THE SOLAR CONSTANT

(A Compilation of Recent Measurements)

DIETRICH LABS

Landessternwarte Heidelberg-Königstuhl, Germany, F.R.

and

HEINZ NECKEL

Hamburger Sternwarte in Bergedorf, Germany, F.R.

(Received 11 January, 1971)

Abstract. A detailed compilation of the most recent values of the solar constant is given (13 values published from 1967 to 1970). The most probable value seems to be 1.95 cal cm^{-2} min^{-1} or 1.36 kW m^{-2} with a formal rms error of $\pm 0.3\%$. The corresponding effective temperature is 5770 K.

Systematic errors of the order of $\pm 1\%$, but also a possible variability of the same order cannot be excluded.

1. Introduction

Induced by the requirements of modern space research as well as for a better understanding of the radiation balance in the Earth's atmosphere, many almost direct observations of the solar constant have been carried out at high altitudes from balloons, research aircraft, a satellite, and even interplanetary space probes, during the last few years. Furthermore, several authors used ground-based, absolute spectrophotometric observations to evaluate the solar constant. However, most of the results have been published either in special research-reports, meteorological journals or other periodicals normally not accessible in astronomical libraries. Since the 'best' value of the solar constant is of some interest to astronomers too, we have tried to collect as far as possible all these recent determinations. Some critical remarks are added.

2. The Individual Observations

The results of all recent measurements of the solar constant are summarized in Table I, which contains also various remarks such as on the techniques applied etc., and in Figure 1.

Five of the thirteen values quoted are related to blackbody radiation. Only one of these (Labs and Neckel, 1970) has been cited to be in accordance with the 'International Practical Temperature Scale of 1968' (IPTS 1968: freezing point of gold $T_{Au}=1337.58$ K, radiation constants $c_2=1.4388$ cm K and $2\,C_1=1.1910\times 10^{20}$ W cm^{-2} $ster^{-1}$ Å^4; see Barber (1969) and Comité International des Poids et Mesures, 1969). Three further values (Sitnik, 1967; Arvesen, 1969; Stair and Ellis, 1968) are related, according to the references given, to the International Temperature Scale of 1948 (ITS 1948: $T_{Au}=1336.2$ K, $c_2=1.438$ cm K). The remaining value (McNutt

Solar Physics **19** (1971) 3–15. *All Rights Reserved*

Recent m... sola

No.	Author	Solar constant $\left[\frac{\text{cal}}{\text{cm}^2\ \text{min}}\right]$	$\left[\frac{\text{kW}}{\text{m}^2}\right]$	Scale	Authors' error	Actual deviation ($S = 1.950$)	Observation platform	Alti... [km]
1	Sitnik, 1967	**2.076** 2.091	1.448 1.458	IPTS 48 IPTS 68	±3.5%	+7.1%	(1) near sealevel (2) high mount. station	(1) 0... (2) 1...
2	v. d. Haar, 1968	**1.99**	1.39	? (complex)	±1.5%	+2.0%	satellite	> 20...
3	Stair and Ellis, 1968	**1.950** 1.964	1.360 1.370	IPTS 48 IPTS 68	±2%	+0.7%	high mountain station	4.0
4	Arvesen *et al.*, 1969	1.943 1.957	1.355 1.365	IPTS 48 IPTS 68	±3%	+0.4%	aircraft	11.6
5	Mariner 6 and 7, 1969	1.940	1.353	electric units	±1.5%	−0.5%	space probe	spac...
6	McNutt and Riley, 1968a	1.939 1.953	**1.352** 1.362	IPTS 48? IPTS 68?	±1.6%	+0.2%	aircraft	11.6
7	Drummond *et al.*, 1968	1.950	**1.360**	IPS 56	±1%	0.0%	(1) aircraft (2) X-15	(1) 1... (2) 8...
8	Kruger, 1968	1.947	**1.358**	electric units	±1.8%	−0.2%	aircraft	11.6
9	Labs and Neckel, 1970	1.947	**1.358**	IPTS 68	±1.4%	−0.2%	high mountain station	3.6
10	Kondratyev and Nikolsky, 1970	**≤1.940**	1.353	IPS 56	±1%	−0.5%	balloon	32.3
11	Duncan and Webb, 1968	**1.934**	**1.349**	IPS 56	±3%	−0.8%	aircraft	11.6
12	McNutt and Riley, 1968b	1.926	**1.343**	IPS 56	±1.9%	−1.2%	aircraft	11.6
13	Murcray *et al.*, 1969	**1.919**	1.338	IPS 56	±0.4%	−1.6%	balloon	31

To Table I: For Kondratyev and Nikolsky, Murcray, Labs and Neckel only the latest, final values are given. Arvesen's value has been corrected according to Duncan (1969). The 'Authors' errors' are not necessarily comparable; partly they are only personal rough estimates. For conversion of solar constant-units, the calorie was assumed to be defined as 4.1840 W s (see e.g. Condon, 1958). Authors' original values are given in boldface numerals.

Drummond (1968) refers to an unpublished aircraft value of Brandhurst which is 1.296 kW m^{-2} at an altitude of 14.5 km. This is in close agreement with the corresponding (uncorrected) value of Drummond which is 1.285 kW m^{-2} at 13.5 km.

A further value of the solar constant ($S = 2.03$ cal cm^{-2} min^{-1}) is given by Makarova and Kharitonov (1968). This value is the integral of a mean spectral irradiance, derived from about 20 individual curves published during the last 6 decades.

