An overview of the physics of the Earth's radiation environment

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1 Introduction

The Earth's radiation environment consists of three major components: the galactic cosmic rays (GCR), the solar energetic particles (SEPs) or solar cosmic rays (SCR), and the trapped particles of the Van Allen belts. In the following sections, we will briefly outline the physical processes that determine the evolution of these components. The level of the paper is designed to provide the necessary tutorial background information for getting familiar with the physics of the radiation environment. It is, however, not aimed at providing a comprehensive review to the subject.

2 Rationale – Physics behind the models

2.1 Cosmic-ray modulation

Before reaching the vicinity of Earth, Galactic cosmic rays (GCR) experience complicated transport in the heliosphere that leads to the GCR modulation, which determines the long-term variations of this component of the radiation environment. The CR transport is described by the Parker's equation (Parker, 1965; Toptygin, 1985):

$$\frac{\partial U}{\partial t} = \nabla \cdot (\mathbf{K^s} \cdot \nabla U) - \nabla \cdot (\mathbf{V_{sw}} U) - \nabla \cdot (\langle \mathbf{v_D} \rangle U) + \frac{1}{3} (\nabla \cdot \mathbf{V_{sw}}) \frac{\partial}{\partial T} (aTU) , \tag{1}$$

where $U(T, \mathbf{r}, t)$ is the CR number density per unit interval of particle kinetic energy, T; $\mathbf{V}_{\rm sw}$ is the solar wind (SW) speed; $a = (T + 2T_r)/(T + T_r)$ where T_r is the particle's rest energy; $\mathbf{K^s}$ is the symmetric part of the diffusion tensor. This equation describes the following basic processes affecting the CR transport in the heliosphere. The diffusion of particles due to their scattering on magnetic inhomogeneities is represented by the first term of the equation. The second term describes the convection of particles by the outblowing solar wind. Next term deals with drifts, via the average drift velocity $\langle \mathbf{v_D} \rangle$, that CR particles experience in the heliosphere. Two types of drifts are important: the gradient-curvature drift in the regular heliospheric magnetic field, and the drift along the heliospheric current sheet (HCS), which is a thin magnetic interface between the two heliomagnetic hemispheres. Note that, although the drifts play an important role in the CR modulation (Jokipii and Thomas, 1981), they do not modify the CR spectrum *per se* but only in combination with other mechanisms. The last term in Eq. 1 accounts for the adiabatic energy losses in the expanding solar wind. The local interstellar spectrum (LIS) of CR forms the boundary condition for the heliospheric transport problem. Since the LIS is not measured directly, i.e. outside the heliosphere, it is not well know in the energy range affected by the CR modulation (below 100 GeV). In this energy range LIS is usually assumed basing on the modeled CR production and transport in the galaxy and/or on inverting the heliospheric modulation models. Presently used approximations for the LIS (e.g. Garcia-Munos et al., 1975; Burger et al., 2000; Moskalenko et al., 2002; Webber and Higbie, 2003) agree with each other for energies above

20 GeV but may contain uncertainties of up to a factor of 1.5 around 1 GeV. These uncertainties in the boundary conditions make the results of the modulation theory slightly model-dependent (see discussion in Usoskin et al., 2005) and require the used LIS model to be explicitly cited.

The transport equation (1) cannot be solved analytically, and a full numerical solution of the 3D time-dependent transport equation is a complicated task and requires knowledge of the heliospheric parameters which cannot be directly measured (e.g., the diffusion tensor – see Burger and Hattingh, 1998). Accordingly, the full solution (e.g. Kota and Jokipii, 1983; Kota, 1995) is usually applied to qualitative theoretical studies, while different simplifications are often used for practical purposes. Usual assumptions on the azimuthal symmetry and quasi-steady changes reduce the problem to a 2D time-independent problem, which can be successfully solved numerically (e.g. Langner et al., 2006; Alanko-Huotari et al., 2007). Note that these simplifications can be applied to time scales of longer than the solar rotation period. As next step one can assume that the heliosphere is spherically symmetric, thus reducing the problem to a 1D case (Gleeson and Axford, 1968). This approximation can be used only for rough estimates, since it eliminates the effect of the drifts, but it is useful for the long-term studies, when the heliospheric parameters cannot be evaluated (e.g., Usoskin et al., 2002; Caballero-Lopez and Moraal, 2004).

Using further but still reasonable assumptions (constant solar wind speed, roughly power-law CR energy spectrum, slow spatial changes of U), one can reduce the 1D equation to the force-field case (Gleeson and Axford, 1968), which can be solved analytically. The differential intensity J_i of cosmic ray nuclei of type i at 1 AU is given as

$$J_i(T,\phi) = J_{\mathrm{LIS},i}(T+\Phi_i)\frac{(T)(T+2T_{\mathrm{r}})}{(T+\Phi)(T+\Phi_i+2T_{\mathrm{r}})}, \quad (2)$$

where $\Phi_i = (Z_i e/A_i)\phi$ for a cosmic nuclei of i-th type (charge and mass numbers are Z_i and A_i), T and ϕ are expressed in MeV/nucleon and in MV, respectively, $T_{\mathrm{r}} = 938$ MeV, We stress again that this approach not only contains the explicit modulation potential ϕ, which corresponds to the mean rigidity losses of a CR particle in the heliosphere, but is also implicitly dependent on the LIS. We note that this approach gives the results at least dimensionally consistent with the full theory. Moreover, the spectrum of different GCR species measured at Earth can be perfectly fitted by Eq. 2 using the only parameter ϕ in a wide range of the solar activity level (see Fig. 1). Therefore, the force-field model provides a very useful and simple parametric approximation of the differential spectrum of GCR. This model contains only one variable parameter and, therefore, the whole energy spectrum (in the energy range from 100 MeV/nucleon to 100 GeV/nucleon) for protons and $\alpha-$particles can be described by a single number, the modulation potential ϕ, within the framework of the adopted LIS. However, we warn again that ϕ is only a formal spectral index whose physical interpretation is not straightforward, especially on short time scales and during periods of active Sun (Caballero-Lopez and Moraal, 2004).

