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WHAT DETERMINES THE RELATIVE AREAS OF SPOTS AND FACULAE ON SUN-LIKE STARS?

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ABSTRACT

We analyze newly digitized Ca K plage area data extending back to 1915, and also the white-light facular area data beginning in 1874, to investigate further our earlier finding that the area ratio of faculae to spots decreases at increasing activity levels. We find that this ratio decreases in plage as well as facular data, so it cannot be an artifact of the visibility function of limb faculae. The decrease is also accentuated in daily data, compared to annual means; we explain this as a consequence of the different dependences of facular, plage, and spot lifetimes upon their emergent magnetic flux. From this we show that subphotospheric field properties are more likely to determine this ratio, rather than photospheric field diffusion rates. Systematic, cycle-to-cycle variations in its value suggest an origin in fluctuations of the field generation mechanism; specifically, a mechanism that produces a positive correlation between magnetic flux generation efficiency, and relative power in the spatial spectrum at low frequencies. Our results also suggest that main-sequence stars about 50% more magnetically active than the present Sun might exhibit ratio values an order of magnitude lower than current solar values. This evidence strengthens our earlier argument that a rapid shift toward dark photospheric structures in both active regions and network provides the most likely explanation of the recently reported sharp increase of photometric variability in late-type stars somewhat more active than the Sun.

Subject headings: stars: activity — stars: magnetic fields — Sun: faculae, plages — sunspots

1. INTRODUCTION

The ratio of facular to sunspot areas is one of the key parameters of solar-terrestrial research because it seems to be the main factor determining the sign and magnitude of variations in total solar irradiance, at least on timescales extending up to the length of the 11 yr activity cycle (Foukal & Lean 1986, 1988; Foukal 1992; Chapman 1987). Facular magnetic fields are more fragmented than spot fields, so time variations of this ratio also offer interesting evidence concerning changes in the spatial power spectrum of solar magnetism since daily measurements are available beginning in 1874. This information is complementary to studies of the field distribution function derived from magnetograms (Schrijver & Harvey 1989) and from X-ray imaging of bipolar magnetic structures (Golub et al. 1981), both based on cycle 21 data.

Previous work indicates that this ratio decreases as spot activity increases, both within the largest amplitude activity cycles (Foukal 1993; hereafter Paper I) and in its average value measured in cycles of different amplitude (Brown & Evans 1980). This decrease is in agreement with findings that very large spots exist on much younger, very active, late-type stars (Radick, Lockwood, & Baliunas 1990). These results led us to propose (Foukal 1994a) that the sharp increase in photometric variations observed on late-type stars only slightly more active than the Sun (Lockwood et al. 1992; Lockwood, Skiff, & Radick 1997) originate in a breakdown of the approximate balance between the irradiance increased caused by faculae and the decrease caused by spots, seen on the present Sun. More recent photometry (Henry 1997) and reanalysis of the earlier data (W. Lockwood 1997, private communication) support the finding of a sharp increase. The additional finding of Lockwood et al. (1992) that the Sun exhibits anomalously low photometric variability compared to stars of similar age, as well as mass, is currently under further investigation (W. Lockwood 1997, private communication; Henry 1997).

In §§ 2 and 3 of this paper we describe the data used in this analysis and present new evidence on the decrease of this key ratio at high solar activity levels. In § 4 we show that the ratio measured in time-averaged data actually depends on two factors. One is the "source" value of the ratio measured during initial emergence of magnetic flux in an active region, as we might expect. But we point out that it is also determined by the different dependences of spot and facular lifetimes, on spot and facular areas at time of emergence. Recognition of the separate roles of these two factors has interesting implications for the behavior of this ratio. In § 5 we examine the application of our results to the solar magnetic field generation mechanism and to the connection between solar and stellar luminosity variations. We state our conclusions in § 6.

2. DATA

The areas of sunspots and white-light faculae used in this study were obtained from the measurements of the Royal Greenwich Observatory (RGO) between 1874 and 1976. Daily facular areas were published for the years 1906–1976; this includes the complete sunspot cycles 16–20. A detailed discussion of the RGO data on white-light faculae (including the precautions required to interpret these observations of structures visible only near the limb) was presented in Paper I. The areas of plages used here were obtained from our digitization of the daily Mount Wilson spectroheliograms obtained in the K line of Ca II between 1915 and 1984. The digitization procedure and reduction of plage areas on these images were described by Foukal (1996). All areas of spots, faculae, and plages used in this study are corrected for foreshortening and are expressed in millionths of a solar hemisphere.

