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THE SUN AS A STAR: THREE-COMPONENT ANALYSIS OF CHROMOSPHERIC VARIABILITY IN THE CALCIUM K LINE

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ABSTRACT

A three-component model of the solar cycle variability of the Ca II K emission is developed using extant contrast and fractional area parameters for (1) cell, (2) network, and (3) plage components that are resolution-consistent. We have been able to fit the quiet-Sun Ca II K emission (at solar minimum) as observed by White and Livingston with cell and network features alone using extant limb-darkening laws. The occurrence of plages during the growth of the solar cycle was found to be insufficient to account for the cycle increase in the K emission and required the introduction of additional network in excess of the quiet-Sun value. The implications of, and evidence for, such an active network are discussed.

Subject headings: Ca II emission — Sun: activity — Sun: chromosphere — Sun: plages — Sun: spectra

I. INTRODUCTION

It has long been recognized that the Ca II K emission reversal is a useful diagnostic for investigating the chromospheric activity of the Sun. This emission has been used to study a variety of solar chromospheric structures (Shine, Milkey, and Mihalas 1975; Ayres 1979), including their rotational behavior (e.g., Antonucci *et al.* 1977) and their association with magnetic activity (Skumanich, Smythe, and Frazier 1975, hereafter SSF). In other solar-like stars K emission has provided estimates of age and rotation (Skumanich 1972), of the total magnetic flux erupting through the photosphere (Skumanich and Eddy 1981), and evidence of cyclic dynamo variability (Wilson 1978).

The most obvious K emission regions on the solar disk are the bright plages. From minimum to maximum of the 11 yr solar cycle, the fraction of the solar disk covered by such plages increases. There is a corresponding increase in the observed K emission from the full solar disk, i.e., for the Sun observed as a star, hereafter called *flux*. In addition, passage of plages across the Sun's disk due to solar rotation produces at times a 27 day (synodic) modulation of the solar K flux.

Less evident is the smaller scale chromospheric activity that occurs in the network structure bordering supergranule cells. In particular, magnetic flux tube remnants of dispersed plage regions, spots, and other magnetic sources collect at the cell boundaries as a result of the sweeping action of supergranulation flows. This network structure has been observed to change with solar activity. Sheeley (1967) noted that the network appears wider and more complete at the time of sunspot maximum than at minimum, when it is fragmentary and tends to disappear almost entirely in some places.

The evolution and decay of plage areas on the solar disk is well documented on a daily basis, over the past few decades (World Data Center/National Oceanic and Atmospheric Administration, hereafter WDC/NOAA, reports). However, these observations only account for the more evident emission structures on the disk and miss a significant portion of the weakly organized emission network (Sheeley 1967). Hence, the relative contribution of the emission from the network to the K flux and its temporal evolution are less documented and remain uncertain, despite the suggestion (Bappu and Sivaraman 1971) that the network is an essential feature in the integrated solar signal.

Recently, White and Livingston (1978, 1981, hereafter called White and Livingston) have reported synoptic flux measurements of the K emission from the Sun for the period 1975–1981. Their concurrent measurements near the center of the solar disk, hereafter called *center*, but averaged over a $1' \times 3'$ region indicate that the center brightness remained constant over the ascending phase of cycle 21. This emission is a mix of contributions from network (39% by area) and nonnetwork (61% by area) regions (SSF). On the average then, no *additional* network appears at disk center. This would suggest that, at least in a first approximation, the variability of the K flux can be considered to arise from changes in the plage area covering the Sun (Cook, Brueckner, and VanHoosier 1980, hereafter Cook *et al.*; White and Livingston). The extent to which this assumption is correct depends on the relative contribution to the flux from *additional* chromospheric network, hereafter called *active network*, that appears at higher latitudes and is due to dispersion of plage remnants (Leighton 1964, 1965).

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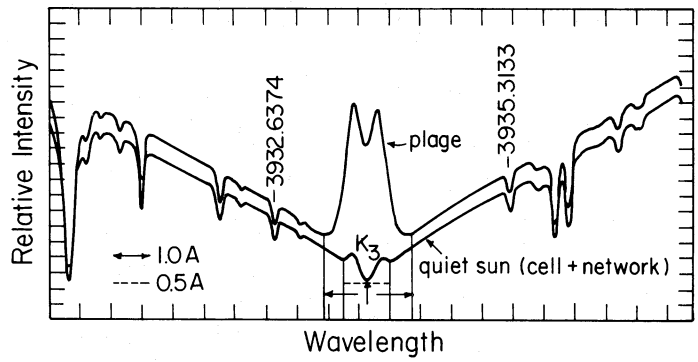

FIG. 1.—Comparison of quiet-Sun and plage Ca II K line profiles. The definition of the K_3 relative intensity and K0.5 and K1.0 bandwidths are indicated (after White and Livingston 1978).

In this paper we use the White and Livingston data together with cotemporal observations of the area, location, and apparent brightness of the individual plage regions present on the solar disk to assess the importance of changes in higher latitude active network for an understanding of solar chromospheric activity.

In § II, relevant K observations of the Sun are described. In § III, a three-component model of the K emission flux is developed. This model includes the flux from a *cell* component, a *network* component, and a *plage* component. The active-network contribution is then derived by fitting the full-disk K emission measurement. Results of the modeling are discussed in § IV, where the model is compared with a parameterized two-component model in which only "quiet" regions and plage areas are used.

