rightarrow p + p + e^- & \text{charged current}, \\
\nu_x + d & \rightarrow p + n + \nu_x & \text{neutral current}, \\
\nu_x + e^- & \rightarrow \nu_x + e^- & \text{electron scattering}. 
\end{align*}
\]

SNO has a threshold of 2.2 MeV for all neutrinos flavors.

• the Auger Observatory is starting to study the highest energy cosmic rays, at energies beyond \(10^{20}\) eV. Auger will be sensitive to very high energy neutrino air showers arriving close to horizon, at very low elevation angles ([22]).

1.3. Gravitational waves
Gravitational waves are not a topic of these lectures, but are briefly mentioned here for completeness. Standard gravitation theories predict that time variable mass quadrupoles emit gravitational waves which carry unique astrophysical information. Gravitational waves, or gravitons, are solutions of a non-linear equation which, for weak gravitational interactions, can be approximated by a wave equation, resulting in a similar description as for electromagnetic radiation: gravitational waves propagate at the speed of light, \(c\), fullfill a dispersion relation defining wavelength, so that a gravitational wave spectrum can be defined, and have polarization, although described through a tensor formalism.

Indirect evidence of gravitational wave emission exists. The orbital decay of the binary pulsar PSR 1913+16 matches beautifully, with high observational accuracy, the prediction of general relativity [29]. The direct detection of these waves, still to be achieved, requires extremely precise measurement of the motion induced in large masses. One of the original experiments was Weber’s resonant bars [89]. At present the ground based detector LIGO measures motions with enormous precision [1]. The LISA experiment, acronym for Large Interferometer Space Antenna, planned for launch in 2012, is to study gravitational waves with a triangular set-up of detectors separated by a baseline of five million kilometers, only achievable in space. It will also benefit from avoiding natural and man-made vibration noise [97].

1.4. Cosmic rays
As proved by Rudolph Hess in the first years of the XX Century, the Earth is constantly bombarded by a large flux of charged particles, later found to be constituted mostly of protons
Figure 2. The entire Cosmic ray spectrum, as observed from Earth. The spectrum is well fitted by a power-law of index -2.7 between \( \lesssim 10^{10} \) eV to \( \sim 5 \times 10^{15} \) eV, and of index -3.1 from there to \( \sim 5 \times 10^{19} \) eV. The data above that energy seems to indicate a spectral softening, to be confirmed with the Auger cosmic ray observatory (figure from [98]).

and heavy nuclei, in the proportion of 90% protons, 9% alpha particles, 1% heavier nuclei and electrons. The measured energies of this particles extend from \( E < \sim 10^{9} \) eV to beyond \( E > \sim 10^{20} \) eV, as show in Figure 2. The energy density of cosmic rays in the solar neighborhood is about 1 eV/cm\(^3\), similar to the energy density of starlight and of the Cosmic Microwave Background. Cosmic rays being charged are deflected by magnetic fields and bear no information about the location of their sources (§3).

1.4.1. From ballons and space  The flux of the lowest energy cosmic rays, \( E \sim 1 \) GeV, is of the order of hundreds of particles m\(^{-2}\)s\(^{-1}\), large enough to be a safety concern for astronauts. It is studied by direct detection with small detectors on balloons or spacecrafts. Space experiments can reach up to particle energies of \( 10^{15} \) eV and are often targeted to investigate the composition along the cosmic ray spectrum, including the electron component [46, 96]. These detectors have effective areas of a few m\(^2\) and are composed of calorimeters, transition-radiation detectors and Čerenkov detectors which serve as element identifiers. The flux of low energy cosmic rays anticorrelates with solar activity, indicating the effect of solar shielding. Solar particles are also detected in this energy range.

1.4.2. From ground  High energy cosmic rays produce particle cascades in the atmosphere which can be studied from ground either detecting the Čerenkov light from the relativistic particles of the cascade (for primary cosmic rays with \( E \gtrsim 10^{11} \) eV), directly recording the particles reaching
ground (primary cosmic rays of $E \gtrsim 10^{14}$ eV $\rightarrow 10^{21}$ eV) or measuring the fluorescent emission induced in atoms present in the atmosphere ($E \gtrsim 10^{17}$ eV $\rightarrow 10^{21}$ eV). Similar techniques are used for searching for high energy photons from cosmic sources, with the larger flux of cosmic rays acting as the background against which the $\gamma$ ray source is to be detected.

2. Stellar physics and solar neutrinos
Stars are the most notorious constituent of the night sky. As such they have been studied in detail since the advent of the telescope and the basic understanding of their functioning was established during the XXth Century. Stars shine generating energy in nuclear reactions and maintaining their surfaces at temperatures where visible light is emitted. A basic prediction of stellar models is the emission of neutrinos, which have the potential of providing instantaneous diagnostic of the conditions at stellar interiors.

2.1. Classifying stars
The understanding of the nature of stars was triggered by establishing a stellar classification based on spectroscopic criteria. Stellar atmospheres, being cooler than the photospheres, absorb photons according to their physical conditions and chemical abundances, producing absorption features in the spectrum. The ubiquity of hydrogen in stars made the Balmer lines the obvious choice for the first stellar classification schemes, which later evolved into the present classification based on lines from different elements according to a temperature sequence. Stellar types are ordered in a sequence of decreasing temperature given by the popular mnemonetic sequence OBAGFKM, with stellar effective temperatures decreasing from 30,000 K to 3,000 K. At a given temperature $T$ spectral line strengths are determined by the abundances of ions, atoms and molecules and the population of their energy levels, given by statistical mechanics relations. In particular the Saha equation relates the number densities of different degrees of ionization (say $n_{i+1}$ and $n_i$) as

$$\frac{n_{i+1}}{n_i} \propto e^{\zeta - \chi/kT},$$  

(8)

where $\chi$ is the ionization potential and the factor $\zeta = \ln(2/n_e \lambda_e^3)$ relates the electron density ($n_e$) to the typical De Broglie length of electrons, given by $\lambda_e = h/(2\pi n_e kT)^{1/2}$ for a thermal population. Under normal, non-degenerate, conditions $\zeta = \zeta(T)$ has values in the range 10 to 30. As a result, even though ionization potentials are often on the range of tens of eV, i.e. above 100,000 K, maximum relative abundances of ionized species ($n_{i+1}/n_i$) are attained at significantly lower temperatures, $kT \sim \chi/\zeta \sim 10^3$ K. Moreover, a relatively small temperature change, $\Delta T \ll T$, modifies substantially the relative densities $n_i$ leading to a noticeable dependence on temperature of the strengths of absorption lines (Figure 3).

In 1905 Hertzsprung confirmed the correlation between absolute magnitudes (luminosities) and spectral types (temperatures) of most stars. In 1914 Russell showed this relation in the form of a diagram, the first version of the Hertzsprung-Russell (HR) diagram ([71]), where the stars within the dominant correlation constitute the main sequence. The HR diagram is the observed relation between spectral class \{ <=> color <=> temperature\} and absolute magnitude \{ <=> luminosity\} observed in stars, the most fundamental tool for stellar studies (Figure 4). The large spread in the luminosities of red stars and the existence of white dwarfs motivated the introduction of luminosity classes within a given stellar type. The luminosity sequence comprises luminous supergiants (luminosity class Ia); less luminous supergiants (Ib); bright giants (II); normal giants (III); subgiants (IV); main sequence stars (V); subdwarfs (VI, sd) and white dwarfs (D). Within the complete scheme the Sun is classified as a G2V star, in terms of its temperature (G2, where the digit sub-divides G stars between G0 and G9) and luminosity (V). a similar relation is followed by blackbodies.
Figure 3. Spectral line strengths as function of temperature and stellar type ([102]). Spectral lines dominate according to the dependence with temperature of electron degeneracy 
\( n_e \lambda^3(T) \ll 1 \) and to the species ionization potentials: \( \chi(\text{He II}) \simeq 54.4 \text{ eV} \), \( \chi(\text{He I}) \simeq 24.6 \text{ eV} \), \( \chi(\text{H I}) \simeq 13.6 \text{ eV} \) and \( \chi(\text{Ca II}) \simeq 11.8 \text{ eV} \).

The HR diagram is dominated by (i) the main sequence, (ii) the giant and supergiant branches, and (iii) the white dwarfs.

Stellar masses, derived usually in binary star systems, allow to derive the empirical mass-luminosity relation \( (L \propto M^4 \text{ for } M \gtrsim 1.0 \, M_{\odot}; L \propto M^{2.3} \text{ for } M \lesssim 0.5 \, M_{\odot}) \). The range in stellar masses takes two orders of magnitudes while the luminosity of a massive star is millions of times larger than that of a star less massive than the Sun. These basic properties of stars can be derived from stellar models based on the generation of energy through nuclear reactions. These models show that the main sequence corresponds to nuclear burning of hydrogen within stars.