3. RESULTS

Figure 1 shows the daily areas of faculae, A_f, plotted against daily areas of sunspots, A_s, individually for the five

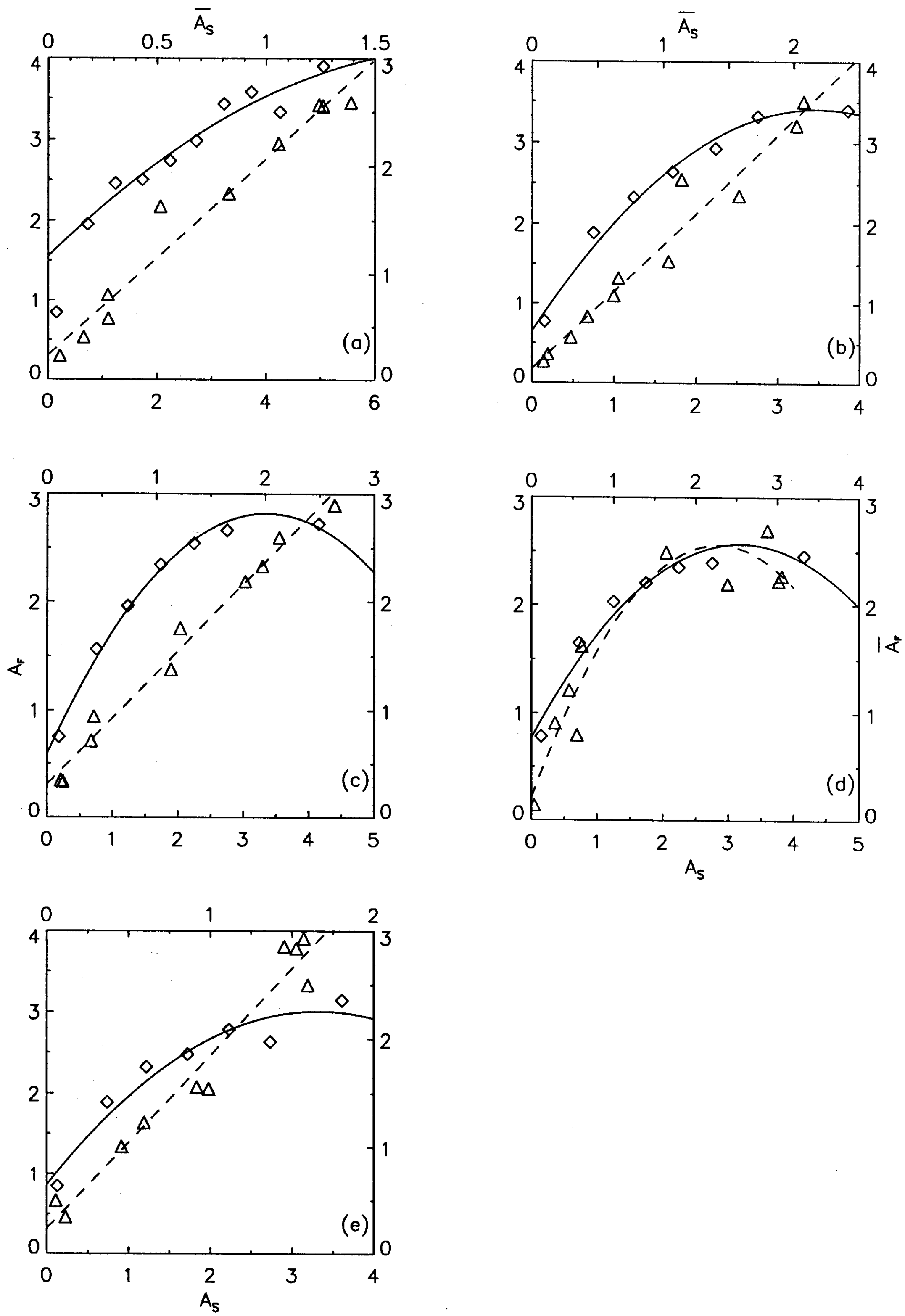

FIG. 1.—Plots of binned daily A_f vs. A_s (*diamonds*) and annual mean A_f vs. A_s (*triangles*), for cycles 16–20 (panels [*a*]–[*e*], respectively). Scales marked along the left and lower axes refer to binned daily data; those on the right and top refer to annual means. Units of A_f and A_s are thousandths of a hemisphere; the bins span intervals of 500 millionths. The solid and dashed lines show least-squares best fits to the daily and annual mean data, respectively.

complete cycles 16–20, for which daily values of A_f and A_p are available. The values of A_f and A_s are binned to show the dispersion of the data without plotting the large number of daily points individually. These plots show the characteristic decrease of the slope dA_f/dA_s with increasing activity that was reported in Paper I. The improved fit achieved with the quadratic curves illustrates the nonlinearity of the A_f versus A_s relation in cycles of both large and small amplitude in A_s. The daily data shown here reveal that this nonlinearity is a characteristic of increasing activity in every cycle, whereas this decrease in slope was detectable only in the largest amplitude cycle 19 when annual means are used, as in Paper I. The linear behavior of the annual means of the same data is also plotted in Figure 1.

A similar nonlinearity is illustrated in the plots of binned daily Ca K plage areas, A_p, versus A_s. These are shown in Figure 2 for the same complete cycles 16–20. Presence of this nonlinearity in the full-disk Ca K plage areas rules out any possibility that the decreasing slope with increasing activity shown in Figure 1 might be caused by factors related to the visibility function of the white-light faculae near the limb. Again, we note that plots of A_p versus A_s using annual mean data (also shown in Fig. 2) exhibit no significant departure from linearity.