The results incorporated in Makarova's value may be divided into 3 categories:

(1) Results published more than 2 decades ago (Abbot 1902–1910, Abbot 1920–1922, Wilsing, Pettit).

(2) Results withdrawn by the authors themselves (Stair, Stair *et al.*, Stair and Johnston, Dunkelman and Scolnik, Labs, 1957).

(3) Results still valid today.

The results of categories 1 and 2 should not be discussed any more; category 3 contains also those results from which the individual authors have derived their own value of the solar constant. These values have been included directly in Table I (Sitnik, Labs and Neckel).

...he solar constant

...o. of ...ays or ...ights	Obs. time per day or flight	Window	Principle method	Observation instrument	Quantity measured
7d	several hours	–	spectro-photometric	spectrophotometer behind coelostat equipment	(a) photoelectric current of multiplier (b) thermoelectric emf of thermocouple
?	several months	no	total	system of black and white flat sensors	emf of thermocouple fastened to sensors
[illegible]	several hours	–	spectro-photometric	spectrophotometer behind diffusing sphere	photoelectric current of multiplier
1	2–4 hours	yes	spectro-photometric	spectrophotometer behind diffusing sphere	photoelectric current of (a) multiplier (b) lead sulfide cell
	several months	no	total	'Temperature Control Flux Monitor' (TCFM)	not quoted
	70–150 min.	yes	total	Hy-Cal normal incidence pyrheliometer	emf of thermopile fastened to blacked metal strip as detector
...) 13 ... 1	20^m–2^h 23 s	(1) yes/no (2) no	total	multichannel radiometer	emf of blacked thermopile used as detector
	70–150 min.	yes	total	cone radiometer	electric energy which heats cone to same temperature as solar radiation
2d	5–12 hours	–	spectro-photometric	spectrophotometer mounted at parallactic telescope	photoelectric current of multiplier
	1–2 hours	yes	total	'actinometer'	resistance of platinum thermometer fastened to detector
	70–150 min.	yes	total	Ångström compensation pyrheliometer	electric current which heats detector strip to same temperature as solar radiation
	70–150 min.	yes	total	Ångström compensation pyrheliometer	electric current which heats detector strip to same temperature as solar radiation
	22–100 min.	yes	total	Eppley normal incidence pyrheliometer	emf of thermopile fastened to blacked metal strip as detector

and Riley, 1968a) is most likely also related to the latter scale, but here no direct comments are given referring to this point.

It is of course the scale of 1968 to which all blackbody values should be related in order to be comparable as perfectly as possible with the values obtained by other absolute methods. To transform the '1948-values' into the 1968-scale, these have to be increased by 0.7% (see Labs and Neckel, 1970, Equation (20)). In Table I both the original 1948- and the transformed 1968-values are given; Table II and Figure 1 are based on the 1968-values alone.

The range covered by all results extends from 1.92 to 2.09 cal cm^{-2} min^{-1}, which is 9%! Nevertheless, we think the 'most probable' value of the solar constant should be derived from these recent data alone, forgetting the huge bulk of discussions about the older, ground-based pyrheliometric values. This restriction seems to be justified in view of the completely new and mostly modern techniques applied in these recent determinations.

Not only the variety of data offered, but also the fact that the techniques used are

No.	Author	Correction for not measured UV-radiation	Correction for not measured IR-radiation	Correction for atmospheric
1	Sitnik, 1967	$\lambda < 0.328\,\mu$: rocket data (Tousey, 1963)	$\lambda > 5\,\mu$: 0.005 cal cm^{-2} min^{-1}	Bouger's method; 2–3 poi and wavelength
2	v. d. Haar, 1968	no correction necessary	no correction necessary	no correction necessary
3	Stair and Ellis, 1968	$\lambda < 0.31\,\mu$: rocket data	$\lambda > 0.53\,\mu$: Johnson's data	Bouger's method; relative between 1.1 and 3
4	Arvesen *et al.*, 1969	$\lambda < 0.3\,\mu$: rocket data	$\lambda > 2.5\,\mu$: 5800 K greybody approximation	Bouger's method; data of combined
5	Mariner 6 and 7, 1969	no correction necessary	no correction necessary	no correction necessary
6	McNutt and Riley, 1968a	as for No. 11 and 12	as for No. 11 and 12	as for No. 11 and 12
7	Drummond *et al.*, 1968	(1) computed from nearest available ozone concentr.: 2.0%; (2) no correction	(1) 3.3% (2) no correction necessary	(1) computed from standar atmosphere: 2.2%; (2) no correction necessary
8	Kruger, 1968	as for No. 11 and 12	as for No. 11 and 12	as for No. 11 and 12
9	Labs and Neckel, 1970	$\lambda < 0.33\,\mu$: rocket data	$\lambda > 1.25\,\mu$: model atmosphere fitted to abs. data for $\lambda < 12.5\,\mu$	Bouger's method; relative between 1.2 and 5; 10–20 p and wavelength
10	Kondratyev and Nikolsky, 1970	$\lambda < 0.3\,\mu$: 0.020 cal cm^{-2} min^{-1}	$\lambda > 3.7\,\mu$: 0.014 cal cm^{-2} min^{-1}	Bouger's method applied radiation; airmass-interval (1–2 h.)
11	Duncan and Webb, 1968	Fit of theoretical extrapolation curve to results obtained at different airmasses (all flights c		
12	McNutt and Riley, 1968b	Theoretical extrapolation curve computed from Johnson's irradiance (including UV and Elterman's Tables of extinction parameters (inclusive ozone absorption) and window tra		
13	Murcray *et al.*, 1969	Computed from Elterman's Tables; inclusive extinction: 0.035 cal cm^{-2} min^{-1}	$\lambda > 4\,\mu$: 0.017 cal cm^{-2} min^{-1}	Computed from Elterman's Tables; combined with UV

partly of very different nature, suggest the need for a proper weighting. Arguments for several different averages could be derived from the mean errors given by the authors, the internal accuracy, the complexity of the experimental devices, the way necessary corrections have been applied etc. However, since it is almost impossible to judge the reliability of all results with the same objective criteria, any weighting is bound to be more or less subjective. Table II may give some idea about the consequences of the vagueness of proper averaging.

