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MAGNETIC MODULATION OF SOLAR LUMINOSITY BY PHOTOSPHERIC ACTIVITY

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ABSTRACT

We study the behavior of slow changes in solar irradiance, *S*, using measurements obtained with radiometers on the *SMM* and *Nimbus 7* spacecraft. Our analysis of the 1978–1984 ACRIM and ERB radiometry reveals low-amplitude (0.04%–0.07%) variations in *S* on time scales of 4–9 months that are well correlated between these two data bases. This agreement on slow variations measured by radiometers on two separate spacecraft, and also the finding that the variations correlate very well with changes in facular radiations as measured by the He I 10830 and CaK plage indices, demonstrates that photospheric activity modulates the total solar irradiance on time scales greatly exceeding the days to weeks known to be caused by disk passage of individual active regions.

We show also that the slow downtrend in *S* seen since 1981 by the ACRIM and ERB arises mainly from a decreasing irradiance contribution of bright photospheric magnetic elements outside the large faculae included in the daily CaK plage index. Our finding that this network contribution is unbalanced over several years shows that photospheric activity has a net influence on solar luminosity, besides the more nearly balanced contributions of the spots and the large faculae.

Our demonstration that solar luminosity variation over the 11 yr activity cycle is controlled by bright photospheric magnetic elements rather than by dark spots significantly increases the likelihood that the Sun was dimmer during extended periods of decreased magnetic activity such as the Maunder minimum. This result indicates that solar dimming over many decades may well have played an important role in climatic anomalies such as the Little Ice Age of the 17th century.

Subject headings: Earth: general — Sun: activity — Sun: faculae — Sun: general — Sun: magnetic fields

I. INTRODUCTION

Observations of the total solar irradiance, *S*, with the active cavity radiometer irradiance monitor (ACRIM) on the *Solar Maximum Mission* (*SMM*) spacecraft and with the Earth radiation budget (ERB) radiometer on the *Nimbus 7* satellite have shown that the solar "constant" fluctuates by up to 0.2% on time scales of days to weeks, in response to changes in projected area of dark spots and bright magnetic faculae on the disk (Willson *et al.* 1981; Hickey *et al.* 1980; Foukal and Lean 1986, hereafter Paper I).

Study of longer term changes in *S* has proven more difficult since it requires radiometer stability to better than 0.1% over time scales of several years. Measurements have been carried out from aircraft, balloons, and rockets since the late 1960s, but their reproducibility is generally considered to be only about 0.3% (Fröhlich 1981). Given this uncertainty, no clear picture of long-term variations in *S* has yet emerged, although interesting evidence for such variations has been presented (e.g., Fröhlich and Eddy 1984).

The ACRIM and ERB radiometry provides a continuous record of the solar irradiance since late 1978. The general downtrend in these data has prompted the suggestion that the total irradiance might be decreasing with declining magnetic activity (Willson 1985; Chapman and Boyden 1986). In a recent study, Willson *et al.* (1986) argue that the decrease in ACRIM measurements of about 0.1% between 1980 and 1984 represents a solar irradiance decrease, since it agrees with a similar difference between a rocket measurement made in 1980 and five other rocket and balloon observations made in 1983 and 1984.

In § II of this paper we present evidence for slow changes in *S* from comparison of variations seen in both the ACRIM and ERB radiometry between 1980 and 1984. In §§ III and IV we investigate these slow variations and also the general downtrend in the radiometer readings, by removing the influence of sunspot blocking and comparing the residual irradiance variations with changes in facular and network radiation as indicated by the He I 10830 and CaK indices. Sections V and VI deal with comparison of the time-integrated sunspot and facular contributions to irradiance variation and its implications for active region energetics.

In § VII we simulate the magnetic activity modulation of *S* over solar cycle 21 from daily data on sunspot blocking and the He I index and compare this simulated irradiance variation to the radiometry since 1978. In § VIII we discuss other recent evidence for an irradiance modulation by magnetic activity. Our conclusions and their possible implications for a direct solar radiative coupling to climate are presented in § IX.

II. EVIDENCE FOR SLOW VARIATIONS IN *S* FROM COMPARISON OF THE ACRIM AND ERB DATA SERIES

The available daily ACRIM radiometry during 1980–1984 and the ERB measurements made in 1978–1986 are shown in Figure 1. The precision of these two data sets and discussions of their calibration have been given recently by Willson (1985) and Hickey (1985), respectively. Both data sets exhibit down-

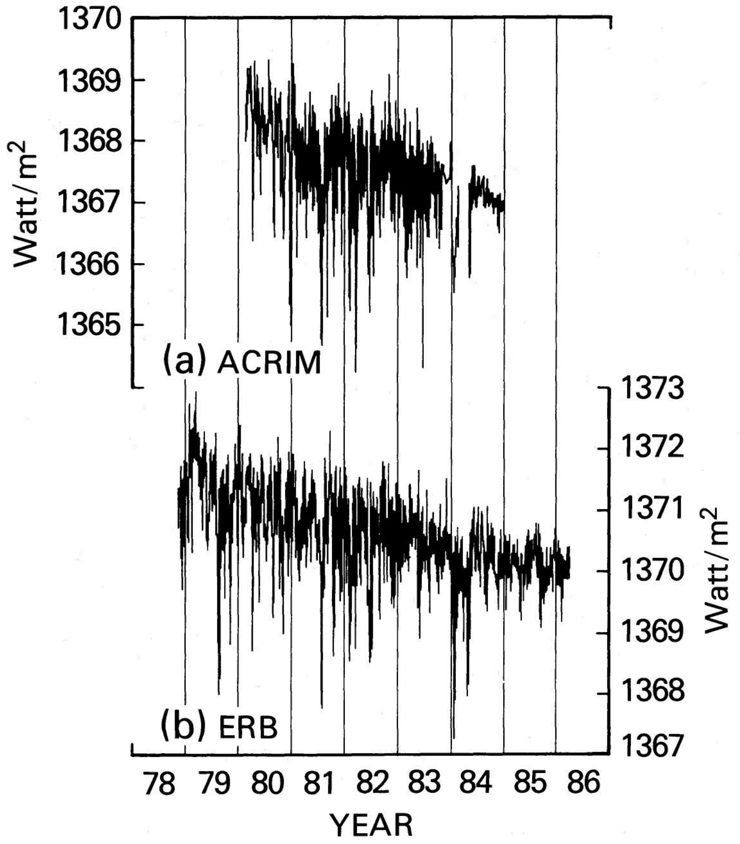

FIG. 1.—Daily irradiance measurements (*a*) for 1980–1984 from the ACRIM and (*b*) for 1978–1986 from the ERB

trends, beginning shortly after their respective launches in late 1978 and in early 1980. This downtrend in both data sets is accentuated within the first year after launch.

In Figure 2 we have plotted the year-to-year changes in linear fits to the two data bases over the 1980–1984 period during which data available to us were taken by both radiometers. The subset of 1312 days on which both ACRIM and ERB obtained data was used in constructing these fits, to ensure that the results are easily comparable. We see that for all five years the signs of the slopes of these linear fits agree between the two data sets, even though this slope changes sign twice during this period.

