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2.7.6 Geomagnetism

The Earth's magnetic field corresponds approximately to that of a dipole situated at the centre of the Earth with its axis inclined at an angle of about 11° to the axis of rotation. There are, however, appreciable temporal and spatial departures from this simple model. According to presently accepted theories, the smooth geomagnetic or 'normal' field and its slow secular change are ascribed to fluid motions in the Earth's electrically conducting core. The influence of magnetic constituents of crustal rocks superposes on the normal field anomalies whose magnitude can, in extreme cases, be comparable to that of the normal field.

In addition, changes on the Sun and of its position relative to the Earth cause erratic and often rapid fluctuations in the magnetic field (magnetic storms) occasionally exceeding one-tenth of the normal field value, as well as smaller and more regular diurnal and seasonal variations.

The geomagnetic field at any point is usually defined by three of seven elements: five intensity components, H (parallel to the Earth's surface), Z (vertically downwards), F or T (total, scalar), X (geographic north) and Y (geographic east); and two angles, D (declination or variation, D = arctan Y/X) and I (inclination or dip, I = arctan Z/H).

The main geomagnetic field, due to internal sources, at points on or above the Earth's surface may be represented by the following series:

$$X = \sum_{n=1}^{k} \sum_{m=0}^{n} (g_n^m \cos m\lambda + h_n^m \sin m\lambda)(a/r)^{n+2} \frac{dP_n^m(\theta)}{d\theta},$$

$$Y = \sum_{n=1}^{k} \sum_{m=1}^{n} (g_n^m \sin m\lambda - h_n^m \cos m\lambda)(a/r)^{n+2} m \operatorname{cosec} \theta P_n^m(\theta),$$

$$Z = -\sum_{n=1}^{k} \sum_{m=0}^{n} (g_n^m \cos m\lambda + h_n^m \sin m\lambda)(a/r)^{n+2}(n+1) P_n^m(\theta),$$

where a is the Earth's mean radius, λ is east longitude, r is radial distance from the Earth's centre and $P_n^m(\theta)$ is an associated Legendre function of the colatitude or north polar distance, θ, of degree n and order m. The set of numerical coefficients (g_n^m, h_n^m), usually expressed in units of nT, constitute a spherical harmonic model of the geomagnetic field.

The associated Legendre functions used in geomagnetism are of the Schmidt quasi-normalized form. They are such that the mean square value of $P_n^m \cos m\lambda$ or $P_n^m \sin m\lambda$ taken over a sphere is $(2n + 1)^{-1}$ and may be derived from the relation:

$$P_n^m(c) = \left(\frac{\delta_m (n - m)!(1 - c^2)^m}{(n + m)!} \right)^{1/2} \frac{d^m}{dc^m} P_n(c)$$

where

$c = \cos \theta$

$\delta_m = 1$ for $m = 0$; 2 for $m \geqslant 1$

and

$P_n(c)$ is the Legendre polynomial of degree n.

The International Geomagnetic Reference Field (IGRF) is a set of 21 spherical harmonic models: 20 describing the main geomagnetic field at epochs from 1900 to 1995, inclusive, five years apart and one for the (predicted) annual rate of secular variation for the interval 1995 to 2000. The main-field models extend to $m = n = 10$ (120 coefficients each) and the secular variation model is truncated at $m = n = 8$ (80 coefficients). Field component values for dates differing from the epochs of the main-field models are derived, for dates before 1995, by linear interpolation and, for dates after 1995, by using the secular variation model to up-date the 1995 main-field model. For further details see R. A. Langel (1992).

(*Click the Images to view Larger Images*)

Contours of magnetic declination at 1995.0 from the 6th generation

Contours of secular variation of magnetic declination for the interval

Figures 1 and 2 show contours of the declination and of the secular variation of the declination, respectively, at 1995 derived from the IGRF. A Fortran subroutine for synthesizing field component values from a spherical harmonic model is described by S. R. C. Malin and D. R. Barraclough (1981).

More detailed world magnetic charts are published by the Hydrographic Office of the Ministry of Defence and are obtainable from Admiralty Chart Agents. The latest charts for all elements are for epoch 1995.

Magnetic elements for London at different epochs

Values from 1850 onwards are for Greenwich. For 1580 the *D* observation was by Borough and the *I* value is Norman's observation made about 1576.

Epoch	*Declination*		*Inclination*		*H*/ μT	*Z*/ μT
	deg	min	deg	min		
1580	11	19 E	71	50	—	—
1665	0	0	—		—	—
1673	—		73	47	—	—
1719	11	30 W	—		—	—
1720	—		75	14*	—	—
1816	24	28 W*	—		—	—

1818	—		70	35	—	—
1850	22	24 W	68	47	—	—
1875	19	21 W	67	42	17.97	43.83
1907	16	0 W	66	56	18.55*	43.57
1913	15	15 W	66	50†	18.53	43.32
1929	12	23 W	66	54	18.38	43.06†
1937	11	1 W	66	59	18.34†	43.17
1946	9	37 W	67	2*	18.39	43.37
1975	6	39 W	66	27	19.16	43.98

* Maximum. † Minimum.

Geomagnetic data 1990

The following table contains the mean values of *D*, *H* and *Z* observed during the year 1990 and their annual rates of change for a selection of permanent magnetic observatories.

Observatory	*Lat.* deg	*Long.* deg	*D* deg	*Annual change* min/yr	*H* nT	*Annual change* nT	*Z* nT	*Annual change* nT/yr
Resolute Bay .	+ 74.7	–94.9	– 48.7	+ 79	1 068	+ 30	58 248	– 30
Bjørnøya . .	+ 74.5	19.2	+ 4.3	+ 5	9 027	– 23	52 875	– 1
Point Barrow .	+ 71.3	–156.8	+ 25.0	– 9	9 504	– 32	56 270	– 6
Tromsø . . .	+ 69.7	18.9	+ 1.5	+ 5	11 146	– 18	51 624	+ 6
College . . .	+ 64.9	–147.8	+ 26.9	– 11	12 751	– 24	55 333	– 6
Lerwick (UK) .	+ 60.1	–1.2	– 6.4	+ 8	14 898	– 4	48 001	+ 17
Magadan . .	+ 60.1	151.0	–13.5	– 2	17 714	– 20	52 610	+ 24
Moscow . . .	+ 55.5	37.3	+ 8.2	+ 1	17 207	+ 13	48 773	+ 5
Eskdalemuir (UK)	+ 55.3	–3.2	– 6.9	+ 7	17 314	+ 2	45 950	+ 16