The nonlinearity seen in Figures 1 and 2 seems to be a property of individual active regions, irrespective of epoch within a solar cycle, rather than a global property of the Sun at the high-activity epoch of a cycle. This follows from

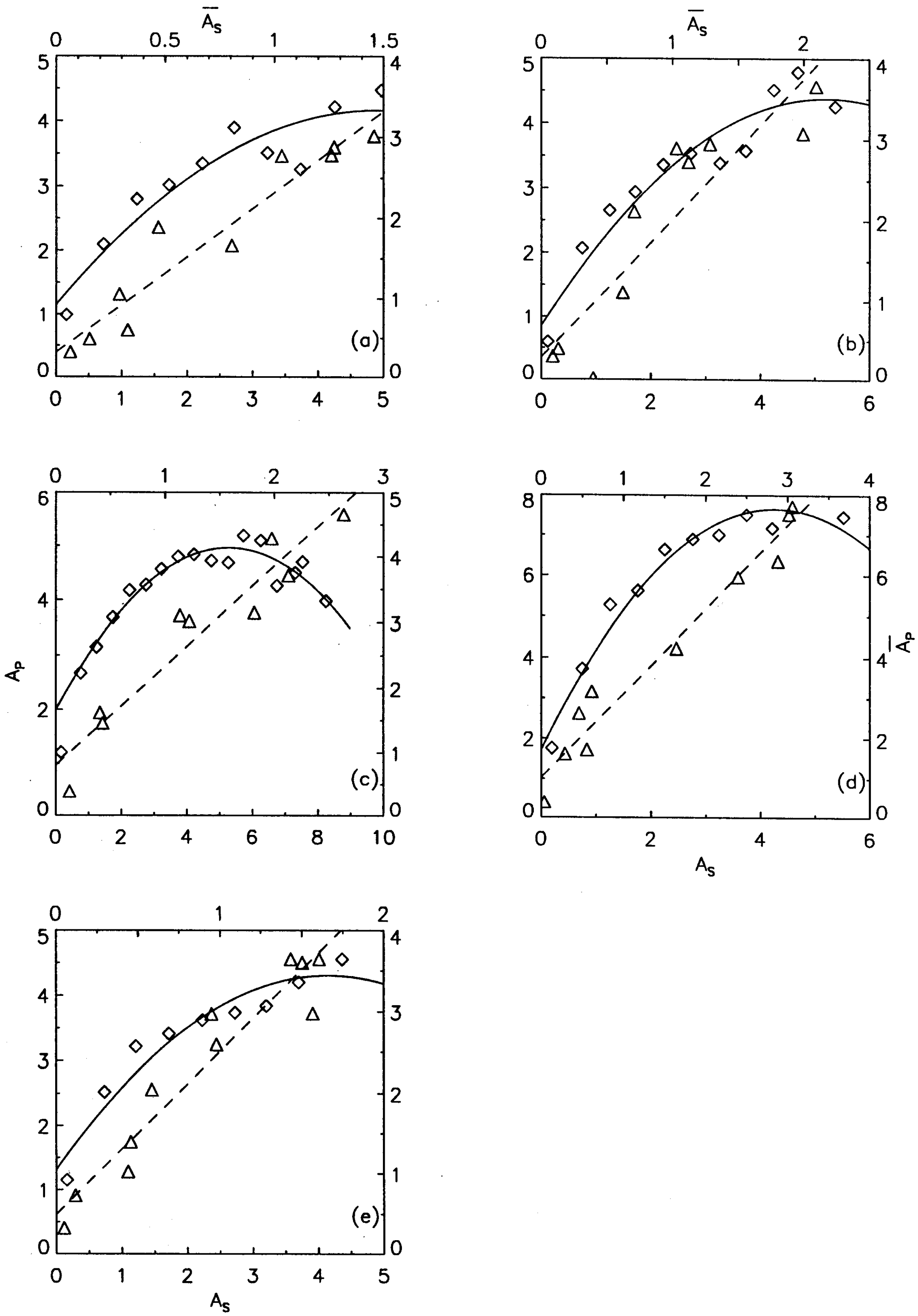

FIG. 2.—As in Fig. 1, but for A_p vs. A_s

the fact that our plots of daily data, which exhibit the nonlinearity, bin together daily data irrespective of epoch within a cycle. The annual means, which do not exhibit the nonlinearity (except in cycle 19), explicitly bin together values measured at a set epoch (i.e., within a given year) of the solar cycle.

4. ANALYSIS OF THE EFFECT OF SUNSPOT AND FACULAR LIFETIMES

To understand why the nonlinearity seen in the daily data is attenuated in the annual means, we investigate the role of different sunspot and facular lifetimes. We note first that the area index, $\bar{A}$, averaged over a time interval, T, is related to the area contributions, A, of n individual active regions on the disk on a given day, by the expression

$$\bar{A} = \frac{1}{T}\sum_t \sum_n A \cong \sum_{n'} \left(\frac{1}{T}\sum_t A\right), \tag{1}$$

where the first expression on the right-hand side expresses first a summation over the n active regions on a given day, and a second, time summation, over the interval T. In the second expression on the right-hand side, the terms are rearranged to show that the contribution of each of n' individual spot groups (observed during the time interval T), to a time-averaged (e.g., annual mean) sunspot area, is proportional to a measure of each group's lifetime, as well as its area. In the second expression, the time summation now extends over the lifetime, τ_s, of each group. The precision of the approximation increases as the ratio T/τ_s.