We see from Table 1 that the yearly slope differences between the two data sets do not have significance at the 95% level in any year except for 1980, when the difference is more than 99% significant. This agreement in slope sign and magni-

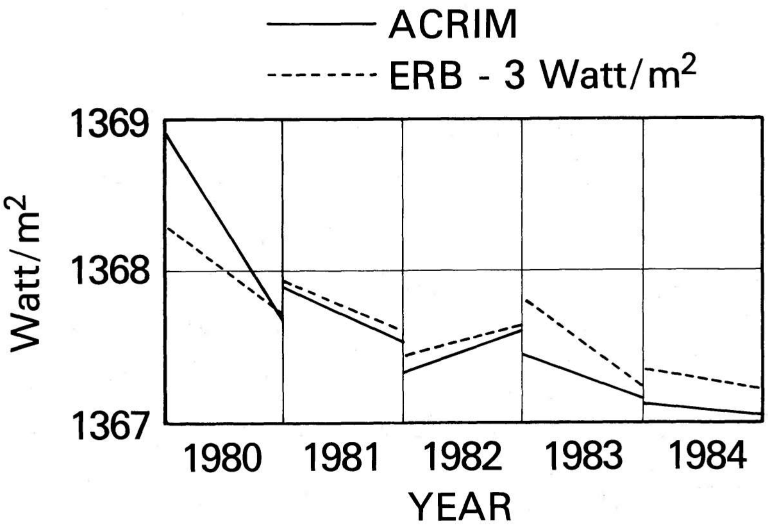

FIG. 2.—Year-to-year variations in linear fits to the ACRIM (*solid lines*) and ERB (*dotted lines*) irradiance data for 1980–1984

TABLE 1

ACRIM and ERB Linear Trend Analysis: 1980–1984

Year	ACRIM	ERB	t
1980	−0.00339 0.00044	−0.00157 0.00047	2.8
1981	−0.00097 0.00039	−0.00090 0.00038	0.1
1982	+0.00075 0.00040	+0.00055 0.00039	0.4
1983	−0.00078 0.00034	−0.00159 0.00027	1.9
1984	−0.00019 0.00025	−0.00037 0.00035	0.4
1980–1984	−0.00073 0.00004	−0.00045 0.00004	6.1

Note.—Slopes (in W m^{-2} day^{-1}) were calculated using only those days on which observations were made by both instruments. The difference in the ACRIM and ERB trends is significant at the 0.1% level if $t > 3.3$, at the 1% level if $t > 2.6$, and at the 5% level if $t > 2.0$. The lower entry in each set denotes one standard deviation.

tude for the four years 1981–1984 strongly suggests that during this time the variations were caused by a solar, rather than an instrumental, effect. The finding that the negative ACRIM slope in 1980 is twice that seen in the 1980 ERB data, and approximately 5 times larger than the ACRIM slope in the four years thereafter, led us to limit our study below to the four years 1981–1984 during which the response of both radiometers seems to have been relatively stable.

The irradiance changes that give rise to the year-to-year slope variations are shown in Figure 3, where the daily ACRIM and ERB data for 1981–1984 are shown on a more expanded time scale. The 81 day smoothed lines plotted in Figure 3 show similar variation in the two data bases, namely local minima in mid-1981, early and mid-1982, and early 1984, with local peaks in early and late 1981, late 1982, and mid-1984. The time scale of these low variations is thus about 4–9 months (peak to peak). Their amplitude is approximately 0.04%–0.07% of the total irradiance.

III. REPRESENTATION OF TOTAL SOLAR IRRADIANCE VARIATIONS WITH FACULAR INDICES

The slow irradiance variations noted above are seen more clearly in Figures 4*a* and 4*b* where the two irradiance data sets for 1981–1984 are shown after subtraction of the function P_s (Fig. 4*c*) which estimates the effect of sunspot blocking from sunspot photometric contrast and daily projected areas (Foukal 1981). The P_s function used is that of Hoyt and Eddy (1982) extended to 1984 by D. Hoyt (1986, private communication) and R. Gilliland (1986, private communication). To express P_s in units of W m^{-2} we used quiet-Sun irradiance values, S_0, of 1366.81 and 1370.1 W m^{-2} for the ACRIM and ERB, respectively, as measured by these radiometers in early 1986.

In Paper I we showed that faculae are the main cause of the day-to-day variations in S that remain after the spot-blocking effect is removed. Thus it is reasonable to inquire whether more gradual facular evolution over time scales of months might

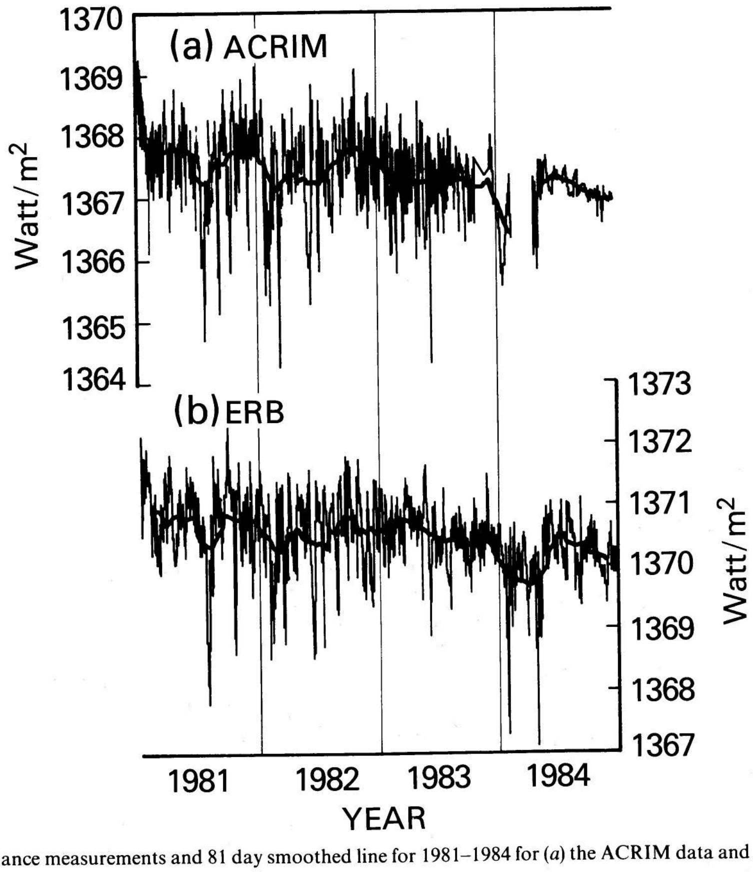

Fig. 3.—Daily irradiance measurements and 81 day smoothed line for 1981–1984 for (*a*) the ACRIM data and (*b*) the ERB data