2.2. Stellar structure

2.2.1. Basic equations

Stellar structure models aim at computing pressure, density and temperature profiles, \( P(r), \rho(r), T(r) \) of a star given its mass and chemical composition. Most models assume mass conservation, spherical symmetry and neglect rotation, although specific models are also built to study particular deviations, like stellar models with strong mass-loss or rapid rotation. Under the basic assumptions, the equations to solve are:

\[
\frac{dP}{dr} = -\rho g = -\rho \frac{GM(r)}{r^2} \rightarrow \text{hydrostatic equilibrium} \tag{9}
\]

\[
\rho = \frac{1}{4\pi r^2} \frac{dM}{dr} \rightarrow \text{mass conservation.} \tag{10}
\]

These first two equations have three unknowns, \( \{P(r), \rho(r), M(r)\} \), and can be solved when assuming a polytropic relation, \( P = K \rho^\gamma \). These were the first stellar models, and their solutions, found by solving the Lane-Emden equation, are still useful for certain applications.

More refined models require solving, mostly numerically, the full system of equations, including the temperature / energy equations. The equation of state, for a classical ideal gas
Figure 4. Some examples of Hertzsprung-Russell diagrams: upper left: temperature-luminosity relation from models of main sequence stars corresponding to stellar types from O5 to M8 [23]; lower left: observational color-magnitude diagram showing different regions of the HR diagram; location of main sequence stars (also from [23]); right: color-magnitude diagram for nearly 5000 nearby stars with measured parallaxes by Hipparcos ([101]).

including the effects of radiation,

\[ P = \frac{\rho k T}{\mu m_H} + \frac{4\sigma T^4}{3c} \quad \rightarrow \quad \text{equation of state}, \]  

where \( \mu \) is the mean molecular weight, \( m_H \) represents the a.m.u. and \( \sigma \) is the Stefan-Boltzmann constant. The chemical mass abundances, \( \{X,Y,Z\} \) for hydrogen, helium and the rest of the elements respectively, determine the mean molecular weight either for a neutral gas, \( \mu_n \), for an ionized gas, \( \mu_i \), or a mixture of both:

\[
\mu_n = \frac{\sum_j N_j A_j}{\sum_j N_j} \Rightarrow \frac{1}{\mu_n} = X + \frac{1}{4} Y + \left\langle \frac{1}{A} \right\rangle_n Z \quad \rightarrow \quad \text{neutral gas},
\]

\[
\mu_i = \frac{\sum N_j A_j}{\sum N_j (1 + z_j)} \Rightarrow \frac{1}{\mu_i} = 2X + \frac{3}{4} Y + \left\langle \frac{1 + Z}{A} \right\rangle_i Z \quad \rightarrow \quad \text{ionized gas},
\]

where \( A_j, N_j, z_j \) are the atomic mass, number of particles and number of electrons per nuclei for the atomic species \( j \). For solar abundances and normal conditions we can use \( <1/A>_n \simeq 1/15.5 \) and \( <1 + z/A>_i \simeq 1/2 \). The equation of state can be used together with a polytrope solution to provide an estimate of the temperature profile \( T(r) \), under the assumption that both relations are satisfied. Again, a proper stellar model requires solving the equations for energy transport.
2.2.2. Energy transport

The mechanisms of energy transport in stars are radiation and convection. Radiative energy transport follows the equation

\[ \frac{dT}{dr} = - \frac{3}{4ac} \bar{\kappa} \rho \frac{L(r)}{4\pi r^2}, \]

\( \to \) radiative transport \( (13) \)

where \( \bar{\kappa} \) is the Rosseland mean opacity, which can include bound-bound, bound-free, free-free and electron scattering processes, under the assumption of an optically thick medium. The case of optically thin stellar atmospheres requires a thorough treatment of the radiation transfer equation.

Energy is also transported by convection, which can usually be assumed adiabatic

\[ \frac{dT}{dr} = - \left( 1 - \frac{1}{\gamma} \right) \frac{\mu m_H GM(r)}{k r^2}, \]

\( \to \) convective transport \( (14) \)

As it could be expected, different transport mechanisms dominate different regions of the star.

2.2.3. Energy production and neutrino production

Last, but certainly not least, the generation of energy has to be considered. The energy production rate in stellar interiors is given by \( \varepsilon_{\text{nuc}} \), the energy released per gram per second by nuclear reactions,

\[ \frac{dL(r)}{dr} = 4\pi r^2 \rho \varepsilon_{\text{nuc}}(r) \]

\( \to \) energy production \( (15) \)

Nuclear reactions happen when particles can overcome the Coulomb barrier and become binded by the strong nuclear force. The neutrino producing weak force has an important role, as it permits the production of helium from hydrogen. The energy production reactions are fundamental in predicting the neutrino luminosity of stellar nuclei, which in the later stages of massive stars can be larger than the photon luminosity. \( \varepsilon_{\text{nuc}} \) must then include photon and neutrino energy.

The energy production rates \( \varepsilon_{\text{nuc}} \) can be found by considering how nuclei bind against electrostatic repulsion. The velocity distribution of nuclei can be described by a Maxwellian function with temperature well below the energies needed to join two charged nuclei against their electrostatic repulsion, as quantum tunnelling allows penetration of the Coulomb barrier by low energy particles. The product of the Maxwell-Boltzmann distribution and the quantum tunnelling penetration of the Coulomb barrier define the Gamow peak for the fusion of two nuclei of charges \( Z_1 e \) and \( Z_2 e \) and reduced mass \( m \) as

\[ E_g = \left( \frac{bkT}{2} \right)^{2/3}, \quad \text{where} \quad b = \frac{2^{3/2} \pi^2 m^{1/2} Z_1 Z_2 e^2}{h}. \]

\( (16) \)

For proton-proton collisions inside the Sun, \( Z_1 = Z_2 = 1, m = m_p/2 \) and \( T \approx 15 \times 10^6 \) K \( \Rightarrow E_g \approx 6 \) keV. The Gamow peak curve indicates that nuclear reactions occur optimally inside a narrow energy band, dependent on the temperature and composition of the gas (fig. 5). The rate itself is given by the area under the Gamow curve, which increases notoriously with temperature. As a consequence the structure of the star is heavily dependent on the nuclear processes included. The most important are:

- the proton-proton chains:
  Nuclear reactions to produce helium from hydrogen initiate with proton-proton collisions, leading to the first proton-proton chain (PP I):

\[ \frac{1}{2} \text{H} + \frac{1}{2} \text{H} \rightarrow \frac{1}{2} \text{H}^+ + \nu_e, \quad \frac{2}{3} \text{H} + \frac{1}{2} \text{H} \rightarrow \frac{2}{3} \text{He} + \gamma, \quad \frac{3}{2} \text{He} + \frac{3}{2} \text{He} \rightarrow \frac{4}{2} \text{He} + \frac{1}{2} \text{H} + \frac{1}{2} \text{H}. \]

\( (17) \)
The most basic nuclear process is the proton-proton collision leading to a deuterium nuclei. Protons have a rest mass of 938.272 MeV each and produce a deuterium of 1875.613 MeV plus a positron of 0.511 MeV plus a neutrino of insignificant mass. Ignoring the initial kinetic energy (≈ 6 keV in the Solar center), there is an energy excess of 0.420 MeV which goes into kinetic energy distributed among the three products of the reaction. While this is the maximum neutrino energy available in the PP I chain, the mean neutrino energy is about 260 keV.

Hydrogen nuclear burning can also proceed by a second chain (PP II) starting with the collision of helium-3 and helium-4 nuclei:

\[
\frac{3}{2}\text{He} + \frac{4}{2}\text{He} \rightarrow \frac{7}{4}\text{Be} + \gamma, \quad \frac{3}{4}\text{Be} + e^- \rightarrow \frac{7}{3}\text{Li} + \nu_e, \quad \frac{7}{3}\text{Li} + \frac{1}{1}\text{H} \rightarrow \frac{3}{2}\text{He} + \frac{4}{2}\text{He}. \quad (18)
\]

The beryllium to lithium weak decay produces neutrinos of either 0.861 MeV or 0.383 MeV, expected to manifest themselves as two thin lines in the solar neutrino spectrum.

The third PP chain can occur through collision of hydrogen and beryllium nuclei:

\[
\frac{7}{4}\text{Be} + \frac{1}{1}\text{H} \rightarrow \frac{8}{5}\text{B} + \gamma, \quad \frac{8}{5}\text{B} \rightarrow \frac{8}{4}\text{Be} + e^+ + \nu_e, \quad \frac{8}{4}\text{Be} \rightarrow \frac{3}{2}\text{He} + \frac{4}{2}\text{He}. \quad (19)
\]

The weak interaction of this PP III process is the boron decay which gives a continuum neutrino spectrum with energies up to ≲ 15 MeV.

