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A METHOD OF DETERMINING POSSIBLE BRIGHTNESS VARIATIONS OF THE SUN IN PAST CENTURIES FROM OBSERVATIONS OF SOLAR-TYPE STARS

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ABSTRACT

Observations of the Sun and a number of stars with mass and age close to the Sun show that changes in magnetic activity and brightness are directly correlated over an activity cycle. The ratio of the two correlated changes shows considerable scatter. If we assume that the scatter represents variability of one solar-type star at different epochs, the aggregate data may represent the range of variation of the Sun over centuries. We illustrate a technique of inferring possible brightness variations of the Sun from a sample of solar-type stars. The observed scatter of the ratio of all 10 solar-type stars in our sample (stars with $0.55 \lesssim (B-V) \lesssim 1.2$ and mean level of chromospheric activity $R'_{\rm HK} \lesssim -4.75$ in the Lockwood et al. 1992 sample) plus the Sun yields a possible increase of 0.2%–0.6% in solar brightness as magnetic activity has increased from the Maunder Minimum (ca. A.D. 1660–1710) to the decade of the 1980s. The limited sample of solar-type stars will need to be extended in order to improve the range of the estimate provided.

Subject headings: star: activity — star: late-type — Sun: activity — Sun: solar-terrestrial relations

1. INTRODUCTION

The variability of the "solar constant" has been the subject of extensive discussion since the launch ca. 1980 of the *Solar Maximum Mission* (*SMM*) and *Nimbus 7* satellites. Highly precise measurements of the solar total irradiance reveal variations on timescales from minutes up to the current length of the observational window, about one solar cycle (Hudson 1988). Irradiance variations observed on different timescales can be attributed to varying components of magnetic activity, for example, surface magnetic inhomogeneities such as sunspots, faculae, and the active network (Hudson 1988; Foukal & Lean 1990; Kuhn & Libbrecht 1991; Willson & Hudson 1991). A sunspot, seen dark in white light, blocks the energy flux from the convective zone (Spruit 1977; Foukal 1987) and can cause a 0.2% fall in solar irradiance in a few days. On the other hand, a facula, which consists of small magnetic tubes, enhances radiation in the active region (Chiang & Foukal 1985).

However, these two components, i.e., sunspots and faculae, cannot account for all irradiance variations observed over an activity cycle (Kuhn & Libbrecht 1991; Willson & Hudson 1991). For example, around the maxima of cycles 21 and 22, the satellite observations showed a substantial excess of solar irradiance, in disagreement with predictions from models based on sunspots and faculae (Willson & Hudson 1991; Livingston 1994). The disagreement suggests that an additional component (e.g., the active network) may be needed (Kuhn & Libbrecht 1991; Willson & Hudson 1991) and may play an important role at other times of the Sun's history. Hence, the current model may not be directly extrapolated for studying irradiance variations over longer timescales.

We already have evidence of variations in the Sun's surface magnetism over centuries, namely, the Maunder Minimum (Eddy 1976). Since surface magnetism and irradiance are observed to be correlated over the timescale of one solar cycle (Hudson 1988), one might expect that variations in irradiance would also follow the activity change on timescales of decades to centuries, although possible contributions to secular irradiance changes from a nonmagnetic component (e.g., change in solar diameters) cannot be ruled out (Gilliland 1982; Kuhn et al. 1988).

Over the coming decades, satellite observations are expected to yield more information on the possible range of changes in the Sun's brightness and their relation to changes in solar magnetic activity. Here, we suggest an alternative to obtain that information by observing a large sample of late-type stars with mass and age close to the Sun.

2. METHOD OF ANALYSIS: ESTIMATES OF POSSIBLE SOLAR BRIGHTNESS VARIATIONS THROUGH THE OBSERVATIONS OF SOLAR-TYPE STARS

Solar-type cyclic surface activity has been observed in other late-type stars (Wilson 1978; Baliunas et al. 1994). In addition, observations of a sample of solar-type stars indicate that photometric brightness variations and Ca II H and K intensities are positively correlated on the timescale of one activity cycle (Radick, Lockwood, & Baliunas 1990), similar to that of the Sun. Although magnetic features are not spatially resolved on stellar surfaces, the Ca II H and K intensities mark both the intensity and coverage of surface magnetic fields on the Sun (Skumanich, Smythe, & Frazier 1975; Schrijver et al. 1989). Therefore, it is likely that changes in the surface brightness of solar-type stars are also associated with changes in surface magnetic activity.

