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OBSERVED VARIABILITY IN THE FRAUNHOFER LINE SPECTRUM OF SOLAR FLUX, 1975-1980

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ABSTRACT

Over the past five years double-pass spectrometer observations of the "sun-as-a-star" have revealed significant changes in line intensities. The photospheric component has weakened linearly with time 0 to 2.3%. From a lack of correlation between these line weakenings and solar activity indicators like sunspots and plage we infer a global variation of surface properties. Model-atmosphere analysis suggests a slight reduction in the lower-photospheric temperature gradient corresponding to a 15% increase in the mixing length within the granulation layer. Chromospheric lines such as Ca II H and K, Ca II 8542 and the CN band head weaken synchronously with solar activity. Thus the behavior of photospheric and chromospheric lines is markedly different, with the possibility of secular change for the former.

INTRODUCTION

Since 1975/1976 systematic observations have been routinely made at Kitt Peak in an attempt to quantify any temporal variation in the Fraunhofer lines. The original hope was that temperature sensitive lines might provide an indication of luminosity variation, assuming $F = \sigma T^4$ (ref. 1). When line strengths are measured near disk center variations of several percent are the rule, both in time and space, owing to a hierarchy of surface inhomogeneities—the granulation, supergranulation, faculae, plage, and so on. But if we observe the whole disk at once, in "integrated light", this fine structure averages out and the variance in line equivalent widths between spectrum scans reduces to

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~0.02%. This very low noise arises because the equivalent width parameter refers to the integral of absorption across the entire line profile, and so is invariant to instrument resolution, and because equivalent width is taken relative to the local continuum and thus is invariant to the transmission fluctuations of the earth's atmosphere. In terms of the predicted change in the high excitation line of CI 5380 our sensitivity is 1 K, or 0.1% in the solar constant assuming the sun is a black body.

After 2 years of data were acquired we noted that CI 5380 was 0.6% weaker than at the beginning and, following the above, we concluded the sun had cooled 6 K (ref. 2). At that point the equivalent width values for the other lines were really inconclusive. Today, however, with 5 years of data before us, the simple picture of temperature change is no longer tenable (ref. 3). As will be shown below all photospheric lines have either weakened or remain fixed, and the degree of weakening obviously depends on other factors besides temperature.

In the sections which follow, the full data set for both photospheric and chromospheric lines is presented. A tentative explanation of photospheric line behavior emerges from a full atmospheric-model analysis The interpretation of the chromospheric Ca II H and K lines appears straightforward in terms of plage.

PHOTOSPHERIC LINES

OBSERVATIONS

All data used in this study were taken with the 13.5 m double-pass grating spectrometer of the McMath Telescope on Kitt Peak. Details of the physical instrument and reduction procedures are given elsewhere (refs. 4, 5, 6).

Table I lists the observed lines together with pertinent line parameters such as excitation potential, Zeeman sensitivity, and temperature sensitivity. Figure 1 gives examples of the run of equivalent width with time. Within the noise band a linear fit adequately represents the data up to the present. The 5 year intercept of this fit, converted to fractional change, is tabulated in the last column of table I.

What is the cause of the scatter in equivalent widths displayed in figure 1? If the scatter were solar in origin, say caused by facular line weakening which at high resolution was discovered by Chapman and Sheeley (ref. 7) then the weakening of different lines should correlate on a day-to-day basis. None is found (ref. 8). We conclude this scatter is instrumental in origin, perhaps arising from several causes such as spectrograph misalignment, grating drive screw error and atmospheric scintillation. Because these errors are all stochastic in nature, with no known secular trend, we accept the scatter as unavoidable with the present technique, but find no reason to doubt the long term changes. Note that the equivalent width of Si I 10827 has remained constant (fig. 1).

INTERPRETATION

In figure 2 we explore a number of mechanisms to explain the observations, (ref. 8). First we evoke a step change in temperature through the line-forming region but immediately find a conflict in sign between carbon and the other lines (fig. 2a). Microturbulance can affect the strength of weak lines, but proves ineffectual here (fig. 2b). Likewise Zeeman broadening alters line strength but doesn't work either (fig. 2c). The best fit between theory and observations follows from a 2.3% change in surface chemical abundance (fig. 2d) but this is considered unacceptable in principle.

Having disposed of the more simple possibilities we turn to the fact that our various lines are formed at differing levels in an atmosphere which possesses a temperature gradient. As shown by the respective contribution functions, C 5380 is formed low, Fe 5250 high, while Si 10827 is common to both regions (fig. 3). The positive thermal response of the carbon line can be combined with the negative response of the iron lines (table I) if we introduce a cooling of the low photosphere while heating up the higher layers. This can be accomplished by a change in the ratio of mixing length to pressure scale height ℓ/H from 2 to 2.3 (fig. 4). This initial value of $\ell/H=2$ is in accord with the recent evolutionary calculations for the sun by Mazzitelli. If we assume this 15% change in ℓ/H is confined to the granulation layer, the luminosity effect is negligible (ref. 9).

