Cosmic Rays - introduction and research topics

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STCE Workshop

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Contents:

• Cosmic rays (CRs) – an introduction – galactic, solar, ground level, underground, anomalous cosmic rays

• Cosmic rays variations – interaction with magnetic fields and solar plasma – application to space weather and space weather forecast – ground based measurements

• Relevant research topics – cosmoclimatology, solar-terrestrial relationship, radiation hazards
The name given to the High Energy ``radiation” that strikes the Earth from space

**Composition:**
- protons ~ 85 - 87 %
- helium nuclei ~10 %
- electrons ~1 %
- gamma ray photons < 1 %
- trace elements HZE ions (C, O, Mg, Si, Fe, ...)
- 0.01 % antimatter

**Sources** – completely efaced by the varius magnetic fields – we use indirect methods to determine the sources;

Why mostly protons and He nuclei? Why electrons are not accelerated as efficiently as protons? ...
- High concentration of light elements: Li, B, Be
- max. flux [100 MeV – 10 GeV], peak at ~0.3 GeV
Solar Cosmic Rays

- As a result of the diffusive propagation in the galactic magnetic field (GaMF) the galactic cosmic rays are virtually isotropic at most energies. However, at the vicinity of stellar objects this is different:

Solar cosmic rays – solar wind (1.5 – 10 keV), solar particle events (GeV) (relativistic)

- composition – varies:
  - protons
  - electrons
  - HZE (C, O, Si, Mg, ...)

- To distinguish between the solar wind and the solar cosmic particles, we call the latter only those which have sufficient energy to be measured by ground based detectors.
- muons formed at about 15 km; mean energy at ground ≈ 4 GeV
- electrons/positrons and gammas
- protons and neutrons

Modelled flux of secondary CRs in the atmosphere

http://cosmic.lbl.gov/SKliewer/Cosmic_Rays/Atmosphere.htm
Altitude intensity

Altitude intensity: Regener–Pfotzer maximum peaks at about 16 km / 100 mm Hg

Cosmic rays variations:

3 general classes of variations (relative variations)

1. Class: variation in the integral multiplicity – mainly due to atmospheric effects.

2. Class: variations of the geomagnetic threshold – geomagnetic perturbations, which are relatively small.

3. Class: variations in the primary component beyond the boundaries of the geo-magnetic field; we will show that this variations are those related to space weather.

ref: L. I. Dorman, 2004
Cosmic ray intensity measured by a Neutron Monitor at Dourbes: effect of atmospheric properties - variations of class 1 - on the measured intensity

Example of data correction (1 to 9 April 2012)

~0.7% for neutron component, ~0.2 for the muon component
Class 2 Cosmic Rays variations:

Variations due to changes in the geomagnetic threshold.

To quantify this variations several concepts have been introduced:

✓ **Asymptotic cones of acceptance (ACA)** for a given observational point on the Earth – this cone is defined as "the solid angle containing the asymptotic directions of approach of cosmic ray particles outside the influence of the geomagnetic field that significantly contribute to the counting of a ground detector” [McCracken, 1959]

✓ **Loss Cone** – the set of angles at which the particle will strike the atmosphere without getting trapped in the magnetosphere; it is defined as the probability of a particle to get lost from the magnetic bottle;

✓ **Geomagnetic rigidity**: characterize the effect of the Earth’s magnetic field on a charged particle – relates the momentum, charge and the field strength.

As result - each ground based observatory is characterized by a parameter – the rigidity cutoff depending on the GMF.
Class 2 effects of the geomagnetic field

Effects of the geomagnetic field:
- rigidity cutoff (low energy cutoff)
- narrow cone of viewing directions – the solid angle within which a NM sees the PCR piercing the magnetosphere

By observation at different sites we can obtain information about the energy and the direction of the primary CRs!

credit: Smart & Shea (1993)
Class 3 cosmic rays variations

• Class 3: variations in the primary component outside the magnetopause:
  ✓ Modulation effects by solar plasma (11 years, 27 day, solar day, 22 years) that occur periodically) ``equilibrium variations’’; Increase before Forbush Effect; Forbush Decrease – deficit during magnetic storms (stochastic) non - equilibrium
  ✓ Effects of solar particles generated on the Sun – Ground Level Enhancement, solar flares from different magnitude

These variations are the most important for our research.
Solar modulation of the CRs seen by the Dourbes Neutron Monitor.
**Forbush decrease:**
result from magnetic fields following a CME suppressing the intensity of the GCR

- The exact mechanisms is still under investigation
- the nucleonic component undergoes a typical reduction during the time of the magnetic storm up to 30 %
- the muon component decrease: 10 %

A magnetic storm decrease in the total count of the Dourbes Neutron Monitor
• **Ground Level Enhancement:** Generation of free particles on the Sun.