Irkutsk . . .	+ 52.2	104.4	– 2.2	+ 2	19 282	– 26	56 999	+ 13
Hartland (UK)	+ 51.0	–4.5	– 6.2	+ 8	19 395	+ 8	43 896	+ 14
Memambetsu .	+ 43.9	144.2	– 8.6	– 2	26 341	– 18	41 641	+ 42
Coimbra . . .	+ 40.2	–8.4	– 6.1	+ 6	25 071	+ 10	36 284	– 12
Fredericksburg	+ 38.2	– 77.4	– 9.5	– 6	20 660	+ 17	50 223	– 105
Kakioka . . .	+ 36.2	140.2	– 6.8	– 2	30 136	– 10	34 953	+ 43
Tucson . . .	+ 32.2	– 110.8	+ 11.8	– 1	25 342	– 32	42 505	– 45
Quetta . . .	+ 30.2	67.0	+ 1.5	+ 1	32 510	– 5	33 550	– 15
Honolulu . .	+ 21.3	– 158.0	+ 11.0	– 4	27 574	– 13	22 048	– 26
Alibag . . .	+ 18.6	72.9	– 0.5	+ 1	37 982	– 10	17 982	+ 3
San Juan . .	+ 18.1	– 66.2	– 10.9	– 8	27 195	– 6	29 585	– 146
Guam . . .	+ 13.6	144.9	+ 1.8	–1	35 863	+ 3	7 269	+ 20
Bangui . . .	+ 4.4	18.6	– 2.0	+ 5	32 028	– 6	– 9 294	– 16
Pamatai . . .	– 17.6	–149.6	+ 11.3	0	30 980	– 34	– 18 926	– 2
Vassouras . .	– 22.4	– 43.6	– 20.3	– 5	20 332	– 91	– 12 167	– 89
Hartebeesthoek	– 25.9	27.7	– 16.0	– 4	12 879	– 16	– 26 148	+ 74
Gnangara . .	– 31.8	116.0	– 3.1	+ 3	23 195	– 2	– 53 802	+ 13
Hermanus . .	– 34.4	19.2	– 23.4	– 3	10 932	– 35	– 24 849	+ 92
Canberra . .	– 35.3	149.4	+ 12.5	+ 1	23 653	– 6	– 53 663	+ 17
Kerguelen . .	– 49.4	70.3	– 53.0	–10	18 603	– 32	– 44 708	– 4
Macquarie Island	– 54.5	159.0	+ 29.7	+ 5	12 577	– 4	– 63 519	+ 32
Mawson . .	– 67.6	62.9	– 64.4	– 8	18 492	+ 14	– 46 015	+ 71

[†] Sign conventions: positive values of latitude are north; of longitude, and of *D* and its annual change are east; and of *Z* and its annual change are downwards.

	Lat.	Long.
North magnetic dip-pole (1995)	+ 78.7°	104.8°W
South magnetic dip-pole (1995)	– 64.6°	138.6°E

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D.R.Barraclough

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For many years, scientists working in a variety of fields, specialists, engineers and students have used Kaye and Laby as an invaluable reference for their work. At launch, this online version includes the entire, unedited contents of the **16th edition (published 1995)** and is crammed full of tables of data, formulae, graphs and charts. This information span topics from fundamental constants to fibre optics, superconductivity to Raman spectroscopy and many others. The contents will be regularly reviewed and updated to reflect advances and developments in the fields of physics and chemistry.

This site is provided free and brought to you by the National Physical Laboratory, where Dr Kaye was Superintendent of the Physics Department in the 1930s.

We thank all those who have contributed to Kaye and Laby over the years to make it what it is today, and send special thanks to the editorial board. You may also be interested to read a history of Kaye and Laby.

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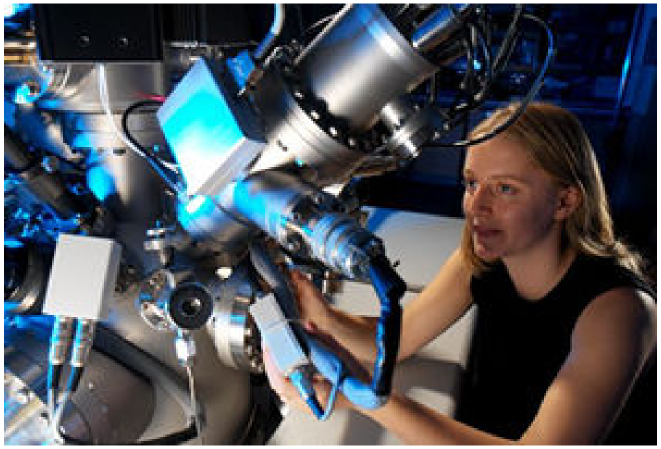

Felicia Green, Analytical Measurement Group at NPL, using G-SIMS, or Gentle Secondary Ion Mass Spectroscopy

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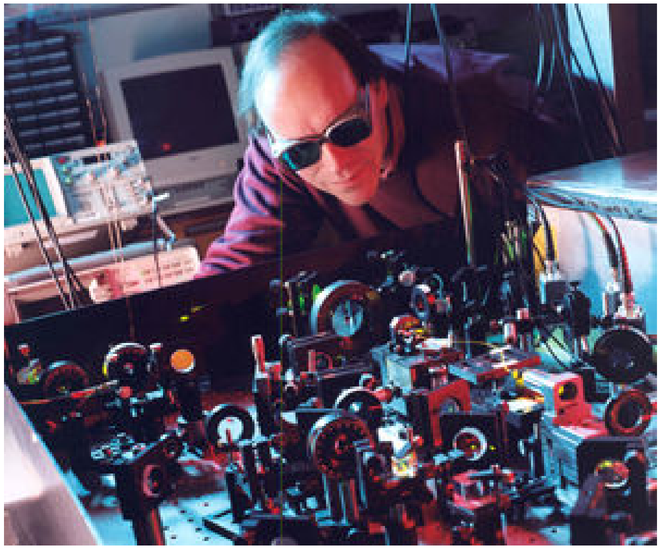

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Douglas Ambrose, O.B.E., B.Sc., Ph.D., C.Chem., F.R.S.C.
David R.Armitage, B.Sc.
Jim Asher, B.Sc., D.Phil., M.Inst.P., C.Phys.
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David R.Bacon, M.A., Ph.D.
The late Arlie Bailey, M.A., C.Phys., F.I.E.E., F.Inst.P., F.Eng.
David R.Barraclough, B.Sc., D.Sc, M.Inst.P, C.Phys, F.R.A.S.
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The late Sir Edward Bullard, M.A., Ph.D., D.Sc., F.R.S.
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Frank J. J. Clarke, O.B.E, B.Sc., D.I.C., Ph.D., C.Phys., F.Inst.P.
Frank Close, B.Sc., D.Phil., F.Inst.P., C.Phys.
Tony R.Colclough, B.Sc., Ph.D., F.Inst.P.

