2. ASTROPHYSICAL CONSTANTS AND PARAMETERS

Table 2.1. Revised February 2012 by E. Bergren and D.E. Groom (LBNL). The figures in parentheses after some values give the 1-σ 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 data sets, priors, and basis parameters used in the fit. Many of the derived parameters reported in this table have non-Gaussian likelihoods. Parameters may be highly correlated, so care must be taken in propagating errors. Unless otherwise specified, cosmological parameters are from six-parameter fits to a flat ΛCDM cosmology using 7-year WMAP data alone [2]. For more information see Ref. 3 and the original papers.

Quantity	Symbol, equation	Value	Reference, footnote
speed of light	c	$299\,792\,458$ m s^{-1}	exact[4]
Newtonian gravitational constant	G_N	$6.673\,8(8) \times 10^{-11}$ m^3 kg^{-1} s^{-2}	[1]
Planck mass	$\sqrt{\hbar c/G_N}$	$1.220\,93(7) \times 10^{19}$ GeV/c^2	[1]
		$= 2.176\,51(13) \times 10^{-8}$ kg	
Planck length	$\sqrt{\hbar G_N/c^3}$	$1.616\,20(10) \times 10^{-35}$ m	[1]
standard gravitational acceleration	g_N	$9.806\,65$ m s$^{-2} \approx \pi^2$	exact[1]
jansky (flux density)	Jy	10^{-26} W m^{-2} Hz^{-1}	definition
tropical year (equinox to equinox) (2011)	yr	$31\,556\,925.2$ s $\approx \pi \times 10^7$ s	[5]
sidereal year (fixed star to fixed star) (2011)		$31\,558\,149.8$ s $\approx \pi \times 10^7$ s	[5]
mean sidereal day (2011) (time between vernal equinox transits)		$23^{\rm h}\,56^{\rm m}\,04\overset{\rm s}{.}090\,53$	[5]
astronomical unit	au, A	$149\,597\,870\,700(3)$ m	[6]
parsec (1 au/1 arc sec)	pc	$3.085\,677\,6 \times 10^{16}$ m $= 3.262\ldots$ ly	[7]
light year (deprecated unit)	ly	$0.306\,6\ldots$ pc $= 0.946\,053\ldots \times 10^{16}$ m	
Schwarzschild radius of the Sun	$2G_N M_\odot/c^2$	$2.953\,250\,077\,0(2)$ km	[8]
Solar mass	$M_\odot$	$1.988\,5(2) \times 10^{30}$ kg	[9]
Solar equatorial radius	$R_\odot$	$6.9551(4) \times 10^8$ m	[10]
Solar luminosity	$L_\odot$	3.828×10^{26} W	[11]
Schwarzschild radius of the Earth	$2G_N M_\oplus/c^2$	$8.870\,055\,94(2)$ mm	[12]
Earth mass	$M_\oplus$	$5.972\,6(7) \times 10^{24}$ kg	[13]
Earth mean equatorial radius	$R_\oplus$	$6.378\,137 \times 10^6$ m	[5]
luminosity conversion (deprecated)	L	$3.02 \times 10^{28} \times 10^{-0.4\,M_{\rm bol}}$ W	[14]
		($M_{\rm bol}$ = absolute bolometric magnitude = bolometric magnitude at 10 pc)	
flux conversion (deprecated)	$\mathscr{F}$	$2.52 \times 10^{-8} \times 10^{-0.4\,m_{\rm bol}}$ W m^{-2}	from above
		($m_{\rm bol}$ = apparent bolometric magnitude)	
ABsolute monochromatic magnitude	AB	$-2.5\log_{10} f_\nu - 56.10$ (for f_ν in W m^{-2} Hz^{-1})	[15]
		$= -2.5\log_{10} f_\nu + 8.90$ (for f_ν in Jy)	
Solar circular velocity v_0 at R_0 from Galactic center	v_0/R_0	30.2 ± 0.2 km s^{-1} kpc^{-1}	[16]
Solar distance from Galactic center	R_0	8.4(4) kpc	[17]
circular velocity at R_0	v_0 or Θ_0	240(10) km s^{-1}	[18]
local disk density	$\rho_{\rm disk}$	3–12 $\times 10^{-24}$ g cm$^{-3} \approx$ 2–7 GeV/c^2 cm^{-3}	[19]
local dark matter density	ρ_χ	canonical value 0.3 GeV/c^2 cm^{-3} within factor 2–3	[20]