2.2 Solar energetic particle transport

Solar energetic particles (SEPs), i.e., solar cosmic rays (SCR), are observed as two major types of events: gradual and impulsive. The gradual events are intense proton-rich particle events lasting from some days to week and having an ion composition close to that of the coronal plasma. The maximum proton energies observed in these events extend up to a few GeV in the most extreme cases. Gradual events are related to coronal mass ejection and gradual X-ray flares. The impulsive events are electron-rich and their ion abundances show huge enhancements of minor ion species such as ^{3}He and heavies relative to the coronal abundances. They last from a few hours up to a day and have smaller proton intensities than the gradual flares. These events are related to impulsive X-ray flares. The two types of events are thought to be accelerated in coronal shocks driven by CMEs and in turbulent magnetized plasma of impulsive flares by wave-particle interactions, respectively. (Reames, 1999)

In principle, SEPs propagate in the interplanetary magnetic field (IMF) according to the same equations of motion as the galactic cosmic rays. Usually, however, effects such as adiabatic deceleration, convection with the solar wind, and drifts due to inhomogeneities in the magnetic field can be neglected in the inner heliosphere for particles of speeds $v \gtrsim 0.2\,c$, where c is the speed of light. In the simplest approach to the SEP transport, one can thus use the same diffusive transport equation (1) as with GCRs, but now with only two terms remaining

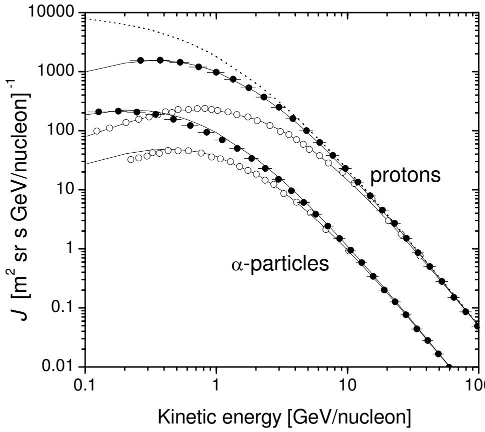

Fig. 1. Differential energy spectra of two most abundant components of GCR, protons (upper curves) and $\alpha-$particles (lower curves). Filled and open dots depict the results of direct measurements for a quite period of June 1998 (Alcaraz et al., 2000a,b) and a solar active period in September 1989 (Webber et al., 1991), respectively. The curves depict the best fit model results with $\phi = 530$ MV and $\phi = 1350$ MV, respectively (Usoskin et al., 2005). The dotted curve corresponds to the LIS ($\phi = 0$) for protons.

$$\frac{\partial U}{\partial t} = \nabla \cdot (\mathbf{K} \cdot \nabla U)\,, \tag{3}$$

where the diffusion tensor is usually taken to be of form $\mathbf{K} = K_{\|}(p,r)\mathbf{bb}$, i.e., only diffusion along the magnetic field, $\mathbf{B} = B\,\mathbf{b}$, is included. However, there is one important distinction relative to GCR that often invalidates the use of diffusive transport to describe SEP transport: unlike the GCR distribution with its quasi-stationary source outside the heliosphere, the SCR distribution has very anisotropic and rapidly evolving character.

The basic processes included in the non-diffusive SEP transport equation are streaming along the magnetic field lines, adiabatic focusing due to the decreasing magnetic field magnitude (by the conservation of the first adiabatic invariant), and pitch-angle diffusion due to the resonant interaction of the streaming energetic particles with the magnetic-field fluctuations (low-frequency plasma waves and/or turbulence), and the corresponding transport equation is known as the focused transport equation (Roelof, 1969; Ruffolo, 1991),

$$\frac{\partial f}{\partial t} + \mu v \frac{\partial f}{\partial s} + \frac{1-\mu^2}{2L} v \frac{\partial f}{\partial \mu} - \frac{\partial}{\partial \mu}\left(D_{\mu\mu} \frac{\partial f}{\partial \mu} \right) = Q, \tag{4}$$

where $f(s,v,\mu,t) = d^6N/(d^3x\,d^3p)$ is the distribution function of the SEPs on a given magnetic field line, s is the coordinate measured along the magnetic field, p is particle momentum, μ is the cosine of pitch angle (with $\mu = 1$ denoting outward propagation), $L = -B/(\partial B/\partial s)$ is the focusing length determined by the mean magnetic field, $B(s)$, as a function of distance, $D_{\mu\mu} = \frac{1}{2}\langle(\Delta\mu)^2\rangle/\Delta t$ is the pitch-angle diffusion coefficient, and $Q = Q(s,v,\mu,t)$ is the source function, determined by the processes that accelerate the particles in the solar corona and solar wind.

