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On the consistency of solar limb darkening observations at UV wavelengths (2000−3300 Å)

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Abstract. — Limb darkening observations are important for the construction and verification of solar model atmospheres. We investigate the consistency of solar limb darkening data, published for the UV wavelength region between 2000 and 3300 Å, from the comparison of F/I_0 ratios based either on direct limb darkening observations or on absolute irradiance (F) and disk–center intensity (I_0) measurements. There exists a discrepancy between the limb darkening data of Moe & Milone and other, direct or indirect, limb darkening observations.

Key words: Sun: atmosphere — UV radiation

1. Introduction

Limb darkening observations and absolute radiation measurements are fundamental parameters for the construction and verification of solar model atmospheres. Limb darkening data are also important for the comparison of disk–integrated spectra of solar type stars with high resolution disk–center spectra of the Sun, like the UV solar atlases of Kohl et al. (1978; KPK) and Allen et al. (1978; AMJ). For the comparison of the IUE recorded UV spectrum of the solar type star 16 Cyg B (Greve et al. 1996) with the KPK and AMJ atlases we investigate here the consistency of direct solar limb darkening observations obtained for the wavelength region 2000−3300 Å. [For the consistency of the most reliable limb darkening observations and absolute intensity measurements of the wavelength region 3300 Å−12 500 Å see Neckel (1984)]. For this purpose we compare ratios F/I_0 of the disk–integrated intensity $F = F(\lambda)$ and disk–center intensity $I_0 = I_0(\lambda)$, derived either from observed limb darkening profiles or from separate absolute measurements of F and I_0. Both methods of observation are linked as follows: the flux $F(\lambda)$ at the surface of the Sun and the irradiance $f(\lambda)$ measured at the top of the Earth's atmosphere are related to the specific intensity $I(\lambda,\,\mu)$ by

$$F(\lambda) = f(\lambda)/\pi(R/D)^2 \qquad (1)$$

and

$$F(\lambda) = 2\int_0^1 I(\lambda,\mu)\mu\mathrm{d}\mu = 2I_0\int_0^1 L(\lambda,\mu)\mu\mathrm{d}\mu \qquad (2)$$

with R the solar radius, D the distance of the Sun, $\mu = \cos(\theta)$, θ the heliocentric angle, and

$$L(\lambda,\mu) = I(\lambda,\mu)/I_0 = I(\lambda,\mu)/I(\lambda,\mu=1) \qquad (3)$$

the limb darkening at the wavelength λ. The F/I_0 ratios based on limb darkening observations are calculated from

$$F/I_0 = 2\int_0^1 L(\lambda,\mu)\mu\mathrm{d}\mu = 2\sum\nolimits_{n=0}^{N} A_n/(n+2) \qquad (4)$$

with the limb darkening expressed as

$$L(\lambda,\mu) = I_\mu/I_0 = \sum\nolimits_{n=0}^{N} A_n\mu^n \qquad (5)$$

The coefficients A_n are fitted to the measurements by a least squares procedure either by the observers ($N = 2$, 5, 6) or by us ($N = 2$).

2. Observations and comparison

Table 1 lists the observations which we compare in this investigation. These observations of the quiet Sun are made at different epochs and thus at different phases of the solar cycle; however, any variation of the irradiance and limb darkening with solar phase is below the accuracy of the observations discussed here (cf. Neckel & Labs 1994). The

