COSMIC RAY VARIATION

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Abstract. In recent years space weather and space climate became very important topics not only for pure astrophysical interest but also for societal ones. In that context cosmic rays play an important role and we will overview their general properties, their origin and give some applications of how they influence the dynamics of the Earth’s atmosphere. We give examples of two selected events and show the correlation between neutron flux measurements and the flare index.

Key words: space weather - cosmic rays - ozone variation

1. Introduction

The detection of cosmic rays goes back first to the detection of natural radioactivity in 1896 (Becquerel). At that time it was assumed that the fact that ionization is observed in the low Earth atmosphere can be explained by natural radioactive sources in or below the Earth’s surface. However, in 1912, V. Hess made his famous free balloon flight experiments and he detected that ionization strongly increases with height in the atmosphere. At the height he reached, 5000 m, the ionization was four times the surface value. In order to explain this remarkable observation he postulated external ionizing radiation, so called cosmic rays.

The next question was which particles can be found in cosmic rays, besides ionizing radiation. This was solved in the subsequent years and before the second World War it was known that the particles mainly consist of high energy protons that lead to a cascade of secondary particles when they enter the Earth’s upper atmosphere. In 1937 P. Auger established the scenario that is still valid (see Figure 1): high energetic particles interact with air nuclei and produce a cascade of secondary showers (of electrons, photons, muons, neutrons).
There is a connection between major solar energetic particle events and cosmic ray measurements. Large solar flares and CMEs can give rise to ground level enhancements (GLEs). In a paper given by Wang and Wang (2006), such events were studied for the solar cycle 23. It was found that for the GLEs observed there is a clear correlation with fast propagating solar coronal mass ejections.

Mavromichalaki et al. (2006) discuss how relativistic (galactic and solar) cosmic rays registered by neutron monitors can play a useful key-role in space weather storms forecasting and in the specification of magnetic properties of coronal mass ejections (CMEs), shocks and ground level enhancements (GLEs).

One other important property of cosmic rays is their usage as a proxy of total solar irradiance (TSI). Both the cosmic-ray intensity and TSI are modulated by the solar activity related magnetic fields. While the cosmic ray intensity depends only on the open fields, a major question is still how the open fields are related to the weak fields in the network on the Sun which seem to be responsible for the solar-cycle modulation of TSI. This was reviewed by Fröhlich, Beer and Muscheler (2005).
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2. Detection of particles

We will briefly overview the detection methods. Extensive Air Showers (EAs) on the ground can be observed by

- Scintillation counters,
- Water Cherenkov counters,
- Resistive plate chambers,
- atmospheric N molecules that emit fluorescent radiation.

The geomagnetic latitude determines the amount of energy a primary cosmic ray particle should have in order to reach the ground via cascade. Near the geomagnetic equator the value is higher than nearer to the poles. The altitude of the monitor station determines the amount of absorption.

2.1. Neutron Monitors

The first were built by Simpson, 1948-50, from the University of Chicago. The primary cosmic rays produce secondary particles, neutrons and the energies range from 100 MeV to several GeV. This causes reactions in lead, atoms become excited and when they return to the ground level, they emit photons that can be detected.

Examples of neutron monitor stations can be found worldwide: The Bartol Research institute operates 10 neutron monitors worldwide: Mc Murdo, South Pole (Antarctica), Thule (Greenland), Newark (Delaware), Inuvik, Fort Smith (NW Territories), Peawanuck (Ontario), Nain, Goose Bay (Labrador), the Climax station, the Moscow Neutron Monitor or the Apatity Neutron Monitor.

2.2. Cherenkov Detectors

When a particle enters a medium with a speed $v$ that is greater than the velocity of light in the medium ($v > c_m$) then a shock is produced and this causes Cherenkov radiation. Cherenkov detectors consist of water tanks with scintillation counters. A recent example of a large Cherenkov detecting system is the Pierre Auger Observatory (distributed over 3000 km$^2$) that...
is constructed in Argentina. It consists of an array of 1600 water detectors, separated by 1.5 km (see e.g. http://www.auger.org/).

The lateral distribution of Cherenkov light of an air shower initiated by a vertical particle of 300 GeV is spread over a filled circle with about 400 m of radius.

