2. ASTROPHYSICAL CONSTANTS

Table 2.1. Revised 1997 by D.E. Groom (LBNL) with the help of G.F. Smoot, M.S. Turner, and R.C. Willson. The figures in parentheses after some values give the one-standard deviation uncertainties in the last digit(s). 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. [1]

G_N **Newtonian gravitational constant**
Value: $6.672\,59(85) \times 10^{-11}$ m^3 kg^{-1} s^{-2} Ref. [2]

AU **astronomical unit**
Value: $1.495\,978\,706\,6(2) \times 10^{11}$ m Ref. [3,4]

yr **tropical year (equinox to equinox) (1994)**
Value: $31\,556\,925.2$ s Ref. [3]

sidereal year (fixed star to fixed star) (1994)
Value: $31\,558\,149.8$ s Ref. [3]

mean sidereal day
Value: $23^{\rm h}\,56^{\rm m}\,04\overset{\rm s}{.}090\,53$ Ref. [3]

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

$\sqrt{\hbar c/G_N}$ **Planck mass**
Value: $1.221\,047(79) \times 10^{19}$ GeV$/c^2$ uses Ref. [2]

Value: $= 2.176\,71(14) \times 10^{-8}$ kg

pc **parsec (1 AU/1 arc sec)**
Value: $3.085\,677\,580\,7(4) \times 10^{16}$ m $= 3.262\ldots$ ly Ref. [5]

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. [6]

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† Subscript 0 indicates present-day values.

$M_\odot$ **solar mass**
Value: $1.988\,92(25) \times 10^{30}$ kg Ref. [7]

$L_\odot$ **solar luminosity**
Value: $(3.846 \pm 0.008) \times 10^{26}$ W Ref. [8]

$R_\odot$ **solar equatorial radius**
Value: 6.96×10^{8} m Ref. [3]

$R_\oplus$ **Earth equatorial radius**
Value: $6.378\,140 \times 10^{6}$ m Ref. [3]

$M_\oplus$ **Earth mass**
Value: $5.973\,70(76) \times 10^{24}$ kg Ref. [9]

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

Value: (M_b = absolute bolometric magnitude

Value: = bolometric magnitude at 10 pc)

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

Value: (m_b = apparent bolometric magnitude)

$\Theta_\circ$ **$v_\odot$ around center of Galaxy**
Value: 220(20) km s^{-1} Ref. [11]

$R_\circ$ **solar distance from galactic center**
Value: 8.0(5) kpc Ref. [12]

H_0 **Hubble expansion rate**†
Value: $100\ h_0$ km s^{-1} Mpc^{-1}

Value: $= h_0 \times (9.778\,13\ \text{Gyr})^{-1}$ Ref. [13]

h_0 **normalized Hubble expansion rate**†
Value: $0.6 < h_0 < 0.8$ Ref. [14]

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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: $2.775\,366\,27 \times 10^{11}\, h_0^2\, M_\odot \mathrm{Mpc}^{-3}$

Value: $= 1.878\,82(24) \times 10^{-29}\, h_0^2$ g cm^{-3}

Value: $= 1.053\,94(13) \times 10^{-5}\, h_0^2$ GeV cm^{-3}

$\rho_{\,\mathrm{disk}}$ **local disk density**
Value: 3–12 $\times 10^{-24}$ g cm^{-3} $\approx$ 2–7 GeV/c^2 cm^{-3} Ref. [15]

$\rho_{\,\mathrm{halo}}$ **local halo density**
Value: 2–13 $\times 10^{-25}$ g cm^{-3} $\approx$ 0.1–0.7 GeV/c^2cm^{-3} Ref. [16]

$\Omega_M \equiv \rho_M/\rho_c$ **pressureless matter density of the universe**†
Value: $0.2 < \Omega_M < 1$ Ref. [17]

$\Omega_\Lambda = \Lambda c^2/3H_0^2$ **scaled cosmological constant**†
Value: $-1 < \Omega_\Lambda < 2$ Ref. [18]

$c^2/3H_0^2$ **scale factor for cosmological constant**†
Value: $2.853 \times 10^{51}\, h_0^{-2}$ m^2

t_0 **age of the universe**†
Value: $11.5 + 1 \pm 1.5$ Gyr Ref. [19]

