Features, and experimental resolutions, of the devices used in the detectors in space: measurements of charge, mass, moment, energy, direction.

Detection of primary cosmic rays with $E < 100$ GeV.

Measurement of the C.R. electromagnetic component: primary photons and electrons

How to detect photons and electrons?

Main characteristics of apparatuses on atmospheric balloons, main results.
The starting point: the "all particle" spectrum

\[
\frac{dN}{dE} = [m^{-2}sr^{-1}s^{-1}GeV^{-1}]
\]

\(~ 1000 \text{ particles/(s} \cdot \text{m}^2)\)

ionized nuclei:
- 90% protons
- 9% \(\alpha\) particles
- heavier nuclei
- what is the origin of cosmic rays? originated in the solar system? a small amount associated with violent phenomena in the Sun and characterized by great temporal variability
- originated in the galaxy: most. An anti-correlation with intense solar activities is also noted
- extragalactic origin: the most energetic part of the spectrum

Direct measures of primary cosmic rays
- in space (satellites)
- in the high atmosphere (balloons)

Indirect measures
- extended atmospheric showers (EAS)
  - Cherenkov in the air
  - Ground detectors
- underground laboratories
Cosmic Photons and Hadrons Fluxes

Direct measurements (roughly)
Sources of astrophysical photons

**Electromag. radiation**
- Synchrotron Radiation due to GeV electrons spiralising into the source magnetic field. Typical source: Pulsar. This radiation has a continuous spectrum up to X

**Radio**
- Typically is a "reprocessed radiation". More energetic radiation interacting with the matter around the source (e, p, atoms) induces molecular rotational/vibrational transitions and loses energy

**Infrared**
- Emitted in transitions of atoms in excited states in Stars

**Optical**
- Radiation emitted typically in Compton scattering (the low energy photon) in sources with production of high energy photons

**Ultraviolet**
- Synchrotron Radiation due to TeV electrons spiralising into the source magnetic field. Typical source: Pulsar.

**X ray**
- High energy photons from sources where electron or proton are accelerated in shock waves.

All these radiations could be also "thermal", i.e. emitted by hot matter in equilibrium with the source temperature.
Synchrotron Radiation

Synchrotron radiation is observed in regions where relativistic electrons spiral around magnetic field lines. This process results in strongly polarised radiation concentrated in the direction of the electrons motion (called “beaming”). Similar to bremsstrahlung, synchrotron has a characteristic shape of its spectra which is a power law spectrum. The shape of the spectrum produced is dependant on the energy distribution of the emitting electrons and is easily distinguishable from thermal blackbody radiation.

where $\sigma_T$ is the Thomson electron cross section, $\gamma$ is electron Lorentz factor and $U_B$ is magnetic energy density. Consequently, there is a proportionality with $E^2$. The characteristic photon energy is $\varepsilon_{\gamma,s} = \hbar \omega_B \gamma^2 / 2\pi = \hbar e B \gamma^2 / (2\pi mc)$.
Bremsstrahlung Radiation

The bremsstrahlung or free-free emission mechanism consists in the emission of a photon by a relativistic electron, $E_e=\gamma m_e c^2$, when deflected by the electrostatic interaction with another charged particle: the electrons path is deviated and it emits a photon with typical energy $E_\gamma \sim E_e/2$. Below $E_e=1$ GeV bremsstrahlung gamma-rays are generated by the same electrons producing galactic synchrotron radio emission.

The bremsstrahlung radiation arises when free electrons that have a thermal distribution of energies (a spread of energies around a mean value relating to their temperature) interact with the Coulomb field of a nucleus. This produces a characteristic spectrum that can be readily identified.

The interaction cross section is proportional to:

$$\sigma_{Brems} \propto Z^2 \alpha^3_{EM}$$

\begin{equation}
- \left( \frac{dE}{dt} \right)_{Brems} = 4nZ^2 R_e^2 \alpha g E \propto nE
\end{equation}

where $R_e$ is the classical electron radius, $\alpha$ is the fine structure constant and $g$ is a factor (Gaunt) that changes its value according to nuclear screening fraction.
Which processes characterize the High Energy sources

leptonic process

Inverse Compton scattering

\[ e^{-} \rightarrow e', \gamma \]

ambient photons
(sync, MWB, IR)

We have to consider also hadronic processes like:

\[ p \rightarrow N, \pi^{\pm}, \pi^{0} \rightarrow \gamma, \nu \]
Synchrotron Self-Compton gamma production model

