Cosmology

Steven Weinberg

Corrections to the First Printing[1]

1. The name "Borgnani" in footnote 7 on p. 85 and in the index on p. 576 should be "Borgani".

2. In figure 9.2, the point labelled γ should instead be labelled Y.

3. On page 451, in the discussion of the lensing of QSO 0957+561, the redshifts of the source and lens were interchanged: the source has redshift 1.41, and the lens has redshift 0.36.

4. On p. 454, on the second line after Eq. (9.5.9), "al a the line of sight" should be "along the line of sight".

5. In the second line of Eq. (9.5.61) on page 464, the exponent -5 of r should be -6. No change is needed in the third line.

6. In footnote 15 on p. 65, and in the author index on p. 579, the name "R. Jiminez" should be "R. Jimenez"; also in footnote 2 on p. 153, and in the author index on p. 581, the names "G. Pastor" and "M. Peiso" should be "S. Pastor" and "M. Peloso". (Thanks to U. França for these corrections.)

7. In footnote 2 on p. 1, "300 light years" should be "300 million light years". (Thanks to F. Maienschein for this correction.)

8. In the term on the left of Eq. (10.4.3) on p. 498, the superscript n on ϕ should be m.

9. Due to a copying error, the fitting formula (6.5.14) for the function $\Delta(\kappa)$ is incorrect. Eq. (6.5.14) should be replaced with

$$\Delta(\kappa) = \frac{(1.1547\kappa)^2 + (0.5986\kappa)^4 + (0.2578\kappa)^6}{1 + (1.723\kappa)^2 + (0.8707\kappa)^4 + (0.4581\kappa)^6 + (0.2204\kappa)^8} \ .$$

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[1]To find the printing of your copy of *Cosmology*, look at the page on the reverse of the title page, on which the copyright notice and ISBN number appear. At the bottom of this page is a decreasing sequence of integers: 10, 9, 8 $\cdots$. The last integer in this sequence gives the printing of your copy.

10. A factor of the gravitational constant G should appear in the definition of Ω_L in the first line after Eq. (9.2.20) on page 440, and the result $N_S = 4\Omega_L$ on the fourth line of page 442 should be $N_S = 2\Omega_L$. (Thanks to H. Zhang for these corrections.)

11. In the Author Index on page 581, the name Mo, M. J. should be Mo, H. J. (Thanks to G. Liu for this correction.)

12. On page 67, seven lines from the bottom, "Eqs. (1.4.9) and (1.4.11)" should read "Eqs. (1.4.9) and (1.4.12)". In Eq. (1.9.13) on page 71, the subscript M should be B. In the last two lines of Eq. (9.3.14) on page 445, and in Eq. (9.3.16), π^2 should be π^3. (Thanks to H. Zhang for these additional corrections.)

13. On page 446, in the line just above Eq. (9.3.16), the reference to Eq. (9.3.15) should be to Eq. (9.3.14).

14. On page 50, in the line just above Eq. (1.6.2), "Eq. (1.5.46)" should be "Eq. (1.5.45)". In the unnumbered equation on p. 418, the factor a_0 in the argument of the sine should be removed. On p. 419, in the line just below Eq. (8.1.50), there should be a factor 4 in the denominator of the formula for R. On page 455, the factor a^2 in the numerator of Eq. (9.5.10) should be removed. On page 456, the subscript d in the second term of the right-hand side of Eq. (9.5.17) should be b. On page 464, the factor r^{-5} in Eq. (9.5.61) should be r^{-6}. (Thanks once more to H. Zhang for these corrections.)

15. In the second sentence on page 1, "about one part in 10^{-5}" should be "about one part in 10^5". In the middle of page 28, "superceded" should be "superseded." (Thanks to H. Lewis for these corrections.)