In all three PP chains two electron neutrinos are produced together with each helium nuclei. However, the neutrino spectrum is particular of each reaction involved and the final spectrum depends on all the reactions involved, including the less important pep and hep reactions:

pep reaction: \[ \frac{1}{1}\text{H} + e^- + \frac{1}{1}\text{H} \rightarrow \frac{2}{2}\text{H} + \nu_e \quad (E_\nu = 1.442 \text{ MeV}) \]

hep reaction: \[ \frac{3}{2}\text{He} + \frac{1}{1}\text{H} \rightarrow \frac{2}{2}\text{He} + e^+ + \nu_e \quad (E_\nu \leq 18.77 \text{ MeV}) \]

The final spectrum is the superposition of all reactions, according to their rates. The particular case of the Sun will be shown in the next section.
The total energy generation rates can be written for nuclear reactions, with a factor $\eta_{\text{pp}}$ accounting for electron screening and other corrections. For the combined pp chain burning at a temperature $T_6 = T/10^6$ K, density $\rho$ and hydrogen mass fraction $X$, [23] give the expression:

$$\varepsilon_{\text{pp}} \simeq 2.38 \times 10^6 \text{erg s}^{-1} \text{g}^{-1} \eta_{\text{pp}} \rho X^2 T_6^{-2/3} e^{-33.80 T_6^{-1/3}}$$

which for $T \simeq 1.5 \times 10^7$ K can be expanded as $\varepsilon_{\text{pp}} \propto \rho X^2 T_6^4$.

- **neutrinos are still produced by electron capture and the star becomes dominated by neutrons.**

- **The CNO chain:**

  At temperatures high enough to overcome the Coulomb barriers of nuclei with larger repulsive charges, hydrogen burning can proceed through the CNO chain discovered by Hans Bethe in 1938 ([17]). The CNO cycle follows the sequence

  $$^{12}\text{C} + \frac{1}{4}\text{H} \rightarrow ^{13}\text{N} + \gamma, \quad ^{13}\text{N} \rightarrow ^{13}\text{C} + e^+ + \nu_e, \quad ^{12}\text{C} + \frac{1}{4}\text{H} \rightarrow ^{12}\text{N} + \gamma$$

  $$^{14}\text{N} + \frac{1}{4}\text{H} \rightarrow ^{15}\text{O} + \gamma, \quad ^{15}\text{O} \rightarrow ^{15}\text{N} + e^+ + \nu_e, \quad ^{15}\text{N} + \frac{1}{4}\text{H} \rightarrow ^{12}\text{C} + ^{4}\text{He},$$

  with two weak interaction processes, $\beta$-decays, giving neutrinos of energies below 1.2 MeV and 1.7 MeV respectively. There is a second CNO branch producing O rather than C in the last reaction, leading to production of $^{17}_8\text{F}$ or $^{18}_8\text{F}$, which can $\beta$-decay to $^{18}_7\text{O}$ or $^{18}_8\text{O}$, producing neutrinos of energies below 1.74 and 0.63 MeV respectively.

  The energy production rate for the entire CNO cycle is

  $$\varepsilon_{\text{cno}} \simeq 8.67 \times 10^{27} \text{erg s}^{-1} \text{g}^{-1} \eta_{\text{cno}} \rho X_{\text{cno}} T_6^{-2/3} e^{-152.2 T_6^{1/3}}$$

  where $X_{\text{cno}}$ represents the combined mass fraction of C, N and O. At $T \simeq 1.5 \times 10^7$ K, roughly the temperature where the CNO cycle overtakes the PP chain, this can be expanded as $\varepsilon_{\text{cno}} \propto \rho X_{\text{cno}} T_6^{19.9}$. At the solar interior the CNO cycle contributes to $\lesssim$ 8% of the energy production; it becomes dominant somewhere in the 1.2 to 1.5 M$_\odot$ range.

- **Helium burning:**

  Once massive stars have exhausted hydrogen, their nuclei contract, rising the pressure and temperature to the point of helium burning through the 3$\alpha$ process

  $$^4\text{He} + ^4\text{He} \leftrightarrow ^8\text{Be}, \quad ^8\text{Be} + ^4\text{He} \rightarrow ^{12}_6\text{C} + \gamma.$$  

  The reaction is a resonant three body collision of rate

  $$\varepsilon_{3\alpha} \simeq 5.09 \times 10^{11} \text{erg s}^{-1} \text{g}^{-1} \eta_{3\alpha} \rho^2 Y^3 T_8^{-3} e^{-44.03 T_8^{-1}}$$

  where $Y$ is the helium mass fraction; this expression which can be expanded close to the optimum temperature, $T \simeq 10^8$ K, as $\varepsilon_{3\alpha} \propto \rho^2 Y^3 T_8^{31}$, showing its extreme dependence with temperature.

  If massive enough, stellar nuclei can undergo further nuclear reactions leading from C to O and Ne; further, rather violent, nucleosynthesis can follow until achieving the production of $^{56}_2\text{Fe}$, the most stable atomic nuclei. Stars producing iron in their nuclei eventually run into the iron catastrophe, which leads to the detonation of a supernova ([34]).

  At temperatures beyond those of the 3$\alpha$ regime, neutrino reactions become important due to the neutrino-electron coupling, $e^+ e^- \rightarrow \nu \bar{\nu}$ ([5]). Even if this reaction is much less probable than electron-positron annihilation, neutrinos escape so easily from stellar interiors that neutrino cooling overtakes photon cooling at about $5 \times 10^8$ K. At high temperatures and densities, electron capture followed by $\beta$-decay, so-called Urca process [37], becomes an important mechanism of neutrino production. When degeneracy becomes extreme, the $\beta$-decay channel is suppressed, neutrinos are still produced by electron capture and the star becomes dominated by neutrons.
2.2.4. The standard solar model and solar neutrinos

It is still somewhat surprising (at least for me) that stellar models can be built just specifying the stellar mass and composition. Stellar models predict large differences between evolution time-scales and parameters for different stellar masses in fairly good agreement with the observed properties of stars. The vintage review by Iben ([55]) still gives a fairly complete scenario of stellar evolution according to these models. The Sun is of particular interest for stellar models, not only because we can test the details of its structure, with techniques like helioseismology which provide insight into the inner structure of the Sun, but also due to the possibility of detecting neutrinos from the present day on-going nuclear reactions. While radiation diffuses through the Sun in very long time-scales, of the order of $10^5$ years, neutrinos from the Sun escape $R_\odot/c \simeq 2$ seconds after production. The study of solar neutrinos gives the only real-time diagnostic of the stellar interior.

The standard solar model is the solution of the equations shown in the previous section for a star with $M = 1 \, M_\odot$ and \{X = 0.73, Y = 0.25, Z = 0.02\}. An updated account of the status of solar neutrinos can be found in John Bahcall’s web page ([100]). Recent versions of the standard solar model use rather precise input abundances, like \{X = 0.7078, Y = 0.2734, Z = 0.0188\} in [13], in agreement with helioseismic data ([15]). Even thought some discrepancies between measured photospheric abundances and helioseismic data exist ([7, 8]), their effect on solar models and neutrino fluxes are small ([14]). In broad terms, the model predicts a core of $0.2R_\odot$, radiative energy transport up to $0.7R_\odot$, and a convective outer layer from there to the photosphere. Using the chemical production rates the evolution of the Sun can be modelled backwards or forwards, showing how its parameters have changed with time, as helium has built up in the inner core (Figure 6).

The flux of solar neutrinos, shown Table 2 is predicted with a relatively small degree of uncertainty, specially for well established PP branching ratios. The solar neutrino spectrum predicted is shown in Figure 7 (from [10, 100]), with the CNO cycle making up for less than 7.8% of the energy production in the Sun ([11]). The shape of the spectrum is relevant for assessing the detectability of solar neutrinos in different experiments. As it can be seen from Fig. 7, Gallium detectors detect PP, B and Be neutrinos; Chlorine experiments are sensitive to Be, B and pep neutrinos, while Čerenkov and heavy water detectors in practise can detect only B neutrinos. The rates predicted for each experiment are shown in Table 3. Except for...
Figure 7. Solar neutrino spectrum predicted by the standard solar model ([100]). Different solar neutrino experiments have different energy thresholds: Gallium $E \geq 0.23$ MeV; Chlorine $E \geq 0.81$ MeV and Čerenkov experiments $E \gtrsim 5$ MeV.

