Cosmic Rays

a review

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Outline

- Introduction
- Cosmic rays characteristics
- Measurement techniques and instruments
- Space weather – why do cosmic rays matter?
- Summary and Outlook

- We will also present the role of cosmic rays in the atmospheric ionization.
- The question of global warming due to the clouds formation by cosmic rays will also be approached, first by recalling the idea of cosmic rays as generators of clouds and secondly, the reaction to this idea.
- The last part will present the CLOUD experiments and results.

Introduction

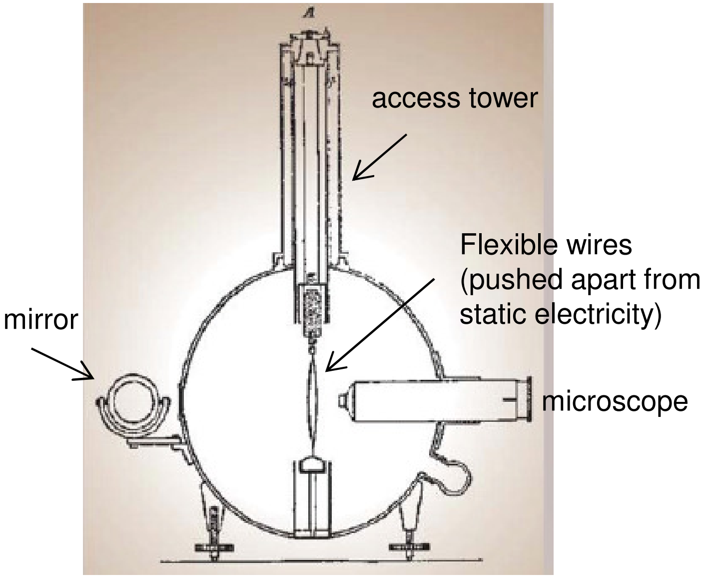
The interplanetary space is continuously traversed by energetic nuclear particles called cosmic rays. Some originate from the Sun and other stars but others are associated with various energetic processes in the galaxy.

The cosmic rays and the associated phenomena are intrinsic part of the space weather.

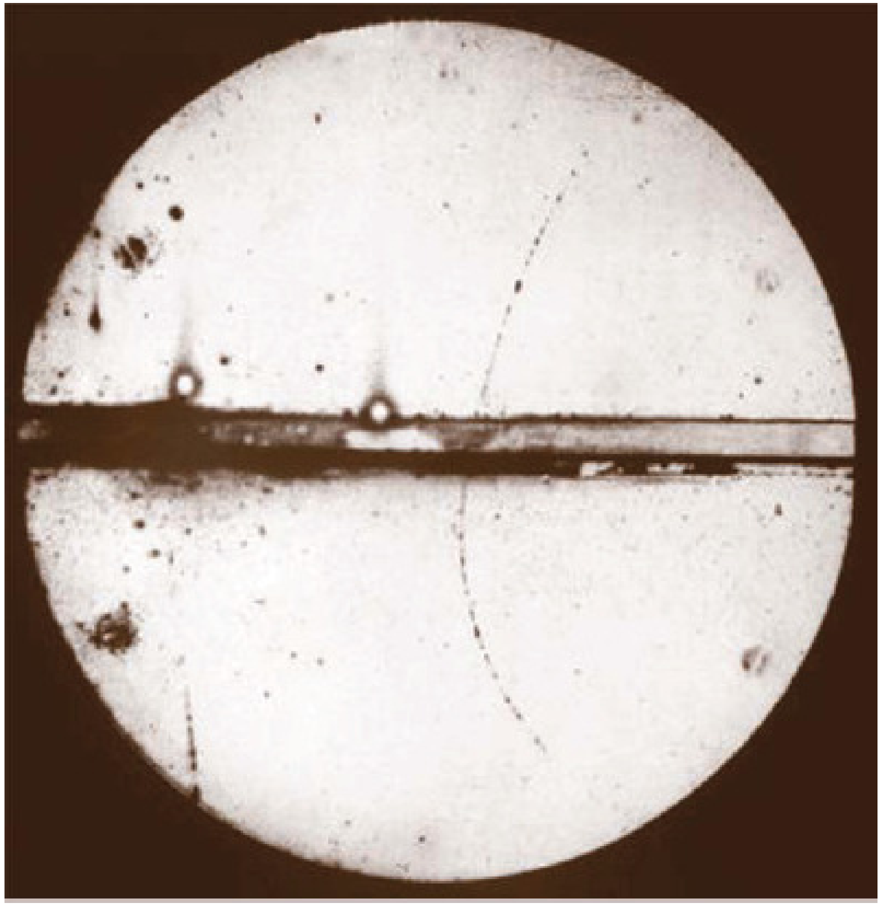
The presentation will review the main features of the cosmic rays and the key instrument for observing their flux, the neutron monitor. A neutron monitor has been in operation at the RMI Geophysical Centre in Dourbes (50.1N, 4.6E) since 1965.

History

At the beginning of the 20th century, many physicists in Europe and North America made important contributions to the **study of atmospheric ionization**. The principal investigative instrument was the electroscope in a closed vessel. With improved insulation, the electroscope’s sensitivity was increased and its discharge rate could be measured. Charles Wilson and others soon reported results of their separate observations of electroscope discharge. They concluded that the **ionization must be caused by either x rays or gamma rays coming from outside** the vessel.



Theodor Wulf’s electroscope, 1909. Shown is the instrument’s 17-cm-diameter zinc cylinder with its pair of flexible wires below the access tower *A*. The wires are pushed apart by static electricity, and the microscope (peering in from the right) measures their separation, illuminated by light from the mirror at left. The air in the cylinder was kept dry by sodium in the small recess below the microscope.



A historic cloud-chamber photograph taken by Carl Anderson in 1932 **shows a positive particle, presumably from a cosmic-ray shower, entering from the top, curving in the chamber’s transverse magnetic field, and losing energy in the lead plate.** After traversing the plate, the track is much too long for a proton of that curvature. Also, the weak ionization density along the track indicated a particle much lighter than the proton. This was the first sighting of the positron proposed by Paul Dirac in 1928.

Source: Carsson (2012): A century of cosmic rays. Physics Today, February 2012, pp. 30-36.

History

Victor Hess in the gondola of his hydrogen-filled balloon some time around 1912.
On **7 August 1912**, he reached an altitude of 5000 m and discovered that the ionizing radiation he was investigating definitely increased with altitude. His finding is regarded as the discovery of cosmic rays.

The 1936 Nobel Prize in Physics was shared **by Victor Hess**, for the discovery of cosmic rays, **and Carl Anderson**, for the discovery of the positron. Arthur Compton, in his letter nominating Hess for the prize, wrote, "The time has now arrived, it seems to me, when we can say that the so-called cosmic rays definitely have their origin at such remote distances from the Earth, that they may properly be called cosmic, and that the use of the rays has by now led to results of such importance that they may be considered a discovery of the first magnitude." The Nobel Committee for Physics pointed out that Hess's discovery opened new vistas for the understanding of the structure and origin of matter. "It is clear," the committee wrote, "that Hess, with his skillful experiments, has proven the existence of an extraterrestrial penetrating radiation, a discovery more fundamental than that of the radiation's corpuscular nature and the latitude variation of its intensity." At the ceremony, Hess (right) and Anderson (middle) are seated beside chemistry laureate Peter Debye.

Source: Carsson (2012): A century of cosmic rays. Physics Today, February 2012, pp. 30-36.

Characteristics

Composition:

- Protons (Hydrogen nuclei) ~ 90 %
- Helium nuclei ~ 9 %
- Electrons ~ 1 %

with few nuclei of heavier and lighter elements:

- Lighter elements (Lithium, Beryllium, Boron) ~ 0.25 % (from bombardment of heavier particles)
- Medium elements (Carbon, Nitrogen, Oxygen and Fluorine) ~ 10 times their abundance in normal matter
- Heavier elements ~ 100 times over normal matter.

Source: Akasofu and Chapman (1972): Solar-Terrestrial Physics, Oxford University Press, Oxford UK.

Characteristics

The **density of cosmic rays** (in interstellar space): about 10^{-3} particles/m^3

The **energy range** of cosmic ray particles: 1 GeV (10^9eV) - 10^{11} GeV (10^{20}eV)

Over the vast distances of interstellar space, galactic cosmic rays are accelerated to speeds approaching that of light. Since the **velocity of galactic cosmic rays approaches the speed of light**, the mass of the particles rises sharply with their velocity.

In accordance with Einstein's relation between energy and mass, **the energy of the particle thus also increases**.

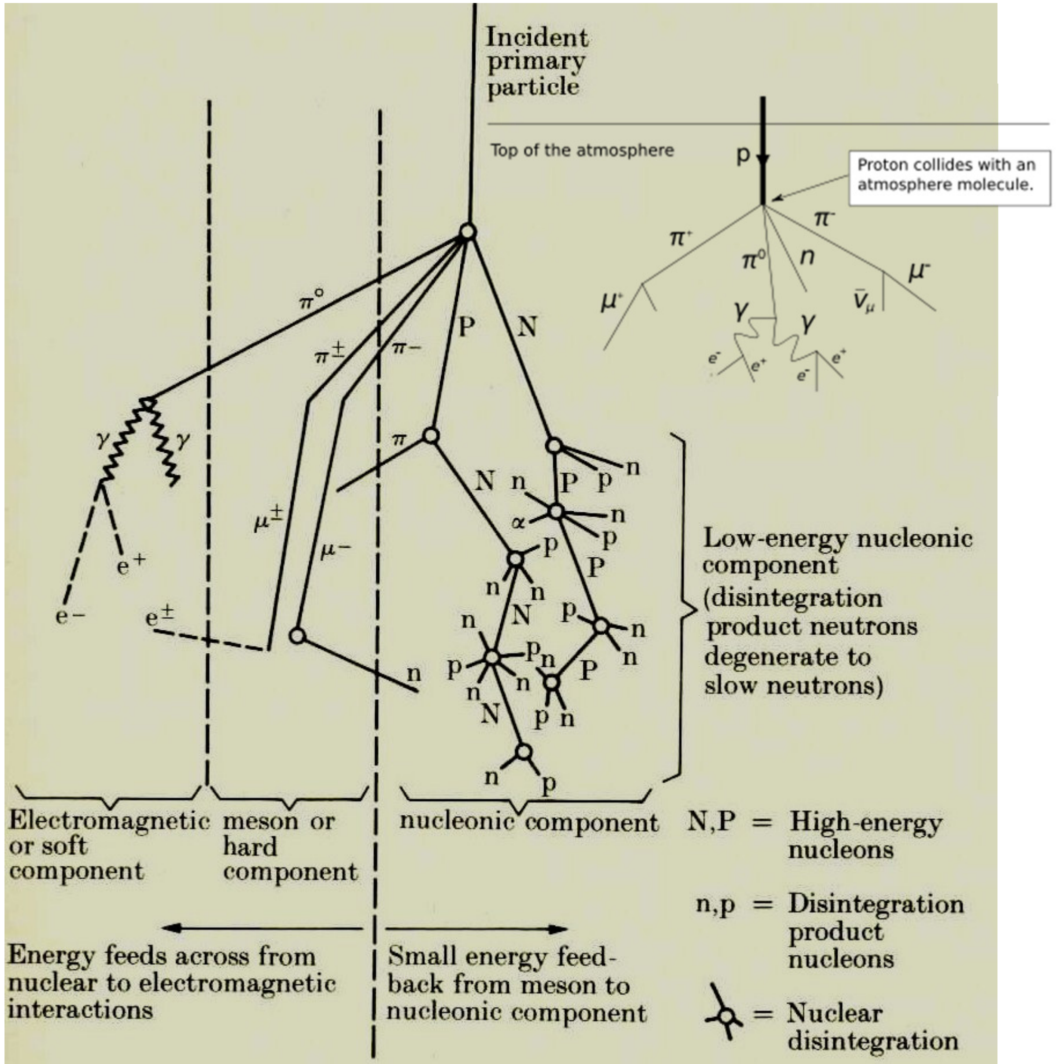
The high energy of galactic cosmic rays means that they also have **a very high penetrating power** for many kinds of materials.