16. On page 89, in the second sentence of the third paragraph of Sec. 1.12, "that are vary little" should be "that vary little." In Eq. (6.4.22) on page 294, there should be a multiplication sign at the beginning of the second line. On page 303, in the line above Eq. (6.4.64), there should be a δ in front of $u_{\gamma q}$. In footnote 1 on page 333, Ω_V should be Ω_Λ. In footnote 1 on page 334, "(5.3.42)" should be "(5.3.43)". In Eq. (7.1.18) on page 336, the "approximately equal" sign under the summation sign should be an equal sign. In the third line above Eq. (9.2.1) on page 436, the word "between" should be deleted. In Eq. (C.25) on page 536, the multiplication sign beginning the second line should be removed, as these are two separate equations. (Thanks to J. Meyers for these corrections.)

17. On page 379, equation numbers (7.4.37) and (7.4.38) refer to the same equation. This should be numbered as equation (7.4.37). On page 393, the next-to-last equation, which gives a formula for the EE multipole coefficient and is now unnumbered, should be numbered as equation (7.4.70). As a result of these two changes, the numbers of all equations that are now numbered as equations (7.4.39) through (7.4.70) should be decreased by one, so that they will appear as equations (7.4.38) through (7.4.69). (Thanks to J. Meyers for pointing this out.)

18. As a result of a last minute insertion of an equation, there are errors in the references in Section 7.4 to equations appearing in this section. After making the changes indicated in item 17 above, the equation numbers in all references to equations from (7.4.31) to the end of Section 7.4 should be increased by one. Thus, for instance, on page 378, in the line just above what now appears as Eq. (7.4.35), "Eq. (7.4.31) then reads" should be "Eq. (7.4.32) then reads". The same changes should be made to references to equations from Section 7.4 appearing in Section 9.5 on pages 465 and 466. For instance, on page 465, three lines above Eq. (9.5.64), "from Eqs. (7.4.76)–(7.4.78)" should be "from Eqs. (7.4.77)–(7.4.79)." (Thanks to H. Zhang and J. Meyers for these corrections.)

19. In footnote 10 on page 179, the name "Klinkhammer" should be "Klinkhamer". The same change should be made in the Author Index, on page 579. (Thanks to C. Rampf for this correction.)

20. The date 1978 in reference 7 on page 176 should be 1979.

21. The second sentence of the last paragraph on page 177 should begin "The conditions for thermal equilibrium will remain violated as long as H stays above the X-particle decay rate, but as long as..." (Thanks to C. Rampf for alerting me to this error.)

22. On page 519, in the unnumbered equation under Eq. (B.34), the function $f(y)$ on the left-hand side should be $f(x)$, and the function $f(x)$ on the right-hand side should be $f(y)$. (Thanks to E. Sabancilar for this correction.)

23. On page 201, five lines from the bottom of the secibd paragraph, the second "was" should be deleted in the sentence "Why was the curvature was so small in the early universe?" In the second term on the second line of Eq. (10.4.18) on page 500 and in the second term

3

of what was originally Eq. (10.4.24) on page 501, the dot and over-bar should be directly above φ, as $\dot{\bar{\varphi}}$. (Thanks to S. Miller for these corrections.)

24. On page 16, in the fourth line of the first marked paragraph, "because they all at the same" should read "because they are all at the same". (Thanks to B. Diamond for pointing this out.)

25. On page 41, in the line just before Eq. (1.5.39), the second "and" should be deleted. On page 333, in the sixth line of footnote 1, and also in the author index on page 575, the name "Ashfordi" should be "Afshordi." (I thank S. Mahmoodifar for these corrrections.)

26. On page 197, two lines above Eq. (3.4.15), "the form (B.44)" should be "the form (B.63)". (Thanks to S. Miller for pointing this out.)

27. On the right-hand sides of both Eq. (6.1.15) on page 262 and Eq. (6.1.44) on page 269, p_j should be $\hat{p}_j$.

28. In the last term in the parenthesis on the right-hand side of Eq. (10.4.3) on page 498, φ^m should be φ^n.

29. On the second line of the caption of Figure 7.7 on page 392, "ref. 21" should be "ref. 22".

Corrections to the Second Printing[2]

1. On the fourth line from the bottom of footnote 1 on page 333, Ω_V should be Ω_Λ.

2. On the third line after Eq. (7.4.49) on page 387, "(7.4.47)" should be "(7.4.48)".

3. On the first line of page 391, "(7.4.60)" should be "(7.4.61)".

4. On the second line of page 398, "(7.4.74) and (7.4.75)" should be "(7.4.75) and (7.4.76)".

5. On the first line below Eq. (7.4.86) on page 398, "(7.4.57)" should be "(7.4.58)".

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[2]All of the errors in the first printing listed above were corrected in the second printing, except for these items.

