4.1.1.3 Solar electromagnetic spectrum

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The electromagnetic spectrum of the Sun extends over more than 14 decades from the γ-ray range to radio waves. The suit of telescopes and spectrometers to cover this large interval is described in Chapter 2 "Solar instruments" and comprises both ground-based and space instrumentation. In this section, the extra-terrestrial radiation of the quiet Sun is considered in the range from $\lambda = 0.1$ nm (soft X rays) to 1 mm (infrared) either as directly measured or corrected for the atmospheric extinction. Advances in the technology in recent years led to an enormous increase in relevant space observations, in particular in the short wavelength ranges. The pioneering work in this field until 1990 is covered in Sect. 3.1.1.3 of [c, d].

Although significant fluxes of hard X and γ rays are emitted by the Sun during solar flares, their contributions to the quiet-Sun radiation can be neglected. They will be discussed in Sect. 4.1.2.7. The radio emission with $\lambda > 1$ mm is likewise not of importance in this context. It is treated in Sect. 4.1.1.6. The range of interest here is subdivided into several intervals according to Table 1 (modified after [j, 04Wil]).

Observations of the electromagnetic spectrum from the ground are possible in two windows of the Earth's atmosphere: the optical window from $\lambda \approx 310$ nm to 2 μm, in which, in particular, the visible radiation (light) is transmitted; and in the radio window at wavelengths longer than a few centimetres and shorter than about 10 m (cf., Fig. 1 in Sect. 1.5.1.2.1. of [n]). Instruments on sounding rockets or spacecraft provide measurements in those spectral regions that suffer from absorption in the terrestrial atmosphere. The atmospheric absorption characteristics below 320 nm are shown in [02Woo] and for longer wavelengths in [04Fro].

Four quantities are of major importance in this section: the "radiant flux density" or "irradiance", E; the "spectral irradiance", E_λ; the "radiance", L; and the "spectral radiance", L_λ. The irradiance is measured as power divided by an area, and the radiance as power divided by an area and a solid angle. The corresponding spectral quantities are, in addition, divided by a certain wavelength interval. Note that the radiance is not dependent on the observing distance, r, whereas the irradiance varies with r^{-2}.

Table 1. Classification of the spectral categories of electromagnetic radiation from the infrared to (soft) X rays. Some modifications with respect to [j] were introduced to avoid overlaps as much as possible. The approximate photon energies are given in the last two columns.

Spectral band	Wavelength, λ		Photon energy[a], ϵ_λ	
Limits:	lower	upper	upper	lower
Infrared radiation	760 nm	1 mm	1.6 eV	1.2 meV
Visible radiation (light)	380 nm	760 nm	3.2 eV	1.6 eV
Ultraviolet radiation	10 nm	380 nm	123 eV	3.2 eV
Near ultraviolet (NUV)	280 nm	380 nm	4.4 eV	3.2 eV
UV-A radiation	315 nm	380 nm	3.9 eV	3.2 eV
UV-B radiation	280 nm	315 nm	4.4 eV	3.9 eV
Middle ultraviolet (MUV)	200 nm	280 nm	6.2 eV	4.4 eV
Vacuum ultraviolet (VUV)	10 nm	200 nm	123 eV	6.2 eV
Far ultraviolet (FUV)	120 nm	200 nm	10.3 eV	6.2 eV
Extreme ultraviolet (EUV)	10 nm	120 nm	123 eV	10.3 eV
X rays	12.3 pm	12.3 nm	100 keV	100 eV
Soft X rays[b]	123 pm	12.3 nm	10 keV	100 eV

[a] 1 eV $\widehat{=}$ $e \times 1$ V, where e is the elementary charge.
[b] There is a slight overlap between the soft X-ray and EUV ranges, in order to achieve a definition in round numbers for the photon energy in the X-ray range.

In a wide range, the solar electromagnetic spectrum can be described as continuum radiation superimposed by an emission spectrum from the chromosphere (cf., Subsect. 4.1.1.4), transition region and corona (cf., Sect. 4.1.1.5) at short wavelengths, or modified by absorption from the upper photosphere and the lower chromosphere (cf., Sect. 4.1.1.4) at longer wavelengths. The first strong emission line at the longest wavelength is Si II at 181.69 nm [58Joh]. The history of the identification of solar VUV lines is described in [03Wil1].