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Howard Cuttler, B.Sc., Ph.D.
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Cyril Dix, B.Sc.
George Doucas, D.Phil., M.Inst.P, C.Phys.
L. E. Drain, M.A., D.Phil.
Tony E. Drake
Ken Elliott
Michael Ewing, Ph.D.
David J.S.Findlay, B.Sc., Ph.D., C.Phys., M.Inst.P., L.R.A.M.
Jack G.Firth, B.Sc.,Ph.D., C.Chem., F.R.S.C.
Colin F.Forno, Ph.D.
Robin A. Forrest, M.A., M.Sc., Ph.D.
John C.Gallop, M.A., D.Phil.
Eric Gillham, M.A.
Teresa Goodman, B.Sc., A.R.C.S., M.Inst.P., C.Phys.
The late Ernest Herington, Ph.D., D.Sc., D.Tech.(Hon), A.R.C.S., C.Chem., M.R.S.C.
Stephen Hill, B.Sc., Ph.D., C.Chem., M.R.S.C., M.I.Env.Sc.
Michael Hillas, Ph.D., F.Inst.P
Sir John Houghton, M.A., D.Phil., F.R.S.
Terry D.James, M.I.O.S.H.
Duncan R. Jarvis, B.Sc., A.R.C.S., Ph.D., C.Phys.
O. Neil Jarvis, B.Sc., Ph.D.
Gareth Jones (R.G.), B.Sc., M.Sc., Ph.D
Owen C. Jones, M.A., D.Phil.,C.Phys.,C.Eng.
Brian J.Keene, B.Sc.
Raymond King, B.Sc., M.Sc., Ph.D.
David J.E.Knight, M.A., D.Phil.
John Leake, B.Eng., Ph.D.,F.I.E.E.
Sylvia Lewis
The late Maxwell McGlashan, M.Sc., Ph.D., D.Sc., C.Chem., F.R.S.C.
Gianfranco Molinar, Dr.
Roger Morrell, B.Sc., Ph.D., FIMMM
John G. Noyes, B.Sc., A.R.C.S., F.Inst.P., C.Phys., C.Eng.
David Parker, M.A., D.Phil., F.Inst.P., M.I.P.E.M.

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Brian Petley, Ph.D.
Geoffrey F. Phillips, O.B.E., M.Sc., Hon.M.R.Pharm.S., Eur.Chem., C.Chem., F.R.S.C.
Justin G.E.Phillips, B.Sc., Ph.D., C.Chem., M.R.S.C.
Stuart Pollitt, M.A., Ph.D.
Mike (D.M.) Poole, B.Sc., M.Sc., D.Phil.
Roy C.Preston, B.Sc., Ph.D., F.Inst.P.
Terry Quinn CBE D.Phil. FRS
Ken W. Raine, B.Sc., Ph.D.
The late Mike Richardson, B.Sc., Ph.D., C.Chem., F.R.S.C.
John Rivière, B.Sc., Ph.D., D.Sc.
Dick Rowley, B.Sc., Ph.D., F.Inst.P., C.Phys.
Michael Sargent, B.Sc., Ph.D., A.R.C.S., D.I.C., C.Chem.,M.R.S.C.
Martin P.Seah, B.Sc., Ph.D.
Martyn R.Sené, M.A., Ph.D.
David I.Simpson
Graham Sims, B.Sc., Ph.D., C.Eng., C.Phys.
The late Mike Sowerby, B.Sc., Ph.D.
Graham Torr, B.Sc., M.Sc., Ph.D., C.Phys.
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Preface to the web edition

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It is now over ninety years since the first edition of Kaye and Laby's tables was published. Over that period a further fifteen editions were published at, roughly, five- to ten-year intervals.

Following the launch of the sixteenth edition, the Editorial Board considered how the next edition should be prepared and what form it should take; should we propose a pocket version or a CD-ROM-based edition? We also explored publishing Kaye and Laby as a web-site.

Above all, we felt, and our contributors agreed, that the tables were still extremely useful and that the tradition started by Kaye and Laby should be maintained.

Our hope was that a paper version and a web-site could be launched together. However our publisher decided, for policy reasons, that he was not able to support the next edition of the book. The contract with the Editorial Board stipulated that, when the stocks of the sixteenth edition were exhausted, ownership of the rights to Kaye and Laby should pass to the Board. No alternative publisher was found.

The Editorial Board agreed then that publication through an internet site should be its prime aim.

Now that internet access is more universal, publishing through a web-site offers several advantages. We can expect a far wider readership, particularly if there is no charge. We would no longer be tied to a date for a next edition and tables may be updated whenever there is new or corrected information. In theory then, Kaye and Laby would be always up-to-date. While the present contributors are included by invitation, the updating potential could attract others to offer contributions to the Editorial Board. Finally, the web-site offers an excellent facility for extraction by its users.

The board felt that they were not able alone to handle the design and development of a web-site together with its publicity and maintenance. They were delighted when the National Physical Laboratory, which has had a close association with Kaye and Laby from the initial edition, offered to host the web-site and meet the costs.

NPL is now the manager of Kaye and Laby with the full support of the Editorial Board, which will act as NPL's advisor and interface with the contributors.

J.N (2004)

Preface to the sixteenth edition

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With this new edition Kaye and Laby achieves 84 years of service. Over this period the scope of physical and chemical data required for everyday use has increased enormously and this is reflected in the size of recent editions. Successive Editorial Boards have always been at pains to ensure that the intentions of the original authors should be maintained: the primary criterion for the inclusion of material is that it should be of value not only to specialists but more generally to scientists working in a variety of fields. The present Board believes that Kaye and Laby's appeal has become more broadly based over the years and it includes material of value also to engineers and to students.

In this edition all the material has been scrutinized and revised as necessary to take account of new results. Several completely new sections have been added covering, for example, medical ultrasonics, fibre optics, high temperature superconductivity, atomic spectroscopy, infra-red and Raman spectroscopy, mass and UV-visible spectrometry, flash points and explosive limits in air and auto-ignition temperatures, Rutherford scattering formulae and magnetic and electrostatic bending radii. In addition, new chapters on laboratory safety and quality assurance have been added and the section on statistical methods has been rewritten as a new chapter. These three chapters are not intended to provide a complete treatment of their subjects, but rather an introduction with pointers to more definitive texts. However, the Board felt strongly that Kaye and Laby should not ignore such subjects. In addition, many of the explanatory texts that accompany the tables of data have been enlarged so as to provide easier access to the information for the non-specialist reader.

Dr G. W. C. Kaye, F.R.S., one of the original authors, was Superintendent of the Physics Department of the UK's National Physical Laboratory and after he died in 1941 other physicists at that laboratory contributed to the 9th edition, which was then in preparation. This close association has continued to the present day but with contributors drawn increasingly from other UK national laboratories and universities as well. This diversity in the backgrounds of the contributors to succeeding editions must be a source of strength for Kaye and Laby. The members of the present Board, who are working or have worked at the National Physical Laboratory, the Laboratory of the Government Chemist and the UK Atomic Energy Authority, hope that they have maintained the traditions of Kaye and Laby while bringing in a degree of freshness to this edition.

The provision of standards of measurement and of high-accuracy data is an important factor in the economic well-being of a nation and has long been accepted as a responsibility of government in industrialized countries. We may perhaps repeat the hope set out in the preface to the previous edition, and now even more urgent, that future governments will continue to support long-term programmes in national laboratories for the generation of scientific data, which only those laboratories can provide.

