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ESTIMATING THE SUN'S RADIATIVE OUTPUT DURING THE MAUNDER MINIMUM

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Abstract. The coincidence between the Maunder Minimum of solar magnetic activity from 1645 to 1715 and the coldest temperatures of the Little Ice Age raises the question of possible solar forcing of the Earth's climate. Using a correlation which we find between measured total solar irradiance (corrected for sunspot effects) and a Ca II surrogate for bright magnetic features, we estimate the Sun's radiative output in the absence of such features to be 1365.43 W/m^2, or 0.15% below its mean value of 1367.54 W/m^2 measured during the period 1980 to 1986 by the ACRIM experiment. Observations of extant solar-type stars suggest that the Ca II surrogate was darker during the Maunder Minimum. Allowing for this, we estimate the total solar irradiance to be 1364.28 W/m^2 or 0.24% below its mean value for the 1980 to 1986 period. The decrease in the global equilibrium temperature of the Earth due to a decrease of 0.24% in total solar irradiance lies in the range from 0.2° C to 0.6° C, which can be compared with the approximately 1° C cooling experienced during the Little Ice Age, relative to the present.

Introduction

Long term changes in solar activity have been speculated recently to have a direct influence on global climate [Reid, 1991; Friss-Christensen and Lassen, 1991], augmenting the original suggestion by Eddy [1976] that the coldest temperatures of the Little Ice Age were a consequence of reduced solar radiative output. Current understanding of this forcing predicts that a change of 0.5% to 1% in total irradiance is necessary to produce a change of ~1° C in terrestrial equilibrium temperature [Wigley and Kelly, 1990; Reid, 1991].

Observations made during the past decade indicate that the total solar irradiance varies with the well-known 11-year activity cycle. This cycle is exemplified in contemporary solar records by the number of sunspots on the solar disc; many spots are present at activity maxima but almost no sunspots are seen for brief periods at activity minima. Dark sunspots signify the emergence of large scale magnetic fields in the solar atmosphere. Bright solar structures associated with smaller scale fields, the faculae, plages and "active" network, also vary throughout the solar activity cycle. Total solar irradiance decreased by ~0.1% in concert with declining activity in solar cycle 21 because of the reduction in the emission from bright solar magnetic features. The brightening due to the absence of sunspots is insufficient to negate this decrease [Foukal and Lean, 1988, 1990; Lean, 1989; Willson and Hudson, 1991].

During contemporary minima of the 11-year solar cycle, when sunspots may be absent entirely from the solar disc, a "quiet" network of bright magnetic elements nevertheless remains on the Sun. Were this network to vary on longer time scales, it could play a role in further modulating the radiative output of the Sun in a way that may be significant for terrestrial climate. Indeed, the disappearance of this network would lead to a "grand" minimum. We can investigate the radiative consequences of the disappearance of the emission from the quiet Sun network, and of consequent decreased emission from the inter-cell regions within the network, by examining the Sun's Ca II K emission. This emission is sensitive to the excess surface emission associated with faculae, i.e., magnetic flux tubes, and can thus be used as an indicator of those changes in the Sun's radiative output caused by the occurrence of bright regions on the visible solar disc [Skumanich et al., 1984; Livingston et al., 1988; Lean, 1991; White et al., 1992].

Wilson [1978] established that Ca II emission is also a diagnostic for activity cycles in other main-sequence stars. In particular, the Ca II emission in both the H and K lines from solar-age G-stars has been observed to be weaker in those stars without apparent activity cycles than in the minima seen in cycling stars [Baliunas and Jastrow, 1990]. This also suggests that larger changes in solar irradiance may have occurred over those longer time scales that include grand minima.

Utilizing current understanding of the origin of the variations in total solar irradiance [Foukal and Lean, 1988, 1990] and in the Ca II emission from the Sun and stars [Skumanich et al., 1984; White et al., 1992], we quantitatively estimate the radiative output from the Sun corresponding to scenarios that might have characterized the Maunder Minimum, a time of reduced solar activity when sunspots were absent from the disc for extended periods.