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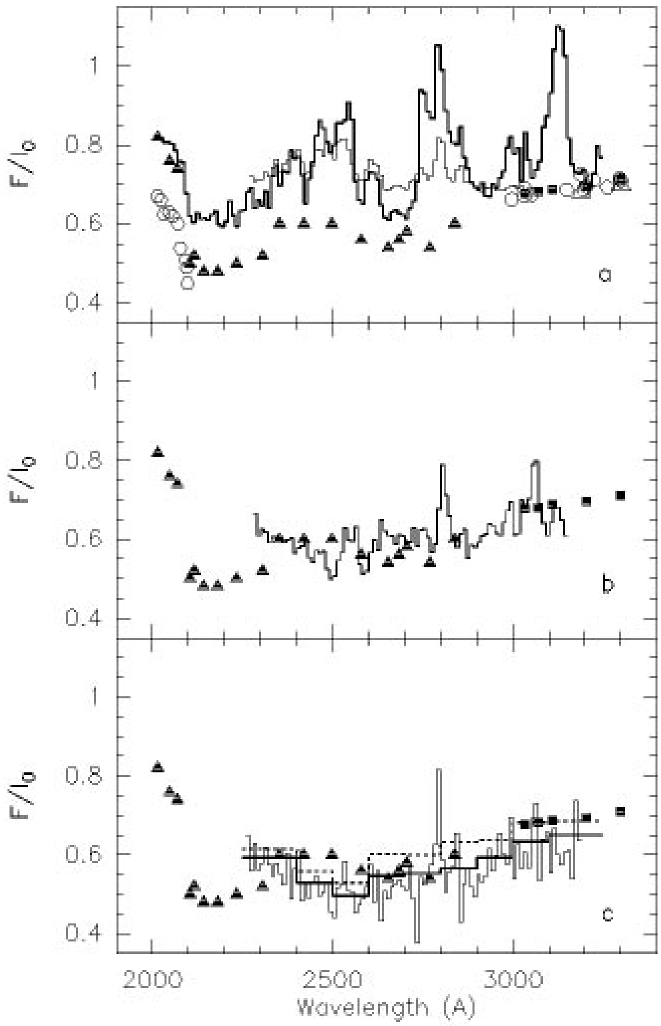

Fig. 1. a) F/I_0 ratios derived from limb darkening observations. Moe & Milone (1978): heavy line, KPK linear limb darkening approximation: thin line, Peyturaux (1955): open triangles, Bonnet (1968): solid triangles, Pierce & Slaughter (1977): solid squares, Samain (1979): diamonds, Mitchell (1981): open circles. **b)** F/I_0 ratios (averages of 10 Å wide intervals) based on irradiance measurements of Labs et al. (LNST, 1987) and disk–center intensities convolved from the Kohl et al. (KPK, 1978) solar atlas: thin line. For the ratios based on limb darkening observations see Fig. 1a. **c)** F/I_0 ratios (averages of 100 Å wide intervals) derived from disk–center intensities tabulated by Kohl et al. (KPK, 1978) and irradiance measurements of Heath (1980): thick line, and irradiance measurements of Labs et al. (LNST, 1987): dashed line. F/I_0 ratios (10 Å wide intervals) of the KPK disk–center intensities and the Mentall et al. (1981) irradiances: thin line. For the ratios based on the limb darkening observations see Fig. 1a

most detailed limb darkening observation of the UV wavelength region by Moe & Milone (1978; MM) is tabulated for 10 Å wide intervals; we comply with this resolution whenever possible or appropriate.

Table 1. Observations used for the determination of F/I_0

Observers	Wavelengths (Å)
(a) Limb Darkening Data	
Peyturaux (1955) $[N = 2]$ [a]	3190, 3300
Bonnet (1968) $[N = 2]$ [a]	2015 – 2839
Pierce Slaughter (1977) $[N = 5]$ [b]	3033, 3070, 3108 3205, 3299
Moe Milone (1978) $[N = 2]$ [b]	2285 – 3245 (MM)
Samain (1979) [c]	1999 – 2098
Kohl Parkinson Zapata (1980) [d]	2270 – 3055
Mitchell (1981) $[N = 6]$ [b]	2997 – 3300
Neckel Labs (1994) $[N = 5]$ [b]	3033, 3108, 3205, 3299
(b) Disk–center intensities (Atlas)	
Kohl Parkinson Kurucz (1978)	2252 – 3196 (KPK)
Allen McAllister Jefferies (1978)	2676 – 2931 (AMJ)
(c) Irradiances	
Heath (1980) [e]	2000 – 3300
Mentall Frederick Herman (1981) [e]	2000 – 3300
Labs Neckel Simon Thuillier (1987)	2000 – 3580 (LNST)

a) least squares fit to original data.
b) from coefficients of a N-th order limb darkening curve.
See the remark in Neckel & Labs (1994) of the superior accuracy of the 5th order approximation of the Pierce & Slaughter and Neckel & Labs observations.
c) F/I_0 ratios published by Samain.
d) from linear limb darkening approximation (Eq.(6)) through the KPK observation at $I(\mu = 1)$ and $I(0.23)$, with $I(0) = 0$.
e) see also the 100 Å averages published by Labs et al. (1987).