In general, time evolution of sunspot group areas is complicated (e.g., Kiepenheuer 1953; Zwaan 1992). But for the large preceding spots that account for most of the contribution to large values of annual mean spot area of interest here, it usually consists of a relatively rapid rise over a few days and then a slow decay over 1–3 months (see, e.g., Bumba 1963). As a measure of the group's area we adopt here its maximum area, A_{so}, (corrected for foreshortening), as a meaningful measure of the total erupted magnetic flux in the group (see, e.g., Zwaan 1992; Harvey 1993). We associate the lifetime, τ_s, of such spots with this decay time.

Therefore, we can relate the annual mean spot area to the contributions of n individual active regions of maximum emerged areas, A_{so}, and lifetimes, τ_s, through the expression

$$\bar{A}_s \propto \sum_n A_{so}\,\tau_s\ . \tag{2}$$

Similarly, we can relate the annual mean facular (or plage) areas to the individual contributions of active regions whose facular (or plage) areas of maximum emerged *sunspot* area are A_{f0} (or A_{p0}), and whose lifetimes are τ_f or τ_p, respectively. The relationships are

$$\bar{A}_f \propto A_{f0}\,\tau_f \text{ and } \bar{A}_p \propto A_{p0}\,\tau_p\ . \tag{3}$$

To discover the relationships between the time-averaged functions, $\bar{A}$, and the "source" functions, A_0, we seek to express the lifetimes, τ, as functions of A_0. For the case of faculae and plages, the most useful data are those of Harvey (1993), which show the lifetimes of active regions (measured from Kitt Peak magnetograms) classified according to their area near the "time of maximum development." We equate this "time of maximum development" to our "time of maximum sunspot area."

These lifetimes and areas are plotted in Figure 3. The relationship is remarkably linear, except for the point

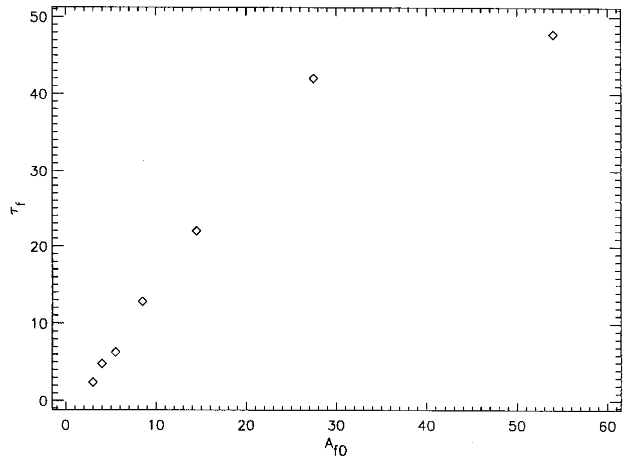

FIG. 3.—Plot of lifetime, τ_f (days), of facular magnetic fields (based on data from Harvey 1993) vs. facular area (millionths × 10^{-2}) at time of maximum sunspot area.

denoting the very largest active regions. Harvey points out an observational cutoff in active region lifetime set by her definition that an active region "disappears" whenever another of substantial size emerges in its place. This artificial cutoff causes the departure of this highest point from the otherwise linear relationship

$$\tau_f \propto A_{f0} \text{ or } \tau_p \propto A_{p0}\ . \tag{4}$$

We note that the linear relationship plotted in Figure 3 is consistent with the random walk model of photospheric magnetic field diffusion (Leighton 1964; Wang & Sheeley 1989) since in a random walk the field area will grow as

$$\frac{dA}{dt} = \frac{\pi L^2}{\tau} = K\ , \tag{5}$$

so

$$\frac{1}{A}\frac{dA}{dt} \propto A^{-1} \tag{6}$$

and

$$\tau_f \propto A_{f0} \text{ or } \tau_p \propto A_{p0}\ , \tag{7}$$

as implied by Harvey's data.

The relationship between τ_s and A_{s0} is less clearly defined. Figure 4 shows a plot of τ_s versus A_{s0} for the largest sunspot groups observed during cycle 18. Unfortunately, cycle 19 data on individual active regions were no longer published by the RGO, and the number of very large sunspots prior to cycle 18 was small, so the data in Figure 5 represent most of the information available to address this question. Also, estimates of spot lifetime from observations of the visible disk provide only bounded lower limits. The lifetimes of the large spots ($A_s \geq 1000$ millionths) of interest here clearly show large intrinsic scatter. The most we can say is that, while large ($A_s = 500$–2000 millionths) spots have longer lifetimes than small ($A_s < 500$ millionths) spots, the very largest spots ($A_s \geq 2000$ millionths) do not have systematically longer lifetimes than those in the range of 500–2000 millionths.

The question asked here about the dependence of τ_s on A_{s0} differs from the question usually asked in studies of spot decay mechanisms (see, e.g., Gokhale & Zwaan 1972; Bumba 1963; Petrovay and Van Driel-Gesztelyi 1997).

