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# THE INFLUENCE OF FACULAE ON TOTAL SOLAR IRRADIANCE AND LUMINOSITY

P. FOUKAL
Atmospheric and Environmental Research, Inc.
AND
J. LEAN
Cooperative Institute for Research in Environmental Sciences, University of Colorado/NOAA
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## ABSTRACT

We investigate the facular contribution to the total solar irradiance, using the daily active cavity radiometer irradiance monitor (ACRIM) radiometry for 1980–1982 and the Earth Radiation Budget (ERB) radiometry for 1978–1982. A calculated sunspot-blocking function $P_s$ is subtracted from the irradiances, $S$, and we study the cross-correlation of these residuals $S - P_s$ with the 205 nm ultraviolet flux measured from the *Nimbus 7* Solar Backscatter Ultraviolet (SBUV) experiment, with a white light modulation function $P_f$ calculated from facular areas and contrasts, and with $P_s$ itself. The correlation coefficient at zero lag between the residuals $S - P_s$ and either $P_f$ or the 205 nm flux is $\sim$25% higher than the correlation between $S - P_s$ and $P_s$. Since the behavior of both $P_f$ and the 205 nm flux is determined by facular rotation and evolution, this suggests that faculae, rather than errors in the $P_s$ function, account best for the irradiance residuals. Further evidence for a considerable facular contribution to $S$ is based on the distinct symmetry of the $S - P_s$ versus 205 nm or $P_f$ cross-correlation functions, on the surprising absence of a 28 day peak in the total irradiance power spectrum, and on analysis of the relative contributions of spot and faculae-associated signals to this power spectrum. Time integration of the spot and facular components of irradiance variation indicate that their contributions over time scales of active region evolution were comparable in 1980. We present several arguments based on the thermodynamics of magnetic energy storage and on the geometry of magnetic connections in active regions and network which indicate that faculae are not likely to act as conduits for reradiation of the missing sunspot heat flux. Rather, they seem to represent an independent magnetic perturbation to photospheric heat flow of opposite sign to that of spots and of comparable magnitude.

*Subject headings:* Sun: faculae — Sun: general — Sun: sunspots

## I. INTRODUCTION

Radiometry from the *Solar Maximum Mission* (Willson *et al.* 1981) and *Nimbus 7* (Hickey *et al.* 1980) satellites has shown variations in the total solar irradiance, $S$, of peak-to-peak amplitude 0.2% over characteristic time scales of $\sim$10 days. A substantial fraction of this variance can be explained as the effect of dark sunspots rotating across the photospheric disk (Willson *et al.* 1981; Hoyt and Eddy 1982). The *SMM* radiometry for 1980 also shows a strong positive correlation with 10.7 cm radio flux, after a calculated variation resulting from changing projected areas of spots is removed from the total irradiance signal (Hudson and Willson 1981). This correlation led the authors to suggest a facular contribution to the total irradiance variation, although some of the correlation could be caused by error in the calculated sunspot contribution to $S$, since large faculae are often associated with spot groups. Comparisons of the ACRIM radiometry for 1980 with irradiance variations calculated from intensity maps made in the wings of the Fe I $\lambda$5250 line, suggest that the facular and spot contributions to $S$ are similar when integrated over time scales of active region evolution (Bruning and Labonte 1983). Evidence presented by Oster, Schatten, and Sofia (1982) for a strong facular influence on $S$ appears to have been based on a serious overestimate of sunspot areas (Hoyt, Eddy, and Hudson 1983).

It has been known for some time from visible light photometry (e.g., Kiepenheuer 1953; Chapman 1980; Lawrence *et al.* 1985) that the radiative flux missing in spots can be roughly comparable to the excess flux from faculae in the same active regions. However, this rough agreement has not proven sufficiently compelling to inspire models of spots and faculae as energetically connected phenomena. The ACRIM irradiance record since 1980 and ERB radiometry since 1978 now provide a long, continuous set of irradiance measurements suitable for a more precise bolometric comparison of spot and facular influences on photospheric heat flow.

The relative facular and spot contributions to $S$ and luminosity $L_\odot$ also bear directly on studies of possible slow trends in $L_\odot$ over longer time scales of more direct climatological significance. Thus, Fröhlich and Eddy (1984) report evidence for such trends at the level of 0.4% over 11 yr. To determine whether such possible trends are likely to involve variations in the output of the quiet Sun, it is important to establish whether the component of solar luminosity modulation due to spots and faculae is positively or negatively correlated with the level of solar magnetic activity. This requires that we determine the relative contributions of the spot-associated dips in irradiance and the facula-associated increases in the 11 yr signal.

In § II of this paper we use a one-year subset of the radiometric data to illustrate the basic features of the correlation between short-term variations in total irradiance, ultraviolet flux, and the calculated contributions of spots and faculae. In § III, we show the full data base used in this study, consisting of radiometric measurements and spot and facular areas from the period 1978–1982, and we cross-correlate these data to study the evidence for a facular contribution to $S$. In § IV, we present further evidence on the frequency structure and total power of the facular contribution, from power-spectrum analysis. In § V, we compare the magnitude of facular and sunspot contributions to $S$. In § VI, we discuss the energy balance of spots and faculae in the broader perspective of other observational and theoretical evidence on their dynamical connection, and we summarize our conclusions in § VII.

## II. COMPARISON OF VARIATIONS IN TOTAL IRRADIANCE, ULTRAVIOLET FLUX, SUNSPOT BLOCKING, AND WHITE-LIGHT FACULAR FLUX IN 1980

Figure 1 shows simultaneous measurements of the total solar irradiance made during 1980 by the ACRIM experiment on the *Solar Maximum Mission* satellite and the ERB experiment on the *Nimbus 7* satellite. Both data sets have been detrended with a twelfth-order polynomial. Our interest is in the relatively short-term variations of an $\sim 10$ day time scale whose timing, amplitude, and shape are seen to agree well in the two radiometric records. Since the ACRIM data between February and December 1980 exhibit lower noise, we concentrate in this section on these data.

Figure 2*a* shows the $P_S$ function that describes the modulation of solar irradiance as calculated from daily projected areas and the estimated photometric contrast of sunspots. The function $P_S$ presented here was calculated by Hoyt (1983, private communication) using procedures and data described by Hoyt and Eddy (1982). Figure 2*b* shows the 1980 ACRIM radiometry after subtraction of this function $P_S$. Also plotted in Figure 2 are (2*c*) the detrended daily ultraviolet flux $F_{uv}$ measured at 205 nm by the SBUV experiment on *Nimbus 7* as supplied by D. Heath and (2*d*) a calculated function $P_f$ that roughly approximates the daily facular contribution to the total irradiance. The function $P_f$ was calculated from daily Ca K plage areas provided by the NOAA World Data Center using a limb-brightened bolometric facular contrast (see, e.g., Foukal 1981).