II. OBSERVATIONS OF THE FULL-DISK SOLAR CALCIUM K EMISSION

The solar K absorption line is an optically thick resonant line ($\sim 5\%$ relative central intensity) with a self-reversed emission core. The emission core originates in the middle to lower chromosphere at temperatures around 7000 K, while the wings of the line are formed much lower in the solar atmosphere at heights below that of the temperature minimum. The strength of the emission core increases linearly with magnetic field strength up to ~ 500 G (SSF). Thus, the Ca II K emission from the quiet Sun is significantly weaker than that from plage regions. This is evident from the comparison in Figure 1, which presents the respective *relative* K line intensities (i.e., intensity relative to a reference continuum intensity linearly interpolated to the center of the line from measurements at $\lambda 3875$ and $\lambda 4019$ [White and Livingston]). We use the standard notation, where the wavelength location and the relative intensity at line center are K_3. For completeness we note that K_{2r} and K_{2v} designate the red and violet emission peaks, while K_{1r} and K_{1v} designate the respective minima between the emission peaks and the wings. Illustrated in Figure 1 is the portion of the emission core defining the K0.5 and K1.0 indices, which represent the relative intensity integrated over 0.5 Å and 1.0 Å windows centered on K_3, in units of Å (of the reference continuum). In the following analysis, the general symbol K refers to any of the K observations, either indices or relative intensities.

The White and Livingston data for the variation of the K1.0 index averaged over a $1' \times 3'$ region at disk center and for the full solar disk (flux) are shown in Figure 2. Similar data are available for K_3 and K0.5. The error associated with each of

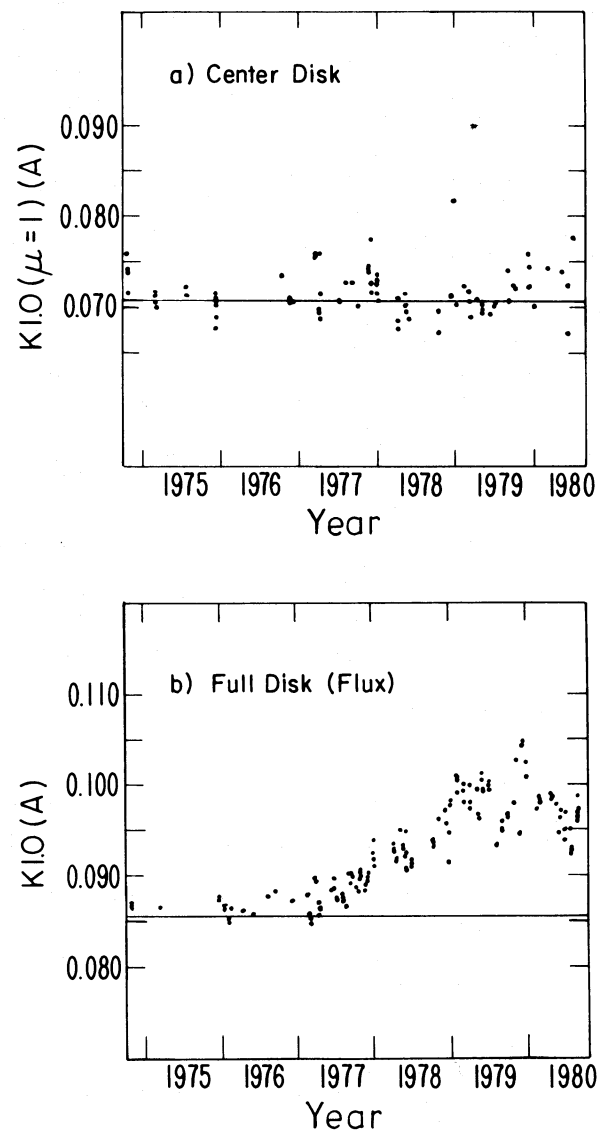

FIG. 2.—Observation of the K1.0 index: (*a*) at the center of the disk of $1' \times 3'$ quiet regions and (*b*) of the entire disk (flux) for solar cycle 21. The horizontal line in (*a*) indicates the mean and in (*b*) the calculated quiet-Sun flux value (see § III*a*).

the flux data points in Figure 2*b* is 0.06%. We note that center measurements, where there is generally little plage or spot activity, sample a combination of both cell and network emission (SSF) and define the *quiet*-Sun emission at $\mu = 1.0$. The average over the full observing period (35 measurements) of the center K1.0 index shown in Figure 2*a* is $\mathrm{K1.0}^{\mathrm{quiet}}(\mu = 1) = 0.071$ Å $\pm$ 0.001 Å. For the K0.5 index and the K_3 intensity, the corresponding values are $\mathrm{K0.5}^{\mathrm{quiet}}(\mu = 1) = 0.032$ Å $\pm$ 0.001 Å and $\mathrm{K}_3^{\mathrm{quiet}}(\mu = 1) = 0.047$ Å $\pm$ 0.001 Å.

III. A THREE-COMPONENT MODEL OF SOLAR CALCIUM K EMISSION

White and Livingston showed that K emission parameters measured over solar cycle 21 correlate with common activity indicators such as the Zurich sunspot number, the 10.7 cm radio flux, and the plage index (a measure of projected plage area weighted by a relative brightness estimate). On this basis they qualitatively interpreted the observed changes in the K line intensity parameters in terms of the addition of active region emission to that from the quiet solar disk, but with the caveat that their observing program did not permit the identification of network variability outside disk center that may affect the full-disk K line variations.

If the total active region contribution to the full-disk Ca II K measurements is modeled by using the WDC/NOAA Ca II K plage records, then the difference between the measured flux and the flux contribution from the active regions can be attributed to excess network at nonequatorial latitudes. We identify this excess as *active network*. By considering the emission from both active network and plage together with the quiet regions, we find that the observed K line variations, both the mean and the rotational fluctuations, can be modeled more closely with *extant* contrast and area values than if the network terms are omitted.