| Source | Termination | $\nu$ energy (MeV) | Flux (cm$^{-2}$ s$^{-1}$) | Cl SNU | Ga SNU |
|--------|-------------|---------------------|--------------------------|--------|--------|
| pp     | 100         | $\leq 0.42$         | $5.94 \times 10^{-10}(1 \pm 0.01)$ | 0.0    | 69.7   |
| pep    | 0.4         | 1.44                | $1.40 \times 10^{-8}(1 \pm 0.02)$ | 0.22   | 2.8    |
| hep    | $2 \times 10^{-5}$ | $\leq 18.8$     | $7.88 \times 10^{-3}(1 \pm 0.16)$ | 0.04   | 0.1    |
| $^7$Be | 15          | 0.38, 0.86          | $4.86 \times 10^{-9}(1 \pm 0.12)$ | 1.15   | 34.2   |
| $^8$B  | 0.02        | $\leq 15$           | $5.82 \times 10^{-6}(1 \pm 0.23)$ | 5.76   | 12.1   |
| $^{13}$N| –           | $\leq 1.2$          | $5.71 \times 10^{-8}(1 \pm 0.36)$ | 0.09   | 3.4    |
| $^{15}$O| –           | $\leq 1.7$          | $5.03 \times 10^{-8}(1 \pm 0.41)$ | 0.33   | 5.5    |
| $^{17}$F| –           | 0.63, 1.74          | $5.91 \times 10^{-6}(1 \pm 0.44)$ | 0.0    | 0.1    |
| Total  | 100         | ...                | ...                      | $8.5 \pm 1.8$ | $131^{+12}_{-10}$ |

Table 2. Standard solar model neutrino fluxes predicted from [13].

the Sudbury Neutrino Observatory, sensitive to neutral current reactions, all experiments report fluxes below the predictions.

The discrepancy between the measurements and the predictions started in the mid-60’s with the Homestake Cl experiments of Raymond Davis ([30, 31]), for two decades the only solar neutrino experiment in the world. The neutrino flux deficit, later confirmed with Kamiokande II, SAGE, GALLEX, lead to a conflict between the standard solar model and observations. The solution to this conflict has been the notion that neutrinos can change flavor, and the confirmation by the Sudbury Neutrino Observatory of neutrino data consistent with neutrino oscillations ([60]). This result has independently been confirmed by the reactor experiment KamLAND [34], with both results in concordance. A fundamental consequence of neutrino flavor oscillations is that neutrinos must posses mass.

According to neutrino oscillation models, neutrinos with mass can oscillate between their three flavors, $\nu_e$, $\nu_\mu$ and $\nu_\tau$, depending on their mass differences, $\Delta m^2$, and mixing angles,
| Experiment         | detector | Predicted (SNU or $10^6$ cm$^{-2}$s$^{-1}$) | Observed (SNU) |
|--------------------|----------|---------------------------------------------|----------------|
| Homestake          | Cl       | 8.5 ± 1.8 SNU                               | 2.5 ± 0.16 SNU |
| Gallex + Gallex NO | Ga       | 131 ± 11 SNU                                | 70.8 ± 4.5 SNU |
| SAGE               | Ga       | 131 ± 11 SNU                                | 70.9 ± 5.3 SNU |
| $^8$B-Kamiokande   | C        | 5.82(1 ± 0.23) SNU                          | 2.8 ± 0.19 SNU |
| $^8$B-Super Kamiokande | C       | 5.82(1 ± 0.23) SNU                          | 2.35 ± 0.02 SNU |
| Sudbury NO         | Č/CC     | 5.82(1 ± 0.23) SNU                          | 1.59 ± 0.08 SNU |
|                    | Č/NC     | 5.82(1 ± 0.23) SNU                          | 5.21 ± 0.27 SNU |

Table 3. Solar neutrino fluxes predicted and observed for different experiments, from [60]. Flux units are SNU when indicated and $10^6$ cm$^{-2}$s$^{-1}$ otherwise. Chemical and Čerenkov detectors are sensitive to e-neutrinos only, while the SNO experiment can study separately e-neutrinos (charged current reactions) and all neutrinos (neutral current reactions).

$\theta$. Neutrino oscillations can occur either in vacuum ([18]) or in matter, through the Mikheyev-Smirnov-Wolfenstein (MSW) effect ([92, 61]). As mass eigenstates propagate at different speeds, the relative phases between flavor and mass eigenstates vary, leading to oscillations in the neutrino flavor. The probability of an oscillation between two flavors 1 and 2 in vacuum is given by

$$P(\nu_1 \rightarrow \nu_2) = \sin^2(2\theta_{12}) \sin^2\left(\frac{2\pi x}{\ell_{\text{vac}}}\right),$$

where $\theta_{12}$ is the mixing angle between both types of neutrinos and the vacuum oscillation length is given by

$$\ell_{\text{vac}} = \frac{4\pi E h}{\Delta m_{12}^2 c^3} \approx 2.5 \, \text{m} \left(\frac{E}{\text{MeV}}\right) \left(\frac{\Delta m_{12}^2}{\text{eV}^2}\right)^{-1},$$

with $E$ the neutrino energy. MSW matter oscillations include the additional contribution of neutrino-electron scattering and can also be represented by an oscillation probability $P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2(2\theta_{m}) \sin^2\left(\frac{2\pi x}{\ell_{m}}\right)$, where the matter mixing angle $\theta_{m}$ and interaction length $\ell_{m}$ are dependent on the neutrino energy and the electron density ([62]). In both cases the parameters to optimize are the mass-squared differences and the mixing angles. The present best-fit values, as constrained by the solar and reactor data, are $\Delta m_{12}^2 = 7.3^{+0.4}_{-0.6} \times 10^{-5} \text{eV}^2$ and $\tan^2\theta_{12} = 0.41 \pm 0.05$. The lower limit to the mass of the heaviest neutrino is then $\approx 0.009 \text{eV}$. In the favoured scenario, the e-neutrino probability is expected to be a function of energy, with vacuum oscillations dominating below 2 MeV and matter oscillations dominating above. The existence of this transition can be tested with $^7$Be experiments ([13]).

3. The Galactic interstellar medium and its cosmic rays

The interstellar medium (ISM) plays an important role in the life of stars. Stars form from large ISM clouds, evolve and eventually expel most or all of their material to the ISM either through stellar winds or supernova explosions. Through this process stars inject energy and chemically enrich the ISM with heavy elements.

3.1. Gas and dust in the galaxy

ISM clouds were first found as dark obscuring clouds in astronomical plates then in absorption features in stellar spectra. The existence of a 2175 Å absorption feature suggest that graphite is a major constituent of interstellar dust [33]. Still, the most important constituent is gas, mainly hydrogen ($\sim 70\%$) and helium ($\sim 23\%$). Hydrogen is observed in different physical
phases: directly in neutral form (HI), through 21-cm observations; in ionized state, through Balmer emission in HII regions; or in molecular form, H$_2$, through iIR observations. Molecular hydrogen is difficult to observe and most its spatial distribution is inferred from millimeter observations using the CO molecule as a tracer. In short, the basic ISM components are

- **HII regions**: these are hydrogen clouds ionized by the presence of a hot massive star, able to provide enough UV photons. They distinguish themselves through prominent Balmer lines.
- **Diffuse HI clouds** contain some 1-100 M$_\odot$, have low temperatures 30 to 80 K and high densities 100 to 800 cm$^{-3}$.
- **Translucent molecular clouds** are similar to diffuse HI clouds, both in mass (3-100 M$_\odot$) and sizes (several pc across) but are cooler (15 to 50 K) and denser (500 to 8000 cm$^{-3}$).
- **Giant molecular clouds** are the largest members of the ISM (up to $\approx 10^6$ M$_\odot$ within $r \gtrsim 50$ pc). Typical temperatures are around 20 K, and densities of 100 to 300 cm$^{-3}$.
- **The cores of GMCs** are hotter (100 to 200 K), much more dense ($10^7$ to $10^9$ cm$^{-3}$) containing anything between 10 to 1000 M$_\odot$ inside 0.05 to 1 pc. They are believed to fragment and evolve into stellar clusters.
- **Bok globules** are cold (10 K), dense ($n > 10^4$ cm$^{-3}$) and fairly large (1-1000 M$_\odot$, 1 pc) very dark regions, harbouring young stars in their centers.

These clouds are notorious part of the ISM, interacting not only with dying and forming stars, but also with the invisible members of the ISM: magnetic fields and cosmic rays.

### 3.2. Magnetic fields and cosmic rays

The interstellar magnetic field has been known for several decades ([52, 49]). It can be measured either through Zeeman splitting of the 21-cm line ([85]) or the rotation measure of the polarization vector in the line of sight of pulsars ([48]). Its typical value is around 3$\mu$Gauss, with large scale and random components of comparable magnitude. Magnetic fields are an important component of the ISM as they couple with matter, affecting its motion, and deflect cosmic rays. The ISM gas, magnetic field and cosmic rays are considered to be in pressure equilibrium

$$\frac{d}{dz} (P_{\text{gas}} + P_B + P_{\text{cr}}) = \rho_{\text{gas}} g_z,$$

where $g$ represents the gravity perpendicular to the Galactic plane, caused by the mass inside stars and gas, acting on the gas mass density $\rho_{\text{gas}}$. The individual components appear to be in a state of pressure / energy density equipartition, $P_{\text{gas}} \approx P_B \approx P_{\text{cr}}$. An interesting loose end is the equipartition of their energy density with that of the Cosmic Microwave Background (CMB).

