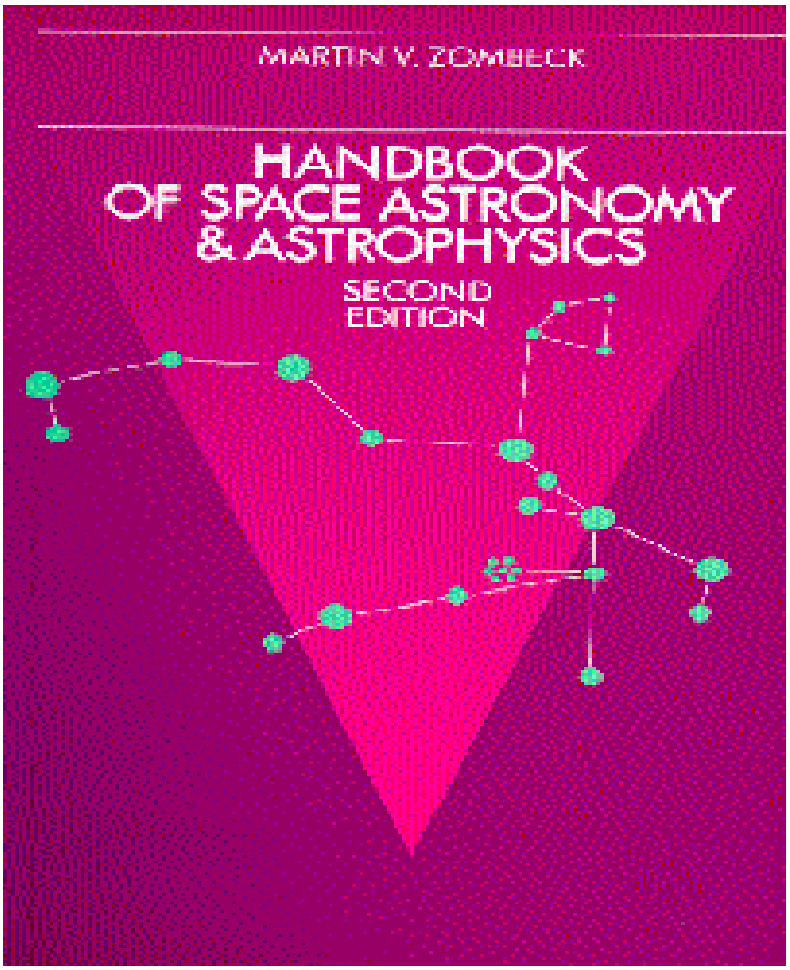
Cambridge University Press

Handbook of Space Astronomy and Astrophysics



Second Edition
by Martin V. Zombeck

ISBN 0 521 34550 2 (hardbook)
ISBN 0 521 34787 4 (paperback)

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Chapter 1

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Fundamental physical constants (SI)

(1986 recommended values of the fundamental physical constants. The digits in parentheses are the one-standard-deviation uncertainty in the last digits of the given value.)

Quantity	Symbol	Value	Units	Relative uncertainty (ppm)
GENERAL CONSTANTS				
UNIVERSAL CONSTANTS				
speed of light in vacuum	c	299 792 458	$m\ s^{-1}$	(exact)
permeability of vacuum	μ_0	$4\pi \times 10^{-7}$	$N\ A^{-2}$	
		$= 12.566\ 370\ 614\ \ldots$	$10^{-7}\ N\ A^{-2}$	(exact)
permittivity of vacuum	ε_0	$1/\mu_0 c^2$		
		$= 8.854\ 187\ 817\ \ldots$	$10^{-12}\ F\ m^{-1}$	(exact)
Newtonian constant of gravitation	G	6.672 59(85)	$10^{-11}\ m^3\ kg^{-1}\ s^{-2}$	128
Planck constant	h	6.626 075 5(40)	10^{-34} J s	0.60
in electron volts, $h/\lvert e\rvert$		4.135 669 2(12)	10^{-15} eV s	0.30
$h/2\pi$	$\hbar$	1.054 572 66(63)	10^{-34} J s	0.60
in electron volts, $\hbar/\lvert e\rvert$		6.582 122 0(20)	10^{-16} eV s	0.30
Planck mass, $(\hbar c/G)^{\frac{1}{2}}$	m_P	2.176 71(14)	10^{-8} kg	64
Planck length, $\hbar/m_P c = (\hbar G/c^3)^{\frac{1}{2}}$	l_P	1.616 05(10)	10^{-35} m	64
Planck time, $l_P/c \quad (\hbar G/c^5)^{\frac{1}{2}}$	t_P	5.390 56(34)	10^{-44} s	64
ELECTROMAGNETIC CONSTANTS				
elementary charge	e	1.602 177 33(49)	10^{-19} C	0.30
	e/h	2.417 988 36(72)	$10^{14}\ A\ J^{-1}$	0.30
magnetic flux quantum, $\hbar/2e$	Φ_0	2.067 834 61(61)	10^{-15} Wb	0.30
Josephson frequency–voltage ratio	$2e/h$	4.835 976 7(14)	$10^{14}\ Hz\ V^{-1}$	0.30
quantized Hall conductance	e^2/h	3.874 046 14(17)	10^{-5} S	0.045
quantized Hall resistance, $h/e^2 = \frac{1}{2}\mu_0 c/\alpha$	R_H	25 812.805 6(12)	Ω	0.045

Bohr magneton, $eh/2m_e$	μ_B	9.274 015 4(31)	10^{-24} J T^{-1}	0.34
in electron volts, $\mu_B/\{e\}$		5.788 382 63(52)	10^{-5} eV T^{-1}	0.089
in hertz, μ_B/h		1.399 624 18(42)	10^{10} Hz T^{-1}	0.30
in wavenumbers, μ_B/hc		46.686 437(14)	m^{-1} T^{-1}	0.30
in kelvins, μ_B/k		0.671 709 9(57)	K T^{-1}	8.5
nuclear magneton, $eh/2m_p$	μ_N	5.050 786 6(17)	10^{-27} J T^{-1}	0.34
in electron volts, $\mu_N/\{e\}$		3.152 451 66(28)	10^{-8} eV T^{-1}	0.089
in hertz, μ_N/h		7.622 591 4(23)	MHz T^{-1}	0.30
in wavenumbers, μ_N/hc		2.542 622 81(77)	10^{-2} m^{-1} T^{-1}	0.30
in kelvins, μ_N/k		3.658 246(31)	10^{-4} K T^{-1}	8.5

