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CHROMOSPHERIC Ca II K-LINE VARIATIONS IN THE SUN AS A STAR OVER A SOLAR CYCLE

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ABSTRACT

The disk-averaged Ca II K profiles obtained at the Kodaikanal solar tower telescope for the period 1969–1984 are used to study the chromospheric variations in the Sun as a star. The 1A index shows an increase of 18% and 28% during the 20th and 21st cycles, respectively. The corresponding enhancements in the central intensity in the K line are 24% and 40%, respectively. The other K-line parameters, such as the intensity of K_2 emission, K-line widths, and the V/R asymmetry, all show systematic variations over the solar cycle. Although the plage seems to be responsible for almost all the variations noticed, the participation of the bright points and the network may have to be taken into consideration to account fully for all the solar cycle–related changes.

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

I. INTRODUCTION

The H and K lines of ionized calcium have been recognized as useful indicators for identifying regions of chromospheric activity on the solar surface since the time when Hale and Ellerman (1903) and Deslandres (1910) first observed the bright reversals in these lines. The apparently simple relation between the line widths of the self-reversed emission peaks in the H and K lines and the luminosity discovered by Wilson and Bappu (1957) for many late type stars, including the Sun, opened up the possibility of using these lines as a reliable diagnostic to probe the chromospheric structure and activity of Sun-like stars. This involves relating the stellar H and K emission measurements with both the spatially resolved and the whole-disk measurements of the Sun. An essential prerequisite to this step is a clear understanding of the long-term variability of the chromospheric behavior of the Sun. Bumba and Topolova (1967), from a plot of the intensity estimates of the violet and red emission peaks of the K line for one solar rotation, demonstrated first that the emission output from the calcium ions would serve as an index of the variability expected in the integrated sunlight. Prompted by this, the late M. K. Vainu Bappu and one of the authors (K. R. S) in 1969 started an observing program at Kodaikanal to monitor the emission output from the solar chromosphere using the K line when the Sun is viewed as a star. Our observations of K spectra now cover well over one solar cycle. Many observers contributed to this program with the intention of ensuring an uninterrupted collection to the extent possible. But, because of unforeseen difficulties and conflicting priorities on the telescope time, there was a minor setback in the tempo of observations around 1970–1973. Since 1973, the observations have been numerous and well distributed.

The integrated sunlight in the Ca II K line displays an emission. The identifiable contributors to this emission are the quiet network, the bright points, the truly quiet chromosphere, the active network, and the plage. The quiet network is an aggregate of mottles, both resolved and unresolved, which gives the network enhanced intensity and a clumpiness of form and encloses the bright points as well as the unresolved truly quiet chromosphere. The bright points, the unresolved quiet chromosphere, and the network form the "quiet" chromosphere component (Skumanich *et al.* 1984). Observations show that active regions fragment in the final stages of their evolution and disperse by a random-walk process, and ultimately mix with the quiet network elements to form the active network component that considerably enhances the emission from the network. The last-named contributor, the plage, is strikingly bright on the solar surface because of the excess emission. During the peak of solar activity plages occupy about 10% of the solar surface. Although this is only a fraction of the area occupied by all the network elements put together, because of the higher intensity contrast of the plages, their contribution to the integrated flux is very large compared with those of the remaining contributors. The area occupied by the plages over the visible solar surface varies in time and exhibits modulation of two different time scales. The first one is the 27 day modulation caused by solar rotation (Bappu and Sivaraman 1971), and the second one is the well-known 11 year cycle modulation (Kuriyan 1967).

White and Livingston (1981) studied the behavior of the Sun in the Ca II K line, both over the whole disk and over a region 1′ × 3′ sampled around the disk center for the years 1976–1980 that represents the ascending phase of solar cycle 21. Skumanich *et al.* (1984) analyzed the data of White and Livingston (1981) in terms of a three-component model: the "quiet" chromosphere, the plage, and the active network. They obtain a good fit for the quiet Sun Ca II K emission using the "quiet" chromosphere component, which includes the bright points and the quiet chromosphere. However, for the solar maximum they find that addition of the second component, namely, the plage, with its enhanced contrast, to the quiet chromosphere is inadequate to account for the cycle increase in emission. To bridge the gap, they introduce a third component related to solar activity, namely, the active network. Keil and Worden (1984) completed a similar K-line program at the Sacramento Peak Observatory for the period 1976–1982, which provides a comparison with the results of White and Livingston (1981). In this paper we report our results on the K-line variation derived from profiles covering a longer period, from 1969 to 1984.