We emphasize here that underlying the introduction of an active-network component is our contention that the extant WDC/NOAA plage data contain, for the most part, those active areas that have contrasts significantly higher, i.e., in the plage range, than the network areas. One can find a fit to the flux (in the mean only) as Cook *et al.* have done, with areas having only plage contrasts, but this requires that plages cover an area a factor of 2 larger (see § IV) than given by the WDC/NOAA data. Such an error in the extant data is, in our view, implausible and indicates to us the need for a third component.

a) *Cell and Network Representation of the Quiet Sun*

It is well known that the "quiet" Sun represents an inhomogeneous solar atmosphere comprised of supergranule cells (magnetically undisturbed chromosphere) and network features. For example, it has been shown that at a 2″.5 × 2″.5 resolution, 39% of the quiet Sun at disk center is covered by K network (SSF). In terms of an average-cell, average-network representation, the center disk K value for the quiet Sun is given by

$$\mathrm{K}^{\mathrm{quiet}}(\mu = 1) = \mathrm{K}^{\mathrm{cell}}(\mu = 1)[1 + f_N^0(C_{\mathrm{K}}^N - 1)] , \qquad (1)$$

where f_N^0 is the fraction of the center covered by network, and C_{K}^N is the contrast between network and cell for the K observable under consideration. It is sufficiently accurate for our purpose to ignore the contribution of network (and plage) to the reference continuum. If we use $f_N^0 = 0.39$, $C_{\mathrm{K1.0}}^N = 1.27$, $\mathrm{K1.0}^{\mathrm{cell}}(\mu = 1) = 0.063$ Å (SSF) in equation (1), we find that $\mathrm{K1.0}^{\mathrm{quiet}}(\mu = 1) = 0.070$ Å. This agrees with the average of 0.071 Å $\pm$ 0.001 Å for the K1.0 measurements over the current solar cycle shown in Figure 2*a*. Thus within the quoted uncertainties, the *extant* network and cell values yield a good representation of the center disk data of White and Livingston.

If we assume further that the full disk at the minimum of solar cycle 21 has a *background* network covering 39% of the entire Sun surface, we can calculate the full-disk K index from that at disk center using appropriate limb-darkening laws. We note that such a background network reflects the effects of residual magnetic field, including the mean poloidal component, dependent in some way on the cumulative behavior of one or more previous cycles. The experimental evidence from White and Livingston shows only that this fraction of network coverage remains invariant over one-half of a solar cycle, but it does not preclude variability with longer time periods.

If $R_{\mathrm{K}}(\mu)$ is the limb-darkening law for the (absolute) K intensity, and $R_C(\mu)$ that for the continuum, one can show that the full-disk quiet-Sun K value is given by

$$\mathrm{K}^{\mathrm{quiet}} = \mathrm{K}^{\mathrm{quiet}}(\mu = 1)\frac{\int_0^1 R_{\mathrm{K}}(\mu)\mu d\mu}{\int_0^1 R_C(\mu)\mu d\mu} . \qquad (2)$$

This result assumes that the limb-darkening law is the same for both cell and network features. Since non-LTE effects hold for the excitation of the line in both features, we expect similar source function variations with depth and hence similar limb-darkening laws (cf. Skumanich 1967). This is in agreement with the measurements of the limb darkening of individual chromospheric K features reported by Macris (1974). We note that such measurements are difficult for both network fragments and cell regions, since small isolated areas of enhanced K emission may contaminate the true center-to-limb dependence of the cell emission and vice-versa. In addition the intensity of the K line tends to fluctuate in time (Jensen and Orrall 1963).

White and Suemoto (1968) measured the limb-darkening curve for the absolute intensity, $I_{\mathrm{K}3}^{\mathrm{quiet}}$, from $\mu = 1.0$ to $\mu = 0.15$. Our own measurements at Kitt Peak indicate that the quiet-Sun intensity at K_3 and the 0.5 Å and 1 Å integrated intensities all darken in the same way. Hence, for the purpose of evaluating equation (2), the integrated K intensity was taken to limb darken according to the K_3 data given by White and Suemoto. This is shown in Figure 3, together with a limb-darkening curve for the continuum, R_C, inferred from Mitchell (1981). The ratio of the darkening integrals is 1.21 so that we find a full disk $\mathrm{K1.0}^{\mathrm{quiet}} = 0.086$ Å from equation (2) if we take a disk center value of $\mathrm{K1.0}^{\mathrm{quiet}}(\mu = 1) = 0.071$ Å as derived earlier. Our calculated value is marked in Figure 2*b* and represents a good fit to the data at solar minimum, i.e., under quiet conditions. We conclude that the cell-network representation at disk center also holds for the integrated disk observations of the quiet Sun.

b) *Plage and Active-Network Representation*

As conditions change during the solar cycle, the increase in the value of the K emission flux above its quiet value depends on the fraction of the solar disk covered by plage and on any *increase* in the network coverage, Δf_N. We assume for lack of more detailed information that the active-network fraction, Δf_N, is uniformly distributed at random across the solar surface. We note that when plages decay, the remnants

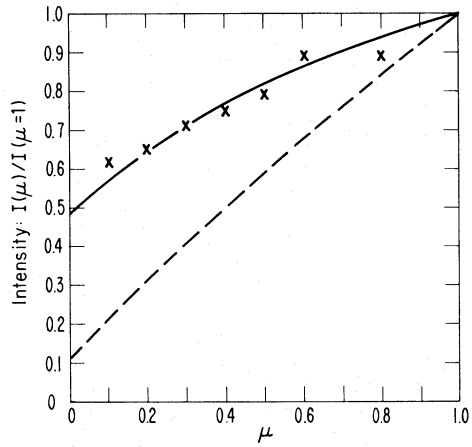

FIG. 3.—Limb-darkening law assumed for the K line (*solid line*) and continuum (*dashed line*). The points marked by crosses are from White and Suemoto (1968) for line center.

tend to drift poleward and eastward because of differential rotation, so that emission from the active network may be distributed more toward higher latitudes. That there is some drift toward the equator as well is indicated by *AE-E* satellite data (Lean *et al.* 1982). This active-network flux contribution is given by

$$\Delta K^{\rm net} = K^{\rm cell} \Delta f_N (C_K^N - 1)\,, \tag{3}$$

where $K^{\rm cell}$ is the full-disk value inferred with equation (2) from the disk center value $K^{\rm cell}(\mu = 1)$ for the K observable under consideration. This is the value one would find if the Sun were covered only by cell emission.