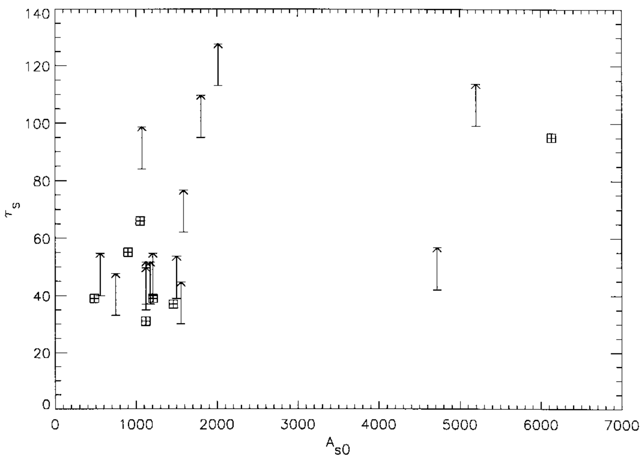

FIG. 4.—Plot of lifetime, τ_s (days), of very large spots vs. spot area at time of maximum development (millionths of a hemisphere), in cycles 18 and 19. Arrows indicate the (statistically bounded) range of lower limits, for spots that were born or disappeared off the disk.

Some of these studies indicate that the decay rate $dA_s/dt \sim$ constant (which is surprising since passive chipping at a spot perimeter should yield $dA_s/dt \propto A_s^{1/2}$). But the question that interests us here is the dependence of this rate upon A_{s0}.

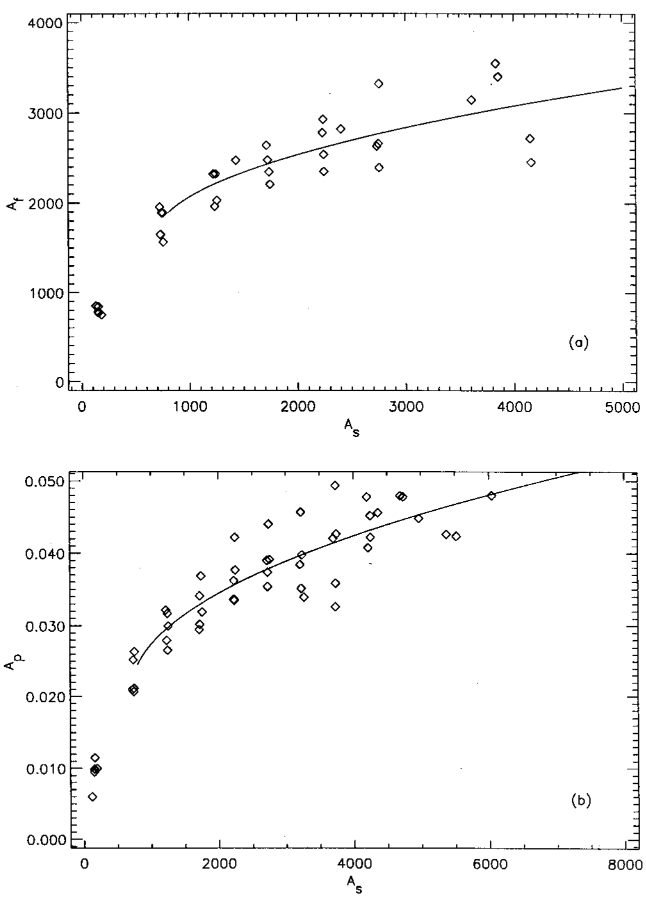

FIG. 5.—Plots of (*a*) daily binned A_f vs. A_s; (*b*) daily binned A_p vs. A_s, for all five cycles 16-20. A vertical offset has been applied to the cycle 19 data, to bring them onto the same scale as the other four cycles. The solid line is a least-squares fit to the function $A_f = a + bA_s + cA_s^{1/2}$, for points of $A_s > 1000$ millionths.

Using the relations (3) and (7) and our finding that $\tau_s \neq f(A_{s0})$ for the largest spots, we can estimate the functional dependence of A_{f0} upon A_{s0} required to achieve the observed linear relation between $\bar{A}_f$ and $\bar{A}_s$. That is, we have

$$\bar{A}_f \propto A_{f0}\,\tau_f \propto A_{f0}^2 \,, \tag{8}$$

and

$$\bar{A}_s \propto A_{s0}\,\tau_s \propto A_{s0} \;; \tag{9}$$

therefore,

$$A_{f0} \propto A_{s0}^{1/2} \,. \tag{10}$$

This calculation indicates that, if the daily data approximate a square-root dependence of A_{f0} upon A_{s0} (or of A_{p0} upon A_{s0}), the dependences of τ_s, τ_f, and τ_p upon A_{s0}, A_{f0}, and A_{p0} could produce the observed linear dependences of the annual mean data.