The flux of incoming cosmic rays at the upper atmosphere is dependent on the solar wind, the Earth's magnetic field, and the energy of the cosmic rays.

Source: Akasofu and Chapman (1972): Solar-Terrestrial Physics, Oxford University Press, Oxford UK.

Characteristics

When penetrating into the atmosphere, **the cosmic rays collide with the atmospheric constituents**. High energy collisions in the upper atmosphere produce cascades of lighter particles.



Protons with energies of about 0.1 GeV isotropically scatter the products of the collisions, such as protons, α-particles, and neutrons. The paths of these products appear as radial lines from the collision point, forming a '**star**'.

If the energy of the protons is of higher order (several GeV), then π mesons (types π^0, π^-, π^+) are also produced, which are scattered forward and their paths appear as a '**shower**'.

When the energy of the incident protons is more than 10^3 GeV, the products are scattered into a very narrow cone called a '**jet**'. The produced protons collide with new atmospheric particles producing similar reactions. The π^- and π^+ mesons decay into muons (μ) and neutrinos (ν), while π^0 decay into γ rays, which further decay into electron pairs (e^-,e^+) emitting bremsstrahlung rays, and so on.

Fig. Interaction of the primary cosmic ray particle and the terrestrial atmosphere, resulting in secondary components of cosmic rays.

Source: Akasofu and Chapman (1972): Solar-Terrestrial Physics, Oxford University Press, Oxford UK.

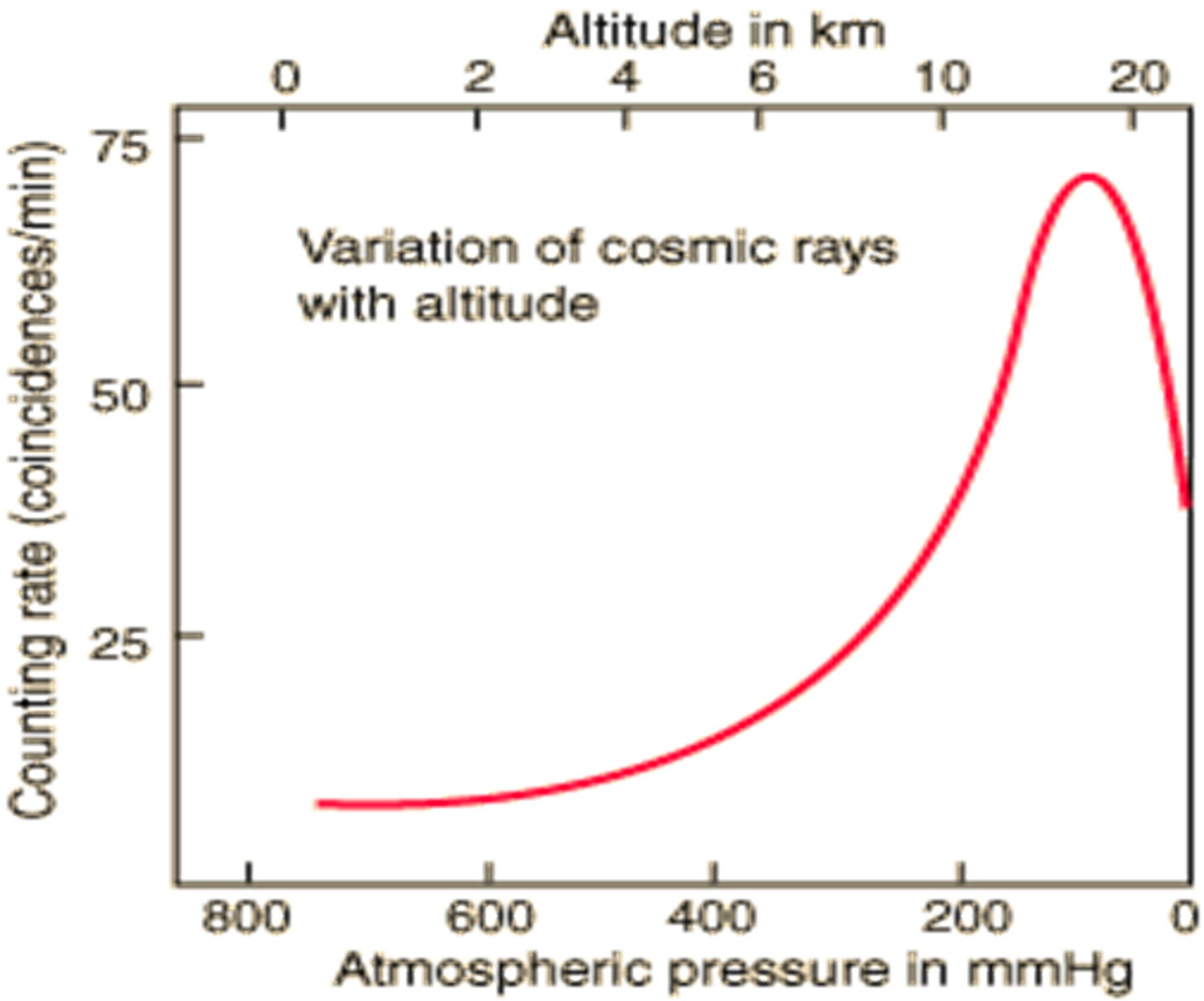
Characteristics

The generated many new rays/particles permeate the atmosphere and **can reach the ground level**.

Muons and neutrons make up more than half of the cosmic radiation at sea level, the remainder being mostly electrons, positrons and photons from cascade events.

Characteristics

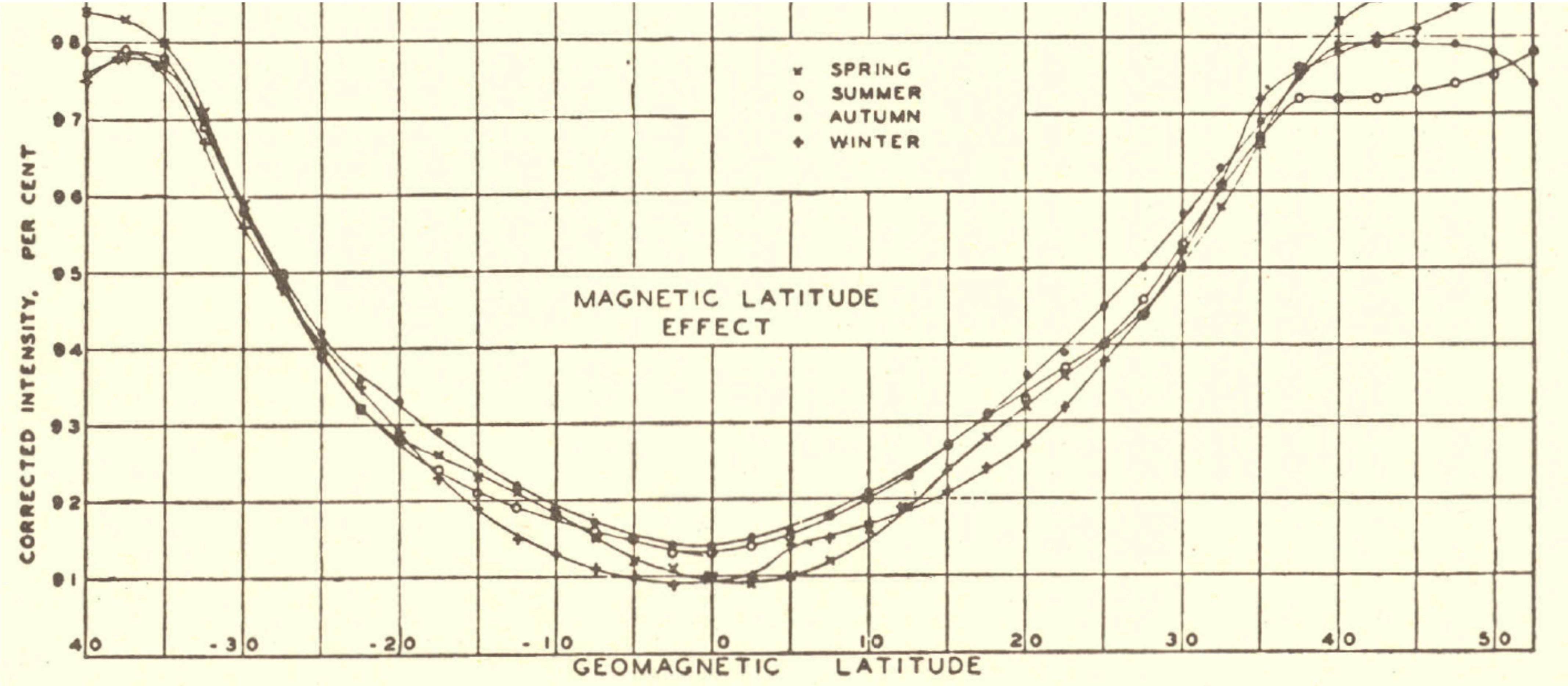
The intensity of **cosmic radiation increases with altitude** (indicating that it comes from outer space)



The detected cosmic ray flux peaks at about 15 km in altitude and then drops sharply (note the logarithmic scale on the altitude).