The flux contribution from plages, where the ith plage is located at μ_i with a physical area A_i, is

$$K^{\rm plage} = \frac{K^{\rm cell}(\mu = 1)}{2\pi \int_0^1 R_C(\mu)\mu d\mu} \sum_i \frac{A_i}{R_\odot^2} \mu_i R_K(\mu_i)(C_K^P w_i - 1)\,, \tag{4}$$

where C_K^P is the ratio of the average intensity for plage to cell emission at $\mu = 1$, and $R_\odot$ is the solar radius. Here w_i is a weighting factor derived from observer estimates of the brightness of the ith plage so that the actual plage contrast is $C_K^P w_i$. The K plage contrasts are usually referenced to a quiet-Sun background (mixture of cell and network) emission. In this case, the intensity ratio for plage to quiet-Sun emission, C_K^{PQ}, is related to C_K^P by

$$C_K^P = C_K^{PQ}[1 + f_N^0(C_K^N - 1)]\,, \tag{5}$$

and similarly for the network contrasts.

Our basic equation for the K flux is then given by the sum of the three contributions,

$$\begin{aligned} K &= K^{\rm quiet} + \Delta K^{\rm net} + K^{\rm plage} \\ &= K^{\rm quiet} + K^{\rm cell} \Delta f_N (C_K^N - 1) + \frac{K^{\rm cell}(\mu = 1)}{\int_0^1 R_C(\mu)\mu d\mu} \\ &\quad \times \sum_i A_i^{\rm WDC} \mu_i R_K(\mu_i)(C_K^P w_i - 1)\,, \end{aligned} \tag{6}$$

where $A^{\rm WDC}$ is the World Data Center plage area (in units of the solar hemisphere), and $K^{\rm quiet}$ is given by equations (1) and (2).

We note here the need for the use of self-consistent area (spatial resolution) and contrast values. We consider the product of area and contrast excess, as in equations (1) and (6), to be invariant under changes of resolution. Better resolved observations of the network lead to higher contrasts and smaller areas. Plages are less susceptible than the network to this issue of spatial resolution since they are intrinsically more extended; however, their inhomogeneous structure must be kept in mind. The K spectroheliograms used for the WDC/NOAA data have a resolution of $\sim 3''$, which is consistent with that used to define our network-cell components (SSF).

c) *Model Parameters*

The disk center values of the mean cell and mean network intensities or contrasts are different for the K_3 relative intensity and the K0.5 and K1.0 indices. Numerical values for $K^{\rm cell}(\mu = 1)$ and $C_K^N = I_K^{\rm net}(\mu = 1)/I_K^{\rm cell}(\mu = 1)$ used in the model are summarized in Table 1. For the K1.0 index, the values are from SSF. The network contrast for K_3 was taken to be the same as that derived by Skumanich and Smythe (1984) from data referring to a 0.17 Å band centered on K_3. This bandwidth represents that available to Macris (1974) in his study of network features from Arcetri spectroheliograms. This K_3 contrast, 1.54, when combined with $f_N^0 = 0.39$, $K_3^{\rm quiet}(\mu = 1) = 0.047$ (White and Livingston), and equation (1) yields our other basic parameter, $K_3^{\rm cell}(\mu = 1) = 0.038$. Independent measurements of this parameter are not available, but, given the agreement of the K1.0 index with equation (1), we feel our procedure is justified. The K0.5 values were derived from the K1.0 values using the White and Livingston cross-correlation relation (see their Table 4), which we corrected for limb darkening. Values of the network to quiet-Sun contrast C_K^{NQ}, calculated via equation (5), are provided in Table 1 for completeness.

The average plage to quiet-Sun contrasts C_K^{PQ} listed in Table 1 are based on generally accepted measurements for these quantities (Shine and Linsky 1974; Lemaire *et al.* 1981). Sheeley (1967) notes that for Mount Wilson K spectroheliograms ($\sim$K0.5) the plage contrast varies between 2 and 4; refer also to Cook (1982). We note that these photographs have a resolution of $\sim 2''$. Knowing C_K^{PQ}, the required C_K^P are determined by using equation (4). According to Hedeman (1982) the K plage intensities vary approximately linearly with the observer-assigned brightness. Hence we use the relation

$$w(I^{\rm obs}) = A_K + B_K I^{\rm obs} \tag{7}$$

to estimate the contrast weighting factor for each plage. The coefficients (A_K, B_K) were determined by requiring the plage contrast $C_K^{PQ}(I^{\rm obs}) = C_K^{PQ} w(I^{\rm obs})$ to match the average value at $I^{\rm obs} = 3$ and to equal the network contrast at $I^{\rm obs} = 1$, i.e., for the weakest plage. The result is shown in Figure 4. If measure-

TABLE 1

SUMMARY OF MODEL PARAMETERS

Parameter	K_3	K0.5 (Å)	K1.0 (Å)
$K^{\rm cell}(\mu = 1)$	0.038	0.028	0.064
C_K^N	1.54	1.41	1.27
C_K^P	4.91	3.81	2.75
C_K^{NQ}	1.30	1.22	1.16
C_K^{PQ}	4.00	3.3	2.5

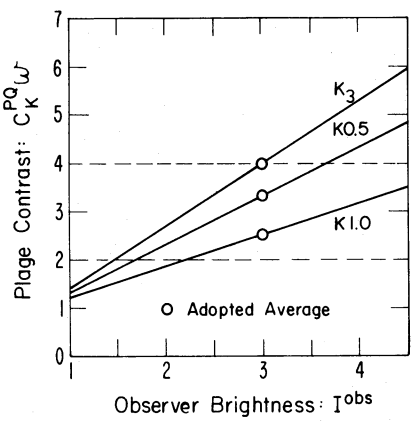

FIG. 4.—The relation between plage contrast (to quiet Sun) and observer brightness. The range observed by Sheeley (1967) for K0.5 is indicated by the dashed lines.

ments of the active-network fraction were available throughout the solar cycle, we would have no *free* parameters in our representation equation (6).

d) *Derivation of the Active-Network Fraction*

In the absence of direct measurements of the *total* network coverage, $f_N^0 + \Delta f_N$, we can use equation (6) and the model parameters from Table 1 together with the White and Livingston measurements of the full-disk K emission to estimate the active-network fractional area Δf_N at different times throughout the ascending phase of solar cycle 21.