Later versions of the focused transport equation have included the effects of adiabatic deceleration and convection (Ruffolo, 1995) and partly even the effects of drift motions due to field inhomogeneities (le Roux et al., 2007). These are necessary especially if the energy changes of the particles in the solar wind, including particle acceleration in interplanetary shock waves, are to be modeled self-consistently. However, in the context of space weather engineering models, like SOLPENCO (see Sanahuja et al., this volume), the acceleration processes are typically handled in a phenomenological manner though an appropriately formulated source function Q. (SOLPENCO can be accessed on-line through http://www.spaceweather.eu .)

The most important unknown parameter in the focused transport equation is the pitch-angle diffusion coefficient. Usually, this parameter, $D_{\mu\mu} = \frac{1}{2}(1-\mu^2)\nu(v,\mu,s)$, is modeled by choosing the scattering frequency, $\nu \equiv \langle(\Delta\alpha)^2\rangle/\Delta t$ (where $\alpha = \arccos\mu$), to be of a power-law form $\nu = A(v,s)|\mu|^{q-1}$. The power-law index is, thus, determined by the spectral index, q, of the intensity of magnetic field fluctuations, $I(k) = I_0|k_0/k|^q$, through the quasi-linear theory (Jokipii, 1966). The magnitude, $A \sim \Omega(k_0 I_0/B^2)|k_0 v/\Omega|^{1-q}$, is related to the gyrofrequency Ω of the particle and to the intensity I_0 of the magnetic fluctuations at a reference wavenumber, k_0, but since the intensity is not known as a function of distance throughout the inner heliosphere, modelers usually fix A by introducing the parallel mean free path, $\lambda_\parallel$, through

$$\lambda_\parallel \equiv \frac{3v}{4}\int_{-1}^{+1}\frac{1-\mu^2}{\nu}d\mu = \frac{3v}{A(2-q)(4-q)}, \tag{5}$$

and adopting a spatial dependence for this parameter. (The rigidity dependence of the mean free path is usually taken to be fixed by q as $\lambda_\parallel \propto R^{2-q}$, consistently with the quasi-linear result.)

The physical meaning of $\lambda_\parallel$ is that under strong scattering, i.e., $\lambda_\parallel \ll L$, particle transport in the interplanetary medium becomes diffusive with the spatial diffusion coefficient along the mean magnetic field given by $K_\parallel = \frac{1}{3}v\lambda_\parallel$. In this case, we can write

$$\frac{\partial U}{\partial t} = \frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2 K_{rr}\frac{\partial U}{\partial r}\right), \tag{6}$$

where $K_{rr} = K_\parallel \cos^2\psi$, $\cos\psi = dr/ds$, ψ is the angle between the radial direction and the magnetic field, and r is the radial distance from the Sun. The attractive feature of this equation is that it can be solved analytically for reasonable assumptions of the spatial dependence of the diffusion coefficient. (See Dorman, this volume, for an example of using this equation to develop a forecasting model of SEP event evolution.)

The focused transport equation cannot be solved analytically in any realistic magnetic field geometry. Several simulation codes exist, however, to provide the numerical solutions, and they fall into two main types of solvers: (i) finite difference (FD) schemes (e.g., Ruffolo, 1991, 1995; Lario et al., 1998) and (ii) Monte Carlo (MC) simulations (e.g., Kocharov et al., 1998; Vainio et al., 2000). In FD schemes, one solves the focused transport equation directly on a grid, and in MC simulations one traces individual particles that follow the stochastic equations of motion equivalent to the focused transport equation. Both numerical methods have some attractive features and some drawbacks. The FD schemes are numerically very efficient and provide the solution for smoothly-behaving initial and boundary conditions very rapidly, but they are not ideally suited for δ-function-like particle injections, like for computing Green's functions of particle transport. The MC schemes, on the other hand are very easy to implement and update, because including a physical transport process to the code usually means a few lines of additional code. They can also easily handle any initial conditions and any boundary conditions that can be specified on a microscopic level, i.e., as rules of particle behavior at the boundaries of the simulation. As a downside, however, MC simulations usually require a large amount of CPU time to collect a large enough number of statistics for the reconstruction of the particle distribution.

2.3 Geomagnetic cutoff

The Earth's magnetosphere represents a natural shield against galactic and solar cosmic rays. The lower energy limit needed for a charged particle to cross the Earth's magnetosphere and access a specific position at the top of the atmosphere decreases with the geomagnetic latitude of the observer, resulting in a cosmic ray flux on Earth increasing poleward.

For the study of the interaction of cosmic rays with the Earth's environment it is important to quantify the cutoff rigidity, which represents roughly the a lower bound of the CR particle's rigidity needed to reach a position from a given direction (Cooke et al., 1991). For the purpose of the study of solar energetic particles observed on Earth during Ground Level Enhancement (GLE) or for the study of cosmic ray anisotropy, it is also important to determine the asymptotic direction of a cosmic ray particle, which represents its direction of motion before entering into the magnetosphere.

