4 The Solar System

4.1 The Sun

4.1.1 The quiet Sun

The term "quiet Sun" refers to solar properties that are statistically uniform over spherical surfaces and only slowly variable, although generally dependent on the distance r from the Sun's center. The disturbances of magnetic origin, such as spots, prominences, flares, etc., are treated in the sections on activity. Here only some properties concerning the 22-year magnetic cycle are included.

4.1.1.1 Solar global parameters

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Table 1. Global parameters of the Sun.

Mean distance (year 2000.5)	$d = 1.0000010178$ astronomical units	[92Sei]
distance at perihelion	$d_{\mathrm{min}} = 1.471 \cdot 10^{11}$ m	
distance at aphelion	$d_{\mathrm{max}} = 1.521 \cdot 10^{11}$ m	
radius	$r_\odot = (6.9574 \pm 0.0011) \cdot 10^8$ m	[04Kuh]
mass	$m_\odot = (1.9889 \pm 0.0003) \cdot 10^{30}$ kg	[02Sti]
mean density	$\bar{\rho} = 1408\,\mathrm{kg/m^3}$	
gravitational acceleration at surface	$g_\odot = 274\,\mathrm{m/s^2}$	
escape velocity at surface	$v_{\mathrm{esc}} = 6.18 \cdot 10^5$ m/s	
mass loss by radiation	$\dot{m}_{\mathrm{rad}} = -4.28 \cdot 10^9$ kg/s	
mass loss by solar wind	$\dot{m}_{\mathrm{wind}} \approx -1 \cdot 10^9$ kg/s	
moment of inertia	$\Theta = 6.9 \cdot 10^{46}\,\mathrm{kg\,m^2}$	[02Sti]
solar "constant"	$S = 1366 \pm 3\,\mathrm{W/m^2}$	[06Fou]
luminosity	$L_\odot = (3.844 \pm 0.010) \cdot 10^{26}$ W	
effective temperature	$T_{\mathrm{eff}} = 5778 \pm 3$ K	
absolute bolometric magnitude	$M_\odot = 4.74$	
color indices	$U - B = 0.195 \pm 0.005$	[86Nec]
	$B - V = 0.650 \pm 0.005$	[86Nec]
age	$t_\odot = (4.57 \pm 0.05) \cdot 10^9$ years	[95Was]

The astronomical unit is the radius of an unperturbed circular orbit around the Sun of a body of negligible mass with period $2\pi/k$ days, where $k = 0.01720209895$. Its value is (149597870691 ± 6) m [06Alm]. The solar radius given above is a space measurement. Ground-based observations yield a value ≈ 200 km larger [02Sti].

Global parameters concerning solar rotation and magnetism are given in Sects. 4.1.1.2.5 and 4.1.1.2.6, respectively. Errors quoted in Table 1 are either from the given references or from conservative estimates in [02Sti].

Table 2. Abundance of elements, $\log(n/n_{\mathrm{H}}) + 12$, in the Sun and in meteorites, after [98Gre].