escape velocity from Galaxy	$v_{\rm esc}$	498 km/s $< v_{\rm esc} <$ 608 km/s	[21]
present day CMB temperature	T_0	2.7255(6) K	[22]
present day CMB dipole amplitude		3.355(8) mK	[2]
Solar velocity with respect to CMB		369(1) km/s towards $(\ell, b) = (263.99(14)^\circ, 48.26(3)^\circ)$	[2]
Local Group velocity with respect to CMB	$v_{\rm LG}$	627(22) km/s towards $(\ell, b) = (276(3)^\circ, 30(3)^\circ)$	[23]
entropy density/Boltzmann constant	s/k	$2\,889.2\,(T/2.725)^3$ cm^{-3}	[14]
number density of CMB photons	n_γ	$410.5(T/2.725)^3$ cm^{-3}	[24]
baryon-to-photon ratio	$\eta = n_{\rm b}/n_\gamma$	$6.19(15) \times 10^{-10}$	[2]
		$5.1 \times 10^{-10} \le \eta \le 6.5 \times 10^{-10}$ (95% CL)	[25]
number density of baryons	$n_{\rm b}$	$(2.54 \pm 0.06) \times 10^{-7}$ cm^{-3}	from η in [2]
		$(2.1 \times 10^{-7} < n_{\rm b} < 2.7 \times 10^{-7})$ cm^{-3} (95% CL)	from η in [25]
present day Hubble expansion rate	H_0	$100\,h$ km s^{-1} Mpc^{-1} $= h\times(9.777\,752$ Gyr$)^{-1}$	[26]
scale factor for Hubble expansion rate	h	0.710(25) WMAP7; WMAP7⊕Cepheids=0.721(17)	[2,27]
Hubble length	c/H_0	$0.925\,063 \times 10^{26}\,h^{-1}$ m $= 1.28(5) \times 10^{26}$ m	
scale factor for cosmological constant	$c^2/3H_0^2$	$2.852 \times 10^{51}\,h^{-2}$ m$^2 = 5.5(5) \times 10^{51}$ m^2	
critical density of the Universe	$\rho_{\rm c} = 3H_0^2/8\pi G_N$	$2.775\,366\,27 \times 10^{11}\,h^2\,M_\odot$Mpc^{-3}	
		$= 1.878\,47(23) \times 10^{-29}\,h^2$ g cm^{-3}	
		$= 1.053\,75(13) \times 10^{-5}\,h^2$ (GeV/c^2) cm^{-3}	
baryon density of the Universe	$\Omega_{\rm b} = \rho_{\rm b}/\rho_{\rm c}$	$^\ddagger\,0.0226(6)\,h^{-2} = {}^\dagger\,0.045(3)$	[2,3]
cold dark matter density of the universe	$\Omega_{\rm cdm} = \rho_{\rm cdm}/\rho_{\rm c}$	$^\ddagger\,0.111(6)\,h^{-2} = {}^\dagger\,0.22(3)$	[2,3]
dark energy density of the ΛCDM Universe	Ω_Λ	$^\ddagger\,0.73(3)$	[2,3]
pressureless matter density of the Universe	$\Omega_{\rm m} = \Omega_{\rm cdm} + \Omega_{\rm b}$	0.27 ± 0.03 (From Ω_Λ and flatness constraint)	[2,3]
dark energy equation of state parameter	w	$^\sharp\,-0.98 \pm 0.05$ (WMAP7+BAO+H_0)	[28]
CMB radiation density of the Universe	$\Omega_\gamma = \rho_\gamma/\rho_{\rm c}$	$2.471 \times 10^{-5}(T/2.725)^4\,h^{-2} = 4.75(23) \times 10^{-5}$	[24]
neutrino density of the Universe	Ω_ν	$0.0005 < \Omega_\nu h^2 < 0.025 \Rightarrow 0.0009 < \Omega_\nu < 0.048$	[29]
total energy density of the Universe (curvature)	$\Omega_{\rm tot} = \Omega_{\rm m} + \ldots + \Omega_\Lambda$	$^\sharp\,1.002 \pm 0.011$ (WMAP7+BAO+H_0)	[2,3]

Quantity	Symbol, equation	Value	Reference, footnote
fluctuation amplitude at $8\,h^{-1}$ Mpc scale	σ_8	$^\dagger\,0.80(3)$	[2,3]
curvature fluct. amplitude at $k_0 = 0.002$ Mpc^{-1}	$\Delta^2_{\mathcal{R}}$	$^\ddagger\,2.43(11) \times 10^{-9}$	[2,3]
scalar spectral index	n_s	$^\ddagger\,0.963(14)$	[2,3]
running spectral index slope, $k_0 = 0.002$ Mpc^{-1}	$dn_s/d\ln k$	$^\sharp\,-0.03(3)$	[2]
tensor-to-scalar field perturbations ratio, $k_0 = 0.002$ Mpc^{-1}	$r = T/S$	$^\sharp < 0.36$ at 95% CL	[2,3]