II. INSTRUMENTATION AND OBSERVATIONS

The entire program of observations has been run at the solar tower telescope at Kodaikanal, essentially with the same setup, and this has provided a long data base with considerable stability and internal consistency. The first two mirrors of the coelostat, each of 60 cm diameter, located on the top of the tower, send a beam of sunlight to an identical third mirror, placed at the base of the tower. The third mirror folds the beam through a right angle and feeds the sunlight to the objective of the horizontal telescope housed in an underground tunnel. The half-degree beam just fills the 38 cm objective, which brings the light to a focus on the slit plane 36 m away. The spectrograph is of the Littrow type and employs an achromat 20 cm aperture, and 18.3 m focal length in conjunction with a Babcock grating of size 200 mm × 135 mm with 600 grooves mm^{-1}, with the blaze in the fifth order at 5000 Å. Our technique for averaging over the solar disk is to diffuse the light from the third mirror by covering it with a diffusing screen coated with white pigment. By retaining the rest of the optics without any change, we ensure no preference for any portion on the solar disk over another. The grating is used in sixth order, and with 103a-O emulsion the exposure times are ~ 150 minutes. The spectrum covers a region of ~ 30 Å centered on the K line. We also obtained integrated spectra by the technique used by Severney (1969), and there is no noticeable difference between the profiles obtained by the two methods. Also, there is good agreement of the solar spectra with spectra made on the blue sky off the Sun without the image-forming optics.

Our spectra of the integrated sunlight on 35 mm filmstrips of 103a-O emulsion were normally made at the rate of one a fortnight, and at times one a week. Large gaps in the data are inevitable, particularly during the monsoon months at Kodaikanal. We scanned these spectra in a direction parallel to the dispersion on a densitometer and derived the relative intensities via the calibration curve following the photometric reduction procedure. To increase the photometric accuracy, we made densitometer traces at three arbitrary locations on each spectrum and derived the final intensity profile, which is the mean from the three traces. We then converted these profiles to intensity units of the continuum, adopting the residual intensity at 3935.16 Å on the red wing of the K line as 13% of the continuum from the photometrically calibrated K-line profiles given by White and Suemoto (1968).

III. RESULTS AND DISCUSSION

The behavior of the K-line profiles and their changes related to the solar cycle, are emphasized by a set of simple parameters that describe the line shape. In this section, we present the behavior of these line parameters over the period 1969–1984, covering solar cycles 20 and 21. Figures 1–8 show the variation of the parameters in the disk-averaged sunlight over this period.

a) K *Emission Index*

The parameter that best quantifies the chromospheric emission in the K line is the so-called K emission index introduced by Wilson (1968). The index is the integrated intensity (or flux) over a 1 Å band centered on the K line and is proportional to the total emission from the chromosphere. The Sun viewed as a star through a 1 A passband filter centered on the K line would appear as a variable, showing both the rotational modulation and the 11 year cycle (Bappu and Sivaraman 1971). The variation of the K 1 Å index over the period of our study is shown in Figure 1. The year 1975/1976 was a period of lowest emission and can, therefore, be taken as the reference over which the excess in other years can be measured. Between 1969/1970 and 1975/1976, the globally averaged K index decreased by 18%, while in 1979/1980 the increase to solar maximum was 28%. These are averages, and the spread in the actual values is larger.

The rise from minimum to maximum epoch is steep, while the fall from the solar maximum peak to minimum is gradual and spread over a longer period of time. In the years following the solar maximum, the active regions disintegrate and are in the process of dispersal. The disintegrated elements, although much smaller in area and lower in brightness contrast compared with the plages, do contribute to the disk-averaged emission, and this makes the decline slower following solar maximum.

