Appendix B

Physical and Orbit Properties of the Sun, Earth, Moon, and Planets

James R. Wertz, *Microcosm/USC*
Nicola Sarzi-Amade, *Microcosm*

This appendix provides physical and orbit data for the Sun, Moon, and planets. Properties of orbits about these bodies are listed in tables throughout the text. Numerical properties of orbits about the Earth are given in App. I. For additional data on virtually all aspects of the Solar System, astrophysics, and astronomy, we highly recommend that the reader consult Cox [2000]. For a detailed explanation and high accuracy numerical methods and tables for computing planetary orbit ephemerides, see Seidelmann [2006]. For lower accuracy, but computationally convenient techniques, see Meeus [1998].

B.1 Gravitational Constants of Major Solar System Bodies

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See website for other solar system bodies. In Table B-1, values of μ = GM are given to their full available accuracy. Other values are rounded. Values for the smaller satellites are estimates based on a typical density and the object's size. Except for the Sun, the last 3 columns are evaluated at the object's surface (or at the largest dimension for irregular bodies). Data from Seidelmann [2006], IAU [2009], and Astronomical Almanac [2010].

Table B-1. Gravitational Parameters for Orbits About Major Solar System Bodies.

Object	μ = GM (m^3/s^2)	Orbital Velocity (km/s)	Orbit Period (min)	Escape Velocity (km/s)
Sun (at surface)	$1.327\ 124\ 400\ 41 \times 10^{20}$	436.6678	166.9117	617.5416
Sun (at 1 AU)	$1.327\ 124\ 400\ 41 \times 10^{20}$	29.7847	525,970	42.1219
PLANETS AND SATELLITES				
Mercury	$2.203\ 21 \times 10^{13}$	3.0051	85.0169	4.2499
Venus	$3.248\ 585\ 917 \times 10^{14}$	7.3266	86.4984	10.3614
Earth	$3.986\ 004\ 356 \times 10^{14}$	7.9054	84.4891	11.1799
Moon	$4.902\ 800\ 15 \times 10^{12}$	1.6799	108.3069	2.3757
Mars	$4.282\ 837\ 522 \times 10^{13}$	3.5512	100.1500	5.0221
Phobos	7.161×10^{5}	0.0073	191.9561	0.0103
Deimos	1.041×10^{5}	0.0037	210.8393	0.0053
Jupiter	$1.267\ 127\ 626 \times 10^{17}$	42.0999	177.8298	59.5383
Io	5.961×10^{12}	1.8052	106.0975	2.5530
Europa	3.203×10^{12}	1.4321	114.2224	2.0252
Ganymede	9.890×10^{12}	1.9384	142.1873	2.7414
Callisto	7.181×10^{12}	1.7265	146.1158	2.4416
Amalthea	1.39×10^{8}	0.0334	392.0009	0.0472
Himalia	2.8×10^{8}	0.0573	155.4302	0.0810
Elara	5.80×10^{7}	0.0367	122.5712	0.0520
Pasiphae	2.00×10^{7}	0.0258	121.6107	0.0365
Sinope	5.3×10^{6}	0.020	75.1	0.028
Lysithea	5.3×10^{6}	0.021	59.6	0.030
Carme	6.0×10^{6}	0.020	78.5	0.028
Anake	2.7×10^{6}	0.016	64.1	0.023
Leda	4.0×10^{5}	0.009	58.5	0.013
Thebe	9.998×10^{7}	0.0415	146.2925	0.0587
Adrastea	1.3×10^{6}	0.010	134.4	0.014
Metis	6.0×10^{6}	0.017	120.9	0.025
Saturn	$3.794\ 058\ 49 \times 10^{16}$	25.0905	251.5398	35.4833
Mimas	2.508×10^{9}	0.1101	196.9388	0.1557

Table B-1. Gravitational Parameters for Orbits About Major Solar System Bodies. (Continued)

Object	μ = GM (m^3/s^2)	Orbital Velocity (km/s)	Orbit Period (min)	Escape Velocity (km/s)
Enceladus	7.21×10^9	0.1675	160.6939	0.2369
Tethys	4.14×10^{10}	0.2767	204.3403	0.3914
Dione	7.32×10^{10}	0.3610	163.0431	0.5105
Rhea	1.540×10^{11}	0.4490	178.1778	0.6350
Titan	8.977×10^{12}	1.8671	144.4226	2.6405
Hyperion	3.79×10^8	0.0481	357.0610	0.0680
Iapetus	1.2054×10^{11}	0.4047	190.4516	0.5723
Phoebe	2.7×10^7	0.016	739.5	0.022
Janus	1.2608×10^8	0.0360	283.4979	0.0509
Epimetheus	3.6×10^7	0.023	316.2	0.032
Helene	1.3×10^6	0.009	218.9	0.012
Telesto	7.7×10^5	0.007	218.9	0.010
Calypso	7.7×10^5	0.007	218.9	0.010
Atlas	1.45×10^6	0.009	218.9	0.013
Prometheus	9.34×10^6	0.011	689.7	0.016
Pandora	8.67×10^6	0.013	458.6	0.018
Pan	2.3×10^5	0.005	218.9	0.007
Uranus	$5.794\,5490 \times 10^{15}$	15.0570	177.7602	21.2938
Ariel	9.0×10^{10}	0.3944	154.2484	0.5578
Umbriel	7.8×10^{10}	0.3657	167.5273	0.5171
Titania	2.35×10^{11}	0.5461	151.3113	0.7722
Oberon	2.01×10^{11}	0.5140	155.0355	0.7269
Miranda	4.64×10^9	0.1390	180.8384	0.1965
Cordella	9.2×10^5	0.008	161.5	0.012
Ophelia	1.4×10^6	0.010	161.5	0.014
Bianca	3.9×10^6	0.014	161.5	0.019
Cressida	1.3×10^7	0.020	161.5	0.028
Desdemona	8.3×10^6	0.018	161.5	0.025
Juliet	3.1×10^7	0.027	161.5	0.039
Portia	1.11×10^8	0.0399	183.8718	0.0564
Rosalind	8.3×10^6	0.018	161.5	0.025
Belinda	1.5×10^7	0.021	161.5	0.030
Puck	1.93×10^8	0.0488	173.7898	0.0690
Caliban	1.1×10^7	0.019	161.5	0.028
Sycorax	3.59×10^8	0.0614	161.9045	0.0869
Neptune	$6.836\,527 \times 10^{15}$	16.6153	156.0781	23.4975
Triton	1.428×10^{12}	1.0274	137.9076	1.4530
Nereid	2.06×10^9	0.1100	161.8084	0.1556
Naiad	1.0×10^7	0.019	160.8	0.027
Thalassa	2.7×10^7	0.026	160.8	0.037
Despina	1.40×10^8	0.0432	181.6878	0.0611
Galatea	2.50×10^8	0.0533	172.8201	0.0754
Larissa	3.30×10^8	0.0583	174.0984	0.0825
Proteus	3.359×10^9	0.1265	173.8690	0.1789
Pluto	9.7178×10^{11}	0.9018	138.7701	1.2753
Charon	1.132×10^{11}	0.4322	146.8216	0.6113
ASTEROIDS LARGER THAN 300 KM DIAMETER				
Ceres	6.264×10^{10}	0.3585	142.3300	0.5070
Pallas	1.367×10^{10}	0.1533	397.6845	0.2167
Vesta	1.792×10^{10}	0.1761	343.7935	0.2490

B.2 Planetary and Natural Satellite Data

See website for Natural Satellite Data.