Corrections to the First and Second Printing

1. On page 3, Eq. (1.1.4) should read $\mathbf{x}' \equiv \mathbf{x}/a$, $z' \equiv z/a$.

2. On page 19, in the 10th line from the bottom of the inset paragraph labelled **Main Sequence**, "Including" should be "Included".

3. On page 527, in the second line from the top, "Eq. (B.40)" should be "Eq. (B.52)"

4. On page 70, in the two displayed but unnumbered equations, a prime should appear on r following the integral sign in both equations.

5. On page 140, in the displayed but unnumbered equation, a multiplication sign $\times$ should appear at the beginning of the second line.

6. On page 127, in the second line after the table, "ionization dropped well below" should be "ionization became well above".

7. On page 129, in the first line, $\ln \mathcal{O}(T)$ should be $\ln[1 - \mathcal{O}(T)]$.

8. On page 519, in Eq. (B.34), a subscript n should be supplied to the final x on both lines, so that these equations read

$$
\begin{aligned}
J^{\mu}(x) &\equiv \frac{1}{\sqrt{-\mathrm{Det}g(x)}} \int du \sum_n e_n\, \delta^4\Big(x_n(u) - x\Big) \frac{dx_n^{\mu}(u)}{du} \\
&= \frac{1}{\sqrt{-\mathrm{Det}g(x)}} \sum_n e_n\, \delta^3\Big(\mathbf{x}_n(t) - \mathbf{x}\Big) \frac{dx_n^{\mu}(t)}{dt} \ .
\end{aligned}
$$

(I am grateful to J. Ganc for corrections 1 through 8 to the first and second printings.)

9. The derivation of the deflection of light by a cosmic string in Section 9.6 applies only for a linear array of non-relativistic masses. For a relativistic string, such as a singularity in vacuum expectation values, the post-Newtonian approximation does not apply. The deflection in this case was derived by A. Vilenkin, Phys. Rev. D **23**, 852 (1981). The deflection by a relativistic string is given by Eq. (9.6.4), but with $\sin \theta$ in the numerator rather than the denominator.

10. On page 250, in the fourth line, "4×4 matrix" should be "3×3 matrix". (Thanks to A. Boonstra for this correction.)

11. On page 39, in the second line from the top, "is *less* than the Hubble time" should be "is no greater than the Hubble time".

12. On page 39, Eq. (1.5.29) should read $t_0 \leq H_0^{-1}$.

13. On page 42, in the first line after Eq. (1.5.44), "Eq. (1.5.43) has..." should be "Eq. (1.5.44) has...".

14. On page 57, in the second line from the top, Ω_V should be Ω_Λ.

15. On page 61, in the fourth line from the top, the first appearance of the word "star" should be omitted.

16. On page 93, in the second line from the bottom, "whatever reservations may have" should be "whatever reservations we may have"

17. On page 94, in the eighth line from the top, Ω_V should be Ω_Λ.

18. On page 95, two lines above Eq. (1.12.23), Ω_V should be Ω_Λ.

19. On page 150, the two lines above Eq. (3.1.2) should read "The second law of thermodynamics implies that a slow change in a system, that takes it from equilibrium at temperature T and volume V to equilibrium at temperature $T + dT$ and volume $V + dV$, produces a change in the entropy given by:".

20. On page 181, in the line above Eq. (3.3.10), the condition $|\mu| \ll 1$ should be $|\mu| \ll k_\mathcal{B} T$.

21. On page 184, in the fifth line of subsection 5, "even the universe starts in a state..." should be "even if the universe starts in a state...".

