2. ASTROPHYSICAL CONSTANTS AND PARAMETERS

Table 2.1. Revised March 2016 by 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 derived from 6-parameter fits to a flat ΛCDM cosmology *Planck* 2015 temperature (TT) + low ℓ polarization data (lowP) + lensing [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 constant of gravitation	G_N	$6.674\,08(31) \times 10^{-11}$ m^3 kg^{-1} s^{-2}	[1]
Planck mass	$\sqrt{\hbar c/G_N}$	$1.220\,910(29) \times 10^{19}$ GeV/$c^2 = 2.176\,47(5) \times 10^{-8}$ kg	[1]
Planck length	$\sqrt{\hbar G_N/c^3}$	$1.616\,229(38) \times 10^{-35}$ m	[1]
standard acceleration of gravity	g_N	$9.806\,65$ m s^{-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	$149\,597\,870\,700$ m	exact[6]
parsec (1 au/1 arc sec)	pc	$3.085\,677\,581\,49 \times 10^{16}$ m $= 3.262\ldots$ ly	exact[7]
light year (deprecated unit)	ly	$0.306\,6\ldots$ pc $= 0.946\,053\ldots \times 10^{16}$ m	
Schwarzschild radius of the Sun	$2G_N M_\odot/c^2$	$2.953\,250\,24$ km	[8]
Solar mass	$M_\odot$	$1.988\,48(9) \times 10^{30}$ kg	[9]
nominal Solar equatorial radius	$\mathcal{R}_\odot$	6.957×10^8 m	exact[10]
nominal Solar constant	$\mathcal{S}_\odot$	1361 W m^{-2}	exact[10,11]
nominal Solar photosphere temperature	$\mathcal{T}_\odot$	5772 K	exact[10]
nominal Solar luminosity	$\mathcal{L}_\odot$	3.828×10^{26} W	exact[10,12]
Schwarzschild radius of the Earth	$2G_N M_\oplus/c^2$	$8.870\,056\,580(18)$ mm	[13]
Earth mass	$M_\oplus$	$5.972\,4(3) \times 10^{24}$ kg	[14]
nominal Earth equatorial radius	$\mathcal{R}_\oplus$	6.3781×10^6 m	exact[10]
luminosity conversion	L	$3.0128 \times 10^{28} \times 10^{-0.4\,M_{\rm bol}}$ W	[15]
		($M_{\rm bol}$ = absolute bolometric magnitude = bolometric magnitude at 10 pc)	
flux conversion	$\mathscr{F}$	$2.5180 \times 10^{-8} \times 10^{-0.4\,m_{\rm bol}}$ W m^{-2}	[15]
		($m_{\rm bol}$ = apparent bolometric magnitude)	
ABsolute monochromatic magnitude	AB	$-2.5\,\log_{10} f_\nu - 56.10$ (for f_ν in W m^{-2} Hz^{-1})	[16]
		$= -2.5\,\log_{10} f_\nu + 8.90$ (for f_ν in Jy)	
Solar angular velocity around the Galactic center	Θ_0/R_0	30.3 ± 0.9 km s^{-1} kpc^{-1}	[17]
Solar distance from Galactic center	R_0	8.00 ± 0.25 kpc	[17,18]
circular velocity at R_0	v_0 or Θ_0	$254(16)$ km s^{-1}	[17]
escape velocity from Galaxy	$v_{\rm esc}$	498 km/s $< v_{\rm esc} < 608$ km/s	[19]
local disk density	$\rho_{\rm disk}$	3–12 $\times 10^{-24}$ g cm$^{-3} \approx$ 2–7 GeV/c^2 cm^{-3}	[20]
local dark matter density	ρ_χ	canonical value 0.3 GeV/c^2 cm^{-3} within factor 2–3	[21]
present day CMB temperature	T_0	$2.7255(6)$ K	[22,24]
present day CMB dipole amplitude		$3.3645(20)$ mK	[22,23]
Solar velocity with respect to CMB		$369(1)$ km s^{-1} towards $(\ell, b) = (263.99(14)^\circ, 48.26(3)^\circ)$	[22,25]
