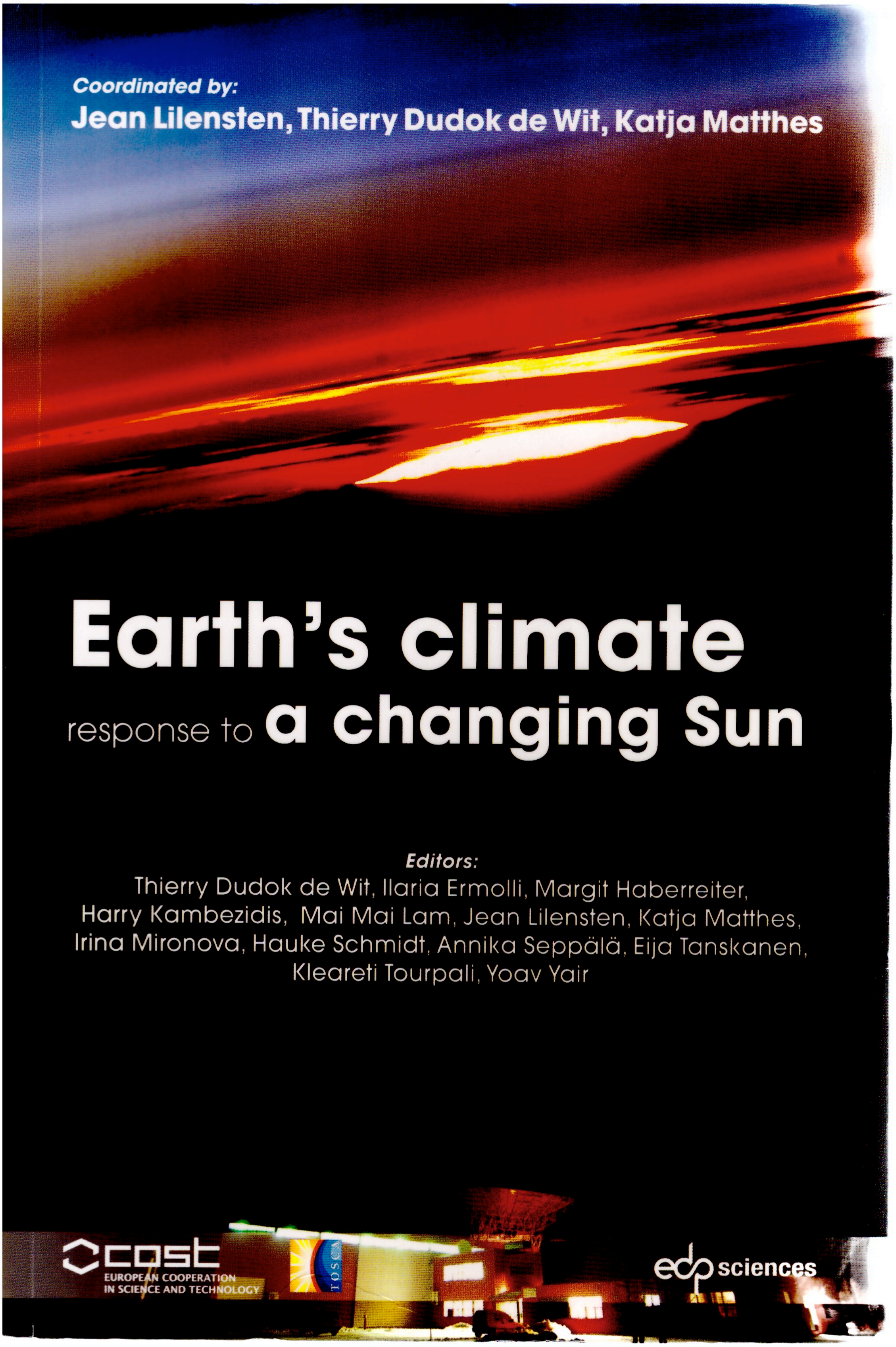

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CHAPTER 2.3

VARIABILITY OF SOLAR AND GALACTIC COSMIC RAYS

Galina A. Bazilevskaya[1] and Irina A. Mironova[2]

1 History

Cosmic rays were discovered in 1912 by Austrian physicist Victor Hess who in 1936 was awarded the Nobel Prize in Physics for his discovery. The term "rays" does not mean that this radiation has purely electromagnetic nature, as sunlight, radio waves or X-rays. This term was introduced after the discovery of the phenomenon of cosmic rays whose nature was not known at that time. Later, however, it became clear that the main component of cosmic rays is related to energetic particles, mostly protons.

