2. ASTROPHYSICAL CONSTANTS AND PARAMETERS

Table 2.1. Revised November 2013 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. (But in multiplications by h^{-2} *etc.* in the table below, independent errors were assumed.) Unless otherwise specified, cosmological parameters are from six-parameter fits to a flat ΛCDM cosmology using CMB data alone: *Planck* temperature + WMAP polarization data + high-resolution data from ACT and SPT [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}	[1,5]
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	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	[6]
sidereal year (fixed star to fixed star) (2011)		$31\,558\,149.8$ s $\approx \pi \times 10^7$ s	[6]
mean sidereal day (2011) (time between vernal equinox transits)		$23^{\rm h}\,56^{\rm m}\,04\overset{\rm s}{.}090\,53$	[6]
astronomical unit	au	$149\,597\,870\,700$ m	exact [7]
parsec (1 au/1 arc sec)	pc	$3.085\,677\,581\,49 \times 10^{16}$ m $= 3.262\ldots$ ly	exact [8]
light year (deprecated unit)	ly	$0.306\,6\ldots$ pc $= 0.946\,053\ldots \times 10^{16}$ m	
Schwarzschild radius of the Sun	$2G_N M_\odot/c^2$	$2.953\,250\,077(2)$ km	[9]
Solar mass	$M_\odot$	$1.988\,5(2) \times 10^{30}$ kg	[10]
Solar equatorial radius	$R_\odot$	$6.9551(4) \times 10^8$ m	[11]
Solar luminosity	$L_\odot$	3.828×10^{26} W	[12]
Schwarzschild radius of the Earth	$2G_N M_\oplus/c^2$	$8.870\,055\,94(2)$ mm	[13]
Earth mass	$M_\oplus$	$5.972\,6(7) \times 10^{24}$ kg	[14]
Earth mean equatorial radius	$R_\oplus$	$6.378\,137 \times 10^6$ m	[6]
luminosity conversion (deprecated)	L	$3.02 \times 10^{28} \times 10^{-0.4\,M_{\rm bol}}$ W	[15]
		($M_{\rm bol}$ = absolute bolometric magnitude = bolometric magnitude at 10 pc)	
flux conversion (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})	[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	$8.4(6)$ kpc	[17,18]
circular velocity at R_0	v_0 or Θ_0	$254(16)$ km s^{-1}	[17]
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	[22,23]
present day CMB dipole amplitude		$3.355(8)$ mK	[22,24]
Solar velocity with respect to CMB		$369(1)$ km/s towards $(\ell, b) = (263.99(14)^\circ, 48.26(3)^\circ)$	[22,24]
Local Group velocity with respect to CMB	$v_{\rm LG}$	$627(22)$ km/s towards $(\ell, b) = (276(3)^\circ, 30(3)^\circ)$	[22,24]
entropy density/Boltzmann constant	s/k	$2\,891.2\ (T/2.7255)^3$ cm^{-3}	[25]
number density of CMB photons	n_γ	$410.7 (T/2.7255)^3$ cm^{-3}	[25]
baryon-to-photon ratio	$\eta = n_{\rm b}/n_\gamma$	$6.05(7) \times 10^{-10}$ (CMB)	[26]
		$5.7 \times 10^{-10} \le \eta \le 6.7 \times 10^{-10}$ (95% CL)	[26]
present day Hubble expansion rate	H_0	$100\ h$ km s^{-1} Mpc^{-1} $= h\times(9.777\,752$ Gyr$)^{-1}$	[29]
scale factor for Hubble expansion rate	h	$0.673(12)$	[2,3]
Hubble length	c/H_0	$0.925\,0629 \times 10^{26}\ h^{-1}$ m $= 1.37(2) \times 10^{26}$ m	
scale factor for cosmological constant	$c^2/3H_0^2$	$2.85247 \times 10^{51}\ h^{-2}$ m^2 $= 6.3(2) \times 10^{51}$ m^2	
critical density of the Universe	$\rho_{\rm crit} = 3H_0^2/8\pi G_N$	$2.775\,366\,27 \times 10^{11}\ h^2\ M_\odot$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}	
number density of baryons	$n_{\rm b}$	$2.482(32) \times 10^{-7}$ cm^{-3}	[2,3,27,28]
		$(2.1 \times 10^{-7} < n_{\rm b} < 2.7 \times 10^{-7})$ cm^{-3} (95% CL)	$\eta \times n_\gamma$
baryon density of the Universe	$\Omega_{\rm b} = \rho_{\rm b}/\rho_{\rm crit}$	$^\ddagger\,0.02207(27)\,h^{-2}$ $=$ $^\dagger\,0.0499(22)$	[2,3]
cold dark matter density of the universe	$\Omega_{\rm cdm} = \rho_{\rm cdm}/\rho_{\rm crit}$	$^\ddagger\,0.1198(26)\,h^{-2}$ $=$ $^\dagger\,0.265(11)$	[2,3]
100 × approx to $r_*/D_{\rm A}$	$100 \times \theta_{\rm MC}$	$^\ddagger\,1.0413(6)$	[2,3]
reionization optical depth	τ	$^\ddagger\,0.091^{+0.013}_{-0.014}$	[2,3]
scalar spectral index	$n_{\rm s}$	$^\ddagger\,0.958(7)$	[2,3]
ln pwr primordial curvature pert. (k_0=0.05 Mpc^{-1})	$\ln(10^{10}\Delta^2_{\mathcal{R}})$	$^\ddagger\,3.090(25)$	[2,3]