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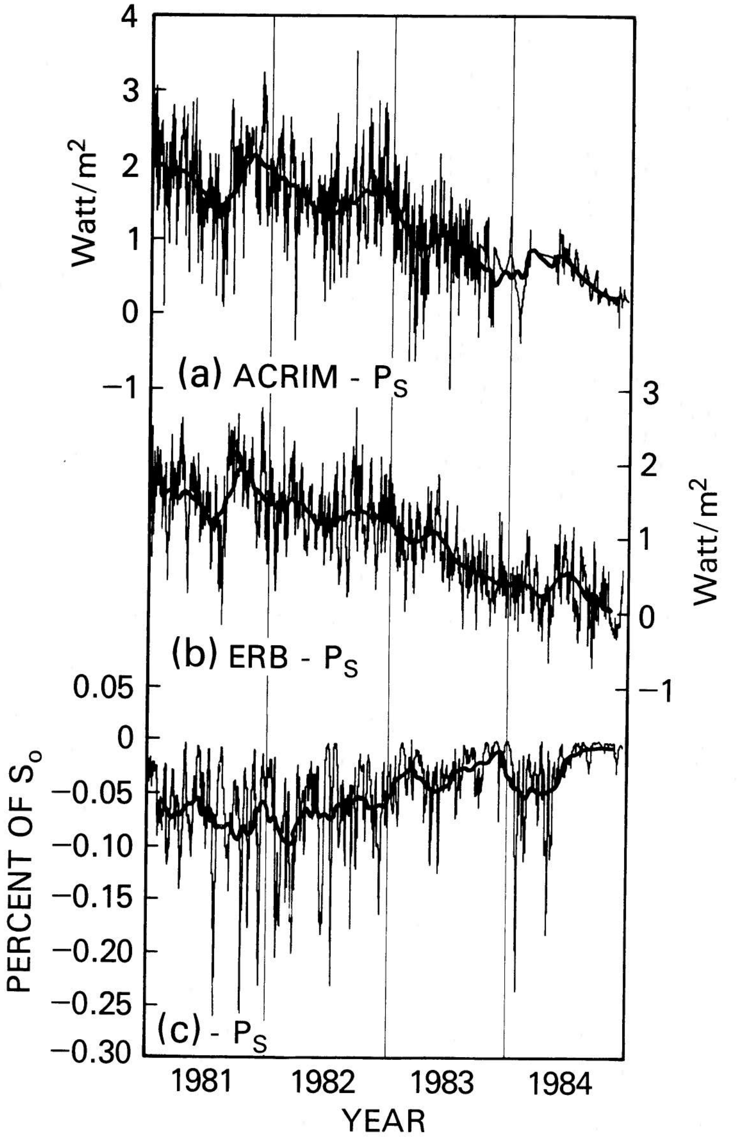

FIG. 4.—The residuals $S - P_s$ for 1981–1984 obtained after subtracting the sunspot blocking function, $-P_s$ from the ACRIM and ERB data are shown in (*a*) and (*b*). The function $-P_s$ is shown in (*c*). Smooth curves are 81 day running means.

account for the slow variations in S, since these slow variations are accentuated in the irradiance residuals plotted in Figures 4*a* and 4*b*.

The general behavior of three indicators of plage and facular radiation between 1975 and 1984 is shown in Figure 5. These are the daily He I 10830 line equivalent widths from Kitt Peak (e.g., Harvey 1984), the disk-integrated 1 Å CaK index values from Tucson (e.g., White and Livingston 1981), and the daily CaK plage index compiled by NOAA-WDC. The solid line smooths each of the data sets with an 81 day running mean.

The first two indices, which record radiations from the whole disk, show a relatively pronounced general decline between peak values in late 1981 and in 1984. In addition, they show features on time scales of roughly 4–12 months. The third, the CaK plage index, is an indicator of variations only in radiations from the few largest plage areas on the disk. This index also shows relatively large variations on the 4–12 month time scales, but it peaks in late 1979 (not late 1981) and it exhibits a less evident general downtrend over the 1981–1984 period.

It has been shown (Harvey 1984) that the He I variations are highly correlated with full-disk CaK variations (White and Livingston 1981). Since the He I 10830 data are available on a daily basis (unlike the full-disk CaK, which is measured only a few times per month), we used them as an indicator of the variation in excess radiation from bright magnetic structures (Donnelly *et al.* 1985), including large faculae and also the network. We use the daily CaK plage index as an indicator of the excess radiations from extended bright facular radiations in active regions. The variations observed in these two indices in 1981–1984 are plotted on an expanded time scale in Figure 6.

Figure 7 shows the correlations obtained between the ACRIM$-P_s$ and ERB$-P_s$ irradiance residuals plotted in Figure 4, and the He I and CaK indices plotted in Figure 6. As expected from the results of Paper I, both indices show a significant correlation with $S - P_s$ (see Table 2), although the He I

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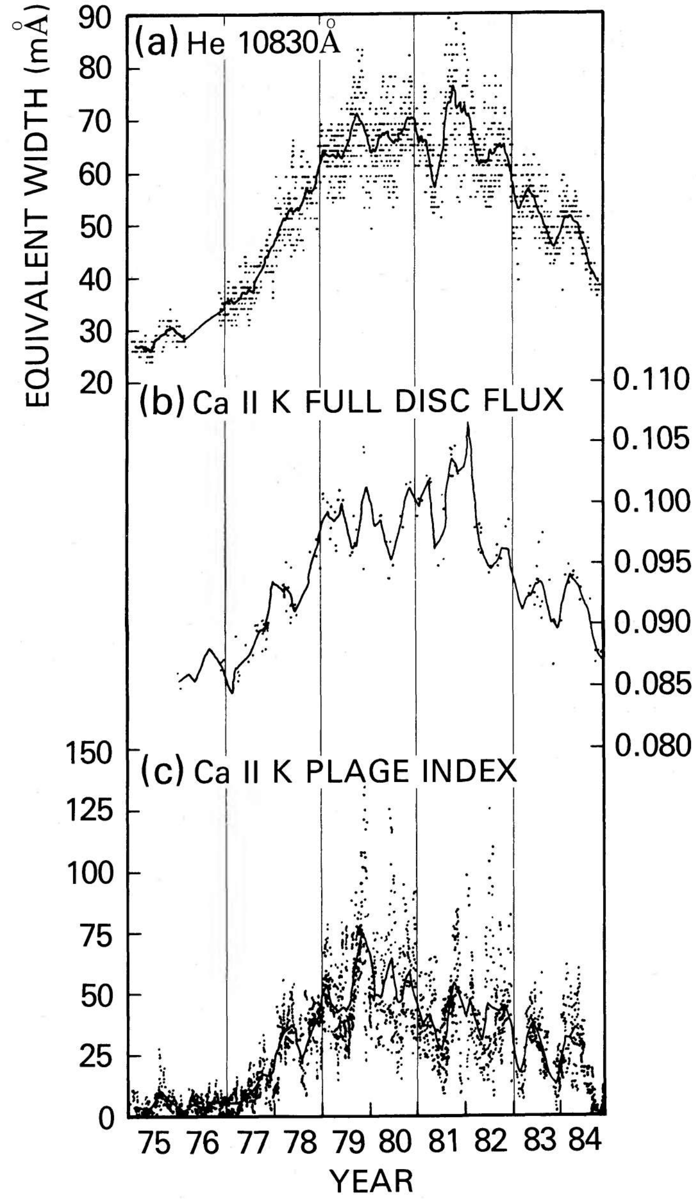

FIG. 5.—Solar cycle 21 behavior (1975–1984) of three activity indices: (*a*) the full disk He I 10830 flux, (*b*) the full disk CaK flux, and (*c*) the CaK plage area index

index appears to provide a more uniformly distributed regression than does the CaK plage.