J.N (1995)

Extract from preface to first edition

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The need for a set of up-to-date English physical and chemical tables of convenient size and moderate price has repeatedly impressed us during our teaching and laboratory experience. We have accordingly attempted in this volume to collect the more reliable and recent determinations of some of the important physical and chemical constants.

To increase the utility of this book, we have inserted, in the case of many of the sections, a brief *resumé* containing references to such books and original papers as may profitably be consulted.

Attention has been paid to the setting and accuracy of the mathematical tables; these are included merely to facilitate calculations arising out of the use of this book, and limitations of space have cut out all but a few of the more essential functions.

We began the book while at the Cavendish Laboratory, Cambridge, and Dr G.A Carse shared in its inception. To Mr G.F.C.Searle, F.R.S., we feel we owe much for his encouragement and suggestions when the scope of the book was under consideration....

G.W.C.K.

September, 1911 T.H.L.

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2.7.5 Gravity

The gravity field of the Earth

The potential of the external gravity field of the Earth is usually expressed as a series of spherical harmonic terms:

$$V = -\frac{GM}{r}\left[1 - \sum_{n=2}^{\infty} J_n \left(\frac{a}{r}\right)^n P_n(\cos\theta) + \text{terms depending on longitude}\right] \mathrm{m^2\ s^{-2}}$$

where r = distance from the centre of the Earth

a = Earth’s equatorial radius, θ = geocentric co-latitude,

M = mass of the Earth (see below)

$P_n(\cos\theta)$ = Legendre function of degree n

$10^6 J_2$ = 1082.63

$10^6 J_3$ = –2.5

$10^6 J_4$ = –2.37

The values of J_n are determined from the behaviour of artificial satellites about the Earth.

(See section 2.7.4)

The corresponding expression for the variation of the acceleration due to gravity over the surface of the (spinning) Earth is

$$g = g_e(1 + \beta_1 \sin^2 \phi - \beta_2 \sin^2 2\phi) - 3.088 \times 10^{-6} H \text{ m s}^{-2}$$

where ϕ is the geographical latitude, H is the height above sea level (in metres) and g_e is the value of gravity at the equator.

The values recommended by the International Union of Geodesy and Geophysics are

$$g_e = 9.780\ 327 \text{ m s}^{-2}$$

$$\beta_1 = 0.005\ 302\ 4$$

$$\beta_2 = 0.000\ 005\ 8$$

The above formula gives the best simple method of calculating g at a place where it has not been measured. It will almost always give results within 10^{-3} and usually within 5×10^{-4} m s^{-2}. The agreement with observa-tion is usually made worse by the application of a correction for the attraction of the land above sea level.

The *standard acceleration of gravity* is defined as 9.80665 m s^{-2} exactly.

Absolute value of the acceleration due to gravity, *g*.

Values of the acceleration due to gravity in terms of the fundamental units of length and time were, until recently, measured at very few sites and values elsewhere were found from measurements of differences. In recent years absolute apparatus using laser interferometer measurements of positions of falling reflectors has become highly developed and easy to use. The constant term in the gravity above is now derived from a number of absolute measurements and it is no longer necessary to give an absolute value at one or two or three preferred sites.

References

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Sir Alan Cook

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2.7.7 Cosmic rays

There is in nearby interstellar space a flux of particles—mostly protons and atomic nuclei—travelling at almost the speed of light, having kinetic energies from below 10^8 eV to above 10^{20} eV. The flux reaching the solar system is virtually isotropic (to within 0.1% below 10^{14} eV) and unchanging, but the flux observed at the Earth varies somewhat because: (a) at energies below a few GeV, particles are affected by interplanetary magnetic fields, which cause intensity variations with an irregular 11-year period; and (b) the geomagnetic field deflects low-energy particles away from low-latitude regions. The particles incident at the top of the atmosphere are mainly protons and bare atomic nuclei: encounters with nuclei in the air generate secondary particles, and the less energetic particles are attenuated on traversing the atmosphere, so that near sea level the dominant particles are the penetrating secondary muons and the rapidly generated secondary electrons, positrons and photons.

Occasional bursts of particles originating in solar flares can reach a few GeV (usually having little effect at most sea level locations); there is also a variable anomalous component of nuclei below 0.1 GeV per nucleon originating in the solar system. These are not tabulated.

Cosmic rays at the top of the atmosphere

The flux of particles per unit time, area and solid angle has a variation with energy of the general form

$$J(E)\,dE \propto E^{-\gamma}\,dE,$$

where E is the particle's kinetic energy (usually quoted in GeV). γ varies between 2.5 and 3.1 in different energy ranges (see below). The integral flux, $I(E)$, gives the flux of particles of kinetic energy > E : $J = -dI/dE$. The table below gives estimates of the particle flux at a time of minimum sunspot activity (when the flux is highest, as in 1965, 1977, 1987) and also (in *italics*) for a period of near maximum solar activity (low flux—though there is no well-defined absolute minimum). J and I are quoted for protons and I for the aggregate of all nuclear particles (including protons). Some compromises between inconsistent data mean that J and I are not always exactly consistent: errors of ~15% may be present in the fluxes for nuclei and protons: the uncertainties for electrons are much larger. To interpolate between quoted fluxes, a power law as quoted above is satisfactory: see also formulae given below. (The coverage is extended by empirical formulae given later.)

Fluxes observed (above atmosphere) where particles are not excluded by geomagnetic field

Differential flux J in m^{-2} s^{-1} sr^{-1} GeV^{-1}, I in m^{-2} s^{-1} sr^{-1}.

E/GeV	J_{proton}		I_{proton}		$I_{\text{all nuclei}}$		J_{elec}		I_{elec}	
0.1	1100	***92***	2900	***1300***	—	—	—	~ 8	—	—
0.2	1500	***210***	2800	***1300***		—	200	~ 5	90	***26***
0.5	1600	***420***	2300	***1200***	2600	***1400***	70	10	60	***24***
1.0	1000	***400***	1700	***1000***	2000	***1100***	30	9	38	***20***
2.0	420	***220***	1000	***700***	1200	***830***	11	6	20	***12***
5.0	90	***64***	410	***340***	540	***420***	1.8	—	5	***4***
10	24	***20***	180	***160***	240	***210***	0.27	—	1.3	***1.2***
20	5	***4.6***	62	***58***	95	***85***	0.034	—	0.3	***0.3***
100	0.066	***0.065***	3.8	***3.7***	7.6	7.3	0.000 17	—	—	—
1000	0.000 12	—	0.067	—	0.16	—	—	—	—	—
5×10^6	—	—	—	—	1.2×10^{-7}		—	—	—	—
10^9	—	—	—	—	1.9×10^{-12}		—	—	—	—
10^{11}	—	—	—	—	0.8 km^{-2} century^{-1} sr^{-1}		—	—	—	—
										—

The ‘electron’ flux includes positrons—about 30% of the total below 0.3 GeV, but only ~7% above 4 GeV. The photon flux above 0.1 GeV is 0.6 m^{-2} s^{-1} sr^{-1} averaged over the sky, but 50% is from galactic latitudes <10°; about 20% is probably of extragalactic origin.