Local Group velocity with respect to CMB	$v_{\rm LG}$	$627(22)$ km s^{-1} towards $(\ell, b) = (276(3)^\circ, 30(3)^\circ)$	[22,25]
number density of CMB photons	n_γ	$410.7(T/2.7255)^3$ cm^{-3}	[26]
density of CMB photons	ρ_γ	$4.645(4)\,(T/2.7255)^4 \times 10^{-34}$ g cm$^{-3} \approx 0.260$ eV cm^{-3}	[26]
entropy density/Boltzmann constant	s/k	$2\,891.2\,(T/2.7255)^3$ cm^{-3}	[26]
present day Hubble expansion rate	H_0	$100\,h$ km s^{-1} Mpc$^{-1} = h \times (9.777\,752$ Gyr$)^{-1}$	[27]
scale factor for Hubble expansion rate	h	$0.678(9)$	[2,3]
Hubble length	c/H_0	$0.925\,0629 \times 10^{26}\,h^{-1}$ m $= 1.374(18) \times 10^{26}$ m	
scale factor for cosmological constant	$c^2/3H_0^2$	$2.85247 \times 10^{51}\,h^{-2}$ m$^2 = 6.20(17) \times 10^{51}$ m^2	
critical density of the Universe	$\rho_{\rm crit} = 3H_0^2/8\pi G_N$	$1.878\,40(9) \times 10^{-29}\,h^2$ g cm^{-3}	
		$= 1.053\,71(5) \times 10^{-5}\,h^2$ (GeV/c^2) cm^{-3}	
		$= 2.775\,37(13) \times 10^{11}\,h^2\,M_\odot$Mpc^{-3}	
baryon-to-photon ratio (from BBN)	$\eta = n_{\rm b}/n_\gamma$	$5.8 \times 10^{-10} \le \eta \le 6.6 \times 10^{-10}$ (95% CL)	[28]
number density of baryons	$n_{\rm b}$	$2.503(26) \times 10^{-7}$ cm^{-3}	[2,3,29,30]
		$(2.4 \times 10^{-7} < n_{\rm b} < 2.7 \times 10^{-7})$ cm^{-3} (95% CL)	$\eta \times n_\gamma$
CMB radiation density of the Universe	$\Omega_\gamma = \rho_\gamma/\rho_{\rm crit}$	$2.473 \times 10^{-5}(T/2.7255)^4\,h^{-2} = 5.38(15) \times 10^{-5}$	[26]
- - - *Planck* 2015 6-parameter fit to flat ΛCDM cosmology - - -			
baryon density of the Universe	$\Omega_{\rm b} = \rho_{\rm b}/\rho_{\rm crit}$	$^\ddagger\,0.02226(23)\,h^{-2} = {}^\dagger\,0.0484(10)$	[2,3,23]
cold dark matter density of the universe	$\Omega_{\rm CDM} = \rho_{\rm CDM}/\rho_{\rm crit}$	$^\ddagger\,0.1186(20)\,h^{-2} = {}^\dagger\,0.258(11)$	[2,3,23]
100 × approx to $r_*/D_{\rm A}$	$100 \times \theta_{\rm MC}$	$^\ddagger\,1.0410(5)$	[2,3]
reionization optical depth	τ	$^\ddagger\,0.066(16)$	[2,3]
scalar spectral index	$n_{\rm s}$	$^\ddagger\,0.968(6)$	[2,3]
ln pwr primordial curvature pert. (k_0=0.05 Mpc^{-1})	$\ln(10^{10}\Delta^2_{\mathcal{R}})$	$^\ddagger\,3.062(29)$	[2,3]

Quantity	Symbol, equation	Value	Reference, footnote
dark energy density of the ΛCDM Universe	Ω_Λ	$^\dagger\, 0.692 \pm 0.012$	[2,3]
pressureless matter density of the Universe	$\Omega_{\rm m} = \Omega_{\rm CDM} + \Omega_{\rm b}$	$^\dagger\, 0.308 \pm 0.012$	[2,3]
fluctuation amplitude at $8\,h^{-1}$ Mpc scale	σ_8	$^\dagger\, 0.815 \pm 0.009$	[2,3]
redshift of matter-radiation equality	$z_{\rm eq}$	$^\dagger\, 3365 \pm 44$	[2]
redshift at which optical depth equals unity	z_*	$^\dagger\, 1089.9 \pm 0.4$	[2]
comoving size of sound horizon at z_*	r_*	$^\dagger\, 144.9 \pm 0.4$ Mpc (*Planck* CMB)	[31]