The quantities irradiance and radiance are not only used to characterize the whole spectrum, but also the radiation in a certain line integrated over its spectral profile to obtain E_{Line} and L_{Line}. Both the (spectral) irradiance and the (spectral) radiance contain detailed information on the Sun and its atmosphere. The (spectral) irradiance controls, in addition, many processes on the Earth and in the solar system. The solar variability and the Earth's climate is treated in [f] and has been reviewed by [05Jag].

Critical aspects of the solar-radiation measurements are their radiometric and spectral calibrations that must be traceable to primary standards, cf., [m, 05McC, 04Mek]. The rules of the International System of Units (SI) [b][1] require that the radiant energy is measured in energy units. The energy is, however, often given in photon units. Radiation with a certain wavelength, λ, has a photon energy of $\epsilon_\lambda = h\ c_0/\lambda$, where $h = 6.626\,0693 \times 10^{-34}$ J s is the Planck constant with a relative standard uncertainty of $u_{\mathrm{r}} = 1.7 \times 10^{-8}$ [02Com], and $c_0 = 299\,792\,458$ m s^{-1} (exact) is the speed of light in vacuum[2] [b].

4.1.1.3.1 Solar irradiance and spectral irradiance

The total solar irradiance (TSI), $E(\overline{r}_\odot)$, at a distance of the mean radius of the Earth's orbit (one astronomical unit), $\overline{r_\odot} = 1$ AU $= 1.495\,978\,706\,91 \times 10^{11}$ m ($u_{\mathrm{r}} = 4 \times 10^{-11}$) [b], is sometimes called "solar constant", although it is, in fact, a function of the solar cycle and subject to variations caused by active regions (increases) and sunspots (decreases) as can be seen from Fig. 1. The average

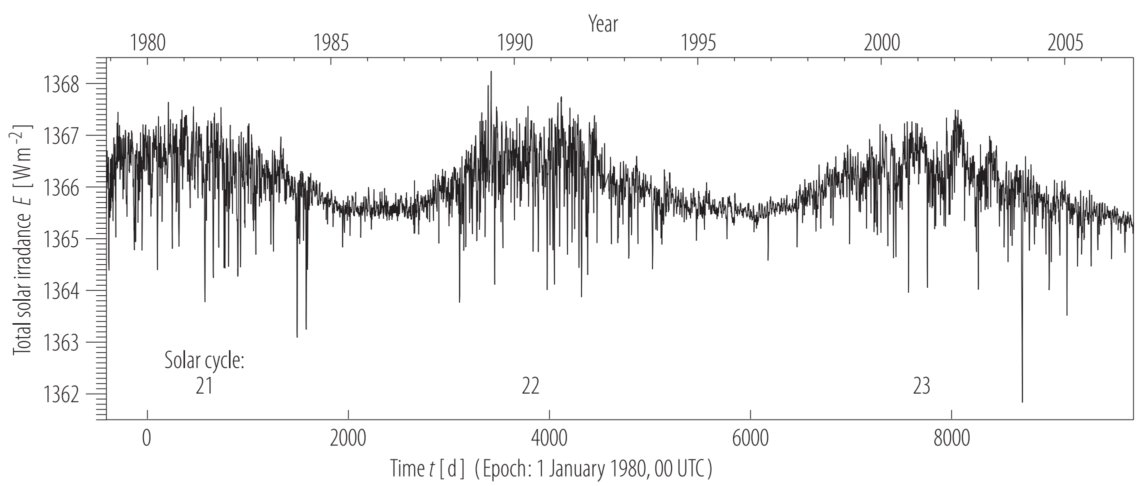

Fig. 1. Daily averages of the total solar irradiance (TSI), $\overline{E}$, at $\overline{r_\odot}$ from 1978 to 2006 as a composite of observations by the spacecraft *NIMBUS 7, SMM, UARS*, and *SOHO*, cf., [06Fro]. (Data: Courtesy of C. Fröhlich, obtained from `ftp.pmodwrc.ch/pub/data/irradiance/composite/DataPlots/composite_d41_61_0611.dat`).

[1] On-line information available at `http://www.bipm.fr/utils/common/pdf/si_brochure_8_fr.pdf`, `http://www.bipm.fr/utils/common/pdf/si_brochure_8_en.pdf`, and `http://physics.nist.gov/cuu/pdf/sp811.pdf`.