The most successful theories to describe the observed gamma spectra predicts an expanding ultra-relativistic shell that moves into the external surrounding medium. The collision of the expanding shell with another shell (internal shocks) or the interstellar medium (external shocks) gives rise to radiation emission through the Synchrotron and Synchrotron Self-Compton processes.
Compton and Inverse Compton scattering

**Compton scattering – photons loose energy**

- Low energy electron
- High energy photon
- Higher energy electron

**Inverse Compton scattering – photons gain energy**

- High energy electron
- Low energy photon
- Higher energy photon
- Lower energy photon
Searching for astrophysical photons
A detector for the study of primary cosmic rays with $E \leq 100\,\text{GeV}$

A small apparatus ($r \sim 6\,\text{cm}$, aperture $\sim 22\,\text{cm}^2\text{sr}$) carried by balloons (a few tens/hundred flight hours $>\) more than $10^5$ events) can collect a discrete statistic in the energy region up to $\sim 10\,\text{GeV}$: $100 \times 22 \cdot 10^{-4} \times 100 \times 3600 = 7.9 \cdot 10^5$

- composition of cosmic rays (photons, protons, heavy nuclei, ...)
- spectrum
- matter/antimatter (identification of positrons, antiprotons, anti-helium, ...)

scintillators, wire chambers, tracking devices, magnetic field, Cherenkov, ....

All particle spectrum
All cosmic ray detectors are constructed according to a common pattern; they are generally composed of the following sub-detectors:

1. a detector consisting of two "distant" planes which measures the position and time of the passage of the particle ➔ the particle velocity measurement;
2. a detector in a magnetic field that tracks the curved trajectory of the particle ➔ a measure of rigidity;
3. a high Z detector in which particles deposit their energy ➔ a measure of energy.
AMS, a complete detector for primary C.R.

- Transition radiation detector
- Time of flight measurement (scintillators)
- Tracking devise in a magnetic field
- Cherenkov light detector
- Electromagnetic calorimeter

AMS on ISS for 3 years
Cosmic Rays detectors: momentum measurement - 1

Consider a region in which there is an electric field \( \vec{E} \) and a magnetic induction field \( \vec{B} \). A charge particle \( q = Ze \) in motion with speed \( \vec{v} \) in that region undergoes a force equal to:

\[
\vec{F} = q(\vec{E} + \vec{v} \times \vec{B})
\]

Let \( \theta \) be the angle between \( \vec{v} \) and \( \vec{B} \). Suppose that the particle has mass \( m \) (\( m = \gamma m_0 \)). Now suppose that only the magnetic induction field is present:

\[
\vec{F} = q\vec{v} \times \vec{B} = ZevB\sin \theta (-\hat{r}_L) = -m\frac{v^2}{r_L}\hat{r}_L = -\gamma m_0 \frac{v^2}{r_L}\hat{r}_L
\]

where \( r_L \) indicates the radius of Larmor. Projecting on \( r_L \) we have:

\[
ZevB\sin \theta = \gamma m_0 \frac{v^2}{r_L} \quad \Rightarrow \quad r_L = \frac{\gamma m_0 v}{ZevB\sin \theta}
\]

It is defined "Rigidity of a particle in a magnetic field"

\[
R = \frac{\gamma m_0 v}{q} = \frac{\gamma m_0 vc}{Ze}
\]

This quantity has the dimensions of an energy divided by the charge and is measured in GV. Based on this definition we can write:

\[
r_L = \frac{R}{Bc\sin \theta}
\]
Momentum measurement

If $\theta$ is the angle formed by the magnetic field $B$ and the particle velocity, the radius of curvature of the trajectory traveled by the particle is

$$ r = \frac{R}{Bc \sin \theta} = \frac{\gamma m_0 v}{Z e B \sin \theta} $$

What is usually measured is the sagitta $S$ of the curved line which represents the trajectory of the particle (it is the length of the segment $AD$).

