Physics and Astroparticle Physics – A. A. 2019-2020

(6 c.f.u, 60 hours of lessons and exercises) – Preliminary program

- Introduction to Cosmic rays Physics.
- Complementarity between the study of Cosmic Rays events/properties and elementary particle physics at accelerators.
- Differential energy flux and mass composition of primary Cosmic Rays. Flux of "secondary C. R." due to the interaction of primary C. R.
- The origin of Ultra High Energy Cosmic Rays, the possible acceleration mechanisms, first and second order Fermi acceleration mechanism.
- Experimental techniques for the observation/study of primary Cosmic Ray fluxes (protons, photons, heavy nuclei, neutrinos) up to energies >10^{22} eV: experiments in the space, in the atmosphere, at ground, deep underground.
- Open problems in particle and astroparticle physics: direct and indirect search for dark matter, matter-antimatter asymmetry, neutrino properties (DAMA, XENON, AMS, PAMELA, FERMI, DAMA, CUORE, IceCube, ANTARES, KM3NeT, ...)
- Astrophysics with High Energy photons: experimental techniques and results (HESS, MAGIC, VERITAS, CTA, LHAASO ...)
- Astrophysics with High Energy neutrinos (IceCube, ANTARES, KM3NeT, ...)
- Astrophysics with High Energy protons and nuclei (E>10^{17} eV): experimental techniques and results: AGASA, HiReS, Telescope Array, The Pierre Auger Observatory, TUNKA.
Basic Bibliography

• A. De Angelis and Mario Pimenta, Introduction to particle and astroparticle physics, Questions to the Universe, Springer, 2015
• Donald Perkins, "Particle Astrophysics" (Oxford University Press)
• H. V. Klapdor-Kleingrothaus, K. Zuber, "Particle Astrophysics" (Institute of Physics Publishing Bristol and Philadelphia)
• J. Cronin, Rev. Mod. Phys., 71 (1999) S165
• M. Lemoine and G. Sigl (Editors), Physics and Astrophysics of ultra high energy cosmic rays, Springer-Verlag Berlin and Heidelberg (2002).
• M. Nagano and A.A. Watson, Rev. Mod. Phys. 72 (2000) 689
Lessons 1 and 2

• Description of the course program and of the bibliography.
• Primary Cosmic Rays (C.R.) intensity, energy spectrum and composition.
• A power law can describe the C.R. energy spectrum.
• Energy density in C.R., in the Microwave Cosmic Background Radiation (MCBR), in the Galactic Magnetic field.
• C.R. composition: relative abundance of elements in the Earth (Solar System) and on the C.R..
• Propagation time of C.R. in our Galaxy.
The first instrument used to demonstrate the existence of C.R. was the “Gold-leaf electroscope” used by Victor Hess in 1911-1912:

From the observation that an electroscope, previously charged, loses its charge, it was already supposed the existence of a “radiation” originated “at Earth”. He observed that the discharge speed of the electroscope was decreasing for a distance from the ground up to 1 km, then was increasing with the height (up to 5.3 km):

⇒ this radiation was not due to processes on the ground but was penetrating the atmosphere from outer space. His discovery was confirmed by R.A. Millikan in 1925, who gave the radiation the name “Cosmic Rays”.

Fig. 2. Victor Hess (in the middle) and his crew in the balloon gondola after the landing in Pienia.
Cosmic Rays flux intensity

Let's define "directional intensity" of particles of a given type the number of particles that cross the surface $dA$, in the time $dt$ within a solid angle $d\Omega$:

$$I(\theta, \varphi) = \frac{dN}{dA \, dt \, d\Omega} \ [\text{part./cm}^{-2}\text{s}^{-1}\text{sr}^{-1}]$$

Often we refer to the energy integrated flux intensity.

It is defined "integrated intensity" (or "omnidirectional") the quantity

$$\phi = \int_{\varphi=0}^{2\pi} \int_{\theta=0}^{\pi/2} I(\theta, \varphi) \cos(\theta) d\Omega \ [\text{part./cm}^{-2}\text{s}^{-1}]$$

We also define $\bar{\phi}$ the number of particles that cross (down-going) the horizontal unit surface $dA$, in the unit time $dt$:

$$\bar{\phi} = \int_{\theta=0}^{\pi/2} \int_{\varphi=0}^{2\pi} I(\theta, \varphi) d\Omega = \int_{\theta=0}^{\pi/2} \int_{\varphi=0}^{2\pi} I(\theta, \varphi) \sin(\theta) d\theta d\varphi =$$

that gives

$$= 2\pi \int_{\theta=0}^{\pi/2} I(\theta) \sin(\theta) d\theta \ [\text{part./cm}^{-2}\text{s}^{-1}]$$

if the particles flux does is not varying with the azimuth angle.
Cosmic Rays energy spectrum

The differential energy spectrum $dN/dE$ has dimensions $[particles/(m^2 \ s \ sr \ GeV)]$.