redshift at decoupling	$z_{\rm dec}$	$^\dagger\,1091(1)$	[2]
age at decoupling	t_*	$^\dagger\,3.79(5) \times 10^5$ yr	[2]
sound horizon at decoupling	$r_s(z_*)$	$^\dagger\,147(2)$ Mpc	[2]
redshift of matter-radiation equality	$z_{\rm eq}$	$^\dagger\,3200 \pm 130$	[2]
redshift of reionization	$z_{\rm reion}$	$^\dagger\,10.5 \pm 1.2$	[2]
age at reionization	$t_{\rm reion}$	430^{+90}_{-70} Myr	[2,30]
reionization optical depth	τ	$^\ddagger\,0.088(15)$	[2,3]
age of the Universe	t_0	$^\dagger\,13.75 \pm 0.13$ Gyr	[2]

‡ Parameter in six-parameter ΛCDM fit [2].
† Derived parameter in six-parameter ΛCDM fit [2].
$^\sharp$ Extended model parameter [2].

References:

1. P.J. Mohr, B.N. Taylor, & D.B. Newell, *CODATA Recommended Values of the Fundamental Constants: 2010*, (to be published); `physics.nist.gov/constants`.
2. N. Jarosik *et al.*, Astrophys. J. Supp. **192**, 14 (2011);
D. Larson *et al.*, Astrophys. J. Supp. **192**, 16 (2011);
E. Komatsu *et al.*, Astrophys. J. Supp. **192**, 18 (2011).
3. O. Lahav & A.R. Liddle, "The Cosmological Parameters," in this *Review.*
4. B.W. Petley, Nature **303**, 373 (1983).
5. *The Astronomical Almanac for the year 2011*, U.S. Government Printing Office, Washington, and The U.K. Hydrographic Office (2010).
6. While A is approximately equal to the semi-major axis of the Earth's orbit, it is not exactly so. Nor is it exactly the mean Earth-Sun distance. There are a number of reasons: a) the Earth's orbit is not exactly Keplerian due to relativity and to perturbations from other planets; b) the adopted value for the Gaussian gravitational constant k is not exactly equal to the Earth's mean motion; and c) the mean distance in a Keplerian orbit is not equal to the semi-major axis a: $\langle r\rangle = a(1 + e^2/2)$, where e is the eccentricity. (Discussion courtesy of Myles Standish, JPL).
7. The distance at which 1 A subtends 1 arc sec: 1 A divided by $\pi/648\,000$.
8. Product of $2/c^2$ and the heliocentric gravitational constant $G_N M_\odot = A^3k^2/86400^2$, where k is the Gaussian gravitational constant, 0.017 202 098 95 (exact) [5]. The value and error for A given in this table are used.
9. Obtained from the $G_N M_\odot$ product [5] and G_N [1]. .
10. T. M. Brown & J. Christensen-Dalsgaard, Astrophys. J. **500**, L195 (1998) Many values for the Solar radius have been published, most of which are consistent with this result.
11. $4\pi\,A^2 \times (1361$ W m$^{-2})$ [31]. Assumes isotropic irradiance.
12. Schwarzschild radius of the Sun (above) scaled by the Earth/Sun mass ratio given in Ref. 5.
13. Obtained from the $G_N M_\oplus$ product [5] and G_N [1]. .
14. E.W. Kolb & M.S. Turner, *The Early Universe*, Addison-Wesley (1990);
The IAU (Commission 36) has recommended 3.055×10^{28} W for the zero point. Based on newer Solar measurements, the value and significance given in the table seems more appropriate.
15. J. B. Oke & J. E. Gunn, Astrophys. J. **266**, 713 (1983). Note that in the definition of AB the sign of the constant is wrong.