Contemporary Solar Irradiance Variability

Satellite measurements of 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 [White et al., 1992], which we denote as K, exist for more than one 11-year solar cycle. Figure 1 demonstrates the linear relationship between K and

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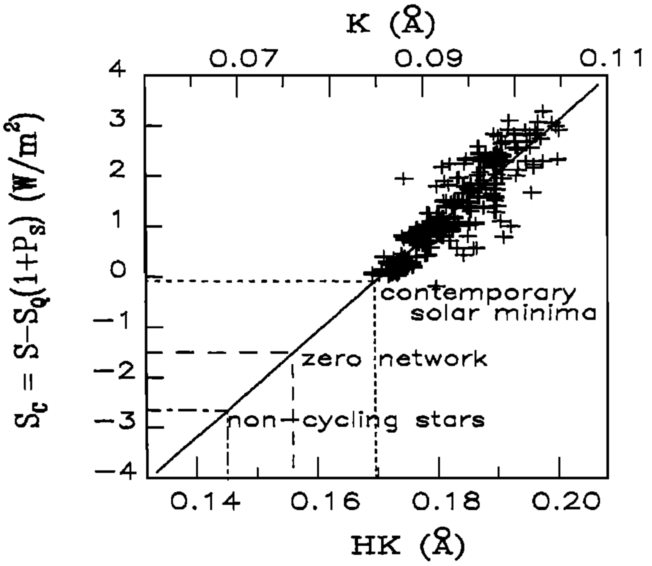

Fig. 1. Correlation of the disc-integrated Ca II solar emission, K, with a residual time series, $S_C = S - S_Q (1 + P_S)$, obtained by removing the sunspot blocking effect [Foukal, 1981], P_S, and the quiet sun, $S_Q = 1366.9$ W/m^2, from the ACRIM measurements of the total solar irradiance, S. This residual time series represents the contribution to the total solar irradiance of excess emission from bright sources. From linear regression, $S_C = -(13.6 \pm 0.5) + (160 \pm 6) \times K$ with r = 0.9. The short dashed line indicates contemporary solar minima (1976 and 1986) values. The long dashed line indicates the values we estimate for the Sun in the absence of surface magnetism (sunspots, plages and network) and the dash-dot line is an estimate for the Maunder Minimum Sun from White et al. [1992].

S_C, the total solar irradiance corrected for the sunspot deficit. The modified time series

$$S_C = S - S_Q \times (1 + P_S) \qquad (1)$$

is obtained by subtracting a function representing the sunspot blocking effect P_S (calculated using formulae and parameters given by Foukal [1981] with the sunspot areas and coordinates provided by the National Oceanic and Atmospheric Administration, World Data Center, Boulder, CO), and the quiet sun irradiance, $S_Q = 1366.9$ W/m^2, from the ~9 year record of total solar irradiance measured by the Active Cavity Radiometer Irradiance Monitor (ACRIM) on the Solar Maximum Mission satellite [Willson and Hudson, 1991].

Ca II activity cycles in stars are measured by the integral of the intensity centered on the unresolved H and K line cores relative to the nearby continuum. For the purpose of comparing the solar K measurements with stellar Ca II HK cycles we have provided, in Figure 1, the equivalent values for the Sun, denoted HK, where

$$HK = 0.04 + 1.53 \times K \qquad (2)$$

[White et al., 1992]. Ca II emission levels seen in stars range from HK = 0.12 to HK = 0.21 [Baliunas and Jastrow, 1990], which is larger than the range seen in the Sun during solar cycle 21, for which HK varied from 0.17 to 0.20. White et al. [1992] have shown that in fact the Sun's contemporary Ca II emission corresponds to that of the ~50% brightest cycling stars observed by Baliunas and Jastrow [1990], and does not overlap the range of lower Ca II emission typical of non-cycling stars, which ranges from HK = 0.12 to HK = 0.155.

Scenarios for the Maunder Minimum Sun

The lack of sunspots during the Maunder Minimum suggests that surface magnetism on the Sun was significantly less than is observed today. Because the numbers and areas of bright faculae and dark sunspots on the solar disc have been observed to rise and fall together with solar activity during the past ten solar cycles, a reduction of bright magnetic features can be assumed to have accompanied the sunspot reduction observed during the Maunder Minimum. Furthermore, in the absence of these activity features, the associated magnetic flux is not expected to simply reappear at smaller scales (Bogdan et al. [1988] have demonstrated that the size distribution of sunspots is maintained throughout all phases of the solar activity cycle and Tang et al. [1984] have demonstrated a similar result for Ca II K plages). Additional evidence for a dearth of magnetic flux on the Sun during the Maunder Minimum includes evidence from eclipse drawings that during this time the solar corona was reduced essentially to the zodiacal background [Eddy, 1976].