Quantity	Symbol, equation	Value	Reference, footnote
dark energy density of the ΛCDM Universe	Ω_Λ	$0.685^{+0.017}_{-0.016}$	[2,3]
pressureless matter density of the Universe	$\Omega_{\rm m} = \Omega_{\rm cdm} + \Omega_{\rm b}$	$0.315^{+0.016}_{-0.017}$ (From Ω_Λ and flatness constraint)	[2,3]
dark energy equation of state parameter	w	$^\sharp\,-1.10^{+0.08}_{-0.07}$ (*Planck*+WMAP+BAO+SN)	[32]
CMB radiation density of the Universe	$\Omega_\gamma = \rho_\gamma/\rho_{\rm c}$	$2.473 \times 10^{-5}(T/2.7255)^4\,h^{-2} = 5.46(19) \times 10^{-5}$	[25]
effective number of neutrinos	$N_{\rm eff}$	$^\dagger\,3.36 \pm 0.34$	[2]
sum of neutrino masses	$\sum m_\nu$	< 0.23 eV (95% CL; CMB+BAO) $\Rightarrow \Omega_\nu h^2 < 0.0025$	[2,30,31]
neutrino density of the Universe	Ω_ν	$< 0.0025\,h^{-2} \Rightarrow\ < 0.0055$ (95% CL; CMB+BAO)	[2,30,31]
curvature	$\Omega_{\rm tot} = \Omega_{\rm m} + \ldots + \Omega_\Lambda$	$^\sharp\,0.96^{+0.4}_{-0.5}$ (95%CL)	[2]
		$^\sharp\,1.000(7)$ (95% CL; CMB+BAO)	[2]
fluctuation amplitude at $8\,h^{-1}$ Mpc scale	σ_8	$^\dagger\,0.828 \pm 0.012$	[2,3]
running spectral index slope, $k_0 = 0.002$ Mpc^{-1}	$dn_{\rm s}/d\ln k$	$^\sharp\,-0.015(9)$	[2]
tensor-to-scalar field perturbations ratio, k_0=0.002 Mpc^{-1}	$r = T/S$	$^\sharp\,< 0.11$ at 95% CL; no running	[2,3]
redshift at decoupling	$z_{\rm dec}$	$^\dagger\,1090.2 \pm 0.7$	[2]
age at decoupling	t_*	$^\dagger\,3.72 \times 10^5$ yr	
sound horizon at decoupling	$r_s(z_*)$	$^\dagger\,147.5 \pm 0.6$ Mpc (*Planck* CMB)	[32]
redshift of matter-radiation equality	$z_{\rm eq}$	$^\dagger\,3360 \pm 70$	[2]
redshift at half reionization	$z_{\rm reion}$	$^\dagger\,11.1 \pm 1.1$	[2]
age at half reionization	$t_{\rm reion}$	$^\dagger\,462$ Myr	
age of the Universe	t_0	$^\dagger\,13.81 \pm 0.05$ Gyr	[2]

‡ Parameter in six-parameter ΛCDM fit [2].
† Derived parameter in six-parameter ΛCDM fit [2].
♯ Extended model parameter [2].