2 Origins of cosmic rays

Cosmic rays may be of galactic or solar origin.

2.1 *Galactic cosmic rays*

The main source of galactic cosmic rays (GCR) in the Galaxy is believed to be explosions of supernova. The observed range of GCR energy extends by nearly 15 orders of magnitude, from 1 MeV ($1.6\,10^{-13}$ J), to an enormous value of $3\,10^{14}$ MeV (48 J). The flux of particles with these ultra-high energies is very low, about 1 particle per 10 km^2 per year, while in the lower part of energy spectrum, say around 100 MeV, intensity of GCR protons is about 1 per cm^2 per second. More than 90% of GCR are protons, helium comprises about 8%, less than about 2% being the other elements. Electrons are a minor constituent of GCR (about 1% or lower).

2.2 *Solar cosmic rays*

Strong increases of the intensity of energetic particles can sporadically occur near Earth, due to arrival of solar energetic particles (SEP) also known as solar cosmic

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rays (SCR), or solar proton events (SPE), since solar protons are far more abundant than other elements. SEP is associated with fast powerful energy release on the Sun, such as solar flares and/or coronal mass ejections (CME). The energy of SEP usually extends from 1 MeV to several GeV/nucleon, but, rarely, can reach several tens of GeV/nucleon. The energy spectrum of SEP covers more than four orders of magnitude in energy and more than 8 orders of magnitude in intensity. However SEP, existing only sporadically during periods of high solar activity, may occasionally enhance the flux of particles with energy tens-hundreds MeV by several orders of magnitude for hours-days, and in rare events called ground level enhancement (GLE) up to several GeV, for minutes-hours. Although the elemental composition of SEP changes from one event to another, it is dominated (larger than 90%) by protons.

3 Cosmic rays in the Earth's vicinity

The flux of primary cosmic rays (CR) outside the Earth's atmosphere depends on the level of solar activity and conditions in magnetosphere. Also, the CR flux is modified while propagating through the atmosphere.

3.1 Cosmic rays in the Earth's geomagnetic field

The Earth possesses its own magnetic field, which can, at a zero approximation, be considered a dipole. This geomagnetic field deflects charged particles and acts as a spectrometer separating the arriving CR particles according to their rigidity which is defined as $R = \frac{cP}{Ze}$ (here c is the speed of light, P is the particle's momentum, Z is the particle's charge number, and e is the unit charge). For protons, R is connected to kinetic energy as $R = \sqrt{E^2 + 2E_oE}$, where $E_o = 0.938$ GeV is the proton's rest mass, R is given in GV and E in GeV. Roughly speaking, the effect of the geomagnetic shielding can be characterised by a cut-off rigidity, Rc, so that particles with lower rigidity cannot reach the given location. The geomagnetic cut-off rigidity Rc varies over the globe from $Rc = 0$ in polar regions (although the atmospheric shielding cut-off of about 1 GV is always present) to $Rc = 13$–17 GV in the equatorial region.

3.2 Cosmic rays in the atmosphere

The Earth's atmosphere also acts as a particle energy spectrometer, separating particles according to their energy. Primary CR particles with energies below several hundreds of MeV/nucleon are simply stopped and absorbed in the atmosphere due to ionisation losses. However, if the energy of a primary particle is sufficiently high, it can collide with a nucleus of an atmospheric gas atom. This results in the generation of secondary cosmic rays via development of a nuclear-muon-electromagnetic cascade in the atmosphere, which involves different species, such as electrons, X-rays, muons, pions, kaons and nucleons. Due to development of the cascade, the flux of ionising particles first increases downwards in the atmosphere reaching maximum at the altitude of 17–27 km depending on the cut-off rigidity Rc and the level of a solar activity, but then decreases with atmospheric altitude due to prevailing absorption (Dorman (2004)). Solar protons with energy below 100 MeV lose their energy in the atmosphere at altitudes above 30 km, mostly due to ionisation of the ambient air (Bazilevskaya et al. (2008)). Moreover, such particles can penetrate only in the polar cap region where there is no geomagnetic shielding. Since such low-energy particles are much more abundant in the SEP spectrum, the strongest effect of SEP events is ionisation produced in the upper polar stratosphere and mesosphere at about 40–90 km altitude (Quack et al. (2001)).