Figure 5 compares the observed K flux with the modeled contribution, $K^{quiet} + K^{plage}$, from quiet Sun and plages alone, for both K1.0 and K_3. The difference between these is ΔK^{net}, from which the estimates of Δf_N shown in Figure 6 were obtained. Since this active network presumably arises from the decay of plage regions and reflects the increase in the number of plage regions toward solar maximum, we have parameterized Δf_N as a linear function of the total plage area on the solar disk smoothed over seven rotations,

$$\Delta f_N(t) = f_0 + f_1 \left\langle \sum A_i^{\mathrm{WDC}}(t) \right\rangle_{7\ \mathrm{rotations}} \equiv f_0 + f_1 \bar{A}^{\mathrm{WDC}}(t) . \tag{8}$$

The choice of seven rotations was based on the observation (Gaizauskas *et al.* 1983) that the average "activity complex" lifetime is of this order. The correlation between Δf_N and plage area $\bar{A}^{\mathrm{WDC}}$ is shown in Figure 7 for K1.0 and K_3. The coefficients f_0 and f_1 were determined from a least squares fit of Δf_N and $\bar{A}^{\mathrm{WDC}}$. We find $(f_0, f_1) = (-0.012, 13.5)$ for K1.0, $(-0.014, 13.2)$ for K_3, and $(-0.036, 14.6)$ for the K0.5 flux data.

IV. DISCUSSION

The agreement between the predicted full-disk quiet-Sun value and the White and Livingston measurements gives us confidence in the use of our cell and network parameters as well as our darkening law for full-disk observations. Of more concern are the plage properties, whose statistics are not as well known.

If one attempts a least squares fit to the full-disk data with only the quiet-Sun and plage terms and with either the plage contrast or area,[3] a free parameter, one finds values that exceed the observed ones. Thus for a fit to the K1.0 data, the plage contrast must be increased by 1.84 over that of our three-component (hereafter 3c) model, i.e., $C_{\mathrm{fit}} = 1.84 C_{3c}$. In the case of area, one finds $A_{\mathrm{fit}} = 2.35 A^{\mathrm{WDC}}$. This latter fit is basically

[3] Recall that, in an average sense, $(C - 1)A$ is the relevant free parameter.

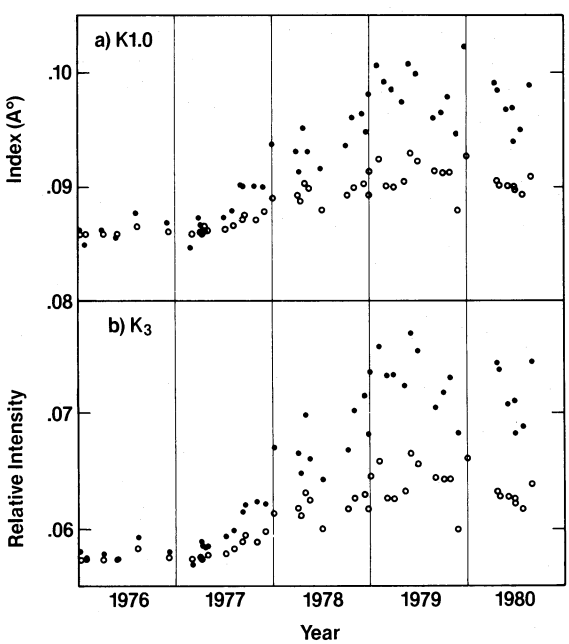

FIG. 5

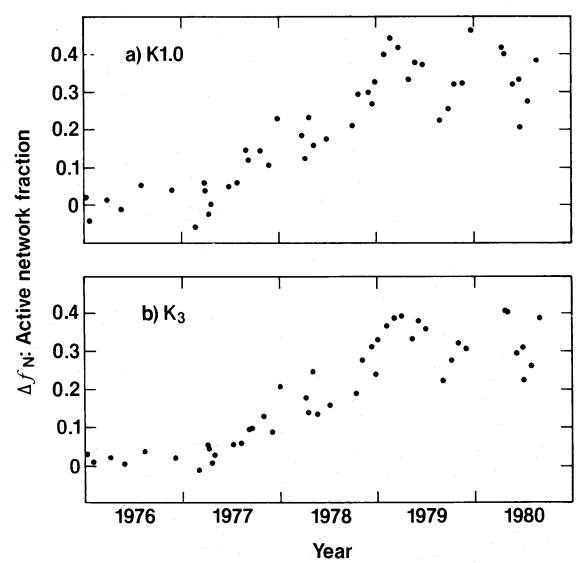

FIG. 6

FIG. 5.—Model calculation with quiet Sun and plage terms (*open circles*) compared with observed full-disk (*filled circles*) for (*a*) K1.0 index and (*b*) K_3 relative intensity. Note that the data and calculations refer to, on the whole, sample points, since observations on successive days have been averaged.

FIG. 6.—Active-network fraction vs. day of the year derived from (*a*) K1.0 index and (*b*) K_3 relative intensity data. Successive days have been averaged.

