1
Cosmic rays

Victor Hess's experiments in manned balloons in 1912 demonstrated the existence of penetrating radiation entering the Earth's atmosphere from space. Hess's original observation was that gold-foil electrometers carried to an altitude of 5300 m indicated a rapid increase of ionization with elevation. Others confirmed this observation, and in 1925 Robert Andrews Millikan coined the term 'cosmic rays'. Hess received the Nobel Prize in Physics in 1936 for his discovery.

The term 'cosmic ray' is in fact a misnomer; it was based on the belief that the radiation was electromagnetic in nature. During the 1930s it was found that the primary cosmic rays are electrically charged – thus particulate – because they are affected by the Earth's magnetic field. Throughout the 1930s, and until the 1950s, before man-made particle accelerators reached very high energies, cosmic rays served as a unique source of particles for studies in high-energy physics, and led to the discovery of various subatomic particles, including the positron and the muon (Powell *et al*. 1959). Studies conducted during this pioneering phase laid the foundations for the theoretical and phenomenological understanding of cosmic rays as relevant for the use in Earth surface sciences today. Subsequent studies have refined this understanding; a process that is still ongoing.

1.1 Origin and nature of cosmic rays

Cosmic rays are high-energy, charged particles that impinge on the Earth from all directions. The majority of cosmic-ray particles are atomic nuclei, but they also include electrons, positrons and other subatomic

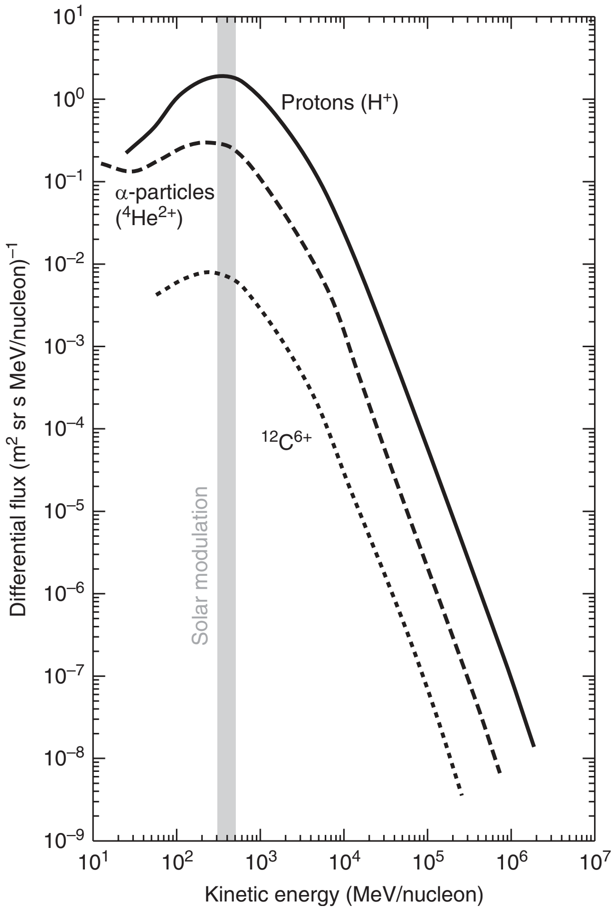

Fig. 1.1. The major components of the primary cosmic ray flux are protons and alpha-particles, the next most common particles are carbon nuclei, though only at less than <1% of the proton flux. Nuclei heavier than carbon are even rarer (not shown); data from (Simpson 1983). For a discussion of solar modulation see Section 1.2.

particles. Typical energy levels range from a few MeV up to $\sim 10^{20}$ eV, with a maximum at a few hundred MeV per nucleon (Fig. 1.1).

The term 'cosmic rays' usually refers to galactic cosmic rays, which originate in sources outside the solar system. However, this term is sometimes also used to include nuclei and electrons accelerated in association with energetic events on the Sun (solar cosmic rays). Solar cosmic rays have much lower energies (<1 GeV; typically 1–100 MeV)

The energy of primary cosmic rays

The energy of cosmic rays is usually provided in units of MeV, for mega-electron volts, or GeV, for giga-electron volts. One electron volt is the energy gained when a particle with a charge equivalent to the charge of an electron is accelerated through a potential difference of 1 volt. Most galactic cosmic rays have energies between 100 MeV (corresponding to a velocity of 43% of the speed of light for protons) and 10 GeV (corresponding to 99.6% of the speed of light). The number of cosmic rays with energies in excess of 1 GeV decreases by about a factor of 50 for every tenfold increase in energy.

than galactic cosmic rays, do not contribute significantly to the cosmogenic nuclide production at the Earth's surface (Masarik and Reedy 1995) and are therefore not considered further in the context of this book. The current understanding is that most galactic cosmic rays derive their energy from supernova explosions, which occur approximately once every 50 years in our Galaxy (Diehl *et al*. 2006). Cosmic rays are accelerated as the shock waves from these explosions travel through the surrounding interstellar gas. Sources of the primary cosmic radiation up to energies of at least 10^{15} eV are located within our galaxy (Eidelman *et al*. 2004). The mean cosmic-ray energy spectrum and integrated cosmic-ray flux is considered to be constant over the last 10 Ma (Leya *et al*. 2000).