The more common nuclei heavier than protons have very similar spectra when expressed in terms of magnetic rigidity $R = c\cdot$ momentum/charge. (When $v \sim c$, $R \approx (E + Mc^2)/eZ$, Z being the nuclear charge number: thus a 100 GeV He nucleus has a rigidity of 52 GV.) Somewhat more convenient is to express the fluxes of cosmic ray nuclei in terms of kinetic energy-per-nucleon, $U = E/A$, where A is the atomic mass number. Over the range ~2 to 10^4 GeV/nucleon, the flux of some types of particles may be expressed to within ~15% by

$j(U) = C(U + V)^{-\gamma}$ particles $\mathrm{m^{-2}\ s^{-1}\ sr^{-1}\ (GeV/nucleon)^{-1}}$

where the following table gives values for C, V and γ for various nuclei—and it also gives as F the accurately measured *relative* flux $j(U)$ at $U = 5$ GeV/n. (Multiplying F by 0.001 65 $\mathrm{m^{-2}\ s^{-1} sr^{-1}\ (GeV/nucleon)^{-1}}$ will give the absolute value of $j(U)$ at $U = 5$ GeV/n.)

	H	He	*Li*	*Be*	*B*	C	N	O	*F*	*Ne*	Mg	*Si*	S	Cl–Cr	Fe	*Ni*	*Cu–Ru*
F	~24 000	3750	16	11	26	104	26	100	2	15	20	16	3	9	11	0.6	0.012
C	24 500	740			12	19	8	19		3.0	4.0	3.5	0.7	2.5	2.3		
V	2.2	1.4			1.5	1.3	1.5	1.3		1.2	1.2	1.2	1.2	1.7	1.7		
γ	2.77	2.66			3.05	2.63	2.84	2.63		2.62	2.62	2.62	2.62	2.77	2.62		
A	1	4	7	9	11	12	14	16	19	20	24	28	32	42	56	58	

This fit over a very wide energy range disguises slightly different forms over a smaller range: for great detail over 1–20 GeV/n see Engelmann *et al*. (1990), *Astronomy & Astrophysics*, **223**, 96–111. For elements given in italics, the fits do not extend to such high energy and the exponents γ may be inaccurate. (These figures refer to conditions not far from maximum flux—minimum solar activity: near maximum of the sunspot cycle, the constant V would be increased, by perhaps 1 GeV/n.) The relative abundances F are closely related to the abundance of the elements in normal matter, though modified by the effect of fragmentation in nuclear collisions: these provide a supply of what would otherwise be uncommon nuclei (e.g. Li, Be, B), though less abundantly at the highest energies. If the fluxes are compared at the same actual kinetic energy $E = AU$, protons are seen to be much less dominant—about 42% of all particles at 10^{12} eV and 27% at 10^{14} eV.

The geomagnetic field prevents the arrival in a vertical direction of particles of rigidity less than $15 \cos^4 \lambda$ GV, where λ is the geomagnetic latitude: particles with rigidity slightly higher than this are admitted at full intensity.

Above about 10^5 GeV, the nuclear composition of cosmic rays is uncertain, but the total flux of particles of all types has been determined. From 10 to 10^6 GeV, the flux $J(E)$ found by adding the above com-ponents may be expressed as $3.1 \times 10^4 (E + 1.35)^{-2.68}\ \mathrm{m^{-2}\ s^{-1}\ sr^{-1}\ GeV^{-1}}$. Above this, the flux has been obtained from studying cascades of particles generated in the atmosphere ('extensive air showers'): from 10^6 to 5×10^6 GeV, $J = 9.33 \times 10^3 E^{-2.60}$; from 5×10^6 GeV (the 'knee of the spectrum') to 10^9 GeV, $J = 6.08 \times 10^6\ E^{-302}$, then more approximately, from 10^9 to 5×10^9 GeV, $J = 8.91 \times 10^7\ E^{-3.15}$, and above this, very roughly, $J = 3.09 \times 10^4\ E^{-2.8}$. (Generally ~ 15% accuracy.) The spectrum extends at least as far as 3×10^{20} eV.

Cosmic rays near sea level

The flux of particles (in $\mathrm{m^{-2}\ s^{-1}\ sr^{-1}}$) arriving nearly vertically above various threshold values of kinetic energy is tabulated below for the more common types of particle (at geomagnetic latitudes > ~40°). R gives also the median range in lead of muons of the specified energy, allowing for track scattering. Other charged particles are less penetrating.

E/GeV	I_{muons}	R_{muons}	$I_{\text{electrons}}$*	I_{photons}†	I_{protons}	I_{neutrons}
0.001	100	—	60	130	2.1	—
0.01	100	—	28	60	2.1	~30‡
0.02	100	—	20	40	2.1	—
0.1	99	4.8 cm	6.0	8	1.9	~10‡
0.2	97	12 cm	3.0	3.5	1.5	—
0.5	86	34 cm	1.0	1.1	0.9	1.5
1	69	69 cm	0.38	0.37	0.51	0.7
2	46	134 cm	0.12	0.11	0.25	—
5	20	3.1 m	0.02	0.02	0.077	—
10	8.6	5.8 m	—	—	0.025	~I_{p}
20	3.0	—	—	—	0.008	—
50	0.58	—	—	—	0.001 6	—
100	0.14	—	—	—	4.3×10^{-4}	—
200	0.030	—	—	—	1.1×10^{-4}	—
500	3.2×10^{-3}	—	—	—	2×10^{-5}	—
1000	5×10^{-4}	—	—	—	—	—

* 40–50% are positrons, above 0.1 GeV (but only ~ 5% at 1 MeV).

† Theoretical values, as measurements are inadequate.

‡ Uncertain angular distribution makes vertical flux uncertain.

Above 100 GeV, pions will have fluxes comparable to nucleons: they are less important at lower energies.

Fluxes are averaged over the 11-year cycle. The total muon flux will vary about 3% either way: above 1 GeV the variation is slight. The muon fluxes are the best determined—a few percent at low E (20% say at 100 GeV); the proton flux is uncertain to tens of percent above a few GeV.

Away from the vertical direction, the muon flux per unit solid angle varies with zenith angle θ, approximately as I α $\cos^{n}\theta$, with $n = 2.15$, out to 80° (these refer to the total flux including all energies: muons of tens of GeV vary little with zenith angle). For the protons and neutrons, however, at least above tens of MeV, $n \sim 8$. About 20% of the electrons striking the ground will be distributed like nucleons, the rest like muons. With a zenith-angle variation of this form, the flux passing through unit horizontal surface, integrated over a hemisphere of angles, is $2\pi/(n + 2)$ times the vertical flux per unit solid angle, as tabulated above. Thus a thin, horizontal plane detector will record a flux per m^2 per second of about 150 muons and, if its wall has 1 MeV electron stopping power, 70 electrons, and 1 proton.

