2. ASTROPHYSICAL CONSTANTS AND PARAMETERS

Table 2.1. Revised 2001 by D.E. Groom (LBNL), February 2004 by M.A. Dobbs (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. The values and uncertainties for the cosmological parameters depend on the exact datasets, priors, and basis parameters used in the fit. Many of the parameters reported in this table are derived parameters or have non-Gaussian likelihoods. Their error bars may be highly correlated with other parameters and care must be taken when extrapolating to higher significance levels. In most cases we report the best fit running spectral index model parameters from the WMAPext plus 2dFGRS and Lyman α forest dataset, as reported in Ref. 2. Refer to Ref. 3 and the original papers for more information.

Quantity	Symbol, equation	Value	Reference, footnote
speed of light	c	299 792 458 m s^{-1}	defined[4]
Newtonian gravitational constant	G_N	$6.6742(10) \times 10^{-11}$ $m^3 kg^{-1}$ s^{-2}	[1, 5]
astronomical unit (mean $\oplus$–$\odot$ distance)	au	149 597 870 660(20) m	[6, 7]
tropical year (equinox to equinox) (2005.0)	yr	31 556 925.2 s	[6]
sidereal year (fixed star to fixed star) (2005.0)		31 558 149.8 s	[6]
mean sidereal day (2005.0)		$23^h\,56^m\,04\overset{s}{.}090\,53$	[6]
Jansky	Jy	10^{-26} W m^{-2} Hz^{-1}	
Planck mass	$\sqrt{\hbar c/G_N}$	$1.22090(9) \times 10^{19}$ GeV/c^2 $= 2.17645(16) \times 10^{-8}$ kg	[1]
Planck length	$\sqrt{\hbar G_N/c^3}$	$1.61624(12) \times 10^{-35}$ m	[1]
Hubble length	c/H_0	$\sim 1.2 \times 10^{26}$ m	[8]
parsec (1 AU/1 arc sec)	pc	$3.085\,677\,580\,7(4) \times 10^{16}$ m = 3.262...ly	[9]
light year (deprecated unit)	ly	0.306 6... pc = 0.946 1... $\times 10^{16}$ m	
Schwarzschild radius of the Sun	$2G_N M_\odot/c^2$	2.953 250 08 km	[10]
solar mass	$M_\odot$	$1.988\,44(30) \times 10^{30}$ kg	[11]
solar equatorial radius	$R_\odot$	6.961×10^8 m	[6]
solar luminosity	$L_\odot$	$(3.846 \pm 0.008) \times 10^{26}$ W	[12]
Schwarzschild radius of the Earth	$2G_N M_\oplus/c^2$	8.870 056 22 mm	[13]
Earth mass	$M_\oplus$	$5.972\,3(9) \times 10^{24}$ kg	[14]
Earth mean equatorial radius	$R_\oplus$	$6.378\,140 \times 10^6$ m	[6]
luminosity conversion	L	$3.02 \times 10^{28} \times 10^{-0.4\ M_{\rm bol}}$ W ($M_{\rm bol}$ = absolute bolometric magnitude = bolometric magnitude at 10 pc	[15]