ATOMIC CONSTANTS

ATOM

fine-structure constant, $\frac{1}{2}\mu_0 ce^2/h$	α	7.297 353 08(33)	10^{-3}	0.045
inverse fine-structure constant	α^{-1}	137.035 989 5(61)		0.045
Rydberg constant, $\frac{1}{2}m_e c\alpha^2/h$	R_∞	10 973 731.534(13)	m^{-1}	0.0012
in hertz, $R_\infty c$		3.289 841 949 9(39)	10^{15} Hz	0.0012
in joules, $R_\infty hc$		2.179 874 1(13)	10^{-18} J	0.60
in electron volts, $R_\infty hc/\{e\}$		13.605 698 1(40)	eV	0.30
Bohr radius, $\alpha/4\pi R_\infty$	a_0	0.529 177 249(24)	10^{-10} m	0.045
Hartree energy, $e^2/4\pi\varepsilon_0 a_0 = 2R_\infty hc$	E_h	4.359 748 2(26)	10^{-18} J	0.60
in electron volts, $E_h/\{e\}$		27.211 396 1(81)	eV	0.30
quantum of circulation	$h/2m_e$	3.636 948 07(33)	10^{-4} m^2 s^{-1}	0.089
	h/m_e	7.273 896 14(65)	10^{-4} m^2 s^{-1}	0.089

ELECTRON

electron mass	m_e	9.109 389 7(54)	10^{-31} kg	0.59
		5.485 799 03(13)	10^{-4} u	0.023
in electron volts, $m_e c^2/\{e\}$		0.510 999 06(15)	MeV	0.30
electron–muon mass ratio	m_e/m_μ	4.836 332 18(71)	10^{-3}	0.15
electron–proton mass ratio	m_e/m_p	5.446 170 13(11)	10^{-4}	0.020
electron–deuteron mass ratio	m_e/m_d	2.724 437 07(6)	10^{-4}	0.020
electron–α-particle mass ratio	m_e/m_α	1.370 933 54(3)	10^{-4}	0.021

Fundamental physical constants (SI) (*cont.*)

Quantity	Symbol	Value	Units	Relative uncertainty (ppm)
electron specific charge	e/m_e	−1.758 819 62(53)	10^{11} C kg^{-1}	0.30
electron molar mass	$M(e)$, M_e	5.485 799 03(13)	10^{-7} kg mol^{-1}	0.023
Compton wavelength, $h/m_e c$	λ_C	2.426 310 58(22)	10^{-12} m	0.089
$\lambda_C/2\pi = \alpha a_0 = \alpha^2/4\pi R_\infty$	$\lambda\!\!\!^{-}_C$	3.861 593 23(35)	10^{-13} m	0.089
classical electron radius, $\alpha^2 a_0$	r_e	2.817 940 92(38)	10^{-15} m	0.13
Thomson cross-section, $(8\pi/3)r_e^2$	σ_e	0.665 246 16(18)	10^{-28} m^2	0.27
electron magnetic moment	μ_e	928.477 01(31)	10^{-26} J T^{-1}	0.34
in Bohr magnetons	μ_e/μ_B	1.001 159 652 193(10)		1×10^{-5}
in nuclear magnetons	μ_e/μ_N	1838.282 000(37)		0.020
electron magnetic moment anomaly, $\mu_e/\mu_B - 1$	a_e	1.159 652 193(10)	10^{-3}	0.0086
electron g-factor, $2(1 + a_e)$	g_e	2.002 319 304 386(20)		1×10^{-5}
electron–muon magnetic moment ratio	μ_e/μ_μ	206.766 967(30)		0.15
electron–proton magnetic moment ratio	μ_e/μ_p	658.210 658 1(66)		0.010
MUON				
muon mass	m_μ	1.883 532 7(11)	10^{-28} kg	0.61
		0.113 428 913(17)	u	0.15
in electron volts, $m_\mu c^2/\|e\|$		105.658 389(34)	MeV	0.32
muon–electron mass ratio	m_μ/m_e	206.768 262(30)		0.15
muon molar mass	$M(\mu)$, M_μ	1.134 289 13(17)	10^{-4} kg mol^{-1}	0.15
muon magnetic moment	μ_μ	4.490 451 4(15)	10^{-26} J T^{-1}	0.33
in Bohr magnetons	μ_μ/μ_B	4.841 970 97(71)	10^{-3}	0.15
in nuclear magnetons	μ_μ/μ_N	8.890 598 1(13)		0.15
muon magnetic moment anomaly, $\|a_\mu\|e\|/2m_\mu\| - 1$	a_μ	1.165 923 0(84)	10^{-3}	7.2
muon g-factor, $2(1 + a_\mu)$	g_μ	2.002 331 846(17)		0.0084
muon–proton magnetic moment ratio	μ_μ/μ_p	3.183 345 47(47)		0.15

PROTON				
proton mass	m_p	1.672 623 1(10)	10^{-27} kg	0.59
		1.007 276 470(12)	u	0.012
in electron volts, $m_p c^2/(e)$		938.272 31(28)	MeV	0.30
proton–electron mass ratio	m_p/m_e	1836.152 701(37)		0.020
proton–muon mass ratio	m_p/m_μ	8.880 244 4(13)		0.15
proton specific charge	e/m_p	9.578 830 9(29)	10^7 C kg^{-1}	0.30
proton molar mass	$M(\mathrm{p})$, M_p	1.007 276 470(12)	10^{-3} kg mol^{-1}	0.012
proton Compton wavelength, $h/m_p c$	$\lambda_{C,p}$	1.321 410 02(12)	10^{-15} m	0.089
$\lambda_{C,p}/2\pi$	$\bar{\lambda}_{C,p}$	2.103 089 37(19)	10^{-16} m	0.089
proton magnetic moment	μ_p	1.410 607 61(47)	10^{-26} J T^{-1}	0.34
in Bohr magnetons	μ_p/μ_B	1.521 032 202(15)	10^{-3}	0.010
in nuclear magnetons	μ_p/μ_N	2.792 847 386(63)		0.023
diamagnetic shielding correction for protons in pure water, spherical sample, 25 °C, $1-\mu'_p/\mu_p$	σ_{H_2O}	25.689(15)	10^{-6}	
shielded proton moment (H_2O, sph., 25 °C)	μ'_p	1.410 571 38(47)	10^{-26} J T^{-1}	0.34
in Bohr magnetons	μ'_p/μ_B	1.520 993 129(17)	10^{-3}	0.011
in nuclear magnetons	μ'_p/μ_N	2.792 775 642(64)		0.023
proton gyromagnetic ratio	γ_p	26 752.2128(81)	10^4 s^{-1} T^{-1}	0.30
	$\gamma_p/2\pi$	42.577 469(13)	MHz T^{-1}	0.30
uncorrected (H_2O, sph., 25 °C)	γ'_p	26 751.5255(81)	10^4 s^{-1} T^{-1}	0.30
	$\gamma'_p/2\pi$	42.576 375(13)	MHz T^{-1}	0.30
NEUTRON				
neutron mass	m_n	1.674 928 6(10)	10^{-27} kg	0.59
		1.008 664 904(14)	u	0.014
in electron volts, $m_n c^2/(e)$		939.565 63(28)	MeV	0.30
neutron–electron mass ratio	m_n/m_e	1838.683 662(40)		0.022
neutron–proton mass ratio	m_n/m_p	1.001 378 404(9)		0.009
neutron molar mass	$M(\mathrm{n})$, M_n	1.008 664 904(14)	10^{-3} kg mol^{-1}	0.014
neutron Compton wavelength, $h/m_n c$	$\lambda_{C,n}$	1.319 591 10(12)	10^{-15} m	0.089
$\lambda_{C,n}/2\pi$	$\bar{\lambda}_{C,n}$	2.100 194 45(19)	10^{-16} m	0.089