4 Variability of cosmic ray fluxes

Cosmic rays are subject to temporal variations on the time-scales from hours to millennia. Solar activity affects the CR fluxes in the lower-energy part of the energy spectrum (up to about 100 GeV).

4.1 11-year solar activity modulation

The 11-year solar cycle causes the most prominent CR modulation. The flux of GCR changes in the opposite phase with 11-year cycle of solar activity. During the solar maximum activity, GCR fluxes with energies above 100 MeV are lower by 35% than during solar minimum, while for GCR with energies above 15 GeV, this value is only 5%, see Figure 1. On the contrary, SEP events occur much more frequently during periods of high solar activity. Number of SEP events affecting the upper Earth's atmosphere (SEP energy above 10 MeV) around solar maximum is about 30 per year, SEP events with relativistic protons (E larger than 1000 MeV) observed on the ground level as ground level enhancements (GLE) occur near the maximum of solar activity at a rate of approximately 3 per year, see Figure 2.

4.2 Forbush decreases and 27-day recurrent variations

A sudden reduction of the CR flux usually associated with a geomagnetic storm was discovered by Forbush (Forbush (1937)) and later named after him. The effect is a result of CR modulation by interplanetary disturbances caused by coronal mass ejections (CME) or fast streams of solar wind. It lasts usually from several hours to 1–2 days and is followed by a longer phase of recovery. The amplitude of the majority of events is about several percent.

Coronal holes or active regions on the Sun live sometimes during several solar rotations and cause long-lived disturbances in the interplanetary space. In this case, Forbush effects may have a recurrent pattern associated with the 27-day synodic rotation of the Sun. Also, CR fluxes may demonstrate rather smooth 27-day recurrent modulation not explicitly due to Forbush effect. The 27-day variation is

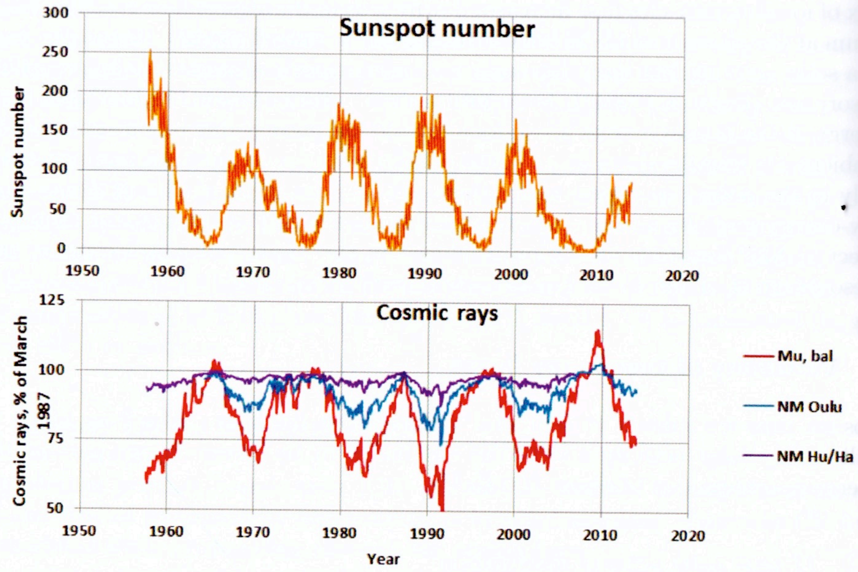

Fig. 1. 11-year modulation of GCR fluxes. Upper panel: monthly data on sunspot number. Lower panel: monthly data on GCR fluxes as observed by balloon-borne counter ($Rc = 0.6$ GV); polar NM Ouly ($Rc = 0.8$ GV); equatorial NM Huancayo/Haleakala ($Rc = 13$ GV). The data series are normalised to 100% at March 1987.

usually more distinctive and persistent during the descending or minimum phases of the solar activity cycle.