age when optical depth equals unity	t_*	373 kyr	[32]
redshift at half reionization	$z_{\rm reion}$	$^\dagger\, 8.8^{+1.7}_{-1.4}$	[2]
redshift when acceleration was zero	z_q	~ 0.65	[32]
age of the Universe	t_0	$^\dagger\, 13.80 \pm 0.04$ Gyr	[2]
effective number of neutrinos	$N_{\rm eff}$	$^\sharp\, 3.1 \pm 0.6$	[2,33]
sum of neutrino masses	$\sum m_\nu$	$^\sharp < 0.68$ eV (Planck CMB); ≥ 0.05 eV (mixing)	[2,34,35]
neutrino density of the Universe	$\Omega_\nu = h^{-2} \sum m_{\nu_j}/93.04\,{\rm eV}$	$^\sharp < 0.016$ (Planck CMB; ≥ 0.0012 (mixing)	[2,34,35]
curvature	Ω_K	$^\sharp\, -0.005^{+0.016}_{-0.017}$ (95%CL)	[2]
running spectral index slope, $k_0 = 0.002$ Mpc^{-1}	$dn_{\rm s}/d\ln k$	$^\sharp\, -0.003(15)$	[2]
tensor-to-scalar field perturbations ratio, k_0=0.002 Mpc^{-1}	$r_{0.002} = T/S$	$^\sharp < 0.114$ at 95% CL; no running	[2,3]
dark energy equation of state parameter	w	-0.97 ± 0.05	[31,36]
primordial helium fraction	$Y_{\rm p}$	0.245 ± 0.004	[22,37]

‡ Parameter in 6-parameter ΛCDM fit [2].
† Derived parameter in 6-parameter ΛCDM fit [2].
♯ Extended model parameter (TT + lensing) [2].

References:

1. CODATA recommended 2014 values of the fundamental physical constants: `physics.nist.gov/constants`.
2. Planck Collab. 2015 Results XIII, Astron. & Astrophys. submitted, `arXiv:1502.01589v2`.
3. O. Lahav & A.R. Liddle, "The Cosmological Parameters," Sec. 25 in this *Review*.
4. B.W. Petley, Nature **303**, 373 (1983).
5. *The Astronomical Almanac Online for the year 2016*, `asa.usno.navy.mil/SecK/Constants.html`.
6. The astronomical unit of length (the au) in meters is re-defined (resolution B2, IAU XXVIII GA 2012) to be a conventional unit of length in agreement with the value adopted in the IAU 2009 Resolution B2; it is to be used with all time scales.
7. The distance at which 1 au subtends 1 arc sec: 1 au divided by $\pi/648\,000$.
8. Product of $2/c^2$ and the observationally determined Solar mass parameter $G_N M_\odot$ [5]. Truncated to 8 places so that TCB and TDB time scale values agree.
9. $G_N M_\odot$ [5] $\div$ G_N [1].
10. XXIXth IAU General Assembly, Resolution B3, "on recommended nominal conversion constants ..." Calligraphic symbol indicates recommended nominal value.
11. See also G. Kopp & J.L. Lean, Geophys. Res. Lett. **38**, L01706 (2011), who give 1360.8 ± 0.6 W m^{-2}. See paper for caveats and other measurements.
12. $4\pi\,(1\text{ au})^2 \times \mathcal{S}_\odot$, assuming isotropic irradiance.
13. Product of $2/c^2$ and the geocentric gravitational constant $G_N M_\oplus$ [5]. Truncated to 8 places so that TCB, TT, and TDB time scale values agree.
14. $G_N M_\oplus$ [5] $\div$ G_N [1].
15. XXIXth IAU General Assembly, Resolution B2, "on recommended zero points for the absolute and apparent bolometric magnitude scales".