flux conversion	$\mathscr{F}$	$2.52 \times 10^{-8} \times 10^{-0.4\ m_{\rm bol}}$ W m^{-2} ($m_{\rm bol}$ = apparent bolometric magnitude)	from above
$v_\odot$ around center of Galaxy	$\Theta_\diamond$	220(20) km s^{-1}	[16]
solar distance from galactic center	$R_\diamond$	8.0(5) kpc	[17]
local disk density	$\rho_{\rm disk}$	3–12 $\times 10^{-24}$ g $cm^{-3} \approx$ 2–7 GeV/c^2 cm^{-3}	[18]
local halo density	$\rho_{\rm halo}$	2–13 $\times 10^{-25}$ g $cm^{-3} \approx$ 0.1–0.7 GeV/$c^2 cm^{-3}$	[19]
present day Hubble expansion rate	H_0	$100\ h$ km s^{-1} Mpc^{-1} $= h \times (9.778\,13\ {\rm Gyr})^{-1}$	[20]
present day normalized Hubble expansion rate	h	$0.71^{+0.04}_{-0.03}$	[2]
critical density of the universe	$\rho_c = 3H_0^2/8\pi G_N$	$2.775\,366\,27 \times 10^{11}\,h^2\ M_\odot {\rm Mpc}^{-3}$ $= 1.878\,37(28) \times 10^{-29}\,h^2$ g cm^{-3} $= 1.053\,69(16) \times 10^{-5}\,h^2$ GeV cm^{-3}	derived
pressureless matter density of the universe	$\Omega_m \equiv \rho_m/\rho_c$	$0.135^{+0.008}_{0.009}/h^2 = 0.27 \pm 0.04$	[2]
baryon density of the universe	$\Omega_b \equiv \rho_b/\rho_c$	$0.0224 \pm 0.0009/h^2 = 0.044 \pm 0.004$	[2]
dark matter density of the universe	$\Omega_{dm} \equiv \Omega_m - \Omega_b$	$0.113^{+0.008}_{-0.009}/h^2 = 0.22 \pm 0.04$	[21]
radiation density of the universe	$\Omega_\gamma = \rho_\gamma/\rho_c$	$(2.471 \pm 0.004) \times 10^{-5}/h^2 = (4.9 \pm 0.5) \times 10^{-5}$	[22]
neutrino density of the universe	Ω_ν	$< (0.0076/h^2 = 0.015)$, 95% C.L.	[2]
dark energy density	Ω_Λ	0.73 ± 0.04	[2]
total energy density	$\Omega_{\rm tot} = \Omega_m + \ldots + \Omega_\Lambda$	1.02 ± 0.02	[2]
number density of baryons	n_b	$(2.5 \pm 0.1) \times 10^{-7}/{\rm cm}^3$	[2]
number density of CMB photons	n_γ	$(410.4 \pm 0.5)/{\rm cm}^{-3}$	[23]
baryon-to-photon ratio	$\eta = n_b/n_\gamma$	$(6.1 \pm 0.2) \times 10^{-10}$	derived
scale factor for cosmological constant	$c^2/3H_0^2$	$2.853 \times 10^{51}\,h^{-2}$ m^2	
dark energy equation of state	w	< -0.78 at 95% C.L.	[2, 24]
fluctuation amplitude at $8h^{-1}$ Mpc scale	σ_8	0.84 ± 0.04	[2]
scalar spectral index at $k_0 = 0.05$ Mpc^{-1}	n_s	0.93 ± 0.03	[2]