The uncertainties of choosing a 'final' value are of the order of $\frac{1}{2}\%$, which appears to be about the limit of accuracy we can reach nowadays with modern techniques. Therefore there seems to be no justification for worrying too much about the 4th digit, and one simply should agree upon a most suitable round value which is

$$1.95_0 \text{ cal cm}^{-2}\text{ min}^{-1} \quad \text{or} \quad 1.36_0 \text{ kW m}^{-2}.$$

ntinued)

…bration	Remarks
tungsten ribbon lamp (being calibrated with reference to blackbody ation) about 5 times per month.	Relative low internal accuracy
ving the equation for the energy balance of sensors and its environment; erial constants from laboratory tests.	Originally intended to determine the radiation budget of Earth's atmosphere; global balance requires $S = 1.92$
1000 W tungsten-filament quartz-iodine lamp (being calibrated with rence to blackbody radiation) several times per day.	
1000 W tungsten-filament quartz-iodine lamp (being calibrated with rence to blackbody radiation) permanently with 30 c/s.	According to Duncan (1969) original value (1.390) has to be lowered by 2.5% due to corr. of lamp calibration
quoted	Only secondary literature available
mparison with standard pyrheliometer (using natural sunglight?) ng calibrated with reference to blackbody radiation.	
Eppley-Ångstrom electrical compensation pyrheliometer (being com- ed frequently with WMO standards in Davos) with natural sunlight; re and after each flight.	
rgy released equals product of electric current times voltage; calibration ends on that of digital voltmeter and standard resistance.	
tungsten ribbon lamp (being calibrated with reference to blackbody iation) every 15 min; direct or indirect scale comparison with 4 other oratories.	
tinometers were repeatedly calibrated by the Sun, i.e. indirectly checked h the USSR reference standard'.	Altogether 25 values; most of them are considerably lower; (aerosol?)
mparison with Eppley standard pyrheliometer at Table mountain and Eppley laboratory; with natural sunlight; after flight program only.	On one day cirrus clouds!
mparison with Eppley standard pyrheliometer at Table mountain and Eppley laboratory; with natural sunlight; before and after flight program.	
mparison with Eppley-Ångstrom pyrheliometer being standardized with pley primary standard; with natural sunlight; before and after each ht.	A 4th flight yielded a 1% lower value; 'question of a residual aerosol correction remains open'.

3. Limitations of Accuracy

From Tables I and II and Figure 1 one might conclude that the deviation of the proposed round value from the 'true' one should be not larger than 0.01 cal cm^{-2} min^{-1} or 0.5%. To prevent an overestimate of the accuracy it seems advisable to point out the following facts:

3.1. Accuracy of blackbody calibration

The uncertainty about the scale which the value of McNutt and Riley is based upon, causes only an uncertainty of 0.1 to 0.2% for the mean values of Table II. The accuracy of the IPTS 1968 is probably of the same order. But the actual realization of black-body radiation and the calibration procedures for the secondary standards possibly

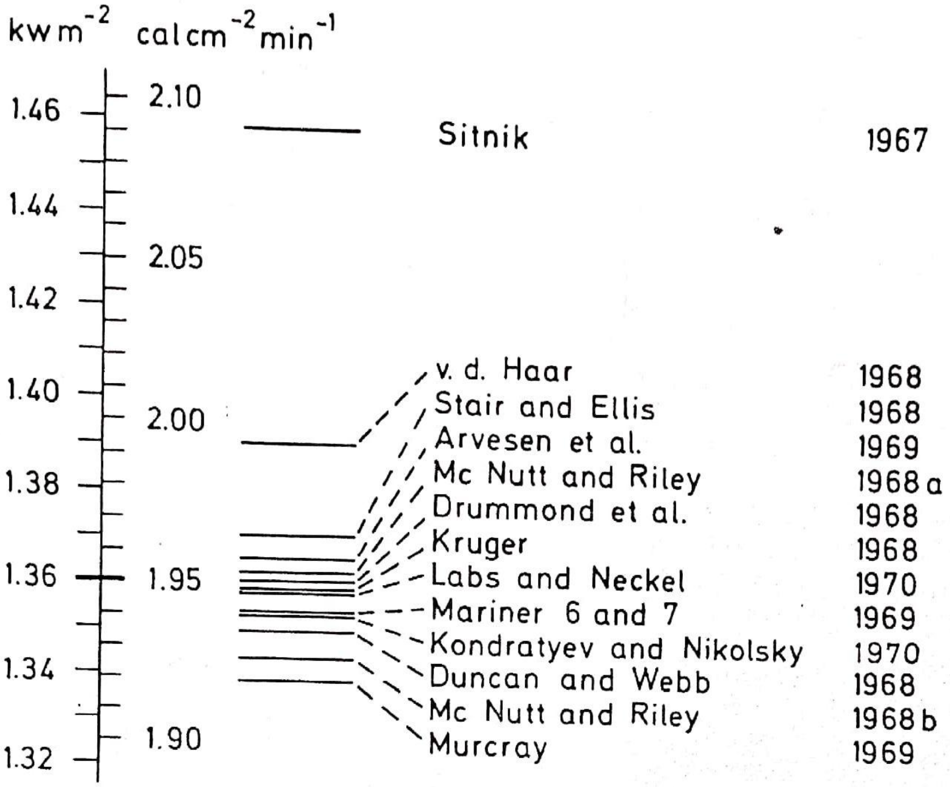

Fig. 1. Recent measurements of the solar constant. (From Table I, col. 3 and 4; blackbody calibrated values in IPTS 1968.)

still involve systematic errors, which might affect all blackbody values by as muc as $\pm 1\%$ or even more.