Cutoff rigidities and asymptotic directions of incidence are computed by using backward trajectory tracing codes, which combine an internal model of the Earth magnetic field and a magnetospheric magnetic field model (Smart et al., 2000; Flückiger and Kobel, 1990; Bobik et al., 2003). In these codes the trajectories of cosmic rays with different rigidities, arriving at the same observing position and from the same direction of incidence, are computed backward in time as illustrated in the main picture in Fig. 2. The curves represent the trajectories of positively charged particles with a rigidity of 20, 10, 5, and 4.52 GV. In this case all the trajectories are initiated in the vertical direction at 20 km altitude above Jungfraujoch Switzerland. Particles with 20 and 10 GV rigidities have small trajectory bending before escaping the Earth's magnetosphere. The particle with 5 GV rigidity is bent stronger but can still escape the Earth's magnetosphere. The 4.52 GV trajectory makes several complex loops before reaching another point on the Earth's surface, illustrating that for this specific rigidity a cosmic ray can not reach the Jungfraujoch location. Some trajectories not shown here, which neither go back to the Earth nor leave the magnetosphere, can also be observed. Trajectories that do not leave the Earth's magnetosphere are called forbidden trajectories while those of particles escaping the Earth's magnetosphere are called allowed trajectories. The direction of motion at the position where an allowed trajectory crosses the magnetopause represents the asymptotic direction of incidence.

Backward trajectories are computed generally for a set of rigidities spanning a large range of values with a constant rigidity interval δR (usually 0.01 GV). The results of such computation for the case of Jungfraujoch is plotted in the right panel of Fig. 2. Three rigidity regions are identified:

i a high rigidity region where all trajectories are allowed;
ii a low rigidity region where all trajectories are forbidden;
iii an intermediate region called the penumbra where bands of allowed trajectories are separated by bands of forbidden ones.

The rigidity of the last allowed computed trajectory before the first forbidden one is called the upper cutoff rigidity R_U. The rigidity of the last allowed trajectory, below which all trajectories are forbidden, is called the lower cut-off rigidity R_L. Finally, the effective cutoff rigidity R_C is given by $R_C = R_U - n\delta R$, where n represents the number of allowed trajectories in the penumbra. The reader will find a complete description of the asymptotic direction computation method and cosmic ray cutoff terminology in Cooke et al. (1991).

For the analysis of the measurements of most ground-based cosmic ray experiments, where mostly vertically incident particles contribute to the counting rate, it is usually assumed that only cosmic rays with rigidity higher than the vertical effective cutoff rigidity R_C can reach the top of the Earth's atmosphere from all directions of incidence. However at high altitude and for positions with high cutoff rigidity or in space, the contribution of non vertical particles becomes important and the variation of R_C with the direction of incidence must be taken into account (Clem et al., 1997; Dorman et al., 2007). The effective cutoff rigidity gives only a rough approximation of the complex structure of the penumbra. Different authors have treated more precisely the geomagnetic transmission in the penumbra region than just by using R_C (e.g., Boberg et al., 1995). In their work, Kudela and co-workers quantify the access of a CR of rigidity R to a given position by the geomagnetic transmissivity $T(R)$ that represents the percentage of allowed trajectories over the rigidity interval $[R, R + dR]$ (Kudela and Usoskin, 2003; Kudela et al., 2007).

The cutoff rigidity and asymptotic direction of incidence vary on different time scales following the variability of the geomagnetic field. The long term variation is due to the secular variation of the internal field. The diurnal variation in the geomagnetic cutoff is the effect of the rotation of the Earth in the magnetosphere, that is oriented in the solar wind flow. A semi seasonal variation is also observed reflecting the seasonal variation of the orientation of the internal field with the solar wind . The geomagnetic transmission depends also strongly on the geomagnetic activity. Different authors have study the variation of cutoff rigidity in function of substorm and storm activity. Flückiger et al. (1981, 1990) and Flückiger and Kobel (1990) have studied the dependence of cutoff rigidity on magnetospheric current systems during magnetic storms. Smart et al. (1999) have calculated the changes of vertical R_C in function of magnetic activity. Belov et al. (2005) have studied the variation of vertical R_C during the big magnetic storm of November 2003. Kudela et al. (2007) have studied the variation of geomagnetic transmissivity