• Large increase in the intensity due to chromospheric flares:
  - increase in the nucleonic component: 100 – 200 %
  - muonic component: 10-20 %

Relatively new observation of Solar particles are the solar relativistic neutrons: the decay product from this neutrons has been observed by the neutron monitors (Bieber et al. 2005, doi:10.1029/2004GL021492)
• Solar activity is very important parameter in several applied and geophysical problems:
  - radio-wave and navigational distortions
  - possible meteorological effects of CRs
  - other phenomena affecting human’s life (radiation hazards)
• The negative effects on terrestrial systems are already well known:
  - radiation damage of spacecraft electronics
  - production of induced voltages in telephone and power cables
  - corrosion of pipelines during geomagnetic storms

``Space weather is the branch of science dedicated to understanding the Solar-Interplanetary-Terrestrial System”
Possible precursors – preincrease and predecrease the complex interaction of the GCR with Solar Flare transients, magnetic clouds, IMF and GMF may lead to pre-increase or suppression; can be measured: a worldwide net of Neutron Monitors: long lead times – up to `4 h.
Observation of precursors by muon monitors

Loss cones precursor anisotropy in a muon telescope (solid circles in the bubble plot) near $0^\circ$ pitch angle.

The pre-decrease is relative to the omnidirectional average.

• Dourbes Neutron Monitor (DRBS):
  ✓DRBS1: 9-NM64 $^{10}$BF3 fluoride gas filled counter tubes
  - Real time CR intensity in Dourbes: http://neutronmonitor.meteo.be/
  - The data is available via: http://www.nmdb.eu
  ✓DRBS2: under construction – an optimised version of NM64 designed and optimised for higher yield
Future development

- Instruments:
  - Muon telescope construction - for space weather applications - allows observation of the temporary anisotropy in the muon flux preceding a CME (loss cone deficiency/pre-decrease)

Data from Sao Martihno muon detector (Brazil), Due to rotation of the detector’s viewing directions With respect to the loss cone The pre-decrease i seen from East over the Zenith and to the west (Bieber, ICRC 2007)
Forecasting space weather events using cosmic rays

Possible approaches:

• Statistical – analysis of past events
• From basic principles – based on the present solar- and interplanetary plasma physics models and MHD transport (e.g. Dorman’s recipe (Dorman et al, 2005) etc.

Requirements:

✓ Data sources:
  - real time data - NMDB, GMF(e.g. Dourbes, ... ) measurements
  - quasi real-time (satellite data monitoring the Sun and the solar wind, e.g. WIND ...)
  - Reconstruction of the GMF at stations of interest

✓ Real-time rigidity spectrum calculation
✓ Data analysis software – AI, fuzzy logic, others;

Real time implementation -> Alert service
Research topics?

- Identify the parameters that affect the space weather and create a model for reliable forecasting of space weather events based on observations of ground based CRs measurements (NM, muon detectors)
- Why for some FDs and GLEs the anisotropies are not detectable?

More fundamental research topics:
- Physics of the interplanetary medium
- Acceleration mechanism in shocks – scattering/focusing, diffraction interference, etc.?
- Magnetic clouds – how do they affect the fast galactic cosmic rays? The exact acceleration mechanisms.
CRs contribution to the absorbed dose

Roughly said: GCR exposure doubles with every 2 km of altitude

- On Earth, a 1-sievert (Sv) equivalent dose increases cancer risk by 5%.

For those who fly frequently, the annual exposure may be comparable with, or even exceed, that of radiation workers in ground-based industries.

How much contributes a GLE event to the absorbed dose?

- flight from Prague to New York during the GLE on 15 April 2001: 20 μSv [Spurny and Dachev (2001)]

Dose equivalent, [mSv] vs. diff. scenarious

Image: NASA/JPL-Caltech/SwRI

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May 17, 2016, Dourbes
Cosmogenic radionuclide dating:

\[ ^{10}\text{Be} \] spallation (N and O) half life \(1.39 \times 10^6\) y

\[ ^{14}\text{C} \] \( ^{14}\text{N} (n, p) ^{14}\text{C} \) half life 5700 y

``Paleocosmic” measurements:

F. Steinhilber et al. doi: 10.1073/pnas.1118965109
1) Cosmic rays may be able to seed cloud formation.
2) Fewer cosmic rays reaching Earth means less cloud formation.
3) Fewer clouds reflecting sunlight means more solar radiation reaching the Earth's surface, and thus warming.

Svensmark et al. doi:10.1103/PhysRevLett.81.5027

Credit: Danish National Space Institute

A detailed study in CERN: CLOUD experiment

annual average CR vs. the annual average global surface temperature (NMDB & NOA)

credit: The Guardian

http://home.cern/about/experiments/cloud
• Daily variations in secondary CRs (underground muon detector) have been associated with planetary scale meteorological phenomena in the stratosphere.

*The effective temperature has been determined by a muon scaling function.

Osprey et al. SSW and MINOS doi:10.1029/2008GL036359
A cloud chamber photography of what is probably the first photo showing the track of a cosmic ray
(1927 by Dmitry Skobelzyn)