Table B-2. Orbit Data for the Planets. Orbit elements are defined with respect to the mean ecliptic and equinox of J2000.0 (epoch JD 2,451,545.0). Data from Seidelmann [2006].

Planet	Eccentricity	Mean Distance (AU)	Tropical Period (Julian years)	Synodic Period (*d*)	Mean Daily Motion, *n* (deg)	Orbital Velocity (km/s)
Mercury	0.205 630 69	0.387 098 93	0.240 844 45	115.877 5	4.092 377 06	47.872 5
Venus	0.006 773 23	0.723 321 99	0.615 182 57	583.921 4	1.602 168 74	35.021 4
Earth	0.016 710 22	1.000 000 11	0.999 978 62		0.985 647 36	29.785 9
Mars	0.093 412 33	1.523 662 31	1.880 711 05	779.936 1	0.524 071 09	24.130 9
Jupiter	0.048 392 66	5.203 363 01	11.856 525 02	398.8840	0.083 129 44	13.069 7
Saturn	0.054 150 60	9.537 070 32	29.423 519 35	378.091 9	0.033 497 91	9.672 4
Uranus	0.047 167 71	19.191 263 93	83.747 406 82	369.6560	0.011 769 04	6.835 2
Neptune	0.008 585 87	30.068 963 48	163.723 204 5	367.486 7	0.006 020 076	5.477 8
Pluto	0.248 807 66	39.481 686 77	248.020 8	366.720 7	0.003 973 966	4.7490

Table B-3. Orbit Data for the Planets. Data from Seidelmann [2006] and Astronomical Almanac [1998].

Planet	Inclination to Ecliptic (deg)	Longitude of Ascending Node (deg)	Longitude of Perihelion (deg)	Planet Longitude on Jan. 1.5 2000 (deg)	Last Perihelion before 2000
Mercury	7.004 87	48.331 67	77.456 45	252.250 84	1999 Nov. 19
Venus	3.394 71	76.680 69	131.532 98	181.979 73	1999 Dec. 1
Earth	0.000 05	–11.260 64	102.947 19	100.464 35	1999 Jan. 3
Mars	1.850 61	49.578 54	336.040 84	355.453 32	1999 Nov. 25
Jupiter	1.305 30	100.556 15	14.753 85	34.404 38	1999 May 20
Saturn	2.484 46	113.715 04	92.431 94	49.944 32	1974 Jan. 8
Uranus	0.769 86	74.229 68	170.964 24	313.232 18	1966 May 20
Neptune	1.769 17	131.721 69	44.971 35	304.880 03	1876 Sept. 2
Pluto	17.141 75	110.303 47	224.066 76	238.928 81	1989 Sept. 5

Table B-4. Physical Data for the Planets. Data from Astronomical Almanac [2010] and Seidelmann [2006].

Planet	Mass[1] (10^{24} kg)	Radius[2] (km)	Flattening[3] (geometric)	Mean Density (g/cm^3)	J_2 ($\times 10^3$)	Sidereal Rotation Period[4] (d)	Incl. of Equator to Orbit (deg)
Mercury	0.330 22	2,439.7	0	5.43		58.6462	0
Venus	4.8690	6,051.8	0	5.24	0.027	–243.0185	177.3
Earth	5.9722	6,378.1366	0.003 353 64	5.515	1.082 6359	0.997 269 63	23.45
Mars	0.641 91	3,396.19	0.006 772	3.94	1.964	1.02 595 676	25.19
Jupiter	1898.8	71,492	0.064 874	1.33	14.75	0.413 54	3.12
Saturn	568.52	60,268	0.097 962	0.69	16.45	0.444 01	26.73
Uranus	86.840	25,559	0.022 927	1.27	12	–0.718 33	97.86
Neptune	102.45	24,764	0.017 081	1.64	4	0.671 25	29.56
Pluto	0.013	1,195	0	1.8		–6.3872	118

Notes for Table B-4:
- The values for the masses include the atmospheres but exclude the satellites.
- The mean equatorial radii are given.
- The flattening is the ratio of the difference of the equatorial and polar radii to the equatorial radius.
- The sidereal rotation period refers to the rotation at the equator with respect to a fixed frame of reference: a negative sign indicates that the rotation is retrograde with respect to the pole that lies to the north of the invariable plane of the solar system. The period is given in days of 86,400 SI seconds.
- The data on the equator, flattening (ellipticity), and sidereal rotation period are based on Seidelmann et al. [2007].

Table Bweb-1. Photometric Data for the Planets. So, Cl = Solid, cloud; for lowest visible surface. Data from Cox [2000].

Planet	Geometric Albedo	Visual Magnitude $V(1,0)$	Visual Magnitude V_0	Effective Temperature (K)	Visible Surface
Mercury	0.106	–0.42	–0.2	—	So
Venus	0.650	–4.40	–4.22	~230	Cl
Earth	0.367	–3.86	—	~255	So, Cl
Mars	0.150	–1.52	–2.01	~212	So
Jupiter	0.520	–9.40	–2.70	124.4 ±0.3	Cl
Saturn	0.470	–8.88	0.67†	95.0 ±0.4	Cl
Uranus	0.510	–7.19	5.52	59.1 ±0.3	Cl
Neptune	0.410	–6.87	7.84	59.3 ±0.8	Cl
Pluto	variable*	–0.81	15.12	50–70	So

* The Pluto visual geometric albedo is variable by 30%. The Pluto color is the combination of the planet and its satellite Charon.
† *V* referts to the Saturn disk only.