[2] A list of physical constants is available from, e.g., `http://www.physics.nist.gov/cuu/Constants/index.html`.

value of the TSI over at least one solar cycle might be called "solar constant", $S = \overline{E(\overline{r_\odot})}$. From the results published between 1967 and 1970, a most probable value of $S = (1360 \pm 14)$ W m^{-2} was deduced by [71Lab], who did not exclude that a portion of the uncertainty quoted was actually caused by a solar variability. In the meantime, such a variability has been established on temporal scales of the solar cycle and rotation (see Fig. 1), but also on shorter scales [04Fro, 03Wil3]. In addition, a relative increase of 0.2 % since the Maunder Minimum at the end of the 17th century has been estimated by [01Lea]; see also [o]. This would imply a change of ≈ 0.06 % per century. A summary of other estimates ranging from no increase to 2.6 W m^{-2} can be found in [05Lea]. More studies are required to determine this important secular change with higher accuracy.

The TSI is measured with the help of active cavity radiometers aboard of spacecraft, e.g., [97Fro, 04Mek]. Some recent TSI measurements are compiled in Table 2, including mean values for minimum and maximum conditions of the solar activity. As indication of the relevant uncertainties might serve the assessment for a single instrument by [04Mek] with ≈ 1 W m^{-2} for the accuracy and ≈ 0.1 W m^{-2} for the precision over eight years. For composite TSI evaluations, uncertainties of $U =$ 0.35 W m^{-2}; ($k = 2$) are estimated [04Dew]. Note, however, that some of the space instruments measured an irradiance much lower than the other instruments revealing an incompatibility of the individual uncertainty assessments, which are therefore not given here. A value of $S = (1366 \pm 2)$ W m^{-2} for the period from 1978 to 2000 (as measured by the majority of the radiometers in space) is given in [p].

Under the assumption that the radiation properties of the Sun are spherically symmetric, the solar constant can be used to calculate the total radiant power (the Sun's absolute luminosity),

$$P_\odot \;=\; 4\pi S\,\overline{r_\odot}^2 \;=(3.842 \pm 0.006) \times 10^{26}\ \text{W} \tag{1}$$

as well as the average "solar emittance" from the photosphere at $r = R_\odot$,

$$\overline{M^+} \;=\; S\,\overline{r_\odot}^2/R_\odot{}^2 \;=\; (6.304 \pm 0.010) \times 10^7\ \text{W m}^{-2}\ , \tag{2}$$

with a solar radius $R_\odot = (696.35 \pm 0.11)$ Mm or $R_\odot = 959.28'' \pm 0.15''$ at 1 AU [04Kuh] measured from space[3]. The Stefan-Boltzmann law

$$\overline{M^+} \;=\; \sigma\, T_{\text{eff}}{}^4 \tag{3}$$

Table 2. Mean total solar irradiance (TSI) data[a]

TSI, $\overline{E}$[W m^{-2}]	Minimum $\overline{E_{\min}}$[W m^{-2}]	Maximum $\overline{E_{\max}}$[W m^{-2}]	Relative variability[b]	Era; Period	Ref.
1 366.22			0.001	March 1992	[96Cro]
	1 365.08	1 367.42		1979 to 1987	[97Cro]
	1 365.6	1 366.8		Sep. 1986; Nov 1989	[00Lea]
			Increase[c]	1978 to 2002	[03Wil3]
	1 365.67	1 367.08		1987; 1991	[04Dew]
	1 365.82	1 367.42		1996; 2002	[04Dew]
	1 365.5	1 366.8	p-t-p ≈ 0.001	1980 to 2000; 11 a	[04Fro]
	≈ 1 364	≈ 1 367	p-t-p ≈ 0.002	1980 to 2000; 27 d	[04Fro]
1 361				Oct. to Nov. 2003	[05Kop]
	1 365.56	1 366.45		1978 to 2005	[06Fro]

[a] Mean values over certain time spans are given. For daily averages see Fig. 1.
[b] p-t-p: relative peak-to-peak variation.
[c] Estimated fractional increase of ≈ 0.05 % per decade between consecutive minima.

[3] Most of the ground-based investigations have not led to consistent results for $R_\odot$ [05Thu]. Current models use $R_\odot = 695.99$ Mm and $P_\odot = 3.846 \times 10^{26}$ W [04Fro].

then yields, with $\sigma = 5.670\,400 \times 10^{-8}$ W m^{-2} K^{-4} ($u_{\mathrm{r}} = 7 \times 10^{-6}$), an effective temperature of $T_{\mathrm{eff}} = (5774 \pm 2)$ K.