Radiative consequences of depleted solar surface magnetism have been examined recently by White et al. [1992]. They determined that in the absence of the chromospheric network (magnetic) emission, the disc-integrated Ca II flux would correspond to K = 0.0758. This value is shown in Figure 1, and is interpreted physically as the Ca II emission when the entire surface of the Sun consists of simply the non-magnetic component corresponding to the center of the supergranule cells, i.e., in the absence of any network brightening. It is equivalent to HK = 0.156 which is near the lowest values of Ca II emission observed in cycling stars.

Those stars observed to be non-cycling, for which the Ca II emission is reduced below that of the cycling stars, have been postulated to be in phases of inactivity analogous to the Maunder Minimum [Baliunas and Jastrow, 1990]. Assuming that this is so, White et al. [1992] used the comparison of cycling stars with non-cycling stars to assess additional radiative variability that might have occurred in the Sun during the Maunder Minimum, relative to its contemporary (cycling) state. Adopting the value of the mean Ca II emission for the non-cycling stars, HK = 0.145, as indicative of the Sun in a non-cycling state, converts to K = 0.0686 which is indicated in Figure 1. Physically, this implies that during the Maunder Minimum, in addition to an absence of sunspots, plages and network, the residual Ca II emission is to be represented by the darkest regions as observed to cover only 11% of the contemporary quiet Sun [Skumanich et al., 1975; White et al., 1992]. This, we believe, is due to the disappearance of weak, non-network magnetic fields.

We can use the linear regression between K and S_C shown in Figure 1 to investigate the impact on the total solar irradiance of reduced emission during times when solar magnetic activity is thought to have been different from the present, such as in the Maunder Minimum. The effect of decreasing K from its contemporary solar minimum value of 0.0847 to a zero surface magnetism value of 0.0758 is to decrease the total solar irradiance from a quiet value of S_Q = 1366.9 W/m^2 to a value of 1365.43 W/m^2. This decrease of 1.47 W/m^2 is 0.1% below the value of the total solar irradiance in the 1986 solar minimum, ~0.15% below the average value for 1980 to 1986, and 0.2% below the maximum irradiance in solar cycle 21. The reduction in the total solar irradiance below the 1986 solar minimum value corresponding to the condition of absent magnetic network and decreased emission from non-magnetic regions, assumed to characterize the Maunder Minimum Sun, is estimated from the regression in Figure 1 to be 2.62 W/m^2, or 0.19%, equivalently a reduction of 0.24% below the mean value of the irradiance in solar cycle 21. A lower limit to the total irradiance can be determined from the lowest values of Ca II emission observed in non-cycling stars, HK = 0.13. Were this low value to cover the entire surface of the solar disc, the disc-integrated K would be 0.0588, which corresponds to an irradiance decrease of 0.35% below the mean value of the total solar irradiance in solar cycle 21.

The cases discussed above are summarized in Table 1, where S is the estimated total irradiance and S_A = 1367.54 W/m^2 is the average total irradiance measured during the period 1980 to 1986, the descending phase of solar cycle 21. Figure 2 indicates the association between the estimates of total irradiance given in Table 1 and the distribution of Ca II emission seen in solar-like stars (from Baliunas and Jastrow [1990]) and in the Sun (from Skumanich et al. [1975] and White et al. [1992]).

Climatic Effects

We have constructed estimates of the radiative output of the Sun during the Maunder Minimum period of solar inactivity by interpreting recent observations of total solar irradiance, and of solar and stellar Ca II emission variability, in

TABLE 1. Solar Radiative Output During the Maunder Minimum

CASE	CaII Emission K	CaII Emission HK	Total Solar Irradiance S	Total Solar Irradiance $(S-S_A)/S_A \times 100$
no spots, plage or network	0.0758	0.156	1365.43	-0.15%
non-cycling stars (average)	0.0686	0.145	1364.28	-0.24%
minimum possible Sun	0.0588	0.130	1362.71	-0.35%