3. Origin of Cosmic rays

First we must make a distinction between charged particles and neutral particle and gamma rays. Only the charged particles are influenced by magnetic fields and there are many overlapping fields on different scales in the universe: galactic field, interstellar fields, heliomagnetic fields and finally the magnetic field of the Earth. Since charged particles are influenced by these, in principle we cannot tell anything about the direct origin of charged particles.

3.1. Highest Energy CR

They are believed to originate outside of our galaxy. The energy is in the range of $10^{20}$ eV. Due to their high momentum they suffer only little deflection during typical travel distances of 50 Mpc. Due to interaction with the cosmic background at energies above $10^{19}$ eV there occurs the so called GZK (K. Greisen, V. Kuzmin, G Zatsepin) cutoff and no particles $> 10^{19}$ eV should occur. Fly’s eye experiment in UTAH detected a particle of $\approx 3 \times 10^{20}$ eV. At surface such high energy particles can be expected as 1 CR /km² per 100 yr. The Pierre Auger Observatory will hopefully elucidate on that problem.

An example how such high energetic particles can be created is NGC 4261: accretion disk (about 100 pc) around a super-massive black hole in the centre of an active galaxy where particles are accelerated.

The origin of highest energy cosmic rays was reviewed by Shapiro, 2005.

3.2. Galactic Cosmic Rays, GCR

These particles originate from inside the galaxy and consist of totally ionized atoms (Fe...). Since they are charged they are trapped by the galactic
magnetic field. One acceleration mechanism may be SN remnants. By interaction with interstellar matter gamma rays are emitted.

3.3. Anomalous Cosmic Rays, ACR

The whole planetary system and beyond is protected by the heliosphere. Neutral particles can enter the heliospheric boundary without any deflection. Charged particles are deflected and can penetrate only when their energy is sufficient. The interstellar neutral gas flows through the heliosphere and when approaching the Sun the particles get ionized either by UV radiation or by charge exchange. Now they have become pick up ions and are transported by magnetic disturbances to the heliospheric termination boundary. At the termination shock many collisions occur, the ions get energy and diffuse again backwards toward the inner heliosphere, now they become ACR. Voyager 1 has passed the termination shock December 2004 and Voyager 2 will pass it in 2008.

3.4. Solar Energetic Particles, SEP

Solar energetic particles (SEPs) are associated with CMEs and solar flares. The particles move away from the Sun due to plasma heating, acceleration, numerous other forces. On the scale of cosmic radiation, SEPs have relatively low energies. An increase in the intensity of solar cosmic rays is followed by a decrease in all other cosmic rays this is called a Forbush decrease.

3.5. Summary

In Table I we give a summary of the properties of CR.

Concerning the variation of Solar cosmic ray particles we can state that there occurs a factor of 2 over the solar activity cycle, however, for single events during a solar flare it can be much higher.

Just for comparison let us give the following numbers:

- Photons from the Sun: 1.4 GW km$^{-2}$. Thus a collector with an area of 1 km$^{2}$ gives enough energy for the supply of a small town.
Table I: Properties of the different types of CR.

<table>
<thead>
<tr>
<th>Type</th>
<th>Energy in eV</th>
<th>Particles</th>
</tr>
</thead>
<tbody>
<tr>
<td>SEP</td>
<td>&lt; 1 MeV</td>
<td>partially ionized</td>
</tr>
<tr>
<td>ACR</td>
<td>10 MeV</td>
<td>singly ionized</td>
</tr>
<tr>
<td>GCR</td>
<td>GeV up to $10^{20}$ eV</td>
<td>fully ionized</td>
</tr>
</tbody>
</table>

- All CR particles: the amount of energy striking the Earth is $5 \text{ J} \text{s}^{-1} \text{km}^{-2}$. Since $J/s = W$ we find that an area of $12 \text{ km}^2$ can supply a 60 W bulb.

In Figure 2 ACE measurements of a spectrum of oxygen nuclei, integrated over a 3-year period and extending over six decades in energy are given.