The behavior seen in Figures 1 and 2 can be understood on the basis of this calculation. At the highest activity levels, the main contributions are from one, or at most a few, very large spot groups on each day. These spots are at or near their peak of evolution in area, thus close to their A_{s0}. Therefore, at high activity levels, the observed behavior should approximate that of A_{f0} versus A_{s0}, or of A_{p0} versus A_{s0}. Figure 5 shows that the observed dependences can be fitted reasonably well as square roots, at the values of $A_s \geq$ 1000 millionths expected from our model. For $A_s \leq 1000$ millionths, the regime in which both τ_s and τ_f increase with A_{s0} and A_{f0}, our explanation predicts that $\bar{A}_f \propto \bar{A}_s$, consistent with the data in Figures 1 and 2.

Our analysis thus suggests that the linear relations between the time-averaged indices arise because the lifetime of faculae and plages continue to increase with A_{f0} and A_{p0} even for the active regions of largest emergent flux, while the lifetime of spots does not increase for $A_{s0} \geq 1000$ millionths. This increased facular lifetime tends to compensate for the decreasing ratio of facular and plage area to spot area, that occurs in newly emerged flux.

This interpretation also suggests why the relation between facular and spot areas found in the largest amplitude cycle (19) is nonlinear, even when annual means are plotted (Fig. 1*d*), although the corresponding plot for annual plage areas in Figure 2*d*, is linear. As pointed out in Paper I, the largest (and oldest) plage areas seen in Ca K are less easily visible in white light. So the lifetime increase of plages responsible for linearization of the relation in Figure 2*d* is likely to be less effective in Figure 1*d*.

5. DISCUSSION

For convenience we adopt in this discussion the notation $R_f = dA_f/dA_s$, and $R_p = dA_p/dA_s$; R is used to denote properties common to both R_f and R_p.

5.1. *What Determines the Area Ratio of Faculae to Spots on the Sun?*

The calculation presented above indicates that the "source" relations between A_{f0}, A_{p0}, and A_{s0} are more closely approximated by the daily data than by the annual means. These "source" relations are of particular interest because they describe the area behavior of faculae, plages, and spots soon after the emergence of magnetic flux, and before photospheric velocity fields can change the value of R. Therefore, it is noteworthy that the nonlinear relationships shown in Figures 1 and 2 are more evident in these daily data, since our results in § 4 then indicate that the decrease in R is most pronounced in recently emerged flux. This implies that the decrease is produced by a subphotospheric mechanism, rather than by photospheric transports, such as the random walk generated by granular and supergranular flows.

Turbulent velocity fields in the convection zone might influence R as flux tubes of high plasma β, generated in a deeper level, move upward toward the photosphere (see, e.g., Moreno-Insertis 1992). However, observational evidence suggests that R is mainly determined by the field generation process itself, which is now expected to occur at yet deeper levels, below the convection zone.

Thus, Brown & Evans (1980) discovered a remarkably linear relation between the slopes R_f^{-1} measured in the early phases of cycles 12–20 and the peak amplitudes of sunspot number achieved later in those same cycles. We have reproduced their relationship for the cycles 16–20 considered here, in Figure 6. Their finding that the value of R_f determined very early in the evolution of a cycle already "knows" the amplitude of activity to be reached several years, later in that cycle seems to argue for direct control of R by the same deep-lying process that determines the generation of flux. It is more difficult to imagine that the global properties of solar convection should change significantly, and in such synchronism with the magnetic field, as to drive the observed variations in R_f.

It is interesting that we were unable to find in our Ca K plage data a corresponding relation for R_p^{-1}. Our explanation is again that the Ca K plage data show the largest and oldest plages better than the white-light data. Therefore, the decrease in R that produces the R_f^{-1} relationship seen by Brown & Evans should be less evident in the plage data than in the white-light facular data. This supports our intepretation that the R_f^{-1} relation arises from subphotospheric mechanisms, which tend to be masked by lifetime effects associated with photospheric flows in the plage data.

If R is determined by the basic properties of solar field generation, then its variation over past cycles may indicate variation in the field generation process. The magnetic fields giving rise to faculae are more spatially fragmented than sunspot fields (see, e.g., Rabin 1992). This indicates that a

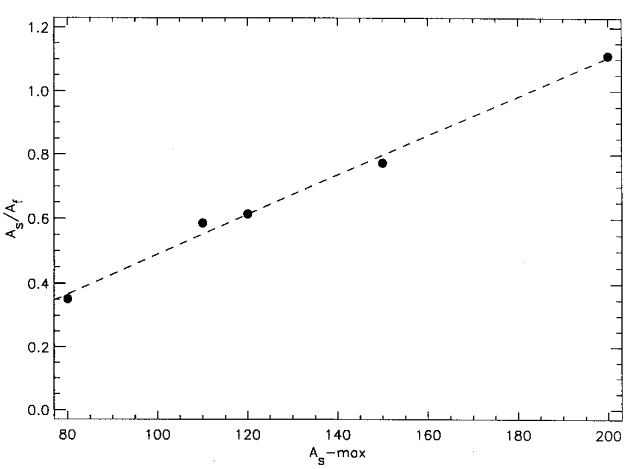

FIG. 6.—Plot of the slopes, dA_s/dA_f, during the early rise phases of cycles 16–20, vs. the peak amplitudes of those same cycles, in A_s. The dashed line denotes a linear least-squares fit.

decrease in R corresponds specifically to an increase in the spectral power in magnetic fields at the lower spatial frequencies associated with sunspots, relative to the higher frequencies associated with faculae.