S_A=1367.54 W/m^2

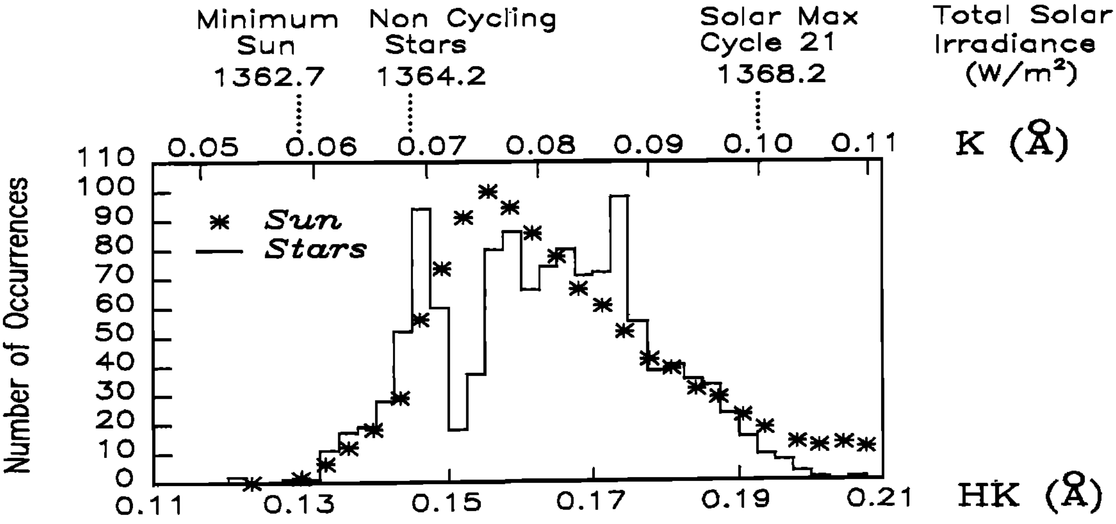

Fig. 2. The solid line is the distribution of Ca II emission (in increments of 0.1 years), primarily from long-term observations of 13 solar-like stars, reported by Baliunas and Jastrow [1990]. The broad peak with higher Ca II emission corresponds to observations of cycling stars, and the extent of solar Ca II emission during solar cycle 21 coincides with roughly the upper half this range. The narrow peak with lower Ca II emission corresponds to non-cycling stars. Also shown as asterisks is the distribution of Ca II K emission measured for the contemporary quiet Sun by Skumanich et al. [1975], converted to irradiances, indicating that current solar data allow for lower values of the Sun's Ca II emission during the Maunder Minimum that are compatible with the stellar observations [White et al., 1992]. Estimates of total solar irradiance deduced from the linear relationship in Figure 1 are indicated.

terms of current understanding of the magnetic origins of their variations. These estimates indicate an irradiance reduction of as much as 0.3% below the recent maximum activity (0.24% below the mean for 1980 to 1986).

A recent analysis [Foukal and Lean, 1990] of historical variations in the Sun's total irradiance caused by the competing effects of dark sunspots and bright faculae alone, indicates a maximum variation from 1874 to the present of 0.1%, with the largest variation occurring in the most recent solar cycle 21. Superimposed on these changes would be the increase of ~0.2% postulated here to have occurred from the time of the Maunder Minimum to current solar minima. Consequently, recent solar values may be an extremum for the past three centuries. White et al. [1992] emphasize that the level of activity on the contemporary Sun is in the same range as the most active G-type stars in the Baliunas and Jastrow [1990] sample. This observation that the Sun is currently in a high activity state is supported by McHargue and Damon [1991] who show ^{10}Be concentration records in ice cores indicating historically low cosmic ray fluxes or equivalently high solar activity. These radioisotope data certainly suggest that the contemporary Sun is approaching a high activity state comparable to that inferred for the 12th century during the Medieval Warm Epoch.

We calculate that the radiative perturbation, ΔQ, at the top of the Earth's atmosphere arising from an increase of 0.24% in solar total irradiance ($\Delta S = 3.3$ W/m^2) is $\Delta Q \sim 0.7\Delta S/4 = 0.58$ W/m^2 for which the change in equilibrium global temperature [Wigley and Raper, 1990] would be in the range 0.2^o C to 0.6^o C. Comparing this with the temperature decrease of ~1^o C that occurred during the Little Ice Age suggests that solar forcing may have contributed some, but not all, of the observed warming from the Little Ice Age to the present time. According to the ^{10}Be record, present solar activity appears to be approaching the levels of the maxima (such as the Medieval Warming) observed in the past 1000 years, implying that our estimates would appear to also constrain solar variations over this longer period.

Our estimates of long term solar radiative output changes are by necessity speculative. In basing these estimates on a data base of total irradiance observations pertaining to only one 11-year solar cycle it is quite possible that variability mechanisms acting over much longer epochs have been omitted (e.g., Schatten [1988]). Only a continuous irradiance record over many solar cycles can begin to address this.

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