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# Solar irradiance during the Maunder minimum

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## RESUMEN

Se calcula la irradiancia solar total durante el período del mínimo de Maunder (1645-1715) usando la rotación solar. Se encuentra que esta irradiancia fue en promedio 0.1 a 0.43 % menor que la actual. Estos resultados concuerdan con la existencia de un periodo global de enfriamiento terrestre durante la segunda mitad del siglo XVII. Nuestro modelo calcula mejor las razones de rotación y los flujos HK que los modelos basados en cambios aparentes del radio solar.

**PALABRAS CLAVE:** Irradiancia solar, mínimo de Maunder.

## ABSTRACT

The total solar irradiance for the Maunder minimum (1645-1715) is obtained using the solar rotation rate calculated from the observations of sunspots recorded at the Observatoire de Paris from 1660-1719. On the average, the irradiance was lower than at present by 0.1 to 0.43 %. This is compatible with the global cooling of Earth observed in the second half of the 17 th century. Our approach allows better calculations of rotation rates and HK fluxes than models based on apparent solar radius changes.

**KEY WORDS:** Solar irradiance, Maunder minimum.

## 1. INTRODUCTION

The Maunder minimum (1645-1715) was a period of uncommonly low solar activity. This is supported by studies indicating a reduction in naked-eye sunspot numbers, suppressed auroral incidence, diminished corona at eclipses, and marked increase in radiocarbon production as detected in tree rings (Eddy, 1980).

The $\alpha$-$\omega$ dynamo theory (Krause and Radler, 1980) indicates that the azimuthal component of the magnetic field (toroidal field) is generated by stretching of the north-south magnetic field lines (poloidal field) due to a radial shear of the internal angular velocity (differential rotation rate). Sunspots are generally thought to be due to toroidal magnetic fields below the photosphere, which erupt to the surface by buoyant forces. The larger a star's rotation rate, the stronger is the stretching of the poloidal field component below the star's surface and the generation of the toroidal component. If the Sun's rotation rate was lower during the Maunder minimum than at present, the toroidal field may have been weaker and the production of sunspots lower than today. The toroidal field derives from the poloidal field of the previous half-solar cycle and viceversa. Poloidal fields are large-scale and extend into the corona. It is now widely accepted that the heating of a star's atmosphere is magnetic (see review by Kuperus *et al.*, 1981). A weaker field produces less heating of the Sun's atmosphere with lower temperatures expressed as reduced solar emission, e. g. in the *Ca II H* and *K* emission lines, that brighten with increasing magnetism (Leighton, 1959; Howard, 1959).

Lean *et al.*, (1992) based their calculations of the reduction in solar luminosity during the Maunder minimum on an empirical correlation between total solar irradiance corrected for sunspot dimming and integrated *Ca II* emission as a surrogate for bright magnetic features. They concluded that the Sun's irradiance in the absence of magnetic bright features, i.e. during quiet Sun periods, may have been between 0.15% to 0.35% below the present average radiative output as measured by the ACRIM radiometer on the Solar Maximum Mission satellite (Willson and Hudson, 1991). Nesme-Ribes and Mangeney (1992) found a 0.2% luminosity decrease from comparison between differential rotation changes during the Maunder minimum and modern time. More recently Nesme-Ribes *et al.* (1993), using apparent solar radius measurements for the Maunder minimum period, find an average of 0.25% to 0.5% of decrease in luminosity.

The Maunder minimum occurred in the so-called Little Ice Age. Eddy (1976) suggested that this cold period might be caused by a reduced solar irradiance. Recent research suggests that changes of 0.1 to 0.5% in total irradiance should produce fluctuations of 0.2°C to 1°C in the terrestrial equilibrium temperature (Reid, 1991). In fact, the Earth did suffer a general cooling during the Maunder minimum. However, though a temperature decrease of up to ~1°C may have occurred in some areas of the globe, especially in Europe, other regions experienced much less cooling.

In the present paper we use the average solar rotation rate calculated by Ribes and Nesme-Ribes (1993), on the assumption that a reduced rotation rate will lower the total solar irradiance. Thus, if we know the rotation rates during the Maunder minimum we may estimate the total solar irradiance during that period.