The main properties of Galactic cosmic rays, briefly outlined here, are review in more detail in [32, 38]. As mentioned before, cosmic rays (CRs) are composed of 99% nuclei and 1% electrons. Heavy nuclei are more abundant in CRs than in the solar neighborhood. In particular elements like {Li, Be, B} and {Sc, V, Ti}, scarcely produced in stellar interiors, are produced in the ISM by spallation of C/O and Fe, becoming a notorious CR component. These secondaries species have steeper spectra than their primary parents. The interpretation is that low energy cosmic rays stay longer in the Galaxy and have a higher probability of interaction; therefore low energy secondaries are created more often than high energy secondaries. Given the cross section for spallation, equivalent to a mass column of 5 to 10 g cm$^{-2}$, a path of 1000 kpc is needed, much larger than the dimensions of the Galaxy. Cosmic rays wander around in the
Galaxy until diffusing out of it. In the “leaky box” model the abundance of a long lived species can be approximated by

\[ N(E, t) = N_0(E)e^{-t/\tau_{esc}}, \quad \tau_{esc} \simeq 6.8 \times 10^6 \text{ years} \left( \frac{n}{1 \text{ cm}^{-3}} \right)^{-1} \left( \frac{E/Z}{4 \text{ GeV}} \right)^{-0.6}, \]  

(28)

where \( n \) is the mean ISM density and the rigidity \((E/Z)\) dependence is to agree with the observed CR spectrum and an injection spectrum \(N_0(E) \propto E^{-2.1}\), concordant with shock acceleration models. Analysis of the CR spectrum of the radioactive species \(^{10}\)Be, which has a lifetime of 3.9 Myrs, provides the reference value of a few \(10^6\) years ([38, 39]).

The CR energy spectrum follows a broken power-law, \(dN/dE \propto E^{-k}\) with the spectral index \(k = 2.7\) for \(E \lesssim 5 \times 10^{15}\) eV (the ”knee”) and \(k = 3.0\) up to at least \(5 \times 10^{18}\) eV (the ”ankle”). There is evidence for another spectral change from the ankle to the highest energies observed, \(10^{20.5}\) eV. This result is still somewhat controversial but is expected to be confirmed with the Auger array, larger by an order and a half of magnitude than any previous cosmic ray experiment ([27]). The total energy density within cosmic rays is difficult to estimate because most of the energy is in the < \(\sim 1\) GeV CRs, which has a large solar modulation. Accounting for solar modulation, the inferred CR energy density is about \(1\) eV/cm\(^3\). Considering the typical escape times and the volume of the Galaxy \((V_{gal} \sim 10^{67}\) cm\(^3\)), the source(s) of cosmic rays must be able to provide

\[ \frac{u_{cr} V_{gal}}{\tau} \approx 2 \times 10^{40} \text{ erg s}^{-1}, \]  

(29)
in the form of high energy nuclei -of course.

Cosmic rays propagate in the Galaxy steered by magnetic fields. The typical gyration radius of a charged particle of energy \(E\) and charge \(q = Z e\) in the Galactic magnetic field is

\[ a \approx \frac{(E/q\mathcal{B}) \sin \alpha}{0.36 \text{ pc}} \left( \frac{E}{\text{TeV}} \right) \left( \frac{\mathcal{B}}{3 \mu\text{G}} \right)^{-1}, \]  

(30)

irrespective of the mass of the charged particle. CR electrons are less common because they radiate their energy rapidly, providing for the radio emission of our Galaxy, first found by Jansky in 1930. Synchrotron losses, negligible for protons, result in electrons radiating their energy in timescales given by

\[ \tau = \frac{3m_e^3c^5/2q^4}{\gamma B_{\perp}} \simeq 0.9 \times 10^6 \text{ years} \left( \frac{m}{m_e} \right)^4 \left( \frac{E}{\text{TeV}} \right)^{-1} \left( \frac{\mathcal{B}}{3 \mu\text{G}} \right)^{-2}. \]  

(31)

The electron spectrum inferred from the Galactic radio emission is \(n(E) \propto E^{-2.14}\) between 70 MeV and 1.2 GeV and \(n(E) \propto E^{-3.0}\) above.

Immune to radiative losses, protons and CR nuclei pervade the Galactic ISM, leading to the main component of the Galactic \(\gamma\) ray emission. This emission arises from collisions of CRs with ISM particles producing \(\pi^0\) which rapidly decay into two high energy photons. With the knowledge -or assumption- of CR density, related to star formation, one can infer the matter distribution in the Galaxy from the \(\gamma\) ray emission ([54]). This analysis is often combined with the distribution of CO to infer the conversion ratio between \(H_2\) and CO ([78]). Cosmic ray electrons contribute to a lower energy component of the Galactic \(\gamma\) ray emission through bremsstrahlung and a higher energy inverse Compton scattering component ([76]).

Cosmic rays below \(10^{15}\) eV are believed to be of Galactic origin, as supported by the difficulty to accelerate CRs above those energies in Galactic environments and by \(\gamma\) ray observations of nearby galaxies. The marginal EGRET detection of the Large Magellanic Cloud (LMC [75]), together with the non detections of the Small Magellanic Cloud (SMC), M31 and nearby
starbursts is consistent with the idea that CR density relates with star formation rate ([21]). The inference is that CRs of energies below $10^{15}$ eV are of local origin, with those observed at Earth being Galactic. The study of nearby normal, starburst and probably luminous infrared galaxies with GLAST will provide the opportunity to indirectly study their CR environment ([82]).

3.3. Galactic cosmic and gamma ray sources

Galactic cosmic ray sources are expected to be high energy $\gamma$ ray sources. The Third EGRET Catalog of celestial sources of photons with energies beyond 100 MeV identifies only pulsars as Galactic $\gamma$ ray sources. In particular normal stars, not even the Sun outside flaring activity, are sources of $\gamma$ rays ([83]). While EGRET detected only half a dozen pulsars, a larger population of about a hundred unidentified sources clearly shows a Galactic distribution ([41]). All these $\gamma$ ray sources are certain sources of Galactic cosmic rays.

3.3.1. Pulsars

Pulsars are the only proven population of Galactic $\gamma$ ray sources. In fact they have long been known to be particle accelerators: the lifetime of high energy electrons emitting optical photons in the Crab nebula (M1) is less than 180 years ([64]), less than the nebula age. X ray emitting electrons in M1 live less than 10 years. Therefore, in order to keep the nebula shining through synchrotron radiation, the pulsar must be supplying high energy electrons. Leptonic $e^\pm$ models can explain the $\gamma$ ray characteristics of pulsars, without requiring proton and nuclei acceleration. The spectrum of the Crab pulsar can be well modelled with a synchrotron and a curvature component (models predict a missing inverse Compton component) while the Crab nebula spectrum is well fitted with synchrotron and inverse Compton ([59]). Whether hadrons are produced is an open question, as these can leave the pulsar environment without radiating significantly or leaving the signature of $\pi^0$ production.

Young rotating neutron stars have an important reservoir of energy in their large spin-down losses. A rotating neutron star of moment of inertia $I$ loses rotational energy at a rate

$$\dot{E}_{\text{rot}} = 4\pi I^2 \dot{P}/P^3 \approx 4 \times 10^{34} \text{ erg/s} \left( \frac{P}{100 \text{ ms}} \right)^{-3} \left( \frac{\dot{P}}{10^{-15}} \right).$$

(32)

About 1500 pulsars are currently known [67]. Those within our Galaxy have an integrated rotational energy loss of about $6.8 \times 10^{38}$ erg/s, with the Crab pulsar contributing to more than half of it. Because pulsar radio emission is significantly beamed, the total population is believed to be a factor of 30 to 100 larger, and can potentially provide the energy required in eq.29. However this requires most of the energy going into high energy protons and nuclei.

Particle acceleration in rapidly rotating neutron stars occurs through potentials induced by the combination of rotation and magnetic field. In the case of vacuum the potential drop available would achieve

$$\Phi_{\text{vac}} \simeq \frac{R_\ast^3 B_\ast \Omega^2}{c^2} \simeq 4.4 \times 10^{16} \text{ Volts} \left( \frac{B}{3.8 \times 10^{12} \text{G}} \right) \left( \frac{P}{33 \text{ ms}} \right)^{-2},$$

(33)

using the numbers for the Crab pulsar. This is an upper limit: pulsar magnetospheres are believed to be filled with an $e^\pm$ plasma which tends to short-circuit any electric field. Particle acceleration takes place either close to the magnetic pole (“polar cap models”) or in outer gaps, where the charge density vanishes and the electric field is not completely cancelled (“outer gap model”). As a result the allowed potential drops are expected to be at least a couple of orders of magnitude lower than $\Phi_{\text{vac}}$ and particles are hardly able to achieve $10^{15}$ eV.