Comparison of the curves 2*b* and 2*c* in Figure 2 shows close correspondence in the timing of large peaks in the total irradiance residuals and in $F_{uv}$. Since variations in $F_{uv}$ are known to be caused primarily by the rotation and evolution of faculae (e.g., Heath 1980; Lean *et al.* 1982), this correlation suggests a facular signal in the total irradiance. The relative amplitude of modulation seen in $F_{uv}$ is similar to the relative amplitude of peaks and troughs in the total irradiance, which is not surprising since the main contribution to the 205 nm emission is from the same photospheric layers below 400 km above $\tau_{0.5} = 1$ (Vernazza, Avrett, and Loeser 1981), which also determine the facular white-light emission. The correspondence in the peak amplitudes shown here is somewhat better than that seen in the comparison of ACRIM radiometry and $F_{10.7}$ presented by Hudson and Willson (1981). This might be expected, since the centimeter wave emission originates at much higher chromospheric and coronal layers.

Comparison of Figures 2*a* and 2*b* shows, however, that the time series of (ACRIM $- P_S$) and $P_s$ are also highly correlated. A substantial contribution to the residuals (ACRIM $- P_S$) might thus result from errors in $P_S$, specifically from a systematic underestimate in the spot areas or bolometric contrasts used to calculate $P_S$. Optimally, to demonstrate a facular signal, we should like to detect a clear increase of $S$ at a time when spot areas were so small that $P_S \approx 0$ (and thus errors in $P_S$ were negligible), while variation in facular area (i.e., in the $P_f$ function plotted in Fig. 2*d*) was large. The function $P_S$ approaches zero closely in 1980 March and August, but the periods of $P_S \approx 0$ are not sufficiently long to separate the

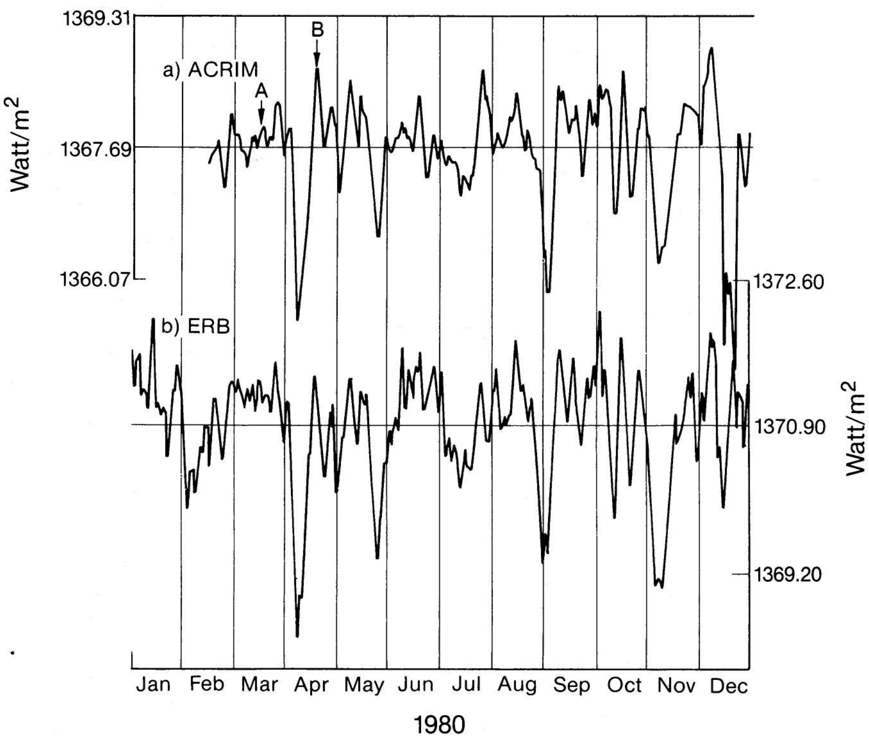


FIG. 1.—Simultaneous daily measurements of the total solar irradiance in 1980 from (*a*) the ACRIM radiometer on the *Solar Maximum Mission* and (*b*) the ERB radiometer on the *Nimbus 7* satellite. Data have been detrended with a twelfth-order polynomial and plotted about the mean value for the five-year period. Points marked A and B refer respectively to values measured on DOY 77 and DOY 110 (*see text*).