Based on similar behaviors of the Sun and solar-type stars, we propose a technique to obtain information on possible changes in solar brightness over timescales of decades to cen-

1994ApJ...427L.111Z

turies by studying a group of solar analogs observed over shorter timescales. We base this method on studies of stellar magnetic activity (Noyes et al. 1984; Baliunas & Jastrow 1990). For example, observations of solar-type stars over 2 decades may have revealed evidence for both the cyclic and the Maunder Minimum phases of activity (Baliunas & Jastrow 1990). Hence, a wide range of behavior in magnetic activity of one star (e.g., the Sun) over a long interval can be represented in observations of a sample of stars with similar mass and age over a much shorter interval.

The sample of stars to be compared to the Sun must be limited in mass and age since both influence the behavior of stellar activity and associated brightness changes. For example, young stars display long-term brightness variations and activity changes that are negatively correlated, in contrast to the positive correlation observed in the Sun and solar-type stars (Radick et al. 1990). Stars of very different mass from the Sun (e.g., early F stars) were omitted from the analysis because their convective zones may have different properties from those of the Sun and they introduce ambiguity in the sample's criterion for stellar age.

Given the existence of the direct correlation and approximately linear relationship between brightness and activity changes for the Sun and solar-type stars observed over one activity cycle, we assume a general linear relationship between brightness (Br) and excess chromospheric emission ($R'_{\rm HK}$):

$$\mathrm{Br} = a + bR'_{\rm HK}\ , \tag{1}$$

where $R'_{\rm HK}$, an indicator of chromospheric activity (Noyes et al. 1984; Schrijver et al. 1989), is derived from the observed relative Ca II flux. $R'_{\rm HK}$ is defined as the ratio of the magnetic components of the chromospheric flux to the bolometric luminosity (Noyes et al. 1984) and allows activity levels of stars with different masses (i.e., $B-V$ color) to be compared. We note that equation (1) is a simplified model since contributions from photospheric dark spots, faculae and the active network to the brightness change cannot be easily separated in solar-type stars (Dorren & Guinan 1982).

Unlike the case of the Sun, the intercept, a in equation (1) cannot be easily determined for stars since the absolute brightness is not measured (Radick et al. 1990; Lockwood et al. 1992). However, the quantity of interest here is the change in brightness, ΔBr, which can be computed from $b\Delta R'_{\rm HK}$ independent of the intercept. The average slope of the ratio of ΔBr to $\Delta R'_{\rm HK}$ for a group of solar-type stars is assumed to represent a statistical connection between variations in brightness and activity over long timescales.

3. RESULTS AND DISCUSSION

The data that went into the analysis of this work are the chromospheric Ca II H (396.8 nm) and K (393.3 nm) emission fluxes (S index) made at Mount Wilson Observatory (Wilson 1978; Baliunas et al. 1994) and the high-precision photometric measurements in the (b) 472 nm and (y) 551 nm passbands obtained at Lowell Observatory (Raddick et al. 1990; Lockwood et al. 1992).

From the available concurrent measurements of brightness and chromospheric emission in 33 dwarf stars, we have used all dwarf stars (a total of 10) with masses between 0.6 and 1.1 $M_\odot$ [corresponding to $1.2 \gtrsim (B-V) \gtrsim 0.55$] and ages greater than a few billion years (estimated from mean level of chromospheric activity, Soderblom, Duncan, & Johnson 1991). An example of parallel records of photometric and chromospheric activity is shown in Figure 1.