Fundamental physical constants (SI) *(cont.)*

Quantity	Symbol	Value	Units	Relative uncertainty (ppm)
neutron magnetic moment[59]	μ_n	0.966 237 07(40)	10^{-26} J T^{-1}	0.41
in Bohr magnetons	μ_n/μ_B	1.041 875 63(25)	10^{-3}	0.24
in nuclear magnetons	μ_n/μ_N	1.913 042 75(45)		0.24
neutron–electron magnetic moment ratio	μ_n/μ_e	1.040 668 82(25)	10^{-3}	0.24
neutron–proton magnetic moment ratio	μ_n/μ_p	0.684 979 34(16)		0.24
DEUTERON				
deuteron mass	m_d	3.343 586 0(20)	10^{-27} kg	0.59
		2.013 553 214(24)	u	0.012
in electron volts, $m_d c^2/\lvert e\rvert$		1875.613 39(57)	MeV	0.30
deuteron–electron mass ratio	m_d/m_e	3670.483 014(75)		0.020
deuteron–proton mass ratio	m_d/m_p	1.999 007 496(6)		0.003
deuteron molar mass	$M(d)$, M_d	2.013 553 214(24)	10^{-3} kg mol^{-1}	0.012
deuteron magnetic moment[60]	μ_d	0.433 073 75(15)	10^{-26} J T^{-1}	0.34
in Bohr magnetons	μ_d/μ_B	0.466 975 447 9(91)	10^{-3}	0.019
in nuclear magnetons	μ_d/μ_N	0.857 438 230(24)		0.028
deuteron–electron magnetic moment ratio	μ_d/μ_e	0.466 434 546 0(91)	10^{-3}	0.019
deuteron–proton magnetic moment ratio	μ_d/μ_p	0.307 012 203 5(51)		0.017
PHYSICO-CHEMICAL CONSTANTS				
Avogadro constant	N_A, L	6.022 136 7(36)	10^{23} mol^{-1}	0.59
atomic mass constant, $m_u = \frac{1}{12}m(^{12}C)$	m_u	1.660 540 2(10)	10^{-27} kg	0.59
in electron volts, $m_u c^2/\lvert e\rvert$		931.494 32(28)	MeV	0.30
Faraday constant	F	96 485.309(29)	C mol^{-1}	0.30

molar Planck constant	$N_A h$	3.990 313 23(36)	10^{-10} J s mol^{-1}	0.089
	$N_A hc$	0.119 626 58(11)	J m mol^{-1}	0.089
molar gas constant	R	8.314 510(70)	J mol^{-1} K^{-1}	8.4
Boltzmann constant, R/N_A	k	1.380 658(12)	10^{-23} J K^{-1}	8.5
in electron volts, $k/\|e\|$		8.617 385(73)	10^{-5} eV K^{-1}	8.4
in hertz, k/h		2.083 674(18)	10^{10} Hz K^{-1}	8.4
in wavenumbers, k/hc		69.503 87(59)	m^{-1} K^{-1}	8.4
molar volume (ideal gas), RT/p				
$T = 273.15$ K, $p = 101\,325$ Pa	V_m	22.414 10(19)	L mol^{-1}	8.4
Loschmidt constant, N_A/V_m	n_0	2.686 763(23)	10^{25} m^{-3}	8.5
$T = 273.15$ K, $p = 100$ kPa	V_m	22.710 18(19)	L mol^{-1}	8.4
Sackur–Tetrode constant (absolute entropy constant)$^{(b)}$ $\frac{5}{2} + \ln[(2\pi m_u kT_1/h^2)^{3/2} kT_1/p_0]$				
$T_1 = 1$ K, $p_0 = 100$ kPa	S_0/R	−1.151 693(21)		18
$p_0 = 101\,325$ Pa		−1.164 856(21)		18
Stefan–Boltzmann constant, $(\pi^2/60)k^4/\hbar^3c^2$	σ	5.670 51(19)	10^{-8} W m^{-2} K^{-4}	34
first radiation constant, $2\pi hc^2$	c_1	3.741 774 9(22)	10^{-16} W m^2	0.60
second radiation constant, hc/k	c_2	0.014 387 69(12)	m K	8.4
Wien displacement law constant, $b = \lambda_{max} T = c_2/4.965\,114\,23\ldots$	b	2.897 756(24)	10^{-3} m K	8.4

(a) The scalar magnitude of the neutron moment is listed here. The neutron magnetic dipole is directed oppositely to that of the proton, and corresponds to the dipole associated with a spinning negative charge distribution. The vector sum, $\mu_n = \mu_p + \mu_e$, is approximately satisfied.

(b) The entropy of an ideal monatomic gas of relative atomic weight A_r is given by

$$S = S_0 + \tfrac{3}{2}R \ln A_r - R \ln(p/p_0) + \tfrac{5}{2}R \ln(T/K).$$

MAINTAINED UNITS AND STANDARD VALUES

A summary of 'maintained' units and 'standard' values and their relationship to SI units, based on a least-squares adjustment with 17 degrees of freedom. The digits in parentheses are the one-standard-deviation uncertainty in the last digits of the given value.

Quantity	Symbol	Value	Units	Relative uncertainty (ppm)
electron volt, (e/C) J $\quad \{e\}$ J	eV	1.602 177 33(49)	10^{-19} J	0.30
(unified) atomic mass unit, 1 u $= m_u = \frac{1}{12}m(^{12}C)$	u	1.660 540 2(10)	10^{-27} kg	0.59
standard atmosphere	atm	101 325	Pa	(exact)
standard acceleration of gravity	g_n	9.806 65	m s^{-2}	(exact)
'AS-MAINTAINED' ELECTRICAL UNITS				
BIPM[a] maintained ohm, Ω_{90-BI}				
$\Omega_{BIPM} = \Omega_{90-BI}$ (1 Jan. 1985)	Ω_{BIPM}	$1 - 1.563(50) \times 10^{-6}$	Ω	
		$= 0.999\,998\,437(50)$	Ω	0.050
drift rate of Ω_{90-BI}	$\frac{d\Omega_{90-BI}}{dt}$	0.0566(15)	$\mu\Omega/a$	—
BIPM maintained volt, $V_{90-BI} = 483\,594$ GHz$(h/2e)$	V_{90-BI}	$1 \quad 7.59(30) \times 10^{-6}$	V	
		$= 0.999\,992\,41(30)$	V	0.30
BIPM maintained ampere, $A_{BIPM} = V_{90-BI}/\Omega_{90-BI}$	A_{BIPM}	$1 - 6.03(30) \times 10^{-6}$	A	
		$= 0.999\,993\,97(30)$	A	0.30
X-RAY STANDARDS				
Cu x-unit: $\lambda(CuK\alpha_1) \equiv 1537.400$ xu	xu(CuKα_1)	1.002 077 89(70)	10^{-13} m	0.70
Mo x-unit: $\lambda(MoK\alpha_1) \equiv 707.831$ xu	xu(MoKα_1)	1.002 099 38(45)	10^{-13} m	0.45
Å*: $\lambda(WK\alpha_1) \equiv 0.209\,100$ Å*	Å*	1.000 014 51(92)	10^{-10} m	0.92

lattice spacing of Si (in vacuum, 22.5 °C)[b]	a	0.543 101 96(11)	nm	0.21
$d_{220} = a/\sqrt{8}$	d_{220}	0.192 015 540(40)	nm	0.21
molar volume of Si, $M(\mathrm{Si})/\rho(\mathrm{Si}) = N_A a^3/8$	$V_m(\mathrm{Si})$	12.058 817 9(89)	$\mathrm{cm^3\ mol^{-1}}$	0.74

[a] BIPM: Bureau International des Poids et Mésures.