16. J. B. Oke and J. E. Gunn, Astrophys. J. **266**, 713 (1983). Note that in the definition of AB the sign of the constant is wrong.
17. M.J. Reid, *et al.*, Astrophys. J. **700**, 137 (2009). Note that Θ_0/R_0 is better determined than either Θ_0 or R_0.
18. Z.M. Malkin, arXiv:1202.6128 and Astron. Rep. **57**, 128 (2013). 52 determinations of R_0 over 20 years are given. The weighted mean of these *unevaluated* results is 7.94 ± 0.05 kpc, with $\chi^2/N_{\rm dof} = 1.26$. If the 8 values more than 3σ from the mean are eliminated, $\langle R_0\rangle = 8.02 \pm 0.06$ kpc and $\chi^2/N_{\rm dof} = 0.67$. The author suggests using $R_0 = 8.00 \pm 0.25$ kpc.
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20. G. Gilmore, R.F.G. Wyse, & K. Kuijken, Ann. Rev. Astron. Astrophys. **27**, 555 (1989).
21. 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); R. Catena & P. Ullio, JCAP **1008**, 004 (2010) conclude $\rho^{\rm local}_{\rm DM} = 0.39 \pm 0.03\,{\rm GeV\,cm^{-3}}$.
22. D. Scott & G.F. Smoot, "Cosmic Microwave Background," Sec. 28 in this *Review.*.
23. Planck Collab. 2015 Results I, Astron. & Astrophys. submitted, `arXiv:1502.01581v3`.
24. D. Fixsen, Astrophys. J. **707**, 916 (2009).
25. G. Hinshaw *et al.*, Astrophys. J. Suppl. 208, 19 (2013), `arXiv:1212.5226`; D.J. Fixsen *et al.*, Astrophys. J. **473**, 576 (1996); A. Kogut *et al.*, Astrophys. J. **419**, 1 (1993).
26. $n_\gamma = \dfrac{2\zeta(3)}{\pi^2}\left(\dfrac{kT}{\hbar c}\right)^3$; $\rho_\gamma = \dfrac{\pi^2 kT}{15\,c^2}\left(\dfrac{kT}{\hbar c}\right)^3$; $s/k = \dfrac{2\cdot 43\cdot\pi^2}{11\cdot 45}\left(\dfrac{kT}{\hbar c}\right)^3$; $kT/\hbar c = 11.902(3)(T/2.7255)/{\rm cm}$.
27. Conversion using length of sidereal year.
28. B.D. Fields, P. Molarto, & S. Sarkar, "Big-Bang Nucleosynthesis," in this *Review*.
29. $n_{\rm b}$ depends only upon the measured $\Omega_{\rm b} h^2$, the average baryon mass at the present epoch [30], and G_N: $n_{\rm b} = (\Omega_{\rm b} h^2)(h^{-2}\rho_{\rm crit})/(0.93711\,{\rm GeV}/c^2$ per baryon).
30. G. Steigman, JCAP **10**, 016, (2006).
31. D.H. Weinberg & M. White, "Dark Energy," Sec. 27 in this *Review*.
32. D. Scott, A Narimani, & D.N. Page, arXiv:1309.2381v2.
33. Summary Tables in this *Review* list $N_\nu = 2.984(8)$ (Standard Model fits to LEP-SLC data). Because neutrinos are not completely decoupled at $e^\pm$ annihilation, the effective number of massless neutrino species is 3.046, rather than 3.
34. 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: $\Delta m^2_{32} = (2.44 \pm 0.06) \times 10^{-3}$ eV^2, so $\sum m_{\nu_j} \geq m_{\nu_3} \approx \sqrt{\Delta m^2_{32}} = 0.05$ eV. About the same limit obtains if the mass hierarchy is inverted, with $m_{\nu_1} \approx m_{\nu_2} \gg m_{\nu_3}$. Alternatively, if the limit obtained from tritium decay experiments ($m_\nu < 2\,$eV) is used for the upper limit, then $\Omega_\nu < 0.05$.
35. 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.
36. É. Auborg *et al.*, Phys. Rev. **D92**, 123516 (2015).
37. E. Aver *et al.*, JCAP **07**, 011 (2015).