Characteristics

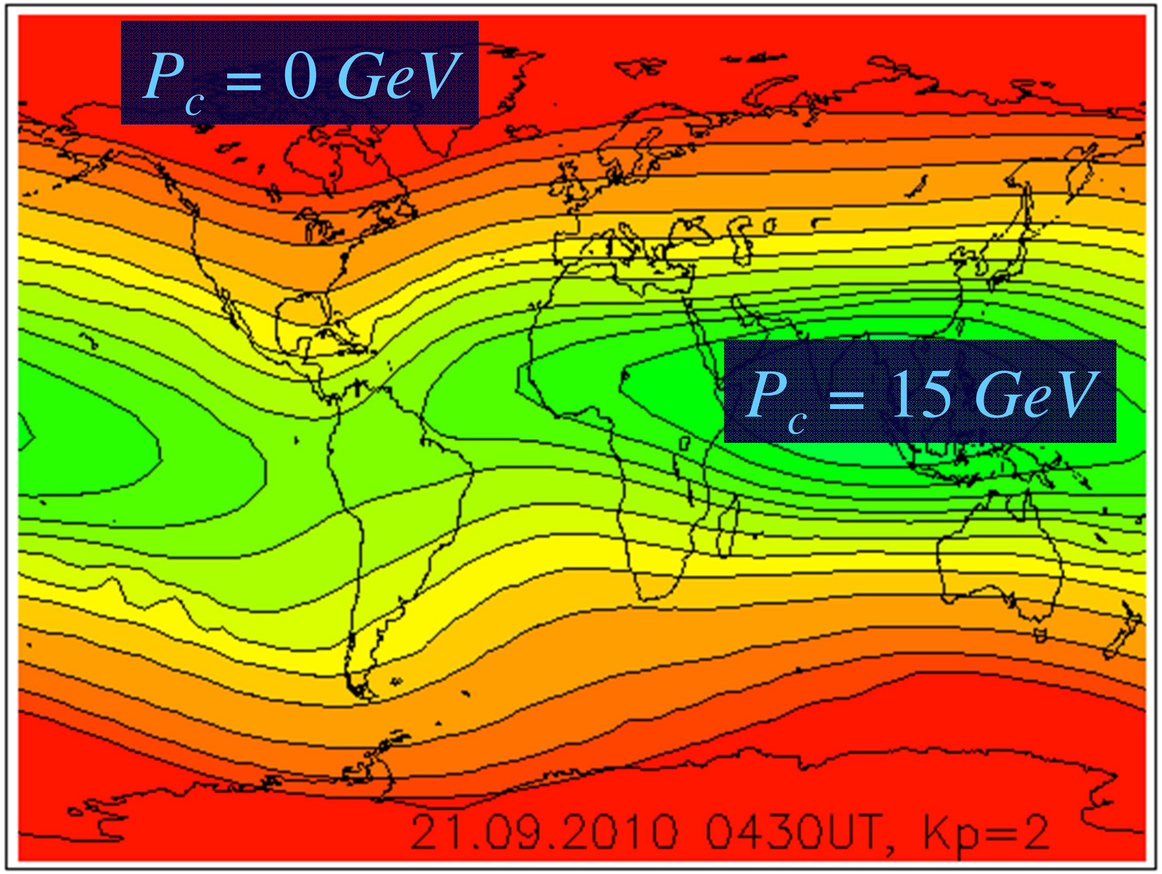
The intensity of **cosmic radiation varies with latitude** (increases at higher latitudes), indicating that it consists at least partly of charged particles which are affected by the Earth's magentic field



A. H. Compton and R. N. Turner, *Phys. Rev.* *52*, 799 (1937)

Characteristics

The intensity of **cosmic radiation depends on geomagnetic latitude and particle energy**.



Geomagnetic cut-off rigidity

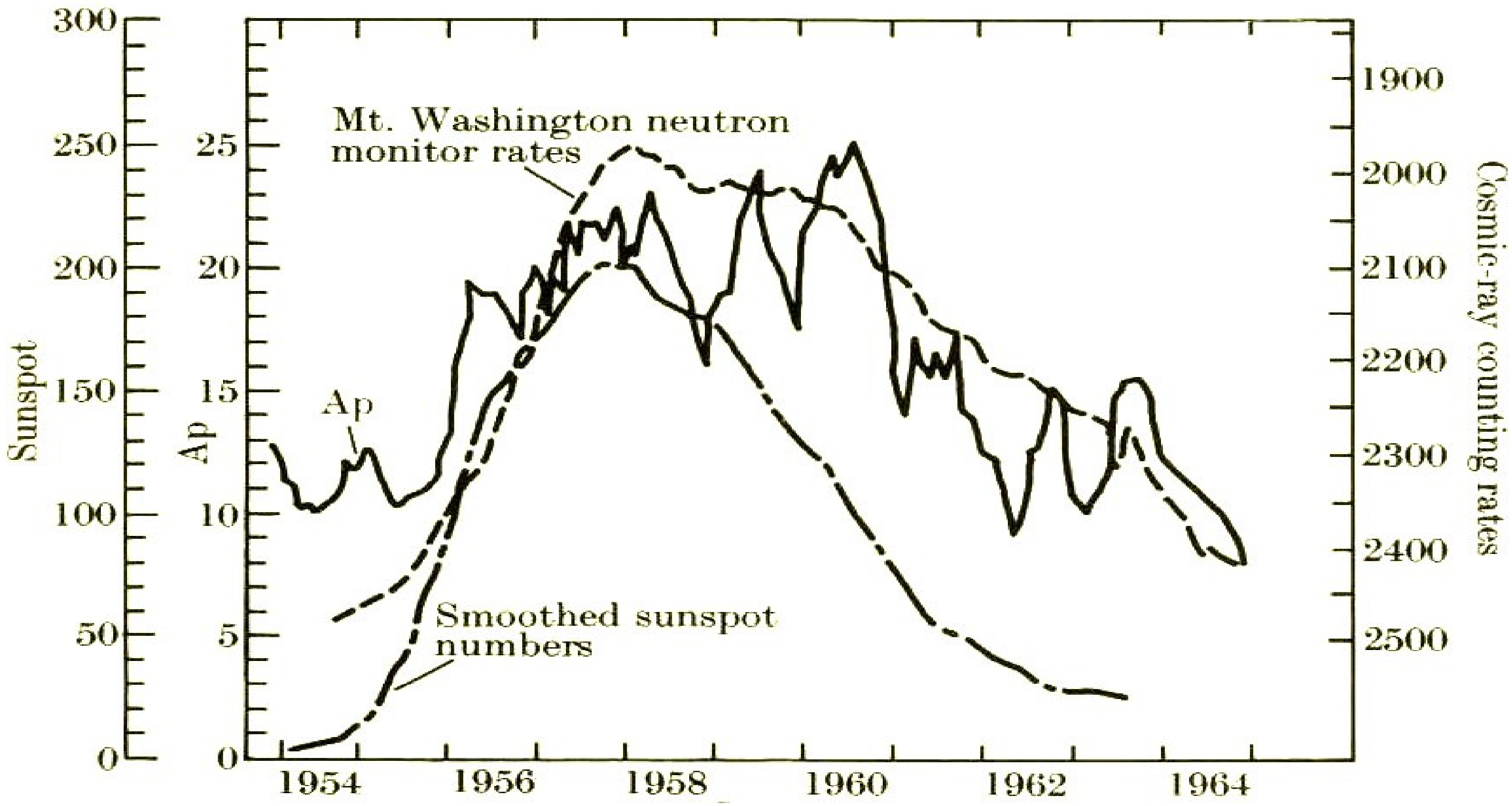
$$P_c \sim 1.9\, M \left(\frac{R_0}{R}\right)^2 \cos^4 \lambda_G$$

M – geomagnetic dipole moment
Ro – Earth radius
R – radial distance from Earth's centre

Fig. A map of cutoff energies is shown in this figure. Red shading at the borders of the map is for regions where protons with energy below 125 MeV can penetrate to the atmosphere (20 km above the ground), while energies above 15 GeV (green colour within the closed contour) are required in equatorial regions above southern Asia. Overall, the closer one approaches the magnetic equator, the higher the minimum energy required for cosmic rays to reach the atmosphere.