At the top of the Earth's atmosphere the cosmic rays are largely composed of protons (87%) and α-particles (12%). A small contribution of heavier nuclei (~1%) is also present (Fig 1.1). Upon entering the Earth's atmosphere these primary cosmic rays produce secondary cosmic rays in interactions with the atoms in air.

1.1.1 The nucleonic component

The high energies of the primary cosmic rays are well in excess of the binding energies of atomic nuclei (typically 7–9 MeV per nucleon). Consequently, the predominant nuclear reaction in the atmosphere is that of spallation. In these reactions, nucleons are sputtered off the target nucleus. Spallation-produced nucleons largely maintain the direction of the impacting particle (Dorman *et al*. 1999) and go on inducing

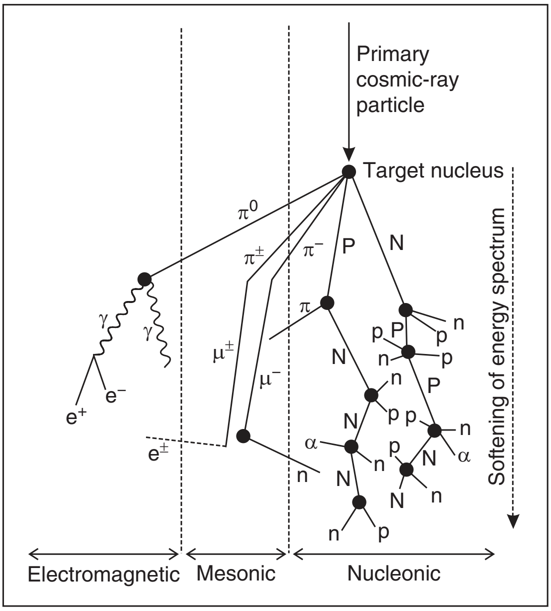

Fig. 1.2. The secondary cosmic ray cascade in the atmosphere. Abbreviations used: n, neutron, p, proton (capital letters for particles carrying the nuclear cascade), α, alpha particle, $e^{\pm}$, electron or positron, γ, gamma-ray photon, π, pion, μ, muon. After Simpson and Fagot (1953), discussion in the text.

spallation in other target nuclides, producing a nuclear cascade in the Earth's atmosphere (Fig. 1.2). Because neutrons do not suffer ionization losses as do protons (Lal and Peters 1967), the composition of the cosmic-ray flux changes from proton-dominated to neutron-dominated in the course of the nuclear cascade. At sea level, neutrons constitute 98% of the nucleonic cosmic-ray flux (Masarik and Beer 1999). Another change in the character of the cosmic rays on their way through the atmosphere is that the energy of the secondary neutrons is significantly lower than that of primaries. At ground level, energies >10 GeV are, for the purpose of Earth-science applications, absent. The neutron energy spectrum has peaks around 100 MeV, 1–10 MeV and <1 eV (Fig. 1.3). The relative shape of the >1 MeV peaks is invariant between sea-level and high-mountain altitude (Nakamura *et al.* 1987, Gordon *et al.* 2004, Kowatari *et al.* 2005). The spectrum only changes at much higher elevations, on approaching 12 km (Lal and Peters 1967, Goldhagen *et al.* 2002).