3.2. Accuracy of IPS 1956

Five of the thirteen values cited are quoted to be in the 'International Pyrheliometri Scale 1956' (IPS 1956) (Drummond, 1968; Kondratyev, 1970; Murcray, 1969; Dunca and Webb, 1968; McNutt and Riley, 1968b). According to Courvoisier (1957) the IP 1956 may be characterized as follows:

(1) '... radiation measurements are normally standardized by one of two types o instrument, the Abbot silver disk pyrheliometer and the Ångström compensatio pyrheliometer'.

(2) 'Ultimate references' are (a) 'a calorimeter maintained by the Smithsonia Institution' and (b) 'a standard Ångström instrument used absolutely'. Secondar instruments are calibrated by comparison with the ultimate references, using the Su (near sealevel) as radiation source.

(3) These 'ultimate references' define (a) 'the Smithsonian Scale of 1913' and (b) 'th original, uncorrected Ångström Scale' respectively.

(4) The difference between both scales, which has never been determined by direc comparison of the 'ultimate references', but only by comparison of secondary in struments, is 3.50% near sea-level, but it increases to 5.27% at the altitude of Davo (1561 m).

TABLE II

Selected mean values and rms-errors
(From Table I, col. 3 and 4; for blackbody-calibrated values IPTS 1968)

	Special mean values cal cm^{-2} min^{-1}	kW m^{-2}	Number of single values	rms-error of single values
All values	1.958 ±0.012	1.366 ±0.008	13	±2.2%
All values without that of Sitnik	1.947 ±0.006	1.358 ±0.004	12	±1.0%
All 'total' values obtained above 11 km	1.944 ±0.007	1.356 ±0.005	9	±1.1%
All spectrophotometric values without Sitnik's (all in IPTS 1968!)	1.956 ±0.005	1.364 ±0.003	3	±0.5%
'Total' IPTS 1968-value	1.953(±0.031)[a]	1.362(±0.022)[a]	1	–
All, total and spectrophotom., IPTS 1968-values (without that of Sitnik)	1.955 ±0.004	1.364 ±0.003	4	±0.4%
All IPS 1956-values	1.934 ±0.005	1.349 ±0.003	5	±0.6%
Values in scale of electric units	1.944(±0.005)	1.356(±0.004)	2	(±0.4%)
Proposed round value	1.95_0 ±0.006[b]	1.36_0 ±0.004[b]	–	–

[a] Author's error, [b] without Sitnik's value.

(5) The IPS 1956 is defined by the instruction: 'Measurements made according to the original Ångström Scale should be increased by 1.5% ... measurements made according to the Smithsonian Scale of 1913 should be reduced by 2.0%'.

(6) But 'the Smithsonian Institution considers the 1913 scale to be in error by 2.5%' (instead of 2.0%), whereas 'the Stockholm Institute considers that a correction of +2% should be made to the Ångström Scale' (instead of 1.5%).

(7) The IPS 1956 was established 'noting the urgent need of a *unique* international scale ... especially during the International Geophysical Year', but obviously the absolute correctness of such a unique scale was of secondary importance.

With respect to the 'true' energy-scale, a systematic error of the IPS 1956, which might be as large as 1% or 0.02 cal cm^{-2} min^{-1}, is quite possible.

A detailed discussion of the radiation scales is given by Duncan (1969).

3.3. Possible Variation of the Solar Constant

The problem of variability of the solar constant is not yet solved. Kondratyev and Nikolsky (1970) believe to have found a correlation between the solar constant and the relative sunspot number R, implying a total variation of the solar constant of as much as 2–2.5% ($S = 1.940$ cal cm^{-2} min^{-1} for $R \approx 80$, and $S \lesssim 1.90$ for $R \approx 0$ or