The evidence we presented in § 3 on the systematic decrease of R with increasing A_s *within* a given cycle thus agrees with the sense of its *cycle-to-cycle* variation as a function of cycle amplitude, illustrated in Figure 6. This agreement suggests that increases of magnetic flux produced by the solar field generation mechanism are accompanied by increased spatial power at low spatial frequencies, whether the flux production event is global on the 11 yr timescale, or local, on much shorter timescales.

Cattaneo, Chuieh, & Hughes (1990) have discussed a magnetic buoyancy instability that might account for the sign of such a correlation. In their model, larger aggregates of flux erupting from the deep-lying layers below the convection zone should exhibit greater helicity than more fragmented flux concentrations. So it is worth looking for a correlation between observed helicity of active region fields, and of R since we have identified higher R-values with greater fragmentation of the field. Increased twist (helicity) of an active region flux rope should produce increased rotation of the region's bipolar axis out of the east-west direction on the Sun's surface (see, e.g., Leighton 1964). Thus, we expect high values of rotation angle, θ, to occur in the active regions of largest sunspot area. However, active regions containing the largest spots tend to have relatively small values of θ (Brunner 1930; Wang & Sheeley 1989), so the importance of helicity, and of the specific mechanism advanced by Cattaneo et al., requires further investigation.

5.2. *The Role of Variations in A_f/A_s in Luminosity Variations of Other Late-Type Stars*

Very large spots are known to account for the amplitude and phasing of luminosity variations measured on much younger stars of similar mass to the Sun (see, e.g., Radick 1992). The decrease in A_f/A_s with increasing activity level discussed here might help to explain the abrupt increase in photometric variability observed in stars, beginning at activity levels only 50% higher than the present Sun (as measured by global Ca K emission level; Lockwood, Skiff, & Radick 1997). The timescale of the stellar luminosity variations of greatest interest to climate studies is in the range 10–10^2 yr. Therefore, it is the behavior of A_f/A_s on these timescales, rather than the "source" values A_{f0}/A_{s0} discussed in the previous section, that are of interest here.

This behavior can be estimated by examining the dependence of the smoothed values of this ratio achieved near the peaks of cycles 12–20 between 1874 and 1976, upon the peak value of smoothed A_s achieved in those same cycles. This dependence is plotted in Figure 7*a*. We can see A_f/A_s has decreased by a factor of about 2, between its value in the small-amplitude cycles 12–16, 20 and its value in the largest amplitude cycle 19. Whether we extrapolate this curve linearly or exponentially, it is clear that a star of only 50% higher sunspot area than the Sun achieved in cycle 19 might exhibit a value of A_f/A_s less than 10% of that experienced during moderate-amplitude cycles such as 20 (or 21 and 22, the cycles for which space-borne pyrheliometry is available). This suggests that stars of somewhat higher magnetic activity level might exhibit significantly higher photometric variability because the facular brightening becomes too small to balance the sunspot dimming.

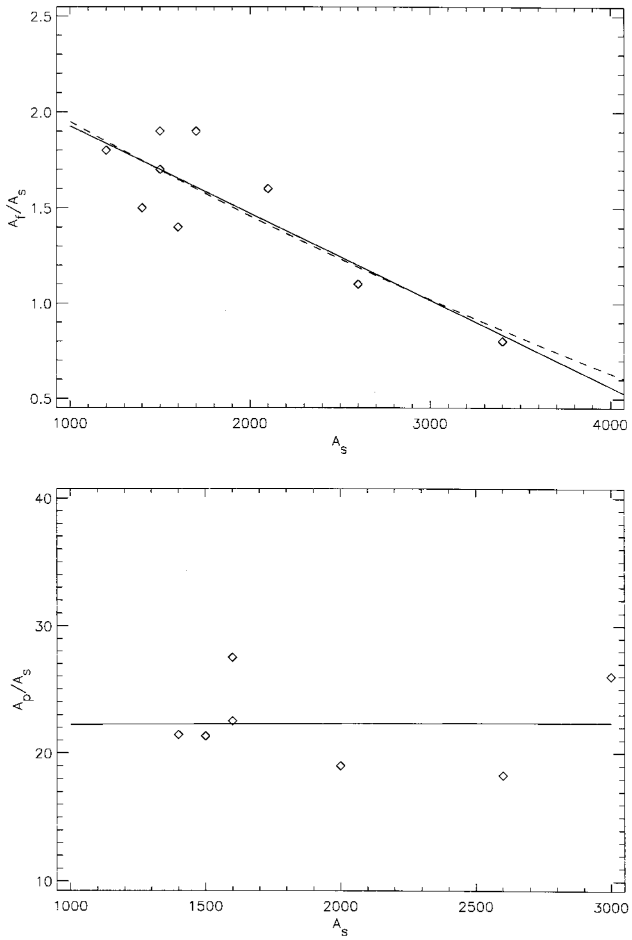

FIG. 7.—Plot of the peak values of (*a*) the ratio A_f/A_s and (*b*) the ratio A_p/A_s, vs. peak A_s, based on 13 month smoothed data for cycles 12–20. The solid line in panel (*a*) shows a least-squares linear fit; the dashed line represents an exponential.