[b] The lattice spacing of single-crystal Si can vary by parts in 10^7 depending on the preparation process. Measurements at Physikalisch Technische Bundesanstalt (FRG) indicate also the possibility of distortions from exact cubic symmetry of the order of 0.2 ppm.

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Fundamental physical constants (e.g.s.)

Speed of light in vacuum	$c = 2.997\,924\,58 \times 10^{10}$ cm s^{-1}
Gravitational constant	$G = 6.672\,59 \times 10^{-8}$ dyn cm^2 g^{-2}
Planck's constant	$h = 6.626\,075\,5 \times 10^{-27}$ erg s
Electron charge	$e = 4.803\,206\,8 \times 10^{-10}$ esu
Mass of electron	$m_e = 9.109\,389\,7 \times 10^{-28}$ g
Mass of proton	$m_p = 1.672\,623\,1 \times 10^{-24}$ g
Mass of neutron	$m_n = 1.674\,928\,6 \times 10^{-24}$ g
Atomic mass unit (amu)	$m_u = 1.660\,540\,2 \times 10^{-24}$ g
Proton-electron mass ratio	$m_p/m_e = 1\,836.152\,701$
Fine structure constant	$hc/2\pi e^2 = 1/\alpha = 137.035\,989\,5$
Classical electron radius	$e^2/m_e c^2 = r_e = 2.817\,940\,92 \times 10^{-13}$ cm
Bohr radius	$h^2/4\pi^2 m_e e^2 = a_0 = 0.529\,177\,249 \times 10^{-8}$ cm
Electron Compton wavelength	$h/m_e c = \lambda_c = 2.426\,310\,58 \times 10^{-10}$ cm
Rydberg constant	$2\pi^2 m_e e^4/ch^3 = R_\infty = 109\,737.315\,34$ cm^{-1}
Boltzmann constant	$k = 1.380\,658 \times 10^{-16}$ erg K^{-1}
Stefan–Boltzmann constant	$\sigma = 2\pi^5 k^4/15 h^3 c^2$
	$= 5.670\,51 \times 10^{-5}$ erg cm^{-2} K^{-4} s^{-1}
Thomson cross-section	$8\pi r_e^2/3 = \sigma_T = 0.665\,246\,16 \times 10^{-24}$ cm^2
Bohr magneton	$e\hbar/4\pi m_e = \mu_B = 9.274\,015\,4 \times 10^{-21}$ gauss cm^3

(Based on constants recommended by the 1986 CODATA Committee in previous table.)

Sun–Earth system constants

Equatorial radius for Earth	$a_e = 6378.140$ km
Dynamical form-factor for Earth	$J_2 = 0.001\,082\,63$
Gravity at Earth's surface (mean)	$g_e = 980.7$ cm s^{-2}
Ratio of mass of Moon to that of Earth	$\mu = 0.012\,300\,02$
Lunar distance (mean)	$3.844\,01 \times 10^{10}$ cm
Astronomical unit	AU $= 1.495\,978\,70 \times 10^{13}$ cm
Mass of the Earth	$M_e = 5.976 \times 10^{27}$ g
Solar parallax	$\pi_\odot = 8''.794\,148$
Tropical year (1900.0)	365.242 days
	3.1557×10^7 ephemeris seconds
Ephemeris day	86 400 ephemeris seconds
Constant of aberration (2000.0)	$K = 20''.495\,52$
Obliquity of the ecliptic (2000.0)	$\varepsilon = 23^\circ\,26'\,21''.448$
General precession in longitude per Julian century (2000.0)	$p = 5029''.0966$
Constant of nutation (2000.0)	$N' = 9''.2055$
Earth's magnetic dipole moment	$M_e = 8.02 \times 10^{22}$ Am^2
Angular rotation rate of Earth	$\Omega = 7.292\,115 \times 10^{-5}$ rad s^{-1}
Average depth of ocean	$H = 3800$ m
Flattening of Earth	$1/f = 298.257$

Cosmological data

Hubble constant	$H_0 = (50\text{–}100)\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ $= (1.6\text{–}3.2) \times 10^{-18}\,\mathrm{s^{-1}}$
Hubble time	$1/H_0 = (19.6\text{–}9.78) \times 10^9$ y
Hubble distance	$R = c/H_0 = (6050\text{–}3025)\,\mathrm{Mpc}$
Critical density	$\rho_c = 3H_0^2/8\pi G$ $= (5\text{–}20) \times 10^{-30}\,\mathrm{g\,cm^{-3}}$
Volume	$\frac{4}{3}\pi R^3 = (9\text{–}1) \times 10^{11}\,\mathrm{Mpc^3}$
Smoothed density of galactic material throughout universe (Allen 1973)	$2 \times 10^{-31}\,\mathrm{g\,cm^{-3}}$ $1 \times 10^{-7}\,\mathrm{atom\,cm^{-3}}$ $3 \times 10^9\,M_\odot\,\mathrm{Mpc^{-3}}$
Space density of galaxies	$0.02\,\mathrm{Mpc^{-3}}$
Luminous emission from galaxies	$3 \times 10^8\,L_\odot\,\mathrm{Mpc^{-3}}$
Mean sky brightness from galaxies	$1.4(m_v = 10)\,\mathrm{deg^{-2}}$
Cosmic background thermodynamic temperature	2.74 ± 0.09 K
Weak coupling constant	$g_{wk} = 1.435 \times 10^{-49}\,\mathrm{erg\,cm^3}$