The paper is structured as follows. Section 2 contains the calculations for estimating the total solar irradiance for the Maunder minimum. In section 3 we compare our results with recent findings on solar irradiance during the period of interest. Section 4 contains a discussion of the results, and in Section 5 we present our conclusions.

## 2. TOTAL SOLAR IRRADIANCE DURING THE MAUNDER MINIMUM

Investigations of surface magnetic fields for stars of about 1 solar mass have shown that emission in the *Ca II*, *H* and *K* lines (HK) varies as the stellar rotation rate $\Omega$ (Skumanich, 1972):

$$HK / HK_o = \Omega / \Omega_o \tag{1}$$

where the subscript *o* corresponds to present values.

Satellite measurements of the total solar irradiance *S* (Willson and Hudson, 1991; Hoyt *et al.*, 1992), and ground-based observations of the Sun's disc-integrated *Ca II* emission *K* (White *et al.*, 1992) exist for several solar cycles. White *et al.* (1992) found a linear relationship between *K* and *Sc*, the total solar irradiance corrected for sunspot deficit. The expression of *Sc* is given by

$$Sc = S - S_{Qo}(1 + Ps) \tag{2}$$

where $S_{Qo}$ is the total solar irradiance for the present quiet Sun, and $Ps$ is the sunspot dimming function (Foukal, 1981).

The linear regression between *K* and *Sc* (White *et al.*, 1992) is:

$$Sc = -(13.6 \pm 0.5) + (160 \pm 6)K \ . \tag{3}$$

White *et al.* (1992) provide a relationship between the solar *K* measurements and the stellar *HK* emission:

$$HK = 0.04 + 1.53K \ . \tag{4}$$

Substituting into (3) the value of *K* from (4), and using (1), we may now write equation (3) in terms of *HK*. With this new form of equation (3) we obtain the total solar irradiance, given by equation (2), during the Maunder minimum ($S_{QMm}$) :

$$S_{QMm} = -13.6 + 160\{[(\Omega_{Mm} / \Omega_o)HK_o - 0.04]/1.53\} + S_{Qo} \, . \tag{5}$$

Here we assume for the quiet Maunder minimum Sun $Ps = 0$ (i. e., no sunspots).

Equation (5) is required for calculating the quiet Sun total solar irradiance for the Maunder minimum. This equation involves the rotation ratio $\Omega_{Mm}/\Omega_o$. The parameters are found in Table 1, and their derivation is justified as follows. Ribes and Nesme-Ribes (1993) reconstructed sunspot numbers, solar cycle lengths and rotation rates for the period 1660-1719 using quantitative sunspot observations at the Observatoire de Paris. From historic quantitative timings of sunspots and solar limbs, they located the sunspots in a heliographic coordinate system. During a period that they identify as the Deep Maunder minimum (1666-1700), 51 sunspots were sighted; all were in the southern hemisphere and hardly exceeded 10° of latitude. A total of 15 sunspots were tracked for at least 2 days, providing an average rotation rate of 13.97° per day for latitudes between 2° and 14°. The rotation rates during this period were lower and more differential than at present. Toward the end of the Maunder minimum (1701-1719) the sunspot activity increased in the southern hemisphere and resumed in the northern hemisphere. A total of 200 sunspots were sighted, 100 for two or more days. The surface rotation rate was less differential than during the deep phase but more differential and lower than at present. An average of between 2° and 14° in the southern hemisphere yields a value of 14.15° per day (see columns 1 and 2 of Table 1).

There are some sources of error. Uncertainty in the spot's position leads to an error of ±0.25° in longitude and ±0.3° in latitude near disk center. The rotation rate is derived from the angular distance between succesive positions of the spot with respect to the solar diameter. A random error of ±2% in the rotation rate is found when sunspot motions are derived from observations in two consecutive days. As there were usually several positions of the same sunspot during its transit across the disc, the error in the rotation rate for individual sunspots is only ±0.6%. Ribes and Nesme-Ribes (1993) show that the historical observations of the positions of the Sun's edges were defined with an accuracy of ~1 arc second for each measurement. Apparently there is an excess of 7 arc seconds in diameter for the Maunder minimum data as compared to modern times. However, the Earth's atmosphere might have increased the apparent solar size. If there is a 7 arc seconds overestimation of the Sun's diameter, a further underestimation of the solar rotation rate by ~0.35% is found. Compared with modern times, the equatorial rate of sunspot rotation decreased ~2% during 1666-1719; thus, at 20° in latitude it was 6 % lower. It is concluded that the errors cannot account for the observed decrease, and we may assume that the decrease was real.