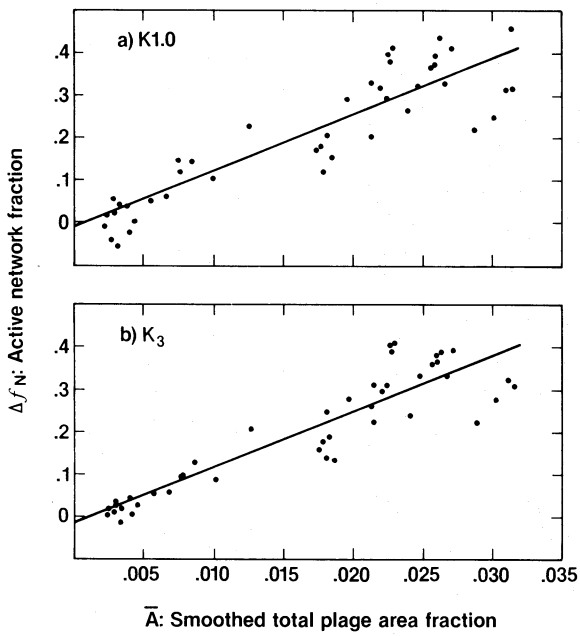

FIG. 7.—Active-network fraction vs. smoothed total plage area fraction (of $2\pi R_\odot^2$). Successive days have been averaged. The least squares fit of equation (8) is shown by the straight line.

the same as that of Cook *et al.* Both of these fits are consistent with the invariant value $(C-1)A \approx 4.6A^{\mathrm{WDC}}$. The *extant* plage (contrast, area) values yield a mean of $(C-1)A \approx 2A^{\mathrm{WDC}}$, a factor of 2 smaller than that needed to fit the data. In either of the two-component model fits, the range of the model values about the data exceeds that of the 3c model by a factor of ~ 2 near solar maximum. The 3c model is not only more realistic with regard to $(C-1)A$ for plages but gives a better representation of the rotational modulation.

In the absence of a comprehensive statistical study of plages, an alternative approach is to determine the plage parameters from a fit to the observed rotational modulation. In this case the active network acts as a slowly varying background. Such a procedure would "calibrate" the contrast-area factor. A daily synoptic program initiated by one of us (W. C. L.) with a photometric system at the KPNO laboratory at Tucson appears to yield indices consistent with the monthly KPNO (mountain) values and will allow such a calibration. We note, however, that the possible demise of the K-plage WDC synoptic program may make such a calibration moot for predictive purposes.

The scatter of the derived active-network values in Figures 6 and 7 is appreciable and must reflect several sources of fluctuations. Among these are observational errors and real short-term (<1 day) changes (Godoli and Fossi 1968) in plage areas and contrasts as well as limitations of the model. Also present are other temporal fluctuations intrinsic to the K emission from the Sun, for example, the occurrence of Ellerman "bombs," or bright "moustaches," dark "whiskers," bright "whiskers," etc. (Beckers and Artzner 1974), which are likely to be more frequent at activity maximum. To the extent to which these features are absent in the SSF data at disk center, they will not contribute to the definition of the three components. A finite element characterization of a continuous distribution of K emission brightness is indeed arbitrary, but a three-component characterization is clearly more accurate than a two-component one.

We note from Figure 7 that at solar maximum the active network fraction amounts to ~ 0.4. Thus the total K "activity" on the Sun, when viewed with 2″.5 resolution, covered the fraction $f_N^0 + \Delta f_N + A^{\mathrm{WDC}} = 0.39 + 0.40 + 0.03 = 0.82$. This appears high when compared with the impression of a visual inspection of K spectroheliograms and suggests that we may have incorrectly characterized the plage and/or active-network component. Alternatively, we may have left out an important component not included in the data of SSF.

Recently, Sivaraman and Livingston (1982) have suggested that transient K_{2v} "grains" (equivalent to the bright "whiskers" mentioned above), which are distributed throughout supergranule cells, represent such an additional component. Since these features are smaller than the resolving power of most spectroheliograms (Beckers 1964), they are unnoticed by the eye, except under conditions of good seeing. These grains are evident in the high-quality K_{2v} spectroheliogram illustrated in Figure 8 (Plate 11). We have determined, by using the data of Liu (1974), that at peak brightness these grains have a K1.0 index which is the same as that of the average network. A surface count on Figure 8 shows that the grain density is $\sim 6.5 \times 10^{-3}$ per square arc second. If grains have a surface area of 1 square arc second, they would contribute a fractional area of only 6.5×10^{-3} to f_N^0. Given their derived contrast, we conclude that they cannot be important contributors to the K flux.

It is also possible that the active-network, Δf_N, and quiet-network, f_N^0, features have different contrasts, implying the need of a fourth component in the model. One need only raise the active-network contrast from 1.27 to 1.54, for K1.0, in order to reduce Δf_N(max) by a half and arrive at 62% total coverage. Available evidence on this point is contradictory. Nauer, Teske, and Elste (1980) suggest no difference between active and quiet network, while Frazier (1977) comes to the opposite conclusion. A statistical study of the active network is needed to settle this issue.

Our choice to parameterize Δf_N in terms of A^{WDC} in equation (8) can be criticized. Yet in the absence of a quantitative prescription of plage flux breakup and loss by reconnection and submergence, we do not feel that a more careful parameterization is appropriate. The value of $f_1 \approx 13$ in equation (8) suggests that, assuming the same flux value, the *mean* magnetic field changes by a factor of 13 between plage structures and network features. If we take the value of 28 G for the mean network field (SSF), we find that mean plage fields should be ~ 340 G, which is consistent with observed values (Frazier and Stenflo 1972; Tarbell, Title, and Schoolman 1979). The specific value of f_1 depends weakly on the time-averaging window. If we average over three rotations, the lower limit of lifetimes of "active complexes" (Gaizauskas *et al.* 1983), f_1 drops by 14%. The values of f_0, which should nominally be zero, represent a measure of the scatter about our quiet-Sun fit. They should be compared with $f_N^0 = 0.39$.