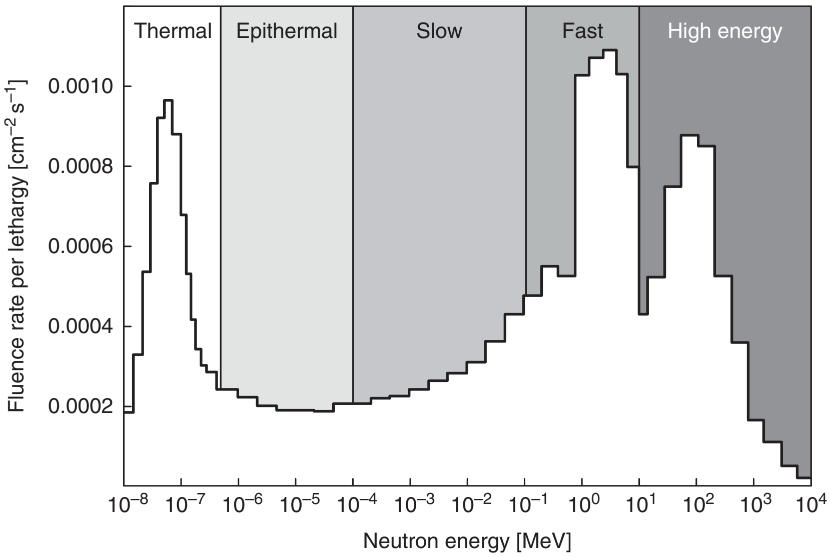

Fig. 1.3. The energy spectrum of secondary cosmic ray neutrons at sea level (data from Goldhagen *et al.* 2002). Lethargy is the natural logarithm of energy. For discussion see text.

1.1.2 The mesonic component

Collisions of high-energy primary cosmic rays with atomic nuclei high in the atmosphere produce mesons. These are mostly pions, which decay within a short distance (a few metres) predominantly to muons (μ^-, μ^+) (Eidelman *et al.* 2004) (Fig. 1.2). Muons belong to the particle family of leptons and can be considered as the heavier brother of the electron (206.7 times heavier). They have a half-life of 2.2 μs. At the speed of light this would give them a range, before they decay, of only 660 m. However, at relativistic speeds, the lifetime of the muon, as we perceive it, is much longer. Due to this time-dilation effect of special relativity, muons can reach the Earth's surface. Muons (μ^-) decay into an electron, an electron-antineutrino, and a muon-neutrino. Antimuons (μ^+) decay to a positron, an electron-neutrino, and a muon-antineutrino.

Muons are produced high in the atmosphere (typically 15 km) and lose about 2 GeV to ionization before reaching the ground. Their energy and angular distribution reflect a convolution of production-energy-spectrum, energy loss in the atmosphere and decay. For example, 2.4 GeV muons have a decay length of 15 km, which is reduced to 8.7 km by energy loss (Eidelman *et al.* 2004). The mean energy of muons at sea level is ~4 GeV

Flavours of neutron energy

High-energy neutrons are capable of producing spallation reactions. They have energies ranging from 10 GeV down to about 10 MeV. High-energy neutrons are themselves the result of spallation reactions, and are the main carrier of the nuclear cascade.
Fast neutrons, 0.1–10 MeV, have insufficient energy to induce spallation reactions. However, they may induce some evaporation reactions, e.g. energetically favourable (n,α)* reactions. Fast neutrons are themselves products of nuclear evaporation: a de-excitation process named by analogy to molecules evaporating from the surface of a heated liquid. Evaporation reactions can be induced by any particle interaction supplying sufficient separation energy (see also Section 1.6).
Slow Neutrons, 100 eV and 100 keV, are produced continuously, as fast neutrons lose energy through elastic and inelastic collisions with nuclei; this process is called moderation.
Epithermal neutrons are produced by further moderation (0.5–100 eV).
Finally, **thermal neutrons** have achieved energy equilibrium with their surroundings; their mean energy at environmental temperatures is ~0.025 eV.

There is no generally accepted convention on the classification of neutrons. The energy ranges defined here for the purpose of this book are customary in cosmic-ray physics; other fields, such as nuclear engineering, use different classifications.

Note: *A note on the notation for nuclear reactions: the first entry in the bracket denotes the impacting particle, the second the outgoing particle. These are most commonly: α = alpha particles (^{4}He-nuclei), n = neutrons, p = protons, γ = gamma-ray photon.

(Eidelman *et al.* 2004). Muons (and other particles) of this energy level are generated within a cone-shaped shower, with all particles staying within about 1 degree of the primary particle's path (Dorman *et al.* 1999).

Because muons interact only weakly with matter (mostly via ionization) they have a much longer range than nucleons, and therefore are the most abundant cosmic-ray particles at sea level (Lal 1988). However, as we will see later in Sections 1.4 and 1.6, the nucleonic component dominates cosmogenic nuclide production at the Earth's surface. Muons, in turn, dominate production at depth in the subsurface.

1.1.3 Electromagnetic component

At the Earth's surface, the electromagnetic component consists of electrons, positrons and photons, primarily from electromagnetic cascades initiated by decay of neutral and charged mesons (Fig. 1.2). Muon decay is the dominant source of low-energy electrons at sea level (Eidelman *et al*. 2004). The electromagnetic component is not relevant for the Earth science applications covered in this book and is therefore not considered further.