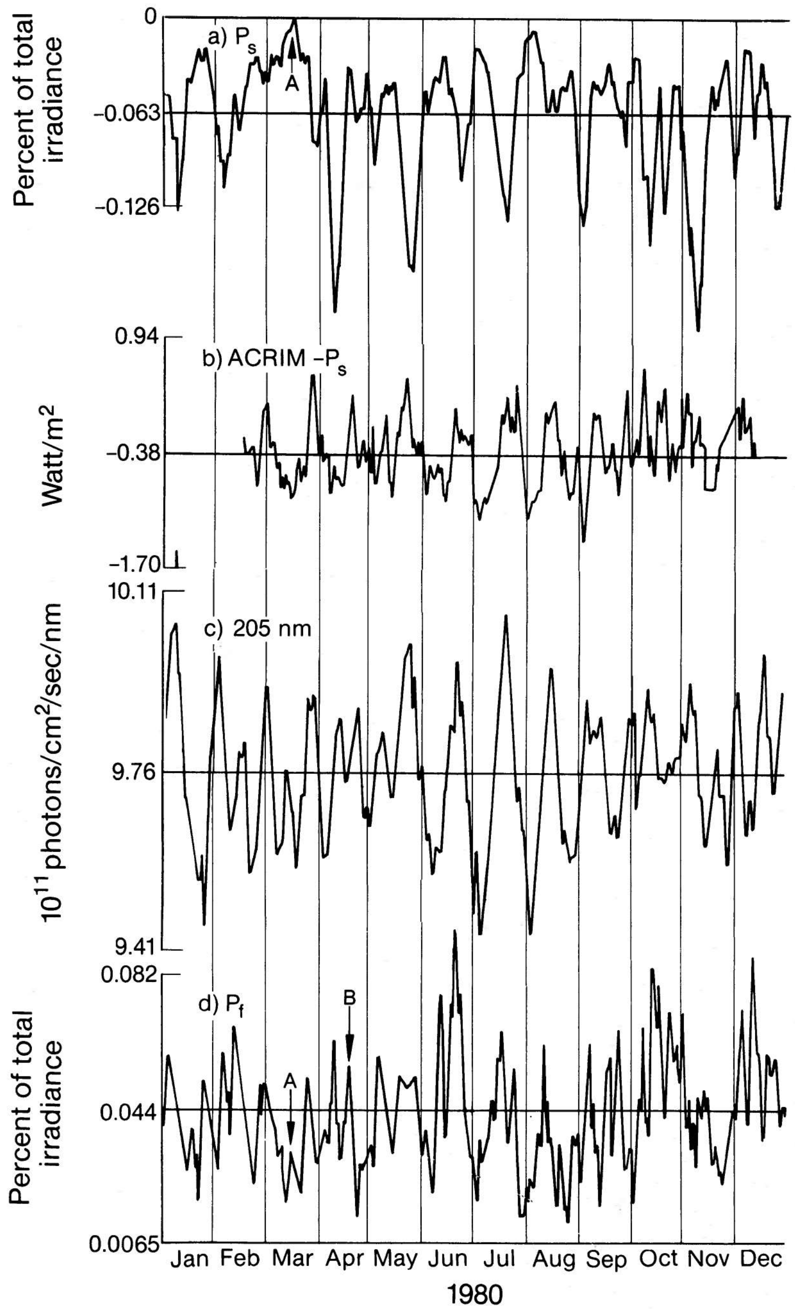


FIG. 2.—Plots of daily values for 1980 of (*a*) $P_S$ function, (*b*) residuals ACRIM − $P_S$, (*c*) 205 nm ultraviolet flux, and (*d*) calculated facular contribution to $S$, the $P_f$ function. Detrended data plotted about the five-year mean value.

facular signal from possible errors in $P_S$. Examination of the $P_S$ and $P_f$ functions in 1981 and 1982 (when the ACRIM measurements were more noisy) also did not reveal sufficiently extended periods to perform an unambiguous separation.

### III. CROSS-CORRELATION OF THE FUNCTIONS $S - P_S$ AGAINST $-P_s$, $F_{uv}$, AND $P_f$

Since the effect of spots and faculae cannot be directly separated in the data available for this study, we performed a cross-correlation of the residuals against $P_S$, $F_{uv}$, and $P_f$ to determine whether faculae or errors in $P_S$ make the dominant contribution to these residuals. This analysis was carried out using both the three years 1980–1982 of ACRIM data and also for the four years 1978–1982 of ERB radiometry. Figure 3 shows the full data base of detrended time series $S - P_S$, $P_S$, $F_{uv}$, and $P_f$ used in this cross-correlation study. These cross-correlations, and also the power spectra discussed later, were calculated using statistical routines developed at NOAA by T. Repoff (Heath, Repoff, and Donnelly 1984).

The cross-correlation functions are shown in Figure 4. The three left panels refer to cross-correlations with $S - P_S$ residuals calculated using ACRIM data for $S$, the three on the right with $S - P_S$ calculated from ERB data. As expected from the inspection of the 1980 data presented in § II, $S - P_S$ shows significant positive correlations near zero lag (i.e., correlation coefficient) with each of the three functions $-P_S$, $F_{uv}$, and $P_f$.

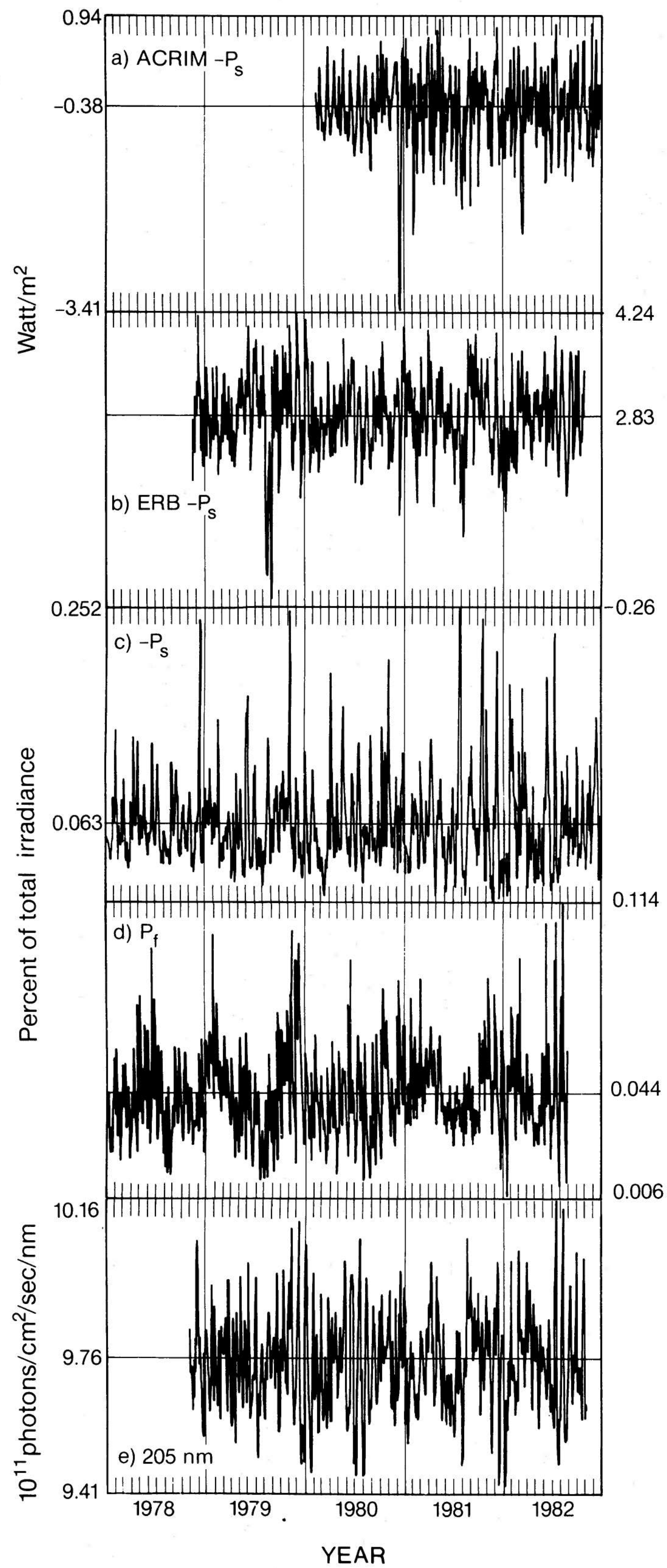


FIG. 3.—Plots of full data sets (1978–1982) used in this study for (*a*) ACRIM $-$ $P_S$ residuals, (*b*) ERB $-$ $P_S$ residuals, (*c*) sunspot-blocking function $P_S$ (plotted with reversed sign facilitate comparison with the peaks of ACRIM $-$ $P_S$ and ERB $-$ $P_S$), (*d*) calculated facular irradiance contribution $P_f$, and (*e*) 205 nm ultraviolet flux. Detrended and plotted about the five-year mean.