The TSI can, in principle, also be obtained by integrating the spectral irradiance

$$E = \int_0^\infty E_\lambda \mathrm{d}\lambda \ . \tag{4}$$

Recent measurements of the spectral irradiance, E_λ, have been performed according to Table 3. In Fig. 2, the solar spectral irradiance of the quiet Sun from 0.1 nm to 2.4 μm is shown. Reference solar spectra are in preparation for an ISO standard [06Gue]. For reference spectra and irradiances see also [06Tob]. Three Jungfraujoch solar atlases in the range from 300 nm to 23.7 μm are described by [95Del]. The spectral irradiance near the Mg II doublet at 280 nm is shown in [03Flo, 04Fro, 05Sno], that of the Ca II H and K lines near 395 nm in [04Fro, 96Siv], and the Al I lines at 394.4 nm and 396.1 nm are analyzed by [02Mau]. For older observations see [a], Sect. 4.1.1.4 and [c, d], Subsect. 3.1.1.3.1, where some representative values of E_λ are given.

The retrieval of the VUV irradiance from discrete emission lines is treated in [06Kre], and from spectral irradiance observations by [06Kri, 05War]. The variability of the spectral irradiance, E_λ, with the solar activity is a strong function of the wavelength [04Fro, 00Lea]. In the soft X-ray range[4] the variations can reach several orders of magnitude, but since the quiet-Sun level is at $\approx 10^{-7}$ W m^{-2} this has no significant effect on the TSI.

In Table 4, some irradiances of bright emission lines in the VUV range are compiled. The wide ranges given for He II 30.4 nm and H I Lyα irradiances do not represent the measurement accuracy with a relative uncertainty of $u_{\mathrm{r}} = 10$ %, but indicate solar cycle and other variations (effects of this type have to be expected for other lines as well). The H I Lyα line is strongly self-reversed as a consequence of radiative transfer processes in the optically-thick plasma of the chromosphere for this line. The spectral irradiance at the centre of this bright line is of interest for studies of

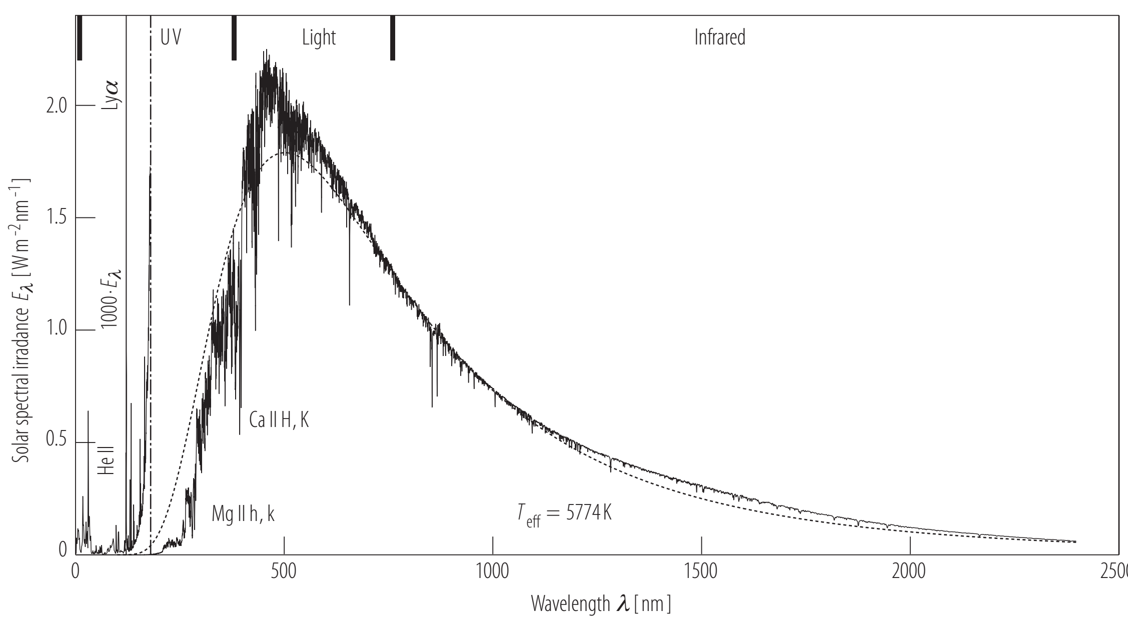

Fig. 2. Solar spectral irradiance, E_λ, at $\overline{r_\odot}$ (Data: Courtesy of G. Thuillier; cf., [04Thu1, 04Thu2]). For wavelengths below $\lambda = 180$ nm, 1000 E_λ is plotted to show the low irradiance values in this range. The H I Lyα line is off the scale (cf., Fig. 3). The ranges of the UV, visible and infrared radiation are marked on the top, and some prominent emission and absorption lines are indicated. The dotted curve shows the radiation of the Sun as a "black body" with $T_{\mathrm{eff}} = 5774$ K and $R_\odot = 696.35$ Mm (cf., Sect. 4.1.1.3.2).