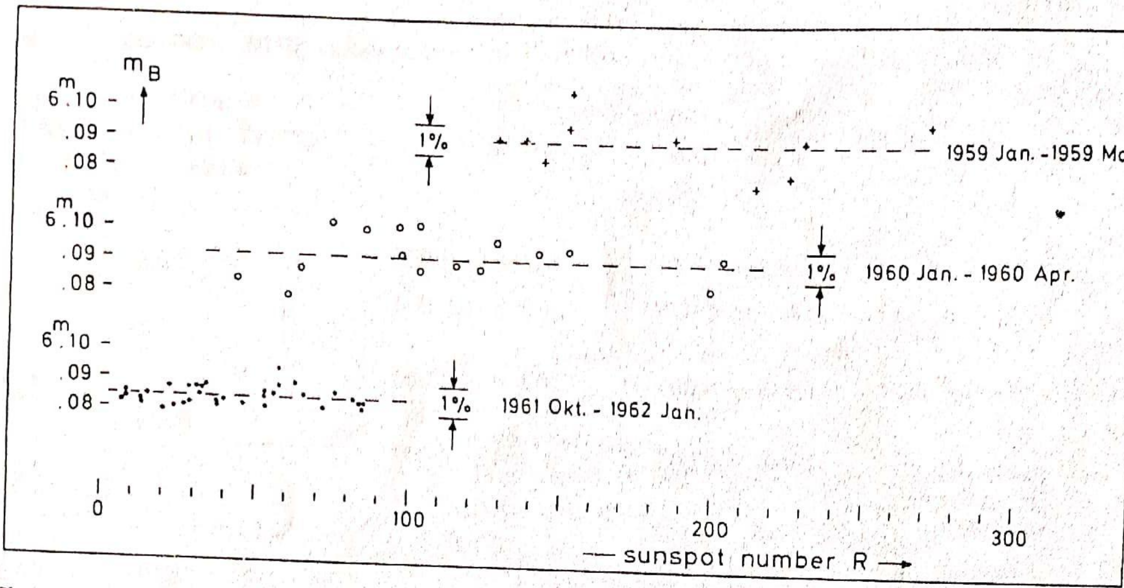

Fig. 2. B-magnitudes (according to Jerzykiewicz and Serkowski, 1966) of the planet Uranus plotted against relative sunspot numbers R as seen from the planet.

Figure 2 gives the B-magnitudes of the planet (according to Jerzykiewicz and Serkowski, 1966, Tables VI and VII respectively) plotted against the sunspot number R (Waldmeier, 1960–1963).

The sunspot numbers have been related to the position of the planet, assuming the numbers did not change significantly during that part of the solar rotation-period which corresponds to the difference of the heliocentric longitudes of Earth and planet (maximal 9 days).

The scatter is possibly due to albedo-variations of the planet during its rotation.

$R \approx 200$). However, as may be seen from Figure 2 this correlation is not confirmed if the brightness of the planet Uranus is used as a measure of solar radiation.

On the other hand, the magnitudes of Uranus and Neptune, which cover the period 1950–1966 (Johnson and Iriarte, 1959; Serkowski, 1961; Jerzykiewicz and Serkowski, 1966), have been analyzed by Albrecht *et al.* (1969) for variations related to the solar rotation period. These authors deduced a magnitude variation with amplitudes between $0\overset{\mathrm{m}}{.}002$ and $0\overset{\mathrm{m}}{.}007$, amplitude and period (correlated to the rotation period of the Sun) being slightly variable during the 11 yr solar-cycle. Supposing that a possible variation of the solar radiation is proportional to $1/\lambda$, these magnitude differences would correspond to a variation of 0.1–0.4% for the solar constant (see Labs and Neckel, 1970, Equation (12)). But also in this case the conclusion drawn by the authors appears to be little convincing because the scatter of the observed magnitudes is about 4 times as large as the amplitude derived. However, the reality of such an effect cannot be ruled out.

More convincing in our opinion is the variation of the annual mean magnitudes of Uranus and Neptune, which have been published by Jerzykiewicz and Serkowski (1966). From 1954, when the observing procedure was changed 'in order to improve the accuracy of the magnitudes ...', to 1966, a correlation between the light curves of both planets is indicated as shown in Figure 3.

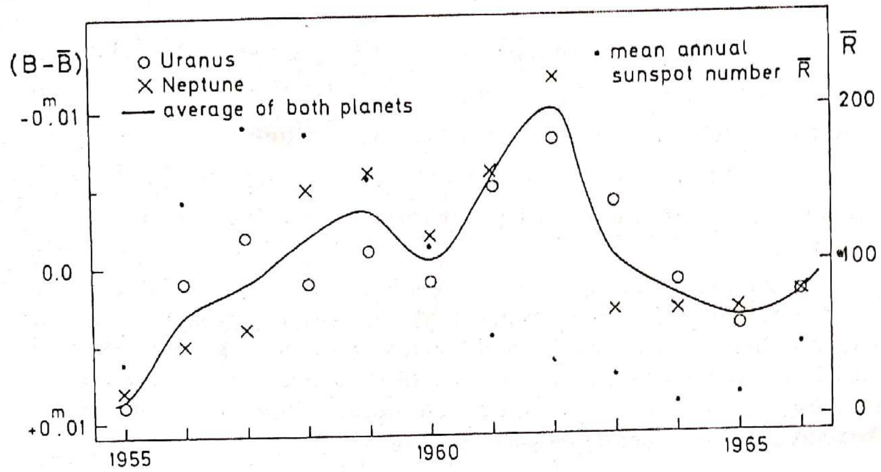

Fig. 3. Deviations of annual mean magnitudes of the planets Uranus and Neptune (according to Jerzykiewicz and Serkowski, 1966) from the mean value of the period 1955–1966. The small dots give the annual mean of the sunspot numbers (according to Waldmeier).

The total amplitude of the averaged light curve is $\Delta B = 0\overset{m}{.}018$ while the internal agreement of the light curves is characterized by a mean error of $0\overset{m}{.}003$ for one single annual mean value. If these variations are not due to either observing and reduction techniques or changes of the planetary albedo, then they do indicate a variability of the solar constant in the order of 1%. A minimum would have occurred in 1955, a maximum in 1962.

On account of the data available at the present time, one cannot rule out variations of the solar constant with total amplitudes up to 1%, but no final conclusions can be drawn about possible periods or correlations to other solar phenomena.