IV. EXPLANATION OF THE SLOW VARIATIONS IN $S-P_s$ IN TERMS OF FACULAR AREA CHANGES BETWEEN 1981 AND 1984

We can simulate total irradiance variations from the daily He I 10830 and CaK plage data using the regressions shown in Figure 7. Figure 8 shows the simulated irradiance residuals $S-P_s$ computed for 1981–1984 from the regressions of the CaK and He I indices with the ACRIM $-P_s$ residuals, and also with the ERB $-P_s$ residuals. We see that although the irradiance variations computed from both indices match very well in the slow variations, those calculated from the He I index show a pronounced general downtrend between 1981 and 1984 that is much less evident in the irradiance residuals computed from the CaK plage index. This is not surprising, given the relatively larger downtrend in the He I index plotted in Figure 6.

The match between the observed irradiance residuals ACRIM $-P_s$ and ERB $-P_s$, and the residuals $S-P_s$ calculated from the He I 10830 data is shown in Figures 9*a* and 9*b*. We see that the correspondence between the observed and computed residuals is very good, using both the ACRIM and ERB data.

TABLE 2

CORRELATION COEFFICIENTS FOR THE IRRADIANCE RESIDUALS AND FACULAR INDICES PLOTTED IN FIGURE 7

Function	Correlation Coefficient
ACRIM $-P_s$ vs. He I	0.77
ACRIM $-P_s$ vs. plage index	0.58
ERB $-P_s$ vs. He I	0.79
ERB $-P_s$ vs. plage index	0.57

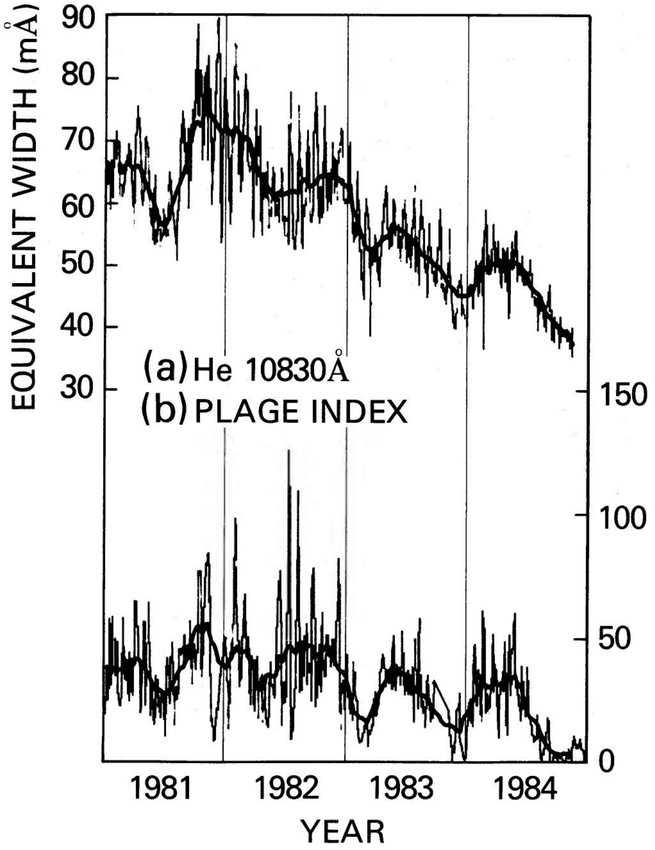

FIG. 6.—Daily values of the He I 10830 index (*a*) and CaK plage index (*b*)

It is remarkable that we are able to fit not only the slow variations, but also the slow trend between 1981 and 1984, using the irradiances computed from He I. A good fit to the slow variations can also be achieved with the irradiances calculated from the CaK plage index (Figs. 9*c* and 9*d*), but the general downtrend is not as well reproduced.

This result indicates that the slow variations of S over the declining part of solar cycle 21 can be attributed to changes in sunspot blocking and (mainly) radiation from bright photospheric magnetic elements. The finding that the irradiance residuals computed from the He I index variation fit the slow downtrend in the data better than do those generated from the CaK plage data seems to indicate that network radiations play an important role in determining this downtrend in the radiometry since 1981.

The results we obtain are not significantly changed if we construct the $S-P_s$ versus He I 10830 regression using data from a given year such as 1982 over which a large range of He I 10830 values were recorded, or over the full four year data base. This indicates that any slow calibration drifts over the four years that might affect the total irradiance values (or, less likely, the He I index values) do not significantly influence the $S-P_s$ versus He I index relation defined by Figure 7. In other words, the simulated irradiance function we calculate appears to be uniquely determined by the level of solar activity as indicated by the daily He I index, without reference to the phase of the solar cycle.

A less likely interpretation might be that the slow downtrend in the observed irradiances is mainly instrumental calibration drift between 1981 and 1984, and only the superposed slow variations are of solar origin. These variations are reproduced almost as well by the CaK plage index as by the He I index. But a downward drift in the calibration of both the He I and CaK full-disk indices of the magnitude shown in Figure 5 seems unlikely (O. White 1987, private communication). So in this case we would need to suppose that the slow decline seen in the He I index does not affect the total irradiance, although the superposed slow variations in this index do correlate well with slow variations in the total irradiance.

V. COMPARISON OF SUNSPOT-BLOCKED RADIATIVE FLUX AND EXCESS FACULAR RADIATION BETWEEN 1981 AND 1984

In Paper I we showed that over time scales of active region evolution the heat flux blocked by spots, represented by the time integral $P_s\,dt$, was comparable to the excess radiative flux attributable to faculae represented by $(S-P_s)dt$. However, only data up to 1982 were available for that study, and the major uncertainty was due to the unknown value of S_0 at truly quiet-Sun conditions. A lower value of S_0 would tend to increase the facular contribution found in Paper I.

We are now in a better position to repeat that investigation, using values of S_0 found from more recent radiometry at very low activity levels in 1986. In calculations given below of the integrals from ACRIM data we use the value of $S_0 = 1366.8$ W m^{-2}, achieved in early 1986 (R. Willson 1986, private communication). Integrals calculated from the ERB data are based on $S_0 = 1370.1$ W m^{-2}, measured by the ERB in early 1986 (J. Hickey 1986, private communication).

We find that in all four years the facular contribution integral rises at about twice the rate of the sunspot contribution. With declining solar activity level from 1982–1984, the magnitude of both integrals decreases, as might be expected. Very similar results are obtained for the ERB and ACRIM data in all four years. Given the high correlation between the irradiance residuals and the He I index, this result indicates that the (positive) irradiance contribution of bright magnetic elements is approximately twice the (negative) blocking by spots. This appears to hold at both high- and low-activity phases of the solar cycle.