We use 10 Å and 100 Å wide intervals for the F/I_0 ratios based on absolute irradiance measurements of Mentall et al. (1981) and Heath (1980), respectively, and absolute disk–center intensities of the KPK atlas which are tabulated for 5 Å wide intervals (Table 2 in KPK). For the F/I_0 ratios based on measurements of Labs et al. (1987; LNST) we use their tabulated irradiances (Table III in LNST) and transmission profiles with which we convolved the KPK disk–center atlas to obtain the corresponding values I_0. From these individual ratios F/I_0 we calculated averages for the 10 Å wide intervals of the MM data grid. The (digitized) KPK atlas has many gaps and we find that on average $\sim$ 10% of the KPK data are missing in each of the LNST transmission profiles. In the convolution we adopt the value zero at the position of missing data. Since the data of the KPK atlas are apparently missing in a random way, we may assume that the corresponding disk–center intensities I_0 derived from the convolution of the KPK atlas with the LNST transmission profiles are too *low* by a similar amount of $\sim$ 10%. This assumption is confirmed in the following way. When comparing the F/I_0 ratios calculated from the LNST irradiances tabulated for

100 Å intervals (Table V in LNST) and the corresponding disk–center intensities of KPK (Table 2 in KPK) with the F/I_0 ratios calculated from the individual LNST observations (Table III in LNST) and the convolved KPK data, we observe that the latter F/I_0 ratios are higher by $10\pm^7_3$%. For this investigation we therefore reduced the F/I_0 ratios, based on the individual LNST observations and the convolved KPK data, by 10%.

Moe (1983) compared F/I_0 ratios derived from MM's limb darkening observation with those derived from a linear limb darkening approximation of KPK's observations at $\mu = 1$ (I_0) and $\mu = 0.23$ ($I(0.23)$), assuming that at the limb $I(0) = 0$. The F/I_0 ratios based on the linear limb darkening approximation of KPK's observation are derived from the relation (cf. Moe 1983)

$$F/I_0 = 0.58 + 0.390\ I(0.23)/I_0 \tag{6}$$

From these individual ratios F/I_0 we calculated averages for the 10 Å wide intervals of the MM data grid.

Both types of F/I_0 ratios, i.e. those derived from limb darkening coefficients and those derived from absolute radiation measurements, are displayed in Figs. 1a-c. The figure shows good agreement between the F/I_0 ratios derived from the limb darkening observations of Peyturaux (1955), Bonnet (1968), Pierce & Slaughter (1977), and Mitchell (1981) and the F/I_0 ratios derived from the tabulated KPK disk–center intensities and the irradiance data of Heath (1980) and Mentall et al. (1981). The F/I_0 ratios derived from the individual LNST observations and the corresponding convolved KPK disk–center intensities agree well with the other observations.

When compared with these F/I_0 ratios, most of the F/I_0 ratios based on Moe & Milone's limb darkening observation are too high while also showing an unrealistic variation with wavelength, in particular at $\lambda \approx 3100$ Å and near the Mg I ionization edge at 2510 Å. Their high ratios F/I_0 near 2800 Å are probably affected by the $\sim \pm$ 150 Å wide Mg II resonance line (2795, 2802 Å) absorption profile, where measurements are difficult because of the low residual intensity in the line core region (cf. Kohl & Parkinson 1976; Greve & McKeith 1980; Greve 1980; Staath & Lemaire 1995).

The F/I_0 ratios based on the linear limb darkening approximation of KPK's observation seem to be too high at wavelengths $\lambda \lesssim 2900$ Å, and in particular near 2500 Å. This fact is important to note since Kohl et al. (1980) derived irradiances under the condition of a linear limb darkening approximation (Eq. (6) and Table 2).

