2. ASTROPHYSICAL CONSTANTS

Table 2.1. Revised 2001 by D.E. Groom (LBNL). The figures in parentheses after some values give the one-standard deviation uncertainties in the last digit(s). Physical constants are from Ref. 1. While every effort has been made to obtain the most accurate current values of the listed quantities, the table does not represent a critical review or adjustment of the constants, and is not intended as a primary reference.

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c **speed of light**
Value: 299 792 458 m s^{-1} defined Ref. [2]

G_N **Newtonian gravitational constant**
Value: $6.673(10) \times 10^{-11}$ m^3 kg^{-1} s^{-2} Ref. [3]

au **astronomical unit (mean $\oplus$–$\odot$ distance)**
Value: 149 597 870 660(20) m Ref. [4, 5]

yr **tropical year (equinox to equinox) (2001.0)**
Value: 31 556 925.2 s Ref. [4]

sidereal year (fixed star to fixed star) (2001.0)
Value: 31 558 149.8 s Ref. [4]

mean sidereal day (2001.0)
Value: $23^{\mathrm{h}}\,56^{\mathrm{m}}\,04\overset{\mathrm{s}}{.}090\,53$ Ref. [4]

Jy **Jansky**
Value: 10^{-26} W m^{-2} Hz^{-1}

$\sqrt{\hbar c/G_N}$ **Planck mass**
Value: $1.2210(9) \times 10^{19}$ GeV/c^2 Ref. [1]

Value: $= 2.176\,7(16) \times 10^{-8}$ kg

pc **parsec (1 AU/1 arc sec)**
Value: $3.085\,677\,580\,7(4) \times 10^{16}$ m $= 3.262\ldots$ ly Ref. [6]

ly **light year (deprecated unit)**
Value: $0.306\,6\ldots$ pc $= 0.946\,1\ldots \times 10^{16}$ m

$2G_N M_\odot/c^2$ **Schwarzschild radius of the Sun**
Value: 2.953 250 08 km Ref. [7]

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† Subscript 0 indicates present-day values.

$M_\odot$ **solar mass**
Value: $1.988\,9(30) \times 10^{30}$ kg Ref. [8]

$R_\odot$ **solar equatorial radius**
Value: 6.961×10^{8} m Ref. [4]

$L_\odot$ **solar luminosity**
Value: $(3.846 \pm 0.008) \times 10^{26}$ W Ref. [9]

$2G_N M_\oplus / c^2$ **Schwarzschild radius of the Earth**
Value: 8.870 056 22 mm Ref. [10]

$M_\oplus$ **Earth mass**
Value: $5.974(9) \times 10^{24}$ kg Ref. [11]

$R_\oplus$ **Earth mean equatorial radius**
Value: $6.378\,140 \times 10^{6}$ m Ref. [4]

L **luminosity conversion**
Value: $3.02 \times 10^{28} \times 10^{-0.4\, M_{\rm bol}}$ W Ref. [12]

Value: ($M_{\rm bol}$ = absolute bolometric magnitude

Value: = bolometric magnitude at 10 pc)

$\mathscr{F}$ **flux conversion**
Value: $2.52 \times 10^{-8} \times 10^{-0.4\, m_{\rm bol}}$ W m^{-2} from above

Value: ($m_{\rm bol}$ = apparent bolometric magnitude)

$\Theta_\circ$ **$v_\odot$ around center of Galaxy**
Value: 220(20) km s^{-1} Ref. [13]

$R_\circ$ **solar distance from galactic center**
Value: 8.0(5) kpc Ref. [14]

H_0 **Hubble expansion rate**†
Value: $100\, h$ km s^{-1} Mpc^{-1}

Value: $= h \times (9.778\,13 \text{ Gyr})^{-1}$ Ref. [15]

h **normalized Hubble expansion rate**†
Value: $(0.71 \pm 0.07) \times^{1.15}_{0.95}$ Ref. [16, 17]

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† Subscript 0 indicates present-day values.

$\rho_c = 3H_0^2/8\pi G_N$ **critical density of the universe**†
Value: $2.775\,366\,27 \times 10^{11}\ h^2\ M_\odot \mathrm{Mpc}^{-3}$

Value: $= 1.879(3) \times 10^{-29}\ h^2\ \mathrm{g\ cm}^{-3}$

Value: $= 1.053\,9(16) \times 10^{-5}\ h^2\ \mathrm{GeV\ cm}^{-3}$

$\rho_{\,\mathrm{disk}}$ **local disk density**
Value: 3–$12 \times 10^{-24}\ \mathrm{g\ cm}^{-3} \approx 2$–$7\ \mathrm{GeV}/c^2\ \mathrm{cm}^{-3}$ Ref. [18]