Element	Photosphere	Meteorites	Element	Photosphere	Meteorites
1 H	12.00	–	42 Mo	1.92 ± 0.05	1.97 ± 0.02
2 He	10.93 ± 0.004	–	44 Ru	1.84 ± 0.07	1.83 ± 0.04
3 Li	1.10 ± 0.10	3.31 ± 0.04	45 Rh	1.12 ± 0.12	1.10 ± 0.04
4 Be	1.40 ± 0.09	1.42 ± 0.04	46 Pd	1.69 ± 0.04	1.70 ± 0.04
5 B	2.55 ± 0.30	2.79 ± 0.05	47 Ag	0.94 ± 0.25	1.24 ± 0.04
6 C	8.52 ± 0.06	–	48 Cd	1.77 ± 0.11	1.76 ± 0.04
7 N	7.92 ± 0.06	–	49 In	1.66 ± 0.15	0.82 ± 0.04
8 O	8.83 ± 0.06	–	50 Sn	2.0 ± 0.3	2.14 ± 0.04
9 F	4.56 ± 0.3	4.48 ± 0.06	51 Sb	1.0 ± 0.3	1.03 ± 0.07
10 Ne	8.08 ± 0.06	–	52 Te	–	2.24 ± 0.04
11 Na	6.33 ± 0.03	6.32 ± 0.02	53 I	–	1.51 ± 0.08
12 Mg	7.58 ± 0.05	7.58 ± 0.01	54 Xe	–	2.17 ± 0.08
13 Al	6.47 ± 0.07	6.49 ± 0.01	55 Cs	–	1.13 ± 0.02
14 Si	7.55 ± 0.05	7.56 ± 0.01	56 Ba	2.13 ± 0.05	2.22 ± 0.02
15 P	5.45 ± 0.04	5.56 ± 0.06	57 La	1.17 ± 0.07	1.22 ± 0.02
16 S	7.33 ± 0.11	7.20 ± 0.06	58 Ce	1.58 ± 0.09	1.63 ± 0.02
17 Cl	5.5 ± 0.3	5.28 ± 0.06	59 Pr	0.71 ± 0.08	0.80 ± 0.02
18 Ar	6.40 ± 0.06	–	60 Nd	1.50 ± 0.06	1.49 ± 0.02
19 K	5.12 ± 0.13	5.13 ± 0.02	62 Sm	1.01 ± 0.06	0.98 ± 0.02
20 Ca	6.36 ± 0.02	6.35 ± 0.01	63 Eu	0.51 ± 0.08	0.55 ± 0.02
21 Sc	3.17 ± 0.10	3.10 ± 0.01	64 Gd	1.12 ± 0.04	1.09 ± 0.02
22 Ti	5.02 ± 0.06	4.94 ± 0.02	65 Tb	-0.1 ± 0.3	0.35 ± 0.02
23 V	4.00 ± 0.02	4.02 ± 0.02	66 Dy	1.14 ± 0.08	1.17 ± 0.02
24 Cr	5.67 ± 0.03	5.69 ± 0.01	67 Ho	0.26 ± 0.16	0.51 ± 0.02
25 Mn	5.39 ± 0.03	5.53 ± 0.01	68 Er	0.93 ± 0.06	0.97 ± 0.02
26 Fe	7.50 ± 0.05	7.50 ± 0.01	69 Tm	0.00 ± 0.15	0.15 ± 0.02
27 Co	4.92 ± 0.04	4.91 ± 0.01	70 Yb	1.08 ± 0.15	0.96 ± 0.02
28 Ni	6.25 ± 0.04	6.25 ± 0.01	71 Lu	0.06 ± 0.10	0.13 ± 0.02
29 Cu	4.21 ± 0.04	4.29 ± 0.04	72 Hf	0.88 ± 0.08	0.75 ± 0.02
30 Zn	4.60 ± 0.08	4.67 ± 0.04	73 Ta	–	-0.13 ± 0.02
31 Ga	2.88 ± 0.10	3.13 ± 0.02	74 W	1.11 ± 0.15	0.69 ± 0.03
32 Ge	3.41 ± 0.14	3.63 ± 0.04	75 Re	–	0.28 ± 0.03
33 As	–	2.37 ± 0.02	76 Os	1.45 ± 0.10	1.39 ± 0.02
34 Se	–	3.41 ± 0.03	77 Ir	1.35 ± 0.10	1.37 ± 0.02
35 Br	–	2.63 ± 0.04	78 Pt	1.8 ± 0.3	1.69 ± 0.04
36 Kr	–	3.31 ± 0.08	79 Au	1.01 ± 0.15	0.85 ± 0.04
37 Rb	2.60 ± 0.15	2.41 ± 0.02	80 Hg	–	1.13 ± 0.08
38 Sr	2.97 ± 0.07	2.92 ± 0.02	81 Tl	0.9 ± 0.2	0.83 ± 0.04
39 Y	2.24 ± 0.03	2.23 ± 0.02	82 Pb	1.95 ± 0.08	2.06 ± 0.04
40 Zr	2.60 ± 0.02	2.61 ± 0.02	83 Bi	–	0.71 ± 0.04
41 Nb	1.42 ± 0.06	1.40 ± 0.02	90 Th	–	0.09 ± 0.02
			92 U	< -0.47	-0.50 ± 0.04

4.1.1.1.1 Chemical composition

For most elements the abundance, relative to hydrogen, is determined by a fit of spectroscopic observations, usually from the "quiet" photosphere, but also from sunspots and from the corona. Solar wind measurements are also used. A special case is helium, for which the effect of partial ionization on the speed of sound enables a helioseimological determination. Results are listed in Table 2, in addition to meteoritic values. A recent downward revision to ≈ 8.66 [04Asp] of the solar abundance of O, and concomittant revisions of C, N, and Ne are still being debated (there is an incompatibility with observed p-mode frequencies [07Bas]) and were not taken into account.