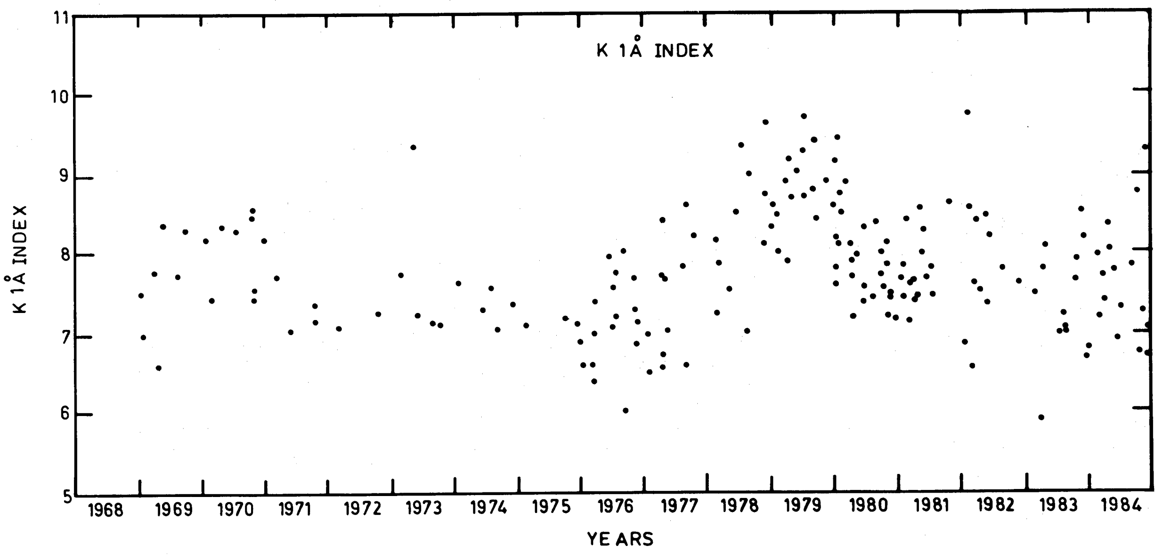

FIG. 1.—Variation of the K 1 Å index in percent of the continuum

1987ApJ...313..456S

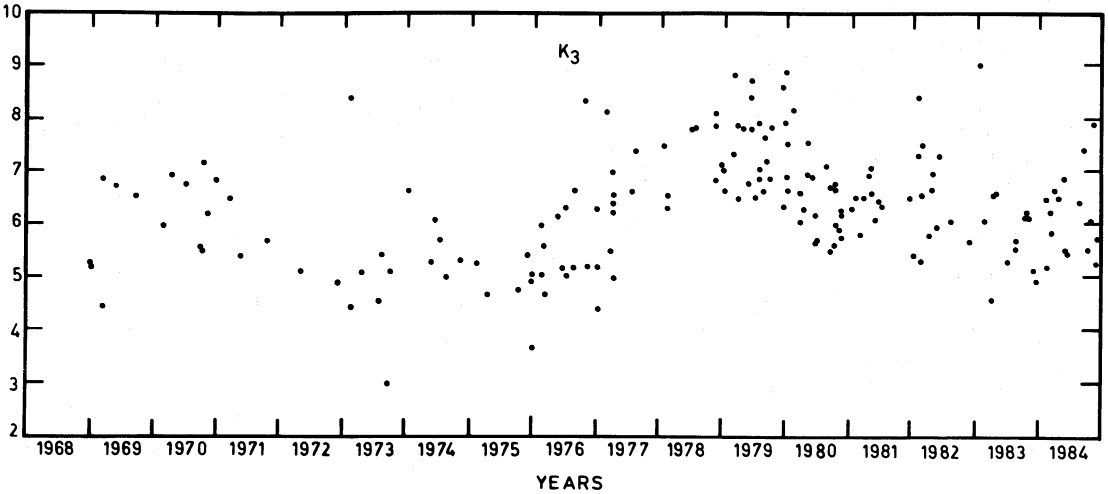

FIG. 2.—Variation of the K_3 central intensity in percent of the continuum

b) K_3 *Central Intensity*

This is defined as the residual intensity in the core, namely, K_3, and, like the 1 Å index, measures the radiative losses, but from the topmost chromospheric layers responsible for the K emission. Our mean value of the residual intensity during the minimum epoch of 1975/1976 is about 5.5% ± 0.062% of the continuum, which agrees well with the minimum value of 5.3% of Beckers, Bridges, and Gilliam (1976). We find from Figure 2 that the K_3 intensity increased by 24% during 1968/1969 and by as much as 40% during 1979 with reference to the minimum in 1975/1976.

