Chapter 8

Cosmic rays

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Chemical composition of primary cosmic rays

Particle group	Charge	Average atomic weight	Intensity†	Corresponding nuclear intensity
Protons	1	1	1300 ± 100	1300
α-particles (^{3}He, ^{4}He)	2	4	94 ± 4	376
Light nuclei (Li, Be, B)	3–5	10	2.0 ± 0.3	20
Middle nuclei (C, N, O, F)	6–9	14	6.7 ± 0.3	94
Heavy nuclei	$\geqslant 10$	31	2.0 ± 0.3	62
Very heavy nuclei	$\geqslant 20$	51	0.5 ± 0.2	25

† Number of particles with energies greater than 2.5 BeV nucleon^{-1} in units of $m^{-2} s^{-1} sr^{-1}$.

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Relative abundances

Relative abundances of the chemical elements in the cosmic rays and in the solar system normalized to 100 at carbon.

Element		z	Cosmic rays	Solar system
H		1	26 000	270 000
He		2	3600	18 728
Li	L	3	18 ± 2	4.2×10^{-4}
Be	L	4	10.5 ± 1	6.9×10^{-6}
B	L	5	28 ± 1	3.0×10^{-3}
C	M	6	100	100
N	M	7	25 ± 2	31.7
O	M	8	91 ± 4	182
F	M	9	1.7 ± 0.4	2.1×10^{-2}
Ne	H	10	16 ± 2	29.2
Na	H	11	2.7 ± 0.4	0.51
Mg	H	12	19 ± 1	8.99
Al	H	13	2.8 ± 1	0.72
Si	H	14	14 ± 2	8.47
P	H	15	0.6 ± 0.2	8.1×10^{-2}
S	H	16	3 ± 0.4	4.24
Cl	H	17	0.5 ± 0.2	4.83×10^{-2}
A	H	18	1.5 ± 0.3	0.99
K	H	19	0.8 ± 0.2	3.6×10^{-2}
Ca	H	20	2.2 ± 0.5	0.611
Sc	VH	21	0.4 ± 0.2	3.0×10^{-4}
Ti	VH	22	1.7 ± 0.3	2.35×10^{-2}
V	VH	23	0.7 ± 0.3	2.22×10^{-3}
Cr	VH	24	1.5 ± 0.4	0.108
Mn	VH	25	0.9 ± 0.2	7.88×10^{-2}
Fe	VH	26	10.8 ± 1.4	7.03
Co	VH	27	<0.2	1.87×10^{-2}
Ni	VH	28	0.4 ± 0.1	0.407
Cu	VH	29		4.58×10^{-3}
Zn	VH	30		1.05×10^{-2}
		31–35	$c.\ 5 \times 10^{-3}$	2.1×10^{-3}
		36–40	$c.\ 5 \times 10^{-4}$	9.4×10^{-4}
	VVH	41–60	$c.\ 5 \times 10^{-4}$	3.0×10^{-4}
		61–80	$c.\ 2 \times 10^{-4}$	4.7×10^{-5}
		>80	$c.\ 10^{-4}$	4.0×10^{-5}

(From Hillier, R., *Gamma Ray Astronomy*, Clarendon Press, Oxford, 1984.)