4.1.1.2 Solar interior

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4.1.1.2.1 Standard model

A *standard solar model* is computed by means of conservation laws and physical input concerning the equation of state, the opacity, energy sources, and energy transport based on experimental and theoretical results. The model listed in Table 4 has been described in [02Sti]. In the convection zone it uses the mixing-length formalism with a mixing length α times the local pressure scale height, and it allows for helium diffusion.

An originally homogeneous star of solar mass, with mass fractions $X = 0.704$, $Y = 0.276$, and $Z = 0.02$ for hydrogen, helium, and the remaining elements, respectively, has been evolved for $t_\odot = 4.57 \cdot 10^9$ years. The mixing length parameter is $\alpha = 1.807$. Due to diffusion, the surface fraction of He is reduced to $Y = 0.245$, and the fraction of H is increased correspondingly.

4.1.1.2.2 Solar neutrinos

Electron neutrinos are emitted as a by-product of nuclear energy release in the solar interior. Table 3 lists neutrino fluxes predicted by standard solar models for the distance of 1 astron. unit, from [06Bah], with "optimistic" uncertainties from [05Bah]. The largest contribution to the flux uncertainties arise from uncertainties in the composition of chemical elements.

Table 3. Energy E_ν of solar neutrinos, and neutrino fluxes Φ_ν, predicted from standard models.

Reaction	E_ν [MeV]	Φ_ν [m^{-2}s^{-1}]	Error [%]
$p(p,e^+\nu)d$	< 0.42	$5.99 \cdot 10^{14}$	± 0.8
$p(pe^-,\nu)d$	1.442	$1.42 \cdot 10^{12}$	± 1.3
$^3He(p,e^+\nu)^4He$	< 18.8	$7.93 \cdot 10^7$	± 15.4
$^7Be(e^-,\nu\gamma)^7Li$	0.38 & 0.86	$4.84 \cdot 10^{13}$	± 9.3
$^8B(,e^+\nu)^8Be^*$	< 15	$5.69 \cdot 10^{10}$	± 12.6
$^{13}N(,e^+\nu)^{13}C$	0.707	$3.05 \cdot 10^{12}$	$+20.2,\ -15.1$
$^{15}O(,e^+\nu)^{15}N$	0.997	$2.31 \cdot 10^{12}$	$+23.3,\ -16.4$
$^{17}F(,e^+\nu)^{17}O$	0.999	$5.83 \cdot 10^{10}$	± 25.1

From the fluxes of solar neutrinos, capture rates for the targets ^{37}Cl and ^{71}Ga are predicted: (8.12 ± 1.0) snu resp. (126.08 ± 8.7) snu (captures per second and 10^{36} atoms). Due to neutrino oscillations the actually measured rates are smaller: (2.56 ± 0.2) snu and (68.1 ± 3.85) snu for chlorine and gallium respectively. The total measured flux of ^8B neutrinos (electron, μ, and τ) is $(4.99 \pm 0.33) \cdot 10^{10}\,m^{-2}s^{-1}$. All these results are quoted in [06Bah].

Table 4. Standard model of the present Sun: Scaled mass and radius, pressure, temperature, density; scaled luminosity, mass fraction of hydrogen, mean molecular weight, excess of logarithmic temperature gradient over adiabatic, convection velocity, abatic exponent; $Z + n$ means $Z \cdot 10^n$.