What other evidence is there to support our active-network fraction? If we consider polar (white light) faculae (lat. $\geq 55°$), which one can take as a signature of magnetic and hence network features (Howard 1965; Sheeley 1966), then observations indicate that the number of such features *increases* sometime after the onset of magnetic flux eruption in the sunspot latitudes (Sheeley 1966, 1976). A comment is in order concerning the delay in their appearance due to transport

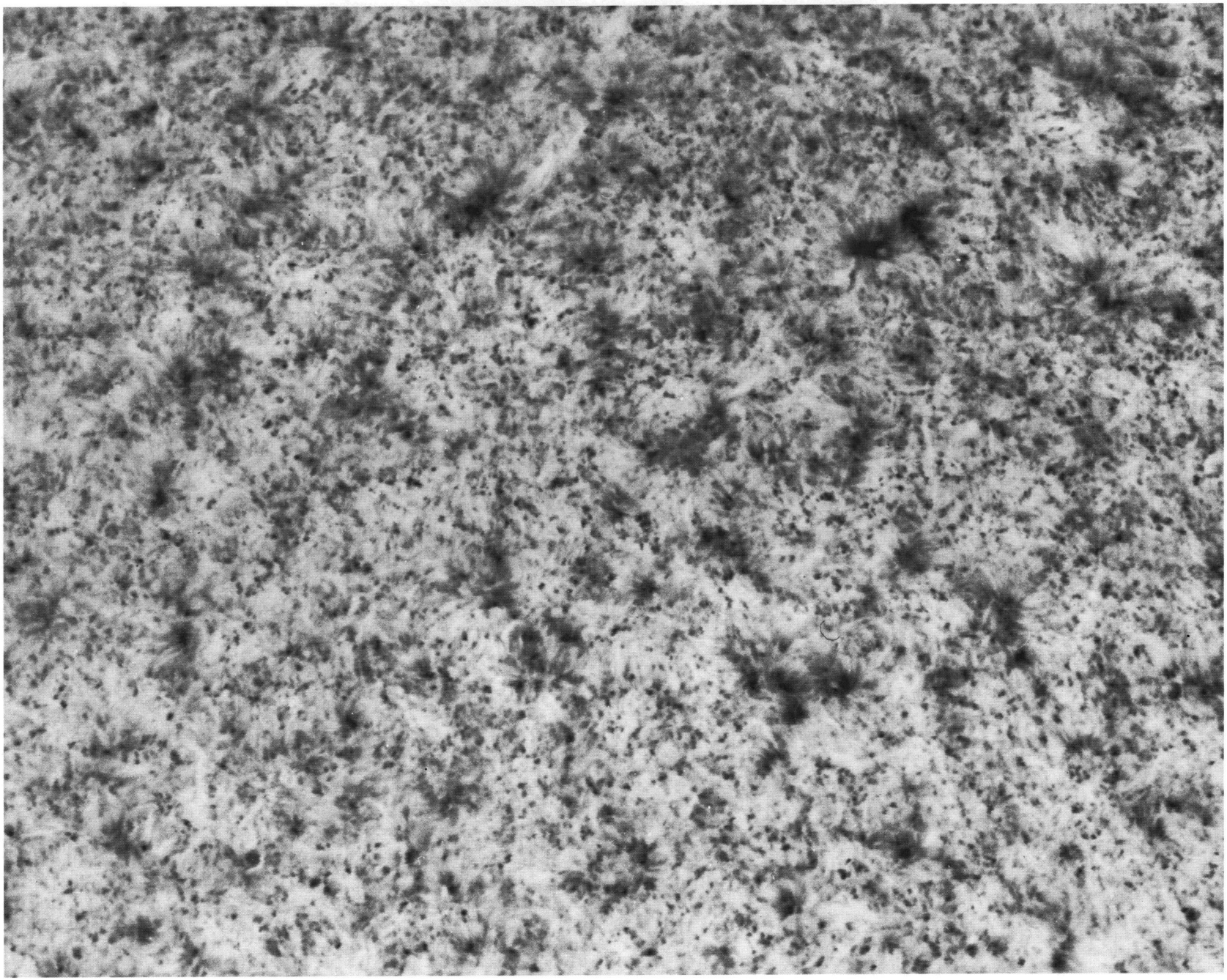

FIG. 8.—A high-resolution Ca II K_{2v} spectroheliogram illustrating the occurrence of K_{2v} grains over the solar surface. The field of view is centered at $\mu \sim 0.55$ and covers 5.76×7.30. (Photograph courtesy J. Harvey, KPNO.)

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from spot latitudes. If we compare Sheeley's facular counts in *each* hemisphere with the occurrence of the maximum of activity in *each* hemisphere for cycle 19 (Waldmeier 1960), we find that the number of polar faculae maximizes approximately 2 yr after maximum activity, a value in better agreement with Howard and Labonte (1981) than Sheeley. Sheeley presents only global sunspot numbers so that it is possible that his results are affected by the fact that maximum activity can occur at different times in the N and S hemispheres. We note further that the Greenwich total sunspot-latitude facular area (Brown and Evans 1980) peaks 3 yr after *global* spot maximum for cycle 19. This further illustrates the problems associated with the use of global spot numbers as a measure of the phase of erupted magnetic fields. In citing polar faculae as evidence for an intermixing active network, we are supposing that they are not due to local sources, e.g., ephemeral active regions.