Nuclear interactions of cosmic rays in the atmosphere generate about 6×10^4 neutrons s^{-1} per m^2 of the Earth at 45° latitude, of which 4×10^4 m^{-2}s^{-1} are absorbed by nitrogen to generate ^{14}C when solar activity is low: the long-term all-Earth average would be about 60% of this. 0.05–0.13 (or 0.2) neutrons s^{-1} are generated per kg of air (or Pb) near sea level, at latitudes >40° at times of low solar activity.

Showers. Primary cosmic rays above ~ 10^{12}eV generate extensive showers of secondary particles in the atmosphere and above ~ 10^{14}eV these penetrate to sea level. At this level, such a shower contains about 1 charged particle per 10 GeV of primary energy (at 10^{14}eV, or 1 per 3 GeV at 10^{17}eV, 1 per 1.6 GeV at 10^{20}eV): 5% of the particles are within 3 m of the centre, 50% are within 40 m and 90% within ~ 250 m. Most of the particles are electrons and positrons; a few percent are penetrating muons. A burst of >100 particles m^{-2} over a few m^2 due to a shower in the air would be seen about once per hour near sea level under a very thin cover (mass can add local showers), and >650m^{-2} once per day, the rate of showers doubling per 100 mb reduction in atmospheric overlay.

Variation with latitude. The number of vertical muons above 0.2 GeV is typically about 13% lower at the equator than at high geomagnetic latitudes; above 50° the flux does not change much. The component generating neutrons by nuclear interactions (largely the neutrons below 1 GeV)—long used to monitor cosmic ray variations—falls by about 24% in going from latitude 55° to the equator.

Variations with time. During the course of the 11-year sunspot cycle, the flux of neutron-generating particles near sea level varies by about 20%, being highest in years of low solar activity (e.g. 1954, 1965, less well-defined in 1977, 1987), though the variation is far from smooth. Flux minima occurred in 1947, 1958, 1969, 1982. The muon flux varies much less.

Cosmic rays as background radiation. Near sea level the dose equivalent rate of cosmic rays, describing their medical (whole body) effect, is about 0.31 mSv per year (somewhat less at latitudes < 30°), but this might be only a third or less of the total natural dose. The dose increases by about 3% per 100 m up in the lower atmosphere. (Above the atmosphere the dose due to low-energy nuclei is very much larger.)

Cosmic radiation is more penetrating than radioactive emissions. The particles penetrating more than 5 cm of lead are mostly muons (only above 0.7 GeV does an electron produce more than 0.5 particle under such a shield), so the particle flux penetrating a thickness *x* of absorber normally may be judged from the table above—shielding materials of ligher elements are more effective than lead (for a given mass per unit area) by about a factor 1.4, but lead is much more effective in cutting out electrons and photons.

Cosmic rays at other levels

Some muons have extraordinary penetrating power. The following table gives their flux in the vertical direction (in $m^{-2}\ s^{-1}\ sr^{-1}$) under specified masses *h* of ‘standard rock’ (having effective $Z^2/A = 5.5$). The mass is given in tonnes m^{-2}, equivalent in mass to metres of water, and, roughly, to feet of rock. The actual depth of water which is estimated to have the same stopping power is also given, though measurements at great depths of water are not yet available.

h (standard rock)	50	100	200	500	1000	2000	4000	7000	10 000
Water depth (km)	0.043	0.087	0.175	0.450	0.92	2.0	4.3	8.2	12.5
Flux ($m^{-2}\ s^{-1}\ sr^{-1}$)	7.7	2.5	0.65	0.081	0.013	1.4×10^{-3}	7.0×10^{-5}	1.9×10^{-6}	1×10^{-7}

At great depths, the chemical composition of the rock (Z^2/A) can have a large effect. The flux at angle θ to the vertical, under rock, may be estimated quite well from the formula

$$I(h,\ \theta) = \frac{1.7 \times 10^6 \sec\theta}{H + 390 \sec\theta} H^{-1.53} e^{-kH} \text{ m}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$$

H being the mass overlay measured along the slant direction from the top of the atmosphere: $H = h_{\text{rock, slant}} + (10 \sec\theta)$. For standard rock, $k = 7.1 \times 10^{-4}$, but if the rock has $Z^2/A = 6.37$, as at the Kolar Gold Fields, where many of the observations were made, $k = 8 \times 10^{-4}$. The formula fits the observations to about 15% for small angles and for depths of more than a few metres, and probably for θ up to 45°.

Above ground level, the absorption length, in which the intensity increases by a factor e, is roughly as follows, for the lower half of the atmosphere:

Nucleons above a few GeV, 110 g cm^{-2}; total muon flux, 550 g cm^{-2};

total electronic flux, 180 g cm^{-2}; nuclear disintegrations 165 g cm^{-2}.

The rate of nuclear disintegration reaches a peak near the 100 millibar level, several hundred times the sea-level rate (depending on latitude). At this level, though, large increases due to solar flares occasionally occur, lasting for a few hours.