But the correlation at zero lag is noticeably ($\gtrsim 25\%$) higher with either $F_{uv}$ or $P_f$ than with $P_S$. This higher correlation coefficient supports the qualitative impression obtained from examination of the 1980 data, that the ultraviolet and white-light signatures of faculae reproduce the frequency content and phase of the $S - P_S$ residuals significantly better than would an explanation in terms of errors in $P_S$.

This explanation of the $S - P_S$ residuals is also supported by the asymmetry of the cross-correlation function of $S - P_S$ against $-P_S$ seen in Figure 4. The main feature of the asymmetry in panel 4*a* is the absence (or at least very low amplitude) of even a first cross-correlation peak at positive lag, relative to the amplitude of strong first and second peaks at negative lags. Positive lag is defined to occur when the $S - P_S$ time series leads the second time series. This asymmetry is very noticeable when compared to the high degree of symmetry seen in cross-correlation with $F_{uv}$ and $P_f$. The dashed lines show the auto-correlation of $S - P_S$ to illustrate the symmetry expected if the two cross-correlated functions were identical.

To interpret this asymmetry, we consider the idealized behavior of the cross-correlation function on various extreme assumptions as to the persistence of the phenomenon that might give rise to the residuals. If $S - P_S$ and $P_S$ were both generated by a nonrecurring feature, their cross-correlation would exhibit only a central peak. If both were long-lived phenomena recurring at the period $P$ of solar rotation, we would expect a symmetric cross-correlation exhibiting recurrence peaks at both positive and negative lag. This seems to be evident in the cross-correlation of $S - P_S$ against $F_{uv}$ and $P_f$. If only $P_S$ is caused by a structure that persists for more than one rotation, we find recurrences at positive lag, whereas if only $S - P_S$ is persistent, we find recurrence peaks only at negative lag.

Since the evidence of Figure 4*a* seems to be best described by this last situation, we identify the cause of the $S - P_S$ residuals with a solar feature that is much longer-lived than the spots which give rise to $P_S$ variations. The strong peaks at positive lag evident in Figure 4*b* and (at least at the first recurrence) in Figure 4*c* show the faculae have the required long lifetime. The longer lifetime of faculae compared to spots, by roughly a factor 3, is well known from statistical studies (e.g., Kiepenheuer 1953).

## IV. POWER SPECTRUM ANALYSIS

Figure 5 shows power spectra for four of the five detrended time series plotted in Figure 3 and also for the detrended ACRIM and ERB radiometry corresponding to the five-year time period 1978–1982 of Figure 3. We note first that the total irradiances (Fig. 5*a*, *b*) do not exhibit significant power at 28 days, although this period is very prominent in the spectra of the $P_S$ and $P_f$ function (Fig. 5*d*, *f*), in the ultraviolet flux (Fig. 5*c*), and in the total irradiance after $P_S$ is subtracted (Fig. 5*e*). A significant peak at 13 days is seen in the ACRIM radiometry, $P_S$ and $P_f$ functions, and most prominently in the $F_{uv}$. This peak may reflect a tendency for active regions to occupy longitude belts $\sim 180°$ apart, during 1978–1982. Its increased strength in $F_{uv}$ could be due to the limb brightening of ultraviolet plages, which enhances their visibility roughly $\pm 6$ days of central meridian passage. The four-day peak seen only in the ERB data (Fig. 4*b*) is caused by the observing cycle of the ERB experiment (Hickey 1985).

The absence of a clear, 28 day peak in the detrended ACRIM or ERB radiometry may seem surprising in view of the demonstrated modulation of the irradiance by spots whose projected