The polar facular observation is in apparent conflict with direct longitudinal magnetic field measurements. Labonte and Howard (1982) present evidence that the *absolute* magnetic flux (sum of absolute values) in an element of area similar in size to that of the SSF sample at latitudes $\pm 58°$ shows *no* secular trend, although episodic intrusions of low-latitude fields appear (Howard and Labonte 1981). We note, however, that a selection effect is present in the data since Labonte and Howard observed only the *quietest* regions. This criterion would avoid regions with active network. We also note that the Mount Wilson observations were made with a resolution window of either 17″.5 (pre-1975) or 12″.5 (post-1975). This is sufficiently large that any intermixing of network scale fields of opposite polarity (cf. Howard 1965) would cancel and not contribute to the observed flux. This is not true of the K or white-light emission signature of these features, which is independent of sign, so that both polarities would contribute to the radiant flux integral. Hence a mixing of preceding-cycle and current-cycle polarities or of leading and following polarities would contribute to a photometric flux but not to a magnetic flux signal.

That both effects may be present in the Labonte and Howard data is suggested by the magnitude of the absolute flux measured at the disk center. In terms of mean absolute field, they find $\langle |B| \rangle = 1.8$ G. Higher resolution data yield 10.8 G (SSF); cf. also Tarbell, Title, and Schoolman 1979). Even if one allows for possible Zeeman saturation effects (Frazier and Stenflo 1972), the Labonte and Howard field would be only 3.3 G and would imply that the selection of overly quiet regions biased the data.[4] We note that a recent test of polarity intermixing reported by J. Harvey (private communication) suggests that this effect may be minimal. If a comparison is made of the disk integral absolute magnetic flux derived from KPNO magnetograph data obtained during solar cycle minimum(maximum) with a 20″ and a 2″ sampling area, one finds that the flux increase at 2″ is no more than 30%(12%). The flux difference was essentially constant from minimum to maximum! We must note further that the situation is somewhat confused since there appears to be a factor of 10 difference in the magnitude of the absolute flux between the KPNO and Mount Wilson data. We conclude that the absence of a secular, or active-network, trend in the Labonte and Howard data is understandable and does not rule out the presence of an active-network component.

[4] Note that these values do not take into account the fractional network coverage, f_N^0.

Further evidence for the need of an active-network component comes from the study of solar variability in the ultraviolet. Vidal-Madjar (1977) found that he had to include a slowly varying *third* component in his modeling of the Lyman-alpha flux history. Lean and Skumanich (1983) identified this as the active-network component and showed that using the present 3c model, an improved fit to the data resulted. In addition, Lean *et al.* (1982) showed that the *Atmosphere Explorer–E* observations made by the Air Force Geophysics Laboratory (Hinteregger, Fukui, and Gilson 1981) which viewed a $22° \pm B_0$ latitude window about the solar equator was best fit with the quiet-Sun mix of cell and network *and* the active-network fraction as modeled by equation (8).

A more systematic sensitivity and/or error analysis than that found above is not warranted at this time. We note, however, that the K1.0 analysis is more sensitive than that of K_3 to changes in the values of the mean network intensities (or contrasts). That both K1.0 and K_3 observables yield similar f_1 values demonstrate the consistency of the contrasts used. This is verified by the fact that the observed K_3 and K1.0 parameters (Table 1) satisfy the White and Livingston cross-correlation relations (after correction for limb darkening).

V. SUMMARY

We find that we can fit the observed Ca II K emission flux from the quiet Sun at solar cycle minimum with extant resolution-consistent contrast and fractional area parameters for *cell* and magnetic *network* features with extant darkening laws. The eruption of new magnetic flux with the advance of the solar cycle introduces a third component, *plage*, that must be included in the K flux signal. The breakup of plages, along with spots, supplies additional network features, called active network, which, by conservation of magnetic flux, are dependent upon the observed plage area. We assume a smoothed linear relation to derive a three-component (3c)

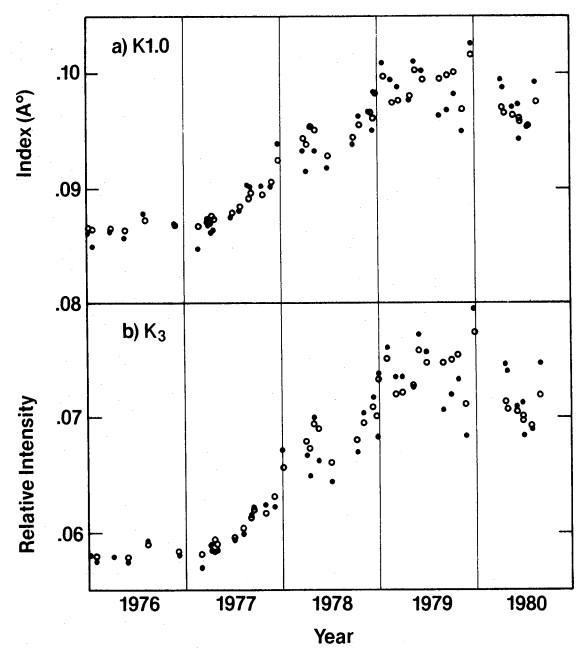

FIG. 9.—Comparison of the three-component model (*open circles*) with the observed full-disk data (*filled circles*) for (*a*) K1.0 index and (*b*) K_3 relative intensity.

model of chromospheric activity variation over the solar cycle. In Figure 9 the resultant 3c model fit to the White and Livingston data for the K_3 and K1.0 observables is illustrated. The standard deviations of the fit for the K1.0, K0.5, and K_3 observables are 8.1×10^{-3} Å, 4.6×10^{-3} Å, and 1.6×10^{-3} Å, respectively, or, corrected for wavelength bandwidth, 8.1×10^{-3}, 9.2×10^{-3}, and 1.6×10^{-3}. These latter values are directly comparable and include not only model errors, e.g., in observed plage areas, but also intrinsic solar fluctuations (refer to § IV). It is not clear to us why the K_3 analysis yields a better fit, although, as we noted in § IV, it is the least sensitive of the observables to model errors. It is also possible that K_3 is least influenced by transient solar processes. Our 3c model should prove useful for the study of the solar-stellar connection as well as for treating the cycle variability of other chromospheric emissions.

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