Given the high variability of $N(E)$, as a function of $E$, is often preferred the quantity $dN/d(\log E)$.

But $d \log E = dE/E$ then

$$\frac{dN}{d \log E} = E \frac{dN}{dE} = E \phi(E) \ [particles/(m^2 \ s \ sr)].$$

All C.R. spectra show a fast decrease of the particles flux for increasing energy. As we will see the C.R. differential flux can be expressed by a power law:

$$\frac{dN}{dE} \propto E^\alpha$$

- $10 \ GeV < E < 1 \ PeV \ (10^{15} \ eV)$ \hspace{1cm} $\alpha = -2.7$
- $10 \ PeV < E < 1 \ EeV \ (10^{18} \ eV)$ \hspace{1cm} $\alpha = -3.1$
- $E > 10 \ EeV$ \hspace{1cm} $\alpha = -2.6$
Charged Cosmic Rays Energy spectrum

- ~ 1000 particles/(s·m²)
  “primary” Cosmic Rays:
    86% protons, 11% α particles, 1% heavier nuclei (up to Uranium), 2% electrons
  “secondary” Cosmic Rays (or atmospheric C.R.):
    $e^+, e^-, p, \bar{p}$, light nuclei and anti-nuclei?
- which is the origin of primary Cosmic Rays?
  - Originated in the solar System? Only a small fraction (at low energies, < 10 GeV), characterized by a strong variability, with time, due to violent phenomena in the Sun
  - Originated in the Galaxy? Yes, a large fraction (>90%). The flux of these C.R. is also anti-correlated with the most intense solar activities
  - Extragalactic? the most energetic part of the spectrum

Primary C.R. flux and composition, for $E_{CR} < 10^{14}$ eV, can be directly measured
in the space (satellites)
in the top part of the atmosphere (balloons)

For $E_{CR} > 10^{15}$ eV -→ indirect measurement
Extensive shower in the atmosphere
• using Cherenkov or Fluorescence det. in air,
• using detectors on the Earth ground
In underground laboratories (neutrino detection)
Different nuclei fluxes and energy spectra

Power law also found for individual elements.

Index of power law almost identical (heavier elements have slightly harder spectra).

Relative abundance of nuclei:

- I : 0.38 : 0.22 : 0.15 : 0.4
For $E<10$ GeV solar and Earth magnetic fields affect the C.R. spectra
C.R. flux intensity and »solar activity» are anti-correlated: the solar magnetic field effect.
"Seasonal" variation of C.R. at the Earth pole: Earth magnetic field effect

- geomagnetic cutoff negligible
- corrected for atm. overburden
• “primary” charged C.R. composition:
  86% protons, 11% $\alpha$ particles, 1% heavier nuclei (up to Uranium), 2% electrons

Particle energy can be evaluated from the measurement of their track deflection in a magnetic field $\vec{B}$.

Let’s recall: the Lorentz force that acts on a particle with charge $e$ that moves with velocity $\vec{v}$ in the magnetic field $\vec{B}$ is given by:

$$F = e\frac{\vec{v}}{c} \times \vec{B}$$

In the time $\delta t$ this force gives to a particle with charge $Ze$ that travel for the length $L$, a transverse momentum $\delta p$:

(let’s assume $\beta=1$).

$$\delta p \approx Z e B \delta t = Z e B \frac{L}{c}$$

It follows

$$\frac{\delta p}{p} \approx Z e B \frac{L}{pc} \approx \frac{\delta x}{L}$$

where

$$\delta x \approx Z e B \frac{L^2}{c}$$

measures the deviation of the particle trajectory (measurable in a spectrometer)

The fraction of particles indicated above, as relative contribution to the CR flux, are given for a given value of the particle:

**Rigidity** = $pc/(Ze)$

i.e. for particles that have the same probability to propagate through the atmosphere under the effect of the Earth magnetic field.
The geomagnetic "cut-off" and the East-West effect

Earth's magnetic field

Vincinity of poles: $B \approx 60 \, \mu T$
Equator: $B \approx 30 \, \mu T$

$$R_L = 3 \times 10^3 \left( \frac{E}{\text{GeV}} \right) \left( \frac{\mu T}{ZB} \right) \text{ km}$$

Radius of curvature smaller than radius of Earth
Relative elemental composition from hydrogen to nickel in the galactic cosmic radiation at > 1 GeV/nucleon kinetic energy arriving near the top of the Earth's atmosphere (o) compared to the solar system or "universal" abundances (●).