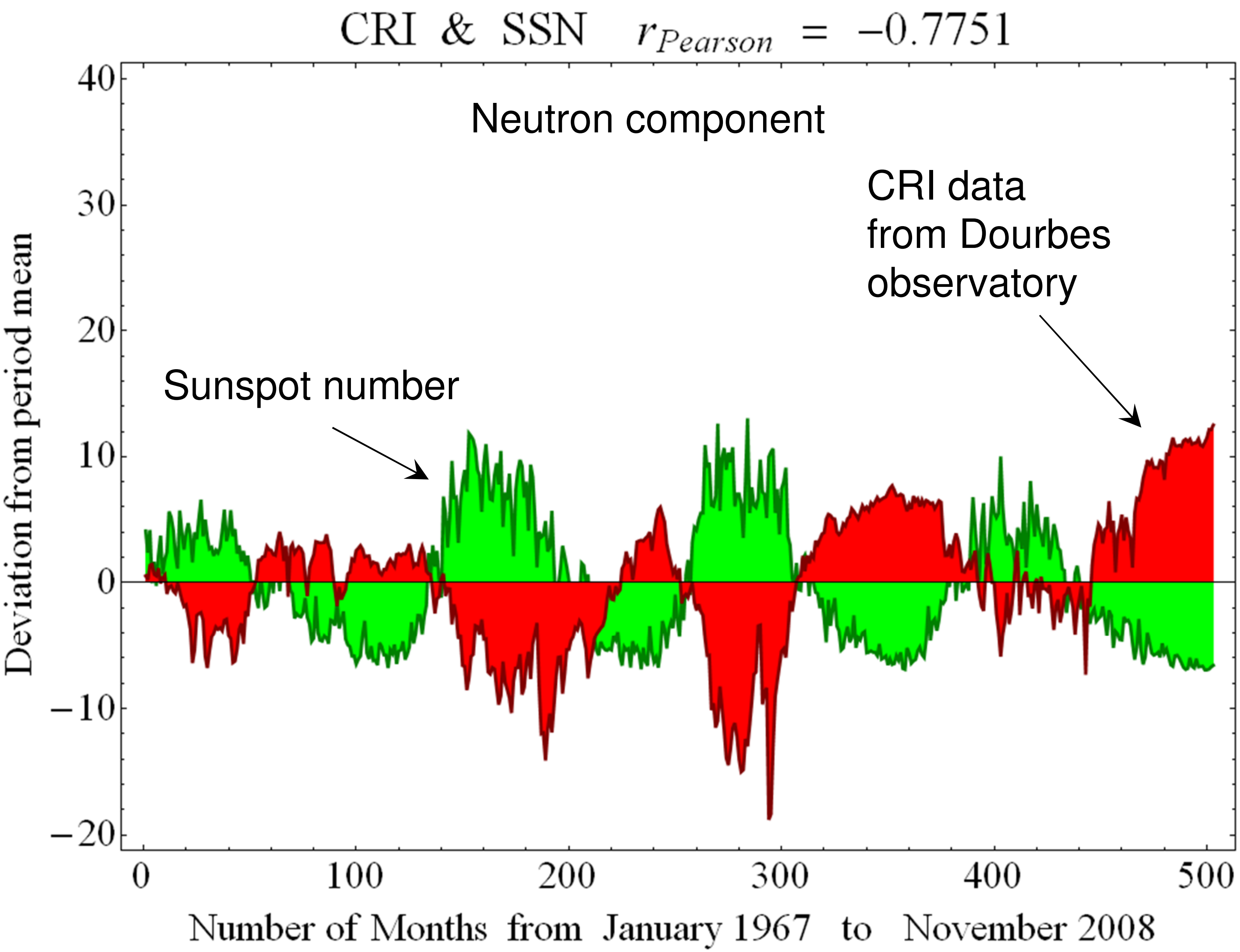
Source: University of Bern

The **cosmic ray intensity varies regularly and inversely to the solar activity cycle**, with the ray flux most pronouncedly decreased at high solar activity.



The level of the cosmic ray flux varies with solar activity - observed is eleven-year cycle variation of the cosmic rays. Because the solar activity varies significantly during the sunspot cycle, it is reasonable to expect that the interplanetary irregularities will also vary during the cycle, affecting the lower-energy cosmic rays much more than the higher-energy ones.

Characteristics



Dourbes

The level of the cosmic ray flux varies with solar activity (negative correlation) - observed is eleven-year cycle variation of the cosmic rays.

Techniques and Instruments

- **Neutron monitor**
- **Muon detector**
- **Extensive air showers arrays**
- **Cherenkov detectors**
- **Balloon detectors**

Ground-based **cosmic ray detectors** can be divided into subgroups according to the components they measure: nucleonic (protons and neutrons), meson (muons) and electromagnetic (photons, electrons, etc) components.

➤ Neutron Monitor (for detection of the nucleonic component, N and P, through their production of further neutrons)

Despite their decades of tradition, **ground based neutron monitors** (NM) remain the state-of-the-art instrumentation for measuring cosmic rays, and they play a key role as a research tool in the field of space physics, solar-terrestrial relations, and space weather applications. They are sensitive to cosmic rays penetrating the Earth's atmosphere with **energies from about 0.5-20 GeV**, i.e. in an energy range that cannot be measured with detectors in space in the same simple, inexpensive, and statistically accurate way. **Two types of standardized detectors** (**IGY**, **NM64**) are in operation in a worldwide network that presently consists of about **50 stations**.

In order to increase the number of particles that are eventually detected, the neutron monitor counters are surrounded by lead. There the secondary nucleons (and a few muons), produce further neutrons. The neutron monitor counts these neutrons, but they ultimately reveal the cosmic ray flux at the top of the atmosphere.

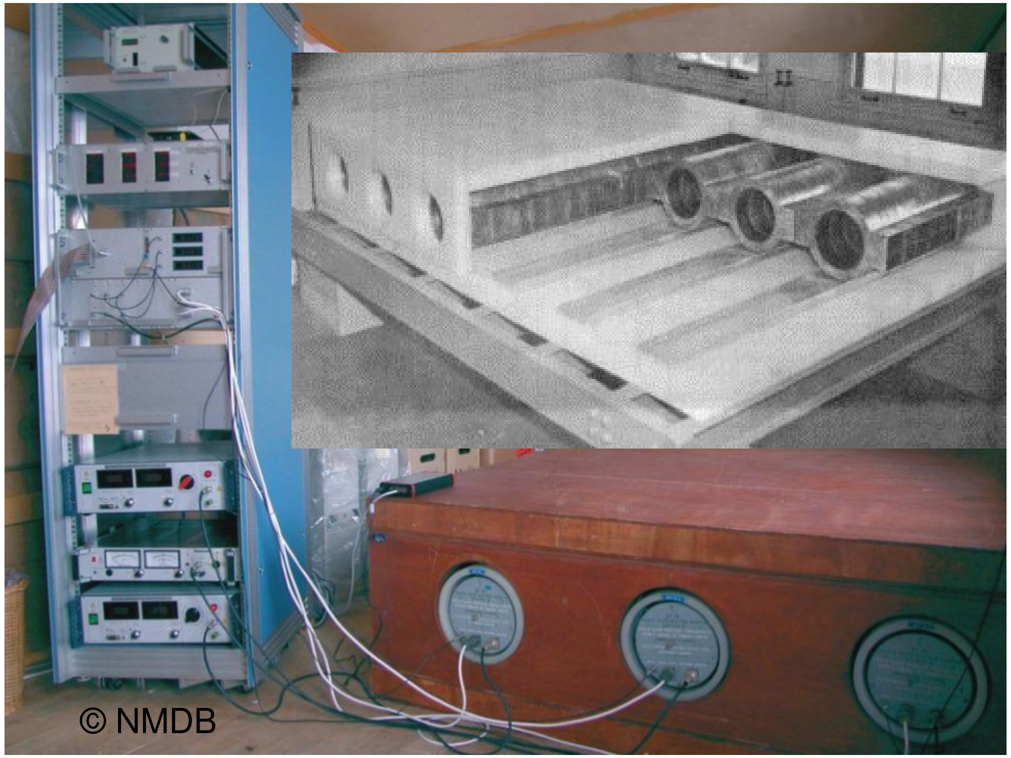


Fig. NM64 neutron monitor with three counter tubes (right, wood casing of reflector and counter tubes are visible) and rack (left) with counter electronics, high-voltage power supplies, and barometer.

Source: Neutron Monitor Database (NMDB)

➢ **Neutron Monitor** (design)

There are two types of standardized neutron monitors. The IGY neutron monitor was designed by Simpson (1958) in the early fifties of last century. It was the standard detector to study the time variations of the primary cosmic ray intensity at GeV-energies near Earth during the International Geophysical Year (IGY) 1957/1958. About ten years later Carmichael (1964) designed the larger NM64 neutron monitor with an increased counting rate. The NM64 was the standard ground-based cosmic ray detector for the International Quiet Sun Year (IQSY) of 1964.

Neutron monitors consist of special gas-filled proportional counters surrounded by a moderator, a lead producer, and a reflector. The incident nucleon component (protons and neutrons) of the secondary cosmic ray flux causes nuclear reactions in the lead, and evaporation as well as low-energy neutrons are produced. These MeV-neutrons are slowed down to thermal energies by the moderator, and in e.g. the NM64 about 6% of the MeV-neutrons are finally detected by the proportional counters tubes. The fact that finally neutrons are detected gives this cosmic ray detector its name: neutron monitor.

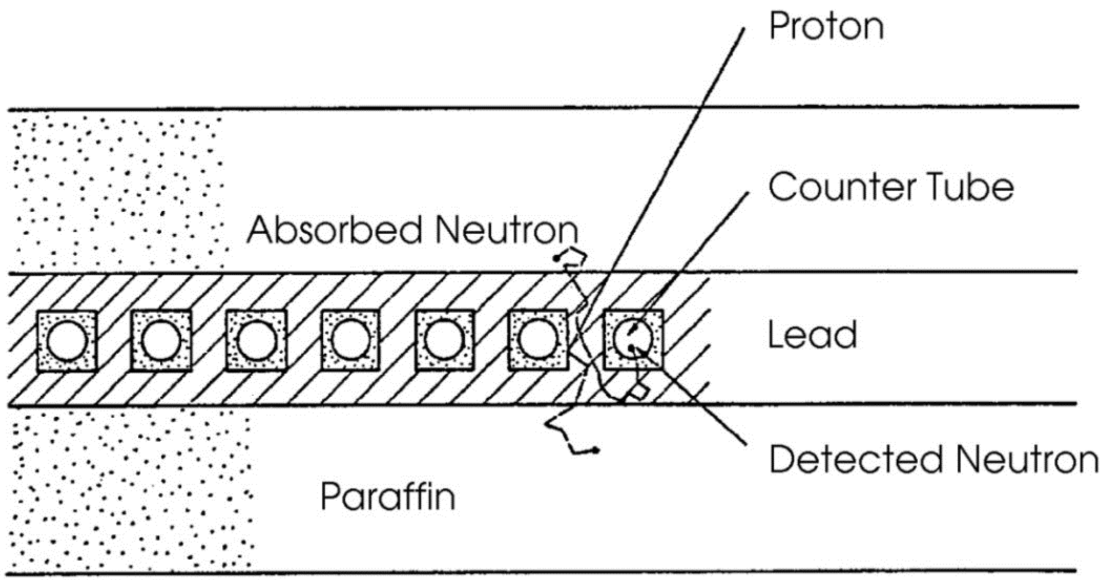


Fig. Shematic view of an IGY neutron monitor. The incident nucleon, here a proton, interacts with the lead. In the illustrated case three evaporation neutrons are produced in this nuclear reaction. In a random walk the neutrons travel in the different materials of the NM. Two neutrons are stopped in the reflector (absorbed neutron) and one evaporation neutron enters the moderator where it is slowed down, and finally it is detected in the counter tube.