Notes for Table Bweb-1:

- The geometric albedo is the ratio of the illumination at the Earth from the planet for phase angle zero to the illumination produced by a plane, absolutely white Lambert surface of the same radius as the planet placed at the same position. This is not to be confused with a planet's bond albedo which is simply the ratio of total reflected light to total incident light. (See Sec. 11.6 in OCDM by Wertz [2009])
- $V(1,0)$ is the visual magnitude when the observer is directly between the Sun and the planet and the product of the Sun-planet distance (in AU) is 1. (See Sec. 11.6 in OCDM by Wertz [2009])
- V_0 is the mean visual magnitude of the planet when at opposition as viewed from the Earth. Magnitudes for Mercury and Venus are at greatest elongation. (See Sec. 11.6 in OCDM by Wertz [2009])

Table Bweb-2. Natural Satellites: Orbit Data. See Table B-1 for gravitational Data.

Sat. #	Satellite Name	Orbital Period[1] [R=Retrograde] (*d*)	Semimajor Axis ($\times 10^3$ km)	Orbit Eccentricity	Orbit Incl. to Planetary Equator (deg)	Motion of Node on Fixed Plane[4] (deg/yr)
			EARTH			
	Moon	27.321 661	384.4	0.054 900 489	18.28–28.58	19.346[6]
			MARS			
I	***Phobos***	0.318 910 23	9.378	0.015	1	158.8
II	***Deimos***	1.262 440 7	23.459	0.000 5	0.9–2.7	6.614
			JUPITER			
I	***Io***	1.769 137 786	422	0.004	0.04	48.6
II	***Europa***	3.551181041	671	0.009	0.47	12
III	***Ganymede***	7.154 552 96	1070	0.002	0.21	2.63
IV	***Callisto***	16.689 018 4	1883	0.007	0.51	0.643
V	***Amalthea***	0.498 179 05	181	0.003	0.4	914.6
VI	***Himalia***	250.566 2	11480	0.157 98	27.63	
VII	***Elara***	259.652 8	11737	0.207 19	24.77	
VIII	***Pasiphae***	735 **R**	23500	0.378	145	
IX	***Sinope***	758 **R**	23700	0.275	153	
X	***Lysithea***	259.22	11720	0.107	29.02	
XI	***Carme***	692 **R**	22600	0.206 78	164	
XII	***Ananke***	631 **R**	21200	0.168 7	147	
XIII	***Leda***	238.72	11094	0.147 62	26.07	
XIV	***Thebe***	0.674 5	222	0.015	0.8	
XV	***Adrastea***	0.298 26	129			
XVI	***Metis***	0.294 78	128			

Table Bweb-2. Natural Satellites: Orbit Data. See Table B-1 for gravitational Data. (Continued)

Sat. #	Satellite Name	Orbital Period[1] [R=Retrograde] (*d*)	Semimajor Axis ($\times 10^3$ km)	Orbit Eccentricity	Orbit Incl. to Planetary Equator (deg)	Motion of Node on Fixed Plane[4] (deg/yr)
	SATURN					
I	***Mimas***	0.942 421 813	185.52	0.020 2	1.53	365
II	***Enceladus***	1.370 217 855	238.02	0.004 52	0	156.2[5]
III	***Tethys***	1.887 802 16	294.66	0	1.86	72.2[5]
IV	***Dione***	2.736 914 742	377.4	0.002 23	0.02	30.85[5]
V	***Rhea***	4.517 500 436	527.04	0.001	0.35	10.16
VI	***Titan***	15.945 420 68	1221.83	0.029 192	0.33	0.521 3[5]
VII	***Hyperion***	21.276 608 8	1481.1	0.104	0.43	
VIII	***Iapetus***	79.330 182 5	3561.3	0.028 28	14.72	
IX	***Phoebe***	550.48 **R**	12952	0.163 26	177[2]	
X	***Janus***	0.694 5	151.472	0.007	0.14	
XI	***Epimethus***	0.694 2	151.422	0.009	0.34	
XII	***Helene***	2.736 9	377.4	0.005	0	
XIII	***Telesto***	1.887 8	294.66			
XIV	***Calypso***	1.887 8	294.66			
XV	***Atlas***	0.601 9	137.67	0	0.3	
XVI	***Prometheus***	0.613	139.353	0.003	0	
XVII	***Pandora***	0.628 5	141.7	0.004	0	
XVIII	***Pan***	0.575	133.583			
	URANUS					
I	***Ariel***	2.52037935	191.02	0.003 4	0.30	6.8
II	***Umbriel***	4.1441772	266.30	0.005	0.36	3.6
III	***Titania***	8.7058717	435.91	0.002 2	0.14	2.0
IV	***Oberon***	13.4632389	583.52	0.000 8	0.10	1.4
V	***Miranda***	1.41347925	129.39	0.002 7	4.20	19.8
VI	***Cordelia***	0.335 033 8	49.77	0.000 26	0.08	550
VII	***Ophelia***	0.376 400	53.79	0.009 9	0.10	419
VIII	***Bianca***	0.434 579 9	59.17	0.000 9	0.19	229
IX	***Cressida***	0.463 569 60	61.78	0.000 4	0.01	257
X	***Desdemona***	0.473 699 60	62.68	0.000 13	0.11	245
XI	***Juliet***	0.493 065 49	64.35	0.000 66	0.07	223
XII	***Portia***	0.513 195 92	66.09	0.001	0.10	203
XIII	***Rosalind***	0.558 459 53	69.94	0.001	0.30	129
XIV	***Belinda***	0.623 527 47	75.26	0.001	0.00	167
XV	***Puck***	0.761 832 87	86.01	0.001	0.31	81
XVI	***Caliban***	579 **R**	7169.00	0.082	139.20	
XVII	***Sycorax***	1,289 **R**	12,214.00	0.509	152.70	
	NEPTUNE					
I	***Triton***	5.876 854 1 **R**	354.76	0.000016	157.345	0.5232
II	***Nereid***	360.136 19	5,513.40	0.7512	27.6[3]	0.039
III	***Naiad***	0.2943 96	48.23	0.0	4.74	626
IV	***Thalassa***	0.311 485	50.07	0.0	0.21	551
V	***Despina***	0.334 655	52.53	0.0	0.07	466
VI	***Galatea***	0.428 745	61.95	0.0	0.05	261
VII	***Larissa***	0.554 654	73.55	0.001 39	0.2	143
VIII	***Proteus***	1.122 315	117.65	0.000 4	0.55	0.5232
	PLUTO					
I	***Charon***	6.38725	19.6	0.001	96.16	

Table Bweb-3. Natural Satellites: Physical and Photometric Data.