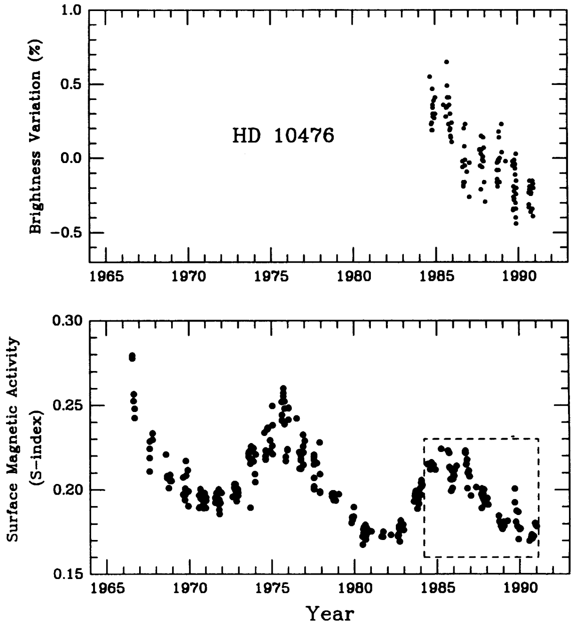

FIG. 1.—Records of the photometric brightness variation (nightly means) and surface magnetic activity (S index, the relative Ca II H and K emission flux, monthly means) for the star HD 10476. The dashed box in the bottom panel denotes the time interval of the concurrent photometric measurements shown in the upper panel.

Figure 2 shows the distribution of rms brightness variations (ΔBr in %) and rms excess chromospheric emission variations ($\Delta R'_{\rm HK}$) computed from the annual means of measurements from 1984 to 1991 for the 10 solar-type stars plus the Sun. Here, we adopt rms variation to represent the change in brightness and chromospheric activity since it is a robust measure of variability (Radick et al. 1990). We have assumed that the measured stellar photometric variability is directly comparable to the variation of the total irradiance (Lockwood et al. 1992). We note that the data in Figure 2 shows considerable scatter

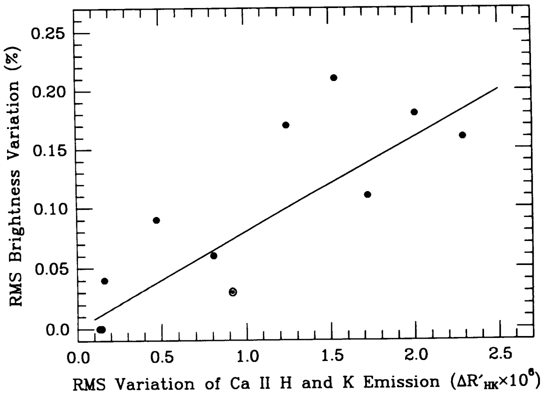

FIG. 2.—The rms variation in brightness (ΔBr in %) vs. the rms variation of excess chromospheric emission ($\Delta R'_{\rm HK}$); the peak-to-peak variations are ∼3 times larger than the rms variations. For each star, the point connected to the origin represents the individual slope of the correlation between the activity and brightness variations. The solar data (⊙) are measurements of total irradiance from *SMM* satellite and Ca II K-line taken during 1980–1988 (Willson & Hudson 1991). The solid line represents the slope of the least-squares fit (eq. [2]).

for individual stars and that the solar point observed during cycle 21 lies near the lower bound of the distribution. This reinforces the recent suggestion of Lockwood et al. (1992) that the solar brightness change in the decade of the 1980s has been atypical.

The least-squares fit on the data gives

$$\Delta \mathrm{Br}\ (\%) \simeq (8.0 \pm 4.0) \times 10^4 \Delta R'_{\mathrm{HK}}\ , \qquad (2)$$

with the scatter defined by the 95% confidence interval for the best-fitted slope. This slope is close to the average (9.4×10^4) of the values of $\Delta \mathrm{Br}/\Delta R'_{\mathrm{HK}}$ of the sample. If we treat some of the less accurate photometric measurements (Lockwood et al. 1992) as upper limits of nondetection and use a linear regression analysis for censored data (Isobe, Feigelson, & Nelson 1986), a slope of 8.9×10^4 is obtained. The consistency of results suggests that the aggregate behavior derived from the group of solar-type stars is not very sensitive to the procedures for handling the data.