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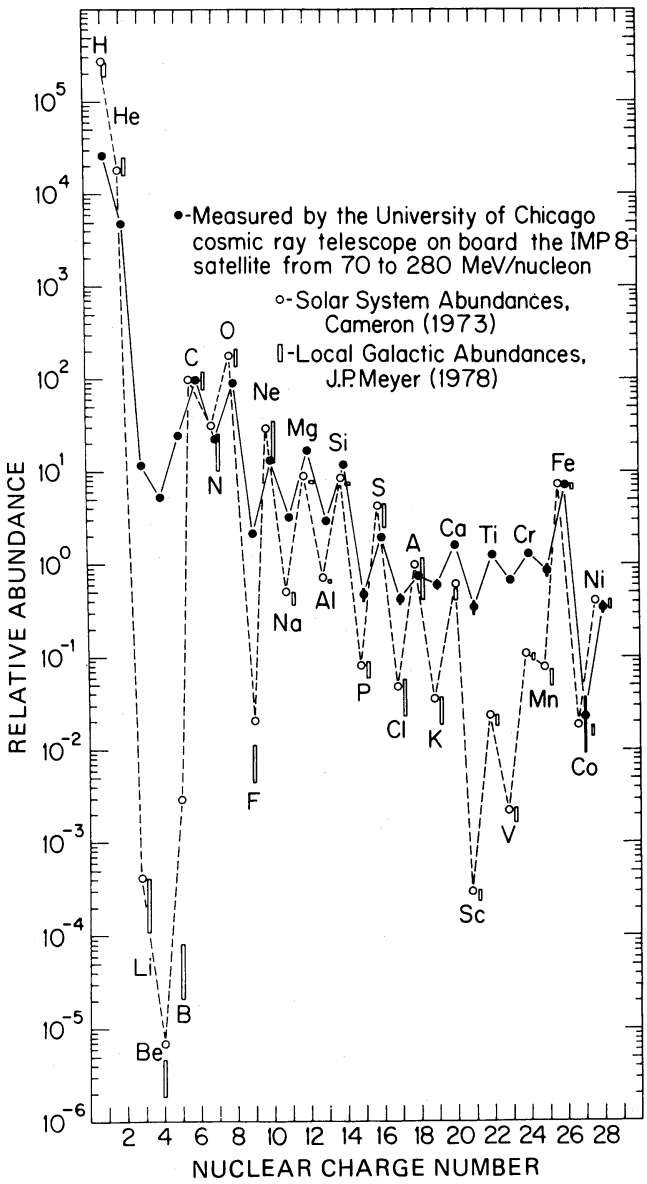
Comparison of the abundances of the elements in the galactic cosmic rays with the solar abundances (normalized to C). (Courtesy of C. Meyer, University of Chicago.)



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Relative abundances of nuclei normalized to oxygen

Element	Solar flare cosmic rays	Sun	Galactic cosmic rays
^{1}H	700	1000	350
^{2}He	107 ± 14	~ 100	50
^{3}Li	...	$<<0.001$	0.3
$^{4}Be\ ^{5}B$	<0.02	$<<0.001$	0.8
^{6}C	0.59 ± 0.07	0.6	1.8
^{7}N	0.19 ± 0.04	0.1	$\leqslant 0.8$
^{8}O	1.0	1.0	1.0
^{9}F	<0.03	$<<0.001$	$\leqslant 0.1$
^{10}Ne	0.13 ± 0.02	?	0.30
^{11}Na	...	0.002	0.19
^{12}Mg	0.043 ± 0.011	0.027	0.32
^{13}Al	...	0.002	0.06
^{14}Si	0.033 ± 0.011	0.035	0.12
^{15}P–^{21}Sc	0.057 ± 0.017	0.032	0.13
^{22}Ti–^{28}Ni	$\leqslant 0.02$	0.006	0.28

(Adapted from Johnson, F. S., ed., *Satellite Environment Handbook*, Stanford University Press, 1965.)