However, a similar plot of A_p/A_s versus A_s Figure 7*b* shows no decrease in this ratio, when Ca K plage data are used, instead of white-light facular data. Again, the reason appears to be that the plage data are more influenced by the lifetime effect described in § 4 than are the facular data. This interpretation implies that the difference between Figures 7*a* and 7*b* lies in the ability of the Ca K data to capture the large-area, oldest plages, whose contrast is too low to pick up in the white-light data. Given the uncertainty in the morphology of such decayed plages on other late-type stars, it is difficult to decide whether long-term irradiance variations on stars somewhat more active than the Sun are more likely to be governed by the behavior shown in Figure 7*a* or in 7*b*.

Radick (1992; Fig. 3), has shown that, for stars with twice or more the mean solar chromospheric emission level, the correlation between chromospheric and photometric brightness fluctuation has changed from positive (as for the Sun) to negative, as might be expected if the behavior seen in Figure 7*a* is relevant. Judging from the plot of rms chromospheric variability versus mean chromospheric emission shown by Lockwood et al. (1992), an increase of 50% in rms amplitude is expected on stars with about twice the mean choromospheric emission level of the Sun, so an explanation in terms of a significant decrease in R seems to be consistent with the results of stellar photometry.

In extrapolating the dependence seen in Figure 7 to other stars, it is worth asking whether the relative lifetimes of stellar spots and faculae might accentuate or diminish the decrease of A_f/A_s with increasing A_s, seen in the Sun. Assuming that the decay processes of starspots and stellar faculae for main-sequence stars are similar to those on the Sun, we evaluate how the diffusion coefficient, K, equation (5) might scale with spectral type. We take L as the characteristic dimension of the convective scale responsible for field diffusion on these stars, τ as its lifetime, and assume that L scales as the pressure scale height, so τ scales as the ratio of pressure scale height to local sound speed. On these assumptions, we find that K scales as $T^{3/2}/g$, where T and g are the star's temperature and surface gravity, respectively.

Using values for main-sequence stars of spectral types that bracket the interval containing most of the stars observed by Lockwood et al., we find that K decreases by a factor 3 as we progress from F0 to K5. A decrease in K implies longer facular lifetimes in our simple model and therefore an increased ability of faculae to cancel sunspot-induced dips in stellar luminosity. This suggests that facular lifetime effects are unlikely to contribute positively to the increased photometric variations reported by Lockwood et al. (1997) in main-sequence stars somewhat cooler than the present Sun. Therefore, the mechanism for the increased luminosity variability of these stars is most likely to be a decrease in the value of A_f/A_s caused by the tendency of the field generation process to favor lower spatial frequencies at high flux levels.

6. CONCLUSION

The main results of this study are as follows:

1. A nonlinear relation between white-light facular areas and spot areas is evident also in the relation between full-disk Ca K plage areas when daily data are used. This demonstrates that the nonlinearity is not an artifact of the limited limb visibility of white-light faculae. A similar nonlinearity has now also been reported in Ca K plage and sunspot area data for cycle 22 (Chapman, Cookson, & Dobias 1997).

2. Our finding that the nonlinearity is more easily seen in daily data than in annual means can be explained by the different dependences of facular, plage, and sunspot lifetimes on emerged flux. Our explanation implies that the nonlinearity is caused by subphotospheric processes and tends to be masked in the annual mean data by the different decay rates of very large spots compared to faculae/plages, which are usually ascribed to a random walk process driven by photospheric velocity fields.

3. We argue from the results of Brown & Evans (1980) that the subphotospheric mechanism determining the "source" value of R_f is more likely to be associated with operation of the deep-seated solar field generation than with properties of the turbulent velocity field in the bulk of the solar convection zone. Our results indicate that increases in the flux-production efficiency of the field generation process are linked with a tendency to increased spectral power at relatively low spatial frequencies corresponding to spot dimensions, compared to the higher spatial frequencies of the more fragmented fields. These findings are consistent with a model put forward by Cattaneo et al. (1990), in which a Kelvin-Holmholtz instability favors the correlation between efficiency and scale we

find here. But we do not see the negative correlation between R and field helicity, also expected from this instability, which depends upon magnetic shear in fields located near the bottom of the convection zone. This discrepancy may arise because the relation between helicity and bipolar tilt is more complicated than envisioned by Leighton (1964) or because the correlation we see has a different explanation than the instability studied by Cattaneo et al.

4. Our finding that A_f/A_s is likely to decrease by an order of magnitude below its cycle 21–22 values in stars only 50% more active than the present Sun strengthens the evidence that a reduction in the areas of faculae relative to spots can explain the increased photometric variability of stars somewhat more active than the present Sun (Paper I; Foukal 1994a, 1994b). Additional evidence favoring this explanation comes from observations (Moran, Foukal, & Rabin 1992; Zirin & Wang 1992; Topka, Tarbell, & Title 1992) which show that only the smallest flux tubes of less than 10^{18} Mx in magnetic flux are brighter than the photosphere, near disk center. This suggests that as the flux level on a star rises, an increasing fraction of that flux (even in plages and network) produces a photometric deficit.

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