In the $S \ll r$ approximation we can write:

$$ AB = r \quad BC = r - S = \sqrt{(AB)^2 - \left(\frac{\ell}{2}\right)^2} \quad S = r - \sqrt{r^2 - \left(\frac{\ell}{2}\right)^2} $$

$$ S = r \left(1 - \sqrt{1 - \left(\frac{\ell}{2r}\right)^2}\right) \approx \frac{\ell^2}{8r} $$
since it holds the relation $pc = 0.3 Br$, where $p$ is the relativistic pulse expressed in GeV/c, $B$ is the magnetic field intensity expressed in Tesla, and $r$ is the radius of curvature in meters, we find

$$S \propto \frac{B \ell^2}{pc}$$

so we see that, with the same spatial resolution in the measurement of the sagitta, the higher the power of analysis $B\ell^2$, the greater the maximum impulse that can be measured.
Tracking detectors - 1

- **Purpose:** measure momentum and charge of charged particles
- **To minimize multiple scattering, we want tracking detectors to contain as little material as possible**
- **Two main technologies:**
  - gas/wire drift chambers (like CDF’s COT)
  - solid-state detectors (silicon)
- **Silicon is now the dominant sensor material in use for tracking detectors at the LHC (especially CMS)**

*The CDF Central Outer Tracker (COT) is a large cylindrical drift chamber, sitting inside CDF's 1.4T magnetic field, outside the CDF silicon trackers*
Tracking detectors - 2

- Wires in a volume filled with a gas (such as Argon/Ethan)
- Measure where a charged particle has crossed
  - charged particle ionizes the gas.
  - electrical potentials applied to the wires so electrons drift to the sense wire
  - electronics measures the charge of the signal and when it appears.
- To reconstruct the particles track several chamber planes are needed
- Example:
  - CDF COT: 30 k wires, 180 μm hit resolution
- Advantage:
  - low thickness (fraction of $X_0$)
  - traditionally preferred technology for large volume detectors
Tracking detectors – 3 silicon detectors

- Semi-conductor physics:
  - doped silicon: p-n junction
  - apply very large reverse-bias voltage to p-n junction
    - “fully depleted” the silicon, leaving E field
- Resolution 1-2% @ 100 GeV
- Important for detection secondary vertices
  - b-tagging (more on this later)
Scintillation detectors

Sodium Iodide Crystal or plastic scintillator
Charge measurement

The value of the nuclei electric charge is measured by the energy lost per unit of path, in fact for the very heavy particles the expression of the energy lost on average by ionization is given by the formula of Bethe-Bloch

\[
-\frac{dE}{dx} = 4\pi Ne r_e^2 m_e c^2 \frac{z^2}{\beta^2} \left( \ln \frac{2m_e c^2 \beta^2 \gamma^2}{I} - \beta^2 - \frac{\delta(\gamma)}{2} \right)
\]

- \(m_e\) and \(r_e\) are, respectively, the mass and the classical radius of the electron
- \(I\) is the ionization potential of the crossed material
- \(\delta(\gamma)\) is a "density correction that, in the limit of high \(\gamma\), limits the logarithmic rise of the energy losses
- \(\beta\) is the particle velocity in terms of the light speed

then:

\[
\frac{dE}{dx} \propto z^2
\]

therefore for particles at the minimum of ionization (or even more energetic) the measure of the loss of energy is essentially a measure of the absolute value of the electric charge.
Knowing $dE / dx$, function of $(z, \beta)$, and the rigidity $R (m_0, z, \beta)$ remains as the only unknown $m_0$ that can be obtained with a measure of $\beta$ with the time of flight system.

The particle identification system is so complete.
Calorimetric measurements of shower energies -1

E.M. Showers development (basic concepts in e.m. calorimeters)

- **e.m. showers formation e.m.**
  - particle multiplication processes
    
    \[ e \rightarrow e'^\gamma \]
    \[ \gamma \rightarrow e^+e^- \]
  - energy degradation processes
  - multiple scattering
  - radiation absorption

- **conversion into visible energy of the deposited kinetic** \(E_{dep}\)
  - Ionization
  - production of electron-hole pairs
  - molecular atomic excitation
    - absorption in luminescent centres
    - return to the ground state with photon / phonon emission
  - Cerenkov light emission
  - energy conversion into thermal phonons
Calorimetric measurements of shower energies -2

- **Purpose:** measure energy of EM particles (charged or neutral)
- **How?**
  - Use heavy material to cause EM shower (brem/pair production)
  - Total absorption / stop particles
  - Important parameter is $X_0$ (usually 15-30 $X_0$ or a high Z material)
  - There is little material before the calorimeter (tracker)
- **Two types of calorimeters:**
  - Sampling
  - Homogeneous
- **Relative energy uncertainty decreases with $E$!**

\[
\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus b \oplus \frac{c}{E}
\]

a: stochastic term (photon counting)
b: constant term
c: noise (electronics)
Pictures of EM and Hadronic showers

Figure 2.5  A photograph of the development of an electromagnetic shower in Pb plates. The number of particles in the shower builds up geometrically. After reaching a maximum, the shower then slowly dies off due to ionization loss ([2] – with permission).