22. On page 190, in Eq. (3.4.14), the exponent $-.54$ should be -0.54.

23. On page 214, in the fourth line from the top, "no longer be satisfied" should be "no longer satisfied".

24. On page 365, in Eq. (7.3.16), two primes should be added in the left-hand side, so that it reads $\langle \beta(\mathbf{q}, \lambda) \, \beta^*(\mathbf{q}', \lambda') \rangle$.

25. On pages 467 and 468, the minus signs should be deleted in Eqs. (9.6.1), (9.6.2) and (9.6.3).

26. On page 469, in the eighth line of the first paragraph, "Eq. (5.4.24)" should be "Eq. (5.4.22)".

27. On page 521, in the second line after the unnumbered displayed equation, "is because non-zero value..." should be "is because a non-zero value...".

28. On page 529, in the line after Eq. (B.74), "This is why this is the linear combination..." should read "This is why $R_{\mu\nu} - g_{\mu\nu}g^{\lambda\kappa}R_{\lambda\kappa}/2$ is the linear combination...".
(Thanks to R. Baierlein for corrections 11 through 28 to the first and second printings.)

29. On page 128, two lines above Eq. (2.3.41), the reference to Eq. (2.3.36) should be to Eq. (2.3.40).

30. On page 134, six lines from the bottom of the first full paragraph, "as a function of photon wavelength, with a result" should be "as a photon of photon wavelength (corrected to remove the effect of the cosmological redshift), with a result".

31. The first sentence on page 131 should read "This effect was first observed in 1969 with a ground based radiometer, but at the time it was only possible to measure the component of the Earth's velocity on a fixed declinatiob $\delta = +32°$, found to be 160 km/sec in a direction corresponding to this declination and right ascension 13h.[1]"

32. On page 146, five lines and seven lines below Eq. (2.6.33), "ℓ_{horizon}" should be "ℓ_H" (defined on the previous page). Also, "$\approx$" on the seventh line below Eq. (2.6.33) should be "$\equiv$", since this is the definition of ℓ_H.

33. On page 147, four lines above Eq. (2.6.34), "$\ell \geq 4$" should be "$\ell \geq 3$".

34. On page 147, two lines above Eq. (2.6.35), "$10 \leq \ell \leq 40$" should be "$3 \leq \ell \leq 40$".

35. On page 147, next to last line of main text, "$\ell = 2$ and $\ell = 3$" should be just "$\ell = 2$".

36. On page 148, top line, "$\ell \geq 4$" should be "$\ell \geq 3$".

37. On page 147, last line of footnote 9, "astro-ph/9601088" should be "astro-ph/9601058".

38. On page 157, middle, the sentence beginning "Once out of equilibrium..." should read "Once out of equilibrium, their momentum simply decayed as $1/a$ (as shown in Section 1.1), so if their chemical

potential was negligible their momentum distribution remained like that of photons, aside from a $+$ instead of a $-$ sign in the denominator of the distribution function, with a temperature less by a factor $(4/11)^{1/3}$."

39. On page 162, second line below Eq. (3.2.11), "Q/k" should be "$Q/k_{\mathcal{B}}$".

40. On page 172, footnote 20, and on page 572 of the author index, the name "Eggleston" should be "Eggleton".

41. On pages 176 and 177, the parenthetical remark beginning on the last line of page 176 and continuing on page 177 should read "(For instance, in some grand unified theories there are "leptoquarks" with mass of order 10^{15} GeV, that decay into either two quarks, with baryon number $2/3$ and lepton number zero, or into an antilepton and an antiquark, with baryon number $-1/3$ and lepton number -1.)"

    (Thanks to E. Komatsu for corrections 29 through 41 to the first and second printings.)

42. On page 106, in the caption to Figure 2.1, the first sentence should read "Comparison of the dipole part (discussed in Section 2.4) of the intensity of radiation observed with the FIRAS radiometer carried by COBE with what would be expected for a black body spectrun with temperature 2.728 K, from D. J. Fixsen *et al.*, *Astrophys. J.* **478**, 576 (1996) [astro-ph/9605054]." (I thank T. Kawarabayashi for this correction.)