Source: Neutron Monitor Database (NMDB)

➢ Muon detector

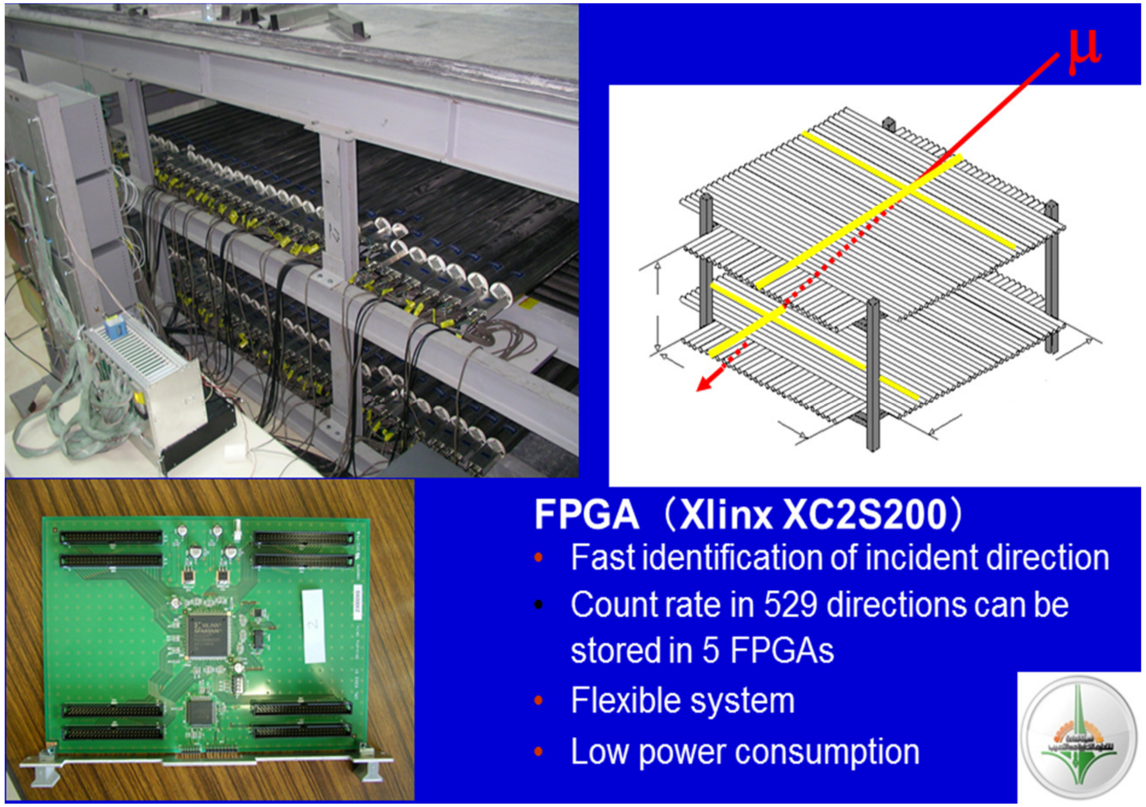
The muon component of the atmospheric cascade is measured by muon detectors. It is important to **note that only primary cosmic ray nucleons >4 GeV** have sufficient energy to generate muons that can penetrate through the atmosphere. The detection of the muons is realized e.g. by utilizing **Geiger-Mueller counters** or **scintillation counters**.

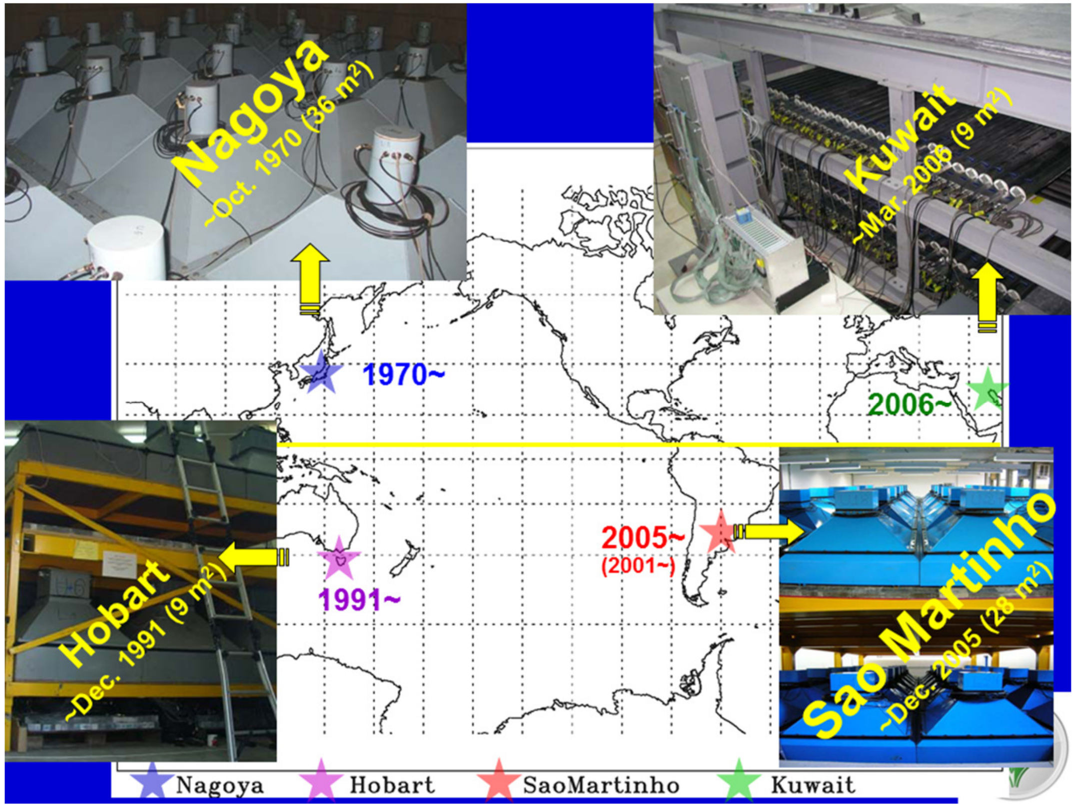
The **Geiger-Mueller counters require high voltage, which creates a very high electric field near the anode of the detectors**. When a CR particle enters a detector, it strips off some electrons from the counting gas and from the counter tube wall. These electrons are accelerated towards the positively charged wire and gain enough energy to strip more electrons from the counter gas molecules. In turn, these electrons are also accelerated and strip off more and more electrons. This electric avalanche consisting of more than a billion negative charges rains down on the positively charged wire, causing a current that flows into the simple detection circuit.

As a single Geiger counter is sensitive to particles coming from any direction, such a detector assembly does not permit the selection of specific orientations and of the particle family. The use of two or more Geiger detectors with the coincidence technique (simultaneous count signal in two or more counter tubes) offers the **possibility of carrying out more sophisticated experiments, e.g. discriminate muons and determine the direction of incidence**. It also allows to exclude the detection of terrestrial radiation.

Source: Neutron Monitor Database (NMDB)

➢ Muon detector





Note: The **high-energy part of the muon component is studied by underground detectors**. These detectors use the good penetration capability of muons in matter to easily distinguish muons from other CR components (except for neutrinos). The underground muon detector may be either a single detector or a small array. (Note that atmospheric, solar and cosmic neutrinos can also be studied deep underground. However, the size of the detector must be very large in order to compensate for the small cross section of neutrinos).

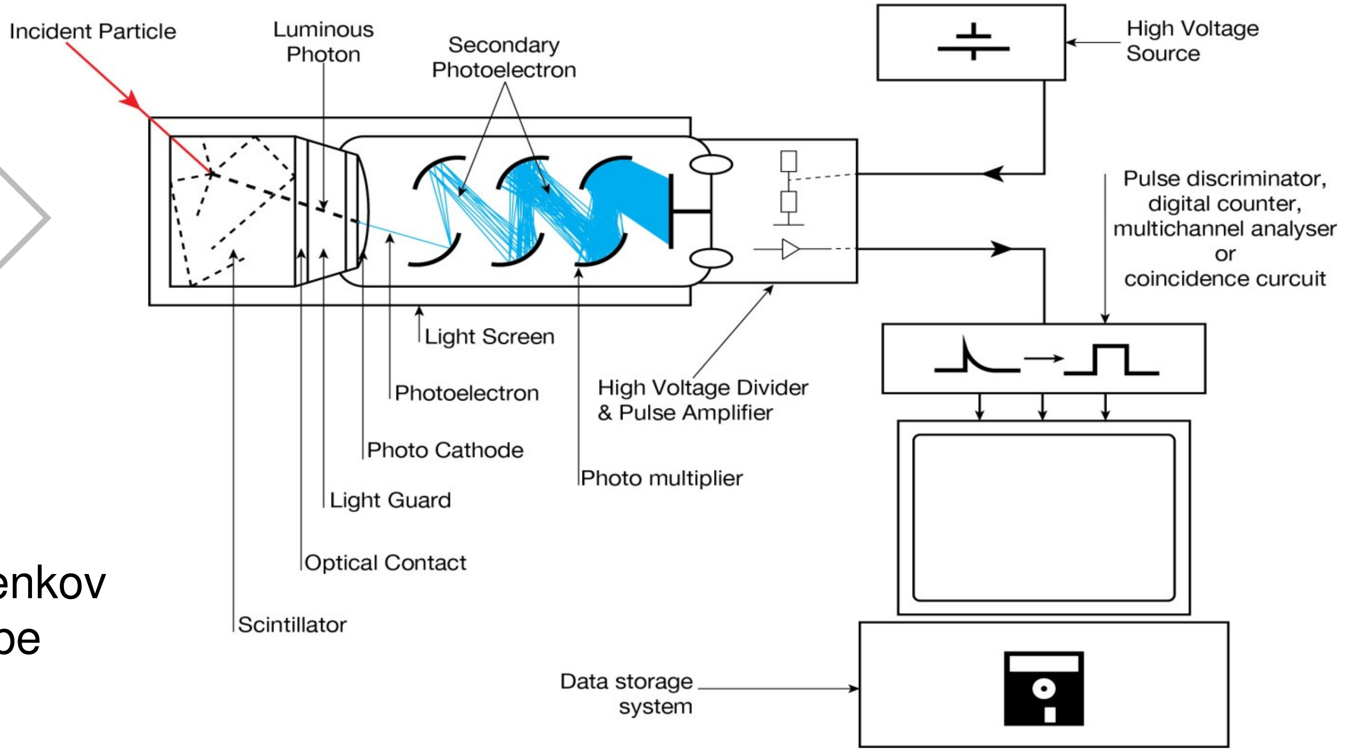
Source: Sabbah (2010): Solar modulation of galactic cosmic rays, Kuwait University.

Instruments

➢ Extensive air showers arrays

Extensive **air showers are detected with different kinds of particle detectors.**

Most common are scintillation counters that allow to measure the time of arrival with high accuracy



Further used devices are water Cherenkov counters, drift chambers, streamer tube detectors, and Geiger-Müller tubes.