$m/m_\odot$	$r/r_\odot$	P [Pa]	T [K]	ρ [kg/m^3]	$L/L_\odot$	X	μ	$\Delta\nabla$	$v\left[\frac{\mathrm{m}}{\mathrm{s}}\right]$	Γ_1
1.0000	1.0000	9.55+03	5.778+3	2.512−4	1.000	.735	1.247		0	1.636
1.0000	.9999	1.18+04	6.229+3	2.868−4	1.000	.735	1.247	9.7-2	152	1.621
1.0000	.9999	1.34+04	6.736+3	3.012−4	1.000	.735	1.247	4.1-1	1181	1.585
1.0000	.9999	1.45+04	7.210+3	3.045−4	1.000	.735	1.247	5.4-1	2172	1.523
1.0000	.9999	1.57+04	7.708+3	3.080−4	1.000	.735	1.246	4.8-1	2586	1.451
1.0000	.9998	1.78+04	8.400+3	3.195−4	1.000	.735	1.242	3.3-1	2644	1.352
1.0000	.9998	2.38+04	9.534+3	3.688−4	1.000	.735	1.220	1.7-1	2340	1.250
1.0000	.9997	3.12+04	1.032+4	4.380−4	1.000	.735	1.195	1.1-1	2093	1.215
1.0000	.9994	5.64+04	1.163+4	6.704−4	1.000	.735	1.139	5.0-2	1725	1.194
1.0000	.9991	1.02+05	1.274+4	1.056−3	1.000	.735	1.089	2.8-2	1461	1.191
1.0000	.9988	1.84+05	1.382+4	1.689−3	1.000	.735	1.044	1.7-2	1251	1.196
1.0000	.9985	3.33+05	1.493+4	2.721−3	1.000	.735	1.004	1.1-2	1077	1.203
1.0000	.9976	1.09+06	1.743+4	7.103−3	1.000	.735	.932	4.7-3	806	1.223
1.0000	.9965	3.56+06	2.059+4	1.836−2	1.000	.735	.865	2.2-3	613	1.252
1.0000	.9952	1.16+07	2.495+4	4.624−2	1.000	.735	.800	1.2-3	479	1.299
1.0000	.9934	3.80+07	3.141+4	1.127−1	1.000	.735	.741	6.2-4	380	1.363
1.0000	.9910	1.24+08	4.166+4	2.610−1	1.000	.735	.692	3.4-4	310	1.461
1.0000	.9874	4.05+08	5.953+4	5.669−1	1.000	.735	.660	1.8-4	258	1.585
1.0000	.9820	1.33+09	8.938+4	1.191+0	1.000	.735	.644	7.7-5	204	1.583
1.0000	.9737	4.33+09	1.342+5	2.513+0	1.000	.735	.630	3.2-5	162	1.604
.9999	.9611	1.41+10	2.073+5	5.187+0	1.000	.735	.620	1.4-5	131	1.654
.9996	.9415	4.62+10	3.273+5	1.058+1	1.000	.735	.616	5.9-6	106	1.666
.9987	.9117	1.51+11	5.209+5	2.152+1	1.000	.735	.614	2.4-6	85	1.668
.9963	.8676	4.93+11	8.315+5	4.378+1	1.000	.735	.613	1.0-6	69	1.667
.9904	.8057	1.59+12	1.320+6	8.826+1	1.000	.735	.612	4.0-7	55	1.665
.9746	.7101	5.96+12	2.230+6	1.955+2	1.000	.735	.611	1.9-8	15	1.665
.9423	.5988	2.20+13	3.153+6	5.180+2	1.000	.714	.614		0	1.665
.9019	.5193	5.75+13	3.822+6	1.120+3	1.000	.712	.616		0	1.666
.8569	.4611	1.21+14	4.403+6	2.039+3	1.000	.710	.616		0	1.667
.7872	.3991	2.75+14	5.158+6	3.984+3	1.000	.708	.617		0	1.667
.7173	.3539	5.14+14	5.831+6	6.589+3	1.000	.706	.618		0	1.668
.6342	.3117	9.32+14	6.583+6	1.058+4	.999	.704	.619		0	1.668
.5445	.2741	1.59+15	7.382+6	1.607+4	.995	.700	.621		0	1.668
.4452	.2376	2.63+15	8.296+6	2.378+4	.980	.694	.624		0	1.668
.3388	.2013	4.26+15	9.362+6	3.444+4	.940	.680	.631		0	1.668
.2430	.1686	6.40+15	1.046+7	4.720+4	.856	.655	.643		0	1.668
.1629	.1391	9.00+15	1.156+7	6.186+4	.721	.617	.663		0	1.668
.0897	.1072	1.25+16	1.280+7	8.193+4	.503	.554	.699		0	1.668
.0310	.0705	1.73+16	1.419+7	1.108+5	.219	.460	.761		0	1.668
.0034	.0321	2.18+16	1.530+7	1.417+5	.028	.369	.833		0	1.668
.0002	.0127	2.31+16	1.559+7	1.513+5	.002	.343	.855		0	1.668
.0000	.0000	2.34+16	1.565+7	1.533+5	.000	.338	.860		0	1.668