An estimate of the relative importance of large active region faculae and the network to the "facular" contribution integrals can be obtained by comparing the time-integrated irradiance contributions associated with the CaK plage index variations and those associated with the He I index changes. To obtain the irradiance residuals associated with large faculae and network combined, the regressions plotted against He I index in Figures 7*a* and 7*c*, are used. The contribution of the large faculae alone is determined from the irradiance residuals against CaK plage index in Figures 7*b* and 7*d*.

The relative irradiance contribution of all bright magnetic elements versus large faculae alone can then be estimated by integrating each of the above functions over the same time period. The zeros of the integrals are chosen to correspond to an He I index value of 27 and a plage index of 4, as measured at the 1975 activity minimum. We find that in each year, the "total" contribution integral obtained from the He I index is approximately twice as large as the integral representing the contribution of the active region faculae alone. Thus, it appears that approximately one-half of the total irradiance effect of bright magnetic elements is caused by the large active region faculae, and about half by the network.

In the years 1981 and 1982, the time-integrated contributions of sunspots and active region faculae are found to agree

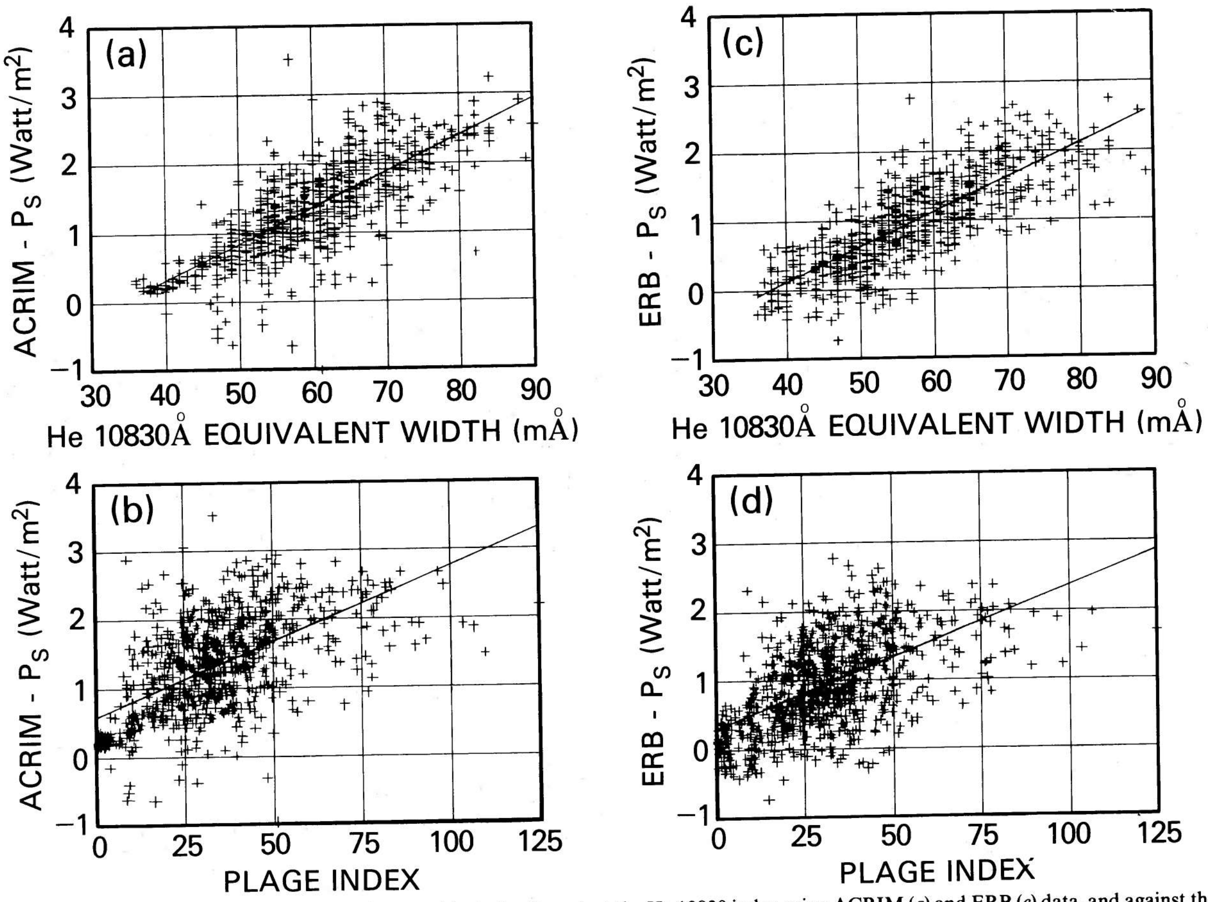

FIG. 7.—Correlation of the daily 1981–1984 irradiance residuals $S - P_s$ against the He 10830 index using ACRIM (*a*) and ERB (*c*) data, and against the CaK plage index (*b*), (*d*).