3.4. Restrictions for High Altitude Measurements

From a critical consideration (of Table I for instance) one must conclude that it is not the use of aircraft, balloons, satellites and space probes which has brought about an improvement but instead the relatively large number of experiments encouraged by these new techniques. A single aircraft value, even if based on several flights, is hardly more accurate than a ground-based value, carefully derived from absolute spectrophotometric observations carried out in high mountain regions. The gain in stability of the transparency of the remaining atmosphere, when ascending from 4 to 11 or 30 km, is at least partly compensated by the disadvantages which are necessarily associated with the flight techniques.

In this respect it ought to be considered that in the case of balloon and aircraft observations the ultraviolet part of the spectrum below about 0.3 μ is cut off by the ozone layer to almost the same extent as in the case of high mountain observations, and the infrared radiation beyond 3–4 μ is generally blocked by one or more glass- or quartz-windows in front of the final sensor. Consequently, the reduction of atmospheric extinction, which is claimed to be the essential advantage, becomes effective only for the spectral region from about 0.3–3μ. But although the amount of extinction is

– of course – considerably less at an altitude of 10 or even 30 km than at 4 km, the accuracy of its derivation suffers here from the fact that the duration of flight is too short for an adequate determination. Approximate values for the extinction have to be used, which are either computed from an adopted standard-atmosphere, or are derived from observations made on different days with different altitudes of the Sun.

Such a treatment of extinction implies the questionable hypothesis that the optical properties of the corresponding atmospheric layers are not variable at all with respect to location and time. We think it is not safe to assume that for instance the zenith-extinction above 11 km is the same in the early morning of August 16 above New Mexico and at noon of September 10 somewhere above the Pacific. In this connection one has to realize that some high altitude flights were obviously disturbed by clouds, others by unusual aerosol contents!

Additionally, the correction for atmospheric extinction is not only subject to the spectral sensitivity of the sensor, but also to the spectral distribution of the solar irradiance. Errors up to at least $\frac{1}{2}\%$ may arise from using incorrect data, as for instance Johnson's (1954) irradiance curve, which has been shown to be in error particularly below 0.5μ, where it had been based on the erroneous data of Dunkelman and Scolnik (1959).

For the same or similar reasons the accuracy of the corrections for the not measured UV- and IR-radiation is also limited.

Concerning the observations from balloons, satellites and space probes, one has to realize that these are made until now only without any direct control by men. But the required high precision can only be achieved by an optimal adjustment of all parts of the equipment. Such optimal adjustment seems hardly guaranteed in unmanned flights.

3.5. Consequences

As a consequence of all the restrictions mentioned, it will be very difficult, if not impossible, to push the accuracy of the solar constant definitely below the 1% limit with respect to the true energy-scale.

In fact, it must sound unrealistic to suppose that the solar radiation can be measured with higher accuracy than the radiation of a terrestrial light source. Only if we have succeeded in obtaining the same results for the radiation flux of any artificial light source with different types of sensors, we can expect to measure the solar radiation with a corresponding accuracy.

4. Conclusion

The recent determinations of the solar constant have brought the result that the 'true' value must be considerably lower than that one generally adopted since Johnson's (1954) analysis of the whole Smithsonian material ($S = 2.00$ cal cm^{-2} min^{-1}). The actual value of the solar constant must in fact be close to

$$1.95 \text{ cal cm}^{-2} \text{ min}^{-1} \quad \text{or} \quad 1.36 \text{ kW m}^{-2}.$$

Except for Sitnik's value, the agreement of the other results is *remarkable* in view of the very different nature of instruments, observing techniques, calibration procedures, and scales applied. The formal rms error of any special mean value is around ±0.3%, the formal rms error of a *single* value ±1% or even less. (The authors' errors are on the average ±1.8%!)

In spite of the good agreement, the actual uncertainty of the solar constant should not be overestimated, not only systematic effects but also an intrinsic variability may possibly be of the order of ±1% or 0.02 cal cm^{-2} min^{-1}.

The value of the effective temperature which corresponds to $S = 1.36_0 \pm 0.01$ kW m^{-2} is

$$T_e = 5770 \pm 10\,\mathrm{K}.$$

(With $\sigma = 5.670 \times 10^{-12}$ W cm^{-2} K^{-4} and $(R/r)^2 = 4.620 \times 10^4$, where R/r = ratio of astronomical unit to solar radius.)

Note added March 23, 1971. After this paper was accepted for publication, M. P. Thekaekara and A. J. Drummond (1971, *Nature, Phys. Sci.* **229**, 6) proposed new 'Standard Values for the Solar Constant and its Spectral Components'.

I. Solar Constant: The proposed value (1.940 cal cm^{-2} min^{-1} or 1.353 kW m^{-2}) is a *weighted* average of the No. 5–8 and 10–13 of our Table I. The results of Sitnik, v.d. Haar, Stair and Ellis, Arvesen, and Labs and Neckel (No. 1–4 and 9 of Table I) have not been taken into account. The result obtained with the blackbody-calibrated Hy-Cal instrument (McNutt and Riley, 1968a) has not been transferred into the IPTS 1968 scale.

The weighting factors, ranging from 3 to 10, 'are based on the evaluations and criticisms of the members of the committee ...'. They demonstrate the difficulty of such a procedure: For example, the value of Kondratyev and Nikolsky (Table I, No. 10) was supposed to be 'based on large samples' and got – besides the Mariner data and the results of Drummond *et al.* (Table I, No. 5 and 7) – maximum weight. Actually it is the result of one single flight only, obtained on June 27, 1967. (7 further values are in the range 1.900–1.932, the rest is below 1.90 cal cm^{-2} min^{-1}.)