Sat. #	Satellite Name	Mass (1/planet)	Radius (km)	Sidereal Period[1] (*d*)	Visual Mag. [*V* (1,0)]	Geo-metric Albedo[9]
			EARTH			
	Moon	0.012 300 034	1737.4	S	+0.21	0.12
			MARS			
I	***Phobos***	1.654×10^{-8}	$13.4 \times 16.2 \times 9.2$	S	+11.8	0.07
II	***Deimos***	3.71×10^{-9}	$7.5 \times 6.1 \times 5.2$	S	+12.89	0.08
			JUPITER			
I	***Io***	$4.704\,1 \times 10^{-5}$	$1830 \times 1818.7 \times 1815.3$	S	–1.68	0.63
II	***Europa***	$2.528\,0 \times 10^{-5}$	1565	S	–1.41	0.67
III	***Ganymede***	$7.804\,6 \times 10^{-5}$	2634	S	–2.09	0.44
IV	***Callisto***	$5.666\,7 \times 10^{-5}$	2403	S	–1.05	0.20
V	***Amalthea***	38×10^{-10}	$131 \times 73 \times 67$	S	+7.4	0.07
VI	***Himalia***	50×10^{-10}	85	0.4	+8.14	0.03
VII	***Elara***	4×10^{-10}	40	0.5	+10.07	0.03
VIII	***Pasiphae***	1×10^{-10}	18		+10.33	0.1
IX	***Sinope***	0.4×10^{-10}	14		+11.6	0.05
X	***Lysithea***	0.4×10^{-10}	12		+11.7	0.06
XI	***Carme***	0.5×10^{-10}	15		+11.3	0.06
XII	***Ananke***	0.2×10^{-10}	10		+12.2	0.06
XIII	***Leda***	0.03×10^{-10}	5		+13.5	0.07
XIV	***Thebe***	4×10^{-10}	55×45	S	+9.0	0.04
XV	***Adrastea***	0.1×10^{-10}	$13 \times 10 \times 8$		+12.4	0.05
XVI	***Metis***	0.5×10^{-10}	20×20		+10.8	0.05
			SATURN			
I	***Mimas***	6.6×10^{-8}	$209.1 \times 196.2 \times 191.4$	S	+3.3	0.5
II	***Enceladus***	1.0×10^{-7}	$256.3 \times 247.3 \times 244.6$	S	+2.1	1.0
III	***Tethys***	1.10×10^{-6}	$209.1 \times 196.2 \times 191.4$	S	+0.6	0.9
IV	***Dione***	1.95×10^{-6}	560	S	+0.8	0.7
V	***Rhea***	4.06×10^{-6}	764	S	+0.1	0.7
VI	***Titan***	$2.366\,7 \times 10^{-4}$	2575	S	–1.28	0.22
VII	***Hyperion***	4.0×10^{-8}	$180 \times 140 \times 112.5$		+4.63	0.3
VIII	***Iapetus***	2.8×10^{-6}	718	S	+1.5	(0.2)[2]
IX	***Phoebe***	7×10^{-10}	110	0.4	+6.89	0.06
X	***Janus***	3.385×10^{-9}	$97.0 \times 95.0 \times 77.0$	S	+4.4	0.9
XI	***Epimethus***	9.5×10^{-10}	$69 \times 55 \times 55$	S	+5.4	0.8
XII	***Helene***		$18 \times 16 \times 15$		+8.4	0.7
XIII	***Telesto***		$15 \times 12.5 \times 7.5$		+8.9	1.0
XIV	***Calypso***		$15.0 \times 8.0 \times 8.0$		+9.1	1.0
XV	***Atlas***		$18.5 \times 17.2 \times 13.5$		+8.4	0.8
XVI	***Prometheus***		$74.0 \times 50.0 \times 34.0$		+6.4	0.5
XVII	***Pandora***		$55.0 \times 44.0 \times 31.0$		+6.4	0.7
XVIII	***Pan***		10			0.5
In 2000, 12 new, small satellites of Saturn were discovered. All are less than 15 km in radius. It is likely that the Cassini spacecraft will discover more.						
			URANUS			
I	***Ariel***	1.56×10^{-5}	$581.1 \times 577.9 \times 577.7$	S	+1.45	0.35
II	***Umbriel***	1.35×10^{-5}	584.7	S	+2.10	0.19
III	***Titania***	4.06×10^{-5}	788.9	S	+1.02	0.28
IV	***Oberon***	3.47×10^{-5}	761.4	S	+1.23	0.25
V	***Miranda***	0.08×10^{-5}	$240.4 \times 234.2 \times 232.9$	S	+3.6	0.27
VI	***Cordelia***		13		+11.4	0.07
VII	***Ophelia***		15		+11.1	0.07
VIII	***Bianca***		21		+10.3	0.07
IX	***Cressida***		31		+9.5	0.07
X	***Desdemona***		27		+9.8	0.07
XI	***Juliet***		42		+8.8	0.07

Table Bweb-3. Natural Satellites: Physical and Photometric Data. (Continued)

Sat. #	Satellite Name	Mass (1/planet)	Radius (km)	Sidereal Period[1] (*d*)	Visual Mag. [*V* (1,0)]	Geo-metric Albedo[9]
XII	***Portia***		54		+8.3	0.07
XIII	***Rosalind***		27		+9.8	0.07
XIV	***Belinda***		33		+9.4	0.07
XV	***Puck***		77		+7.5	0.075
XVI	***Caliban***		30			0.07
XVII	***Sycorax***		60			0.07
			NEPTUNE			
I	***Triton***	2.089×10^{-4}	1353	S	–1.24	0.77
II	***Nereid***	2×10^{-7}	170		+4.0	0.4
III	***Naiad***		29		+10.0	0.06
IV	***Thalassa***		40		+9.1	0.06
V	***Despina***		74		+7.9	0.06
VI	***Galatea***		79		+7.6	0.06
VII	***Larissa***		104×89		+7.3	0.06
VIII	***Proteus***		$218 \times 208 \times 201$		+5.6	0.06
			PLUTO			
I	***Charon***	0.125	593	S	+0.9	0.5

Notes for Tables Bweb-2 and Bweb-3:
- Sidereal periods, except that tropical periods are given for satellites of Saturn.
- Relative to the ecliptic plane.
- Referred to the equator of 1950.0.
- Rate of decrease (or increase) in the longitude of the ascending node.
- Rate of increase in the longitude of the apside.
- On the ecliptic plane.
- *S* = synchronous, rotation period same as orbital period.
- Bright side, 0.5; faint side, 0.05.
- *V* (Sun) = –26.75.

B.3 Physical Properties of the Sun

Table B-5. Physical Properties of the Sun. Data from Cox [2000] and Astronomical Almanac [2010].