Figure 2.10  Photograph of a 200 GeV pion interaction ([5] – with permission).
Calorimetric measurements of shower energies -3

- **Sampling calorimeter**
  - active medium which generates signal
    - scintillator, an ionizing noble liquid, a Cherenkov radiator…
  - a passive medium which functions as an absorber
    - material of high density, such as lead, iron, copper, or depleted uranium.
    - $\sigma E/E \sim 10\%$

- **Homogeneous calorimeter**
  - the entire volume generates signal.
  - usually electromagnetic
  - inorganic heavy (high-Z) scintillating crystals
    - CsI, NaI, and PWO, ionizing noble liquids…
    - $\sigma E/E \sim 1\%$
AMS - a cosmic rays detector
Astronomy with R.C. and with "cosmic" photons
The first historical measurements of the antiproton/proton ratio
Atmospheric Balloons and C.R. physics

National Scientific Balloon Facility

FLOAT ALTITUDE: 120,000-130,000 FEET
PAYLOAD WEIGHT: 6,000 POUNDS

MYLAR BALLOON
40 million cubic feet
24 miles of seams
13 acres of fabric

At launch
Washington Monument
At float altitude
Balloon data: positron fraction before 1990

An evidence for an “excess of antimatter”? A first evidence of “dark matter”? 
Cosmic Rays and Antiparticles

The interaction of primary C.R. with the InterStellar Medium (ISM) can explain (at least part of) the observed antimatter.
MASS - Matter Antimatter Space Experiment

Designed to measure

- antiprotons with \( E \approx 4-20 \text{ GeV} \)
- positrons with \( E \approx 4-10 \text{ GeV} \).

It is the evolution of MASS1 (exp. brought in flight already in 1989), with the tracing apparatus improved thanks to a system of "drift chambers".

The identification of particles is possible thanks to the gas-Cherenkov (Freon-12) detector and to a calorimeter made of brass-streamer tubes (and Isobutane). The experiment was carried out for 23 hours in September 1991 by Ft. Sumner, after 10 hours the magnetic field was lost.
Matter Antimatter Space Spectrometer 2
MASS - 1991

GAS CHERENKOV
TOF
TRACKING SYSTEM
TOF
CALORIMETER

1 m

Antiproton/Proton Ratio

10^{-3}

10^{-4}

10^{-5}

100

1000

10000
Isotope Matter Antimatter Experiment

Made to be transported in the upper atmosphere with balloons and to measure abundance in galactic C.R. of protons, antiprotons, deuterium, helium-3 and helium-4 in the energy range $\sim 0.2 \div 3.2$ GeV/nucleon. In this region of energies there is the maximum intensity for the expected flows of the particles to be observed.

IMAX measures the magnetic rigidity of charged particles that pass through the apparatus (by tracking in the drift chambers (DC) and in the multiwire proportional counters (MWPC)), the charge (via dE/dx in the scintillators (S1, S2) that provide also the time-of-flight (TOF)), and the speed (via time-of-flight (TOF) and the Cherenkov aerogel meters (C2 and C3)). By combining these three quantities it is possible to identify the particle by mass, charge and sign of the charge.

IMAX was launched in July 1992 starting from Lynn Lake, Manitoba, Canada, has reached the quota of about 36 km (with a residual atmosphere of 5 g/cm$^2$) and during about 16 hours has collected more than 3 million of events (collecting a statistic 10 times greater than previous experiments).
IMAX – the flight

FLIGHT

16-17 July 16-17, 1992, Lynn Lake, Manitoba, Canada. Float was reached about 7 hours after launch. The instrument took data throughout ascent, recording about $1.4 \times 10^6$ events. These data will be used to determine altitude-dependent particle spectra. At the end of the float period, the magnet was ramped down and data was taken with the magnet off in order to check the alignment of the tracking chambers. Landing was near Peace River, Alberta, Canada, with the instrument being recovered in excellent condition. All payload and detector systems appear to have performed well throughout the flight. Over $3.4 \times 10^6$ events were recorded during the float period.