5 Measurements of cosmic rays

Since both energy and intensity ranges of GCR and SCR cover many orders of magnitude, a wide number of instruments is needed for the CR observation. In order to study relations between CR and atmospheric processes, the long-term homogeneous sets of CR data are necessary. CR with energy below several hundreds MeV are well measured onboard numerous spacecraft, while balloon-borne detectors are more suitable to detect CR with energy between 100 and 500 MeV. The most energetic CR (above 1000 MeV) which generate the nucleonic-electromagnetic cascade in the atmosphere are recorded by ground-based detectors, such as neutron monitors or muon telescopes.

5.1 *Ground-based instruments*

A ground-based neutron monitor (NM) was proposed by J.A. Simpson in 1948 as a standard instrument to measure cosmic ray intensities at Earth. He initiated the worldwide network of standard installations which has operated since the 1950s, about 50 stations operating nowadays. The NM is an energy-integrated device which measures all cosmic rays above the detection threshold. The effective energy of CR measured by NM is about 6 to 20 GeV for the high-latitude stations and 20 to 40 GeV for equatorial stations. Another common type of ground-based cosmic ray detectors is a muon telescope, which measures the muon component of the cosmic ray induced atmospheric cascade. Because of the high penetration ability of muons, such detectors are often located at shallow underground depth to study higher energies of primary cosmic rays. The effective energy of muon detectors varies from 50 to 70 GeV for a ground-based instrument to TeV energy for underground.

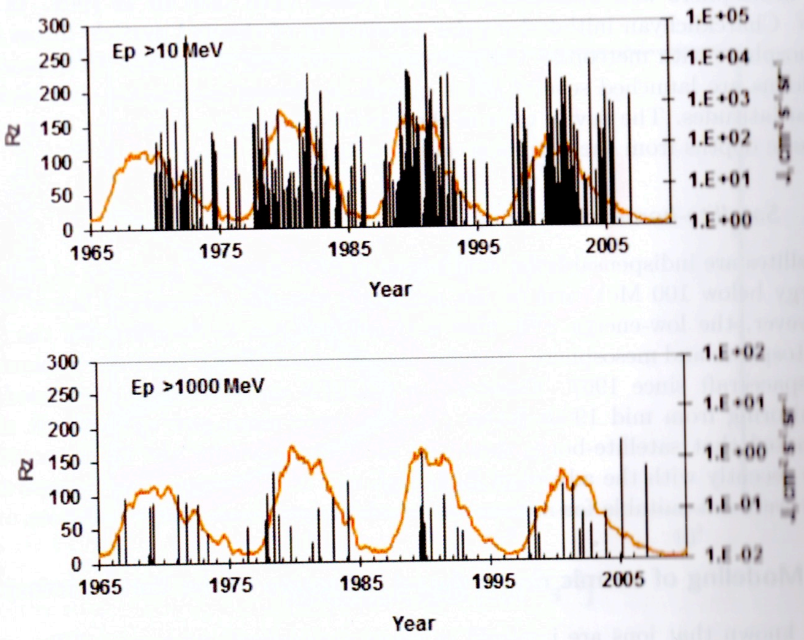

Fig. 2. Solar energetic particle events alongside with sunspot number Rz (7-months smoothed) vs. time. Each vertical bar indicates the time of a SEP event occurrence and represents maximum SEP flux during this event J. Upper panel: SEP events with $J(> 10 \text{ MeV}) > 1 \text{ cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$ (`http://www.wdcb.ru/stp/index.en.html`). Lower panel: ground level enhancements (GLE), recorded by neutron monitors (`http://www.nmdb.eu/`).

5.2 *Balloon-borne monitoring*

Balloon-borne devices allow to measure radiation at various levels of the atmosphere. First series of regular balloon measurements of the ion production rate in the atmosphere were conducted by H.V. Neher from 1930 up to 1969. In 1957, A.N. Charckhchyan initiated regular monitoring of charged particle fluxes in the atmosphere with meteorological balloons that is being performed up to now. The balloons are launched several times a week at several geographic sites including polar latitudes. The device returns the flux of secondary cosmic rays at the atmospheric depths from the ground level up to altitude of about 35 km.