Unit conversions

1 keV: $hc/E = 12.398\,54 \times 10^{-8}$ cm
1 keV: $E/h = 2.417\,965 \times 10^{17}$ Hz
1 keV: $E/k = 11.6048 \times 10^6$ K
1.0 EHz: $h\nu = 4.135\,71$ keV
1 keV = $1.602\,177 \times 10^{-9}$ erg
1 joule = 10^7 erg
1 calorie = 4.184 joule
1 parsec = 3.261 633 light years = $3.085\,678 \times 10^{18}$ cm
1 light year = $9.460\,530 \times 10^{17}$ cm
1 XU = $1.002\,09 \times 10^{-11}$ cm
1 Ångstrom = 1×10^{-8} cm
1 amu: $Mc^2 = 1.492\,41 \times 10^{-3}$ erg = 931.494 MeV
760 torr = 1.013×10^6 dyn cm^{-2} = 1 atmos. = 1.013 bars = 1.013×10^5 Pascals
1 Rayleigh $\equiv (1/4\pi) \times 10^6$ photons cm^{-2} s^{-1} sr^{-1}
1 Uhuru ct s^{-1} = 1.7×10^{-11} erg cm^{-2} s^{-1} (2–6 keV)
= 2.4×10^{-11} erg cm^{-2} s^{-1} (2–10 keV)
1 flux unit $\equiv 10^{-26}$ watt m^{-2} Hz^{-1} $\equiv$ 1 Jansky
1.0 μJy = 10^{-17} erg cm^{-2} s^{-1} EHz^{-1}
= 0.242×10^{-11} erg cm^{-2} s^{-1} keV^{-1} = 1.509×10^{-3} keV cm^{-2} s^{-1} keV^{-1}
1 curie: amount of material undergoing 3.7×10^{10} disintegrations s^{-1}
1 nautical mile = 1852 m
1 statute mile = 1609.344 m
intensity (erg cm^{-2} s^{-1} Hz^{-1}) = $3.33 \times 10^{-9}\,\lambda^2$(Å) intensity (erg cm^{-2} s^{-1} Å^{-1})
1 barn = 10^{-24} cm^2
1 tesla = 10^4 Gauss
0 °C = 273.15 K

Conversion tables

(A given amount of a physical quantity, expressed in the units of one system, is expressed as an equivalent number of units in another system.)

Quantity	Amount	Unit	Amount	Unit
LENGTH				
	1	meter (SI)	1.000 00E − 02	centimeter (cgs)
	1	light year	= 9.460 53E 15	meter (SI)
	1	parsec	= 3.085 68E + 16	meter (SI)
	1	Angstrom	= 1.000 01E − 10	meter (SI)
	1	Angstrom	1.000 01E 08	centimeter (cgs)
	1	micron	1.000 00E 06	meter (SI)
	1	XU	= 1.002 09E − 13	meter (SI)
	1	fermi	1.000 00E − 15	meter (SI)
	1	nautical mile	= 1.852 00E + 03	meter (SI)
	1	statute mile	= 1.609 34E + 03	meter (SI)
	1	astron. unit (AU)	1.495 98E + 11	meter (SI)
	1	solar radius	6.959 90E + 08	meter (SI)
	1	centimeter (cgs)	= 3.240 78E − 19	parsec
	1	centimeter (cgs)	6.684 56E − 14	astron. unit (AU)
	1	meter (SI)	= 3.240 78E − 17	parsec
	1	meter (SI)	= 6.684 54E − 12	astron. unit (AU)
	1	inch (Eng)	2.540 00E − 02	meter (SI)
MASS				
	1	kilogram (SI)	1.000 00E − 03	gram (cgs)
	1	at. mass unit (amu)	= 1.660 54E − 24	gram (cgs)
	1	at. mass unit (amu)	= 1.660 54E − 27	kilogram (SI)
	1	solar mass	= 1.989 10E + 33	gram (cgs)
	1	solar mass	= 1.989 10E + 30	kilogram (SI)

	1	gram (cgs) = 6.02214E + 23	at. mass unit (amu)
	1	gram (cgs) = 5.027 40E − 34	solar mass
	1	kilogram (SI) = 6.022 14E + 26	at. mass unit (amu)
	1	kilogram (SI) = 5.027 40E − 31	solar mass
	1	kilogram (SI) = 2.204 62E + 00	pound (avdp.)
	1	kilogram (SI) = 3.527 40E + 01	ounce (avdp.)
	1	pound (avdp.) = 4.535 92E − 01	kilogram (SI)
	1	pound (avdp.) = 1.600 00E + 01	ounce (avdp.)
	1	ounce (avdp.) = 2.834 95E + 01	gram (cgs)
	1	gram (cgs) = 3.527 40E − 02	ounce (avdp.)
ENERGY			
	1	joule (SI) = 1.000 00E + 07	erg (cgs)
	1	joule (SI) = 6.241 51E + 18	electron volt (eV)
	1	erg (cgs) = 1.000 00E − 07	joule (SI)
	1	erg (cgs) = 6.241 51E + 11	electron volt
	1	electron volt = 1.602 18E − 12	erg (cgs)
	1	amu × c^2 = 9.314 95E − 08	electron volt
	1	gm (cgs) × c^2 = 5.609 59E + 32	electron volt
	1	calorie = 4.184 00E + 00	joule (SI)
FORCE			
	1	newton (SI) = 1.000 00E + 05	dyne (cgs)
	1	dyne (cgs) = 1.000 00E − 05	newton (SI)
PRESSURE			
	1	pascal (SI) = 1.000 00E + 00	newton m^{-2} (SI)
	1	bar = 1.000 00E + 06	dyne cm^{-2} (cgs)
	1	bar = 9.869 23E − 01	atmosphere
	1	torr = 1.333 22E − 03	bar
POWER			
	1	watt (SI) = 1.000 00E + 07	erg s^{-1} (cgs)
	1	horsepower = 7.457 00E + 02	watt (SI)
	1	Btu s^{-1} (Eng) = 1.055 80E + 03	watt (SI)

Conversion tables (*cont.*)

Quantity	Amount	Unit	Amount	Unit
TIME				
	1	second (SI)	= 1	second (cgs)
	1	minute	= 6.000 00E − 01	second
	1	hour	= 3.600 00E − 03	second
	1	day	= 8.640 00E − 04	second
	1	tropical year	= 3.155 69E − 07	second
	1	tropical year	= 3.652 42E 02	day
	1	second	= 3.168 88E 08	tropical year
	1	sidereal second	= 9.972 70E 01	second
	1	sidereal year	= 3.652 56E 02	day
TEMPERATURE				
	T	kelvin	$= T - 273.15$	celsius
	T	kelvin	$= (9/5) \times (T - 273.15) - 32$	fahrenheit
	T	celsius	$= T + 273.15$	kelvin
	T	fahrenheit	$= (5/9) \times (T - 32) + 273.15$	kelvin
	T	celsius	$= (9/5) \times T + 32$	fahrenheit
	T	fahrenheit	$= (5/9) \times (T - 32)$	celsius
Energy equivalence	1	electron volt	= 1.160 48E + 04	kelvin
Temperature equivalence	1	kelvin	= 8.617 12E − 05	electron volt
ELECTRICITY AND MAGNETISM				
Charge	1	coulomb	= 2.997 92E + 09	statcoulomb
Charge density	1	coulomb m^{-3}	2.997 92E 03	statcoul cm^{-3}
Current	1	ampere (coul s^{-1})	2.997 92E 09	statampere
Current density	1	ampere m^{-2}	= 2.997 92E + 05	statamp cm^{-2}
Electric field	1	volt m^{-1}	3.335 65E 05	statvolt cm^{-1}
Potential	1	volt	= 3.335 65E − 03	statvolt