3.3.2. Galactic compact accelerators

Most unidentified EGRET sources are distributed along the Galactic plane -as young pulsars- or forming an halo around the Galactic center, defining
two populations of objects [40]. The predominant idea is that these objects might be related to radio-quiet pulsars, separated in young pulsars along the Galactic plane and older pulsars, even millisecond pulsars, forming an halo around the Galactic center ([45]).

Magnetars, like soft gamma ray repeaters, can also be considered as particle accelerators. The difference between magnetars and pulsars resides in that magnetar activity is based on the release of magnetic energy instead of rotational energy. Magnetars stored magnetic energy is of the order of \( \sim B_2 R_3 = 10^{48} \text{ erg} \left( B/10^{15} \text{ G} \right)^2 \left( R/10 \text{ km} \right)^3 \). The recent and spectacular giant flare of SGR 1806–20, is to become a reference for these events [69]. The estimated energy release was \( \gtrsim 3 \times 10^{44} \text{ erg} \), most of it in midly relativistic material [43]. The required Galactic rate for these events, of a few hundred per day, is unlikely to be met.

Gamma ray bursts are believed to be SN like events where the initial ejecta is a highly collimated and relativistic outflow and the emission is accordingly beamed. The total energy released is of the same order of magnitude as that of SNe, so these events can be included in that category (§3.3.3). Short duration GRBs are believed to be a different type of events, namely degenerate star mergers. Neutron star mergers are likely to release close to \( 10^{53} \text{ erg} \). The rate of these events in our galaxy is unknown, but a few objects with merger times of \( 10^8 \) years are known in the Milky Way; one would require mergers to occur every \( 10^4 \) years in order to be able to contribute significantly to the Galactic cosmic rays.

As summarized in [84], objects not related to neutron stars can be \( \gamma \) ray sources and, therefore, cosmic ray accelerators. These include massive stars with powerful winds, and microquasars, associated to black-hole systems. Although no detailed study has been carried out concerning their contribution to the Galactic cosmic rays both types of objects are unlikely to provide the required energetics.

3.3.3. Shock acceleration at supernovae remnants Other possible sources of cosmic rays are inferred from circumstancial evidence, with the basic requirement of being a potential particle accelerator. Since Fermi showed in 1949 ([36]) that shocks can accelerate charged particles producing a power-law spectrum, these became the preferred cosmic ray production mechanism. The mechanism proposed by Fermi, often referred to as second order Fermi shock acceleration, involves many encounters between the particle and a scattering entity (a magnetic mirror), where the particle might earn or lose energy on each encounter but ends up with a net energy gain. Much of the elegance of this mechanism is to naturally lead to a \( N(E) \propto E^{-k} \) spectrum with \( k > 2 \). A review on astrophysical particle acceleration can be found in [20].

Supernovae remnants have long been the most popular provider of shoks, as they have an expanding shock front and inject \( E_{sn} \sim 10^{51} \text{ erg} \) to the ISM every \( \Delta t_{sn} \lesssim 30 \text{ years} \), satisfying with ease the energetic requirements of cosmic rays,

\[
\frac{E_{sn}}{\Delta t_{sn}} \gtrsim 10^{42} \text{ erg s}^{-1} \gg \frac{u_{cr} V_{gal} \tau}{\tau}.
\]

More recently, the X ray emission of the remnant of SN 1006 has been interpreted as synchrotron emission by \( 10^{15} \) eV electrons. Most of the X-rays observed are in the rims of the nearly circular nebula, suggesting that particle acceleration does take place in the SNR front shock ([58]).

However the low level of supportive clear GeV and TeV detections of SNRs is a source of concern ([51]). SNR have been tentatively association with EGRET sources ([79]), but the limited sensitivity and spatial resolution of EGRET does not allow to discard a neutron star origin for these \( \gamma \) ray sources. GLAST observations are likely to shown the emission to be extended and finally establish SNR as \( \gamma \) ray sources. Čerenkov telescopes have reported TeV emission from some SNRs, like Cas A ([2]) and SN 1006 ([80]), with hadronic models providing fairly good fits to the data. The ultimate evidence for hadronic acceleration would come from a \( \pi^0 \) signature, only present if hadrons interact within the SNR region.
3.3.4. Extended Galactic accelerators Giant molecular clouds (GMC) were the original cosmic ray accelerator proposed by Fermi, with SNR becoming the preferred option. Fermi conceived the collision of charged particles with magnetic mirrors inside GMCs as the mechanism for particle acceleration. The CR energy would then come at the expense of the kinetic energy of these clouds. A GMC of 100 M⊙ moving at 30 km/s has a kinetic energy of the order of $Mv^2 \sim 3 \times 10^{48}$ erg and there might be as much as $10^{54}$ erg of energy in this form.

Within the Galactic scales, the Galaxy itself could be the largest particle accelerator. This might be an attractive option for CR with energies between the knee and the ankle, i.e. above $10^{15}$ eV, as a large Larmor radius is required to attain high energies. Models for cosmic ray acceleration have included the Galactic disk [56], apparently limited in the particle energies reachable, and the Galactic wind [57], with better possibility to reach up to $10^{17}$ eV in its termination shock [86].

4. High-energy cosmic rays, stellar explosions and neutrinos in the local universe

Leaving the Galactic scenario, I proceed to review the highest energy cosmic rays before returning to topics related to stellar evolution, to consider supernovae events and neutrino production.

4.1. The highest energy cosmic rays

As mentioned in the previous section, the sources of cosmic rays with energies above some $10^{15}$ eV are uncertain. Without getting into the details of the acceleration process, one can set some basic physical limits on the properties of the sources of the highest energy cosmic rays. Hillas first pointed out ([50]) that in an acceleration process involving an induced electric field of the form $\vec{E} = \vec{\beta} \times \vec{B}$ where $\beta c$ is the speed of the inductor -the rotational speed of a neutron star for example-, the maximum energy gain that can be expected in a region of dimension $L$ is

$$E_{\text{max}} \approx q \Phi \approx ZeL\beta B,$$  \hspace{1cm} (35)
where \( q = Z e \) is the charge of the particle and \( B \) the magnetic field in the accelerator. Setting \( E_{\text{max}} = 10^{20} \text{ eV} \) one can draw the lines of \( B \propto 1/L \) below which such particle energy cannot be attained. The resulting plot, often called "Hillas plot" is shown in Figure 8. The perturbing feature is the absence of known celestial objects above the line, even allowing for induction at relativistic speeds, \( \beta \approx 1 \). Recent versions of this diagram leave only AGN and the lobes of radio galaxies as potential sources of the highest energy cosmic rays ([88]). In this respect, the fact that Centaurus A, the nearest radio galaxy, was almost certainly detected by EGRET as a high energy \( \gamma \)-ray source is significant.

A particular class of AGNs were found to be \( \gamma \) ray sources. These are radio loud flat spectrum objects, in particular blazars ([68]). They present superluminal motions and particle acceleration is believed to occur in relativistic jets beamed towards us. Objects like 3C 279 present extreme variability and are good candidates to produce high energy hadrons. Between 66 and 100 of these objects were included in the Third EGRET Catalog of high energy sources [47]. Only the closest of these EGRET sources were detected with TeV Čerenkov telescopes. This observations can be explained considering the absorption of TeV photons by pair production with a background photon. As a first consideration, interaction with CMB photons would severely affect high energy \( \gamma \)-rays of energies \( 10^{15} \text{ eV} \) (Figure 9), so that these cannot travel distances of more than 10 kpc. In fact photons between \( 10^{14} \) and \( 10^{19} \text{ eV} \) are severely constrained to come from \( \gamma \) ray sources within 1 Mpc. TeV photons are immune to the CMB but are affected by radiation from the diffuse infrared background, for which they satisfy the pair production criterion \( E_1 E_2 \gtrsim (mc^2)^2 \). The high energy observations of blazars made with EGRET and Čerenkov telescopes support this view, as only the two or three nearest EGRET blazars have been detected with Čerenkov telescopes ([24]). These observations are used to bound the unmeasured portions of the diffuse infrared background ([77]).