5.3 *Satellite-borne monitoring*

Satellites are indispensable for monitoring of SEP since the majority of SEP have energy below 100 MeV and do not penetrate into the atmosphere below 30 km. However, the low-energy SEP play a significant role in chemistry of the upper stratosphere and mesosphere. Regular measurement of SEP has been implemented by spacecraft since 1967. Geostationary GOES satellites have performed SEP monitoring from mid 1980s [`http://spidr.ngdc.noaa.gov/spidr/`]. It should be noted that satellite-borne detectors are being used for the GCR monitoring only recently with the advent of PAMELA and AMS instruments because earlier they were not suitable for measurements of fluxes of high-energy particles.

6 Modeling of cosmic rays induced ionisation of the Earth atmosphere

It is known that ions are involved in many atmospheric processes. CRs are the most important contributor to ion-pair production in the atmosphere from about 3–4 km up to about 50 km. When energetic particles penetrate the atmosphere, they lose energy for ionisation. The process can be modeled by different approaches depending on the particle's energy. In all models, the ionisation energy losses of particles (either primary or secondary of different nature) are converted into the production of ion pairs, assuming that one ion–electron pair is produced, on average, per each 35 eV of deposited energy (Porter et al. (1976)). This process is well understood but cannot be modeled analytically and requires a full Monte-Carlo approach. It is worth noting that cosmic ray induced ionisation (CRII) rate will be dependent on three main variables: altitude, geographical location (via the local geomagnetic rigidity cut-off *Rc*), and time (via the variability of the integrand energy spectrum), see tables (http://cosmicrays.oulu.fi/CRII/CRII.html). Presently there are two basic numerical approaches to the CRII simulation: ATMOCOSMICS/ PLANETOCOSMICS model developed on the basis of the GEANT- (Desorgher et al. (2005)) and the CRAC (Cosmic Ray Atmospheric Cascade) model developed on the basis of CORSIKA+FLUKA packages (Usoskin and Kovaltsov (2006); Usoskin et al. (2010)). Figure 3 shows production over geomagnetic pole (*Rc* smaller than 1 GV) by GCR during maxima and minima solar activity as well as by SEP during a moderate and a GLE events. The maximum ionisation by galactic cosmic rays appears at about 15 km altitude in the polar region, where the ionisation rate is several orders of magnitude greater than that at sea level. The difference in the ionisation rate between the equatorial and polar regions is of the order of a factor 3–5. Variability of CRII over a solar cycle is from 10–20% in the troposphere up to a factor of 2 in the polar stratosphere. The maximum ionisation by SEP appears at about 40 km altitude in the polar region, while the ionisation rate may be negligible at sea level.

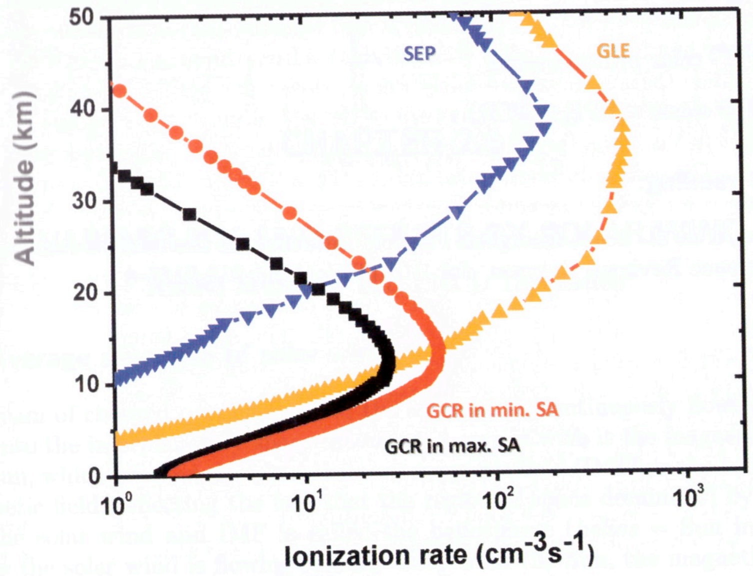

Fig. 3. Ionisation rates of galactic and solar cosmic rays. Cosmic ray induced ionisation (CRII) rates calculated by CRAC:CRII model. *Red circles* – Galactic CRII during minima solar activity (SA). *Black squares* – Galactic CRII during maxima solar activity (SA). *Upward pointing orange triangle* – Solar CRII like GLE of 20th January 2005. *Downward pointing blue triangle* – Solar CRII as lower energy SEP of 17th January 2005.