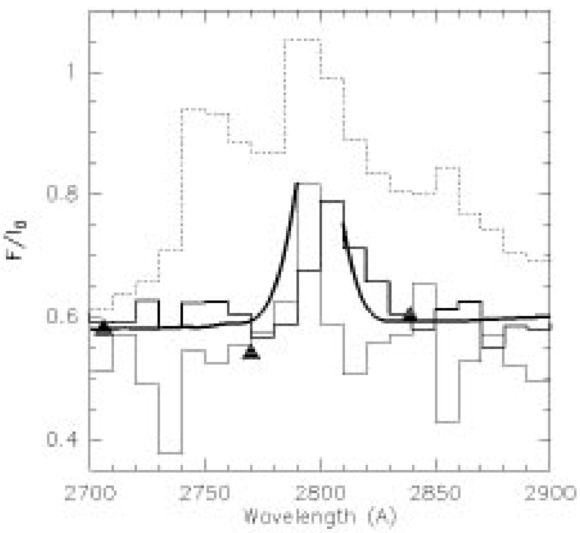

Fig. 2. F/I_0 ratios in the region of the Mg II resonance lines. Labs et al. (LNST) data and convolved KPK data: heavy histogram, Mentall et al. data and KPK data: thin histogram, Moe & Milone data: dashed histogram, Bonnet data: triangles, model calculation (Greve 1980): heavy line

3. Remarks

We make the following remarks with respect to similarities and discrepancies of the data shown in Fig. 1:

1) At the common wavelengths (Table 1) there exists agreement of the F/I_0 ratios derived from Pierce & Slaughter's (1977) and Neckel & Labs' (1994) observations. The Neckel & Labs' data are therefore not shown in Fig. 1.

2) The F/I_0 ratios derived from Pierce & Slaughter's limb darkening observations are accurate within 0.5% at $\lambda \geq 3300$ Å (cf. Neckel & Labs 1984). There is no reason to expect a significantly lower accuracy at $\lambda \leq 3300$ Å and this assumption is supported by the agreement with the F/I_0 ratios derived from Peyturaux's, Mitchell's, and Neckel & Labs' limb darkening observations. Note that the position on the Sun of the KPK observation was determined from the comparison of their measured limb/disk intensity ratio and the limb darkening observation of Peyturaux, checked in turn against the limb darkening observations of Pierce & Slaughter.

3) The accuracy of the F/I_0 ratios derived from Bonnet's limb darkening observation is estimated to be of the order of 5% (see his Figs. 4 and 5). The F/I_0 ratios derived from Bonnet's observation agree well with the F/I_0 ratios derived from the various absolute measurements of F and I_0. However, when compared at the position $\mu = 0.25$, the intensity ratios $I(0.25)/I_0$ of Bonnet's observation are on average ~ 35% smaller than the corresponding ratios $I(0.23)/I_0$ of KPK's observation (Kohl et al. 1980).

4) There occurs a strong variation of the F/I_0 ratios between 2000 Å and 2100 Å when crossing the Al I absorption edge at 2071−2076 Å. This variation is evident from the data of Bonnet, Moe & Milone, and the limb darkening observation of Samain (1979).

5) At the common wavelengths (Table 1) there exists agreement between the F/I_0 ratios based on the

individual LNST irradiances and the corresponding disk–center intensities I_0 derived from the convolution of the KPK atlas (with the values I_0 increased by 10%) and the ratios obtained from a similar convolution of the AMJ atlas.

6) As shown by Kohl et al. (1980) there exists agreement between the $I(0.23)/I_0$ ratios derived from MM's observation and KPK's observation. There exists also some similarity between the F/I_0 ratios derived from MM's observation and those derived from the linear limb darkening approximation of KPK's observation. However, both F/I_0 ratios disagree with the ratios based on other limb darkening observations and absolute radiation measurements.

7) The F/I_0 ratios derived from Moe & Milone's limb darkening coefficients have apparently the lowest accuracy. MM deduce the limb darkening from intensities measured at 6 positions within 300″ of the limb ($0.685 \leq \sin(\theta) \leq 0.998$); the associated disk–center intensities are obtained from extrapolation of the 'mean' intensity to $\sin(\theta) = 0$. Obviously, the accuracy is less than 15% as claimed by Moe & Milone.