3.6. Observed GLEs

On January 20, 2005, the Sun emitted CRs of sufficient energy to increase radiation levels at the surface of the Earth. The GLE was especially intense at the South Pole, Mc Murdo, Antarctica. The largest ever recorded GLE was that of February 23, 1956 (Meyer, Parker and Simpson, 1956). For the flare event the following data can be found in the paper:

- Visual observations
  - $H \alpha$ max. intensity: 3.42, Febr. 23.
  - $H \alpha$ line width 18 Å.
  - area $1.3 \times 10^{-3}$ of visible surface.

- effect on ionosphere
  - SID beginning daylight side 0.30 to 0.32 UT
  - dark side on Earth: effect similar to sunrise on the ionosphere

- solar radio burst emission: onset 3.33 UT

- Geomagnetic storm: 3.09 UT, Febr. 25.
3.7. LONG TERM MODULATION OF CR DURING SOLAR CYCLES

The CR data clearly are related to solar activity. This was described by Sabbah and Rybanský (2006), where more references can be found. These authors used neutron monitor counts at Climax from 1953 - 2001. This long data set covers the solar activity cycles 19, 20, 21, 22 and part of 23. They found that the best correlation of CR with solar activity is with the total solar coronal hole area (correlation coefficient r=0,93) and not e.g. with the sunspot number.

The CR intensity is anti-correlated to the magnitude of the interplanetary magnetic field $B$ as well as to the product of $B$ and solar wind speed $V$. Concerning the correlation to the coronal hole area, there is a lag by 3-6 solar rotations. This can be explained as follows: the solar wind propagates...
Figure 3: Results of the cosmic ray measurements, adapted from Meyer, Parker and Simpson, (1956)

<table>
<thead>
<tr>
<th>Surface</th>
<th>Radiation dose</th>
</tr>
</thead>
<tbody>
<tr>
<td>Earth</td>
<td></td>
</tr>
<tr>
<td>Polar</td>
<td>40 - 120 milliSievert per year</td>
</tr>
<tr>
<td>Equator</td>
<td>3 - 8 milliSievert per year</td>
</tr>
<tr>
<td>Japan</td>
<td>10 - 30 milliSievert per year</td>
</tr>
<tr>
<td>Moon</td>
<td>600 - 1500 milliSievert per year</td>
</tr>
<tr>
<td>Mars</td>
<td>600 - 1500 milliSievert per year</td>
</tr>
</tbody>
</table>

and it needs this time to reach 25-50 AU where the modulation of CR starts.

3.8. Radiation on different surfaces

The radiation on different surfaces is given in Table II.

For the Moon and Mars the values are identical, for Mars the GCR is enhanced over the SEPs.
4. Cosmic rays and Clouds

The global annual mean forcing owed to various types of clouds, from the Earth Radiation Budget Experiment (ERBE) was described in detail in Dorman (2006).

We give some important numbers from that table. The net forcing in Wm$^{-2}$ for high clouds is 2.4 (for thin) and -7.0 for thick clouds. An increase in thick clouds thus leads to a cooling whereas for thin clouds to a slight warming. For middle clouds the values are 1.1 (thin clouds) and -7.5 for thick clouds. Thus an additional production of thick clouds there again cools the atmosphere. The most pronounced effect of cooling is for low clouds of all types. Here the albedo dominates and thus the cooling effect is -16.7 Wm$^{-2}$. If all the net values are added for clouds in different heights, the net cooling is -27.7.

Now the critical link to cosmic rays might be that they produce more low clouds by acting as condensation nuclei. That mechanism was pointed out by Svensmark and Friis-Christensen (1997) and Svensmark (1998, 2000).

![Diagram](image)

*Figure 4: Cosmic ray and cloud formation*

These authors claim an increase in global cloudiness by 4-5% over an activity cycle which corresponds to a radiative forcing of about 0.7 Wm$^{-2}$. In this context let us consider the magnetic latitude dependent variation of cosmic rays over a solar cycle: near the magnetic poles the variation is $\approx 50\%$, near the magnetic equator the variation is $\approx 5\%$. The average variation is about $\approx 15\%$. The ionization rate near the surface is two ion pairs s$^{-1}$ cm$^{-3}$ and at the top of the troposphere about 40.

The theory of a cosmic ray generated cloud cover was tested by several
other authors and we want to note that this is still regarded as controversial.