A.M.Hillas

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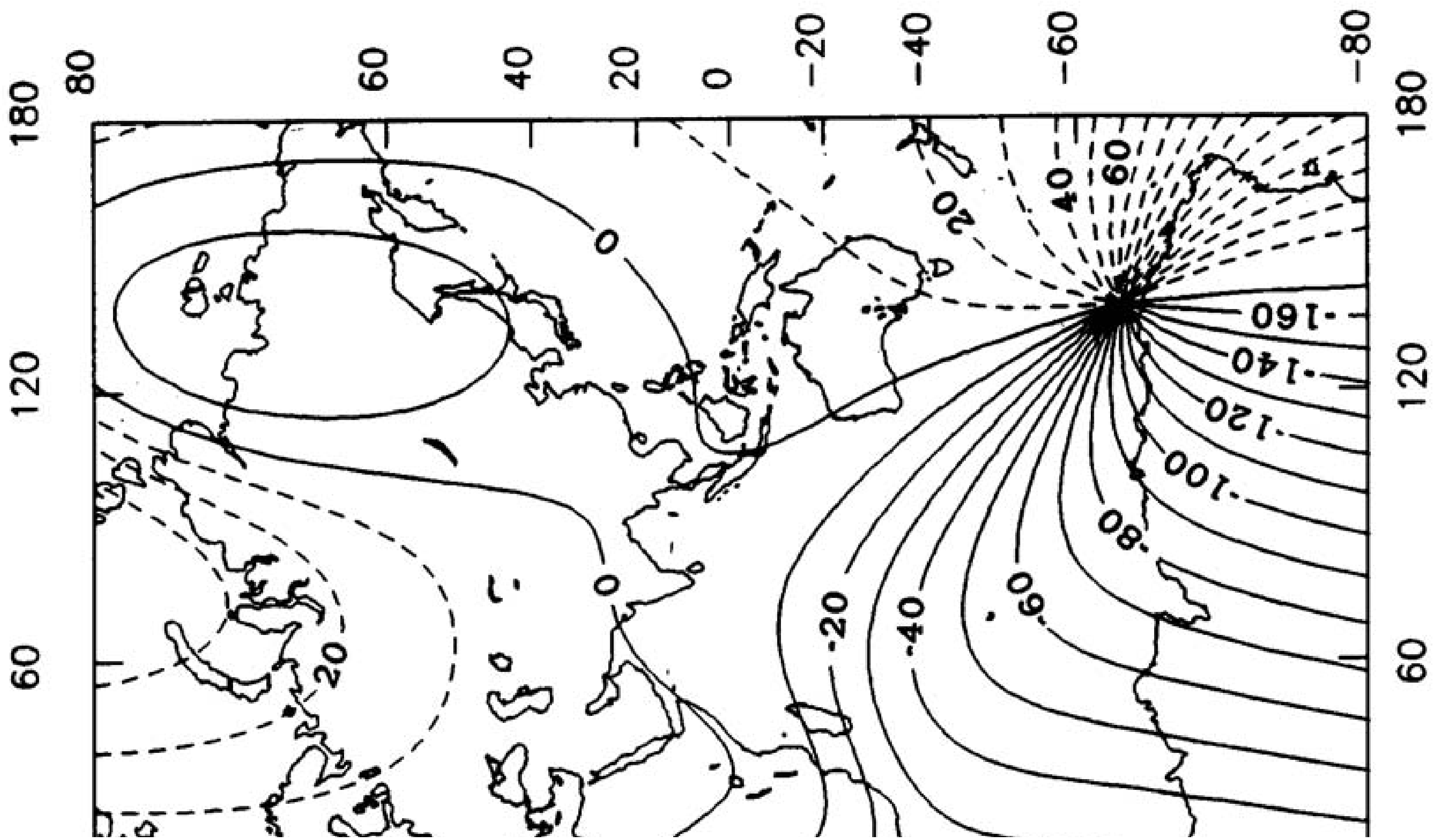
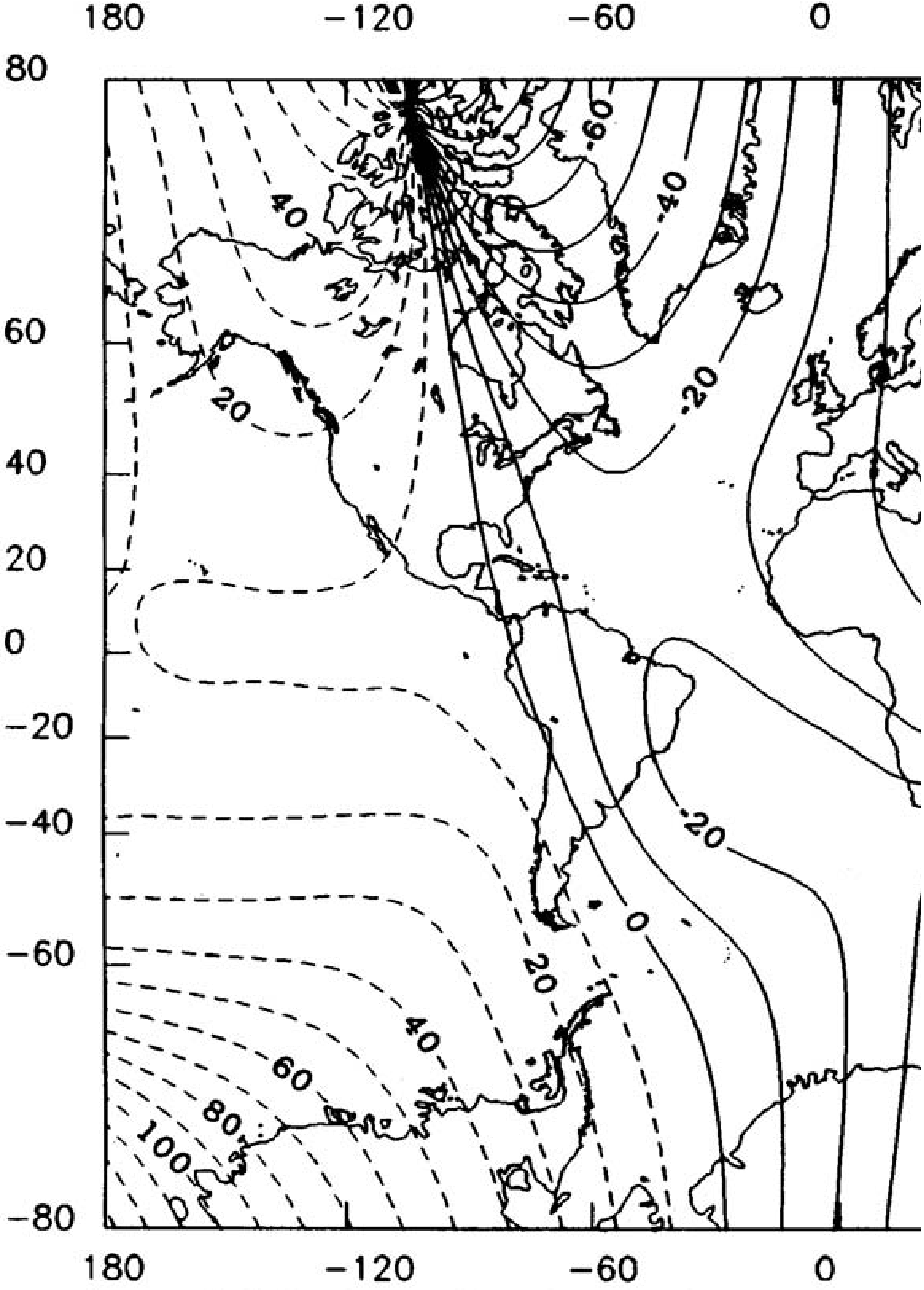


F, in degrees.
y dashed lines, zero and negative (or west) declination



Contours of magnetic declination at 1995.0 from the 6th generation IGR
The contour interval is 10°. Positive (or east) declination is indicated b
is indicated by solid lines.