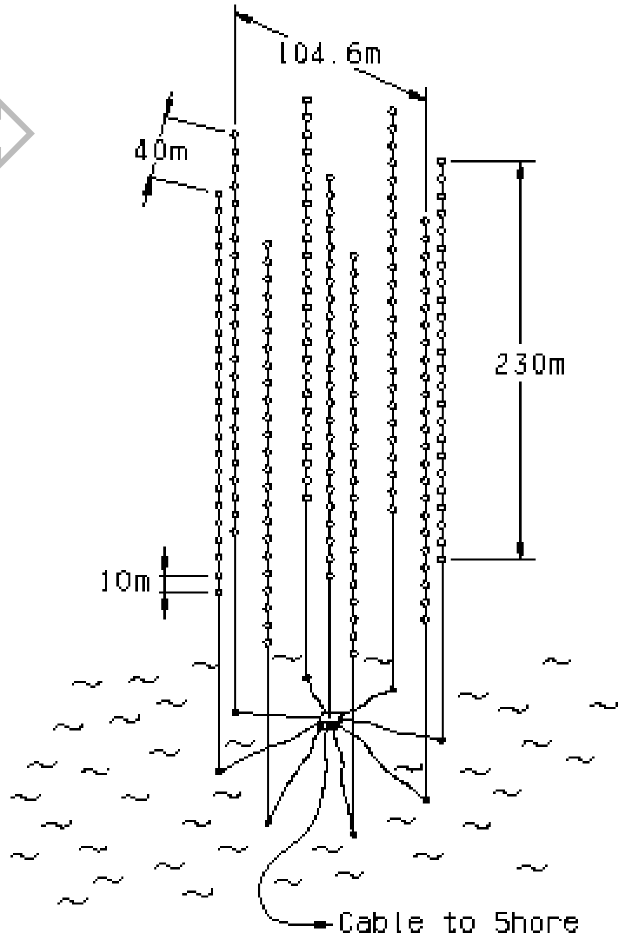
Position-sensitive devices allow to **measure the incidence direction of the particles**.
To detect extensive air showers coincidences of several particle detectors of **an array of tens or hundreds of detectors separated by 10-30 meters are required**. For the very large showers with billions of particles, the detectors have to be placed in a network with mash size of typically one kilometer. Therefore, **the size of an air shower array varies from hundreds of meters to tens of kilometers**.
Such arrays allow to study primary CRs with energies in the range 10^{12}-10^{21} eV.

Source: Neutron Monitor Database (NMDB)

➢ Cherenkov detectors

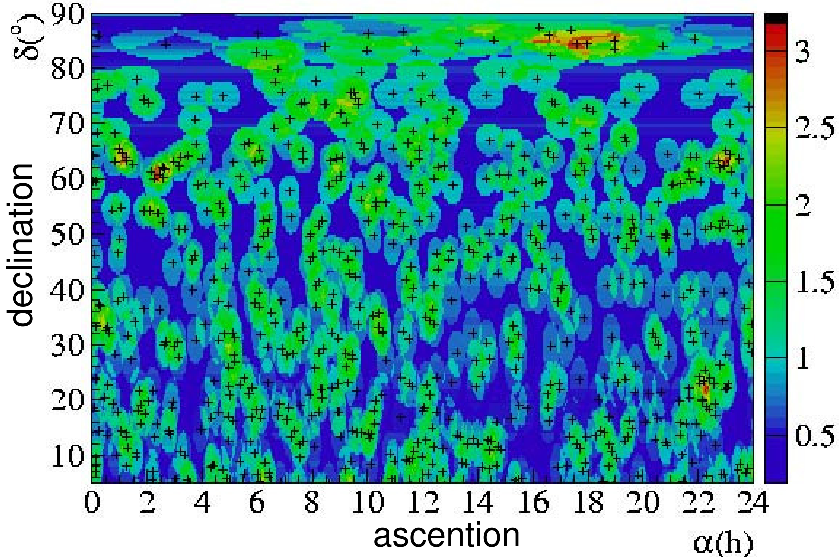
Relativistic electrons and positrons produced in the atmospheric cascade **generate Cherenkov emission in visible light** when propagated at a speed greater than the speed of light in that medium. The Cherenkov array collects these light pulses from a large volume (thousand cubic kilometers).

A similar technique is also used to study neutrinos where Cherenkov light pulses are produced under water (e.g. Deep Underwater Muon And Neutrino Detector, DUMAND)



or in ice (e.g. IceCube Neutrino Observatory or Antarctic Muon And Neutrino Detector Array, AMANDA).

Fig. 2000-02 upper limits (90% confidence level) on the neutrino flux integrated above 10 GeV in equatorial coordinates for declination δ>5◦. Limits (scale on right axis) are given in units of [×10^−8 cm^−2 s^−1] for the assumed E^−2 spectrum. The cross symbols represent the observed events. (Ackermann et al., 2004)



Source: Neutron Monitor Database (NMDB)

Instruments

➢ **Baloon detectors** (for primary CR particles)

Modern balloons bring detectors **up to altitudes of 40-70 km**. At these high altitudes, the atmosphere above the balloon is negligible for CR, and therefore the **balloon borne detectors observe directly primary CR particles**. In this sense they are like low-orbit satellites, only much cheaper and easier to operate.

Earlier, rather small and simple detectors were flown on balloons. However, today rather large and **complicated telescopes** such as the BESS (Balloon Borne Experiment with Superconducting Solenoidal Spectrometer) **detectors are flown on balloons**.

- The geomagnetic rigidity cutoff is still a significant effect for balloon observations. Moreover, the **atmospheric albedo particles** (particles reflected or scattered back into space from the atmosphere) **are also measured by balloon detectors** and therefore have to be taken into account.
- The main **disadvantage of balloon-borne experiments is that they are campaign-like experiments**, operating only for a short time interval.

Source: Neutron Monitor Database (NMDB)

Geofysisch Centrum van het KMI * Centre de Physique du Globe de l'IRM

Dourbes (50.1N, 4.6E)

The Royal Meteorological Institute (RMI) Geophysics Centre at Dourbes (4.6°E, 50.1°N) is a complex observational site consisting of several observatories/stations – atmospheric, ionospheric sounding, cosmic rays, geomagnetic, GPS, etc.

Instruments

Neutron monitor

Neutron monitors have been used since the 1950s. They are still the state-of-the-art instrumentation for measuring cosmic rays from the Sun and the low-energy component of cosmic rays from elsewhere in the universe.


Dourbes

Dourbes Neutron Monitor (9-NM64)