CHROMOSPHERIC LINES

OBSERVATIONS

Figure 5 displays the essence of the variation seen in the calcium K profile, which occurs in the line core primarily, if not wholly, and arises from the contribution of plage over the visible disk. As described elsewhere (ref. 6), we measure both the central intensity of the line (K_3 intensity) but also, for comparison with stellar observers, the 1 A equivalent width (K-index). The temporal behavior of K_3-intensity and K-index are essentially the same, figure 6, except the modulation of the K-index somewhat less than the former. The proof that the Ca K-line variation is due to chromospheric plage is given by the correlation of K_3-intensity with Mt. Wilson plage area index, figure 7. Similar results are found for Ca II 8542, and CN 3883, although the correlation coefficient is less (ref. 10).

CONCLUDING REMARKS

We have seen that over our 5 year time base photospheric lines have weakened linearly with time while chromospheric indicators mimic the activity cycle. Remaining unanswered are the following questions:

1. Is the photospheric variation truly global, or does it reflect unresolved elements of solar activity (faculae, for instance)?

2. Is the time scale of the photospheric variation tied to the (22 y) solar cycle or is it evidence of some secular change of unknown duration?

3. In effect we are observing a change in line-blanketing. Will this affect solar irradiance?

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TABLE I. PHOTOSPHERIC LINE PARAMETERS AND OBSERVED 5-YEAR CHANGE

	Wavelength (A)	Equivalent Width W (mA)	EP (eV)	Landé g	$\Delta W/W$* K^{-1} (%)	$\Delta W/W$** obs. (%)
Fe I	5249.1	42.	4.5	0.9	-0.07	-0.45
Fe I	5250.2	74.	0.1	3.0	-0.09	-0.50
Fe I	5250.6	108.	2.2	1.5	-0.05	-0.17
Fe I	5379.6	62.	3.7	1.0	-0.05	-0.60
C I	5380.3	22.	7.7	1.0	+0.12	-2.30
Ti II	5381.0	65.	1.6	0.9	-0.00	-0.71
Si I	10827.1	423.	4.9	1.5	-0.04	0.00