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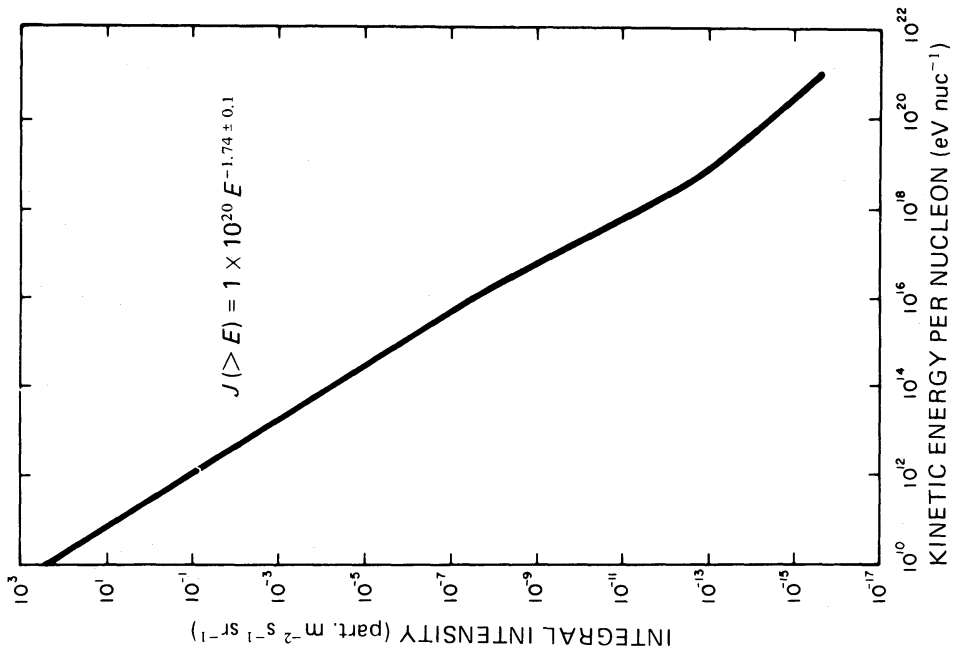
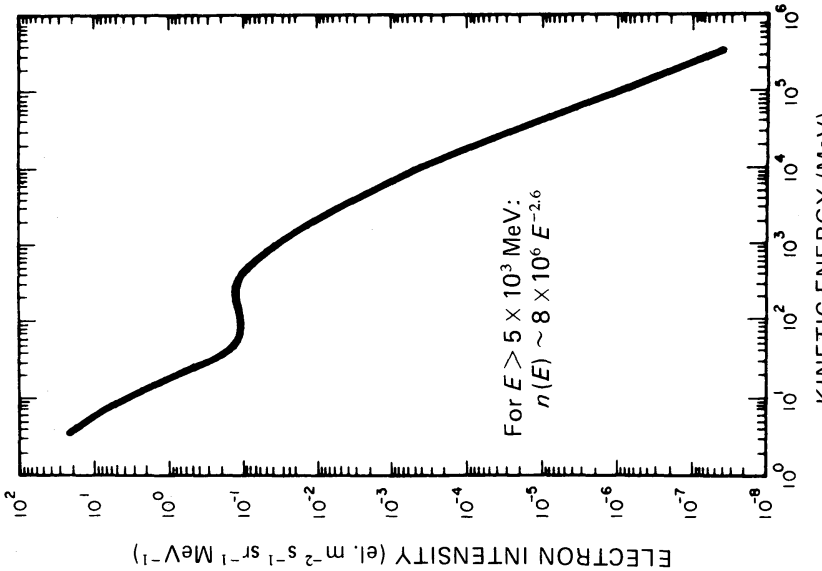
Integral energy spectrum of cosmic ray particles.



Energy spectrum of the primary cosmic ray electrons.



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Cutoff rigidity

The Earth's magnetic field affects the penetration of charged particles in the vicinity of the Earth. The minimum rigidity (cutoff rigidity) necessary to reach some geomagnetic latitude L and geocentric radius R is given by:

$$\frac{pc}{ze} = \frac{M}{R^2} \frac{\cos^4 L}{[(1+\cos\theta\cos^3 L)^{1/2}+1]^2},$$

where

M is the Earth's dipole moment,

$\left(\frac{pc}{ze}\right)$ is the magnetic rigidity of the particle; for charge $z=1$ it is numerically equal, when expressed in volts, to the momentum in units of ev/c,

$\left(\frac{M}{R_0^2}\right) \approx 60 \times 10^9$ volts, where R_0 is the radius of the Earth,

θ is the angle between the direction of arrival of the particle and the tangent to the circle of latitude. ($\theta = 0$ corresponds to arrival from the *west* for *positive* particles; $\theta = 0$ corresponds to arrival from the *east* for *negative* particles.)