**Table 1**

Parameters used to calculate the total solar irradiance during the Maunder Minimum

| $Rz$ | $\Omega_{Mm}$ (deg/day) | $\Omega_o$ (deg/day) | $S_{Qo}$ (W/m$^2$) | $HK_o$ |
|---|---|---|---|---|
| 1.457[a] | 13.97[c] | 14.48[e] | 1371.38[f] | 0.164[h] |
| 10.526[b] | 14.15[d] | | 1366.99[g] | 0.123[i] |

(a) Sunspot average number for 1666-1700, Ribes and Nesme-Ribes (1993).

(b) Sunspot average number for 1701-1719, Ribes and Nesme-Ribes (1993).

(c) Southern hemisphere average for 2°-14° of heliolatitude, 1666-1700, Ribes and Nesme-Ribes (1993).

(d) Southern hemisphere average for 2°-14° of heliolatitude, 1701-1719, Ribes and Nesme-Ribes (1993).

(e) Average for 2°-14° of modern rotation rate of sunspots during 1977-1984, obtained from a polynomial fitting. Ribes and Nesme-Ribes (1993).

(f) Modern average measurements for 1986 from ERB, Hoyt *et al.* (1992).

(g) Modern average mesurements for 1986 from ACRIM, Hoyt *et al.* (1992).

(h) Usual *Ca II H* and *K* flux ratio observed for solar minimum times. Wilson (1978).

(i) Minimum *Ca II H* and *K* flux observed in very quiet solar regions, Schrijver *et al.* (1989)

The longest modern measurements of $S$ were obtained by the Earth Radiation Budget Experiment (ERB) on the Nimbus 7 satellite from November 1978 through November 1992 (Hickey *et al.*, 1988), and by the Active Cavity Radiometer Irradiance Monitor (ACRIM) on the Solar Maximum Mission satellite from February 1980 to November 1989 (Willson and Hudson, 1991). The yearly mean values of total solar irradiance for the solar minimum or quiet Sun in 1986 (i. e. the mean irradiance for all 1986) as measured in these experiments are shown in Table 1. The distributions of the irradiance values of ERB and ACRIM with time are quite similar (Hoyt *et al*, 1992). The corresponding values appear in column 4.

The magnetic activity $HK$ is usually given as the ratio of the fluxes in the $H$ and $K$ *Ca II* emission cores over the nearby continuum fluxes. The observed values for the Sun range between 0.164 and 0.178 as the solar cycle evolves from minimum to maximum (Wilson, 1978). The minimum value in the centers of supergranulation cells in very quiet regions on the Sun is around 0.123, associated with values of the mean magnetic flux density not significantly different from zero (Schrijver *et al.*, 1989). This low value is very close to the minimum stellar flux ratio observed for solar-type stars which is 0.120 (Baliunas and Jastrow, 1990). This information is provided in column 5 of Table 1.

Entering the values from Table 1 in equation (5) we obtain average total solar irradiance values for the quiet Sun during two periods in the Maunder minimum. The results appear in Table 2, columns 2 and 3; column 1 contains the periods. The average quiet sun irradiance increased towards the end of the Maunder minimum, due to an increased rotation rate $\Omega_{Mm}$ which caused an increase in the ratio $\Omega_{Mm}/\Omega_o$ in equation (5). The absolute irradiances derived from ACRIM are lower than the results of ERB, because ACRIM measurements of $S_{Qo}$ are consistently lower than the values reported by ERB. This reflects differences in absolute irradiance calibration of the two instruments.