The difference between the value proposed by Thekaekara and Drummond and that proposed in this paper is insignificant. It demonstrates the effect of the individual choice of the weighting procedure (cf. Table II).

II. Spectral Irradiance: The proposed data are essentially based on the 'NASA 711 Galileo' flight experiment of the Goddard Space Flight Center (GSFC; M. P. Thekaekara *et al.*: 1968, *Appl. Opt.* **8**, 1713). Minor modifications ($\leqslant$2.4%) have been made on account of the – preliminary – filter data given by Drummond *et al.* (1967, *J. Spacecraft Rockets* **4**, 1200). 'Because of the large uncertainties in extrapolating to zero air mass, the ground based work was not considered strong enough to modify the GSFC (monochromator) data'.

The advantage of this restriction to the high altitude measurements only is very dubious: As may be seen from Figure 17 of the GSFC-paper cited above, the differences

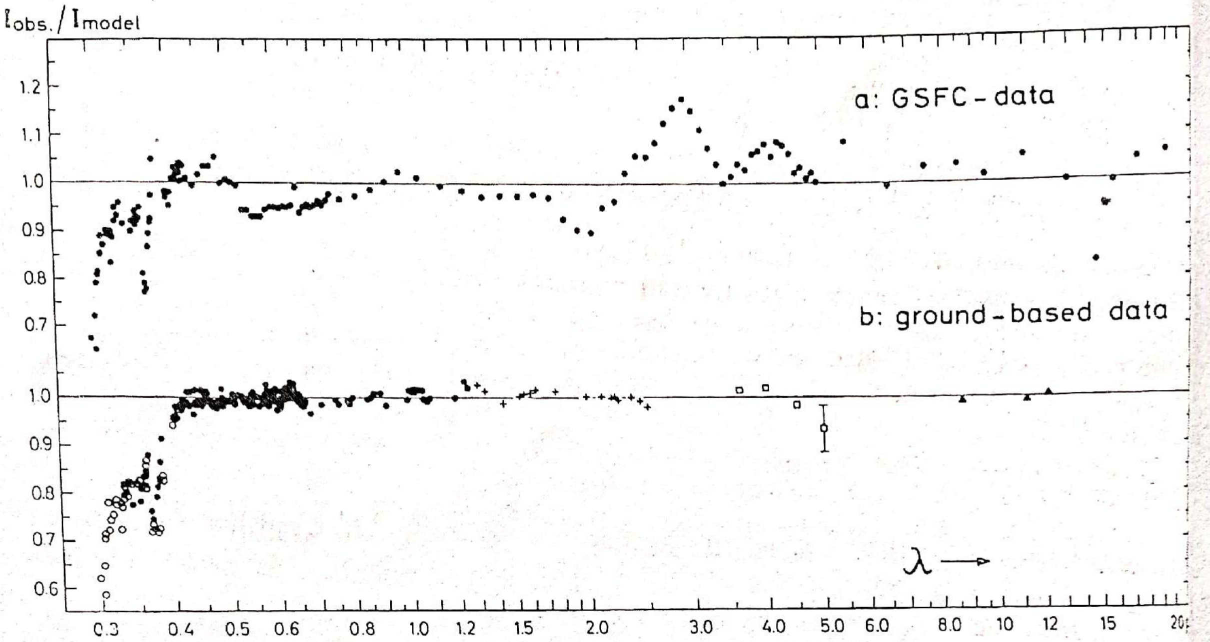

Fig. 4. Ratio of observed 'continuum' intensities to model-continuum. (Below 0.5μ the observe intensities are those in the highest 'windows'. For details see Labs and Neckel, 1968, 1970.) (a) Fo the 'GSFC-continuum' corresponding to the irradiance observed within 'NASA 711 Galileo' fligh experiment of GSFC. (b) For high mountain observations with careful determination of atmospher extinction, according to Houtgast (○) 1970, Labs and Neckel (●) 1970, Pierce (+) 1954, Farme and Todd (□) 1964, and Saiedy (▲) 1960.

between the individual GSFC-experiments amount up to 10–20%. Similarly, the dif ferences between Drummond's filter data and the mean GSFC-values are in the aver age 5.4%, amounting up to 11–12%. These experimental errors are considerably large than those caused by atmospheric extinction, if the observations are carried out a high mountain stations with stable meteorological conditions. With such favourab conditions, it is no problem to keep extinction errors of ground based spectrophoto metric observations below the 1% limit (for $\lambda > 0.33\mu$, except – of course – in water vapour bands etc.). Furthermore, for ground based observations also the other ex perimental errors may be kept in the order of 1–2% only (see chapter 3.4).

In Figure 4 we have related both the GSFC-data and some ground based observa tions to the model continuum. At least above 0.4μ the evaluation of a 'GSFC-con tinuum' is no problem and can here be achieved from the irradiance data with a accuracy of about $\pm 1\%$ (for details, especially concerning line blanketing data an the ratio mean to central intensity, but also for the irradiance data corresponding t the observations plotted in Figure 4b, see Labs and Neckel, 1968, 1970). In this spe tral region also the uncertainty of the adopted model continuum (Labs and Neckel 1968, Table 6) is generally less than 1%, as may be seen from a comparison with th continuum of the 'Harvard-Smithsonian Reference Atmosphere' (Gingerich *et al.* 1971, preprint). Therefore, it appears to be highly probable that the 'waves' of th 'GSFC-continuum' relative to the model continuum (Figure 4a) reflect just the ex perimental inaccuracies of the GSFC-irradiance rather than intrinsic characteristics o the solar atmosphere (see Labs and Neckel, 1968, Figure 9 and conclusion).