c) K_2 *Emission Intensity*

The violet emission peak, K_{2V}, shows an increase of 29% in the 20th cycle and 36% in the 21st cycle compared with the minimum level of 1975/1976 (Fig. 3). Such enhancements in K_{2V} are not surprising considering that increases of as much as 45%–50% in the K_{2V} emission of individual bright points are quite common in time-sequence profiles (Sivaraman 1984*a*). As can be seen from our data, the global enhancement in K_{2V} emission depends on the total strength of the cycle concerned. The 20th cycle, which had the maximum activity lower than the 21st cycle (judged by the sunspot number), has a K_{2V} emission maximum also correspondingly smaller. Extrapolating back in time, we would expect that the solar maximum of 1958/1959, which was as strong as the one of 1979/1980, would also have shown a large increase in K_{2V}. If so, Sheeley's (1967) estimate of K_{2V} enhancement of 40% for this period would agree with such an expected value. It should be borne in mind that this level of enhancement is not representative for any maximum epoch, but changes from cycle to cycle, depending on the level of activity.

The ratio of the intensities K_{2V}/K_3 varies as shown in Figure 4. This ratio has the lowest value during 1969/1970 and 1979/1980, showing that the increase of K_3 is as high as K_{2V} or even more during the solar maximum. This brings out clearly the contribution of the plages, whose profiles show strong K_{2V} with equally enhanced K_3 central intensity. The influence of the plages comes about through the combined effect of their area as well as their higher contrast due to excess emission. Both the plage areas and their contrast increase substantially during periods of high activity. The result that the influence of the plage profile becomes recognizable in the disk-averaged profiles is of great advantage when examining other stars to