An analogous and more problematic situation occurs with cosmic rays above \( 10^{19} \text{ eV} \). In 1966, Greisen and Zatsepin & Kuzmin ([44, 94]) (GZK) independently showed that protons with energies above \( 3 \times 10^{19} \text{ eV} \) are prone to photopion production with CMB photons, \( p\gamma \rightarrow n\pi \). The cross section for this interaction reaches \( \sigma \gtrsim 5 \times 10^{-28} \text{ cm}^2 \) at \( \sqrt{s} \approx 320 \text{ MeV} \) ([63]). This means that a \( 10^{20} \text{ eV} \) proton will have maximum cross section with CMB photons of energies \( \sim (320 \text{ MeV})^2/10^{20} \text{ eV} \approx 10^{-3} \text{ eV} \). The number density of CMB photons at those frequencies is of the order of \( \nu n_{\nu} \sim 200 \text{ cm}^{-3} \), from where the mean free path for protons ends up to
be $\ell = (n\sigma)^{-1} \sim 3$ Mpc. A more precise calculation gives $\ell \approx 10$ Mpc. This process affects cosmic rays of energies above $3 \times 10^{19}$ eV, predicting a drop in the cosmic ray flux above those energies for distant sources. The real puzzle comes in that the present data does not provide evidence for the GZK cutoff. If anything, the CR flux appears to increase relative to a $E^{-3}$ spectrum (Figure 10). Three options have been considered: (1) ultra high energy cosmic rays (UHECRs) sources are located within $\sim 20$ Mpc of us; (2) GZK physics are wrong; (3) data are not yet conclusive. Option (2) is hard to support, as interaction cross sections come from accelerator measurements and are fairly well known. The third option is to be resolved within a few years, as the Auger observatory is already gathering data at the highest energies. will provide enough statistics to confirm or discard the GZK cutoff. As far as it seems, option (1) is unavoidable.

As discussed in terms of the arguments put forward by Hillas, it is already hard to find any object able to produce UHECRs. Nearby radio galaxies, like Centaurus A, are among the most favorable options. Gamma ray bursts have also been suggested as sources of cosmic rays from $10^{14}$ up to $\gtrsim 10^{20}$ eV [91]. At these energies the energetic requirements are less stringent than for Galactic cosmic rays, but all the GRBs known have occurred outside the boundary imposed by the GZK cutoff. Although [88] argues that gamma ray bursts may occur often enough in the local universe to account for the UHECRs, the issue remains open.

The difficulty of finding source of UHECR in the nearby universe has lead to the development of alternative production models, based on the decay of exotic particles with masses of the order of the grand unification energies, $\gtrsim 10^{13}$ GeV ([73]). These particles could be supermassive semi-stable relic with lifetime comparable to that of the universe, or even cosmic strings or magnetic monopoles produced during the inflation era ($\S 5.2$). Again, these have to decay into UHECRs within the local universe for the resulting cosmic rays to reach us unattenuated by the GZK cutoff.

### 4.2. Supernovae and neutrinos

Having addressed Galactic and extragalactic cosmic rays, we now return back to neutrino astronomy, outside the realm of the Milky Way. Low mass stars like the Sun develop an inert degenerate helium core, surrounded by a hydrogen burning shell and a very large low density envelope, becoming red giant stars. As the helium core becomes more massive it may reach the temperature and pressure conditions to undergo nuclear reactions. However, nuclear burning of degenerate matter is unstable and leads to a runaway explosive reaction, unless the energy released can lift the degeneracy. This is the case for stars like the Sun, where the degenerate core will burn in several flaring episodes, starting with the helium flash which releases very large amounts of energy just for a few seconds. The final result of the succession of unstable energy
release events is blowing the outer layers of the star, leaving a helium rich white dwarf.

More massive stars, initially above 2.3 \( M_\odot \) get a non degenerate helium core with stable \( 3\alpha \) reactions leading to a carbon-oxygen core. The structure of the star is the CO degenerate core, surrounded by a He burning shell, surrounded by an inert He layer, surrounded by a H burning shell, surrounded by a tenous envelope, the whole forming a red giant or supergiant. Eventually the CO core might end up as a CO white dwarf and/or acquire enough mass, just about the Chandrasekhar limit, to undergo catastrophic explosive burning and become a type Ia supernova. In binary systems the CO white dwarf might accrete the required mass from a companion filling its Roche lobe.

Stars with masses initially above 8 \( M_\odot \) develop a non degenerate CO core which eventually burns into Ne, Mg, Na, ... up to the formation of Fe. The core of these stars have temperatures above \( 5 \times 10^8 \) K where neutrino cooling is more important than photon cooling (§2). These stars develop an onion-like structure with an inert iron core at the center surrounded by a burning silicon shell, surrounded by an inert Si shell, surrounded by a burning oxygen shell, etc... In the last few hundred years of the star the neutrino luminosity exceeds the photon luminosity, up to a factor of \( L_\nu/L_{\text{opt}} \sim 10^7 \) during the extremely short lived Si burning stage. The reactions arrive to a dead-end, where no further energy can be produced. The last stages of the massive stellar evolution involve also iron photodisintegration reactions

\[
\frac{56}{26}\text{Fe} + \gamma \rightarrow 13\left(\frac{4}{2}\text{He}\right) + 4n \\
\frac{3}{2}\text{He} + \gamma \rightarrow \frac{1}{2}\text{H} + \frac{1}{2}\text{H} + 2n
\]

(36)

| Fuel | \( \rho_c \) (g cm\(^{-3}\)) | \( T_c \) (10\(^9\) K) | \( \tau \) (years) | \( L_{\text{phot}} \) (erg s\(^{-1}\)) | \( L_\nu \) (erg s\(^{-1}\)) |
|------|----------------|----------------|----------------|----------------|----------------|
| H    | 5.6           | 0.040          | \( 10.0 \times 10^6 \) | \( 2.7 \times 10^{38} \) | \( < 10^{36} \) |
| He   | 940           | 0.19           | \( 0.95 \times 10^6 \) | \( 5.3 \times 10^{38} \) | \( 7.4 \times 10^{39} \) |
| C    | \( 2.7 \times 10^5 \) | 0.81          | 300            | \( 4.3 \times 10^{38} \) | \( 1.2 \times 10^{43} \) |
| Ne   | \( 4.0 \times 10^6 \) | 1.7           | 0.38           | \( 4.4 \times 10^{38} \) | \( 7.4 \times 10^{43} \) |
| O    | \( 6.0 \times 10^6 \) | 2.1           | 0.50           | \( 4.4 \times 10^{38} \) | \( 7.4 \times 10^{43} \) |
| Si   | \( 4.9 \times 10^7 \) | 3.7           | 2 days         | \( 4.4 \times 10^{38} \) | \( 3.1 \times 10^{45} \) |

Table 4. Burning stages in the evolution of a 20 \( M_\odot \) star; from [6]
and electron capture,

\[ p + e^- \rightarrow n + \nu_e \]

producing neutrons and neutrinos. The neutron rich core is left to fall onto itself, becoming an over-compressed degenerate neutron star, which bounces out to create a shock wave which burns all the outer material, creating a supernova explosion. The actual bounce is in fact stalled by the infalling material; neutrinos, for once in an optically thick regime, provide the energy to push the infalling matter out and continue the delayed outward shock.

4.3. SN 1987A neutrinos and neutrino properties

In February 23.316, 1987, the brightest supernova in 383 years was observed. The wealth of information regarding SN 1987A is certainly beyond the scope of these notes. The early review by [6] gives most of the characteristics of this event. Among the most intriguing fact was that the precursor turned out to be a blue supergiant star, instead of a red giant. The event was a factor of ten underluminous, reaching an absolute magnitude \( M = -15.5 \) instead of the standard \( M = -18 \) typical of type II supernovae -defined by the presence of hydrogen lines. The expansion velocities first measured were particularly large, up to 30,000 km/s.

SN1987A remains the only supernova event for which neutrinos have been observed. Neutrino events were detected at least two experiments, Kamiokande II ([53]) and IMB ([19]), with a controversial third report by the Baksan detector ([4]). Kamiokande recorded 12 neutrinos, the first 9 within 2 seconds, followed by three events between 9 and 12 seconds after the initial one. IMB recorded 8 events, 6 within 2.68 s and two more about 5 s after the initial event (Figure 12). These events are the first observational evidence of neutron star formation. A trend of decreasing energy with time is observed, specially in the IMB data. According to the SN 1987A models two neutrino emissions are expected: first a short (20 ms) emission from...
neutrinos produced in the bounce of the neutron star; then a more intense neutrino emission, lasting several seconds, due to the cooling of the newly formed star. The SN 1987A data are consistent with this thermal emission, with an initial temperature of about 4.2 MeV decaying exponentially with a characteristic time of 4.5 seconds. The total neutrino emission calculated was about $6 \times 10^{52}$ erg, in good agreement with previous theoretical wisdom.

The SN 1987A event allowed to set physical limits on the neutrino properties. The neutrino mass had to satisfy $m_\nu \leq 16 \text{ eV}$ in order to account for the small time differences between neutrinos observed with different energies. The electric charge had to be $\leq 3 \times 10^{-17} \text{ e}$ in order for the different energy neutrinos to keep the same paths. Finally, the lifetime of neutrinos at rest, $\tau_0$, was found to comply with $\tau_0 \geq 5 \times 10^5 \text{ s} (m_\nu/1 \text{ eV})$.