[4]See the *GOES* data at `http://www.goes.noaa.gov/` and [06Rot].

Table 3. Recent solar spectral irradiance data with relative uncertainties

Wavelength range	Data[a]	Resolution	Uncertainty, u_r	Ref.
100 pm to 2.4 μm	E_λ	0.5 nm	0.03 to 0.4	[04Thu1]
1 nm to 2 μm	E_λ		0.05 to 0.1	[06Rot]
10 nm to 410 nm	E_λ, T_B[b]	0.3 nm to 0.6 nm	≥ 0.02	[03Flo]
15 nm to 120 nm	E_λ, model			[05War]
27 nm to 194 nm	E_λ	0.4 nm	0.1 to 0.2	[06Woo]
31 nm to 38 nm	E_λ, E_{Line}	30 pm	≈ 0.45	[00Bre]
52 nm to 63 nm	E_λ, E_{Line}	60 pm	≈ 0.45	[00Bre]
100 nm to 70 μm	E_λ, $E_{\lambda,\text{G}}$			[04Fro]
120 nm to 900 nm	E_λ, Tables	≥ 0.1 nm	≥ 0.03	[89Nic]
120 nm to 2.5 μm	E_λ		0.05 to 0.2	[96Col]
184.5 nm to 232.5 nm	E_λ	10 pm	0.1	[01Tar]
200 nm to 350 nm	E_λ	1.1 nm	0.025	[96Ceb]
210 nm to 1.6 μm	E_λ, T_B			[05Rot]

[a] $E_{\lambda,\text{G}}$: Spectral irradiance on the ground; $\Delta E_\lambda = (E_{\lambda,\max} - E_{\lambda,\min})/E_{\lambda,\min}$.
[b] T_B: Brightness temperature

Table 4. Line irradiances of some bright emissions in the VUV range

Atomic species	Spectral lines	Wavelength, λ	Irradiance, E_{Line}	Relative uncertainty, u_r	Ref.
He^+	He II	30.37804 nm	(0.6 ... 2.0) mW m^{-2}	$\approx$0.1	[02McC]
Mg^{8+}	Mg IX	36.8071 nm	26.6 μW m^{-2}	0.25	[00Bre]
He^0	He I	58.43340 nm	(28.9 ... 29.3) μW m^{-2}	0.15	[98Wil]
O^{4+}	O V	62.9730 nm	41.4 μW m^{-2}	0.19	[02Wil2]
C^{2+}	C III	97.7020 nm	131 μW m^{-2}	0.18	[02Wil2]
H^0	H I Lyα	121.567 nm	(5.7 ... 11.4) mW m^{-2}	0.1	[00Woo][a]
N^{4+}	N V	123.8821 nm	$\approx$ 10 μW m^{-2}	$\approx$ 0.07	[99Wil]
C^{3+}	C IV	154.8202 nm	$\approx$ 80 μW m^{-2}	$\approx$ 0.06	[99Wil]

[a] Further irradiance data products can be obtained from
`http://daac.gsfc.nasa.gov/SORCE/data_products.shtml`.

its interaction with the hydrogen in the planetary system that is, in most cases, relatively cool. The relation between the line irradiance of Lyα, $E_{\text{Ly}\alpha}$, which can be measured with low-resolution spectrometers, and the spectral irradiance at the centre, E_{λ_0}, is found to be (in photon units) by [05Eme]:

$$E_{\lambda_0}[10^{12}\ \text{s}^{-1}\ \text{cm}^{-2}\ \text{nm}^{-1}] = 0.64\left[E_{\text{Ly}\alpha}[10^{11}\ \text{s}^{-1}\ \text{cm}^{-2}]\right]^{1.21} \pm 0.08 \quad . \tag{5}$$