Radius of the photosphere	$6.960\,00 \times 10^{5}$ km
Angular diameter of the photosphere at 1 AU	0.533 13 deg
Mass	1.9884×10^{30} kg
Mean density	1.409 g/cm^3
Gravity at surface	2.740×10^{4} cm/sec^2
Moment of inertia	5.7×10^{53} g cm^2
Angular rotation velocity at equator	2.85×10^{-6} rad/sec
Angular momentum (based on surface rotation)	1.63×10^{48} g cm^2 /sec
Escape velocity at solar surface	6.177×10^{7} g cm/sec
Total radiation emitted	3.845×10^{26} W
Total radiation per unit area at 1 AU (solar constant)*	1,366 W/m^2
Apparent visual magnitude at 1 AU	–26.75
Absolute visual magnitude (magnitude at distance of 10 parsecs)	+4.82
Color index, B-V	+0.65
Spectral type	G2 V
Effective temperature	5777 K
Inclination of the equator to the ecliptic	7.25 deg
Adopted period of sidereal rotation	25.38 days
Corresponding synodic rotation period (relative to Earth)	27.2753 days
Oblateness: semidiameter equator-pole difference	0."0086
Velocity relative to nearby stars	19.7 km sec

* The World Radiation Center in Switzerland has taken the data from a number of satellites and created a consensus on the solar constant. The World Radiation Center is the official international keeper of the solar constant. The value of the constant has a variation of –0.5 W/m^2 at solar min and +0.5 W/m^2 at solar max [World Radiation Center, 2006].

Table Bweb-4. Sunspot Cycles, Maxima, and Minima.

Sunspot Cycle Number	Year of Minimum	Smallest Smoothed Monthly Mean	Year of Maximum*	Largest Smoothed Monthly Mean†	Rise to Max (Years)	Fall to Min (Years)	Cycle Length (Years)
–12	1610.8	—	1615.5	—	4.7	3.5	8.2
–11	1619.0	—	1626.0	—	7.0	8.0	10.5
–10	1634.0	—	1639.5	—	5.5	5.5	13.5
–9	1645.0	—	1649.0	—	4.0	6.0	9.5
–8	1655.0	—	1660.0	—	5.0	6.0	11.0
–7	1666.0	—	1675.0	—	9.0	4.5	15.0
–6	1679.5	—	1685.0	—	5.5	4.5	10.0
–5	1689.5	—	1693.0	—	3.5	5.0	8.0
–4	1698.0	—	1705.5	—	7.5	6.5	12.5
–3	1712.0	—	1718.2	—	6.2	5.3	12.7
–2	1723.5	—	1727.5	—	4.0	6.5	9.3
–1	1734.0	—	1738.7	—	4.7	6.3	11.2
0	1745	—	1750.3	92.6	5.3	4.9	11.6
1	1755.3	8.4	1761.5	86.5	6.2	5.0	11.1
2	1766.5	11.2	1769.8	115.8	3.3	5.7	8.3
3	1775.5	7.2	1778.4	158.5	2.9	6.4	8.6
4	1784.8	9.5	1788.2	141.2	3.4	10.2	9.8
5	1798.4	3.2	1805.2	49.2	6.8	5.5	17.0
6	1810.7	0.0	1816.3	48.7	5.6	7.1	11.1
7	1823.4	0.1	1829.9	71.7	6.5	4.0	13.6
8	1833.9	7.3	1837.3	146.9	3.4	6.3	7.4
9	1843.6	10.5	1848.2	131.6	4.6	7.8	10.9
10	1856.0	3.2	1860.2	97.9	4.2	7.1	12.0
11	1867.3	5.2	1870.7	140.5	3.4	8.3	10.5
12	1879.0	2.2	1883.9	74.6	5.0	6.3	13.3
13	1890.3	5.0	1894.1	87.9	3.8	8.0	10.1
14	1902.1	2.6	1906.2	64.2	4.1	7.5	12.1
15	1913.7	1.5	1917.7	105.4	4.0	6.0	11.5
16	1923.7	5.6	1928.3	78.1	4.6	5.5	10.6
17	1933.8	3.4	1937.3	119.2	3.5	6.9	9.0
18	1944.2	7.7	1947.4	151.8	3.2	6.9	10.1
19	1954.3	3.4	1958.3	201.3	4.0	6.5	10.9
20	1964.8	9.6	1968.9	110.6	4.1	7.6	10.6
21	1976.5	12.2	1980.0	164.5	3.5	6.8	11.1
22	1986.8	12.3	1989.6	158.5	2.8	7.2	9.6
23	1996.8	5	2000.6	170.1	3.8	—	11.0
Mean Cycle		**6**		**112.9**	**4.7**	**6.3**	**10.9**

* When observations permit, a date selected as either a cycle minimum or maximum is based in part on an average of the times extremes are reached in the monthly mean sunspot number, in the smoothed monthly mean sunspot number, and in the monthly mean number of spot groups alone. Two more measures are used at time of sunspot minimum: the number of spotless days and the frequency of occurrence of "old" and "new" cycle spot groups.

† The smoothed monthly mean sunspot number is defined here as the arithmetic average of two sequential 12-month running means of monthly mean numbers.

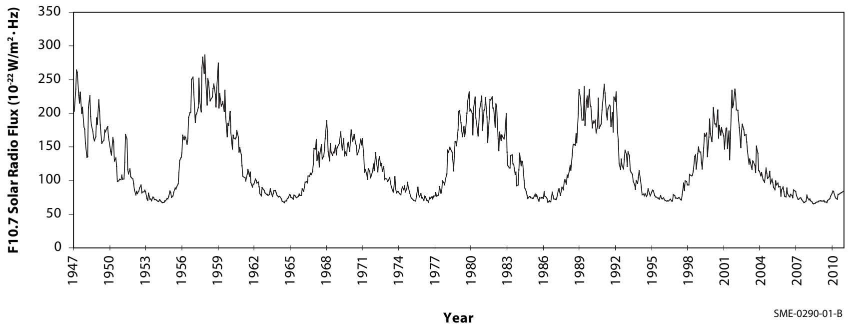

Fig. B-1. Historical Monthly 10.7 cm Radio Flux from the Sun (F10.7 Index) Since January 1947. For daily variations, see Fig. 9-16 in Sec. 9.4.4. (Plot courtesy Dave Bouwer, Space Environment Technologies)

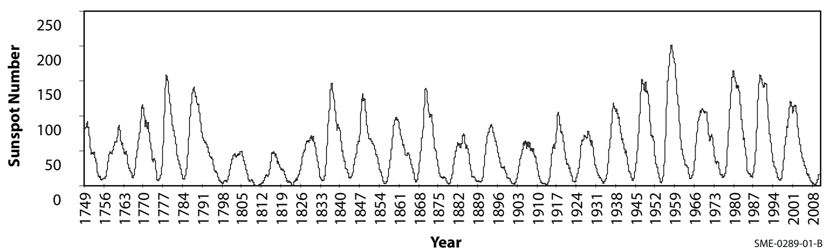

Fig. B-2. Historical Smoothed Sunspot Values from the 18th Century to Present. (Plot courtesy Dave Bouwer, Space Environment Technologies)

B.4 Physical and Orbit Properties of the Earth

Table B-6. Physical and Orbit Properties of the Earth.