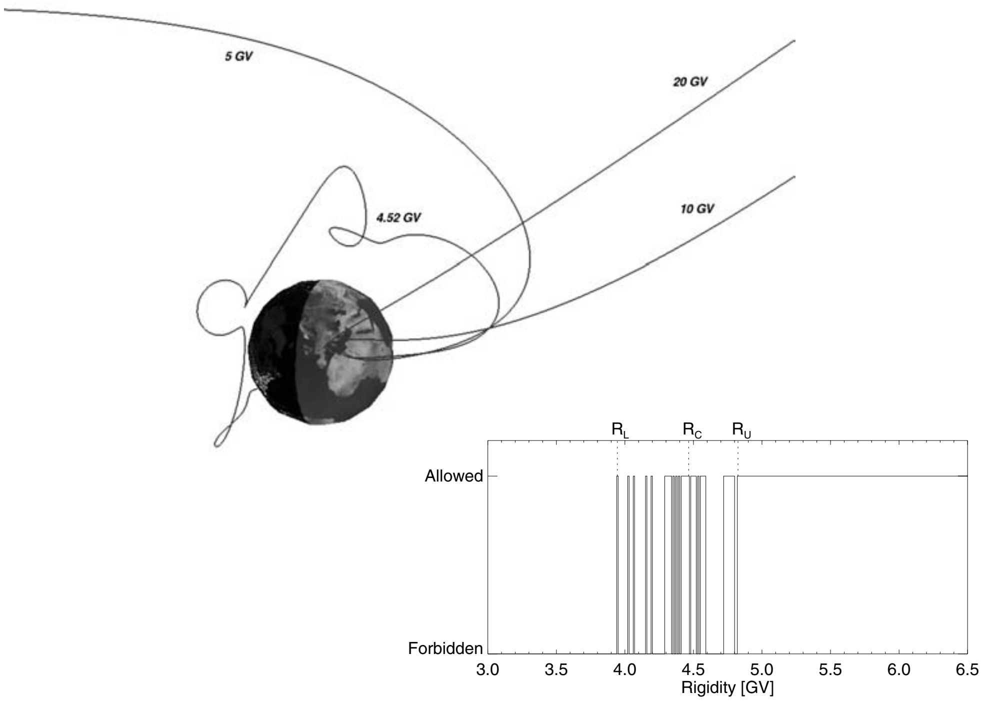

Fig. 2. Illustration of the backward trajectory technique used for computing cutoff rigidities and asymptotic directions. See the text for details.

and asymptotic direction during big magnetic storms using different magnetic field models (see also Desorgher et al. in this issue).

A significant limiting factor in the precision achieved by computation of cutoff rigidity and asymptotic direction is the accuracy of magnetic field model. Over the last two decades models of the Earth's magnetospheric magnetic field have been continuously improved to describe more precisely the different magnetospheric current systems (magnetopause current, symmetric and partial ring currents, tail currents and field aligned currents) and their time variation during magnetic storms. In the joint paper of Desorgher et al. some of these models are compared in the context of cosmic ray physics.

Different possibilities are available today for computing cutoff rigidity and asymptotic direction for space weather purpose. Some groups have made their source code available (e.g., Desorgher, 2005). World grid of vertical R_C on Earth and at low Earth orbit can be found in the literature (e.g., Smart and Shea, 1997). Different websites have been developed to offer the possibility to compute on-line the cutoff rigidity in function of position, time and magnetic activity (e.g., http://www.spaceweather.eu). For a rapid first order estimate of the cutoff rigidity analytical approximations exist. By approximating the geomagnetic field by a dipole, the cutoff rigidity is expressed by the Størmer cutoff formula

$$R_C = \frac{M \cos^4 \lambda}{r^2(1 + (1 - \cos^3 \lambda \cos \epsilon \sin \eta)^{1/2})^2} \tag{7}$$

where M is the dipole moment, r is the distance from the dipole center, λ is the geomagnetic latitude, ϵ is the azimuthal angle measured clockwise from the geomagnetic east direction (for positive particles), and η is the angle from the local magnetic zenith direction (Cooke et al., 1991). Shea et al. (1987) have shown that the vertical effective cutoff rigidity $R_C^{\perp}$ and the McIlwain L shell parameter are linked approximately by the relation

$$R_C^{\perp} = KL^{-\alpha} \tag{8}$$

where K and α depend on the epoch considered. Recently Storini et al. (2007) have extended this study and have found that the Eq. (8), with $K = 16.293$ GV and $\alpha = 2.073$ provides the best fit to compute cutoff rigidity at low and mid latitudes for the period 1955–1995. (Note that for a geocentric dipole field, the field line equation, $r = Lr_{\mathrm{E}} \cos^2 \lambda$ where r_{E} is the Earth's radius, predicts that $\alpha = 2$.) They have shown that for the epoch of 1990, this formula reproduces the computed R_C within an accuracy of 0.05 GV for 21 out of 31 sites over Europe. It is important to mention that while this formula allows a quick computation of the cutoff rigidity it should be used only for quiet geomagnetic time and for low and mid geomagnetic latitudes.

2.4 Atmospheric cascade

Cosmic rays that penetrate into the Earth's atmosphere interact by electromagnetic and hadronic processes with the atoms of the atmosphere. This interaction results in a cascade of secondary particles also called cosmic ray shower (Grieder, 2001). The lowest energy needed for a cosmic ray particle to produce a cascade of secondary particles that can be observed on ground is roughly 500 MeV nucleon^{-1} and is referred as the atmospheric cutoff. The maximum flux of secondaries in an atmospheric cascade, referred as the Pfotzer maximum, takes place typically around 100–200 g/cm^{-2} of atmospheric depth.

Hadronic interactions of high energy primary and secondary nucleons and ions with atoms of the atmosphere produce mainly pions, but also nucleons, nuclear fragments and gammas. Neutral pions decay rapidly into energetic gammas that initiate electromagnetic cascades made of positrons, electrons and secondary gammas. The development of these electromagnetic cascades is controlled by the gamma pair production, photo electric, Compton scattering, and bremsstrahlung processes. Gamma nuclear interactions can also take place but these processes are not dominant in the development of an atmospheric cascade.

Charged pions decay into muons and neutrinos. These muons will either survive all their way through the atmosphere and be observed on ground and underground, or decay before and produce neutrinos, electrons and positrons which themselves are the source of electromagnetic cascades. Muons are also produced by the decay of kaons and charmed particles at higher energy. The flux of muons is higher than the protons and electronic flux at low altitude and is therefore a dominant source of ionization close to the ground.