8) The F/I_0 ratios based on Peyturaux's, Bonnet's, Pierce & Slaughter's, Mitchell's, and Neckel & Labs' observations refer to high points of the spectrum ('continuum windows'; spectral resolution $\lesssim$ 0.1 Å for Pierce & Slaughter, Neckel & Labs, and $\lesssim$ 0.4 Å for Peyturaux & Bonnet); the other F/I_0 ratios discussed here refer to averages of 10 Å and 100 Å wide intervals which include many absorption lines (cf. Greve & McKeith 1995; Greve et al. 1996). Since, generally, the strength of absorption lines increases towards the limb, the F/I_0 ratios averaged over the wider wavelength intervals are estimated to be smaller by 1−2% with respect to those based on continuum windows. However, this effect may be neglected in view of other errors, except for regions with strong absorption lines like the Mg II (2795, 2802 Å) resonance lines and the Mg I 2852 Å line (cf. Neckel & Labs 1984).

The F/I_0 ratios for a 200 Å wide interval centered on the Mg II resonance lines are shown in Fig. 2. However, the Mg II resonance lines produce the strongest and widest absorption feature of the solar spectrum (equivalent width = 83 Å, Greve & McKeith 1980) and thus are exceptional. The figure shows also the F/I_0 ratios derived from model calculations of the Mg II resonance lines (Greve 1980) in which the limb darkening at the far wings of these lines (2700 Å, 2900 Å) was adjusted to the observation of Bonnet. A recent determination of the limb darkening at the core of the Mg II resonance lines (2800.2 Å and 2807.7 Å) and the core of the Mg I line (2847−2849.5 Å) agrees with the limb darkening observations of Peyturaux and Bonnet (Briand & Lemaire 1994; Staath & Lemaire 1995).

9) We have based the disk–center intensities I_0 exclusively on the KPK solar atlas. The error in the absolute calibration of the KPK disk–center atlas is quoted as ± 12% (Kohl & Parkinson 1976; KPK 1978; Kohl et al. 1980); we assume a similar accuracy for the KPK tabulated disk–center intensities. The AMJ atlas was calibrated against the KPK atlas.

Kohl et al. (1980; KPZ) use the linear limb darkening approximation of the KPK data to calculate irradiances for 100 Å wide intervals. In Table 2 we compare these KPZ irradiances with corresponding values measured by LNST. We find significant differences for the wavelength region 2400−2600 Å and systematically higher irradiances than measured by LNST, although the deviations in the wavelength region 2600 Å $\lesssim \lambda$ do not exceed 20%. The consistency of the LNST data with other absolute measurements is discussed in the publication of LNST and is estimated to be ∼ 5%.

Table 2. Solar irradiances (in $\mathrm{Wm^{-2}}$)

Wavelength interval (Å)	KPZ [a]	LNST [b]	KPZ/LNST (%)
2300 – 2400	0.54	0.46	17
2400 – 2500	0.74	0.54	37
2500 – 2600	1.12	0.79	42
2600 – 2700	2.39	2.09	14
2700 – 2800	2.41	2.09	15
2800 – 2900	3.74	3.15	19
2900 – 3000	5.82	5.73	1.5

a) Kohl et al. (1980), b) Labs et al. (1987).

10) The error in the Mentall et al. (1981) irradiance data is ± 8%; a similar error must also be assumed for the irradiance data of Heath (1980). The rms–error of the Labs et al. (LNST 1987) irradiance data is quoted as ∼ 5%, neglecting a possible systematic difference in spectral response between the laboratory (calibration) and (Spacelab–) in–orbit measurements.

4. Conclusion

We conclude that the displayed F/I_0 ratios, and their basic limb darkening observations and absolute radiation measurements, agree within the limits of the quoted errors, except for the ratios based on Moe & Milone's limb darkening observation. We feel that considerable caution should be exercised when using these data, in particular when applied to extrapolate near limb observations or disk–averaged observations to disk–center intensities, and vice versa.

There remains the fact that the F/I_0 ratios and irradiances derived from the linear limb darkening approximation of KPK's observation are consistently too high, though only by ∼ 20%, except near 2500 Å where the discrepancy is 30−40%.

We notice that the important limb darkening determinations of the discussed UV wavelength region between 2000 and 3300 Å are made before ∼ 1980. It may be worth the effort and costs to repeat a detailed limb darkening observation in this wavelength region.

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