		Reference
Equatorial radius, *a*	6,378.1366 km	IAU [2009]
Flattening factor (ellipticity), $f \equiv (a - c)/a$	1/298.256 42 ≈ 0.003 352 820	Astronomical Almanac [2010]
Polar radius,* *c*	$6.356\,752 \times 10^6$ m	
Mean radius,* $(a^2 c)^{1/3}$	6,371.0004 km	
Eccentricity,* $(a^2 - c^2)^{1/2}/a$	0.081 819 301	
Surface area	$5.100\,657 \times 10^8$ km^2	Cox [2000]
Volume	$1.083\,207 \times 10^{12}$ km^3	Cox [2000]
Ellipticity of the equator $(a_{max} - a_{min})/a_{mean}$	~ 1.1×10^{-5}	Groten [2000]
Longitude of the maxima	15° W, 165°E	Groten [2000]
Ratio of the mass of the Sun to the mass of the Earth	332 946.0487	IAU [2009]
Geocentric gravitational constant, $GM_E \equiv \mu_E$	$3.986\,004\,356 \times 10^{14}$ m^3/ s^2	IAU [2009]
Mass of the Earth	5.9722×10^{24} kg	Astronomical Almanac [2010]
Mean density	5.515 g/cm^3	Astronomical Almanac [2010]
Gravitational field constants (See Eq. (9-23) in Sec. 9.4.1.)	$J_2 = +1.082\,63 \times 10^{-3}$	Astronomical Almanac [2010]
	$J_3 = -2.64 \times 10^{-6}$	Astronomical Almanac [2010]
	$J_4 = -1.61 \times 10^{-6}$	Astronomical Almanac [2010]
Mean distance of Earth center from Earth-Moon barycenter	4,671 km	Seidelmann [2006]
Average lengthening of the day (See Fig. B-3)	0.0015 sec/century	Seidelmann [2006]
General precession in longitude (i.e., precession of the equinoxes) per Julian century at epoch J2000	1.396 887 83 deg/century	Astronomical Almanac [2010]
Rate of change of precession at epoch J2000	$+6.184 \times 10^{-4}$ deg/century^2	Wertz [2009]
Rate of change of the obliquity at epoch J2000	$-1.301\,021 \times 10^{-2}$ deg/Julian Century	Astronomical Almanac [2010]
Amplitude of the Earth's nutation	$2.557\,01 \times 10^{-3}$ deg	Astronomical Almanac [2010]
Sidereal period of rotation, epoch J2000	0.997 269 68 d= 86 164.090 53 s = 23h56m4.09053 s	Astronomical Almanac [2010]
Length of tropical year (ref. = ♈), epoch J2000	$3.155\,692\,522 \times 10^7$ s = 365.242 190 d	Astronomical Almanac [2010]
Length of sidereal year (ref. = fixed stars), epoch J2000	$3.155\,8150 \times 10^7$ s = 365.256 36 d	Cox [2000]
Length of anomalistic year (perihelion to perihelion), epoch J2000	$3.155\,843\,255 \times 10^7$ s = 365.259 636 d	Astronomical Almanac [2010]

* Based on adopted values of *f* and *a*.

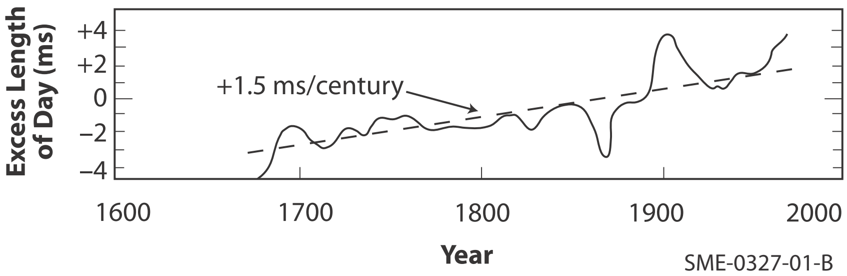

Fig. B-3. Variations in the Length of Day. On average, the Earth is slowing down by 1.5 ms/century, but local variations are large and very difficult to model.

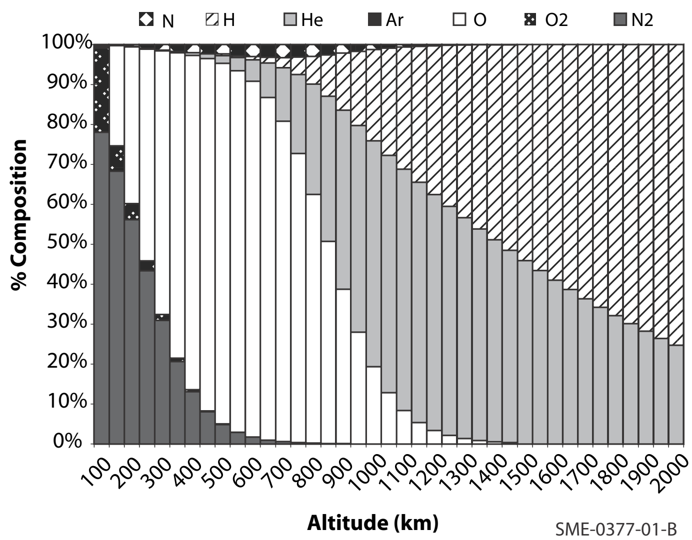

Fig. B-4. Mass Spectrometer Incoherent Scatter (MSIS) Atmospheric Species Percentage Composition vs. Altitude. [Hedin, 1987]. For atmospheric density, see Fig. 9-17 in Sec. 9.4.4.

Table B-7. Atmospheric Layers and Transitions. Data from Cox [2000].