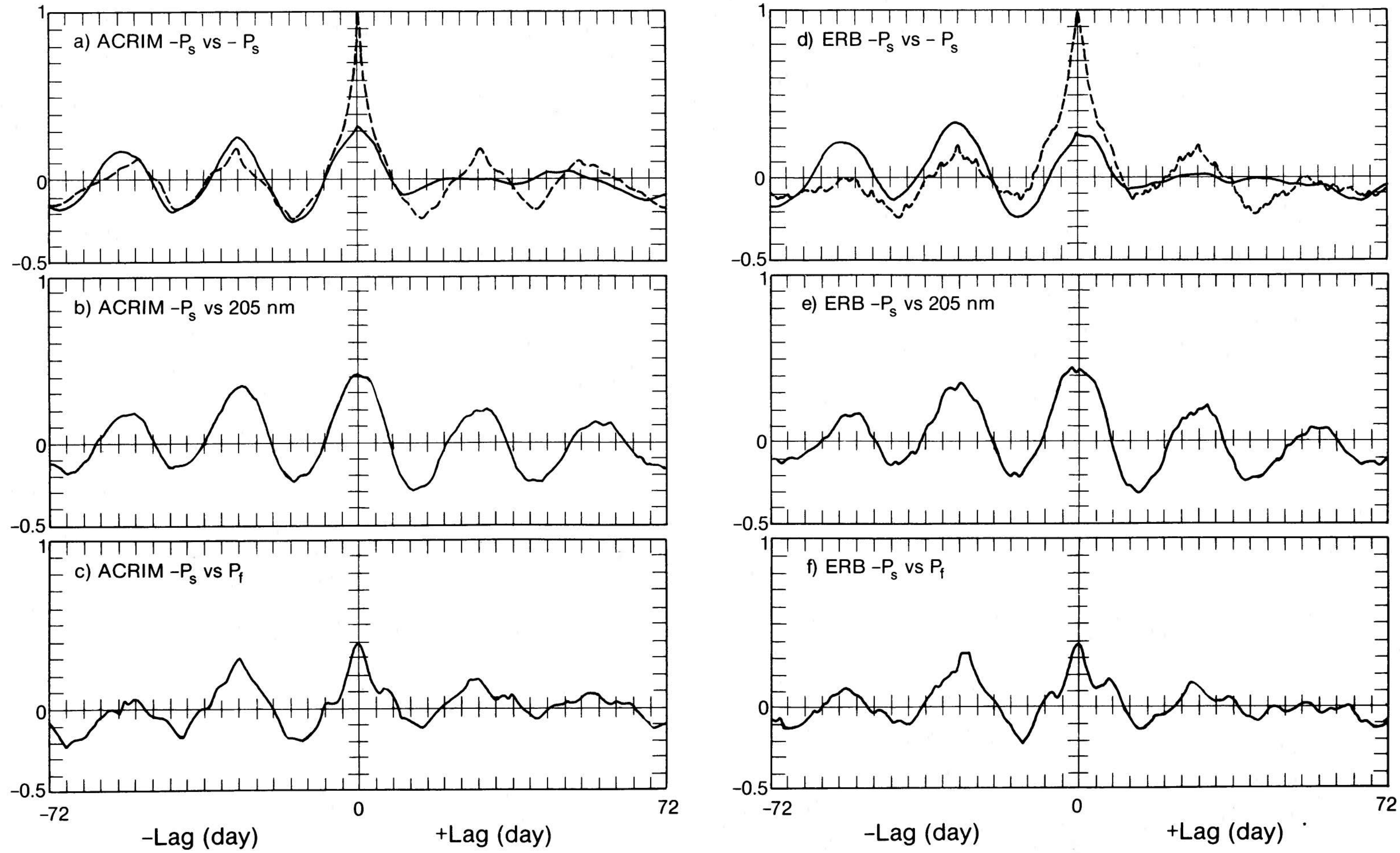


FIG. 4.—Cross-correlation functions (*solid lines*) of ACRIM − $P_S$ vs. (*a*) $-P_S$, (*b*) 205 nm flux, and (*c*) $P_f$, and ERB − $P_S$ vs. (*d*) $-P_S$, (*e*) 205 nm, and (*f*) $P_f$. Dashed lines in (*a*) and (*d*) give autocorrelation functions of ACRIM − $P_S$ and ERB − $P_S$, respectively

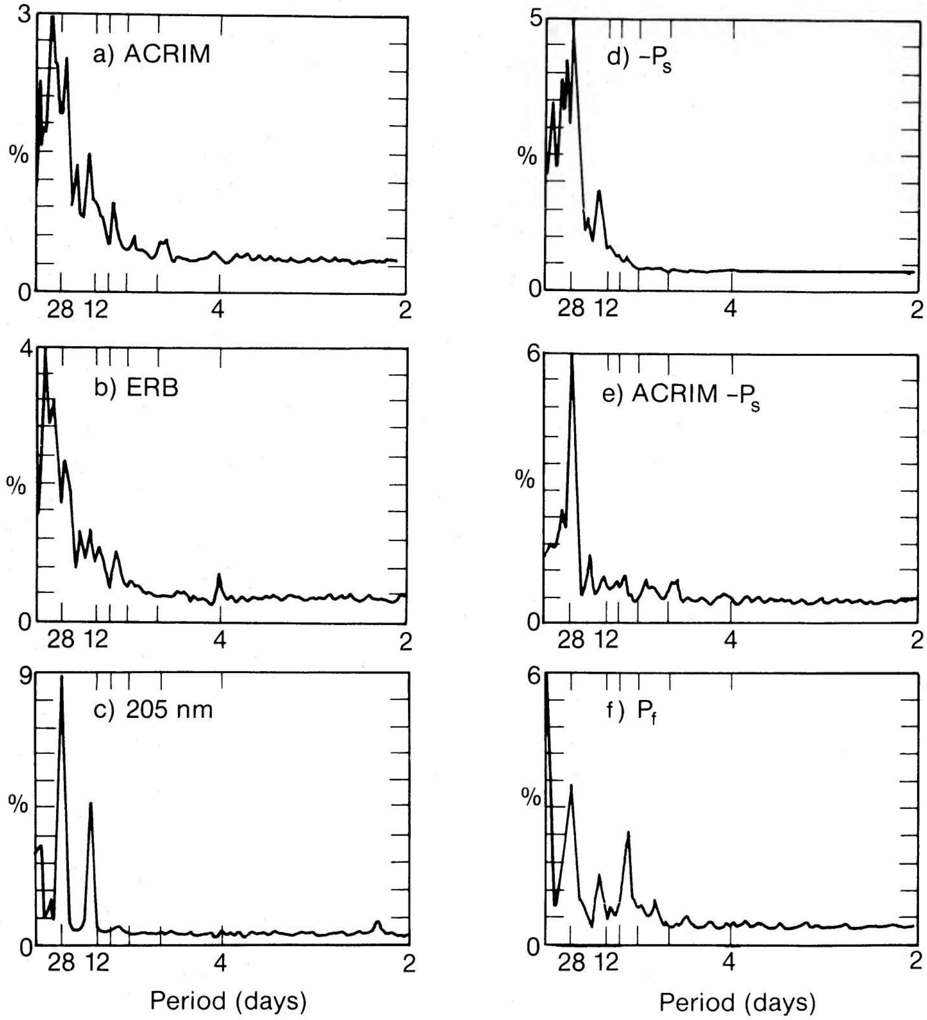


FIG. 5.—Normalized power spectra of (*a*) detrended ACRIM radiometry 1980–1982, (*b*) detrended ERB radiometry 1978–1982, (*c*) 205 nm ultraviolet flux, (*d*) (sign-reversed) sunspot-blocking function $-P_S$, (*e*) ACRIM $- P_S$ residuals, and (*f*) calculated facular irradiance contribution $P_f$. Ordinate is in percent of integrated power.

areas (i.e., $P_S$) show a significant 28 day peak. But it becomes understandable if we remember that the facular and sunspot influences of opposite sign are close to being in phase and so will tend to cancel rather than add in the irradiance time series. Consequently, we expect to find the signal at 28 days to be more closely proportional to the difference in power at 28 days between the $P_S$ and $P_f$ power spectra. The power at 28 days might actually be lower than at adjacent periods where the $P_S$ and $P_f$ power spectra are substantially different. Examination of the ACRIM and ERB power spectra in Figure 5*a*, *b* does indeed show in both cases a significant local minimum in power around 28 days. The amplitude of this relative dip is a rough measure of the difference in contribution by faculae and spots to the total irradiance at a 28 day period.