43. On page 91, third line above Eq. (1.12.8), "(1.1.2)" should be "(1.12.2)".

44. On page 117, in Eq. (2.3.9), $(B_2 - B_n)$ in the argument of the exponential should be $(B_n - B_2)$.

45. On page 156, fourth line from the bottom, "photons" should be "positrons".

46. On page 183, first line of Eq. (3.3.20), $\tilde{n}_i$ should be $\bar{n}_i$.

47. On page 185, in Eq. (3.3.24), a minus sign should multiply the right-hand side.

48. On page 190, third and sixth lines below Eq. (3.4.14), G_F should be G_{wk}.

49. On page 198, first line below Eq. (3.4.18), "and Eq. (3.4.17) has" should be "and Eq. (3.4.18) has".

50. On page 198, second line below Eq. (3.4.8), a dot is missing over φ in two places, so that "solutions $\varphi = $ constant and $\varphi \propto 1/a^3$" should be "solutions $\dot{\varphi} = $ constant and $\dot{\varphi} \propto 1/a^3$"

51. On page 212, on the sixth line below Eq. (4.2.16), "$8\pi G\varphi_1^2/\alpha$" should be "$4\pi G\varphi_1^2/\alpha$". In consequence, on the eighth line below Eq. (4.2.16), "$|\varphi_1| > \sqrt{31/\pi G}$" should be "$|\varphi_1| > \sqrt{62/\pi G}$" and on the fifth line above the bottom of the page, "$g \ll 2 \times 10^{-5}$" should be "$g \ll 5 \times 10^{-6}$".

52. On page 224, in the first and second lines of footnote 2, h_{jk} should be h_{ij}.

53. On page 225, in the tenth line from the top, $\bar{p}\delta_{ij}$ should be $\bar{p}h_{ij}$.

54. On page 244, in the first line below Eq. (5.3.50), "definitions (5.3.18)" should be "definitions (5.3.17)"

55. On page 248, last displayed equation, the coefficient -2 in the last term on the right-hand side should be $+2a^2$.

56. On page 262, in the second Eq. (6.1.18), the left-hand side $\delta u_{Bk}(\mathbf{x}, t)$ should be $\delta u_{Bi}(\mathbf{x}, t)$

57. On page 264, Eq. (6.1.24), a factor $1/a(t)$ should be supplied in the last term on the right-hand side.

58. On page 265, Eq. (6.1.28), a factor $1/a(t)$ should be supplied in the last term on the right-hand side.

59. On page 266, in the second of the three displayed but unnumbered equations in the middle of the page, $\hat{q}_i$ should be $\hat{q}_j$.

60. On page 266, Eq. (6.1.34), a factor $1/a$ should appear on the left-hand side.

61. On page 288, the line above Eq. (6.3.32), the formula $\delta_{Dq} \rightarrow 9q^2 t \mathcal{R}_q^o/10a^2$ should be $\delta_{Dq} \rightarrow 9q^2 t^2 \mathcal{R}_q^o/10a^2$.

62. On page 289, third and fourth lines below the displayed but unnumbered equation, "Adding the inhomogeneous term (6.3.25)," should be "Adding the limit (6.3.31) of the inhomogeneous term,"

63. On page 294, two lines above Eq. (6.4.23), v_s^2 should be v_s.

64. On page 305, two lines above displayed but unnumbered equation in middle of page, "$(t/3H_{\mathrm{EQ}})(a/a_{\mathrm{EQ}})^{3/2}$" should read "$(2\sqrt{2}/3H_{\mathrm{EQ}})(a/a_{\mathrm{EQ}})^{3/2}$".

65. On page 317, in the second line of Eq. (6.6.25), "$\mathcal{D}_q(t)$" should be a time-derivative, "$\dot{\mathcal{D}}_q(t)$".

66. On page 319, Eq. (6.6.34), a factor $P_\ell(\mu)$ should be inserted after $(2\ell + 1)$.

67. On page 319, in the last line of the last displayed but unnumbered equation on the page, $\hat{p}_i\hat{p}_i\hat{p}_j\hat{p}_k$ should be $\hat{p}_i\hat{p}_j\hat{p}_k\hat{p}_l$.

(My thanks to A. Schafer for corrections 43 to 67 to the first and second printings.)