4.1.1.2.3 Global oscillations

Global stellar oscillations are classified as f, g, and p modes (for "fundamental", "gravity", and "pressure", respectively). The f and p modes have been identified on the Sun. In addition, there is evidence for internal gravity waves in the solar atmosphere [76Sch], but for the velocity of *global* g modes only an upper limit, of ≈ 1 cm/s for frequencies of $\approx 200\,\mu$Hz, has been set [00App].

The p modes are characterized by their angular degree l and radial order n. Degrees of observed p modes range from 0 to ≈ 4000, orders from 0 to ≈ 30 (depending on l). Frequencies of low-l p modes are listed in Table 5. The error is generally less than 1μHz. Differences between different observed frequency sets are of the same order. They arise partly from the differences in data reduction techniques, partly from real solar variation. A significant frequency shift of $\approx 0.4\,\mu$Hz occurs from minimum to maximum of the solar activity cycle [85Woo, 92Ang, 99How, 07Cha]. Table 5 refers to years of low activity. Frequencies of low-l oscillations with very low order n are given in [90Ang, 00Ber2], frequencies of high degree modes are listed in [88Lib].

Table 5. Frequencies, in μHz, of low-degree solar p modes. For $l = 0$ to 3: from BiSON whole-disc data 1994–97 [99Cha]. For $l \geq 4$: from SOHO/MDI data of 1996 [97Rho, Table in the Internet]. The amplitudes of these modes vary from ≈ 3 cm/s at the edges of the recognizable frequency range to ≈ 20 cm/s around 3 mHz.

	Degree l									
Mode	0	1	2	3	4	5	6	7	8	9
p 7						1401.6	1443.7	1483.4	1521.2	1557.7
p 8			1394.7		1500.3	1545.3	1587.5	1627.5	1665.8	1702.4
p 9		1472.8	1535.9		1641.0	1685.9	1727.8	1767.6	1806.2	1843.7
p 10	1548.3	1612.7	1674.5		1778.0	1823.4	1866.2	1906.8	1946.1	1984.2
p 11	1686.6	1749.3	1810.4	1865.3	1914.8	1960.5	2004.2	2045.9	2086.1	2125.2
p 12	1822.2	1885.1	1945.7	2001.2	2051.7	2098.4	2142.6	2184.5	2225.2	2264.6
p 13	1957.4	2020.8	2082.1	2137.8	2188.4	2235.4	2279.9	2322.2	2362.9	2402.4
p 14	2093.5	2156.8	2217.7	2273.5	2324.2	2371.2	2415.6	2458.2	2499.4	2539.6
p 15	2228.7	2292.0	2352.2	2407.7	2458.6	2506.1	2551.1	2594.3	2636.2	2677.0
p 16	2362.8	2425.6	2485.9	2541.7	2593.0	2641.2	2687.0	2731.1	2773.8	2815.2
p 17	2496.2	2559.1	2619.7	2676.2	2728.3	2777.3	2823.7	2868.3	2911.5	2953.5
p 18	2629.7	2693.3	2754.4	2811.4	2864.2	2913.7	2960.6	3005.6	3049.1	3091.4
p 19	2764.1	2828.1	2889.6	2947.0	3000.1	3049.9	3097.2	3142.7	3186.7	3229.5
p 20	2899.0	2963.4	3024.7	3082.3	3135.9	3186.2	3233.9	3279.8	3324.3	3367.8
p 21	3033.7	3098.1	3159.9	3217.8	3271.6	3322.5	3370.8	3417.4	3462.4	3506.1
p 22	3168.5	3233.2	3295.1	3353.4	3408.0	3459.3	3508.2	3555.2	3600.9	3645.4
p 23	3303.5	3368.6	3431.0	3489.5	3544.4	3596.5	3645.9	3693.6	3739.4	3784.1
p 24	3439.0	3504.0	3567.1	3626.1	3681.4	3733.7	3783.7	3832.0	3878.3	3923.3
p 25	3575.0	3640.3	3703.2	3762.6	3818.9	3871.9	3922.1	3970.4	4017.1	4062.8
p 26	3710.7	3776.9	3840.1	3900.5	3956.3	4009.8	4060.7	4109.6	4156.5	4202.2
p 27	3847.6	3913.4	3977.2		4093.9	4147.5	4198.9	4248.3	4295.8	4341.6
p 28	3984.4				4231.2	4286.3	4338.1	4387.3	4435.0	4481.8
p 29					4371.0	4424.4	4476.5	4526.9	4575.5	4622.5