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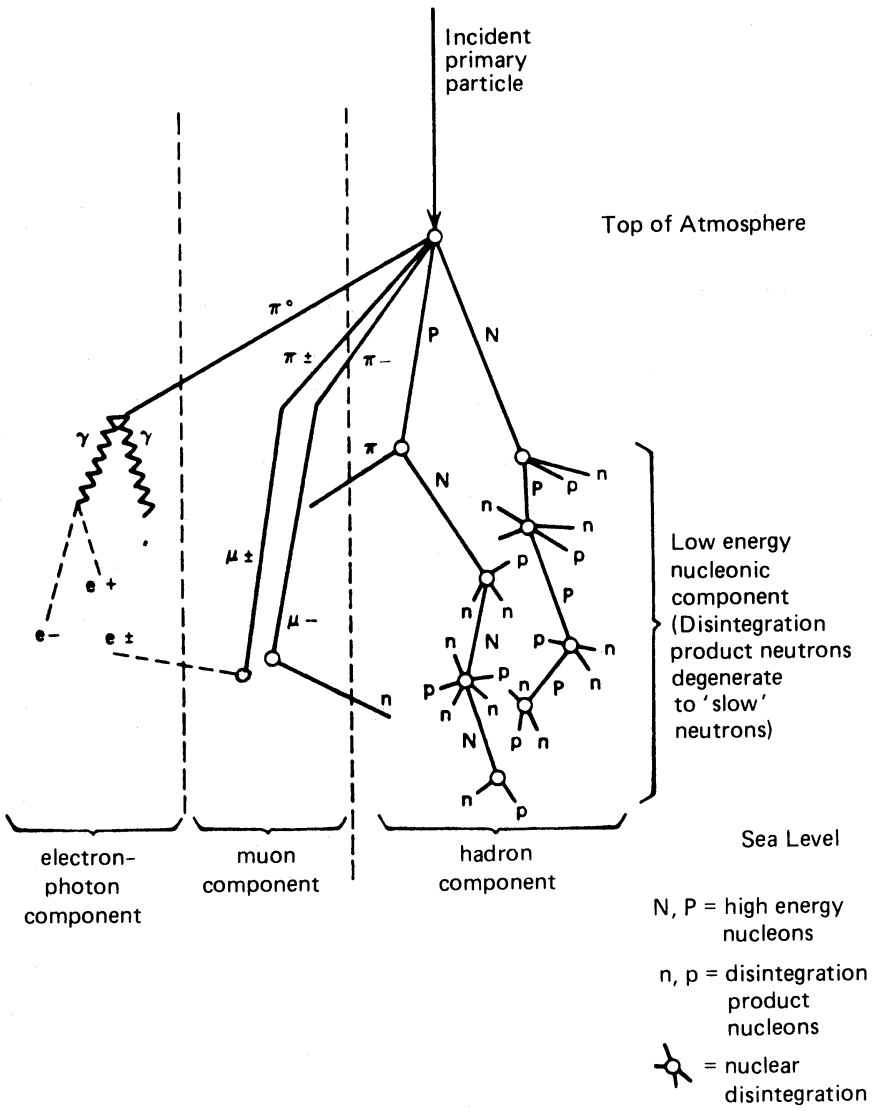
Particle production in the atmosphere

Schematic representation of the development of particle production in the atmosphere. (Adapted from Simpson *et al.*, *Phys. Rev.*, **90**, 934, 1953.)