The data are normalized to the cosmic ray carbon abundance, set to 100 %, obtained with the satellite IMP-8 (Wefel, 1991; Simpson, 1983 and 1997).
Within C.R. heavy elements ($Z>1$) are present with higher relative abundance, relative to protons, if compared to the same quantity for the matter of the Solar System:
- within C.R., with respect to what happens in the Solar System, the percentage of protons is reduced due to the higher ionization potential of H (if compared with heavier nuclei)
- within C.R. the elements: Li, Be, B, Sc, Ti, V, Cr, Mn are much more abundant than in the Solar System matter: these elements would be nearly absent in the final state of a stellar nucleosynthesis. Within C.R. These elements do exist as result of nuclear interaction of heavier elements present in C.R., i.e. Oxigen (C, O, Fe, ...) and Iron (Sc, V, Cr, Mn) with Inter-Stellar Medium (ISM). From this assumption we can derive information on the permanence time of C.R. in our Galaxy. Indeed we have to assume that nuclei slightly heavier (C, O, Fe, ...) have the possibility to interact, i.e. that they cross an amount of matter $X = 5$-$10$ g/cm$^2$
- we know that the density of protons in the galactic disk is $\rho_p \sim 1$ protone/cm$^3 = 1.67 \cdot 10^{-24}$ g/cm$^3$
- then we can evaluate the length of the trajectory that C, O, Fe, ... have to cross in order to explain the observed amount of B, Be, Sc, ... . This length can be expressed in pc
  \[ \frac{X}{(m_p \cdot \rho_p)} = 3 \cdot 10^{24} \text{ cm} \sim 1000 \text{ kpc} \]
  \[ 1 \text{ pc} = 1 \text{ AU/secondo di grado} = 1.5 \cdot 10^{13}/4.85 \cdot 10^{-6} \]
  \[ 1 \text{ pc} = 3.1 \cdot 10^{18} \text{ cm} = 3.26 \text{ Ly} \]
- C.R., travelling at the light speed, remain trapped in our Galaxy per $\tau_{esc} \sim 3 \div 10$ millions of years $\sim 1 \div 3 \cdot 10^{14}$ s

Elements relative abundance in primary C.R. (He to Ni, continuous line) relative to Si (100%), compared to nuclei relative abundance in the Solar System (dashed line).
Cosmic Rays in our Galaxy

Let’s recall: \(1 \text{ pc} \sim 3.1 \cdot 10^{18} \text{ cm}\)

If we assume the Galaxy like a disk with radius \(r_{\text{gal}} = 15 \text{kpc} \sim 45 \cdot 10^{21} \text{ cm}\)

and height \(h_{\text{gal}} = 300 \text{pc} \sim 10^{21} \text{ cm}\)

the galactic volume can be evaluated as

\[V_{\text{disk}} = \pi r_{\text{gal}}^2 h_{\text{gal}} \sim 10^{67} \text{ cm}^3\]
Our Galaxy and its galactic magnetic field

\[ R_L \approx 1 \text{ pc} \times \left( \frac{E}{10^{15} \text{ eV}} \right) \left( \frac{\mu G}{ZB} \right) \]

Diffusion: distance scales \( \sim (\text{time})^2 \)

Extragalactic sources unlikely

Magnetic field not well known, \( B = 3 \mu G = 30 \text{ nT close to Solar System} \)
How much power is needed to justify the energy transported by C.R.? 

Assumption: entire galaxy homogeneously filled with cosmic rays

Density of particles for given flux

\[ \frac{dN}{dEdV} = \frac{4\pi}{c} \frac{dN}{dEd\Omega dAdt} \]

Isotropy \[ \int d\Omega = 4\pi \]

Total cosmic ray energy

\[ E_{\text{tot}} = \int dV \int dE \ E \cdot \frac{dN}{dEdV} \]

Mean escape time \[ \tau_{\text{esc}} \approx 10^7 \text{ years} \]
C.R. energy density

\[ \Phi = \text{C.R. flux that crosses the unit surface } A \]

can be expressed using the "cosmic rays density"

\[ \rho_{RC} = \text{number of particles/unit \text{à} of volume} \]

\[ \Phi = \frac{\rho_{RC} A \beta c t}{4\pi A t} \left[ \text{particelle} \right] \frac{cm^2 s sr}{cm^2 s sr} = \frac{\rho_{RC} \beta c}{4\pi} \]

In the same way we can define the energy density carried by C.R. as

\[ \rho_E = \int_{E_{\text{min}}}^{\infty} \rho_{RC} E \, dE = 4\pi \int_{E_{\text{min}}}^{\infty} \frac{\Phi}{\beta c} E \, dE = \]

\[ 4\pi \int_{E_{\text{min}}}^{\infty} \frac{dN}{\beta c} E \, dE = 4\pi \int_{E_{\text{min}}}^{\infty} \frac{E^2}{\beta c} \frac{dN}{dE} \, d\ln E \]

Measurement of the C.R. energy density performed in periods with different solar activity

LIS (Local Intestellar medium):

- protons \( \rho_E \approx 0.83 \text{ eV/cm}^3 \)
- Helium \( \rho_E \approx 0.27 \text{ eV/cm}^3 \)

(remember 1 eV = 1.6 \cdot 10^{-12} \text{ erg})
The median of the C.R. kinetic energy distribution in the Inter Stella Medium (ISM) is about 6 GeV: more than 90% of the C.R. kinetic energy carried by particles with \( E < 50 \text{ GeV} \).