For any given l the frequencies are nearly equidistant; the "large separation" $\Delta\nu = \nu_{n+1,l} - \nu_{n,l}$ is, asymptotically,

$$\Delta\nu = \left(2\int_0^{r_\odot} \frac{dr}{c}\right)^{-1} \approx 136\,\mu\text{Hz}\,. \quad (1)$$

Modes with order and degree (n, l) and $(n-1, l+2)$ have a "small separation" $\delta\nu_{n,l} = \nu_{n,l} - \nu_{n-1,l+2}$ of their frequencies. For $l = 0$, 1 and $n = 13 \ldots 25$ there is a linear approximation [92Ang],

$$\delta\nu_{n,l} = a_l + b_l(n-19)\,, \quad \text{where} \tag{2}$$

$$a_0 = 9.75 \pm 0.07, \quad b_0 = -0.32 \pm 0.02, \quad a_1 = 16.90 \pm 0.21, \quad b_1 = -0.49 \pm 0.06\,, \tag{3}$$

with no significant dependence on the level of solar activity (the definition of $\delta\nu_{n,l}$ in [92Ang] differs by 1 in the order n).

The fundamental, or f, mode is closely approximated by a deep-water surface wave, especially for large l. Its frequencies are therefore

$$\nu_l \approx \frac{1}{2\pi}\left(\frac{Gm_\odot l}{r_\odot^3}\right)^{1/2}, \tag{4}$$

which has been used for a precise determination of the solar radius [97Sch, 98Ant].

4.1.1.2.4 Convection zone

In the outer part of the Sun the opacity increases due to the ionization of H and He. Therefore radiative transport becomes inefficient, and energy is transported by convection. Within the convection zone the temperature gradient is nearly adiabatic, see Table 4. The base of the convection zone has been determined by helioseismology [91Chr, 97Bas]:

$$r_{\rm base}/r_\odot = 0.713 \pm 0.001 \tag{5}$$

Evolutionary models of the Sun yield approximately the same result [02Sti].

4.1.1.2.5 Solar rotation and meridional circulation

Global parameters corresponding to the rotation of the Sun are listed in Table 6. For the inclination of the solar axis, the *Astronomical Almanac* uses the traditional value $i = 7.25°$ of R. C. Carrington, instead of the value given here. The present longitude of the ascending node is ☊(2008) = 75.87° [06Alm]. For the oblateness there is evidence of variation, by a sizable fraction of the measured value, although helioseismic and shape measurements are at variance [07Emi].

Table 6. Global parameters related to the solar rotation.

inclination of rotation axis	$i = (7.12 \pm 0.05)°$	[87Bal]
ecliptic longitude of ascending node of equator	☊(1850) = 73.67°	[81Sta]
sidereal (Carrington) period of rotation	$T_{\rm sid} = 25.38$ days	[06Alm]
Mean synodic period of rotation	$T_{\rm syn} = 27.2753$ days	[06Alm]
sidereal rotation rate of core	$\Omega_{\rm core} = 2.73 \cdot 10^{-6}\,{\rm s}^{-1}$	[00Ber1]
oblateness of surface	$(r_{\rm equ} - r_{\rm pole})/r_\odot \approx 10^{-5}$	[06Egi]
gravitational quadrupole moment	$J_2 = (2.18 \pm 0.06) \cdot 10^{-7}$	[98Pij]
spin angular momentum	$H = (1.900 \pm 0.015) \cdot 10^{41}\,{\rm kg\,m^2/s}$	[98Pij]

The differential rotation of the surface layer has been measured by the migration of spots and other visible tracers across the solar disc, by the magnetic structure correlation, and by the Doppler shift of spectral lines. Table 7 gives the coefficients of the expression

$$\Omega = A + B\sin^2\psi + C\sin^4\psi\,, \tag{6}$$

where ψ is heliographic latitude. There exists a solar-cycle related variation (misleadingly called the *torsional oscillator*): Alternating narrow latitude ranges rotate faster resp. slower than average and thereby propagate towards the equator [80How, 00How].