References

Albrecht, R., Maitzen, H. M., and Rakos, K. D.: 1969, *Astron. Astrophys.* **3**, 236.

Arvesen, J. C., Griffin, R. N., and Pearson, B. D.: 1969, *Appl. Opt.* **8**, 2215.

Barber, C. R.: 1969, *Nature* **222**, 929.

Comité International des Poids et Mesures: 1969, *Metrologica* **5**, 35.

Condon, E. U.: 1958, in *Handbook of Physics* (ed. by E. U. Condon and H. Odishaw), McGraw-Hill Book Comp. New York, Toronto, London, p. 5–13.

Courvoisier, P.: 1957, *Meddel. Sver. Meteorol. Inst. (B)* **13**, 18, 48.

Drummond, A. J. and Hickey, J. R.: 1968, *Solar Energy* **12**, 217.

Drummond, A. J., Hickey, J. R., Scholes, W. J., and Laue, E. G.: 1968, *Nature* **218**, 259.

Drummond, A. J. and Laue, E. G.: 1968, Jet Propuls. Lab. Report, Cal. Inst. Techn., Pasadena, California.

Duncan, C. H.: 1969, *Radiation Scales and the Solar Constant*, Goddard Space Flight Center Report No. X-713-69-382, Greenbelt, Maryland.

Duncan, C. H. and Webb, J. J.: 1968, in *The Solar Constant and the Solar Spectrum Measured from a Research Aircraft at 38000 Feet*, Goddard Space Flight Center Report No. X-322-68-304, Greenbelt, Maryland, p. 29.

Dunkelman, L. and Scolnik, R.: 1959, *J. Opt. Soc. Am.* **49**, 356.

Elterman, L.: 1966, *An Atlas of Aerosol Attenuation and Extinction Profiles for the Troposphere and Stratosphere*, Air Force Cambridge Res. Lab., Environm. Res. Paper No. 241.

Elterman, L. and Toolin, R. B.: 1965, Chapter 7 in *Handbook of Geophysics and Space Environments*, Scientific Editor: S. L. Valley; McGraw-Hill Book Comp. Inc., New York, San Francisco, Toronto, London, Sydney.

Farmer, C. B. and Todd, S. J.: 1964, *Appl. Opt.* **3**,453.

Gingerich, O., Noyes, R. W., Kalkofen, W., and Cuny, Y.: 1971, *Solar Phys.* **18**, 347.

v. d. Haar, Thomas H.: 1968, in *Meteorological Satellite Instrumentation and Data Processing*, Final Scientific Report, Dept. of Meteorology, University of Wisconsin, Madison, Wisc., p. 31.

Houtgast, J.: 1970, *Solar Phys.* **15**, 273.

Jerzykiewicz, M. and Serkowski, K.: 1966, *Lowell Obs. Bull.* No. 137, Vol. VI, p. 295.

Johnson, F. S.: 1954, *J. Meteorol.* **11**, 431.

Johnson, H. L. and Iriarte, B.: 1959, *Lowell Obs. Bull.* No. 96, Vol. IV, No. 18.

Kondratyev, K. Y. and Nikolsky, G. A.: 1968, *Meddel. Sever. Meteorol. Hydrogr. Inst. (B)* **28**, 14.

Kondratyev, K. Y. and Nikolsky, G. A.: 1970, *Quart. J. Roy. Meteorol. Soc.* **96**, 509; Preprint 1969.

Kruger, R.: 1968, in *The Solar Constant and the Solar Spectrum Measured from a Reseach Aircraft at 38000 Feet*, Goddard Space Flight Center Report No. X-322-68-304, Greenbelt, Maryland, p. 18.

Labs, D. and Neckel, H.: 1968, *Z. Astrophys.* **69**, 1.

Labs, D. and Neckel, H.: 1970, *Solar Phys.* **15**, 79.

Makarova, E. A. and Kharitonov, A. V.: 1968, *Soviet Astronon.* **12**, 599.

Mariner 6 and 7: 1969, note in *Spaceflight* **11**, 354.

McNutt, A. and Riley, T. A.: 1968a, in *The Solar Constant and the Solar Spectrum Measured from a Research Aircraft at 38000 Feet*, Goddard Space Flight Center Report No. X-322-68-304, Greenbelt, Maryland, p. 24.

McNutt, A. and Riley, T. A.: 1968b, in *The Solar Constant and the Solar Spectrum Measured from a Research Aircraft at 38000 Feet*, Goddard Space Flight Center Report No. X-322-68-304, Greenbelt, Maryland, p. 27.

Murcray, D. G.: 1969, Air Force Cambridge Res. Lab. Report, Contract AF 19 (628)-4177.

Pierce, A. K.: 1954, *Astrophys. J.* **119**, 312.

Saiedy, F.: 1960, *Monthly Notices Roy. Astron. Soc.* **115**, 493.

Serkowski, K.: 1961, *Lowell Obs. Bull.* No. 116, Vol. V, p. 157.

Sitnik, G. F.: 1967, *Astr. Cirk. Izdav. Bjuro Astr. Soobsh. Kazan* No. 444.

Stair, R. and Ellis, H. T.: 1968, *J. Appl. Meteor.* **7**, 635.

Tousey, R.: 1963, *Space Sci. Rev.* **2**, 3.

Waldmeier, M.: 1960–1963, Die Sterne **36**, 121; **37**, 139, **38**, 149; **39**, 207.