The scatter of Figure 2 may have several causes, including: (1) intrinsic scatter, because the interval of observation is finite it may not sample the full range of variation; (2) measurement errors; (3) presence of subtle physical differences among stars in the sample (e.g., mass, age, metallicity effects); (4) a possible effect of inclination angle of stellar rotational axis (Schatten 1993).

The long-term precision in Ca II measurements is $\sim 0.1 \times 10^{-6}$ in the units of R'_{HK} determined from a group of standard stars (Baliunas et al. 1994). Brightness variations for stars in our sample are measured relative to a group of comparison stars. Errors in the different photometry are difficult to estimate due to the complication in identifying a nonvarying standard star (Lockwood et al. 1992). However, such errors appear too small to explain the scatter in Figure 2. For example, both the Sun at lower bound and some of the stars at the high bound of Figure 2 have precise brightness measurements and they do not overlap within the uncertainties. In addition, no notable influence of mass and age can be discerned in this sample. Although other causes of scatter cannot be completely discounted, we will assume that the scatter in Figure 2 is caused mainly by the finite interval of observation for any one star so that the full range of variations over many decades is under sampled. Although not definitive, the most direct evidence that supports this assumption is the different response of solar irradiance to surface magnetism around the maxima of cycles 21 and 22 (Livingston 1994) compared to the variations observed during the intermediate times of the two-cycle maxima. Therefore, we assume that the general trend and part of the scatter in Figure 2 represents the variation of solar brightness and magnetic activity on timescales of decades to centuries. We will use the 95% confidence interval of the fitted slope, which encompasses the observed scatter in Figure 2, to characterize the possible range in the estimate of solar brightness changes.

If the behavior of the Sun on longer timescales conforms to the aggregate trend of solar-type stars, equation (2) can yield values of solar brightness change, for example, from the Maunder Minimum to the present, when combined with information about $\Delta R'_{\mathrm{HK}}$ for the Sun (see Table 1). Direct measurements of R'_{HK} for the Sun are only available for the last 20 odd years, but the value of the solar R'_{HK} in the Maunder Minimum can be estimated from observations of solar-type stars (Baliunas & Jastrow 1990). Using the estimate of the 95% confidence interval of the fitted slope of Figure 2 to characterize the range of possible solar variations, we infer that the solar brightness could have increased by as small as 0.2% or by as large as 0.6% (rounded to the nearest tenth of a percent), with a mean of ~0.4% in response to the net increase in magnetic activity between the Maunder Minimum and the decade of the 1980s. If we allow for an uncertainty of ±0.005 in the value of S during the Maunder Minimum (Baliunas & Jastrow 1990) in addition to the scatter in Figure 2, the range of solar brightness change during the interval is enlarged by 15%, leading to a lower bound of ~0.2% and an upper bound of 0.7%.

TABLE 1

MEAN $\langle S \rangle$ INDEX AND R'_{HK} OF THE SUN AND MEAN SUNSPOT NUMBERS $\langle \mathrm{SN} \rangle$

Interval	$\langle S \rangle$	R'_{HK} (10^{-5})	$\langle \mathrm{SN} \rangle$
1660–1710	0.145	0.788	19
1966–1976	0.171	1.157	63
1976–1986	0.176	1.229	77
1981–1991	0.177	1.243	89

NOTES.— The recent $\langle S \rangle$ values are from the available measurements (White & Livingston 1981; Wilson 1978) of the Sun, while a typical mean S value of 0.145 is assumed for the Sun and solar-type stars (Baliunas & Jastrow 1990) in magnetically low and less-active states such as the Maunder Minimum. The S index over the interval of 1976–1991 (White & Livingston 1981) was converted from the solar Ca II K-line measurements (Lockwood et al. 1992).