7 Abbreviations used in Part 2.3

- CME - coronal mass ejection
- CR - cosmic rays
- CRII - cosmic ray induced ionisation
- GLE - ground level enhancement
- GCR - galactic cosmic rays
- NM - neutron monitor

- SCR - solar cosmic rays
- SEP - solar energetic particles
- SPE - solar proton events
- (SEP event ≡ SPE ≡ SCR)

Further reading:

Mironova, I. et al. 2015, Energetic Particle Influence on the Earth's Atmosphere, Space Science Reviews, in press, doi: 10.1007/s11214-015-0185-4

CHAPTER 2.4

VARIABILITY AND EFFECTS BY SOLAR WIND

Kalevi Mursula[1] and Eija I. Tanskanen[2]

1 Average structure of solar wind

A stream of charged particles, called the solar wind, continuously flows from the Sun into the interplanetary space. Solar wind carries with it the magnetic field of the Sun, which is called the interplanetary magnetic field (IMF) or the heliospheric magnetic field, reflecting the fact that the region of space dominated by the Sun via the solar wind and IMF is called the heliosphere (*helios* = Sun in Greek). While the solar wind is flowing radially away from the Sun, the magnetic field is turned to a spiral structure due to the rotation of the Sun, much in the same way as the water running out from a rotating garden hose.

The time of the solar wind to reach the Earth at its typical speed of about 400 km s^{-1} takes about 4 days. While expanding into open space, the solar wind gets diluted, and at the Earth, solar wind is already a very tenuous gas, containing only some of 5–10 particles per cubic centimeter. During this expansion, the solar wind cools down roughly by a factor of ten from the initial temperature of a couple of million degrees of the solar corona. The strength of the IMF also weakens from the Sun to the Earth to about 5 nanoTesla, which is only one in ten thousand when compared to the Earth's magnetic field on the ground. Most of solar wind energy is in the form of kinetic energy related to its anti-solar motion, with smaller contributions in thermal and magnetic energy.

The properties of the solar wind and IMF vary significantly, reflecting the nature of their coronal source. The solar wind can be roughly classified into two groups: the slow solar wind and the fast solar wind. The fast solar wind (faster than about 500 km s^{-1}) originates from large regions of solar corona that are seen as dark when viewed in normal light. Darkness is due to the low density of these regions. These rather empty regions of solar corona are called coronal holes. The low density results from the specific magnetic structure of these regions, which opens directly into space, having no magnetic loops that can contain high densities

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Earth's climate response to a changing Sun

Editors:
Thierry Dudok de Wit, Ilaria Ermolli, Margit Haberreiter,
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For centuries, scientists have been fascinated by the role of the Sun in the Earth's climate system. Recent discoveries, outlined in this book, have gradually unveiled a complex picture, in which our variable Sun affects the climate variability via a number of subtle pathways, the implications of which are only now becoming clear.

This handbook provides the scientifically curious, from undergraduate students to policy makers with a complete and accessible panorama of our present understanding of the Sun-climate connection. 61 experts from different communities have contributed to it, which reflects the highly multidisciplinary nature of this topic.

The handbook is organised as a mosaic of short chapters, each of which addresses a specific aspect, and can be read independently. The reader will learn about the assumptions, the data, the models, and the unknowns behind each mechanism by which solar variability may impact climate variability. None of these mechanisms can adequately explain global warming observed since the 1950s. However, several of them do impact climate variability, in particular on a regional level. This handbook aims at addressing these issues in a factual way, and thereby challenge the reader to sharpen his/her critical thinking in a debate that is frequently distorted by unfounded claims.

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