Nucleons and nuclear fragments are produced at all energy and are the main product of hadronic interaction below the energy threshold of pion productions. Protons and ions with energy smaller than 100 MeV are rapidly stopped by coulomb interactions while the neutrons continue to interact. Below 10 MeV neutrons decelerate continuously by enduring elastic scattering on atmospheric nuclei, before being captured at thermal energy.

Following the description given above an atmospheric shower can be divided in three principal components:

- i the electromagnetic or soft part made of gammas, electrons and positrons;
- ii the hard component produced by the muons;
- iii the nucleonic component made of secondaries neutrons and protons.

Below 40 km the shower particles are the main source of the ionization of the atmosphere. The impact of this ionization on the ozone layer and on the formation of clouds in the troposphere is the object of intense actual researches (Ermakov, 1997; Jackman, 2001; Marsh and Svensmark, 2000; Arnold, 2006). Some balloon experiments allow to measure the atmospheric ionization locally (Neher, 1971; Ermakov, 1997). However today a coordinated continuous world wide measurement of this ionization rate is still missing and computing codes have to be used to quantify it. The paper by Usoskin et al. (this volume) presents new achievements in cosmic ray induced ionization modeling, that have been obtained during this COST action.

Secondary albedo particles refer to shower secondaries produced at high altitude that escape the atmosphere upward. Albedo particles are an important source of space radiation at low altitude. Protons produced by the decay of albedo neutrons close to the Earth may be trapped in the Earth's magnetic field. This so called cosmic ray albedo neutron (CRAND) process represents the major source of the inner radiation belt proton. Energetic albedo protons can be shortly trapped in the magnetic field of the Earth before re-entering into the atmosphere. These particles also known as sub-cutoff particles were observed for the first time by the AMS experiment (Alcaraz et al., 2000c).

2.5 Particle transport in the radiation belts

A very dangerous source of radiation in near-Earth space is constituted by the radiation belts. The radiation belts are ions (mainly protons) and electrons in an energy range from roughly a few tens of keV up to hundreds of MeV (10 MeV for electrons) trapped in the magnetosphere between an altitude of roughly 200 km and $7\,r_{\rm E}$.

The mean motion of radiation belt particles is characterized by a very rapid gyration around magnetic field lines, a slower bouncing of the gyration center along magnetic field lines between the northern and southern mirror points, and finally a very slow drift motion around the Earth (Roederer, 1970). The bouncing and drift motion of the gyration center make that particles in a static magnetic field move on so-called magnetic shells surrounding the Earth.

The gyration, bounce and drift motion are each quantified by a an adiabatic invariant that remains constant in time as far as the magnetic field varies slower than their typical time scales. The dynamics of the radiation belt is modeled by the Fokker-Plank diffusion equation in the adiabatic invariant phase space, where radial, pitch angle and energy diffusion, energy loss by friction with the atmosphere and the plasmasphere, and particle sources are considered (Shultz and Lanzerotti, 1974; Bourdarie et al., 1996). Radial diffusion represents the diffusion of the particles across the magnetic shells and is caused by variations of the magnetic field and electric field on a time scale shorter than the drift period (e.g., ULF waves, variation of the large scale convection electric field). Pitch angle diffusion spreads and mixes the particle mirror point distribution along magnetic field lines. It is produced by particle wave interactions and coulomb collision with the atmosphere. It is generally invoked as a loss process as it is the source of precipitation of the particles in the atmosphere, but can be also the source of particle acceleration. Indeed pitch angle and energy diffusion by whistler waves, combined with radial diffusion seems to be the most promising mechanism to explain the acceleration of electrons during magnetic storms inside the magnetosphere (Varotsou et al., 2005; Horne et al., 2005). For a more detailed description of the radiation belt dynamics and modeling we refer to the specific paper of Horne and Boscher (this volume).

3 Conclusion

A short description of physical processes governing the dynamics of the earth's radiation environment was given. The review is not a comprehensive one but will give necessary background information for the upcoming specific papers of this report.

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References

Alanko-Huotari, K., I.G. Usoskin, K. Mursula, G.A. Kovaltsov: Stochastic simulation of cosmic ray modulation including a wavy HCS. J. Geophys. Res., **112**, A08101, (2007).

Alcaraz, J., et al. (The AMS collaboration): Cosmic protons. Phys. Lett. B, 490, **27** (2000a).

Alcaraz, J., et al. (The AMS collaboration): Helium in near Earth orbit. Phys. Lett. B, **494**, 193 (2000b).

Alcaraz, J., et al. (The AMS collaboration): Protons in near Earth orbit. Phys. Lett. B, **472**, 215–226 (2000).

Arnold, F.: Atmospheric Aerosol and Cloud Condensation Nuclei Formation: A Possible Influence of Cosmic Rays? Space Sci. Rev., **125**, 169–186 (2006).

Belov, A., L. Baisultanova, E. Eroshenko, H. Mavromichalaki, V. Yanke, V. Pchelkin, C. Plainaki, and G. Mariatos: Magnetospheric Effects in Cosmic Rays During the Unique Magnetic Storm of November 2003. J. Geophys. Res., **110**, A09S20, doi:10.1029/2005JA011067 (2005).

Boberg, P. R., A. J. Tylka, J. H. Adams, E. O. Flückiger, and E. O. Kobel: Geomagnetic Transmission of Solar Energetic Protons during the Geomagnetic Disturbances of October 1989. Geophys. Res. Lett., **22**, 1133–1136 (1995).

