

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 $1\text{-}\sigma$ 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 Λ CDM 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	$299\,792\,458\text{ m s}^{-1}$	exact[4]
Newtonian gravitational constant	G_N	$6.673\,8(8) \times 10^{-11}\text{ m}^3\text{ kg}^{-1}\text{ s}^{-2}$	[1,5]
Planck mass	$\sqrt{\hbar c/G_N}$	$1.220\,93(7) \times 10^{19}\text{ GeV}/c^2$ $= 2.176\,51(13) \times 10^{-8}\text{ kg}$	[1]
Planck length	$\sqrt{\hbar G_N/c^3}$	$1.616\,20(10) \times 10^{-35}\text{ m}$	[1]
standard gravitational acceleration	g_N	$9.806\,65\text{ m s}^{-2}$	exact[1]
jansky (flux density)	Jy	$10^{-26}\text{ W m}^{-2}\text{ Hz}^{-1}$	definition
tropical year (equinox to equinox) (2011)	yr	$31\,556\,925.2\text{ s} \approx \pi \times 10^7\text{ s}$	[6]
sidereal year (fixed star to fixed star) (2011)		$31\,558\,149.8\text{ s} \approx \pi \times 10^7\text{ s}$	[6]
mean sidereal day (2011) (time between vernal equinox transits)		$23^{\text{h}}\,56^{\text{m}}\,04^{\text{s}}.090\,53$	[6]
astronomical unit	au	$149\,597\,870\,700\text{ m}$	exact [7]
parsec (1 au/1 arc sec)	pc	$3.085\,677\,581\,49 \times 10^{16}\text{ m} = 3.262\dots\text{ly}$	exact [8]
light year (deprecated unit)	ly	$0.306\,6\dots\text{pc} = 0.946\,053\dots \times 10^{16}\text{ m}$	
Schwarzschild radius of the Sun	$2G_N M_\odot/c^2$	$2.953\,250\,077(2)\text{ km}$	[9]
Solar mass	M_\odot	$1.988\,5(2) \times 10^{30}\text{ kg}$	[10]
Solar equatorial radius	R_\odot	$6.9551(4) \times 10^8\text{ m}$	[11]
Solar luminosity	L_\odot	$3.828 \times 10^{26}\text{ W}$	[12]
Schwarzschild radius of the Earth	$2G_N M_\oplus/c^2$	$8.870\,055\,94(2)\text{ mm}$	[13]
Earth mass	M_\oplus	$5.972\,6(7) \times 10^{24}\text{ kg}$	[14]
Earth mean equatorial radius	R_\oplus	$6.378\,137 \times 10^6\text{ m}$	[6]
luminosity conversion (deprecated)	L	$3.02 \times 10^{28} \times 10^{-0.4 M_{\text{bol}}}\text{ W}$	[15]
flux conversion (deprecated)	\mathcal{F}	$2.52 \times 10^{-8} \times 10^{-0.4 m_{\text{bol}}}\text{ W m}^{-2}$ (M_{bol} = absolute bolometric magnitude = bolometric magnitude at 10 pc)	from above
ABsolute monochromatic magnitude	AB	$(m_{\text{bol}} = \text{apparent bolometric magnitude})$ $-2.5 \log_{10} f_\nu - 56.10$ (for f_ν in $\text{W m}^{-2}\text{ Hz}^{-1}$) $= -2.5 \log_{10} f_\nu + 8.90$ (for f_ν in Jy)	[16]
Solar angular velocity around the Galactic center	Θ_0/R_0	$30.3 \pm 0.9\text{ km s}^{-1}\text{ kpc}^{-1}$	[17]
Solar distance from Galactic center	R_0	$8.4(6)\text{ kpc}$	[17,18]
circular velocity at R_0	v_0 or Θ_0	$254(16)\text{ km s}^{-1}$	[17]
local disk density	ρ_{disk}	$3\text{--}12 \times 10^{-24}\text{ g cm}^{-3} \approx 2\text{--}7\text{ GeV}/c^2\text{ cm}^{-3}$	[19]
local dark matter density	ρ_χ	canonical value $0.3\text{ GeV}/c^2\text{ cm}^{-3}$ within factor 2-3	[20]
escape velocity from Galaxy	v_{esc}	$498\text{ km/s} < v_{\text{esc}} < 608\text{ km/s}$	[21]
present day CMB temperature	T_0	$2.7255(6)\text{ K}$	[22,23]
present day CMB dipole amplitude		$3.355(8)\text{ mK}$	[22,24]
Solar velocity with respect to CMB		$369(1)\text{ km/s}$ towards $(\ell, b) = (263.99(14)^\circ, 48.26(3)^\circ)$	[22,24]
Local Group velocity with respect to CMB	v_{LG}	$627(22)\text{ km/s}$ towards $(\ell, b) = (276(3)^\circ, 30(3)^\circ)$	[22,24]
entropy density/Boltzmann constant	s/k	$2\,891.2 (T/2.7255)^3\text{ cm}^{-3}$	[25]
number density of CMB photons	n_γ	$410.7 (T/2.7255)^3\text{ cm}^{-3}$	[25]
baryon-to-photon ratio	$\eta = n_{\text{b}}/n_\gamma$	$6.05(7) \times 10^{-10}$ (CMB) $5.7 \times 10^{-10} \leq \eta \leq 6.7 \times 10^{-10}$ (95% CL)	[26]
present day Hubble expansion rate	H_0	$100 h\text{ km s}^{-1}\text{ Mpc}^{-1} = h \times (9.777\,752\text{ Gyr})^{-1}$	[29]
scale factor for Hubble expansion rate	h	$0.673(12)$	[2,3]
Hubble length	c/H_0	$0.925\,0629 \times 10^{26} h^{-1}\text{ m} = 1.37(2) \times 10^{26}\text{ m}$	
scale factor for cosmological constant	$c^2/3H_0^2$	$2.85247 \times 10^{51} h^{-2}\text{ m}^2 = 6.3(2) \times 10^{51}\text{ m}^2$	
critical density of the Universe	$\rho_{\text{crit}} = 3H_0^2/8\pi G_N$	$2.775\,366\,27 \times 10^{11} h^2 M_\odot\text{ Mpc}^{-3}$ $= 1.878\,47(23) \times 10^{-29} h^2\text{ g cm}^{-3}$ $= 1.053\,75(13) \times 10^{-5} h^2 (\text{GeV}/c^2)\text{ cm}^{-3}$	
number density of baryons	n_{b}	$2.482(32) \times 10^{-7}\text{ cm}^{-3}$ $(2.1 \times 10^{-7} < n_{\text{b}} < 2.7 \times 10^{-7})\text{ cm}^{-3}$ (95% CL)	[2,3,27,28]
baryon density of the Universe	$\Omega_{\text{b}} = \rho_{\text{b}}/\rho_{\text{crit}}$	$\ddagger 0.02207(27) h^{-2} = \dagger 0.0499(22)$	[2,3]
cold dark matter density of the universe	$\Omega_{\text{cdm}} = \rho_{\text{cdm}}/\rho_{\text{crit}}$	$\ddagger 0.1198(26) h^{-2} = \dagger 0.265(11)$	[2,3]
$100 \times$ approx to r_*/D_A	$100 \times \theta_{\text{MC}}$	$\ddagger 1.0413(6)$	[2,3]
reionization optical depth	τ	$\ddagger 0.091^{+0.013}_{-0.014}$	[2,3]
scalar spectral index	n_{s}	$\ddagger 0.958(7)$	[2,3]
ln pwr primordial curvature pert. ($k_0=0.05\text{ Mpc}^{-1}$)	$\ln(10^{10}\Delta_{\mathcal{R}}^2)$	$\ddagger 3.090(25)$	[2,3]