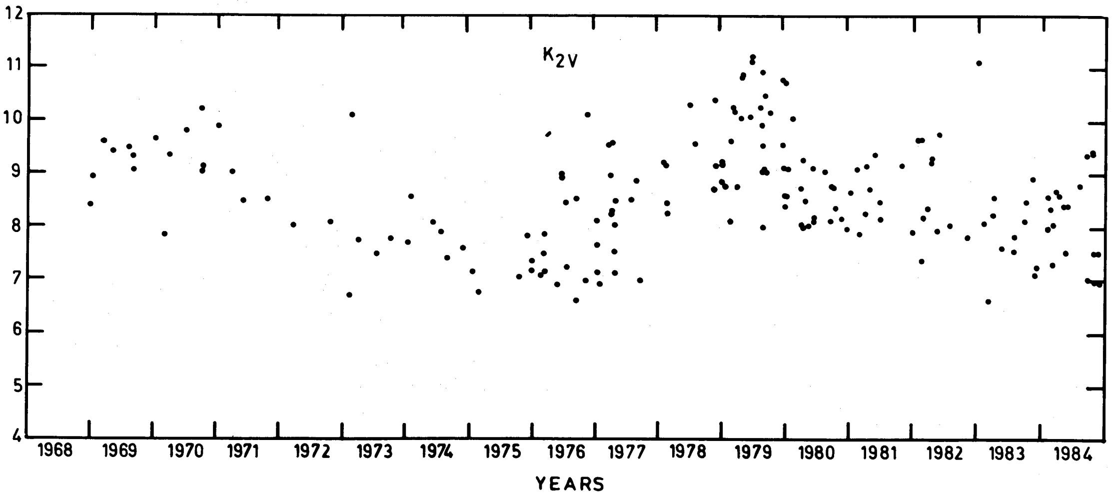

FIG. 3.—Variation of the intensity of K_{2V} in percent of the continuum

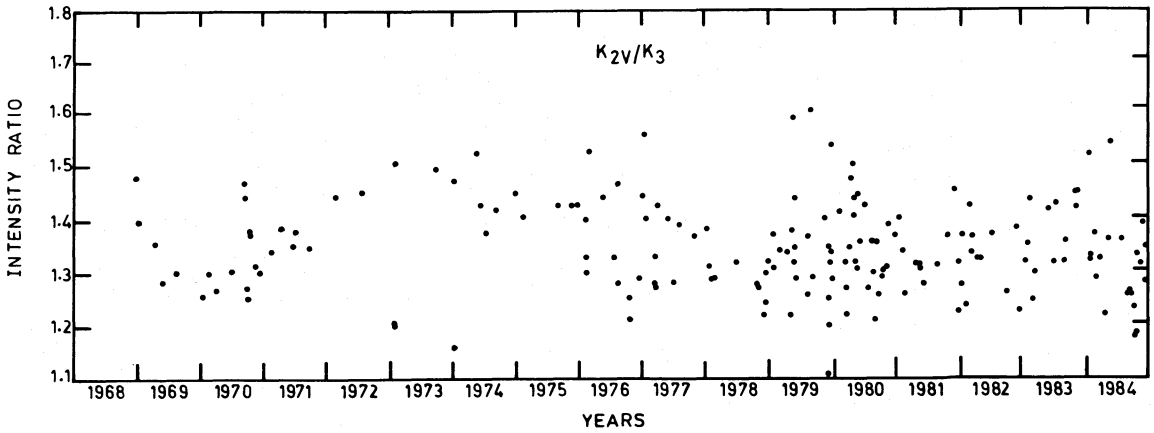

FIG. 4.—Variation of the intensity ratio K_{2V}/K_3

infer the possible existence and similar influence of the plages in their spectra.

The ratio K_{2V}/K_{2R} of the intensities of the violet and red K_2 emission peaks brings out the variation of V/R asymmetry over the cycle. This is shown in Figure 5. This ratio, which rises to ~ 1.11, shows that the asymmetry is most pronounced during the solar minimum. During the solar maximum the ratio is closer to unity (~ 1.04 both in 1969/1970 and in 1979/1980). This again brings out the influence of the plage profiles, which are characterized by a minimum asymmetry or a ratio $V/R \approx 1$.

d) *Emission-Line Width*

This is defined as the wavelength separation between the K_{2V} and K_{2R} emission peaks expressed in angstroms. This quantity, measured for all the profiles, is plotted in Figure 6. The wavelength separation is least during the solar maximum and largest during the minimum epoch, and the variation is of the order of 0.03–0.04 Å. This is another parameter that confirms the influence of the plages in determining the overall shape of the disk-averaged profile because it is consistent with the observed narrowing of the K_3 core in the spectra of plages.

e) K_1 *Width*

In Figure 7 we plot the K_1 width or the wavelength separation between the K_1 minima on either side. The variation between the maximum and minimum epochs is as high as 0.10 Å. If the K_1 minima represent the level of the temperature minimum in the solar atmosphere (Ayres, Linsky, and Shine 1975), this is an indication of cycle variation of the depth of this minimum region.

f) *Wilson-Bappu Parameter*

This is the width (or wavelength separation) at the intensity level midway between the K_2 maxima and the K_1 minima on the violet and red edges of the line. The Wilson-Bappu (W-B) width by definition is measured at the $1/e$ value of the difference between the intensity of the brighter K_2 peak over the K_1 minima reckoned from the latter level (Bappu and Sivaraman 1977). We find that the width measured at the half-intensity levels behaves in exactly the same way as the Wilson-Bappu width and have therefore used half-intensity width values in the present study. A plot of such measures is shown in Figure 8. The changes shown by this W-B parameter are in the direction opposite to the changes seen in the K_2 separation shown in