1.2 Interaction with magnetic fields

Primary cosmic rays, i.e. protons and α-particles, are fast-moving, positively charged particles. As is valid for any moving charged particle, magnetic and electrical fields affect primary cosmic rays. Electric fields accelerate or decelerate them in the direction of the field. In magnetic fields, the Lorentz force, F_L, accelerates charged particles radially, causing them to curve perpendicularly to both their initial vectors of movement v and the prevailing magnetic field B. The larger the angle between B and v is, the stronger the deflecting force. Furthermore, the slower the particle, i.e. the lower its kinetic energy, the more it will be deflected. As a result, low-energy particles follow intricate trajectories before reaching the Earth's surface, whereas the trajectories of high-energy particles are considerably less complex (Smart *et al*. 2000).

Primary cosmic-ray particles with energies <10 GeV are modulated by the solar wind and by the Sun's 11-year solar activity cycle (Lal and Peters 1967, Eidelman *et al*. 2004). As a consequence of this modulation, galactic cosmic-ray particles with rigidities (see text box) smaller than 0.6 GV on average (Michel *et al*. 1996) cannot approach the Earth (at present the solar modulation potential parameter ϕ ranges from 0.3–1.2 GV, depending on solar activity; Michel *et al*. 1996, Masarik and Beer 1999, Usoskin *et al*. 2005, Wiedenbeck *et al*. 2005; see also Fig. 1.1).

Near-vertically incident particles dominate the primary cosmic-ray flux near the Earth's surface (Dorman *et al*. 1999; see also Section 1.3). Consequently, primary particles approaching the Earth's geomagnetic equator travel perpendicular to the geomagnetic field, whereas near the poles they travel essentially parallel to the magnetic field lines. Virtually all rigidities are permitted at the poles, while near the equator, rigidities well in excess of 10 GV are required to approach the Earth. The solar modulation limits the lowest energies at the poles to >0.6 GV, having

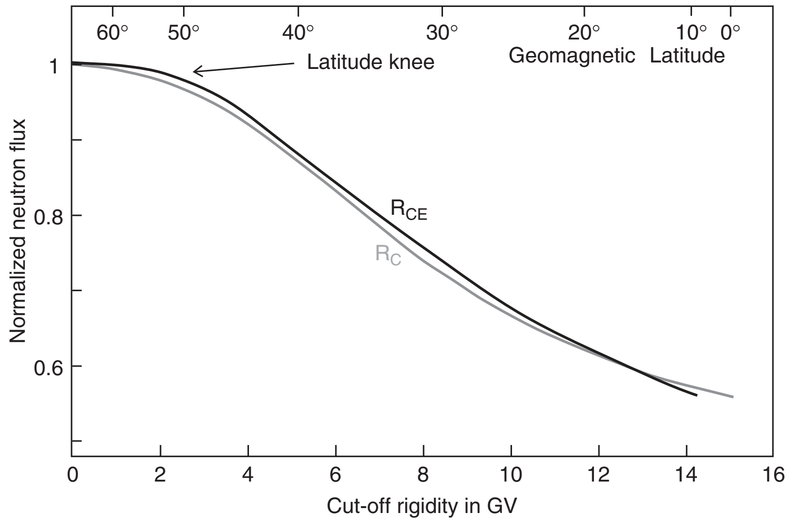

Fig. 1.4. The neutron flux at sea level varies as a function of the cut-off rigidity. The two lines show the results for two different approaches to calculate the cut-off rigidity. The curve labeled with R_{CE} was derived by trajectory tracing and the data of Rose *et al*. (1956), as derived by Desilets *et al*. (2001). The curve labeled R_C was derived using Equation 1.2 and data from Rose *et al*. (1956) from areas with a dominant dipole field (i.e. >70% dipole), as derived by Dunai (2000, 2001). To help to relate cut-off rigidity to physical locations on the globe the corresponding geomagnetic latitude is indicated as well. These were calculated for present-day field strength and should be used as an approximate guide only. See text for discussion.

a consequence that the cosmic-ray flux does not increase monotonously approaching the poles, but levels off at rigidities close to the solar modulation potential (Fig. 1.4). Furthermore primary particles with energies close to the solar modulation potential are not energetic enough to generate a secondary particle cascade that can reach the surface. The resulting break in trend at high latitudes is referred to as the ‘latitude knee’. The decrease of the cosmic-ray flux with decreasing latitude below the latitude knee is sometimes referred to as the ‘latitude effect’.