$\rho_{\,\mathrm{halo}}$ **local halo density**
Value: 2–$13 \times 10^{-25}\ \mathrm{g\ cm}^{-3} \approx 0.1$–$0.7\ \mathrm{GeV}/c^2 \mathrm{cm}^{-3}$ Ref. [19]

$\Omega_M \equiv\ \rho_M/\rho_c$ **pressureless matter density of the universe**†
Value: $0.15 \lesssim \Omega_M \lesssim 0.45$ Ref. [16, 20]

$\Omega_B \equiv\ \rho_B/\rho_c$ **baryon density of the universe**
Value: $0.0095 \lesssim \Omega_B h^2 \lesssim 0.023$ Ref. [21]

$\Omega_\Lambda = \Lambda c^2/3H_0^2$ **scaled cosmological constant**†
Value: $0.6 \lesssim \Omega_\Lambda \lesssim 0.8$ Ref. [16]

$c^2/3H_0^2$ **scale factor for cosmological constant**†
Value: $2.853 \times 10^{51}\ h^{-2}\ \mathrm{m}^2$

Ω_{tot} [22] $\boldsymbol{\Omega_M + \Omega_\Lambda + \ldots}$ [22]
Value: see footnote Ref. [23]

t_0 **age of the universe**†
Value: 12–18 Gyr Ref. [16]

T_0 **cosmic background radiation (CBR) temperature**†
Value: 2.725 ± 0.001 K Ref. [24, 25]

solar velocity with respect to CBR
Value: $371 \pm 0.5\ \mathrm{km\ s}^{-1}$ Ref. [25]

Value: towards $(\alpha, \delta) = (11.20^{\mathrm{h}} \pm 0.01^{\mathrm{h}}, -7.22^\circ \pm 0.08^\circ)$

Value: or $(\ell, b) = (264.31^\circ \pm 0.17^\circ, 48.05^\circ \pm 0.10^\circ)$

v_{LG} **Local group velocity with respect to CBR**
Value: $627 \pm 22\,\mathrm{km\,s}^{-1}$ Ref. [25]

Value: towards $(\ell, b) = (276^\circ \pm 3^\circ, 30^\circ \pm 3^\circ)$

ρ_γ **energy density of CBR**
Value: $4.641\,7 \times 10^{-34}\,(T/2.725)^4$ g cm^{-3} Ref. [12, 25]

Value: $= 0.260\,38\,(T/2.725)^4$ eV cm^{-3}

$\rho_{\rm rel}$ **energy density of relativistic particles (CBR + $\boldsymbol{\nu}$)**
Value: $7.804\,2 \times 10^{-34}\,(T/2.725)^4$ g cm^{-3} Ref. [12, 25]

Value: $= 0.437\,78\,(T/2.725)^4$ eV cm^{-3}

$\Omega_{\rm rel} = \rho_{\rm rel}/\rho_c$
Value: $4.153\,4 \times 10^{-5} h^{-2} (T/2.725)^4$

n_B **number density of baryons**
Value: $2.6 \times 10^{-10} < n_B/n_\gamma < 6.2 \times 10^{-10}$ Ref. [21]

s/k **entropy density/Boltzmann constant**
Value: $2\,889.2\;(T/2.725)^3$ cm^{-3} Ref. [12]

† Subscript 0 indicates present-day values.

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1. P.J. Mohr and B.N. Taylor, "CODATA Recommended Values of the Fundamental Physical Constants: 1998," J. Phys. Chem. Ref. Data **28**, 1713–1852 (1999).
2. B.W. Petley, Nature **303**, 373 (1983).
3. The value of G_N [1] is the same as in Ref. 26, but the quoted error is 12 times larger. See Measurement, Science, and Technology **10**, No. 6 (June 1999), special section: "The gravitational constant: Theory and experiment 200 years after Cavendish."

   Eight or more measurements of G_N have been published 1997–2000. See Fig. 3 in Quinn *et al.*, Phys. Rev. Lett. **85**, 2869 (2000). The measurements are not mutually compatable and most are higher than the CODATA value.

   In the context of the scale dependence of field theoretic quantities, it should be remarked that absolute lab measurements of G_N have been performed on scales of 0.01–1.0 m.
4. *The Astronomical Almanac for the year 2001*, U.S. Government Printing Office, Washington, and Her Majesty's Stationary Office, London (1999).
5. JPL Planetary Ephemerides, E. Myles Standish, Jr., private communication (1989).
6. 1 AU divided by $\pi/648\,000$; quoted error is from the JPL Planetary Ephemerides value of the AU [5].