Figure 6 shows a power spectrum of the $S - P_S$ residuals on an expanded period scale, along with the power in these residuals at each frequency that can be explained by variations in (6*a*) $-P_S$ itself, (6*b*) $F_{uv}$, and (6*c*) $P_f$. The results for $S - P_S$ calculated from the ACRIM data are shown in the left panels, and for the ERB data on the right. These plots show that, at least for the dominant power peak around 28 days, the $F_{uv}$ and $P_f$ variations each can account for $\sim 80\%$ of the observed variance in $S - P_S$, while $P_s$ can account for only $\sim 50\%$. Again, this points to faculae as providing a stronger component of the $S - P_S$ residuals than do errors in $P_S$. Note that these results are similar for both the ACRIM and ERB residuals.

## V. RELATIVE MAGNITUDE OF TIME-INTEGRATED SUNSPOT AND FACULAR CONTRIBUTIONS TO S

The evidence presented above points to a significant facular influence on the total irradiance. In this section we discuss the magnitude of the time-integrated facular contribution relative to that of spots. We wish to determine whether it is thermodynamically plausible that the heat flux blocked by spots might be balanced over time scales of active region evolution, by excess facular radiation.

To compare these contributions, we divide the total solar irradiance signal $S$ into three components:

$$S = S_0 + \Delta S_s + \Delta S_f , \quad (1)$$

where $S_0$ is the "quiet-Sun" value of the solar constant in the absence of spots and faculae, and $\Delta S_s$, $\Delta S_f$ are, respectively, the (negative) change in irradiance caused by dark spots and the

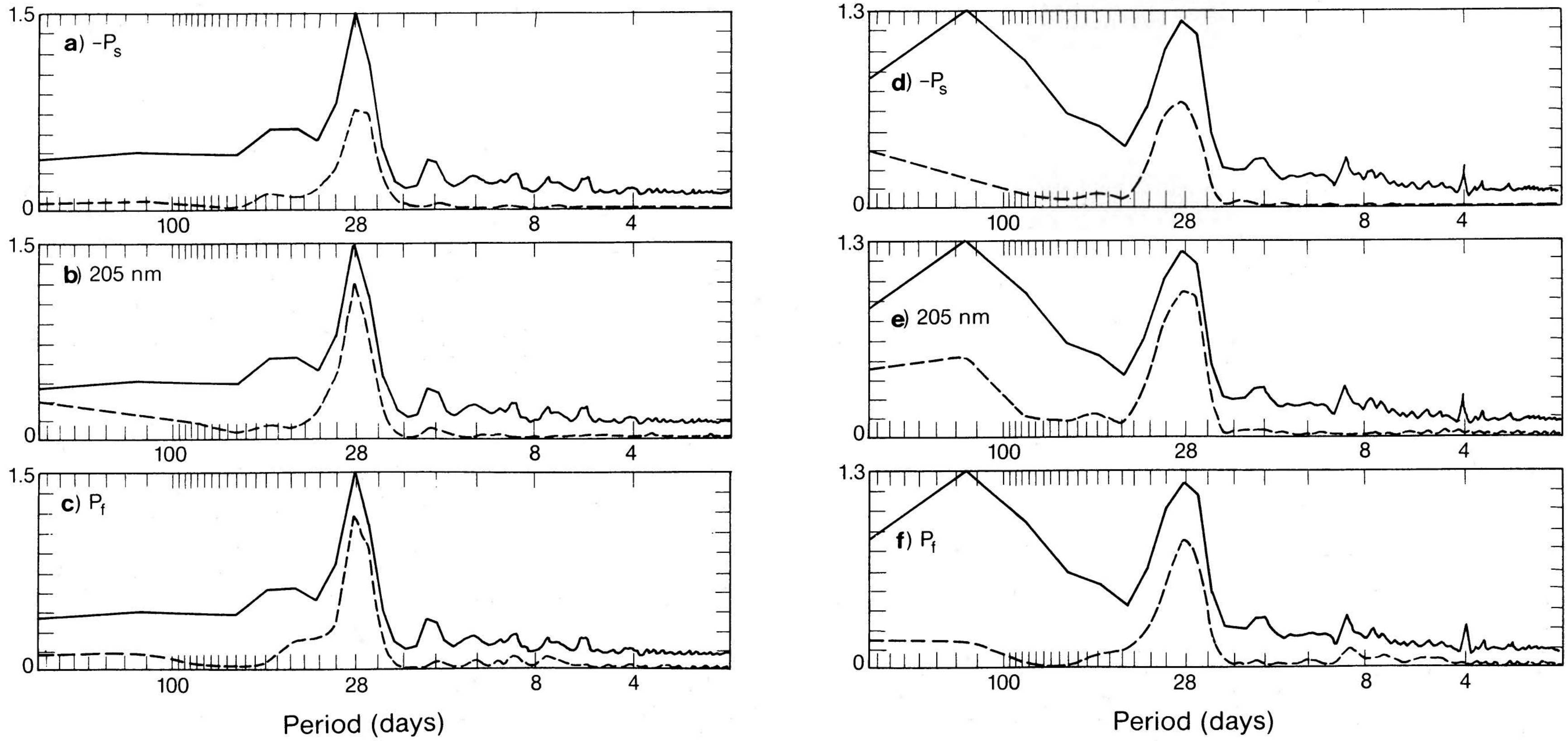


FIG. 6.—Power spectra of ACRIM − $P_S$ residuals (*a*, *b*, *c*) and ERB − $P_S$ residuals (*d*, *e*, *f*) plotted on solid lines together with (*dashed lines*) the power explained as a function of period by the variations in $-P_S$, in 205 nm flux, and in $P_f$.