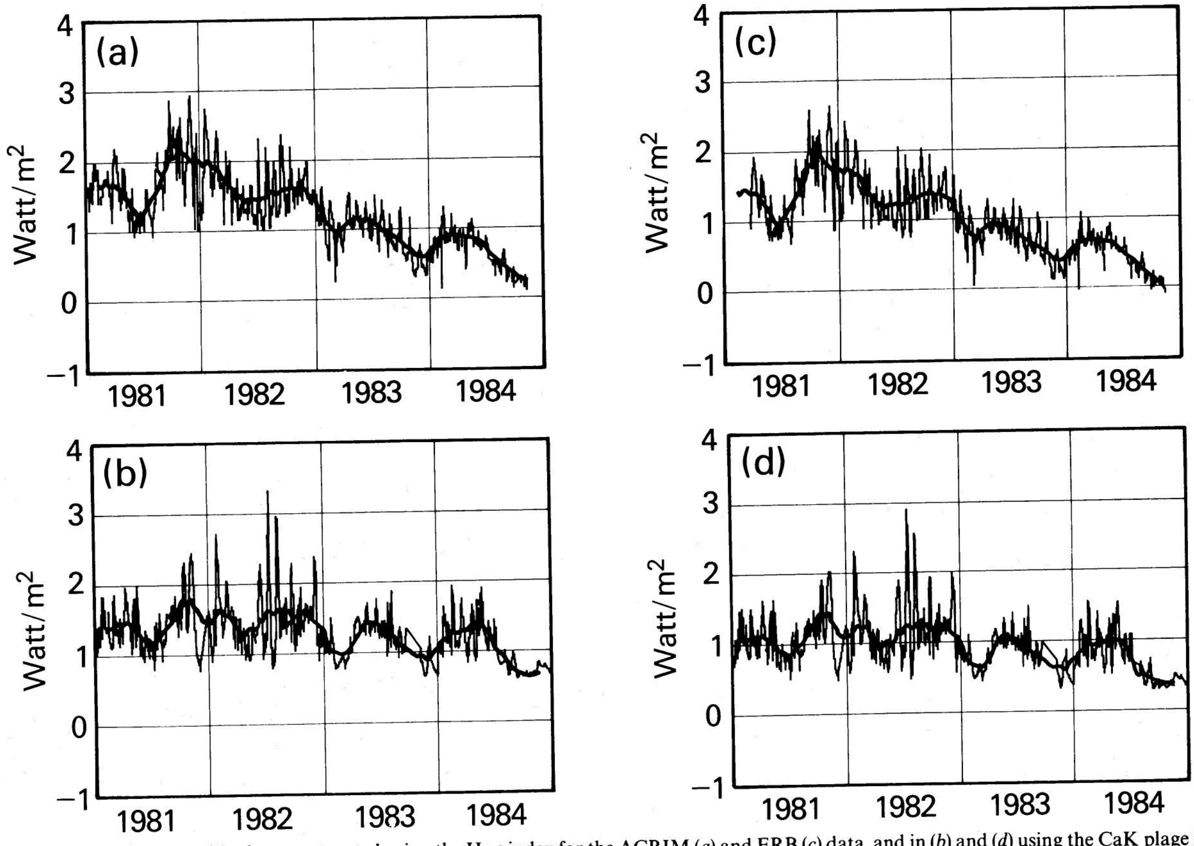

FIG. 8.—The irradiance residuals reconstructed using the He I index for the ACRIM (*a*) and ERB (*c*) data, and in (*b*) and (*d*) using the CaK plage index

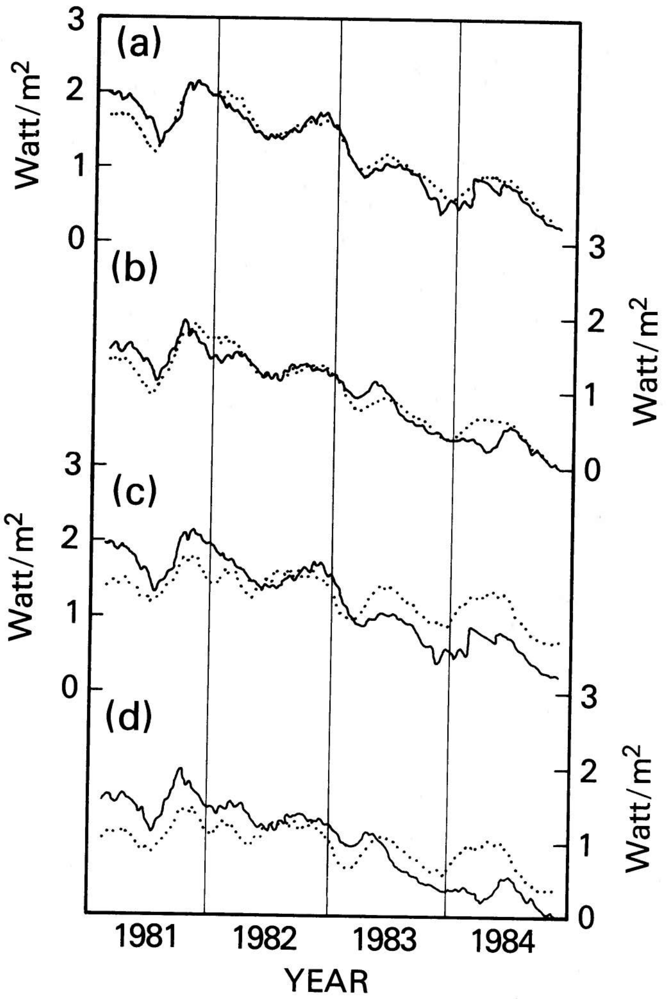

FIG. 9.—Comparison of the observed irradiance residuals $S - P_s$ (*solid lines*) for the ACRIM (*a*), (*c*) and ERB (*b*), (*d*) data, with the irradiance residuals (*dotted lines*) calculated using the He I (*a*), (*b*) and CaK (*c*), (*d*) indices.

remarkably well, to better than 5%. Given the uncertainties in calculating the functions P_s and P_f, and in the zero point used in calculating integrals, this agreement in 1981 and 1982 is much better than the expected precision of the comparison, and is likely to be fortuitous. In the years 1983 and 1984 (and also in 1980) the agreement is less good, with the large faculae contributing 20%–40% more than the spot missing energy in each of these three years.

As noted above, another interpretation might be that most of the general downtrend in S since 1981 is instrumental (or solar, but not associated with spots and faculae), that the facular and spot integrals generally match, and the network contributes little to the irradiance. But then it is hard to understand why the facular irradiance function calculated from the He I 10830 data so successfully reproduces not only the slow irradiance variations on time scales of months to a year, but also the overall decline in S between 1981 and 1984.

VI. PHYSICAL INTERPRETATION OF THE FACULAR INFLUENCE ON SOLAR IRRADIANCE AND LUMINOSITY

The correspondence we find between the irradiance residuals and indices of bright photospheric magnetic elements suggests a fairly simple physical explanation of the decline in S since 1981, and more generally for solar irradiance modulation over the solar activity cycle. It is well known (e.g., Zwaan 1965, Spruit 1976) that the increased magnetic pressure in both sunspot and facular flux tubes should cause a decrease in their internal gas pressure and opacity relative to layers of equal geometrical depth in the photosphere. The net effect of this decrease in opacity is to enable the relatively hot layers of the convection zone around the flux tube to radiate more directly into space.

Models of the relatively small-diameter flux tubes of faculae and network indicate that this enhanced radiative loss can be more important than the inhibition of axial heat transport by convection that may also be caused by the magnetic field, and the result can be a structure with excess brightness temperature (Spruit 1976; Deinzer *et al.* 1984; Ferrari *et al.* 1985). On the other hand, the convective inhibition tends to dominate in the large-diameter flux tubes because its importance relative to the radiative leak scales as the ratio of area to diameter, so spot darkness can also be explained.

In the thermal model outlined above, the irradiance variations associated with large facular areas in active regions, and also with the network, can be interpreted as changes in solar luminosity due to changes of the thermal impedance in photospheric levels. These impedance changes seem to be caused by variations in the total area covered by small-diameter magnetic flux tubes. The general downtrend in S between 1981 and 1984, then, represents a luminosity decrease of 0.07% caused in roughly equal parts by decreases in the network and active region facular radiations. The 0.04%–0.07% amplitude slow changes on 4–9 month time scales seem to be caused by the more transient luminosity increases due to the large bright facular areas that dominate the irradiance contribution of active complexes.

Our finding that an unbalanced irradiance contribution from the network exists over four years, thus on time scales of many solar rotations, demonstrates that this irradiance contribution is a true solar luminosity change, rather than an irradiance effect caused by the anisotropic radiation field of bright facular magnetic elements. It also demonstrates that the excess radiation from these bright magnetic network elements cannot represent the reradiation of blocked sunspot heat flux. Both of these results are consistent with the thermal model, which predicts a net increase in photospheric heat flux due to faculae.

Our comparison of the facular and spot contributions is in general agreement with the findings from ground-based photometry that bright facular radiations are comparable to the missing energy of spots (Chapman 1987). However, the agreement seems to be only to about a factor 2, and appears to be variable in time. The statistical significance of the close agreement found in 1981–1982 requires closer investigation, but the energetics of spot and facular radiations seem quite consistent with the thermal model, although more complex models (e.g., Schatten, Mayr, and Omidvar 1987) cannot be excluded.