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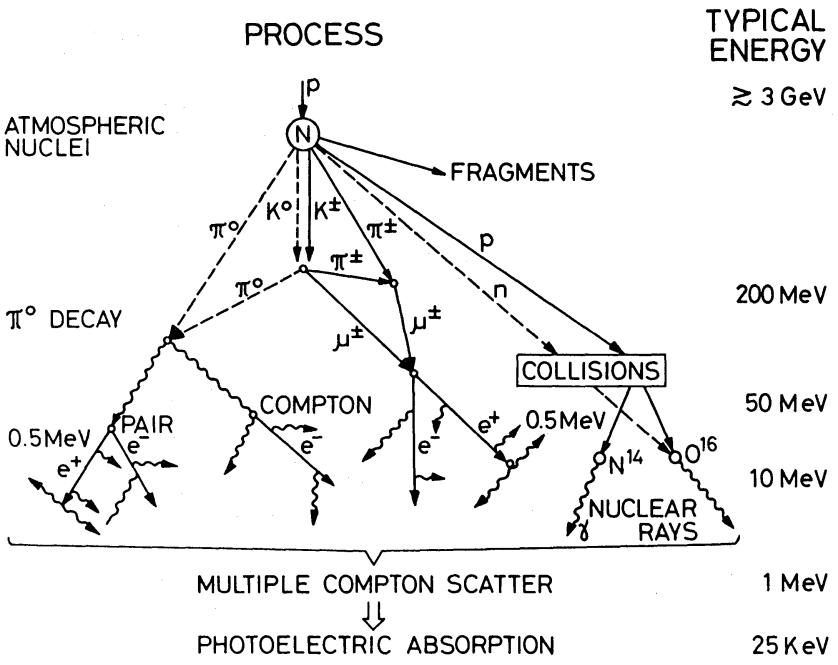
Gamma-ray production in the atmosphere

Schematic diagram of gamma-ray production processes in the atmosphere. Neutrinos are ignored. (From Allkofer, O. C. & Grieder, P. K. F., *Cosmic Rays on Earth*, Physik Daten, ISSN 0344–8401, 1984.)



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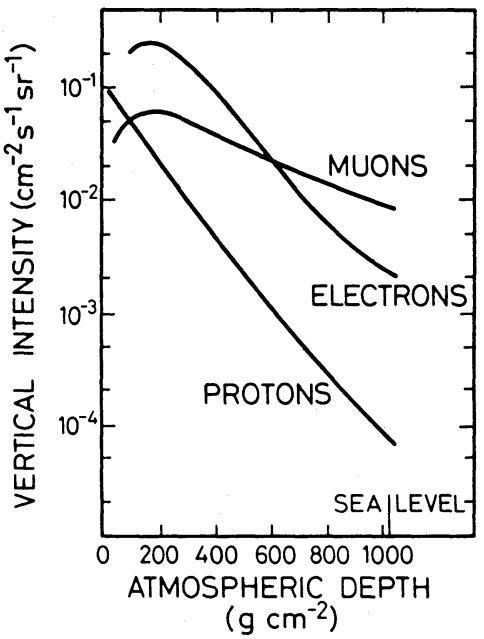
Altitude variation of cosmic rays

Altitude variation of the main cosmic ray components. (From Allkofer, O. C. & Grieder, P. K. F., *Cosmic Rays on Earth*, Physik Daten, ISSN 0344–8401, 1984.)



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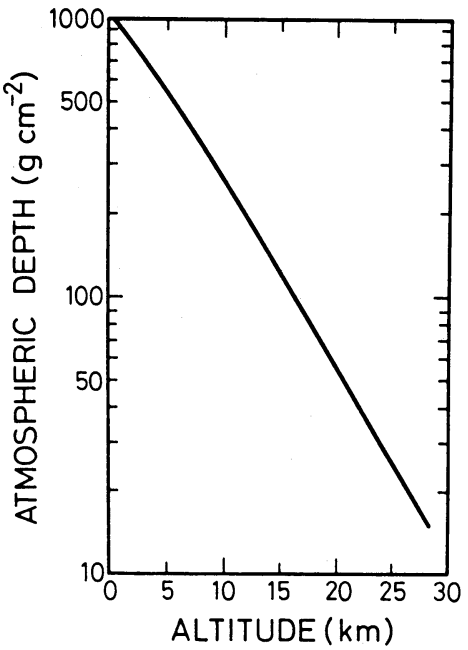
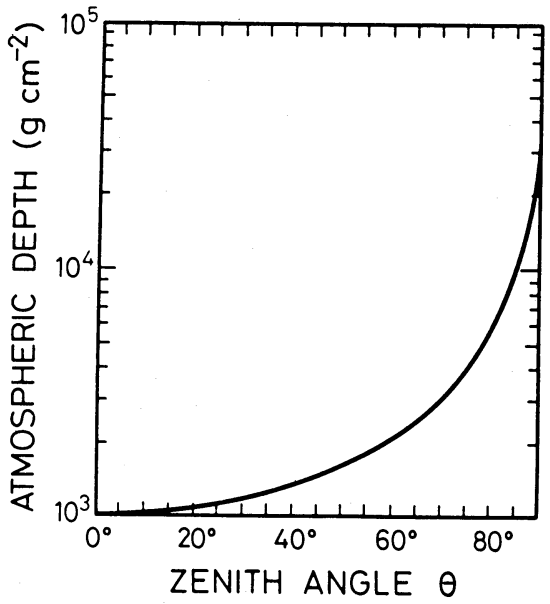
Atmospheric depth