Observations

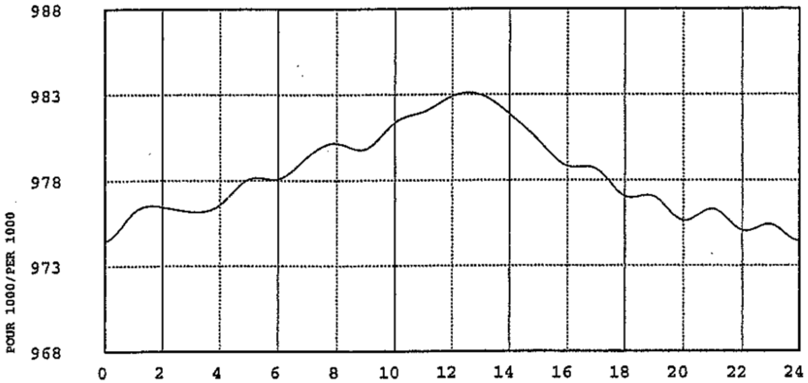
Dourbes

DOURBES JUILLET JULI

RAYONNEMENT COSMIQUE KOSMISCHE STRALING

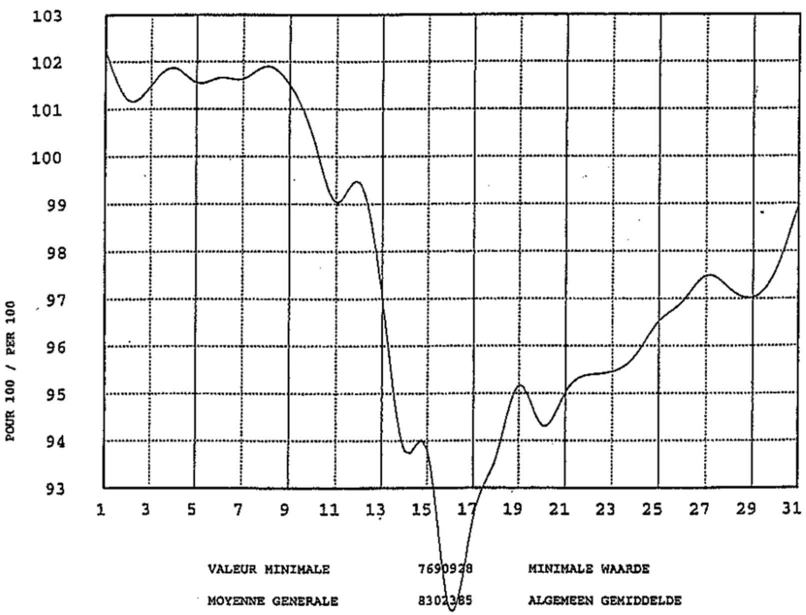
diurnal

VARIATION DIURNE NM64 DAGELIJKSE VARIATIE

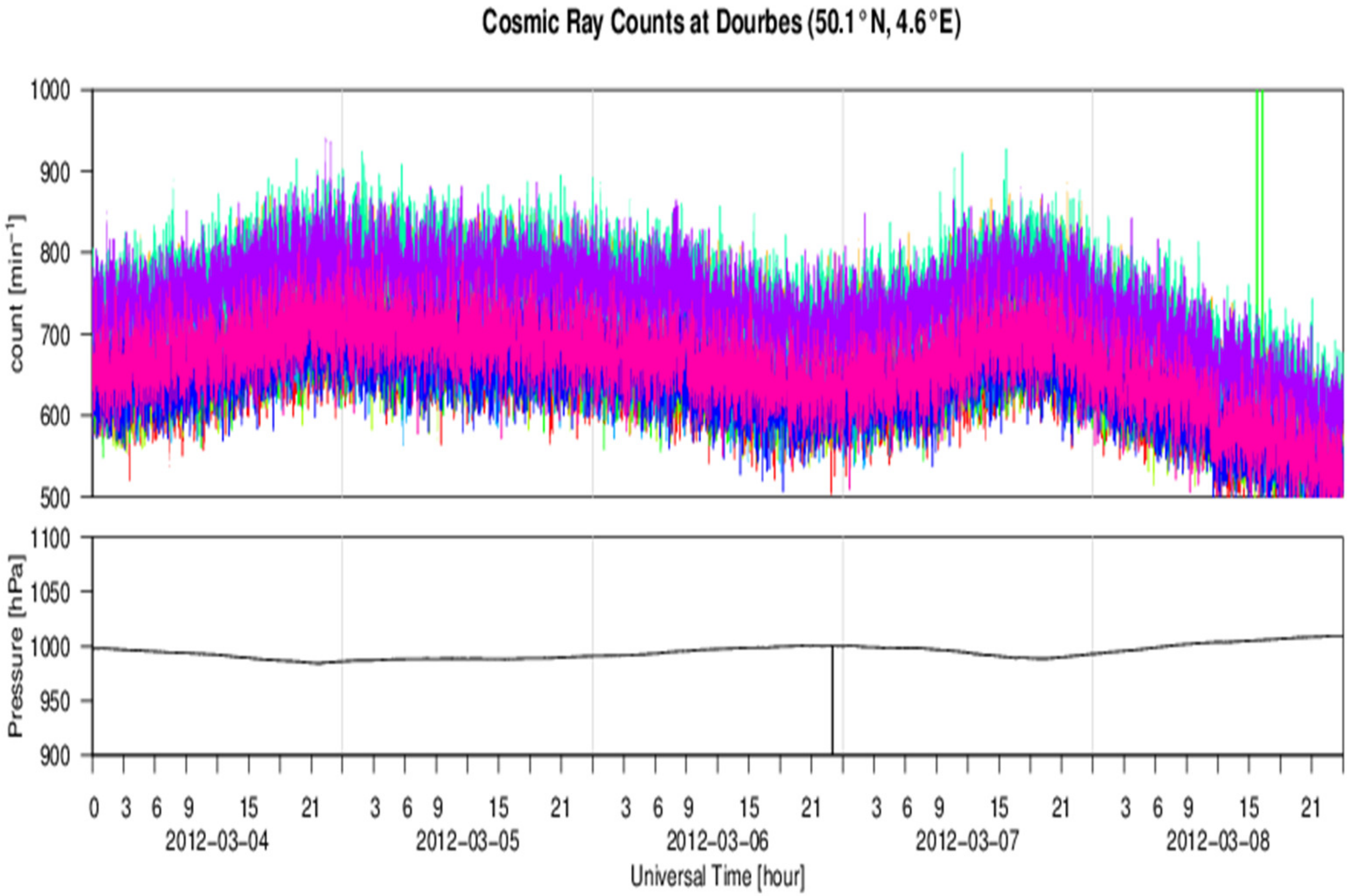


daily, over a month

INTENSITE JOURNALIERE NM64 DAGELIJKSE INTENSITEIT



VALEUR MINIMALE	7690928	MINIMALE WAARDE
MOYENNE GENERALE	8302385	ALGEMEEN GEMIDDELDE
VALEUR MAXIMALE	8690822	MAXIMALE WAARDE



July 2000 March 2012

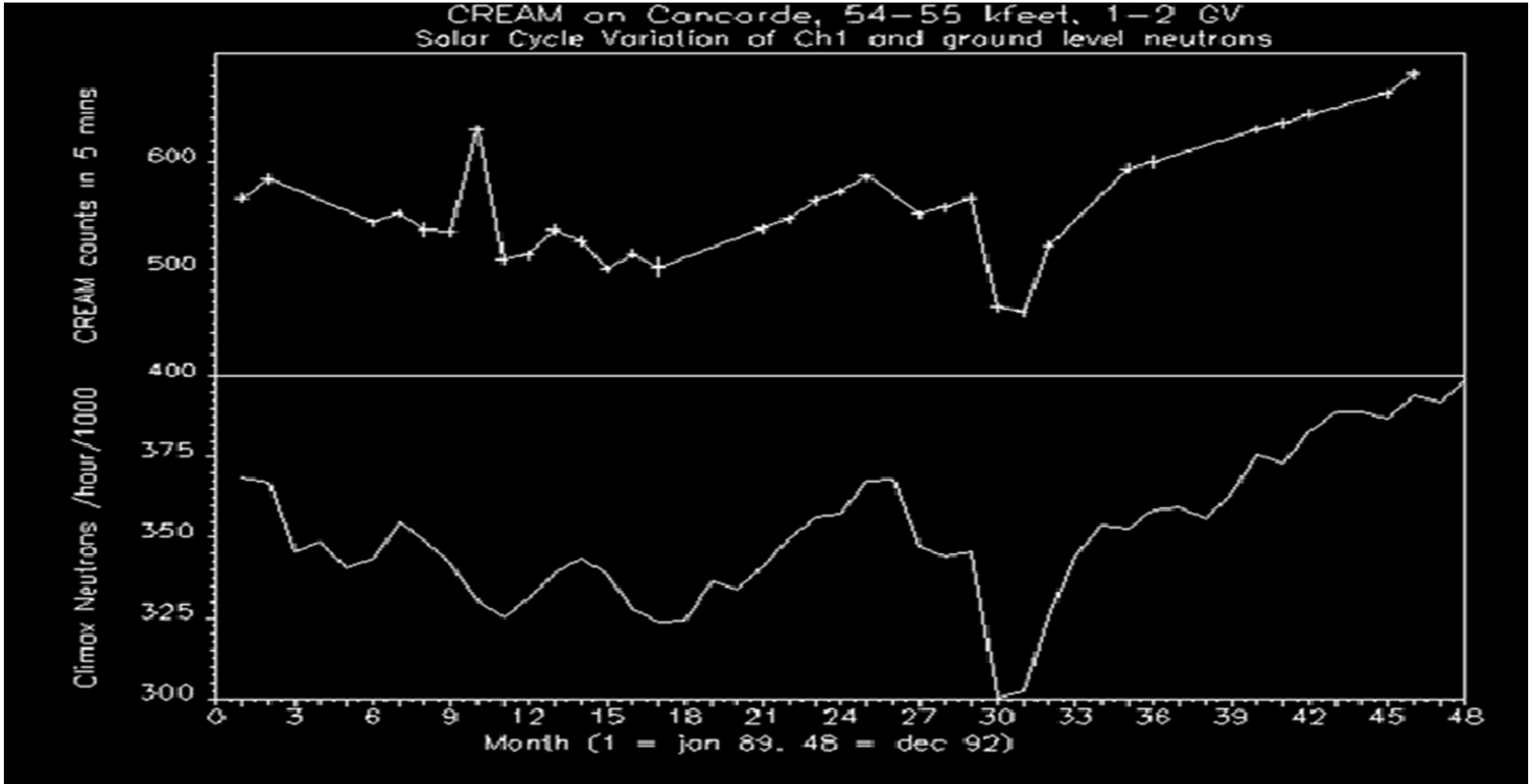
Why do cosmic rays matter ?

Cosmic rays are a formidable source of information about the universe and are still **an important topic of international research**, with many open questions waiting for answer. For example, under what circumstances and how charged particles are accelerated to such high energies or speeds.

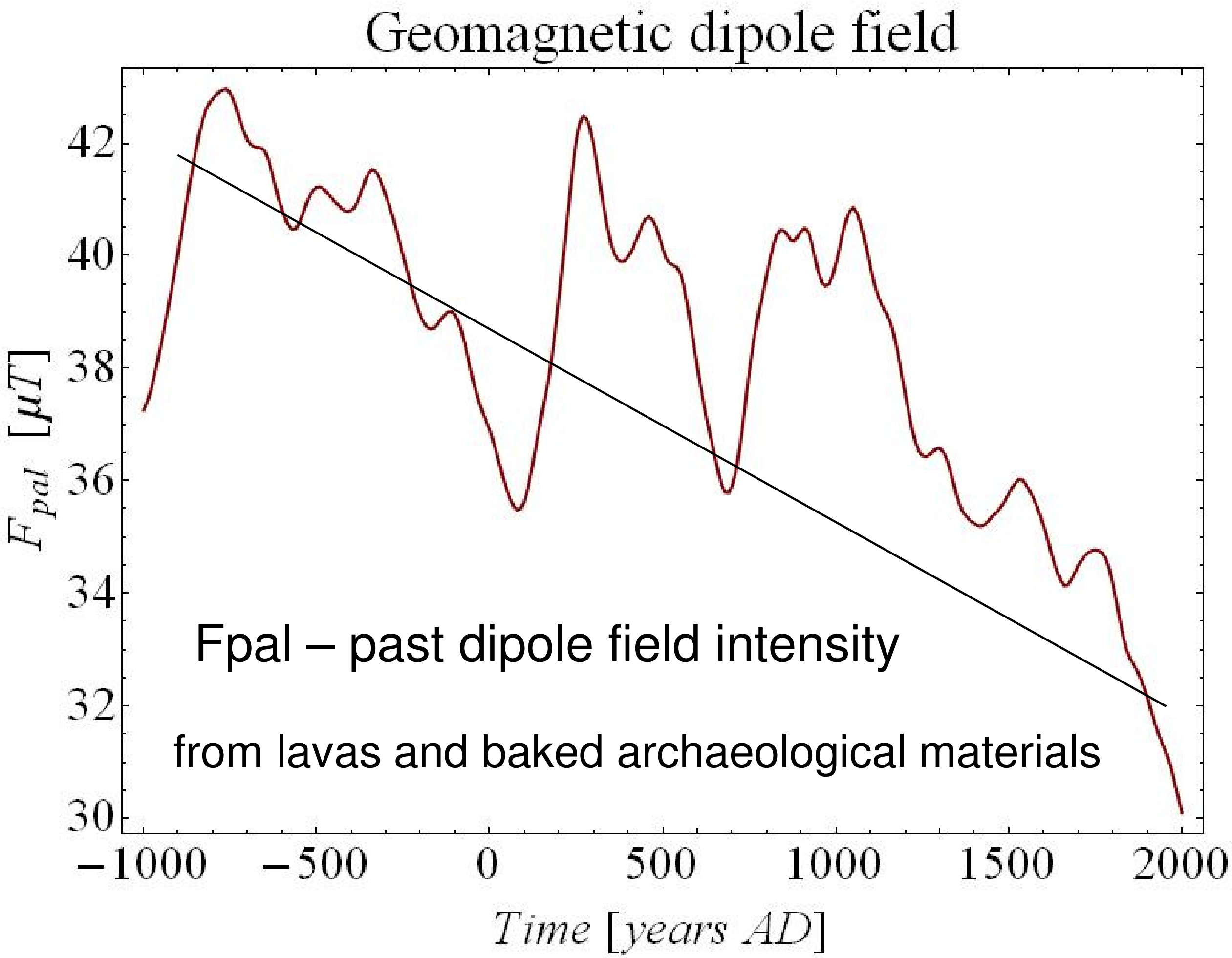
Cosmic rays can be used to monitor perturbations of the interplanetary medium that might reach the Earth. Many observations have shown that the galactic cosmic ray intensity is modulated by the magnetic field of the heliosphere: when the Sun has many spots, the magnetic field is strong in the heliosphere, and the intensity of galactic cosmic rays is reduced at the Earth. When there are no spots, the shielding is weak, and many cosmic rays reach the Earth. Faster intensity variations can be generated by solar eruptions, where magnetic fields are expelled into the heliosphere.