Layer	Height, *h* (km)	Characteristics
Troposphere	0–11	Weather, *T* decreases with *h*, radiative-convective equilibrium
Tropopause	11	Temperature minimum, limit of upward mixing of heat
Stratosphere	11–48	*T* increases with *h* due to absorption of solar UV by O_3, dry
Stratopause	48	Maximum heating due to absorption of solar UV by O_3
Mesophere	48–85	*T* decreases with *h*
Mesopause	85	Coldest part of atmosphere, noctilucent clouds
Thermosphere	85–exobase	*T* increases with *h*, solar cycle and geomagnetic variations
Exobase	500–1000 km	
Exosphere	> exobase	Region of Rayleigh-Jeans escape
Ozonosphere	15–35 km	Ozone layer (full width at e^{-1} of maximum)
Ionosphere	> 70 km	Ionized layers
Homosphere	< 85 km	Major constituents well-mixed
Heterosphere	> 85 km	Constituents diffusively separate

Table Bweb-5. Atmospheric Layers and Transitions. P = pressure, T = temperature, ρ = mass density, N = number density, H = scale height, and I = mean free path. Data from U.S. Standard Atmosphere. [COESA, 1976]. See also tables inside the rear cover for additional atmospheric data and related orbit decay parameters.

Altitude	log P (Pa)	T (K)	log ρ (kg m^{-3})	log N (m^{-3})	H (km)	log I (m)
0	+5.006	288	+0.088 1	25.41	8.4	–7.2
1	+4.95	282	+0.046 0	25.36	8.3	–7.1
2	+4.90	275	+0.002 86	25.32	8.1	–7.1
3	+4.85	269	–0.041 3	25.28	7.9	–7.0
4	+4.79	262	–0.087	25.23	7.7	–7.0
5	+4.73	256	–0.133	25.19	7.5	–7.0
6	+4.67	249	–0.180	25.14	7.3	–6.9
8	+4.55	236	–0.279	25.04	6.9	–6.8
10	+4.42	223	–0.384	24.93	6.6	–6.7
15	+4.08	217	–0.71	24.61	6.4	–6.4
20	+3.74	217	–1.05	24.27	6.4	–6.0
30	+3.08	227	–1.73	23.58	6.7	–5.4
40	+2.46	250	–2.40	22.92	7.4	–4.7
50	+1.90	271	–2.99	22.33	8.0	–4.1
60	+1.34	247	–3.51	21.81	7.4	–3.6
70	+0.72	220	–4.08	21.24	6.6	–3.0
80	+0.022	199	–4.73	20.58	6.0	–2.4
90	–0.74	187	–5.47	19.85	5.6	–1.6
100	–1.49	195	–6.25	19.08	6.0	–0.85
110	–2.15	240	–7.01	18.33	7.7	–0.10
120	–2.60	360	–7.65	17.71	12.1	+0.52
150	–3.34	634	–8.68	16.71	23.0	+1.52
220	–4.07	855	–9.59	15.86	36.0	+2.38
250	–4.61	941	–10.22	15.28	45.0	+2.95
300	–5.06	976	–10.72	14.81	51.0	+3.41
400	–5.84	996	–11.55	14.02	60.0	+3.80
500	–6.52	999	–12.28	13.34	69.0	+4.89
700	–7.50	1000	–13.51	12.36	131.0	+5.86
1000	–8.12	1000	–14.45	11.74	288.0	+6.49

B.4.1 Geocentric and Geodetic Coordinates on the Earth

The *geocentric latitude*, ϕ', of a point, P, on the surface of the Earth is the angle at the Earth's center between P and the equatorial plane. The *geodetic* or *geographic latitude*, ϕ, is the angle between the normal to an arbitrarily defined reference ellipsoid (chosen as a close approximation to the oblate Earth) and the equatorial plane. *Astronomical latitude* and longitude are defined relative to the *local vertical*, or the normal to the equipotential surface of the Earth. Thus, *astronomical latitude* is defined as the angle between the local vertical and the Earth's equatorial plane. Maximum values of the *deviation of the vertical*, or the angle between the local vertical and the normal to a reference ellipsoid, are about 1 minute of arc. Maximum variations in the height between the reference ellipsoid and *mean sea level* (also called the *equipotential surface*) are about 100 m.

The shape of the reference ellipsoid is most commonly defined by the *ellipticity* or *flattening factor*, $f \equiv (a - b)/a \approx 1/298.256\ 42 \approx 0.003\ 352\ 820$, where a is the equatorial radius of the Earth and b is the polar radius. Also used is the eccentricity of the reference ellipsoid, $e \equiv (a^2 - b^2)^{1/2}/a \approx 0.081\ 819\ 301$. These are related by:

$$e \equiv \sqrt{f(2-f)} \tag{B-1}$$

$$f = 1 - \sqrt{1-e^2} \tag{B-2}$$

On the surface of the Earth, the geodetic and geocentric latitude are related by:

$$\tan\phi = \tan\phi' / (1-f)^2 = 1.006\ 739\ 515\ \tan\phi' \tag{B-3}$$

where f is the flattening factor. At satellite altitudes the computation is more complex. As shown in Fig. B-5, the line normal to the oblate Earth through the satellite does not go through the Earth's center.

Geocentric coordinates are commonly expressed as Cartesian coordinates, (x, y, z). We then define the geocentric

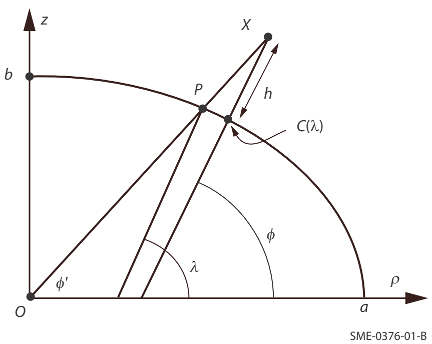

Fig. B-5. Relationship Between Geocentric Latitude, ϕ', and Geodetic Latitude, ϕ.

latitude, ϕ', and the radius in the equatorial plane, ρ, by:

$$\rho \equiv \sqrt{x^2 + y^2} \quad \text{(B-4)}$$

$$\tan\phi' \equiv z / \rho \quad \text{(B-5)}$$

Given the geodetic coordinates, ϕ and h, as defined in Fig. B-5, we can immediately determine the geocentric coordinates from:

$$\rho = \left(N_\phi + h\right)\cos\phi \quad \text{(B-6)}$$

$$z = \left[\left(1 - e^2\right)N_\phi + h\right]\sin\phi \quad \text{(B-7)}$$

where the radius of curvature of the ellipse, N_ϕ, is given by:

$$N_\phi = \frac{a}{\sqrt{1 - e^2 \sin^2\phi}} \quad \text{(B-8)}$$

Determining the geodetic coordinates from the geocentric coordinates is more complex and requires an iterative technique. The approach used here is that of Nievergelt and Keeler [2000], which includes references to a number of earlier, less satisfactory methods. With a single iteration, this approach is good to 2×10^{-6} deg for the geodetic latitude and 1 mm in geodetic altitude. Successive iterations can improve this, although that would rarely be needed. The 4-step iterative approach is as follows:

Step 1

Set the iteration counter, $n = 0$. Compute $\rho \equiv \sqrt{x^2 + y^2}$ and the initial altitude estimate:

$$h_0 = \left[1 - 1/\sqrt{(\rho/a)^2 + (z/b)^2}\right]\sqrt{\rho^2 + z^2} \quad \text{(B-9)}$$

Step 2

Compute the cosine, $u_0 = \cos(\lambda)$, and sine, $v_0 = \sin(\lambda)$, of the initial latitude estimate $\phi_0 = \lambda$ and the initial value of the intermediate variable, w_0:

$$u_0 = \frac{\sigma^2 \rho}{\sqrt{\sigma^4 \rho^2 + z^2}}, \; v_0 = \frac{z}{\sqrt{\sigma^4 \rho^2 + z^2}}, \quad \text{(B-10)}$$

$$w_0 = \sqrt{1 - e^2 v_0^2}$$

where

$$\sigma \equiv b / a \quad \text{(B-11)}$$

Step 3

Compute the cosine, u_{n+1}, and sine, v_{n+1}, of the improved latitude estimate ϕ_{n+1}, the corresponding value w_{n+1}, and the improved altitude estimate h_{n+1}:

$$u_{n+1} = \frac{\left[a\sigma^2 + h_n w_n\right]\rho}{\sqrt{\left[a\sigma^2 + h_n w_n\right]^2 \rho^2 + \left[a + h_n w_n\right]^2 z^2}} \quad \text{(B-12)}$$

$$v_{n+1} = \frac{\left[a + h_n w_n\right] z}{\sqrt{\left[a\sigma^2 + h_n w_n\right]^2 \rho^2 + \left[a + h_n w_n\right]^2 z^2}}$$

$$w_{n+1} = \sqrt{1 - e^2 v_{n+1}^2}$$

$$h_{n+1} = \sqrt{\left[\rho - \frac{a u_{n+1}}{w_{n+1}}\right]^2 + \left[z - \frac{a\sigma^2 v_{n+1}}{w_{n+1}}\right]^2}$$

Step 4

Compute $\phi_{n+1} = \arctan(v_{n+1}/u_{n+1})$ with a standard algorithm that is stable near ±90 deg.

B.5 Physical and Orbit Properties of the Moon

Table B-8. Physical Parameters of the Moon. Data from Cox [2000] and Astronomical Almanac [2010]. For an extended discussion of lunar properties see Eckart [1999] and Heiken et al., [1991].

Radii: (a) Toward Earth, (b) Along orbit, (c) Toward pole	
Mean radius (b + c) / 2	1,738.2 km
a – c	1.09 km
a – b	0.31 km
b – c	0.78 km
Semi-diameter at mean distance	15′32″.6
Mass	7.3483×10^{22} kg
Mean density	3.341 g cm^{-3}
Surface gravity	162.2 cm/s^2 = 0.1654 g
Surface escape velocity	2.38 km/s
Extreme range	356,400 – 406,700 km
Inclination of orbit to ecliptic oscillating ±9′ with period of 173 d	5° 8′ 43″.42
Sidereal period (fixed stars)	27.321 661
Mean orbital speed	1.023 km/sec
Synodical month (new Moon to new Moon)	29. 530 588
Surface area of Moon at some time visible from Earth	59%
Inclination of lunar equator	
To ecliptic	1° 32′ 32″.7
To orbit	6° 41′

Table B-9. Gravity Field of the Moon. Data from Cox [2000].

$\alpha = (C - B) / A = 0.000\ 400$	$C / MR^2 = 0.392$
$\beta = (C - A) / B = 0.000\ 628$	$I = 5{,}552''.7 = 1°32'32$
$\gamma = (B - A) / C = 0.0002278$	

$C_{20} = -\,0.000\ 202\ 7$	$C_{30} = -\,0.000\ 006$	$C_{32} = +\,0.000\ 004\ 8$
$C_{22} = +\,0.000\ 022\ 3$	$C_{31} = +\,0.000\ 029$	$S_{32} = +\,0.000\ 001\ 7$
	$S_{31} = +\,0.000\ 004$	$C_{33} = +\,0.000\ 001\ 8$
		$S_{33} = -\,0.000\ 001$

Table B-10. Orbit of the Moon About the Earth. Data from Cox [2000] and Seidelmann [2006].

Sidereal mean motion of Moon	$2.661\ 699\ 489 \times 10^{-6}$ rad s^{-1}
Mean distance of Moon from Earth	384 400 km
	60.27 Earth radii
	0.002 570 AU
Equatorial horizontal parallax	57′02″.608
at mean distance	3,422″.608
Mean distance of center of Earth from Earth-Moon barycenter	4.671×10^3 km
Mean eccentricity	0.054 90
Mean inclination to ecliptic	5.145 396 deg
Mean inclination to lunar equator	6°41′
Limits of geocentric declination	± 29 deg
Period of revolution of node	18.612 Julian years
Period of revolution of perigee	8.849 Julian years
Mean orbital speed	1,023 ms^{-1} = 0.000 591 AU/d
Mean centripetal acceleration	0.00272 ms^{-2} = 0.0003 g
Optical libration in longitude (selenocentric displacement)	± 7.883 deg
Optical libration in latitude (selenocentric displacement)	± 6.85 deg
Saros = 223 lunations = 19 passages of Sun through node = 6,585 1/3 days	
Moment of inertia (about rotation axis)	$0.396\ M_\oplus b^2$
Gravitational potential term	$J_2 = 2.027 \times 10^{-4}$
No. of strong mascons on the near side of the Moon	4 exceeding 80 milligals
Mean surface temperature	+107 C (day), 153 C (night)
Temperature extremes	–233 C, +123 C
Moon's atmospheric density	~10^4 molecules cm^{-3} (day); 2×10^5 molecules cm^{-3} (night)
No. of maria & craters on lunar surface w/ diam. > d	$5 \times 10^{10} d^{-2.0}$ per 10^6 km^2 (d in m)

Phase Law and Visual Magnitude of the Moon

A summary of the visual magnitude of the Moon as a function of distance and phase is provided in Section 11.6 in OCDM by Wertz [2009]. (See Table 11-5 in OCDM for Moon's phase law.) At the mean distance of the Earth, the visual magnitude of the Moon at opposition is –12.74. However, at first and last quarters, when half of the visible surface of the Moon is illuminated the intensity drops to only 8% of the full Moon value and the brightness drops by 2.74 magnitudes. For a more extended discussion see Cox [2000].

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For annotated bibliography of Appendix B, see the book website.

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