Resistance	1	ohm = 1.112 65E − 12	$s\ cm^{-1}$
Resistivity	1	ohm m = 1.112 65E − 10	s
Conductance	1	siemens, mho = 8.987 52E − 11	$cm\ s^{-1}$
Conductivity	1	mho m^{-1} = 8.987 52E − 09	s^{-1}
Capacitance	1	farad = 8.987 52E − 11	cm
Magnetic flux	1	weber = 1.000 00E − 08	$gauss\ cm^{2}$ (maxwell)
Magnetic flux density	1	tesla = 1.000 00E − 04	gauss
Magnetic field	1	ampere-turn m^{-1} = 1.256 64E − 02	oersted
Inductance	1	henry = 1.112 65E − 12	$s^{2}\ cm^{-1}$
MISCELLANEOUS			
Radio-activity	1	curie (SI) 3.700 00E − 10	disinteg. s^{-1}
Intensity	1	rayleigh 7.957 75E − 04	$ph\ cm^{-2}\ s^{-1}\ sr^{-1}$
Flux density	1	fu or jansky = 1.000 00E − 26	$watt\ m^{-2}\ Hz^{-1}$
Flux density	1	jansky = 1.000 00E − 05	$erg\ cm^{-2}\ s^{-1}\ Hz^{-1}$
Flux density	1	jansky = 2.420 00E − 06	$erg\ cm^{-2}\ s^{-1}\ keV^{-1}$
Flux density	1	jansky = 1.509 00E + 03	$keV\ cm^{-2}\ s^{-1}\ keV^{-1}$
Energy equivalence	1	eV : 1.239 85E + 04	Ångstrom
Energy equivalence	1	eV : 2.417 97E + 14	Hz
Wavelength equivalence	1	Ångstrom : 1.239 85E + 04	eV
Angle	1	arcsec = 4.848 14E − 06	radian
Angle	1	arcmin 2.908 88E − 04	radian
Angle	1	degree 1.745 33E − 02	radian
Solid angle	1	$arcsec^{2}$ 2.350 40E − 11	steradian
Solid angle	1	$arcmin^{2}$ 8.461 70E − 08	steradian
Solid angle	1	deg^{2} 3.046 20E − 04	steradian

Numerical constants

$\pi = 3.141\,592\,7$
$e = 2.718\,281\,8$
$\ln 2 = 0.693\,147\,2$
$\log_{10} 2 = 0.301\,030\,0$
$\ln 10 = 2.302\,585\,1$
$\log_{10} e = 0.434\,294\,5$
$(2\pi)^{1/2} = 2.506\,628$
$\pi^2 = 9.869\,604$
$2^{10} = 1024$
$e^{-1} = 0.367\,879\,4$
$\Gamma(n+1) = n!$, integer n
$\Gamma(1/2) = \pi^{1/2}$
Feigenbaum's number: $\delta = 4.669\,201\,6$

$\text{rad} = 57.295\,78\ \text{deg}$
$= 3.437\,747 \times 10^{3}\ \text{arcmin}$
$= 2.062\,648 \times 10^{5}\ \text{arcsec}$
$\text{steradian} = 32\,400/\pi^2 = 3.2828 \times 10^{4}\ \text{deg}^2$
$= 1.1818 \times 10^{9}\ \text{arcmin}^2$
$= 4.2545 \times 10^{10}\ \text{arcsec}^2$
$\text{degree} = 0.017\,453\,3\ \text{rad}$
$\text{arcmin} = 2.908\,88 \times 10^{-4}\ \text{rad}$
$\text{arcsec} = 4.848\,137 \times 10^{-6}\ \text{rad}$
$\text{deg}^2 = 3.0462 \times 10^{-3}\ \text{steradian}$
$\text{arcmin}^2 = 8.4617 \times 10^{-8}\ \text{steradian}$
$\text{arcsec}^2 = 2.3504 \times 10^{-11}\ \text{steradian}$

	Powers of 2:		*Number system conversions:*			
n	2^n	$\log 2^n$	Decimal	Octal	Binary	Hexadecimal
0	1	0.00	0	0	0000	0
1	2	0.30	1	1	0001	1
2	4	0.60	2	2	0010	2
3	8	0.90	3	3	0011	3
4	16	1.20	4	4	0100	4
5	32	1.51	5	5	0101	5
6	64	1.81	6	6	0110	6
7	128	2.11	7	7	0111	7
8	256	2.41	8	10	1000	8
9	512	2.71	9	11	1001	9
10	1024	3.01	10	12	1010	A
11	2048	3.31	11	13	1011	B
12	4096	3.61	12	14	1100	C
13	8192	3.91	13	15	1101	D
14	16 384	4.21	14	16	1110	E
15	32 768	4.52	15	17	1111	F
20	1 048 576	6.02	16	20	10000	10
25	33 554 432	7.53				
n		$0.301n$				

Mathematical formulae

$(a+x)^n = a^n + na^{n-1}x + \frac{n(n-1)}{2!}a^{n-2}x^2 + \frac{n(n-1)(n-2)}{3!}a^{n-3}x^3 + \cdots + nax^{n-1} + x^n$,
where n is any positive integer.

$e^x = 1 + x + \frac{x^2}{2!} + \frac{x^3}{3!} + \cdots$.

$\ln(1+x) = x - \frac{x^2}{2} + \frac{x^3}{3} - \frac{x^4}{4} + \cdots$ for $-1 < x \leq 1$.

$\sin x = x - \frac{x^3}{3!} + \frac{x^5}{5!} - \frac{x^7}{7!} + \cdots$, $\cos x = 1 - \frac{x^2}{2!} + \frac{x^4}{4!} - \frac{x^6}{6!} + \cdots$.

$\int u\,dv = uv - \int v\,du + C$, $\int_0^{\pi} \sin^2 nx\,dx = \int_0^{\pi} \cos^2 nx\,dx = \frac{\pi}{2}$
for an integer, $n \neq 0$.

$\int_0^{\infty} e^{-a^2x^2}\,dx = \pi^{1/2}/2a$; $\int_0^{\infty} x^n e^{-ax}\,dx = \Gamma(n+1)/a^{n+1}$.

$F(u) = \int_{x=-\infty}^{\infty} f(x)\,e^{-2\pi iux}\,dx \leftrightarrow f(x) = \int_{-\infty}^{\infty} F(u)\,e^{2\pi iux}$.

$n! \approx (2\pi)^{1/2} n^{n+1/2} e^{-n}$ (for large n).

$\int_a^b f(x)\,dx = -\int_b^a f(x)\,dx$, $\int_a^b f(x)\,dx = \int_a^c f(x)\,dx + \int_c^b f(x)\,dx$.

$\frac{d}{dx} f[u(x)] = \frac{df}{du}\frac{du}{dx}$, $\frac{d}{dx}[u(x)v(x)] = v\frac{du}{dx} + u\frac{dv}{dx}$.

$\frac{d}{dx}\ln y(x) = y'(x)/y(x)$. $2.30 \log_{10} x = \log_e x$

$\sin(A+B) = \sin A \cos B + \cos A \sin B$.

$\cos(A+B) = \cos A \cos B - \sin A \sin B$.

$e^{ix} = \cos x + i \sin x$.