16. M.J. Reid & A. Brunthaler, Astrophys. J. **616**, 872 (2004) as corrected using new value for Solar proper motion in Ref. 18. Note that $v_\odot/R_0$ is better determined than either Θ_0 or R_0.
17. A. M. Ghez *et al.*, Astrophys. J. **689**, 1044 (2008);
S. Gillessen *et al.*, Astrophys. J. **692**, 1075 (2009);
M. Shen & Z. Zhu, Chin. Astron. Astrophys. **7**, 120 (2007). In their Fig. 2 Zhu & Chin present a summary of a dozen values published 1984–2007. Most are closer to $R_0 = 8.0(5)$ kpc than those cited above.
18. C. McCabe, Phys. Rev. **D82**, 023530 (2010) Other papers report values closer to 220(20) km s^{-1};
S.E. Koposov, H.-W. Rix, & D.W. Hogg, Astrophys. J. **712**, 260 (2010);
P.J. McMillan & J.J. Binney, (2009) `arXiv:0907.4685`.
19. G. Gilmore, R.F.G. Wyse, & K. Kuijken, Ann. Rev. Astron. Astrophys. **27**, 555 (1989).
20. Sampling of many references:
M. Mori *et al.*, Phys. Lett. **B289**, 463 (1992);
E.I. Gates *et al.*, Astrophys. J. **449**, L133 (1995);
M.Kamionkowski, A.Kinkhabwala, Phys. Rev. **D57**, 325 (1998);
M. Weber, W. de Boer, Astron. & Astrophys. **509**, A25 (2010);
P. Salucci *et al.*, Astron. & Astrophys. **523**, A83 (2010).
21. M. C. Smith *et al.*, Mon. Not. R. Astr. Soc. **379**, 755 (2007) (`astro-ph/0611671`).
22. D. Fixsen, Astrophys. J. **707**, 916 (2009).
23. D. Scott & G.F. Smoot, "Cosmic Microwave Background," in this *Review.*
24. $n_\gamma = \dfrac{2\zeta(3)}{\pi^2}\left(\dfrac{kT}{\hbar c}\right)^3$ and $\rho_\gamma = \dfrac{\pi^2}{15}\dfrac{(kT)^4}{(\hbar c)^3c^2}$; $\dfrac{kT_0}{\hbar c} = 11.900(4)$/cm.
25. B.D. Fields, S. Sarkar, "Big-Bang Nucleosynthesis," this *Review.*
26. Conversion using length of sidereal year.
27. Average of WMAP7 [2] and independent Cephid-based measurement by A.G. Reiss *et al.*, Astrophys. J. **730**, 119 (2011). Other high-quality measurements could have been included.
28. R. Amanullah *et al.*, Astrophys. J. **716**, 712 (2010). Fit with curvature unconstrained. For a flat Universe, $w = -1.00 \pm 0.08$.
29. $\Omega_\nu h^2 = \sum m_{\nu_j}/93\,$eV, where the sum is over all neutrino mass eigenstates. The lower limit follows from neutrino mixing results reported in this *Review* combined with the assumptions that there are three light neutrinos ($m_\nu < 45$ GeV/c^2) and that the lightest neutrino is substantially less massive than the others: $\Delta m^2_{32} = (2.43 \pm 0.13) \times 10^{-3}$ eV^2, so $\sum m_{\nu_j} \geq m_{\nu_3} \approx \sqrt{\Delta m^2_{32}} = 0.05$ eV. (This becomes 0.10 eV if the mass hierarchy is inverted, with $m_{\nu_1} \approx m_{\nu_2} \gg m_{\nu_3}$.) Astrophysical determinations of $\sum m_{\nu_j}$, reported in the Full Listings of this *Review* under "Sum of the neutrino masses," range from $< 0.17\,$eV to $< 2.3\,$eV in papers published since 2003. Alternatively, if the limit obtained from tritium decay experiments ($m_\nu < 2\,$eV) is used for the upper limit, then $\Omega_\nu < 0.04$.
30. If the Universe were reionized instantaneously at $z_{\rm reion}$.
31. G. Kopp & J.L. Lean, Geophys. Res. Lett. **38**, L01706 (2011). Kopp & Lean give 1360.8 ± 0.6W m^{-2}, but given the scatter in the data we use the rounded value without quoting an error.