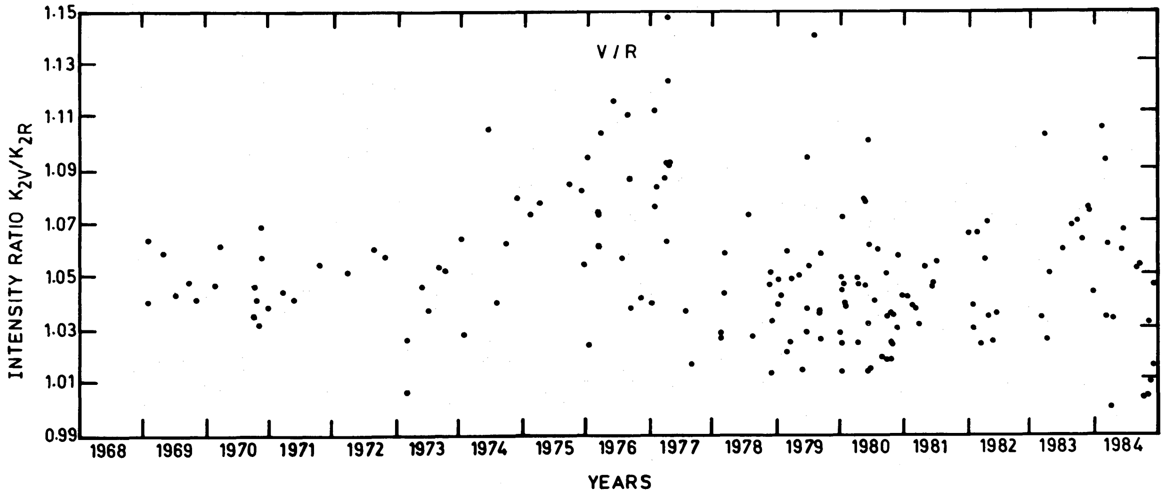

FIG. 5.—Variation of the intensity ratio K_{2V}/K_{2R} or the asymmetry parameter V/R

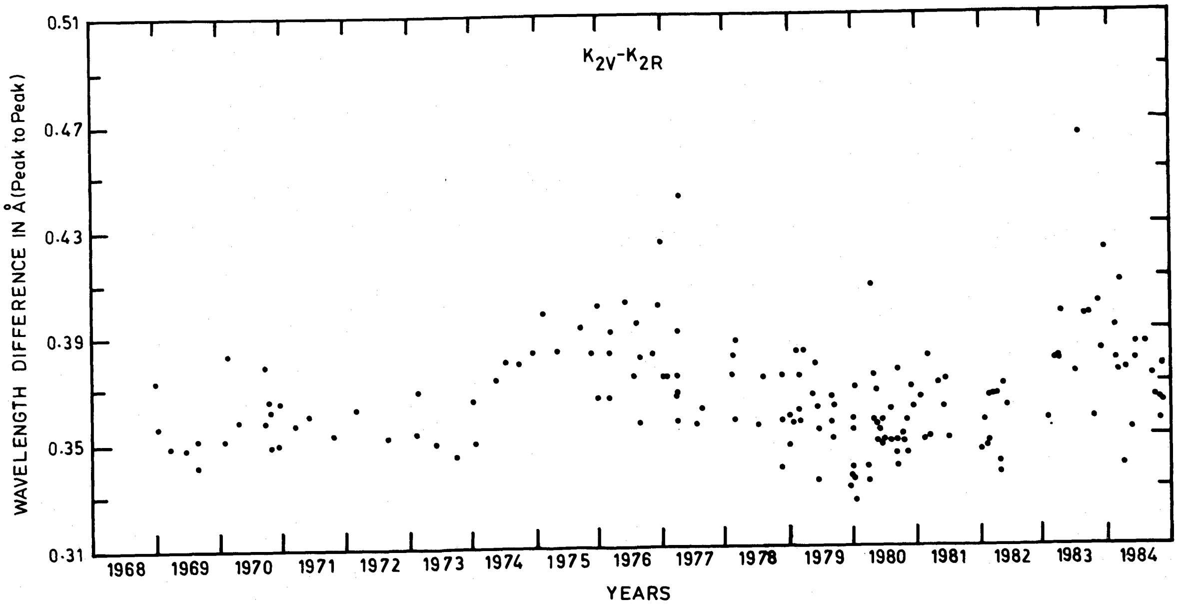

FIG. 6.—Variation of the separation between the violet and red K emission peaks (peak-to-peak width) in angstroms