(positive) change resulting from faculae. It is convenient to express the measured irradiances as normalized differences from $S_{max}$, the highest solar irradiance signal recorded by the ACRIM in 1980. We then have

$$S' = \frac{S_{max} - (S_0 + \Delta S_s + \Delta S_f)}{S_{max}} \tag{2}$$

or

$$S' = \left(\frac{S_{max} - S_0}{S_{max}}\right) - \left(\frac{\Delta S_s + \Delta S_f}{S_{max}}\right). \tag{3}$$

The value of $S_{max}$ is measured from the data before detrending to be 1369.35 $Wm^{-2}$ on DOY 110 (April 16) (DOY ≡ day of year). The value of $S_0$ is taken to be 1369.01 $Wm^{-2}$, the ACRIM reading on DOY 77 (March 17), when the value of the calculated sunspot-blocking $P_S$ was approximately zero (see Fig. 2*a*), indicating a very low projected area of spots on the disk. The contribution of faculae on that day (estimated by the $P_f$ function) was also relatively low, given the high activity level in 1980 (see Fig. 2*d*). With these values, we find $(S_{max} - S_0)/S_{max} = 2.5 \times 10^{-4}$. Using this constant difference, the expression (3) can be written as

$$\frac{\Delta S_s + \Delta S_f}{S_{max}} = 2.5 \times 10^{-4} - S' . \tag{4}$$

The time integral of the combined contributions resulting from spots and faculae is then

$$\int_{t1}^{t2}\left(\frac{\Delta S_s + \Delta S_f}{S_{max}}\right)dt = 2.5 \times 10^{-4}(t_2 - t_1) - \int_{t1}^{t2} S'dt . \tag{5}$$

Integration of this expression using ACRIM data (not detrended) yields the values given in Table 1 as a function of $t_2$ (with $t_1$ = DOY 47). We see from Table 1 that the right-hand side is always negative, as expected if the sunspot blocking exceeds the radiation from faculae. However, the value of $S_0$ adopted here quite certainly overestimates the true quiet-Sun irradiance, since considerable facular area was still present on the disk on March 17. This will cause, in turn, an underestimate of the first term on the right-hand side and thus an underestimate of the faular contribution.

The amount of this underestimate can be evaluated using the information contained in the ratio of the $P_f$ functions on DOY 110 and DOY 77. If we call the "true" quiet-Sun irradiance $S_1$, we can write on DOY 77:

$$S_0 = S_1 + \Delta S'_f , \tag{6}$$

TABLE 1

NET CONTRIBUTION OF SUNSPOTS AND FACULAE TO $S_a$

| $t_2 - t_1$ ($t_1$ = DOY 47) | $2.5 \times 10^{-4}(t_2 - t_1)$ (% of $S_{max}$) | $\int_{t_1}^{t_2} S'dt$ (% of $S_{max}$) | $\int_{t_1}^{t_2}\left(\frac{\Delta S_s + \Delta S_f}{S_{max}}\right)dt$ (% of $S_{max}$) |
|---|---|---|---|
| 50 | 1.25 | 2.00 | −0.75 |
| 100 | 2.50 | 5.48 | −2.98 |
| 150 | 3.75 | 8.49 | −4.74 |
| 200 | 5.00 | 11.44 | −6.44 |
| 250 | 6.00 | 14.85 | −8.85 |

[a] Calculated from eq. (5).

since $\Delta S'_s = 0$ on that day. On DOY 110 we have

$$S_{max} = S_1 \times \Delta S''_f + \Delta S''_s , \tag{7}$$

which yields

$$\frac{S_{max} - S_1}{S_0 - S_1} = \frac{\Delta S''_f + \Delta S''_s}{\Delta S'_f} < \frac{\Delta S''_f}{\Delta S_f} , \tag{8}$$

since $\Delta S''_s$ is always negative (and nonzero on DOY 110). We can also make the reasonable approximation:

$$\frac{\Delta S''_f}{\Delta S'_f} \approx \frac{P''_f}{P'_f} , \tag{9}$$

since the $P_f$ function should be a good estimate of at least the relative effects of faculae on the total irradiance on the two days. The ratio $P''_f/P'_f \approx 2$ (see Fig. 2*d*), so, substituting in equations (9) and (8) we have

$$\frac{S_{max} - S_1}{S_0 - S_1} < 2 , \tag{10}$$

and, since

$$(S_{max} - S_1) = (S_0 - S_1) + (S_{max} - S_0) , \tag{11}$$

we find that

$$(S_0 - S_1) > (S_{max} - S_0) . \tag{12}$$

It follows that the first term on the right-hand side of equation (5) is probably at least twice as large as that used in Table 1, which is sufficient to approximately balance the facular and spot contributions over the time scales considered here.

## VI. DO FACULAE RERADIATE THE MISSING RADIATIVE FLUX OF SUNSPOTS?

The results obtained above indicate that the sunspot-induced reduction of $S$ is comparable to the excess radiation of faculae over time scales of active region evolution during 1980. This suggests that energetic balance between spots and faculae is not unreasonable. However, we present in this section several arguments against the view that faculae are conduits for the reradiation of missing sunspot heat flux, based on considerations that go beyond balance of radiometric contributions to $S$.

### *a) Correlation of Spot and Facular Areas*

Daily observations of white-light faculae and spots over a solar cycle by the Greenwich photoheliograph observers (see the detailed summary of their results given by Kiepenheuer 1953) show that roughly ~10% of all faculae (by area) are unaccompanied by any discernible spots. This finding comes from the study of large-scale photographic plates on which even small, ephemeral spots were identified. It shows that the spatial correlation of faculae and spots in individual active regions is far from perfect. This can be seen also from the large scatter in a plot of Ca K facular areas and white-light spot areas on the disk for 1550 days in 1969–1974, based on NOAA-WDC data (Foukal and Vernazza 1979).

An extreme case of this loose correlation between spot and facular areas on the disk is found in 1913 (J. Eddy, private communication). During that year, which lies at the lowest activity minimum since 1810, the sunspot number was identically zero for three consecutive months in April, May, and June, while facular areas in excess of 250 millionths of the disk area were seen in white light by the Greenwich observers. The white-light observations do not reveal faculae inward of $\mu = 0.5$, so they underestimate the facular areas that would be measured by Ca K observations. Detailed balance of sunspot and facular radiations would then have required storage of sunspot missing flux for three months before it was reradiated by faculae.

### *b) Difficulties with Magnetic Storage of Sunspot-blocked Energy*

It has been suggested that the required long storage and reradiation locally from faculae might be explained if excess facular brightness is fueled by dissipation of magnetic energy representing sunspot-blocked heat stored in magnetic flux tubes (Wilson 1981; Chapman 1984). But the magnetic energy of a flux tube is increased only if either the magnetic intensity or the volume of a flux tube increase in time, so only spots growing in area or in magnetic field strength should cause irradiance dips. This prediction does not appear to be compatible with the irradiance record which exhibits large dips whose time profiles follow changes in the projected area of spots. The true area of these spots, measured to the accuracy of the NOAA-WDC records, is not in general found to change significantly during the time of the dip. The change in area or magnetic intensity required to store the energy of order $10^{36}$ ergs blocked during a large irradiance dip should be easily detectable (Foukal 1981). Changes in magnetic energy stored at some depth might be invoked, but it seems difficult to understand how such deep changes in spot structure can occur on the short time scale of the irradiance dips while leaving the umbral area and field intensity relatively unaffected.