VII. MODULATION OF SOLAR LUMINOSITY DURING SOLAR CYCLE 21

We can use the sunspot blocking function calculated from spot coordinates and areas between 1975 and 1984, and the facular irradiance contribution calculated from He I 10830 data over the same period, to compute the magnetic modulation of the solar luminosity caused by dark spots and bright faculae during solar cycle 21. The facular irradiance contribution, P_f, shown in Figure 10*b* is calculated from daily KPNO

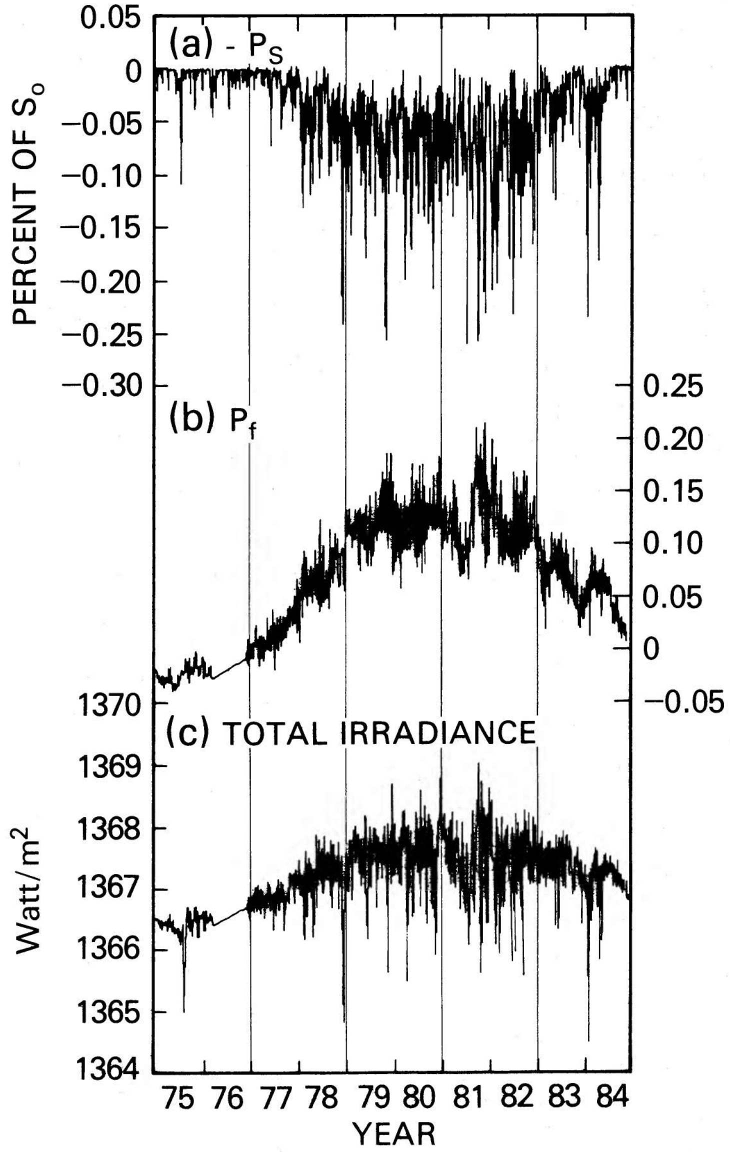

FIG. 10.—Solar cycle 21 behavior of (*a*) the daily sunspot blocking function P_s, (*b*) the daily facular irradiance excess calculated from the He I index, and (*c*) the reconstructed total solar irradiance.

He I 10830 data provided for 1975–1984 by Harvey (private communication), using the regressions of S upon He I shown in Figure 7.

The modulation of S during solar cycle 21 computed from the spot and facular influences is plotted in Figure 10*c*. The ordinate scale is determined by using a value of $S_0 = 1366.81$ W m^{-2}. The increase of luminosity predicted between activity minimum in 1975 and maximum in late 1981 is approximately 0.12%. The decline in S expected between late 1981 and the end of 1984 is approximately 0.07%, in very good agreement with the decline of 0.95 W m^{-2} in the ACRIM over that time period and the slightly smaller decline in the ERB readings (Fig. 3).

Two other aspects of this computed irradiance variation are worth comparing to the behavior of radiometry since 1978. For one, we see in Figure 10*c* that during 1980, the computed irradiance is still rising, which does not agree with the steady downtrend since 1980 exhibited by the radiometry, in particular the relatively steep decline during 1980 shown by the ACRIM.

Second, the computed irradiance variation also disagrees with the steady decline in ERB measurements since 1978, since the activity modulation might be expected to have increased by almost as much (0.05%) between the beginning of ERB data taking in late 1978 and peak activity in late 1981, as it seems to have declined between 1981 and 1984.

These disagreements suggest that the overall downtrends in S seen by both the ERB and ACRIM since their respective launches are not explainable in terms of irradiance modulation by photospheric activity, except after 1981. Calibration changes in the He I data large enough to cause this disagreement seem unlikely (Harvey, private communication). Change in the effective temperature of spots over the solar cycle (Albregtsen and Maltby 1981) would act in the wrong direction. This might mean that the decline in S since 1978 is determined by solar influences other than photospheric magnetic activity, such as deep-seated convective changes. An alternative interpretation, discussed below, is that the model is correct, but both radiometers initially declined in responsivity after their respective launches and then stabilized.

VIII. COMPARISON WITH OTHER RECENT EVIDENCE ON SOLAR IRRADIANCE BEHAVIOR DURING SOLAR CYCLE 21

Several lines of evidence bear on the possibility of small calibration drifts in the ERB and ACRIM radiometers, which could influence the comparison between our model and the radiometry prior to 1981.

For one, the prominent increase seen in the ERB data in Figure 1*b* soon after launch and extending into early 1979, occurred at a time of anomalously high *Nimbus 7* spacecraft temperatures, apparently caused by operation of the ERB experiment scanning photometer. Given this correlation, and uncertainties in the temperature coefficient of the ERB radiometer, it has been suggested that the rise and fall of the ERB data prior to mid-1979 might be spurious (J. Hickey, private communication). Comparing Figure 1 with Figure 10, it is clear that the agreement between the model and the ERB radiometry is much better if the data prior to mid-1979 are discounted.

The ACRIM data indicate a steeper decrease in *S* during 1980 than that seen either in the model or in the ERB data. As pointed out in § II above, when only days of common measurements are used, the ACRIM downslope in 1980 is more than twice the ERB downslope in that year (see Table 1). We note that the plot of the 1980 ACRIM/ERB ratios presented by Willson *et al.* (1986) shows a peak-to-peak variation of 0.1%. This does not support the statement by those authors that the scatter in this ratio is below 100 parts per million and thus does not rule out the small slope difference suggested here.