Relation between atmospheric depth and altitude for an isothermal atmosphere. (From Allkofer, O. C. & Grieder, P. K. F., *Cosmic Rays on Earth*, Physik Daten, ISSN 0344–8401, 1984.)



Relation between zenith angle and atmospheric depth at sea level in an isothermal atmosphere. (From Allkofer, O. C. & Grieder, P. K. F. *Cosmic Rays on Earth*, Physik Daten, ISSN 0344–8401, 1984.)



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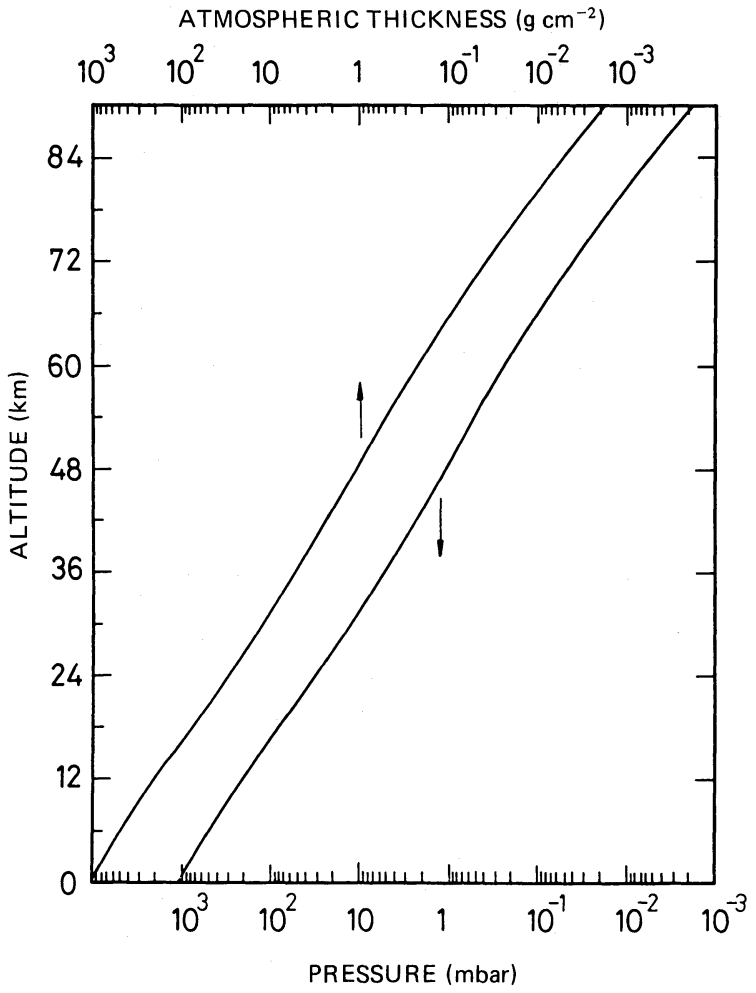
Relations between altitude and pressure, and altitude and depth in the real atmosphere. (After Cole, A. E. & Kantor, A. J., Air Force Reference Atmosphere, AFGL-TR-78-0051, 1978.)



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'Cosmic rays on Earth', Allkofer, O. C. & Grieder, P. K. F. in *Physics Data*, ISSN 0344–8401, 1984, nr. 25-1, Fachinformationszentrum, Karlsruhe.

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