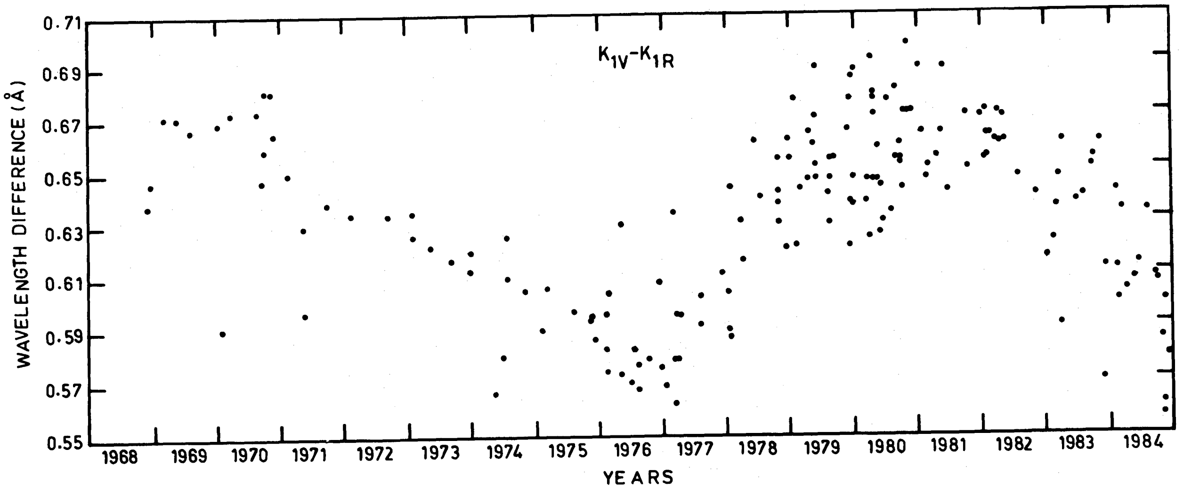

FIG. 7.—Variation of the separation between the violet and red K_1 minima (K_1 width) in angstroms

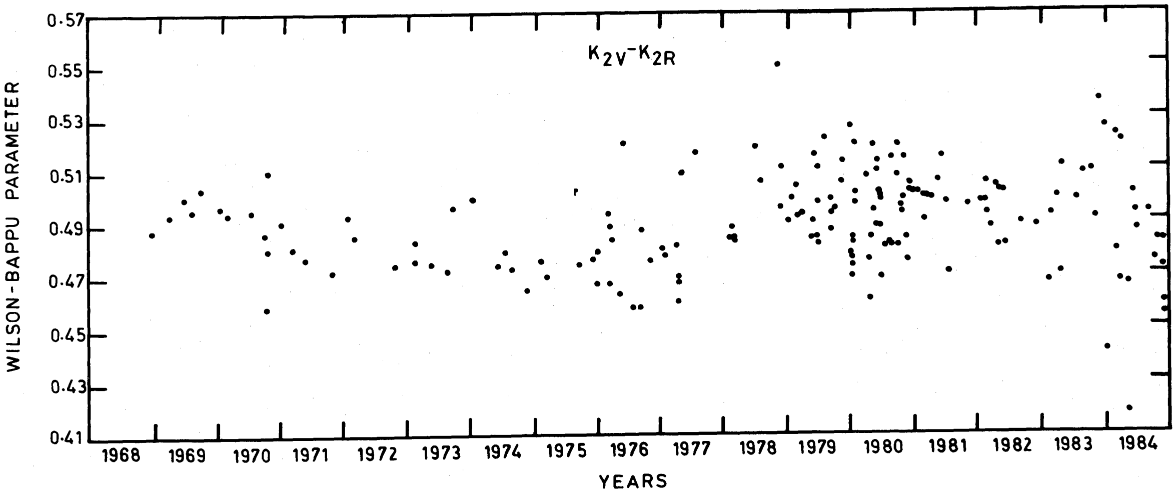

FIG. 8.—Variation of the width in angstroms at the half-intensity level (Wilson-Bappu parameter)

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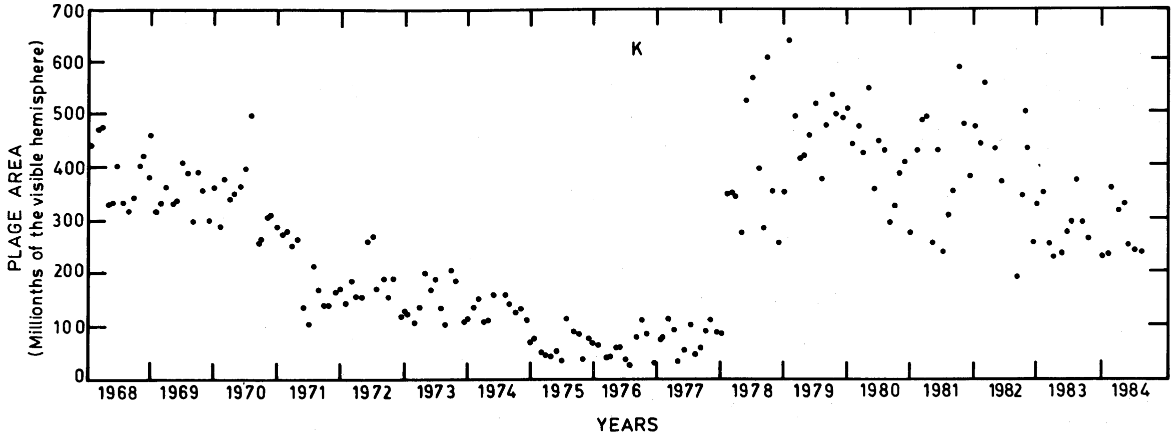