In addition to the total excursion in brightness from the Maunder Minimum to the present, we can estimate the timing of the change at intermediate times in the 350 year interval by using the sunspot record. The sunspot record is first smoothed with an 11 year running mean in order to remove short-timescale fluctuations. Using Table 1, we calibrated $\langle S \rangle$ and $\langle \mathrm{SN} \rangle$ using the least-squares fit and assuming that photospheric and chromospheric activities are correlated (Schrijver et al. 1989). We then translated the smoothed sunspot record into a record of the S-index of solar magnetic activity since the Maunder Minimum. The time series of S-index values for the Sun is then converted to R'_{HK} (Noyes et al. 1984). Finally, the change in the mean level of magnetic activity (i.e., $\Delta R'_{\mathrm{HK}} = R'_{\mathrm{HK}} - [R'_{\mathrm{HK}}]_{1660-1710}$) is computed with respect to the activity level of the Maunder Minimum interval and equation (2) is applied to obtain the corresponding relative brightness changes. We note that the choice of this reference point is arbitrary since we are only interested in the relative change in solar brightness in response to a net change in activity. Using the 95% confidence interval on the slope of equation (2), we constructed the 4 century (1660–1990) history of solar brightness variations in Figure 3. The full range of possible variations is indicated by the shaded area.

Our results suggest that during the Maunder Minimum, the solar brightness could have been 0.2% to 0.6% lower than the values of the decade of 1980s. The lower limit of 0.2% change in solar brightness agrees with the result of a linear extrapolation of the current solar irradiance model (Lean et al. 1992; Hoyt & Schatten 1993) based on the satellite observations during the 1980s. The upper limit of 0.6% is in reasonable agreement with Reid's (1991) results, which indicate a change in solar irradiance of ~1% from the Maunder Minimum to the 1980s.

The sunspot numbers which enter into the analysis leading to Figure 3 are well determined for the recent epoch. The early

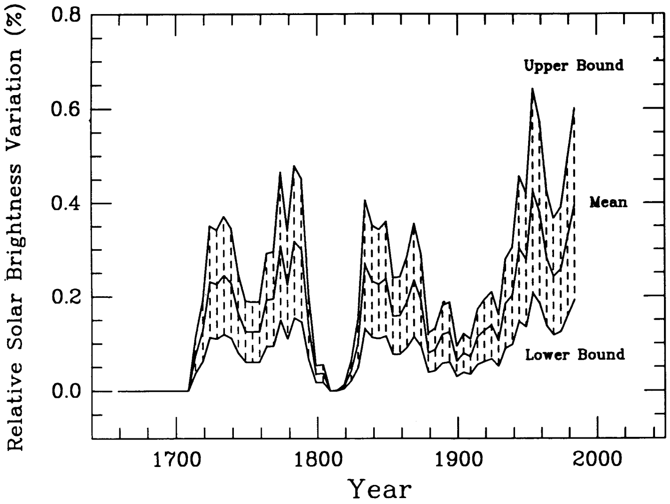

FIG. 3.—The relative change in solar brightness reconstructed using the 11 yr running mean of sunspot numbers and the brightness variation vs. the variation of surface magnetic activity relation of Fig. 2. The range of retrodiction of the solar brightness variation was calculated using the 95% confidence interval in the slope of eq. (2).

values for the Maunder Minimum, which range between 3 and 19, are less certain because of differences in the historical records (Eddy 1977; Schove 1983). The results for the overall increase of (0.2–0.6)% of the Sun's brightness from the Maunder Minimum to the decade of the 1980s are primarily determined by the increase in values of the estimate of the solar R'_{HK} between the endpoints of that 350 yr interval. However, the detailed history of changes in solar brightness at intermediate times—the decade-to-decade changes in brightness over 350 yrs—depends on the sunspot observations. If we take a different historical sunspot record (Eddy 1977) than the record (Schove 1983) adopted in Figure 3, it leads to a change of no more than 0.1% in amplitude at times of low average activity, e.g., ca. 1810.

In summary, we presented in this *Letter* a method to extract information concerning the possible brightness variation of the Sun from observations of a group of solar-type stars. However, we caution that the realization of the full potential of the technique may require a larger sample of stars with mass and age close to the Sun. Further studies of the possible influence of subtle physical differences in the stellar sample would also be a useful endeavor.

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