**Table 2**

Average total solar irradiance values for the quiet Sun during the Maunder minimum

| Period | $S_{QMm}$ (W/m$^2$) | $S_{QMm}$ (W/m$^2$) |
|---|---|---|
| | ERB | ACRIM |
| 1666-1700 | 1370.14[a]<br>1366.01[b] | 1365.75[a]<br>1361.62[b] |
| 1701-1719 | 1370.36[a]<br>1366.17[b] | 1365.97[a]<br>1361.78[b] |

(a) Estimations for the solar minimum activity $HK_o$ flux= 0.164
(b) Estimations for the minimum observed $HK_o$ flux = 0.123

Now let us compare the values of $S_{QMm}$ during the Maunder minimum (Table 2) with modern average values measured from ERB: $S_A$(1978-1993)=1371.92 W/m$^2$ (Kyle *et al.*, 1994), and from ACRIM: $S_A$(1980-1988)= 1367.46 W/m$^2$ (Hoyt *et al.*, 1992). The percentages appear in Table 3, columns 2 and 3. An upper limit for the average percentages can be obtained by comparing the *Ca II HK* possible minimum solar flux (0.123) and the Maunder minimum quiet Sun irradiance flux (Table 2) with the modern solar maximum irradiance values. These values are $S$(1979) =1373.33 W/m$^2$ from ERB (Hoyt *et al.*, 1992), and $S$(1980)=1368.27 W/m$^2$ from ACRIM (Hoyt *et al.*, 1992). The results also appear in Table 3, columns 4 and 5.

**Table 3**

Percentages of the total solar irradiance values during the Maunder minimum with respect to modern values

| Period | % ERB | % ACRIM | % ERB | % ACRIM |
|---|---|---|---|---|
| 1666-1700 | - 0.11[a]<br>- 0.43[b] | - 0.13[a]<br>- 0.43[b] | - 0.53 | - 0.49 |
| 1701-1719 | - 0.11[a]<br>- 0.42[b] | - 0.11[a]<br>- 0.42[b] | - 0.52 | - 0.47 |

(a) Corresponds to $HK0$ = 0.164
(b) Corresponds to $HK0$ = 0.123

## 3. COMPARISON WITH OTHER RESULTS

In order to evaluate the results from the previous section, we plotted in Figure 1 the reconstruction found by Nesme-Ribes *et al.* (1993) of the total solar irradiance during the Maunder minimum using the apparent solar radius (short dash curve), and our results from Table 3, column 3. We only plotted the solar irradiance corresponding to the $S_{Qo}$ from ACRIM data, because as Table 3 shows, the difference between the results of ACRIM and ERB is negligible.

The apparent solar radius percentage irradiance lies more or less within the percentages found for $HK_o = 0.164$ (upper solid line) and $HK_o = 0.123$ (lower solid line), around the years 1700 to 1719. Between 1666 to 1699 the percentage of the apparent solar radius irradiance was sometimes well above and sometimes well below our results.

In Figure 2 we show the rotation rates corresponding to apparent solar radius irradiance, in the Maunder Minimum period, using equation (5) and the average ACRIM and ERB values for $S_{Qo}$ (see Table 1). The observed average for 1666-1700 is 13.97 deg/day (short dashed horizontal line), while for 1701-1719 it is 14.15 deg/day (solid horizontal line) (see also Table 1). The average resulting rotation rates are quite different from the observed ones. From 1666 to 1700, the average for $HK_o = 0.164$ (solid curve) is 9.003 deg/day, while from 1701 to 1719 it is 11.732 deg/day. For $HK_o = 0.123$ (short dashed curve), the average found for 1666-1700 is 12.004 deg/day, while for 1701-1719 it is 15.643 deg/day.