Arnold and Wilhelm (2003), found of support of the hypothesis of cosmic ray-induced formation of aerosol particles and cloud condensation nuclei. Hedfors et al. (2006) investigated satellite data of cloudiness over Scandinavia and stated that the results indicate a coherent negative correlation between total cloud cover and $^7$Be on intra-seasonal, seasonal, and decadal scales. Palle, Butler and O’Brien (2004) stated that a reduction in low cloud cover since the late 19th century, combined with the direct forcing by solar irradiance can explain a significant part of the global warming over the past century, but not all. Usoskin et al. (2004) claimed that the time evolution of low cloud amount can be decomposed into a long-term trend and inter-annual variations - a clear 11 - year cycle with strong correlation with cosmic ray induced ionization.

4.1. Cosmic rays and climate

The cosmic ray flux is modulated by solar activity. When solar activity is at maximum, the flux is reduced because of the stronger heliomagnetic field. Therefore, solar activity and cosmic ray particle flux are anti-correlated. Cosmogenic isotopes like $^{10}$Be or $^{14}$C can serve as proxies. There are well documented phases of reduced solar activity over longer periods. The Maunder Minimum between 1645 and 1715 is a very well known example. From $^{10}$Be proxy data it can be reconstructed that the cosmic ray particle flux at 1 GeV was 3 times that of sunspot minimum in 1965. Since an enhanced CR flux correlates with enhanced global cloudiness which reduces surface temperatures, that period of cool climate can be explained by low solar activity and enhanced CR flux induced cloud production. The modulation of the galactic cosmic radiation over the past 1150 years is investigated using $^{10}$Be data from Greenland and the South Pole (Mc Cracken et al., 2004). In their studies they took into account the secular variations of the magnetic Earth dipole. They found high values for the cosmic ray flux in the Sporerer minimum (1429-1540), Maunder Minimum (1645-1715) and a lower cosmic ray intensity than that attained in 1739 was not observed again until after 1950, at a time of high solar activity.
4.1.1. **COSMIC RAYS AND OZONE CONCENTRATION**

Ozone is a very important trace gas in the stratosphere especially from the biological point of view. The Chapman reactions which can be found in textbooks on the atmosphere, describe the balance between ozone creation and destruction. How does solar variability influence on the ozone concentration?

1. Radiation: enhanced UV radiation warms the stratosphere and destructs the ozone by the reaction

   \[ \text{O}_3 + h\nu \rightarrow \text{O}_2 + \text{O} \quad \lambda < 320\text{ nm} \quad (1) \]

2. SEP: solar protons lead to enhanced ionization thus secondary electrons are produced that enhance the dissociation of \text{N}_2 and creation
of NO and O and also OH is increased that destructs ozone.

Therefore during solar protons events the ozone shield will be reduced. The reduction of ozone during SEPs increases with height in the atmosphere, e.g. in the mesosphere 70-80% of ozone was destructed during events like Oct 1989 or the Bastille day event on July 14th 2000.


In Figure 5 we show on the upper part the Climax neutron monitor measurements and on the lower part the global mean ozone concentration variation of the Nov 4, 2001 event. For that event the proton flux > 10 MeV was given at 31700, from Nov 4, 17.05 UT to Nov 6, 20.15 UT. An X1 flare was observed on Nov 4, 16.20 UT.

In Figure 6 the variation for neutrons and ozone is given for the Bastille day event, July 14, 2000. The proton flux > 10 MeV during July 14, 10.45 UT and July 15, 12.20 was 24000. An X5 flare appeared on July 14 at 10.24.

The two selected examples show that the cosmic ray flux variation on short time scale shows little influence on the ozone measurements on global
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![Graphs showing Flare Index vs Climax Data for 2000 and 2005.](image)

*Figure 7: Daily Climax neutron measurements and flare index.*

scale and averaged over the whole atmosphere. The effect is most pronounced in mesospheric layers. In both cases the variation is about 1% for the total ozone content.

4.1.2. COSMIC RAYS AND FLARE INDEX

In Figure 7 we show the flare index plotted against the Climax cosmic ray flux for the years 2000 (solar maximum) and 2005 (near minimum). It is clearly seen that there is a trend towards lower neutron fluxes for increasing flare index for both years. Flare Index Data used in this study were calculated by T. Ataç and A. Özgüç from Boğaziçi University Kandilli Observatory, Istanbul, Turkey.

**References**

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