References:

1. P.J. Mohr, B.N. Taylor, and D.B. Newell, J. Phys. Chem. Ref. Data 41, 043109, (2012); `physics.nist.gov/constants`.
2. P.A.R. Ade, *et al.*, (Planck Collab. 2013 XVI), `arXiv:1303.5076v1`.
3. O. Lahav and A.R. Liddle, "The Cosmological Parameters," in this *Review.*
4. B.W. Petley, Nature **303**, 373 (1983).
5. T. Quinn *et al.*, Phys. Rev. Lett. **111**, 101102 (2013). See especially Fig. 3.
6. *The Astronomical Almanac for the year 2011*, U.S. Government Printing Office, Washington, and The U.K. Hydrographic Office (2010).
7. Astronomical_Constants_2014.pdf, downloaded from `asa.usno.navy.mil/SecK/Constants.html`; also see `www.iau.org/static/resolutions/IAU2012_English.pdf`. The Gaussian gravitational constant k is now deleted from the system of astronomical constants.
8. The distance at which 1 au subtends 1 arc sec: 1 au divided by $\pi/648\,000$.
9. Product of $2/c^2$ and the observationally determined Solar mass parameter $G_N M_\odot$ [7](TDB time scale).
10. $G_N M_\odot$ [7] $\div$ G_N [1].
11. T. M. Brown and 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.
12. $4\pi\,(1\text{ au})^2 \times (1361\text{ W m}^{-2})$, assuming isotropic irradiance; G. Kopp and J.L. Lean, Geophys. Res. Lett. **38**, L01706 (2011) give $1360.8 \pm 0.6\text{W m}^{-2}$, but given the scatter in the data we use the rounded value without quoting an error.
13. Product of $2/c^2$ and the geocentric gravitational constant $G_N M_\oplus$ [7](TDB time scale).
14. $G_N M_\oplus$ [7] $\div$ G_N [1].
15. E.W. Kolb and 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.
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, Astron. Rep. **57**, 128 (2013). 56 determinations of R_0 are given. The weighted mean of these unevaluated results is 8.0(4), with $\chi^2/dof = 1.2$.
19. G. Gilmore, R.F.G. Wyse, and 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 and A.Kinkhabwala, Phys. Rev. **D57**, 325 (1998); M. Weber and W. de Boer, Astron. & Astrophys. **509**, A25 (2010); P. Salucci *et al.*, Astron. & Astrophys. **523**, A83 (2010); R. Catena and P. Ullio, JCAP **1008**, 004 (2010) conclude $\rho_{\rm DM}^{\rm local} = 0.39 \pm 0.03\,\text{GeV cm}^{-3}$.
21. M. C. Smith *et al.*, Mon. Not. R. Astr. Soc. **379**, 755 (2007) (`astro-ph/0611671`).
22. D. Scott and G.F. Smoot, "Cosmic Microwave Background," in this *Review.*
23. D. Fixsen, Astrophys. J. **707**, 916 (2009).
24. G. Hinshaw *et al.*, Astrophys. J. Suppl. in press, `arXiv:1212.5226`; D.J. Fixsen *et al.*, Astrophys. J. **473**, 576 (1996); A. Kogut *et al.*, Astrophys. J. **419**, 1 (1993).
25. $n_\gamma = \dfrac{2\zeta(3)}{\pi^2}\left(\dfrac{kT}{\hbar c}\right)^3$; $\rho_\gamma = \dfrac{\pi^2 kT}{15\,c^2}\left(\dfrac{kT}{\hbar c}\right)^3$; $s/k = \dfrac{2\cdot 43\cdot\pi^2}{11\cdot 45}\left(\dfrac{kT}{\hbar c}\right)^3$; $kT_0/\hbar c = 11.902(4)/\text{cm}$.
26. B.D. Fields, P. Molarto, and S. Sarkar, "Big-Bang Nucleosynthesis," in this *Review.*
27. $n_{\rm b}$ depends only upon the measured $\Omega_{\rm b}h^2$, the average baryon mass at the present epoch [28], and G_N: $n_{\rm b} = (\Omega_{\rm b}h^2)h^{-2}\rho_{\rm crit}/(0.93711\,\text{GeV}/c^2 \text{ per baryon})$.
28. G. Steigman, JCAP **0610**, 016, (2006).
29. Conversion using length of sidereal year.
30. $\Omega_\nu h^2 = \sum m_{\nu_j}/93.04\,\text{eV}$, 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: $\Delta m^2_{32} = (2.32^{+0.12}_{-0.08}) \times 10^{-3}$ 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 $m_{\nu_1} \approx m_{\nu_2} \gg m_{\nu_3}$.) Alternatively, if the limit obtained from tritium decay experiments ($m_\nu < 2\,\text{eV}$) is used for the upper limit, then $\Omega_\nu < 0.04$.
31. Astrophysical determinations of $\sum m_{\nu_j}$, reported in the Full Listings of this *Review* under "Sum of the neutrino masses," range from $< 0.17\,\text{eV}$ to $< 2.3\,\text{eV}$ in papers published since 2003.
32. M.J. Mortonson, D.H. Weinberg, and M. White, "Dark Energy," in this *Review.*