Most of the wavelengths of the spectral lines in Tables 4 and 7 are taken from [k].[5]

[5] The general theory of relativity gives a gravitational red shift for spectral lines emitted from the photosphere of $\Delta\lambda/\lambda_0 = 2.1 \times 10^{-6}$. This shift affects the rest wavelength of all lines, and is taken into account when wavelength measurements of lines from highly-charged ions are performed by comparison with known solar lines. The shift has, however, to be considered, if solar spectral lines are compared with lines emitted in the terrestrial environment, cf., [04Wil]. Bulk motions in the solar atmosphere also lead to wavelength shifts, but can be considered to cancel out for measurements of the central wavelength, if averaged over the whole Sun.

4.1.1.3.2 Solar radiance and spectral radiance

The irradiance can be measured with "full-disk" instruments without spatial resolution, i.e., the Sun is observed as a star. If solar observations with spatial resolution are available, the quantities radiance, L, or spectral radiance, L_λ, and their relationship to the irradiance have to be considered. The (spectral) irradiance can be obtained by integrating the (spectral) radiance over the solar disk (and the corona):

$$E = \int_{Sun} L \, \mathrm{d}\Omega \quad \text{and} \quad E_\lambda = \int_{Sun} L_\lambda \, \mathrm{d}\Omega \ , \tag{6}$$

where $\mathrm{d}\Omega = \mathrm{d}F/r_\odot^2$ is the solid angle element, $\mathrm{d}F$ the (projected) area on the disk, and $r_\odot$ the distance of the observing instrument from the Sun. As mentioned before, the solar irradiance is usually adjusted to $r_\odot = 1$ AU.

The spectral radiance of a black body follows from Planck's law:

$$L_\lambda \ = \ B_\lambda(T_\mathrm{B}) \ = \ \frac{2\,h\,c_0^2}{\lambda^5} \left[\exp\left(\frac{h\,c_0}{\lambda\,k\,T_\mathrm{B}} \right) - 1 \right]^{-1} \ , \tag{7}$$

where T_B is the brightness temperature and $k = 1.380\,6505 \times 10^{-23}$ J K^{-1} ($u_\mathrm{r} = 1.8 \times 10^{-6}$) the Boltzmann constant. Assuming an effective temperature of $T_\mathrm{eff} = 5774$ K (cf., the previous section), eqs. (6) and (7) yield, together with the solar radius, $R_\odot$, the dotted curve in Fig. 2.

The spectral-radiance and the line-radiance data must refer to specific solar locations, events, or conditions, such as quiet-Sun areas, active regions, coronal holes or limb observations. Data