Willson *et al.* (1986) acknowledge that comparison of the three ACRIM channels does not test against possible degradation common to all three channels such as vacuum outgassing of the paint solvent. From analysis of the behavior in space between 1984 October and 1985 July of similarly constructed solar irradiance sensors flown on the *Earth Radiation Budget* (*ERBS*) and *NOAA 9* satellites, Lee, Barkstrom, and Cess (1987) find evidence for a calibration change in excess of 0.03% during the first year of operation of such a sensor. A drift of the ACRIM calibration during 1980 by about this amount would explain the difference between the ACRIM readings and our model. It is doubtful whether a drift as small as this can be excluded by the comparisons with rocket and balloon data and other calibration checks described by Willson *et al.* (1986).

IX. DISCUSSION AND CONCLUSIONS

We find that the slow variations over time scales of four to nine months seen by the ACRIM and ERB radiometers are well correlated between these two data sets. This correlation between radiometers on two different spacecraft demonstrates that the total irradiance varies at the 0.04%–0.07% level over time scales much longer than the day-to-week time scale fluctuations well known to be caused by disk passage of large individual sunspot or facular groups.

These slow changes are more prominent in the irradiance residuals after sunspot blocking changes are removed and are very well correlated with similar slow variations in the He I 10830 and CaK plage indices of facular radiation. Using the regression of daily observed irradiance residuals upon observed daily He I 10830, we are able to reconstruct the variation in *S* observed between 1981–1984 including the general downtrend over those four years. This indicates that the radiation of bright photospheric magnetic elements more than compensates sunspot blocking of photospheric radiation and accounts for most of the slow variations and downtrend in *S* since 1981.

The first evidence for a significant facular influence on the total irradiance was based on analysis of ground-based pyrheliometry and early results from space radiometry (Abbot 1942*a*, *b*; Foukal, Mack and Vernazza 1977; Foukal and Vernazza 1979; Sofia, Oster, and Schatten 1982). Our study of the 1978–1982 data from the ACRIM and ERB in Paper I showed that the facular irradiance signal is at least comparable to that of spots on time scales of active region evolution. Several studies based on photometric estimates of the bolometric contrast of spots and faculae have also predicted approximate balance between their contributions to the total irradiance over similar time scales (e.g., Chapman 1980, 1987, Oster, Schatten, and Sofia 1982, Hirayama, Okamoto, and Hudson 1984, Lawrence 1987). The results presented here clearly demonstrate a facular signal in the simultaneous rises and falls of two highly precise radiometers measuring the total irradiance from space over the time scales of months to years of direct interest to climate studies.

We find that the irradiances reconstructed from daily CaK plage areas are also able to match the slow variations, but not the general downtrend. This indicates that facular radiations from long-lived activity complexes modulate *S* on the time scales of 4–9 months, but a decline in network radiation (not included in the CaK plage index) mainly determines the general downtrend.

Although the variations in total irradiance discussed are a small fraction of *S*, they are far too large to be caused by chromospheric and coronal radiations of the plages and network. Variations of the observed amplitude can, however, be explained as changes in the excess photospheric radiation of faculae and network in the visible and ultraviolet continua (Lean *et al.* 1983).

The clear connection we are able to establish between slow solar variations and facular area changes strengthens the interpretation of the slow decline in *S* measured since 1981 by the ACRIM and ERB radiometers, as a real solar irradiance decrease. However, the modulation of solar irradiance that we simulate for cycle 21 using spot areas and He I index values for 1975–1984, predicts a maximum of solar irradiance in 1981. This disagrees with the ERB and ACRIM radiometry before 1981, which shows a general decline from the beginning of observations with the two radiometers in 1978 and 1980, respectively. We suggest that both radiometers may have experienced significant initial calibration drifts after their respective launches in 1978 and 1980. A longer time base of comparison between our model of magnetic modulation of *S* and the ACRIM and ERB radiometry will help to understand the basis of this disagreement.

The general decline of irradiance since 1981 might be interpreted as an increase of photospheric thermal impedance caused by decreased photospheric area coverage by bright magnetic elements in the network. This interpretation is quite consistent with the explanation of the excess brightness of small-diameter magnetic flux tubes as a consequence of locally decreased opacity (Zwaan 1965). Our finding that the network elements can make such a large unbalanced contribution to *S* (see also Labonte 1986), shows that their excess brightness temperature does not imply reradiation of blocked sunspot missing energy, nor can it be due primarily to the anisotropy of facular radiation (Oster, Schatten, and Sofia 1982).

We find a remarkably close balance between sunspot and facular contributions to S made by active regions over the two year period 1981 and 1982. This agreement to better than 5%, using full-disk, bolometric data integrated over many solar rotations, is closer than found in previous studies using ground-based photometry of individual active regions (e.g., Bruning and Labonte 1983, Hirayama, Okamoto, and Hudson 1984, Chapman *et al.* 1984, Chapman, Herzog, and Lawrence 1986). Since the balance appears less good in 1980, 1983, and 1984, further study of the accuracy of these integrals (and thus of the statistical significance of their agreement) is required.

Our demonstration that faculae and network mainly determine solar luminosity modulation over the 11 year cycle explains why the Sun is brighter at high magnetic activity levels, not dimmer as expected from consideration of the sunspot blocking contribution alone. The amplitude of the solar cycle modulation of S is relatively small—about 0.12% between activity maximum and minimum in cycle 21, which was one of the larger amplitude cycles in sunspot area recorded since the late 19th century. However, the facular and network control of total irradiance found here means that the Sun would have been dimmer than average during extended periods of depressed solar activity such as the Maunder minimum of activity in the 17th century. This raises the very interesting possibility of a direct radiative coupling between the effective temperature of the solar photosphere and tropospheric temperatures during climatic anomalies such as the so-called Little Ice Age of the 17th century (Eddy 1977). The previously held view that the Sun would have been brighter during the Maunder minimum due to absence of dark spots argued against such a direct radiative coupling.

The actual irradiance values during the Maunder minimum are likely to have been lower than the value of S_0 used here, since facular areas might be expected to decay to even lower values than those recorded during a typical activity minimum. Since the 0.09% decrease in S between 1981 and 1986 corresponds to an He I equivalent-width decrease from about 75 mÅ to about 35 mÅ, a further decrease in S of perhaps 0.05% might accompany very low facular and network area during a protracted activity minimum. In addition, the Maunder minimum extended for about 70 years, so we might expect that any climatic influences of a low solar irradiance would act much longer than the two to three years experienced during a typical recurrence of low activity during the 11 year spot cycle.

The dominance of bright magnetic elements in determining the Sun's luminosity modulation over the 11 year cycle points to the need for closer study of facular evolution, which has been much less widely studied than the evolution of sunspot areas. If our model is correct, the record of total solar irradiance is more sensitive to the difference in solar cycle amplitudes as measured by the cycle peaks in spot and facular areas than to the amplitude of the cycle as measured by spots alone.

The behavior of facular and network radiations during extended periods of depressed solar activity will be difficult to determine from direct studies of the historical record of solar observations during the Maunder minimum, but interesting insights might be accessible from observations of other late-type stars, e.g., Labonte (1986), and from semiempirical numerical simulations of the photospheric magnetic field evolution (e.g., Sheeley, Devore, and Shampine 1986).

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