Furthermore, cosmic rays have a substantial impact on the Earth. They affect the Earth's atmosphere: by the secondary particles they produce when colliding with atmospheric atoms, and by the ionisation of atmospheric atoms. **Fast charged particles are a source of irradiation, as are X-rays, and therefore can be hazardous**. While there seems to be little effect on the ground, aircraft and spacecraft crews are less protected by the atmosphere and effects need to be monitored and investigated.

If protective measures are not taken, they can be a considerable **hazard to the aircraft/rocket crews**. Interestingly, CR flux at 10-15 km is much larger than at an altitude of 25 km.



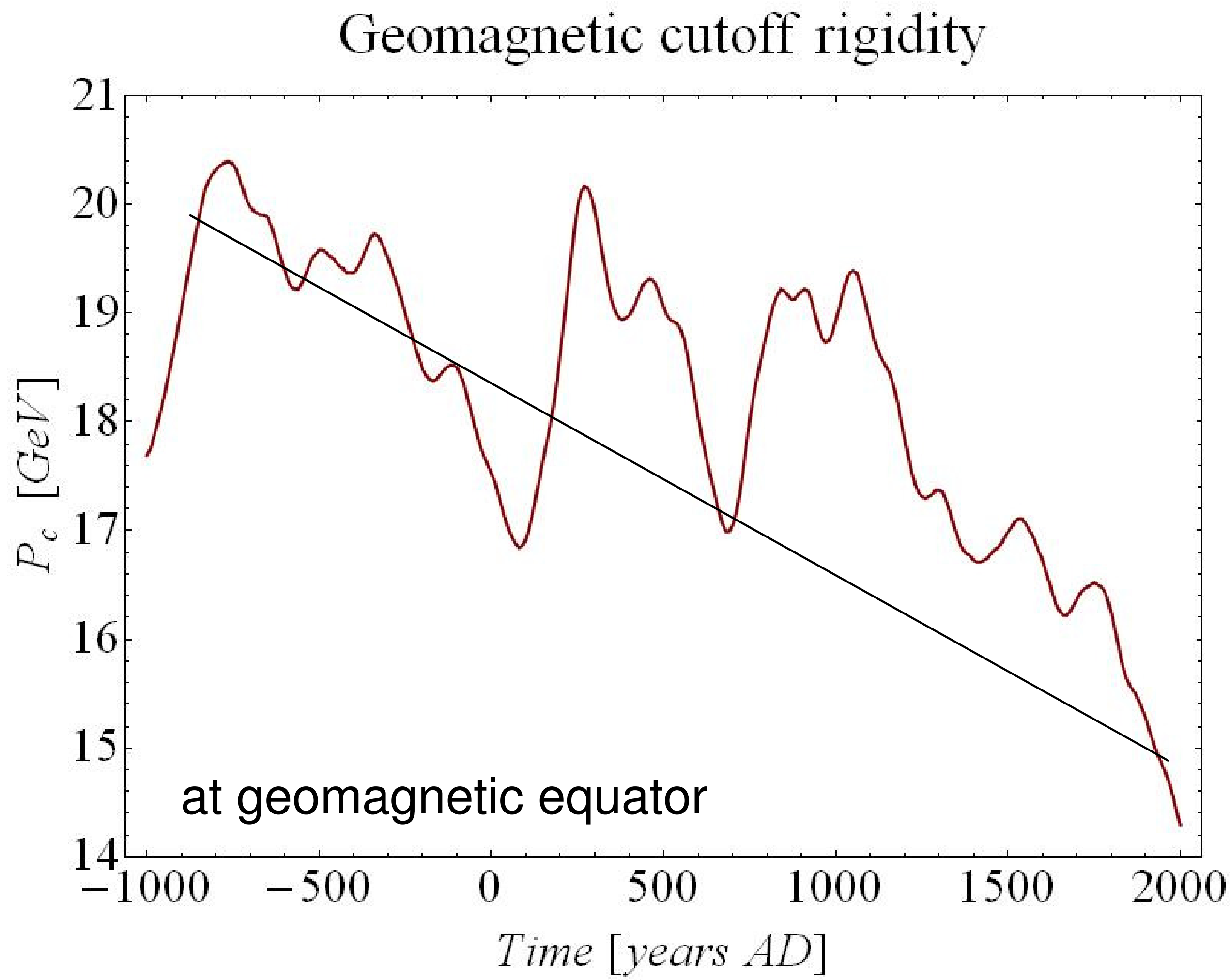
Cosmic rays rather than aurora cause increased radiation doses at aircraft altitudes. This figure shows the variation in cosmic ray flux over a number of years as measured by Concorde (top) and the ground based Climax neutron monitor (bottom). Note the sharp peak in September 1989. This was produced by a large solar particle storm.



Variations in µT range.

Decrease of ~30 % during the last 3000 years.

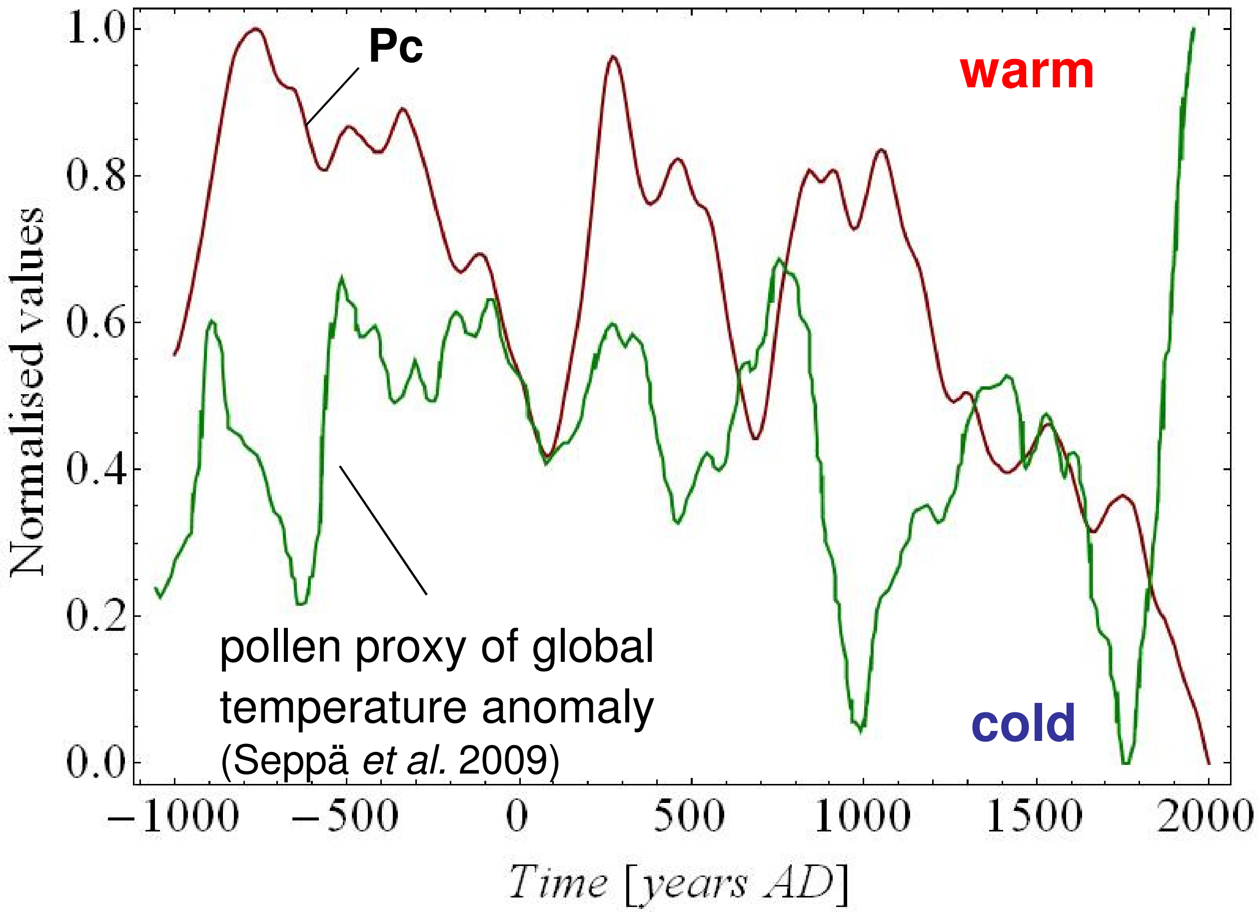
Secular variations and general decrease observed.



Today

Smaller cut-off rigidity

More cosmic radiation is able to penetrate the atmosphere than 3000 years ago.



Apparent negative correlation

Weaker field leads to:

-> more cosmic radiation

-> elevated atmospheric opacity

-> less LW (long wave) radiation emitted into space

-> increased surface temperature (~ warmer climate)

Neutron Monitor Database

Summary and Outlook

- The 100 years since Hess's discovery have seen **remarkable developments**. For example, the flux of high-energy particles arriving at Earth from beyond the solar system includes not only charged particles but also neutrals like gammas and neutrinos. There are also reported evidences that the cosmic-ray flux at the highest energies might be dominated by iron nuclei rather than protons.

- Cosmic-ray research today **benefits from new detector technologies** originally developed for particle physics. Large detectors nowadays fly on satellites as well as on balloons.

➢ **Research** on space weather effects associated with cosmic rays needed, many open questions exist and investigations are carried on.

➢ **Development of services** based on real-time monitoring of cosmic rays (e.g. solar and geomagnetic activity, detection of anomalous phenomena, etc.) complementing other services offered at RMI Geophysical Department.

➢ **NMDB (full) membership** to be maintained, with real time data provision and, in return, access to world-wide data