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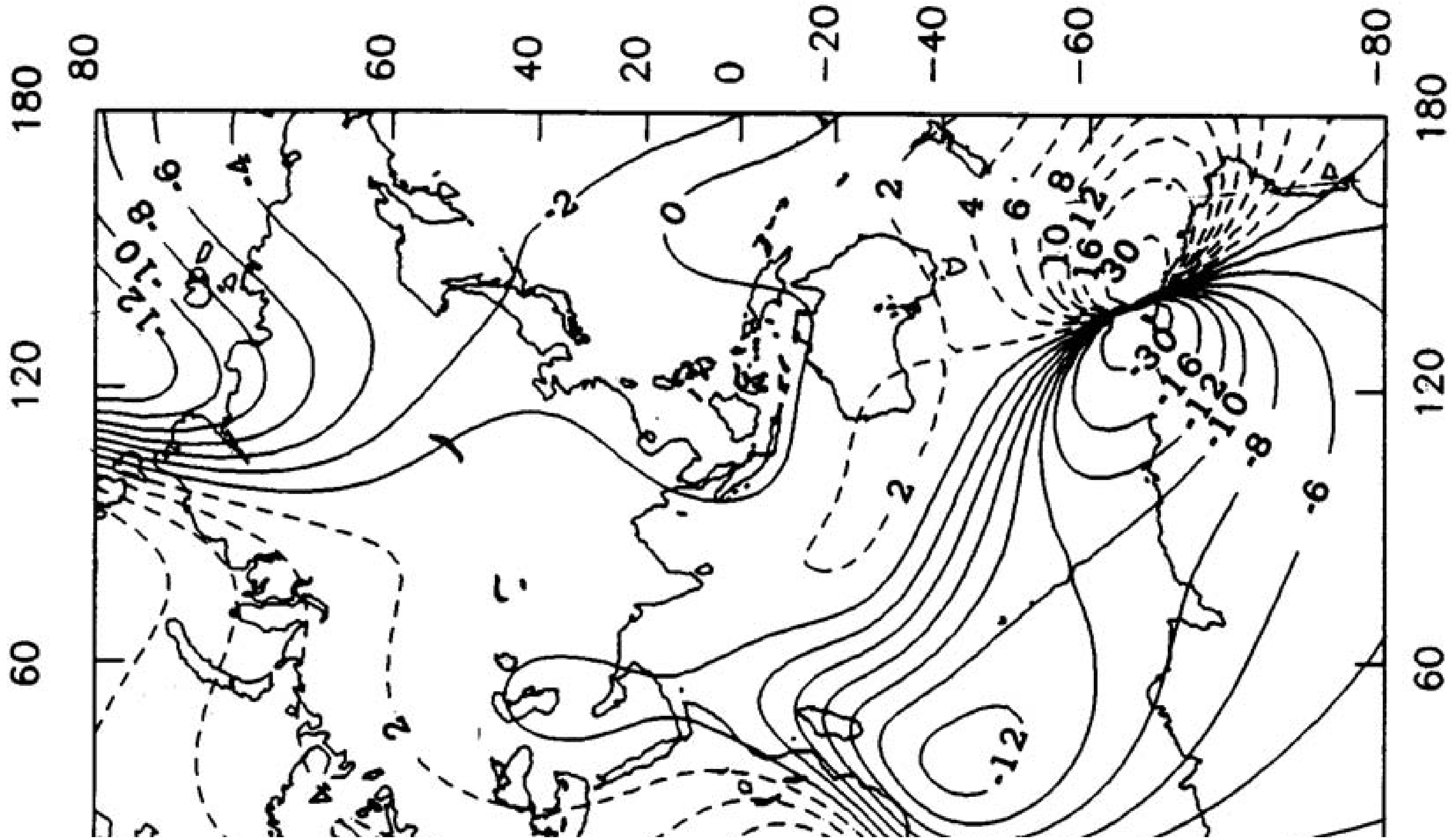
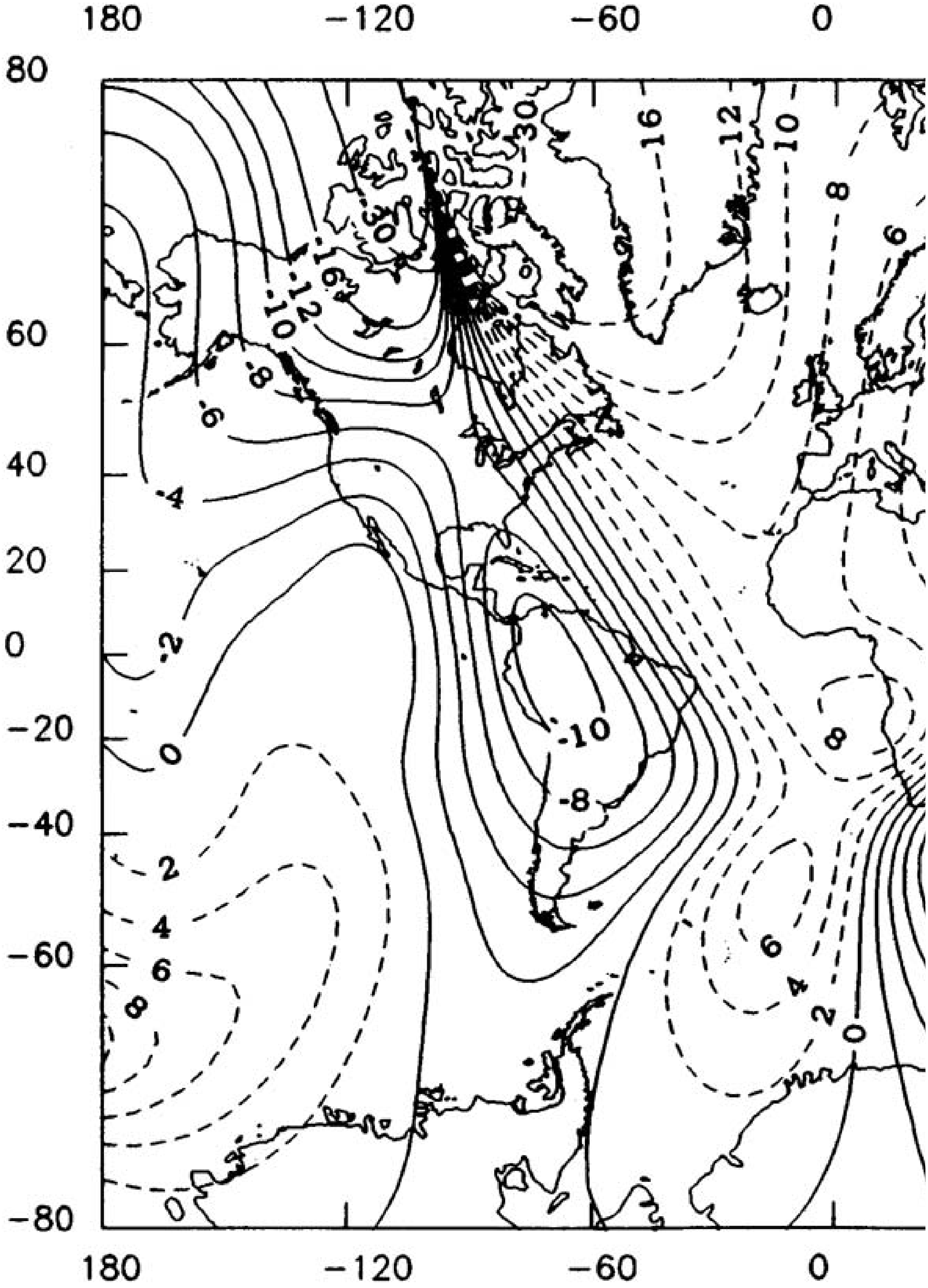


1995 from the 6th generation IGRF, in arcminutes/year.
ed by dashed lines, zero and negative (or west) values



Contours of secular variation of magnetic declination for the interval 1990–
The contour interval is 2 arcmin/yr. Positive (or east) values are indicat
are indicated by solid lines.