Approximating the Earth as a dipole field, the cut-off rigidity R_C for vertically incident particles is

$$R_C = \frac{M\mu_0 c}{16\pi \mathrm{RE}^2}\cos^4\lambda \ [\mathrm{V}] \tag{1.1}$$

(Elsasser *et al*. 1956), where M is the dipole moment, μ_0 the permeability of free space, c the speed of light, RE the radius of the Earth and λ the geomagnetic

Rigidity and cut-off rigidity

Rigidity (R) is momentum per unit charge. All particles having the same magnetic rigidity, charge sign and initial conditions will have identical trajectories in the Earth's magnetic field, independent of particle mass or charge. For instance, a proton with a kinetic energy of 10 GeV and an α-particle of 5 GeV both have a rigidity of 10 GV. Cut-off rigidity is the minimum rigidity required to penetrate the Earth's magnetic field, usually presented in units of GV. Thus: $R = pc/e$ [GV], where p is the momentum of the particle [GeV/c], c is velocity of light and e the particle charge.

latitude. To enable the consideration of non-dipole components of the geomagnetic field, Eqn (1.1) can be rewritten as

$$R_C = \frac{\text{RE}}{4} \frac{Hc}{(1 + 0.25 \tan^2 I)^{2/3}} [\text{V}] \qquad (1.2)$$

(Rothwell 1958), where H is the horizontal field intensity and I the inclination. This analytical equation provides a phenomenological description of the cosmic-ray flux. Using Eqn (1.2) in regions with a predominant dipole field (>70% of local field), locations with the same R_C will have the same primary cosmic-ray flux (±2%; e.g. Dunai 2001a). Equation 1.2 being an expanded dipolar equation, it may fail to accurately predict cosmic-ray flux in regions with extreme non-dipole magnetic field anomalies, such as in the South Atlantic (Dunai 2001a, Lifton *et al.* 2005), which presently cover less than ~15% of the globe (www.ngdc.noaa.gov/geomag/).

Equations 1.1 and 1.2 provide a simplified picture of the energy spectrum of the primary cosmic-ray flux. This is a consequence of the solid Earth being opaque to cosmic rays, and some of the intricate trajectories at energy levels close to the cut-off rigidity intersect with the Earth and are therefore 'forbidden' (Smart *et al.* 2000). The series of allowed and forbidden rigidities for particle access near the cut-off rigidity is called the cosmic-ray penumbra (Smart *et al.* 2000). If exact high-order descriptions of the geomagnetic field are available, then numerical trajectory tracing of numerous (up to several million) modelled particles can provide an accurate image of the structure of the lowest energy levels permitted to pass the field (Smart *et al.* 2000). The mean cut-off rigidity between the first and the last permitted trajectory in the cosmic-ray penumbra defines the effective cut-off rigidity R_{CE} (Smart *et al.* 2000). The trajectory tracing-derived R_{CE} provides an accurate phenomenological description of the primary cosmic-ray flux. When using accurate descriptions of the geomagnetic field for trajectory tracing, locations with the same R_{CE} will have the same primary cosmic-ray flux (±0.3%; e.g. Villoresi *et al.* 1997). It is important to note that the numeric values of R_C and R_{CE} for the same location are usually different (Fig. 1.4), and they must be used consistently and not be mixed for evaluations of the cosmic-ray flux (see also Section 3.3). R_C and R_{CE} are both calculated parameters that predict the primary cosmic-ray flux, which is further modulated by the atmosphere (Section 1.3).

The flux of muons with energies above 3 GeV, i.e. those responsible for nuclear reactions pertinent for Earth surface sciences (Section 1.2), changes by less than 10% with geomagnetic latitude and/or solar activity (Stone *et al.* 1998). This lack of sensitivity to magnetic fields arises from the fact that the primary particles that produce >3 GeV muons in the upper atmosphere, which have high enough energy to reach ground level, have rigidities well in excess of 5 GV, as muons lose about 2 GeV to ionization before reaching the ground (Section 1.1). A full energy transfer from primary particle to pion (which, in turn, decays to a muon) is unlikely, as pions usually share the energy of the primary particle with other secondary particles of the nuclear cascade (Fig. 1.2). At >20 GeV, muons (or more accurately their primaries) become completely insensitive to the Earth's magnetic field (Stone *et al.* 1998).

1.3 Interactions with the Earth's atmosphere

As described earlier, the atmosphere is the location of the nuclear cascade producing secondary neutrons. After attaining a maximum of secondary neutrons at the top of the atmosphere, their abundance N decreases approximately exponentially with increasing atmospheric depth:

$$N(d) = N_0 e^{-d/\Lambda} \quad (1.3)$$

with N_0 being the number of nucleons at the top of the atmosphere, d the atmospheric depth (in units of g cm^{-2}; N.B. standard sea-level pressure