FIG. 9.—Variation of the plage area uncorrected for foreshortening, expressed in millionths of the visible hemisphere

Figure 6. The increase in the K_1 width and the decrease in the K_2 separation associated with plage profiles alters the slope of the outer edges of the K emission profiles and causes the increase in the W-B parameter during maximum. The behavior of these width parameters again demonstrates the importance of plages, i.e., plage profiles have small K_2 separation but become wider at the half-intensity levels as compared with the quiet Sun profile.

g) Plage Area

Finally, we show variation of the calcium plage area as measured daily from the K_{232} spectroheliograms at Kodaikanal. In Figure 9 we plot the monthly mean of the uncorrected plage area over the same period for which we have disk-averaged profiles, and in Table 1 we tabulate these areas. The correlations between the plage areas and each one of the quantities discussed above are obvious and have been worked out quantitatively by White and Livingston (1981), as well as by Keil and Worden (1984). Thus, the plage makes an overwhelmingly large contribution, mainly because of the increase in contrast, in explaining the difference in the disk-averaged K-line profiles observed between solar minimum and solar maximum.

However, it would be worthwhile to find out whether the other components of K emission, namely, the quiet network and the bright points, make any solar cycle–related contribution at all. Skumanich *et al.* (1984) estimate the fractional area covered by the bright points and their contrast and conclude that they cannot be important contributors to the solar flux. Sivaraman (1984*b*) finds that their number increases by 30% or more during solar maximum. Considering this, and the possible increase in their contrast, it is reasonable to expect a variation in their contribution between the minimum and maximum of the solar cycle, although this may be small but not negligible. Measurements by one of us (K. R. S.) for determining the contribution from the network elements to the K emission over the solar cycle are in progress. Once these contributions are known, it should be possible to construct synthetic profiles simulating variability in the Ca II K line that are solar cycle–related and match the observed profiles.

One of us (K. R. S.) was initiated into this study by the late Dr. M. K. Vainu Bappu and had the opportunity to share many of the latter's views on this topic, some of which have strongly influenced this paper. Dr. Bappu would have been happy to see the first phase of this study completed.

Many observers at the Kodaikanal tower telescope have spent much time and effort in collecting the data needed for

TABLE 1

MONTHLY MEANS OF CALCIUM PLAGE AREAS ON THE SUN'S SURFACE, 1969–1984[a]

Years	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1969......	314	340	361	329	336	406	388	296	389	359	299	358
1970......	287	375	339	348	362	396	494	252	267	305	310	288
1971......	273	276	199	214	133	99	211	171	138	137	163	168
1972......	143	185	156	152	256	266	167	187	154	187	116	128
1973......	123	105	130	201	167	187	130	102	204	185	107	111
1974......	136	154	110	111	156	159	158	141	123	129	111	69
1975......	78	50	44	42	52	35	114	88	84	36	75	65
1976......	63	39	41	60	56	34	22	76	110	85	30	68
1977......	79	114	91	32	53	102	48	58	89	211	190	182
1978......	349	351	344	276	522	567	398	281	603	351	255	353
1979......	639	493	412	422	458	517	380	477	539	499	488	509
1980......	442	476	426	547	331	448	431	294	326	388	408	276
1981......	428	486	499	251	433	237	308	356	588	478	383	475
1982......	442	558	617	436	369	414	223	192	347	434	256	326
1983......	351	252	229	221	269	287	368	284	257	...	...	220
1984......	225	350	307	319	242	233	228	...	...	...	...	...

[a] The areas are uncorrected for foreshortening and are in millionths of the visible hemisphere (Kodaikanal data).

this study. We express our thanks to every one of them, and especially to Messrs. P. P. Venkatachalam and M. Jayachandran. Our thanks are due to Messrs. R. Kariyappa and R. Surendranath, who helped us in reducing part of the data. We thank the referee, Dr. O. R. White, for his valuable comments and for his well-considered and helpful criticism.

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