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

\ddagger Parameter in six-parameter Λ CDM fit [2].

\dagger Derived parameter in six-parameter Λ CDM fit [2].

$\#$ Extended model parameter [2].

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- The distance at which 1 au subtends 1 arc sec: 1 au divided by $\pi/648000$.
- Product of $2/c^2$ and the observationally determined Solar mass parameter $G_N M_\odot$ [7] (TDB time scale).
- $G_N M_\odot$ [7] $\div G_N$ [1].
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- Product of $2/c^2$ and the geocentric gravitational constant $G_N M_\oplus$ [7] (TDB time scale).
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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.
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Note that Θ_0/R_0 is better determined than either Θ_0 or R_0 .
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D.J. Fixsen *et al.*, *Astrophys. J.* **473**, 576 (1996);
A. Kogut *et al.*, *Astrophys. J.* **419**, 1 (1993).
- $n_\gamma = \frac{2\zeta(3)}{\pi^2} \left(\frac{kT}{hc}\right)^3$; $\rho_\gamma = \frac{\pi^2 kT}{15 c^2} \left(\frac{kT}{hc}\right)^3$; $s/k = \frac{2 \cdot 43 \cdot \pi^2}{11 \cdot 45} \left(\frac{kT}{hc}\right)^3$;
 $kT_0/hc = 11.902(4)/\text{cm}$.
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- n_b depends only upon the measured $\Omega_b h^2$, the average baryon mass at the present epoch [28], and G_N :
 $n_b = (\Omega_b h^2) h^{-2} \rho_{\text{crit}} / (0.93711 \text{ GeV}/c^2 \text{ per baryon})$.
- G. Steigman, *JCAP* **0610**, 016, (2006).
- Conversion using length of sidereal year.
- $\Omega_\nu h^2 = \sum m_{\nu_j} / 93.04 \text{ eV}$, 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 ($m_\nu < 45 \text{ GeV}/c^2$) and that the lightest neutrino is substantially less massive than the others: $\Delta m_{32}^2 = (2.32^{+0.12}_{-0.08}) \times 10^{-3} \text{ eV}^2$, so $\sum m_{\nu_j} \geq m_{\nu_3} \approx \sqrt{\Delta m_{32}^2} = 0.05 \text{ eV}$. (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 $\Omega_\nu < 0.04$.
- 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.
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