Elementary particles (short list)

Particle	Charge	Mass (amu)	Spin	Magnetic moment	Mean life[a] (s)
Photon	0	0	1	0	stable
π-meson	$+1, -1$	0.149 84	1	0	2.60×10^{-8}
	0	0.144 90	0	0	0.83×10^{-16}
Neutrino	0	$< 10^{-6}$	1/2	~ 0	stable
Electron, positron	$-1, +1$	0.000 548 6	1/2	$1.001\,160\,\mu_B$[b]	stable
μ-meson	$-1, +1$	0.1134	1/2	$0.004\,842\,\mu_B$	2.20×10^{-6}
Proton	$+1, -1$	1.007 276	1/2	$2.792\,85\,\mu_N$[c]	stable
Neutron	0	1.008 665	1/2	$-1.913\,06\,\mu_N$	917 ± 14

[a] half-life $= \text{mean life} \times \ln 2$

[b] $\mu_B = eh/4\pi m_e c = 9.274\,015\,4(31) \times 10^{-24}$ J T^{-1}

[c] $\mu_N = eh/4\pi m_p c = 5.050\,786\,6(17) \times 10^{-27}$ J T^{-1}.

(Data from 'Reviews of Particle Properties', *Rev. Mod. Phys.* 52, No. 2, April 1980)

Elementary Particles

(The second column is the isospin I, while the next column is the spin and parity, J^P. Masses and lifetimes have generally been rounded; see the original reference for error bars and a complete listing of particle properties.)

Particle	I	J^P	Mass (MeV)	Mean life (s)
LEPTONS				
e		$\frac{1}{2}$	0.511 003	Stable
μ		$\frac{1}{2}$	105.6594	$2.197\,14 \times 10^{-6}$
τ		$\frac{1}{2}$	1784	5×10^{-13}
NONSTRANGE BARYONS				
p	$\frac{1}{2}$	$\frac{1}{2}^+$	938.280	Stable
n	$\frac{1}{2}$	$\frac{1}{2}^+$	939.573	925
Δ	$\frac{3}{2}$	$\frac{3}{2}^+$	1232	6×10^{-24}
STRANGENESS $= -1$ *BARYONS*				
Λ	0	$\frac{1}{2}^+$	1115.60	2.63×10^{-10}
Σ^+	1	$\frac{1}{2}^+$	1189.36	8.00×10^{-11}
Σ^0	1	$\frac{1}{2}^+$	1192.46	6×10^{-20}
Σ^-	1	$\frac{1}{2}^+$	1197.34	1.48×10^{-10}
STRANGENESS $= -2$ *BARYONS*				
Ξ^0	$\frac{1}{2}$	$\frac{1}{2}^+$	1314.9	2.9×10^{-10}
Ξ^-	$\frac{1}{2}$	$\frac{1}{2}^+$	1321.3	1.64×10^{-10}
STRANGENESS $= -3$ *BARYON*				
Ω^-	0	$\frac{3}{2}^+$	1672.5	8.2×10^{-11}
NONSTRANGE CHARMED BARYON				
Λ_c^+	0	$\frac{1}{2}^+$	2282	1×10^{-13}
NONSTRANGE MESONS				
$\pi^\pm$	1	0^-	139.567	2.603×10^{-8}
π^0	1	0^-	134.963	8.3×10^{-17}
η	0	0^-	548.8	8×10^{-19}
ρ	1	1^-	769	4.3×10^{-24}
ω	0	1^-	782.6	6.6×10^{-23}
η'	0	0^-	957.6	2.4×10^{-21}
ϕ	0	1^-	1019.6	1.6×10^{-22}
J/Ψ	0	1^-	3096.9	1.0×10^{-20}
Υ		1	9456	1.6×10^{-20}
STRANGENESS $= -1$ *MESONS*				
$K^\pm$	$\frac{1}{2}$	0	493.67	1.237×10^{-8}
$K^0, \bar{K}^0$	$\frac{1}{2}$	0	497.7	K_S: 8.92×10^{-11}
				K_L: 5.18×10^{-8}
CHARMED NONSTRANGE MESONS				
D	$\frac{1}{2}$	0^-	1869.4	9×10^{-13}
D^+, D^0	$\frac{1}{2}$	0^-	1864.7	5×10^{-13}
CHARMED STRANGE MESON				
$F^\pm$	0	0^-	2021	2×10^{-13}

(From Shapiro, S. L. & Teukolsky, S. A., *Black Holes, White Dwarfs, and Neutron Stars*, John Wiley and Sons, 1983; with permission.)