5. Particles and cosmology

5.1. The composition of the universe

Until now we have dealt with neutrinos, protons, nuclei, electrons, all of them common-day baryons and leptons. However in the last decades evidence has built around the notion that baryonic matter constitutes only a small fraction of the matter in the universe.

Jan Oort was the first to introduce the notion of dark matter when he showed that the density of stars (0.064 M$_{\odot}$ pc$^{-3}$) and gas (0.024 M$_{\odot}$ pc$^{-3}$) in the Solar neighborhood was below the value needed (0.15 M$_{\odot}$ pc$^{-3}$) to account for the gravity component perpendicular to the Galactic plane ([65]). This indicated that more mass is present than inferred from visible light, as expressed by the mass-to-light ratio, $M/L \geq 2.4$ given by the analysis made by Oort. The study of the rotation curves of spiral galaxies has shown the existence of dark haloes beyond the observable stars. From its rotation curve, one can estimate that 70% to 90% of the mass of the Milky Way resides in its halo ([25]). This finding triggered the search for massive compact halo objects (MACHOs) through sudden gravitational microlensing of background stars. In 1993 Alcock et al. ([3]) reported the first observation of a microlensing event of a star in the LMC. Although microlensing events appear to be too few to account for the mass of the Galactic halo, they proved the existence of MACHOs which are commonly believed to be extremely dim objects related to stars, like old white dwarves, red dwarves, neutron stars, isolated black holes...

Much of the evidence in favor of dark matter resides in the dynamics of galaxies and clusters of galaxies. The measured $M/L$ values range from 50 to 80 in the Milky Way neighborhood to $M/L \approx 400$ to 700 in clusters like Coma. Other data concur with the notion of dark matter: the extended X ray halo of the giants elliptical galaxy M 87 indicates a total mass of the order of 2 to $4 \times 10^{13}$ M$_{\odot}$ within 300 kpc ([35]), indicating $M/L \approx 750$. Current large scale surveys, like the Sloan Digitized Sky Survey (SDSS, [99]) are gathering data of millions of objects, probing the large scale structure of the universe. The total density of matter in the universe, as measured through gravitational means is $\Omega = \rho/\rho_{\text{crit}} \approx 0.3$, where $\rho_{\text{crit}} = 3H_0^2/8\pi G \approx 10^{-29}$ g cm$^{-3}$ is the critical density required for a closed universe ($H_0$ is the Hubble constant).

By now it is well established that luminous matter is the exception, not the rule, in the universe. Still, dynamical evidence does not lead to the belief that this matter has to be different from normal matter. The most important evidence for the existence of non baryonic dark matter comes from the abundances of light elements compared to the predictions of primordial nucleosynthesis models. Most of the $^4\text{He}$ formed in the early universe, when temperatures were high enough to sustain nucleosynthesis. Other notorious light species were created when the universe was three minutes old, namely deuterium, helium-3 and lithium-7. The abundances of these nuclei depend crucially on the past (and therefore present) baryon density, $\Omega_b$. Primordial nucleosynthesis models indicate that $\Omega_b h^2 = 0.022 \pm 0.001$ ([87, 28]). This result, when combined with $\Omega \approx 0.3$, indicates that less than 10% of matter is baryonic. The matter content of the universe is dominated by non baryonic dark matter. Simulations of the formation of large scale structures in the universe favor the presence of non baryonic cold dark matter, where the term...
cold denotes non relativistic particles ([26]).

More recently, data from high redshift supernovae ([70, 66]) have indicated that the universe expansion is accelerating, leading to the need of a cosmological constant within the standard model. The present favored model for the universe, consistent with supernovae, CMB experiments like WMAP ([16]) and the Sloan Digitized Sky Survey ([81]), indicates that the total density of the universe is \( \Omega = 1.02 \pm 0.02 \), with the most important contribution being the cosmological constant -often referred as “dark energy”- with \( \Omega_\Lambda \simeq 0.73 \), non baryonic dark matter, \( \Omega_{nb} \simeq 0.23 \), and baryonic dark matter, \( \Omega_\Lambda \simeq 0.04 \). The fact that all the data are consistent with the standard cosmological model, together with the tight determination of the cosmological parameters has lead to the concept of “concordance cosmology” ([74]).

5.2. Dark matter particle candidates
The most natural cosmological issue for astroparticle physics is the nature of dark matter (DM). A good review of this problem can be found in [42], which is the basis of the following discussion. At present we do not know any particle that could constitute dark matter. In order to make some progress particles can be separated in broad classifications, the most natural being hot or cold DM particles, and thermal relics/non-relics, where a thermal relic is a particle left-over from the big bang. [42] uses a more subjective -but rather useful- classification, separating DM candidates as (1) known, (2) tentative, (3) speculative.

5.2.1. Known particles The main candidate is the neutrino. The combination of solar and laboratory neutrino data indicate that the heaviest neutrino has a mass somewhere in the interval \( 0.05 \text{ eV} \leq m_\nu \leq 2.8 \text{ eV} \). Concordance cosmology constraints the number density of neutrinos, from where one can find the upper limit to their contribution as dark matter, \( \Omega \leq 0.0076 \). Neutrinos cannot provide enough mass to account for dark matter. Furthermore, they are a hot form of dark matter which is disfavored relative to cold dark matter by large scale structure simulations ([26]). With neutrinos discarded the list of known particles as DM candidates is done.

5.2.2. Tentative candidates These are particles proposed within other problems of particle physics which could also account for dark matter. The three main candidates discussed in [42] are heavy active neutrinos, neutralinos and axions. The first two are examples of weakly interacting massive particles (WIMPs), which could have been in thermal equilibrium with other particles in the early universe -thermal relics. Thermal WIMPs decoupled from each other once their annihilation rate dropped below the expansion rate of the universe, giving the condition

\[
\Omega_w h^2 \simeq 3 \times 10^{-27} \text{ cm}^3\text{s}^{-1} \langle \sigma v \rangle^{-1},
\]  

where \( \sigma \) is the WIMP annihilation cross-section, \( v \) the relative speed between WIMPs and \( \Omega_w \) their density. This relation indicates that less interactive thermal relics (low \( \sigma \)) must be more numerous (high \( \Omega_w \)) and viceversa.

(i) Heavy neutrinos could exist within a fourth group of Standard Model of Particle Physics (SMPP, to distinguish it from the Cosmological Standard Model). Depending on their mass, heavy neutrinos can be underabundant (\( \Omega_{h\nu} \lesssim 0.01 \)), overabundant (\( \Omega_{h\nu} \geq 1 \)) or in the right proportion. This condition defines two useful mass ranges for the heavy neutrino, \( 1 \text{ eV} \leq m_{h\nu} \leq 20 \text{ eV} \) and \( 0.3 \text{ GeV} \leq m_{h\nu} \leq 10 \text{ GeV} \). The lower mass interval has the disadvantage of corresponding to hot DM, disfavored by structure formation simulations and concordance cosmological parameters; neutrinos in the upper mass interval are excluded by accelerator measurements.
(ii) neutralinos are the lightest particle in supersymmetric extensions of the SMPP. It is a stable and weakly interactive particle by construction. Its relic density depends on its cross section, which itself depends on its mass. It is not possible to provide meaningful bounds to the neutralino mass within particle physics, without fixing before the parameters of the extended SMPP. At present cosmological bounds, under the assumption that the neutralino can be the main DM particle, are used to tune the extended SMPP.

(iii) axions were proposed to explain charge-parity violations which are in conflict with measurements of the dipole moment of the neutron. Axions are non thermal relics which might be produced by the decay of cosmic strings. They are produced as cold particles with small masses, between 1 $\mu$eV and 1 meV, numerous enough to be good DM candidates. They are predicted to couple with photons and, as a consequence, being in principle detectable experimentally. On-going experiments should confirm or discard axions as DM in the near future.

5.2.3. Speculative candidates This category includes any particle postulated, included some put forward to solve the DM problem itself. These include self interactive dark matter particles, proposed to reconcile structure formation simulations with observations, and which have almost been ruled out as DM.

Another notorious example are WIMPZILLAs, very massive ($\sim 10^{13}$ GeV) relics from the big bang. WIMPZILLAs could have been produced at the end of inflation, would be fairly stable, with lifetimes comparable to the age of the universe, leading to the speculative but attractive possibility of decaying into high energy cosmic rays above the GZK limit.

Acknowledgments
I would like to thank the Sociedad Mexicana de Física, and in particular the organizers of the XI Mexican School of Particles and Fields for the invitation to give the Astroparticle Physics course during this Summer School. The venue of the Museo Nacional de Antropología in Xalapa was magnificent.

This review and research work made use of NASA’s Astrophysics Data System.

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