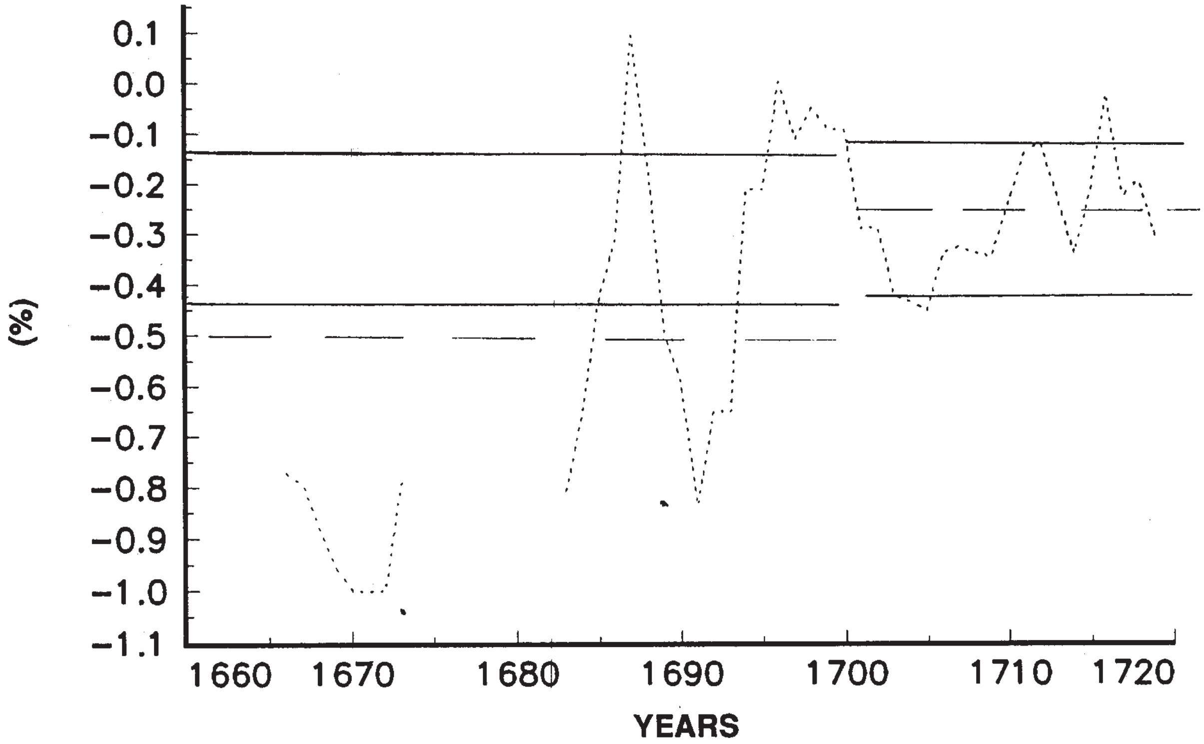

Fig. 1. Percentage obtained in the present work for the ACRIM data. Lower solid line corresponds to $HK_0 = 0.123$, upper solid line corresponds to $HK_0 = 0.164$. Percentages of the total solar irradiance obtained by Nesme-Ribes *et al.* (1993) during the Maunder minimum (short dash curve). We also show the average percentages found by Nesme-Ribes *et al.* as dashed horizontal lines.

Furthermore, from (1) we may obtain the *Ca II H* and *K* apparent solar radius fluxes shown in Figure 3. Between 1666 and 1685 the values are well below the minimum flux observed in solar-type stars, which is 0.120 (line d) (Baliunas and Jastrow, 1990). A value for around 1687 is above the present maximum flux observed by Wilson (1978) in the Sun which is 0.178, (line a). From 1693 to 1719 the values oscillate roughly between the minimum and the maximum of observed current Sun fluxes at solar minimum time (lines c and b respectively).

In comparison, the values of the *HK* flux that we obtain for the Maunder minimum, assuming a minimum possible present $HK_0$ solar flux of 0.123, are 0.119 for the Deep Maunder minimum and 0.120 for the End of Maunder minimum. Both values are consistent with the minimum *HK* flux observed for solar-type stars which is 0.120 (see lower short dashed lines). If we assume a present $HK_0$ flux of 0.164 as observed for minimum solar activity, we find an *HK* flux for the Deep Maunder minimum of 0.158 or 0.160 for the End of the Maunder minimum. These figures are below the present minimum Sun $HK_0$ flux but well above the minimum flux observed in solar-type stars (upper short dashed lines). In the figure we also compile results obtained by other authors such as the flux from average total solar irradiance using the apparent solar radius $HK = 0.109$ (1666-1700) and $HK = 0.142$ (1701-1719) (Nesme-Ribes *et al.*, 1993, long dashed lines). The average flux from the theoretical model based on differential rotation changes by Nesme-Ribes and Mangeney (1992) is also 0.142. The thin horizontal solid lines correspond to estimations of total solar irradiance for the Maunder minimum by Lean *et al.* (1993).

Note that the irradiance results by Nesme-Ribes *et al.* are rough upper limit estimations based on empirical relationships between apparent radius and sunspot numbers. The apparent solar radius changes include effects of solar irradiance, solar magnetic field and Earth's atmosphere that are difficult to evaluate (Ribes *et al.*, 1991). Discrepancies would be expected between such estimates and the present work. However, the average percentage decreases in luminosity of 0.5 (1666-1700) and of 0.25 (1701-1719) obtained from the apparent solar radius are in good agreement with our results.