Table 7. Coefficients for the Sun's angular velocity at the surface, sidereal, in degrees/day.

	A	B	C	Ref.
Mt. Wilson, spots 1921–1982	14.522	−2.84		[84How]
Greenwich, spots 1874–1976	14.551	−2.87		[86Bal]
Mt. Wilson, Doppler shift 1967–1984	14.050	−1.492	−2.606	[84Sno]
Mt. Wilson, Doppler correlation 1967–1987	14.71	−2.39	−1.78	[90Sno]
Kitt Peak, magnetogram correlation 1975–1991	14.42	−2.00	−2.09	[93Kom1]
SOHO/EIT, bright points 1998–1999	14.6	−3.0		[01Bra]

The interior angular velocity has been determined by the rotational splitting of p-mode frequencies. From the surface inwards, there is a slight increase of Ω down to $r/r_\odot \approx 0.95$ [98Sch], while in the bulk of the convection zone the surfaces of isorotation nearly coincide with the surfaces of constant latitude. At the base of the convection zone, there is a transition region of thickness less than $\approx 0.1 r_\odot$ (depending on latitude), called the tachocline [92Spi, 98Sch], to uniform rotation in the core. The core rotation rate is $\Omega/2\pi \approx 435\,\text{nHz}$ [00Ber1].

Theoretically, the differential rotation has been explained in mean-field models as a consequence of the Reynolds stresses [80Rüd, 01Kük, 05Kük], and in three-dimensional numerical models by the influence of the Coriolis force on global convection and latitudinal entropy variation [00Mie, 06Mie]. At the solar surface, the Reynolds stress component $\langle v_\theta v_\phi \rangle$ is of order $2 \cdot 10^3\,(\text{m/s})^2$ [98Pul], in agreement with earlier results. The rotational history of the Sun depends on the internal torques [89Pin, 96Rüd].

A large-scale meridional flow of order 10 m/s, has been found by the Doppler effect on spectral lines [84Sno], by observation of tracers [93Kom2], and by a helioseismological method [00Hab]. The flow is predominantly poleward, especially during the phase of activity minimum [06Jav], but equatorward flows within limited belts of latitude have also been found. The evidence for a solar-cycle variation is however not unambiguous: The proper motion of sunspots indicates that the flow diverges from the centers of activity [83Tuo, 86How, 01Wöh]; on the other hand, time-distance helioseismology yields a flow that converges toward the centers of activity [04Zha].

4.1.1.2.6 General magnetic field

In addition to the magnetic field of sunspots, the Sun possesses a field that is inhomogeneously distributed over its entire surface. Averaged over a large scale, the solar magnetic field exhibits global properties which vary with the activity cycle. Here, an average over longitude will be considered as *the general magnetic field* of the Sun. This field is conveniently described in terms of its poloidal (in meridional planes) and toroidal (azimuthal) components. The cyclic reversal of the toroidal component is inferred from the polarity of bipolar sunspot groups. A corresponding variation occurs with the poloidal component, with the two most recent reversals completed in Dec 1990 (Mar 1992) and Oct (Dec) 2001 in the northern (southern) polar cap [00Sno, 03Dur].

Table 8. Global parameters related to the solar magnetic field.

Absolute magnitude of mean polar field strength	up to $\approx 10^{-3}$ T	[04Ben]
Absolute total magnetic flux in polar caps	up to $\approx 10^{14}$ Wb	[04Ben]
Total absolute magnetic flux in polar caps	$\approx 2.5 \cdot 10^{14}$ Wb	[04Ben]
Total absolute magnetic flux through surface	up to $\approx 10^{16}$ Wb	[94Sch]
Estimated field strength of tubes in interior	$\approx 10\,T$	[95Cal, 87Cho]
Estimated energy of interior toroidal field	$\approx 10^{32}$ J	[96Sch]
Luminosity variation during solar cycle	$\approx \pm 0.04\%$	[06Fou]

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