7. Product of $2/c^2$ and the heliocentric gravitational constant [4]. The given 9-place accuracy seems consistent with uncertainties in defining the earth's orbital parameters.
8. Obtained from the heliocentric gravitational constant [4] and G_N [3]. The error is the 1500 ppm standard deviation of G_N.
9. 1996 mean total solar irradiance (TSI) $= 1367.5 \pm 2.7$ [27]; the solar luminosity is $4\pi \times (1\ \mathrm{AU})^2$ times this quantity. This value increased by 0.036% between the minima of solar cycles 21 and 22. It was modulated with an amplitude of 0.039% during solar cycle 21 [28].

   Sackmann *et al.* [29] use TSI $= 1370 \pm 2$ W m^{-2}, but conclude that the solar luminosity ($L_\odot = 3.853 \times 10^{26}$ J s^{-1}) has an uncertainty of 1.5%. Their value comes from three 1977–83 papers, and they comment that the error is based on scatter among the reported values, which is substantially in excess of that expected from the individual quoted errors.

   The conclusion of the 1971 review by Thekaekara and Drummond [30] ($1353 \pm 1\%$ W m^{-2}) is often quoted [31]. The conversion to luminosity is not given in the Thekaekara and Drummond paper, and we cannot exactly reproduce the solar luminosity given in Ref. 31.

   Finally, a value based on the 1954 spectral curve due to Johnson [32] ($1395 \pm 1\%$ W m^{-2}, or $L_\odot = 3.92 \times 10^{26}$ J s^{-1}) has been used widely, and may be the basis for the higher value of the solar luminosity and the corresponding lower value of the solar absolute bolometric magnitude (4.72) still common in the literature [12].
10. Product of $2/c^2$, the heliocentric gravitational constant from Ref. 4, and the earth/sun mass ratio, also from Ref. 4. The given 9-place accuracy appears to be consistent with uncertainties in actually defining the earth's orbital parameters.
11. Obtained from the geocentric gravitational constant [4] and G_N [3]. The error is the 1500 ppm standard deviation of G_N.
12. E.W. Kolb and M.S. Turner, *The Early Universe*, Addison-Wesley (1990).
13. F.J. Kerr and D. Lynden-Bell, Mon. Not. R. Astr. Soc. **221**, 1023–1038 (1985). "On the basis of this review these [$R_\circ = 8.5 \pm 1.1$ kpc and $\Theta_\circ = 220 \pm 20$ km s^{-1}] were adopted by resolution of IAU Commission 33 on 1985 November 21 at Delhi".
14. M.J. Reid, Annu. Rev. Astron. Astrophys. **31**, 345–372 (1993). Note that $\Theta_\circ$ from the 1985 IAU Commission 33 recommendations is adopted in this review, although the new value for $R_\circ$ is smaller.
15. Conversion using length of tropical year.

16. M. Fukugita and C.J. Hogan, "Global Cosmological Parameters: H_0, Ω_M, and Λ," Sec. 17 of this *Review*.
17. The final uncertainty arises from dichotomous estimates of the distance to the Large Magellanic Cloud.
18. G. Gilmore, R.F.G. Wyse, and K. Kuijken, Annu. Rev. Astron. Astrophys. **27**, 555 (1989).
19. E.I. Gates, G. Gyuk, and M.S. Turner (Astrophys. J. **449**, L133 (1995)) find the local halo density to be $9.2^{+3.8}_{-3.1} \times 10^{-25}$ g cm^{-3}, but also comment that previously published estimates are in the range 1–10 $\times 10^{-25}$ g cm^{-3}.
 The value 0.3 GeV/c^2 has been taken as "standard" in several papers setting limits on WIMP mass limits, *e.g.* in M. Mori *et al.*, Phys. Lett. **B289**, 463 (1992).
20. Fukugita and Hogan find a more restrictive limit, $0.2 \lesssim \Omega_M \lesssim 0.4$, if the Universe is flat.
21. B.D. Fields and S. Sarkar, "Big-Bang nucleosynthesis," Sec. 16 of this *Review*.
22. In addition to the pressureless mass density Ω_M and the scaled cosmological constant Ω_Λ, $\Omega_{\rm tot}$ contains very small contributions from the cosmic background radiation, the primordial neutrino energy density, and perhaps other sources. $1 - \Omega_{\rm tot}$ is the three-dimensional scalar curvature scaled by the squared inverse Hubble length, variously written as $kc^2/(H_0R(t_0))^2$ [12], Kc^2/H_0^2 [36], and Ω_k[37]. Thus $\Omega_{\rm tot} = 1$ indicates a flat universe.
23. Recent results from both BOOMERANG [33] and MAXIMA-1 [34] indicate $\Omega_M + \Omega_\Lambda \approx 1$ with $\approx 10\%$ uncertainties, providing the strongest evidence to date for a flat universe. See discussions elsewhere in this *Review* concerning the remarkable consistency of Ω_M and Ω_Λ measurements by different methods [16,25,35].
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