Energy conversions

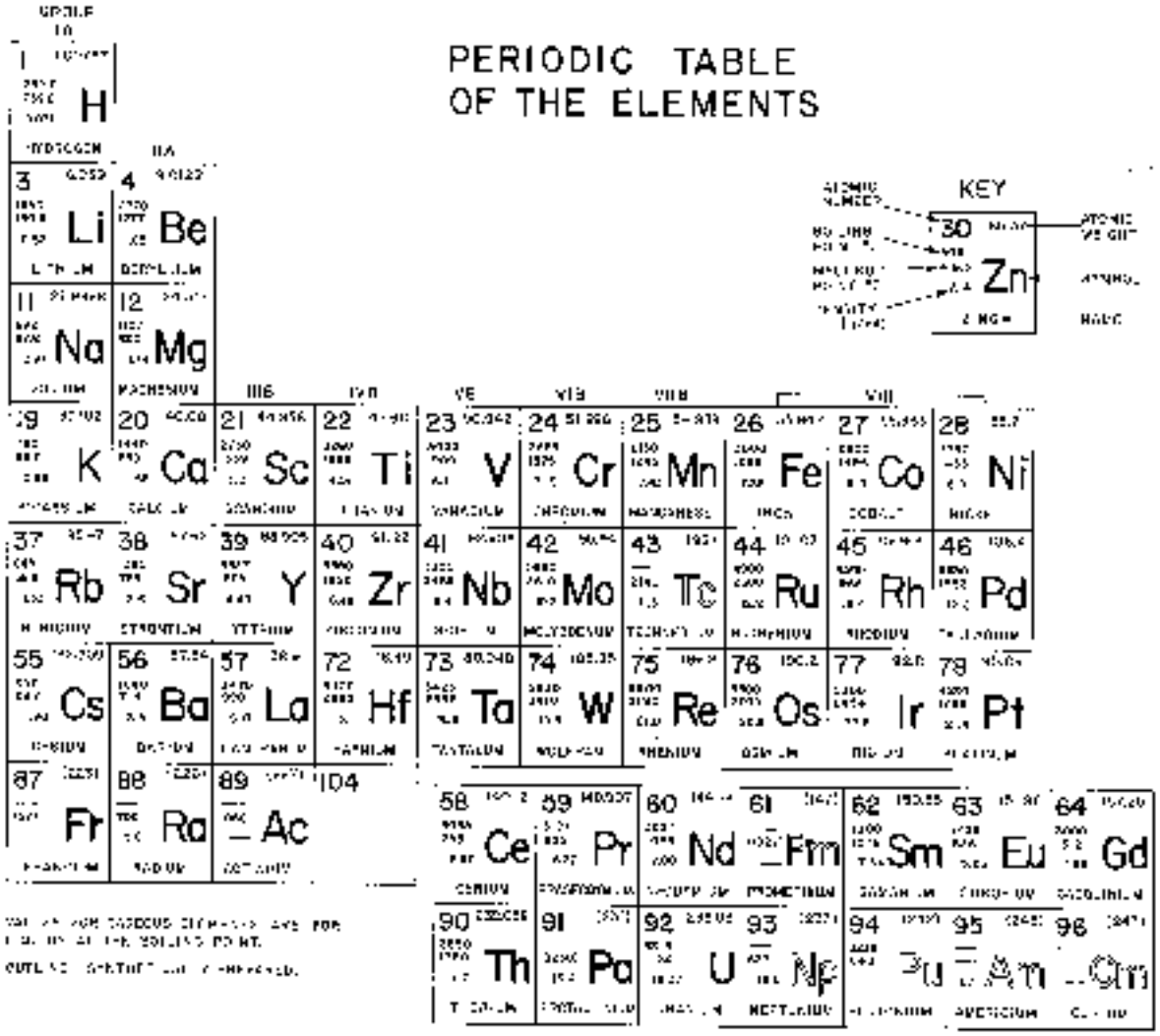
1 erg	= 1 dyne-centimeter = 10^{-7} joule
1 joule	= 1 newton-meter
1 foot-pound	= 1.356 joule
1 calorie	= 4.184 joule
1 Btu	= 1.055×10^{3} joule
1 horsepower-hour	= 2.6845×10^{6} joule
1 Kilowatt-hour	= 3.6×10^{6} joule = 3.413×10^{3} Btu
1 MeV	= 1.6×10^{-6} joule
Energy of fission of 1 atom of ^{235}U	= 199 MeV = 3.2×10^{-11} joule
Energy equivalent of 1 ton of TNT	= 4.2×10^{9} joule
Energy of fission of 1 kilogram of ^{235}U	= 20 kilotons of TNT
Hydrogen fusion:	$D + T \rightarrow {}_2He^4 + n + 17.6$ MeV
Energy equivalent of 1 gram of matter	= 9×10^{13} joule
High heat value of 1 ton of coal	= 26×10^{6} Btu
High heat value of 1 cord of red oak	= 30×10^{6} Btu
High heat value of 100 gallons of fuel oil	= 15×10^{6} Btu
High heat value of 20 000 cu ft natural gas	= 20×10^{6} Btu
US energy consumption	= 10^{20} joule yr^{-1} (proj. 1970–2000)
Earth's daily receipt of solar energy	= 1.49×10^{32} joule = 4.2×10^{12} Mwh
Earth's rotational energy	= 2.2×10^{29} joule
Earth's total heat content	= 3×10^{31} joule
1 D-cell flashlight battery	= 10 watt-s = 10^{2} joule

Prefixes and symbols

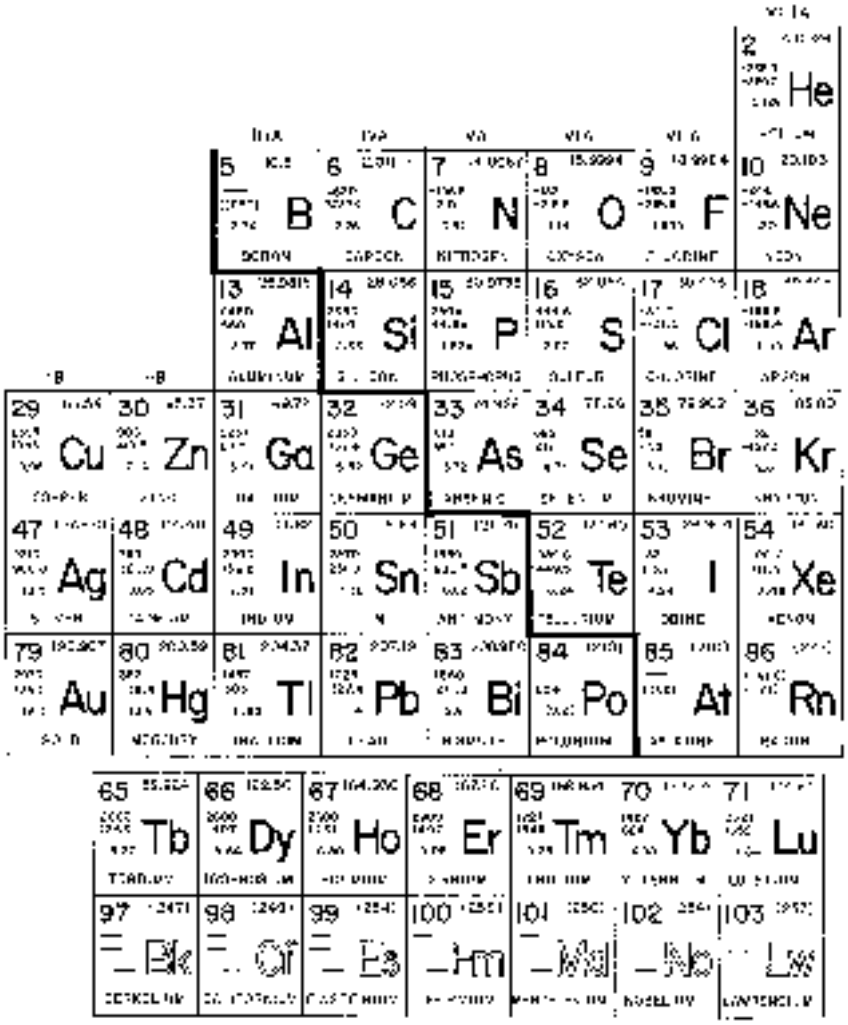
(used with SI units to indicate decimal multiples and submultiples)

Multiples			Submultiples		
Factor	Prefix	Symbol	Factor	Prefix	Symbol
10^{18}	exa	E	10^{-1}	deci	d
10^{15}	peta	P	10^{-2}	centi	c
10^{12}	tera	T	10^{-3}	milli	m
10^{9}	giga	G	10^{-6}	micro	μ
10^{6}	mega	M	10^{-9}	nano	n
10^{3}	kilo	k	10^{-12}	pico	p
10^{2}	hecto	h	10^{-15}	femto	f
10	deca	da	10^{-18}	atto	a

Periodic table of the elements



Periodic table of the elements (*cont.*)



Greek alphabet

A	α	Alpha	N	ν	Nu
B	β	Beta	Ξ	ξ	Xi
Γ	γ	Gamma	O	o	Omicron
Δ	δ	Delta	Π	π	Pi
E	ε	Epsilon	P	ρ	Rho
Z	ζ	Zeta	Σ	σ	Sigma
H	η	Eta	T	τ	Tau
Θ	θ	Theta	Υ	υ	Upsilon
I	ι	Iota	Φ	ϕ	Phi
K	κ	Kappa	X	χ	Chi
Λ	λ	Lambda	Ψ	ψ	Psi
M	μ	Mu	Ω	ω	Omega

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Chapter 2

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