* Predicted from HSRA model

** Total change over 5 years

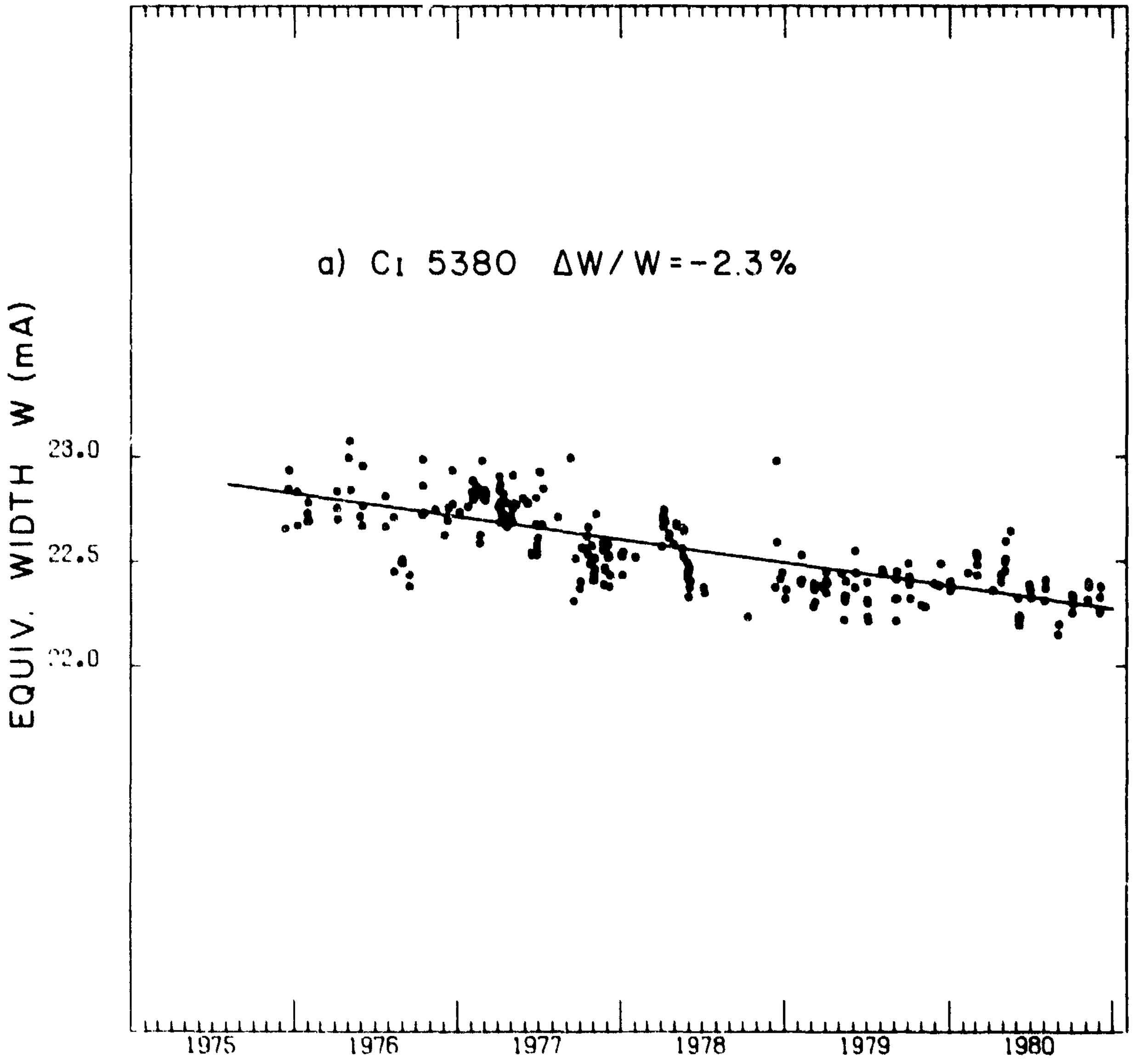

Figure 1a. Observed equivalent width in mA over 4-5 year time span: CI 5380

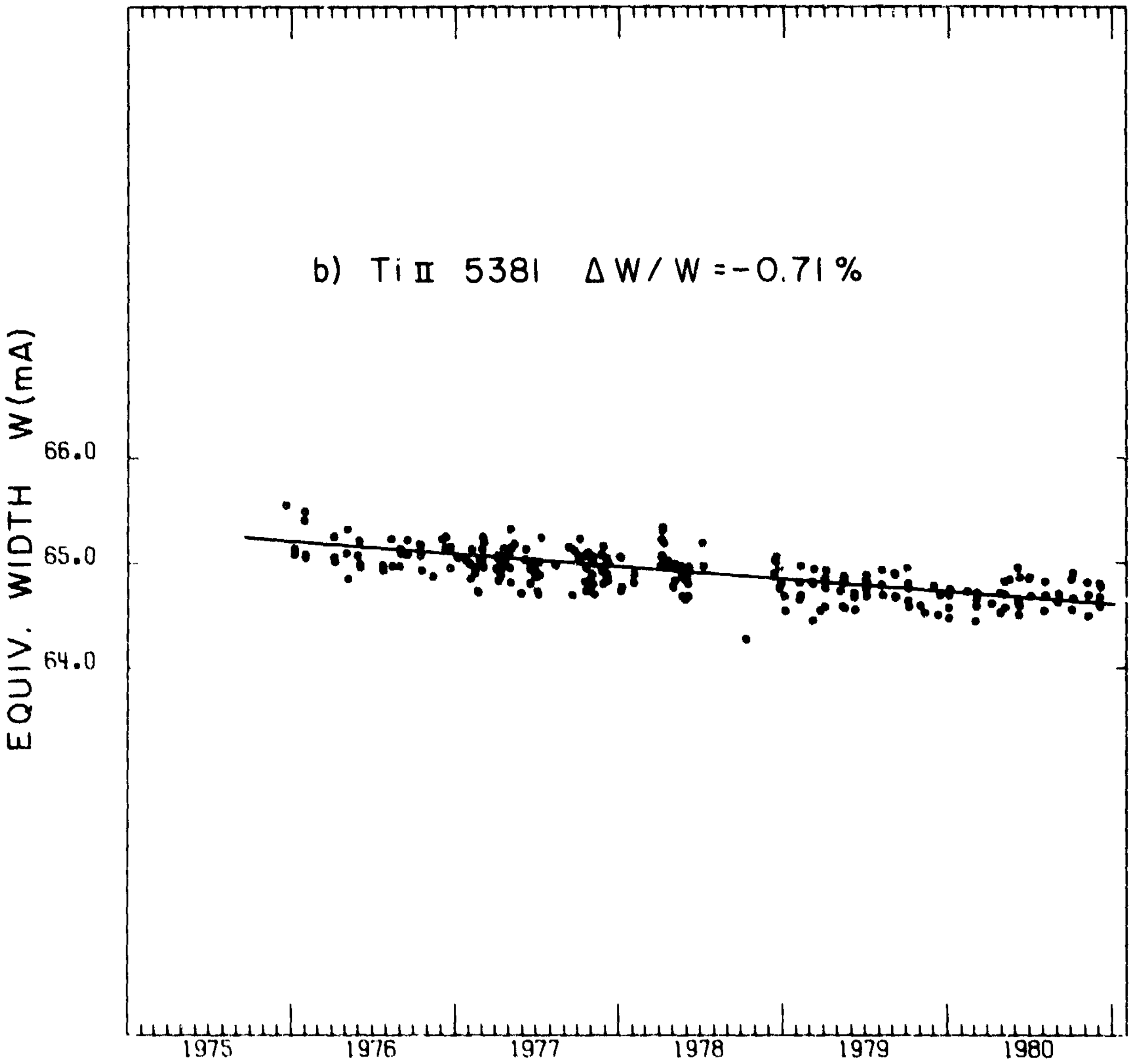