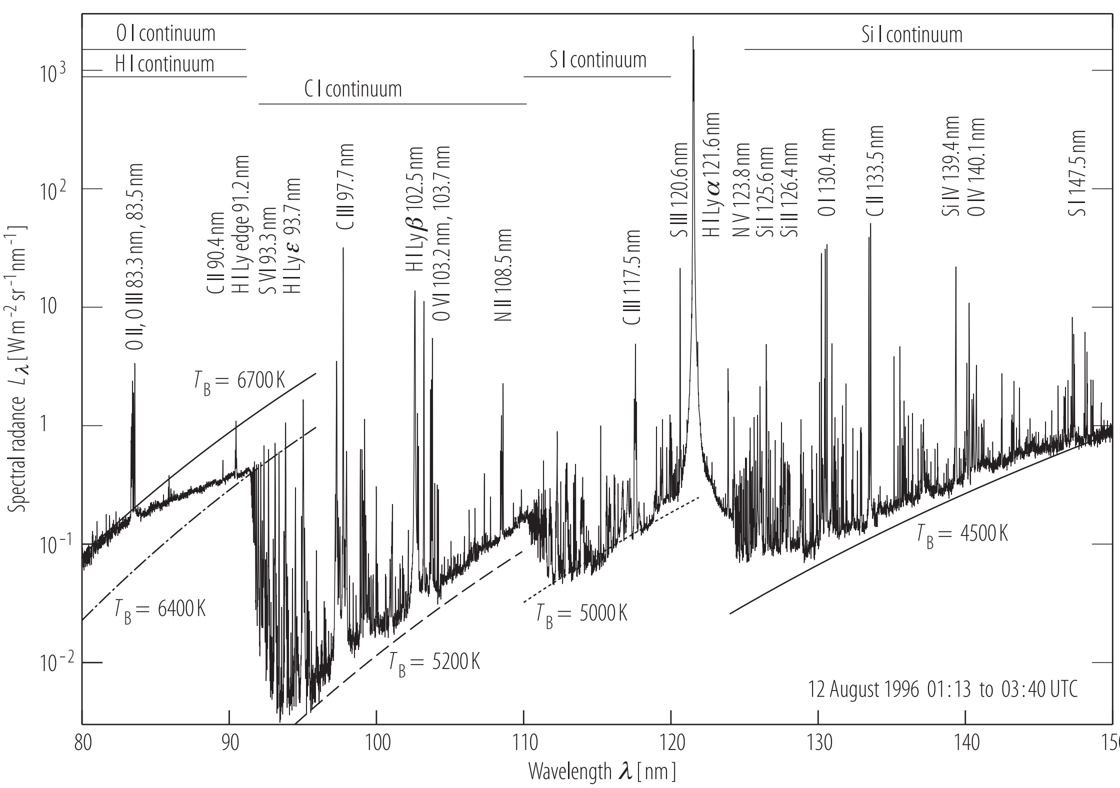

Fig. 3. Spectral radiance of the quiet Sun near the centre of the disk from $\lambda = 80$ nm to 150 nm. The spectral radiances expected for some brightness temperatures, T_B, are shown as approximations of the continua in this wavelength range [02Wil2].

Table 5. Radiance spectra of the quiet Sun

Wavelength interval[a], λ	Data[b]	Origin[c]	Ref.
16 nm ... 134.4 nm	Tables, Id.	QS	[90Lan]
30.8 nm ... 63.3 nm	L_λ, Id.	QS	[99Bro]
66 nm to 161 nm	L_λ, Id.	QS, CH	[01Cur][d]
66 nm to 161 nm	L_λ, Id.	C	[04Cur][e]
66 nm to 161 nm		QS composite	[06Kre]
70 nm to 91.2 nm	L_λ, T_B	QS	[03Wil2]
175 nm to 210 nm	L_λ	QS, plage	[76Bru]
225.2 nm to 319.6 nm	L_λ	Disk centre, limb	[80Koh]
357 nm to 22 μm	L_λ, Id.	QS, umbra	[03Hin][f]

[a] Intervals indicated by λ_0 ... λ_1 are not covered completely.
[b] Typical uncertainties of VUV radiances are given in [06Wil]; Id.: Line identification.
[c] QS: quiet Sun; CH: coronal hole; C: corona.
[d] An updated version is available from
`http://www.mps.mpg.de/homes/curdt/diskatlas_new.pdf`.
[e] An updated version is available from
`http://www.mps.mpg.de/homes/curdt/coronal_atlas.pdf`.
[f] A description of eight solar atlases is given.
They can be obtained via anonymous ftp from `argo.tuc.noao.edu, cd pub/atlas`.

for quiet-Sun conditions are compiled in Table 5, and a selection of line lists derived from recent VUV irradiance or radiance spectra is presented in Table 6. Line lists for longer wavelengths are given in Sect. 3.1.1.3 of [c]. The spectral radiance of the quiet Sun in a portion of the VUV range is shown in Fig. 3. The brightness temperatures, T_B, of the C I, S I and Si I continua are lower than $T_{eff} = 5774$ K valid for the solar disk, indicating that they originate near the temperature minimum at the photosphere/chromosphere interface. The H I Lyman continuum, on the other hand, with greater brightness temperatures is emitted from higher layers of the chromosphere and transition region.

The radiance, L_λ, is, in general, a complicated function of many parameters (cf., e.g., [02Wil1]). In particular, it depends on the angle, ϑ, defined by the line-of-sight direction and the solar radius vector, or $\mu = \cos\vartheta$ with $\mu = 1$ at the centre of the disk and $\mu = 0$ at the limb. Under the assumption that $L_\lambda(\mu)$ is (at a certain wavelength) only dependent on μ, a limb-brightening or

Table 6. Line lists[a] from solar VUV irradiance or radiance spectra

Wavelength interval, λ	Resolution[b], $\Delta\lambda_D$	Data	Origin	Ref.
30.7 nm to 38.0 nm	≈ 30 pm	λ, Id.	disk	[00Bre]
51.5 nm to 63.2 nm	≈ 60 pm	λ, Id.	disk	[00Bre]
30.8 nm ... 63.3 nm	≈ 12 pm	λ, Id.	QS	[99Bro]
46.5 nm to 160.9 nm	4.4 pm, (2.2 pm)	λ, Id.	various	[01Cur]
46.5 nm to 160.9 nm	4.4 pm, (2.2 pm)	λ, Id.	corona	[97Fel]
65.7 nm to 117.6 nm	4.4 pm, (2.2 pm)	λ, Id.	limb	[97Cur]

[a] Comprehensive line lists can be found, e.g., at
`http://www.physics.nist.gov/PhysRefData/ASD/lines_form.html` and
`http://cfa-www.harvard.edu/amdata/ampdata/kurucz23/sekur.html`.
[b] Second-order values in parentheses.