Bobik, P., M. Storini, K. Kudela, and E. G. Cordaro: Cosmic-Ray transparency for a medium latitude observatory. Il Nuovo Cimento, **26 C**, 2, 177–189 (2003).

Bourdarie, S., D. Boscher, T. Beutier, J. A. Sauvaud, and M. Blanc: Magnetic storm modeling in the Earth's electron belt by the Salammbo code. J. Geophys. Res., **100**, 14853 (1996).

Burger, R.A., and M. Hattingh: Toward a Realistic Diffusion Tensor for Galactic Cosmic Rays. Astrophys. J., **505**, 244–251 (1998).

Burger, R.A., M.S. Potgieter, B. Heber: Rigidity dependence of cosmic ray proton latitudinal gradients measured by the Ulysses spacecraft: Implication for the diffusion tensor. J. Geophys. Res., **105**, 27447 (2000).

Caballero-Lopez, R. A., and H. Moraal: Limitations of the force field equation to describe cosmic ray modulation. J. Geophys. Res., **109**, A01101 (2004).

Clem, J. M., J. W. Bieber, M. Duldig, P. Evenson, D. Hall, and J. Humble: Contribution of Obliquely Incident Particles to NM Counting Rate. J. Geophys. Res., **102**, 26919-26926 (1997).

Cooke, D.J., J. E. Humble, M. A. Shea, D. F. Smart, N. Lund, I. L. Rasmussen, B. Byrnak, P. Goret, and N. Petrou: On Cosmic-Ray Cutoff Terminology. Il Nuovo Centimento, **14 C**, 213–234 (1991).

Desorgher, L.: The MAGNETOCOSMICS code. http://cosray.unibe.ch/~laurent/magnetocosmics (2005).

Dorman L.I., O. A. Danilova, N. Iucci, M. Parisi, N.G. Ptitsyna, M. I. Tyasto, and G. Villoresi: Effective non-Vertical and Apparent Cutoff Rigidities for a Cosmic Ray Latitude Survey form Antarctica to Italy in Minimum of Solar Activity. Adv. Space Res., in press (2007).

Ermakov, V. I., G. A. Bazilevskaya, P. E. Pokrevski, and Yu. I. Stozhkov: Ion Balance equation in atmosphere. J. Geophys. Res., **102(D19)**, 23413–23419 (1997)

Flückiger, E. O., D. F. Smart, and M. A. Shea: On the effect of magnetospheric current systems on cosmic ray cutoff rigidities. in Proc. 17th Internat. Cosmic Ray Conf.,**4**, 244 (1981).

Flückiger, E. O., and E. Kobel: Aspects of Combining Models of the Earth's Internal and External Magnetic Fields. J. Geomag. Geoelectr., **42**, 1123–1136 (1990).

Flückiger, E. O., D. F. Smart, and M. A. Shea: Determining the strength of the ring current and the magnetopause currents during the initial phase of a geomagnetic storm using cosmic ray data. J. Geophys. Res., **95**, 1113 (1990).

Garcia-Munoz, M., G.M. Mason, J.A. Simpson: The anomalous ^{4}He component in the cosmic-ray spectrum at $\leq$50 MeV per nucleon during 1972–1974. Astrophys. J., **202**, 265 (1975).

Gleeson L.J., and Axford, W.I.: Solar Modulation of Galactic Cosmic Rays. Astrophys. J., **154**, 1011 (1968).

Grieder, P. K. F.: Cosmic rays at Earth – Researcher's reference manual and data book. Elsevier (2001).

Horne R. B., R. M. Thorne, S. A. Glauert, J. M. Albert, N. P. Meredith, and R. R. Anderson: Timescale for radiation belt electrons acceleration by Whistler mode chorus waves. J. Geophys. Res., **110**, A03225 (2005).

Jackman, C.H., R.D. McPeters, G.J. Labow, E.L. Fleming, C.J. Praderas, and J.M. Russell: Northern hemisphere atmospheric effects due to the July 2000 solar proton event. Geophys. Res. Lett., **28**, 2883 (2001).

Jokipii, J.R.: Cosmic-ray propagation. I. Charged particles in a random magnetic field. Astrophys. J., **146**, 480 (1966).

Jokipii, J.R., and B. Thomas: Effects of drift on the transport of cosmic rays. IV - Modulation by a wavy interplanetary current sheet. Astrophys. J., **243**, 1115–1122 (1981).

Kocharov, L., R. Vainio, G. A. Kovaltsov, J. Torsti: Adiabatic deceleration of solar energetic particles as deduced from Monte Carlo simulations of interplanetary transport. Solar Phys., **182**, 195 (1998).

Kota, J.: Three-dimensional transport of cosmic rays in the heliosphere. Nucl. Phys. B Proc. Suppl., **39 A**, 111–120 (1995).

Kota, J., and J. R. Jokipii: Effects of drifts on the transport of cosmic rays. VI. A three-dimensional model including diffusion. Astrophys. J., **265**, 573–581 (1983).

Kudela, K., and I. Usoskin: On Magnetic Transmissivity of Cosmic Rays. Czechoslovak J. Phys.,**54**,2, 239–253 (2003).