### *c) Similarity between Faculae and Network*

Studies of photospheric flux tubes indicate that facular regions are similar in magnetic field intensity and atmospheric structure to the network flux tubes. The main difference seems to be that in facular areas, a larger number of flux tubes are packed together over a larger area than in the network (see, e.g., review by Zwaan 1981). Given this similarity, it seems reasonable that if the excess flux of faculae is to be derived from sunspot-blocked flux, so should the excess flux of every network element on the Sun, including polar faculae and quiet network. One might suppose that only magnetic elements around active regions derive their excess radiation from spots, while other mechanisms fuel the excess radiation of flux tubes in high latitudes and other distant quiet regions. However, this qualitative distinction seems contrived and has no observational support.

### *d) Topology of Spot and Facular Flux Tubes in Active Regions*

The concept of faculae as conduits of enhanced (nonthermal) flux also encounters difficulties when we consider the topology of active region magnetic fields, as suggested by the types of observations that led to the conventional Babcock (1961) model of the solar activity cycle. Within this model, each bipolar active region is supposed to represent a $\Omega$-shaped stitch of magnetic flux connected to submerged fields on either side. If this picture is accepted, it is difficult to see how fluxes of, e.g., Alfvén waves blocked by a spot could be channeled to a facula in the *same* active region unless it travels through the corona, which seems highly unlikely (Beckers and Schneeberger 1977). One might envisage such a redirected flux into a facular area in an adjoining active region in the same hemisphere. But in that case, we would expect to see a better correlation between the facular sunspot brightness and area in adjacent active regions in the same hemisphere than within the same region, where energy balance arguments have generally been applied.

One might depart from the Babcock model to form a U-shaped subphotospheric connection between facula and spot within the same active region. But then it becomes difficult to understand why the Hale-Nicholson polarity laws should be so regularly obeyed, since each active region would constitute a self-contained loop disconnected from the subphotospheric solar field.

## VII. DISCUSSION AND CONCLUSIONS

The main result of this study is the finding that the solar irradiance records from the ACRIM and ERB radiometers, after subtraction of the calculated sunspot-blocking contribution, exhibit a short-term modulation that is better explained by faculae than by errors in the sunspot-blocking function, $P_s$.

This evidence is based on the 25% higher correlation coefficients found between the residuals $S - P_s$ and the facula-modulated 205 nm flux or the facular contribution function $P_f$, as compared to the correlation coefficient found with the $P_s$ function itself. It is further based on the asymmetry of the cross-correlation function of $S - P_s$ against $P_s$, in contrast to the symmetry found in the cross-correlation functions of $S - P_s$ against 205 nm flux or against $P_f$. This shows that the $S - P_s$ residuals are generated by solar structures whose lifetimes are typically at least two solar rotations, significantly greater than the typical lifetime of the spots observed between 1978–1982.

While the absence of a distinct peak at 28 days in the total irradiance power spectrum (actually, the presence of a local dip at this period) seems surprising, given the very strong peaks at 28 days found in the power spectra of 205 nm, $P_s$, $P_f$, and $S - P_s$, the most likely explanation is that the photometric contributions of spots and faculae are of roughly comparable magnitude, similar in phase and opposite in sign, thus causing cancellation of the two signals and reducing the amplitude of the 28 day power-spectrum peak that is found in each separately. Last, we find that $\sim 80\%$ of the power in the residuals $S - P_s$ near 28 days is attributable to solar structures whose modulation of $S$ follows the facula-generated 205 nm flux and $P_f$ function, while only $\sim 50\%$ can be attributed to the sunspot-generated $P_s$ function.

Taken together, these four lines of evidence indicate that faculae produce an important contribution to short-term modulation of the total solar irradiance. Similar results in cross-correlation and power-spectrum analysis have recently been reported by Fröhlich (1984), although he did not identify faculae as the solar structures causing the additional modulation of irradiance beyond that of spots. The results found here from analysis of the space radiometry are also consistent with the finding of a significant cross-correlation (with recurrences at multiples of the solar rotation period) between facular areas and the APO ground-based radiometry (Foukal and Vernazza 1979).

Our calculation of the net contribution of spots and faculae to the irradiance during 1980 indicates that the facular contribution is comparable to that of spots over time scales of active region evolution in that year. This result seems to be in agreement with the conclusions of Bruning and Labonte (1983), but in disagreement with those of Hoyt, Eddy, and Hudson (1983), who concluded that the facular contribution is small. These last authors did not specifically compare the time-integrated contributions of spots and faculae, so their conclusion applies to the relative *modulation* caused by spots and faculae, rather than to the time-integrated contributions that require an accurate estimate of the quiet-Sun irradiance. A definitive measurement of the relative facular and spot contributions should be possible from total irradiance data and projected areas of spots and faculae during the solar activity minimum period, since the main uncertainty in our result lies in the need to apply an uncertain correction for the facular contribution to the quiet-Sun irradiance on DOY 77.

Several arguments we present on the storage time of energy in active regions, its dependence on spot evolution, and considerations of magnetic field-line geometry between faculae and spots lead us to conclude that faculae are unlikely to represent direct conduits for channeling and reradiation of the missing sunspot radiative flux, even though such a detailed balance probably cannot be ruled out on energetic grounds alone. To us, the evidence seems to favor the view that faculae in active regions, polar areas, and the general network represent independent local perturbations to photospheric heat flow of opposite sign to that of spots and of comparable magnitude. Reasonable physical models of such facular flux tubes and their effect as local photospheric heat leaks have been given by Zwaan (1965), Spruit (1976), Deinzer *et al.* (1984), and Chiang and Foukal (1984). Further progress on this topic would seem to require direct observational tests of such models using photometric, magnetic, and velocity measurements on faculae, rather than relying mostly studies of the global energy balance between spots and faculae, which have been emphasized so far.

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PETER FOUKAL: Cambridge Research and Instrumentation, Inc., 21 Erie Street, Cambridge, MA 02139

JUDITH LEAN: NOAA/ERL, 325 Broadway, Boulder, CO 80303