## 4. DISCUSSION

The reduction of the solar rotation rate was the cause of the reduced solar activity in the period known as the Maunder minimum. Under this scenario, one result would be a reduced solar emission, which in turn should produce a decrease in the Earth's temperature.

From earlier approaches, using only the solar rotation rate, we derived equation (5) to estimate the total solar irradiance for the Maunder minimum. We found an average change of irradiance of 0.11 % to 0.43 % below the mod–

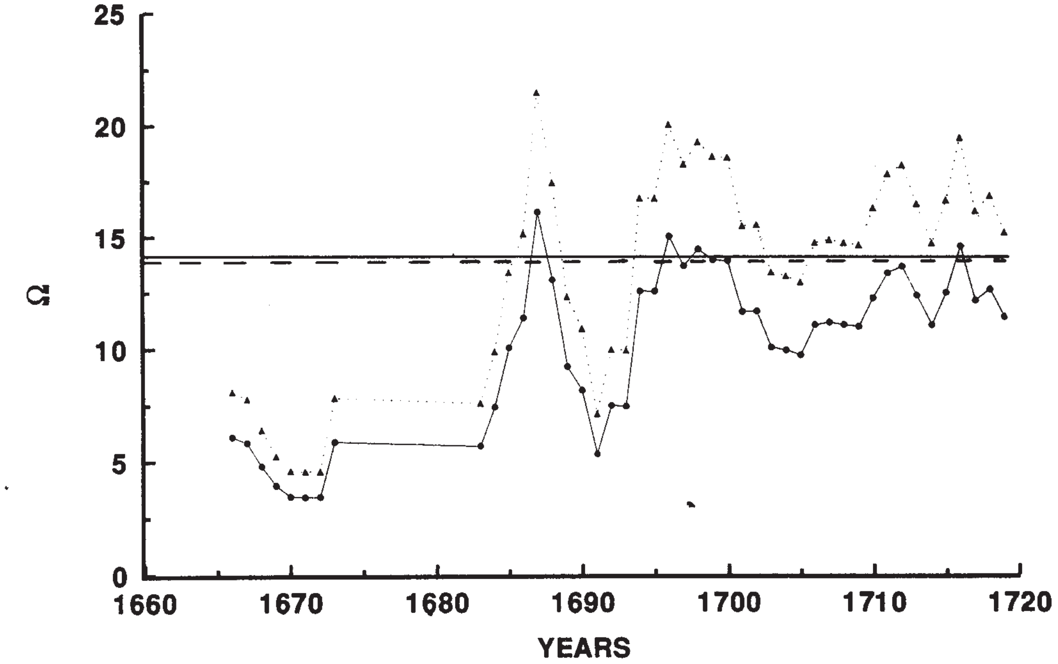

Fig. 2. Maunder minimum rotation rate *Ω* (in deg/day), using the total solar irradiance values obtained from the apparent solar radius measurements (Nesme-Ribes *et al.*, 1993). We plotted two cases: $HK_0$ = 0.123 (short dash curve) and $HK_0$ = 0.164 (solid line curve). The horizontal solid line corresponds to the observed average of 14.5 deg/day (from 1666-1700) and the long dash horizontal line corresponds to the observed average of 13.97 deg/day (from 1701-1719).