Quantity	Symbol, equation	Value	Reference, footnote
running spectral index slope at $k_0 = 0.05$ Mpc^{-1}	$dn_s/d\,ln\,k$	$-0.031^{+0.016}_{-0.018}$	[2]
tensor to scalar field perturbations ratio at $k_0 = 0.002$ Mpc^{-1}	$r = T/S$	< 0.71 at 95% C.L.	[2, 25]
reionization optical depth	τ	0.17 ± 0.04	[2]
age of the universe	t_0	13.7 ± 0.2 Gyr	[2]
present day CBR temperature	T_0	2.725 ± 0.001 K	[26]
solar velocity with respect to CBR		368 ± 2 km/s towards $(\ell, b) = (263.85° \pm 0.10°, 48.25° \pm 0.04°)$	[27, 28]
Local group velocity with respect to CBR	$v_{\rm LG}$	$627 \pm 22\,{\rm km\,s^{-1}}$ towards $(\ell, b) = (276° \pm 3°, 30° \pm 3°)$	[27]
entropy density/Boltzmann constant	s/k	$2\,889.2\ (T/2.725)^3$ cm^{-3}	[15]

References:

1. P.J. Mohr and B.N. Taylor, CODATA 2002; `http://physics.nist.gov/cuu/Constants`.
2. D.N. Spergel *et al.*, Astrophys. J. Supp. **148**, 175 (2003).
3. O. Lahav, A.R. Liddle, "The Cosmological Parameters", this *Review*.
4. B.W. Petley, Nature **303**, 373 (1983).
5. 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.
6. *The Astronomical Almanac for the year 2005*, U.S. Government Printing Office, Washington, and Her Majesty's Stationary Office, London (2003).
7. JPL Planetary Ephemerides, E. Myles Standish, Jr., private communication (1989).
8. Derived from H_0 [2].
9. 1 AU divided by $\pi/648\,000$; quoted error is from the JPL Planetary Ephemerides value of the AU [7].
10. Product of $2/c^2$ and the heliocentric gravitational constant [6]. The given 9-place accuracy seems consistent with uncertainties in defining the earth's orbital parameters.
11. Obtained from the heliocentric gravitational constant [6] and G_N [1]. The error is the 150 ppm standard deviation of G_N.
12. 1996 mean total solar irradiance (TSI) = 1367.5 ± 2.7 [29]; the solar luminosity is $4\pi \times (1\ {\rm AU})^2$ 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 [30].

    Sackmann *et al.* [31] use TSI = 1370 ± 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 [32] ($1353 \pm 1\%$ W m^{-2}) is often quoted [33]. The conversion to luminosity is not given in the Thekaekara and Drummond paper, and we cannot exactly reproduce the solar luminosity given in Ref. 33.

    Finally, a value based on the 1954 spectral curve due to Johnson [34] ($1395 \pm 1\%$ 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 [15].
13. Product of $2/c^2$, the heliocentric gravitational constant from Ref. 6, and the earth/sun mass ratio, also from Ref. 6. The given 9-place accuracy appears to be consistent with uncertainties in actually defining the earth's orbital parameters.
14. Obtained from the geocentric gravitational constant [6] and G_N [1]. The error is the 150 ppm standard deviation of G_N.
15. E.W. Kolb and M.S. Turner, *The Early Universe*, Addison-Wesley (1990).
16. 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".
17. 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.
18. G. Gilmore, R.F.G. Wyse, and K. Kuijken, Ann. 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 $1\text{–}10 \times 10^{-25}$ 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. Conversion using length of tropical year.
21. Derived from [2].
22. $\rho_\gamma = \dfrac{\pi^2}{15}\dfrac{(k_B T)^4}{(\hbar c)^3}$, using T_0 from Ref. 26.
23. $n_\gamma = \dfrac{2\zeta(3)}{\pi^2}\left(\dfrac{k_B T}{\hbar c}\right)^3$, using T_0 from Ref. 26.
24. Note that one of the priors assumed when deriving this parameter is $w \geq -1$.
25. There are several definitions of r used in the literature, here r corresponds to the definition used by Ref. 2.
26. J. Mather *et al.*, Astrophys. J. **512**, 511 (1999). This paper gives $T_0 = 2.725 \pm 0.002$K at 95%CL. We take 0.001 as the one-standard deviation uncertainty.
27. D. Scott and G.F. Smoot, "Cosmic Microwave Background", this *Review*.
28. C.L. Bennett *et al.*, Astrophys. J. Supp. **148**, 1 (2003).
29. R.C. Willson, Science **277**, 1963 (1997);
    the 0.2% error estimate is from R.C. Willson, private correspondence (1998).
30. R.C. Willson and H.S. Hudson, Nature **332**, 810 (1988).
31. I.-J. Sackmann, A.I. Boothroyd, and K.E. Kraemer, Astrophys. J. **418**, 457 (1993).
32. M.P. Thekaekara and A.J. Drummond, Nature Phys. Sci. **229**, 6 (1971).
33. K.R. Lang, *Astrophysical Formulae*, Springer-Verlag (1974);
    K.R. Lang, *Astrophysical Data: Planets and Stars*, Springer-Verlag (1992).
34. F.S. Johnson, J. Meterol. **11**, 431 (1954).