Kudela, K., R. Bucik, and P. Bobik: Transmissivity of low energy cosmic rays in the disturbed magnetosphere. To be published in Proc. European Cosmic Ray Symposium, Lisbon, Portugal (2007).

Langner, U.W., M.S. Potgieter, H. Fichtner, and T. Borrmann: Effects of Different Solar Wind Speed Profiles in the Heliosheath on the Modulation of Cosmic-Ray Protons. Astrophys. J., **640**, 1119–1134 (2006).

Lario, D., B. Sanahuja and A. M. Heras: Energetic particle events: efficiency of interplanetary shocks as 50 keV $< E <$ 100 MeV proton accelerators. Astrophys. J., **509**, 415–434 (1998).

le Roux, J. A., G. M. Webb, V. Florinski, and G. P. Zank: A Focused Transport Approach to Pickup Ion Shock Acceleration: Implications for the Termination Shock. Astrophys. J., **662**, 350–371 (2007).

Marsh, N., H. Svensmark: Low cloud properties influenced by cosmic rays. Phys. Rev. Lett., **85**, 5004–5007 (2000).

Moskalenko, I.V., A.W. Strong, J.F. Ormes, and M.S. Potgieter: Secondary antiprotons and propagation of cosmic rays in the galaxy and heliosphere. Astrophys. J., **565**, 280 (2002).

Neher, H.V.: Cosmic rays at high latitude and altitudes covering four solar maxima. J. Geophys. Res., **76**, 1637–1651 (1971).

Parker, E. N.: The passage of energetic charged particles through interplanetary space. Planet. Space Sci., **13(1)**, 9–49 (1965).

Reames, D.V.: Particle acceleration at the Sun and in the heliosphere, Space Sci. Rev., **90**, 413–491 (1999).

Roederer, J. G.: Dynamics of Geomagnetically Trapped Radiation, Springer: New York (1970).

Roelof, E. C.: Propagation of Solar Cosmic Rays in the Interplanetary Magnetic Field. In H. Ögelman and J. R. Wayland: Lectures in High-Energy Astrophysics, NASA SP-199, p. 111 (1969).

Ruffolo, D.: Interplanetary transport of decay protons from solar flare neutrons. Astrophys. J., **382**, 688–698 (1991).

Ruffolo, D.: Effect of adiabatic deceleration on the focused transport of solar cosmic rays. Astrophys. J., **442**, 861–874 (1995).

Shea, M. A., D. F. Smart, and L. C. Gentile: Estimating cosmic ray vertical cutoff rigidities as a function of the McIlwain L-parameter for different epochs of the Geomagnetic Field. Phys. Earth Plan. Int., **48**, 200–205 (1987).

Shultz, M., and L. J. Lanzerotti: Particle Diffusion in the Radiation Belt, Springer: New York (1974).

Smart D. F., and M. A. Shea: World Grid of Calculated Cosmic Ray Vertical Cutoff Rigidities for Epoch 1990. Proc. 25th Int. Cosmic Ray Conf., **2**, 401–404 (1997).

Smart D. F., M. A. Shea, E. O. Flückiger, A. J. Tylka, and P. R. Boberg: Changes in Calculated Vertical Cutoff Rigidities at the Altitude of the International Space Station as a Function of Magnetic Activity. Proc. 26th Int. Cosmic Ray Conf., **7**, 398–401 (1999).

Smart D. F., M. A. Shea, and E. O. Flückiger: Magnetospheric Models and Trajectory Computation. Space Sci. Rev., **93**, 305–333 (2000).

Storini, M., P. Metteo, and G. Moreno: Effects of the Geomagnetic Secular Variations on Cosmic Rays Access to the Terrestrial Environment. Adv. Space Res., in press (2007).

Toptygin, I.N.: Cosmic rays in interplanetary magnetic fields. Dordrecht, Kluwer (1985).

Usoskin, I.G., K. Alanko, K. Mursula, G.A. Kovaltsov: Heliospheric modulation strength during the neutron monitor era. Solar Phys., **207**, 389–399 (2002).

Usoskin, I.G., K. Alanko-Huotari, G.A. Kovaltsov, and K. Mursula: Heliospheric modulation of cosmic rays: Monthly reconstruction for 1951–2004. J. Geophys. Res., **110**, A12108 (2005).

Vainio, R., L. Kocharov, and T. Laitinen: Interplanetary and interacting protons accelerated in a parallel shock wave. Astrophys. J., **528**, 1015 (2000).

Varotsou A., D. Boscher, S. Bourdarie, R. B. Horne, S. A. Glauert, and N. P. Meredith: Simulation of the outer radiation belt electrons near geosynchronous orbit including both radial diffusion and resonant interaction with Whistler-mode chorus, Geophys. Let., **32**, L19106 (2005).

Velinov, P. L. Y., L. Mateev, and N. Kilifarska: 3-D model for cosmic ray planetary ionisation in the middle atmosphere. Ann. Geophys., **23**, 3043–3046 (2005).

Webber, W. R., and P.R. Higbie: Production of cosmogenic Be nuclei in the Earth's atmosphere by cosmic rays: Its dependence on solar modulation and the interstellar cosmic ray spectrum. J. Geophys. Res., **108(A9)**, 1355 (2003).

Webber W.R., et al.: A measurement of the cosmic-ray H-2 and He-3 spectra and H-2/He-4 and He-3/He-4 ratios in 1989. Astrophys. J., **380**, 230 (1991).