Table 7. Centre-to-limb variations in some spectral ranges and of a few emission lines

Spectrum	Wavelength, λ	Category[a]	Ratio	Data[b]	Ref.
He I	58.43340 nm	N	≈ 1	$\rho_\lambda(\mu)$, QS	[98Wil]
O V	62.9730 nm	B	≈ 4.7	$\rho_\lambda(\mu)$, QS, CH	[98Wil]
Ne VIII	77.0428 nm	B	≈ 5	$\rho_\lambda(\mu)$, QS, CH	[98Wil]
N V	123.8821 nm	B	≈ 17	$\rho_\lambda(\mu)$, QS, CH	[98Wil]
N V	124.2804 nm	B		$\Delta\lambda_D$	[98Erd]
C IV	154.8202 nm	B	≈ 11	$\rho_\lambda(\mu)$, QS, CH	[98Wil]
	300 nm to 2.4 μm	D		Table, function	[91Mak]
	303 nm to 357 nm	D	Model		[98Hes]
	303 nm to 1099 nm	D		Coefficients	[94Nec]
	416 nm to 1099 nm	D	Model		[98Hes]
H I	337.566 μm	B	1.09		[00Cla]
	850 μm	B	1.12	Disk map	[93Bas]

[a] Behaviour of $\rho_\lambda(\mu)$: limb darkening (D); brightening (B); neutral (N).
[b] QS: quiet Sun; CH: coronal hole; $\Delta\lambda_D$: Doppler width.

limb-darkening function, $\rho_\lambda(\mu)$, can be defined so that

$$\overline{L_\lambda} = 2\ L_\lambda(1) \int_0^1 \rho_\lambda(\mu)\mu\ \mathrm{d}\mu \tag{8}$$

is the mean spectral radiance of the Sun at the wavelength λ [p, q, 98Wil]. Strong limb brightening can be observed for emission lines in the VUV range originating in optically-thin regions of the solar atmosphere [l, 97Lem, 78Mar], whereas limb darkening prevails in the visible range, cf., [p]. In Table 7, centre-to-limb variations are compiled for typical spectral lines and ranges. The centre-to-limb variation of Ca II K spectroheliograms is treated by [98Bra] for various activity levels. Studies of the formation region of the Fraunhofer lines led to the definition of the line depression contribution function (LDCF) [94Gro, 86Mag]. A tabulation of the line blocking coefficients is provided by [85Nec] in the range from 330 nm to 686 nm with a resolution of 1 nm to 2 nm. Radiance images of the Sun[6] in VUV lines are shown in [e].

4.1.1.3.3 The second solar spectrum

Linear polarization of the solar spectrum due to coherent scattering has been observed near the limb of the Sun since 1963 [63Bru, 74Ste, 75Wie]. The name "second solar spectrum" was given by [91Iva] to its UV portion, but is now applied to the whole spectrum [96Ste]. Graphical representations of this spectrum in high resolution obtained with ZIMPOL II [04Gan] are published in three wavelength ranges for observations near the limb ($\mu = 0.1$): 462.5 nm to 699.5 nm [g], 391.0 nm to 463.0 nm [h], and 316.0 nm to 391.5 nm [i]. Observations of the second solar spectrum are useful to measure weak and turbulent magnetic fields through the Hanle effect [98Bia, 98Ste, 04Tru]. An average value of $B = 3.8$ mT (38 G) was found for heights between 220 km and 370 km above the limb. A theory for the formation of the polarized continuum is given in [05Ste].

[6] More images of the Sun can be obtained in wide wavelength ranges from, i.e., `http://sohowww.nascom.nasa.gov/data/`, `http://stereo.gsfc.nasa.gov/`, and `http://umbra.nascom.nasa.gov/`.

4.1.1.3.4 References for 4.1.1.3

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