We know that the energy density carried by C.R. in the local (galactic) I.S.M. is

\[
\rho_{E,RC} = \frac{4\pi}{c} \int E \frac{dN}{dE} dE \sim 10^{-12} \text{ erg/cm}^3
\]

Assuming this value for the energy density in C.R., the value \( V_{\text{disk}} = 10^{67} \text{ cm}^3 \) for the volume of our Galaxy and \( \tau_{\text{esc}} \sim 3 \times 10^6 \text{ years} \sim 10^{14} \text{ s} \) as the time of permanence of C.R. in the Galaxy, we can evaluate the amount of power needed to maintain such a phenomenon

\[
\frac{\rho_{E,RC} V_{\text{disk}}}{\tau_{\text{esc}}} \sim \frac{10^{-12} \times 10^{67}}{10^{14}} \sim 10^{41} \text{ erg/s}
\]

We know that a SuperNova release a flux of particles that can carry a kinetic energy as high as a \( 10^{51} \text{ erg} \).

In our Galaxy we do expect 1 SN event each 30 years - this corresponds to an emitted "power" equivalent to \( 10^{51} \text{ erg} / (30 \times 3.14 \times 10^7 \text{ s}) = 10^{42} \text{ erg/s} \) (the two numbers are compatible assuming a 10% efficiency for the proton acceleration)
LIS (Local Intestellar medium):

protons $\rho_E \sim 0.83$ eV/cm
Helium $\rho_E \sim 0.27$ eV/cm$^3$

How this energy density compares with the one associated to the galactic magnetic field $B \sim 3 \mu$Gauss ???

$$ (\rho_E)_B = \frac{1}{2} \frac{B^2}{\mu_0} = 0.21 \text{ eV/cm}^3 $$
a calculation exercise ...

A useful exercise: the calculation of the energy density associated with the Galactic magnetic field

\[(\rho_E)_B = \frac{1}{2} \frac{B^2}{\mu_0}, \quad \text{dove} \quad B = 3 \mu G = 3 \cdot 10^{-10} T\]

Let’s recall: \(\mu_0 = 4\pi \cdot 10^{-7} \frac{N}{A^2}, \quad 1G = 10^{-4} T, \quad 1T = 1 \frac{Wb}{m^2} = 1 \frac{N}{A m}\), therefore

\[
(\rho_E)_B = \frac{1}{2} \frac{B^2}{\mu_0} \frac{\text{Joule}}{m^3} = \frac{1}{2} \frac{(3 \cdot 10^{-10})^2}{12.56 \cdot 10^{-7} N A^{-2}} \frac{T^2}{25 \cdot 10^{-7} A^2 m^2 NA^{-2}} = 36 \cdot 10^{-22} \cdot 10^7 \frac{N}{m^2}
\]

\[
(\rho_E)_B = 36 \cdot 10^{-15} \frac{J}{m^3} = 36 \cdot 10^{-21} \frac{J}{cm^3}
\]

then recalling that \(1 eV = 1.6 \cdot 10^{-19} J\) we have:

\[
(\rho_E)_B = \frac{36 \cdot 10^{-21}}{1.6 \cdot 10^{-19}} = 0.21 \frac{eV}{cm^3}
\]
A useful exercise: the calculation of the energy density associated with the Cosmic Microwave Background (CMBR) radiation field

Let’s recall: the density of photons in the Universe is ~ 411 photons/cm³

The CMBR can be represented as a black body with T=2.725 K

\[ kT = (8.617 \cdot 10^{-5} \text{eV/K}) \cdot 2.725K = 2.35 \cdot 10^{-4} \text{eV} \]

But: \[ E_{\text{peak}} = 2.70 \cdot k \cdot 2.725 = 6.34 \cdot 10^{-4} \text{eV} \]

\[ E_{\text{mean}} = 2.82 \cdot k \cdot 2.725 = 6.62 \cdot 10^{-4} \text{eV} \]

Let's use for these photons an energy in the high energy tail \[ E_g = 1.4 \cdot 10^{-3} \text{eV} \]

we have:

\[ (\rho_{\text{CMBR}}) = 411 \cdot 1.4 \cdot 10^{-3} \frac{\text{eV}}{\text{cm}^3} = 0.58 \frac{\text{eV}}{\text{cm}^3} \]