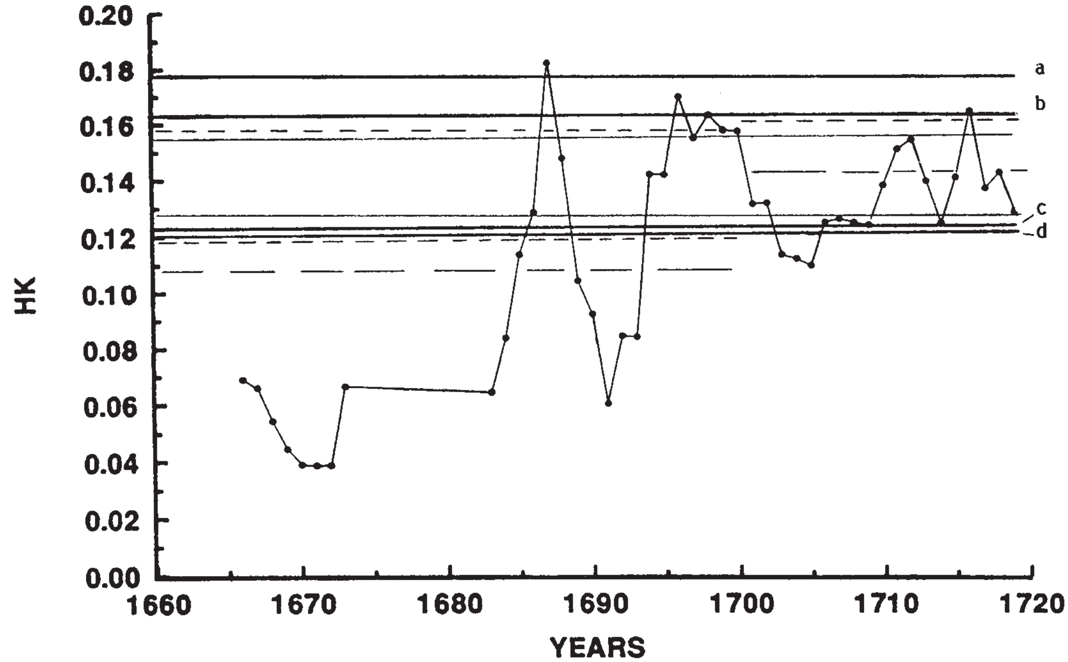

Fig. 3. The thick horizontal solid lines correspond to: a) Observed modern flux for solar activity maximum $HK_0$ = 0.178 (Wilson, 1978). b) Observed modern solar flux for solar activity minimum $HK_0$ = 0.164 (Wilson, 1978). c) Minimum observed solar flux, $HK_0$ = 0.123 (Schrijver *et al.*, 1989). d) Minimum flux observed in solar type stars, *HK* = 0.120 (Baliunas and Jastrow, 1990). The curve corresponds to the Maunder minimum *HK* flux using the apparent solar radius total irradiance (Nesme-Ribes *et al.*, 1993). The two long dash horizontal lines: fluxes given by the average total solar irradiance using also the apparent solar radius (Nesme-Ribes *et al.*, 1993) *HK* = 0.109 (1666-1700) and *HK* = 0.142 (1701-1719). Thin horizontal lines: estimations of the total solar irradiance given by Lean *et al.* (1993). The short dash horizontal lines: the present work for *HK* = 0.119 (1666-1700) and *HK* = 0.120 (1700-1719) using $HK_0$ = 0.123, and *HK* = 0.158 (1666-1700) and *HK* = 0.160 (1701-1719) using $HK_0$ = 0.164.

ern value during 1666 to 1700, a time when sunspots were nearly absent. From 1701 to 1719 the rotation rate increased and the average percentages were 0.11 % to 0.42 %. These results are consistent with previous estimates. However, the findings of Nesme-Ribes *et al.* (1993) obtained by using the apparent solar radius change present some discrepancies with our results within the frame of equations (1) and (5). The apparent solar radius change is difficult to interpret in terms of other physical parameters, and results obtained using it are probably best taken as qualitative rather than quantitative. Using average observed rotation rates, we found values for *Ca II H* and *K* fluxes which are quite consistent with the minimum values observed for solar-type stars. We conclude that the solar rotation rate may be a quantitatively reliable parameter for estimating the total solar irradiance.

The Earth's equilibrium temperature is a first-order approximation to the average terrestrial temperature. We find that the average Maunder minimum equilibrium temperature is 0.5°C lower than at present. Reid (1991) suggested that a change of 0.1 to 0.5% in total solar irradiance should be enough to produce a change of 0.2°C to 1°C in the terrestrial equilibrium temperature. Our findings are in good agreement with the range of irradiances and terrestrial equilibrium temperatures predicted by Reid (1991).

## 5. CONCLUSIONS

We suggest that the solar rotation rate may be a quantitatively reliable parameter for estimating total solar irradiance. The mean total solar irradiance during the years 1666-1719 is lower than modern values by 0.11 % to 0.43 %. These results are compatible with a cold episode occurring during the second half of the 17 th century. We found values of the *Ca II H* and *K* fluxes which are in good agreement with the minimum fluxes observed for solar-type stars. Our approach allows for more quantitative limits to rotation rates and HK fluxes than provided by models based on apparent solar radius change.

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