$\Omega_0 h_0^2$ for $\Lambda = 0$
Value: ≤ 2.4 for $t_0 \geq 10$ Gyr Ref. [10]

Value: ≤ 1 for $t_0 \geq 10$ Gyr, $h_0 > 0.4$ Ref. [10]

Value: ≤ 0.53 for $t_0 \geq 10$ Gyr, $h_0 > 0.6$ Ref. [20]

T_0 **cosmic background radiation (CBR) temperature**†
Value: 2.728 ± 0.002 K Ref. [21,22]

solar velocity with respect to CBR
Value: 369.3 ± 2.5 km s^{-1} Ref. [22,23]

ρ_γ **energy density of CBR**
Value: $4.662\,3 \times 10^{-34}\, (T/2.728)^4$ g cm^{-3} Ref. [10,22]

Value: $= 0.261\,53\, (T/2.728)^4$ eV cm^{-3}

ρ_R **energy density of relativistic particles (CBR + ν)**
Value: $7.838\,8 \times 10^{-34}\, (T/2.728)^4$ g cm^{-3} Ref. [10,22]

Value: $= 0.439\,72\,(T/2.728)^4$ eV cm^{-3}

n_γ **number density of CBR photons**
Value: $411.87\,(T/2.728)^3$ cm^{-3} Ref. [10,22]

s/k **entropy density/Boltzmann constant**
Value: $2\,899.3\,(T/2.728)^3$ cm^{-3} Ref. [10]

† Subscript 0 indicates present-day values.

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1. B.W. Petley, Nature **303**, 373 (1983).
2. E.R. Cohen and B.N. Taylor, Rev. Mod. Phys. **59**, 1121 (1987). The set of constants resulting from this adjustment has been recommended for international use by CODATA (Committee on Data for Science and Technology).
   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 only on scales of $10^{-1\pm1}$ m.
3. *The Astronomical Almanac for the year 1994*, U.S. Government Printing Office, Washington, and Her Majesty's Stationary Office, London (1993). Where possible, the values as adjusted for the fitting of the ephemerides to all the observational data are used.
4. JPL Planetary Ephemerides, E. Myles Standish, Jr., private communication (1989).
5. 1 AU divided by $\pi/648\,000$; quoted error is from the JPL Planetary Ephemerides value of the AU [4].
6. Heliocentric gravitational constant from Ref. 3 times $2/c^2$. The given 9-place accuracy appears to be consistent with uncertainties in actually defining the earth's orbital parameters.
7. Obtained from the heliocentric gravitational constant [3] and G_N [2]. The error is the 128 ppm standard deviation of G_N.
8. 1996 mean total solar irradiance (TSI) $= 1367.5 \pm 2.7$ [24]; the solar luminosity is $4\pi \times (1\text{ AU})^2$ 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 [25].
   Sackmann *et al.* [26] 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 is based on 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 [27] ($1353 \pm 1\%$ W m^{-2}) is often quoted [28]. The conversion to luminosity is not given in the Thekaekara and Drummond paper, and we cannot exactly reproduce the solar luminosity given in Ref. 28.

Finally, a value based on the 1954 spectral curve due to Johnson [29] ($1395 \pm 1\%$ W m^{-2}, or $L_\odot = 3.92 \times 10^{26}$ J s^{-1}) has been used widely, and may be the basis for higher value of the solar luminosity and corresponding lower value of the solar absolute bolometric magnitude (4.72) still common in the literature [10].

9. Obtained from the geocentric gravitational constant [3] and G_N [2]. The error is the 128 ppm standard deviation of G_N.
10. E.W. Kolb and M.S. Turner, *The Early Universe*, Addison-Wesley (1990).
11. 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".
12. 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.
13. Conversion using length of tropical year.
14. See the section on the Hubble Constant (Sec. 17 of this *Review*).
15. G. Gilmore, R.F.G. Wyse, and K. Kuijken, Annu. Rev. Astron. Astrophys. **27**, 555 (1989).
16. 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 1–10×10^{-25} g cm^{-3}.
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