Figure 1b. Observed equivalent width in mA over 4-5 year time span: Ti II 5381

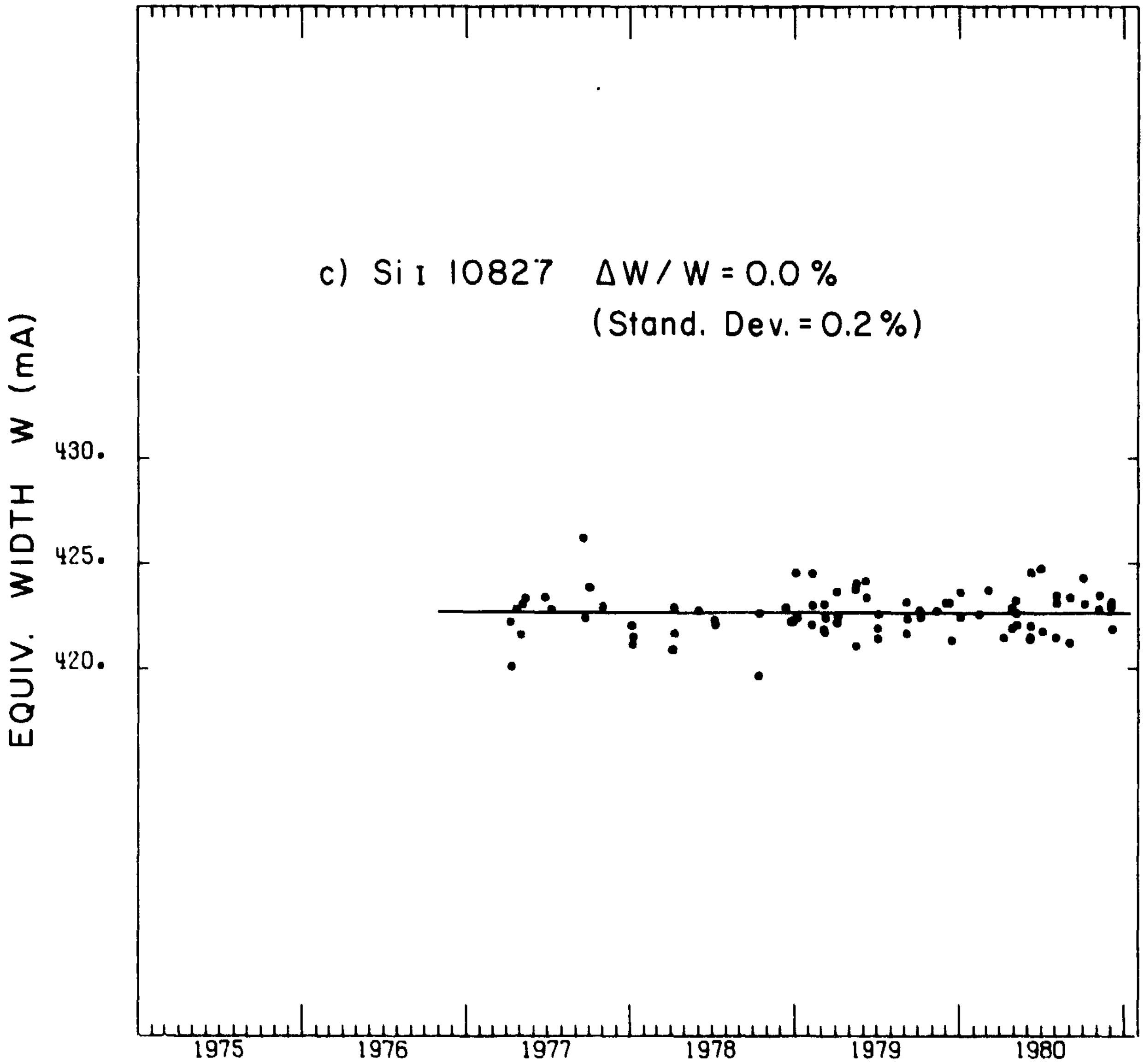

Figure 1c. Observed equivalent width in mA over 4-5 year time span: Si I 10827

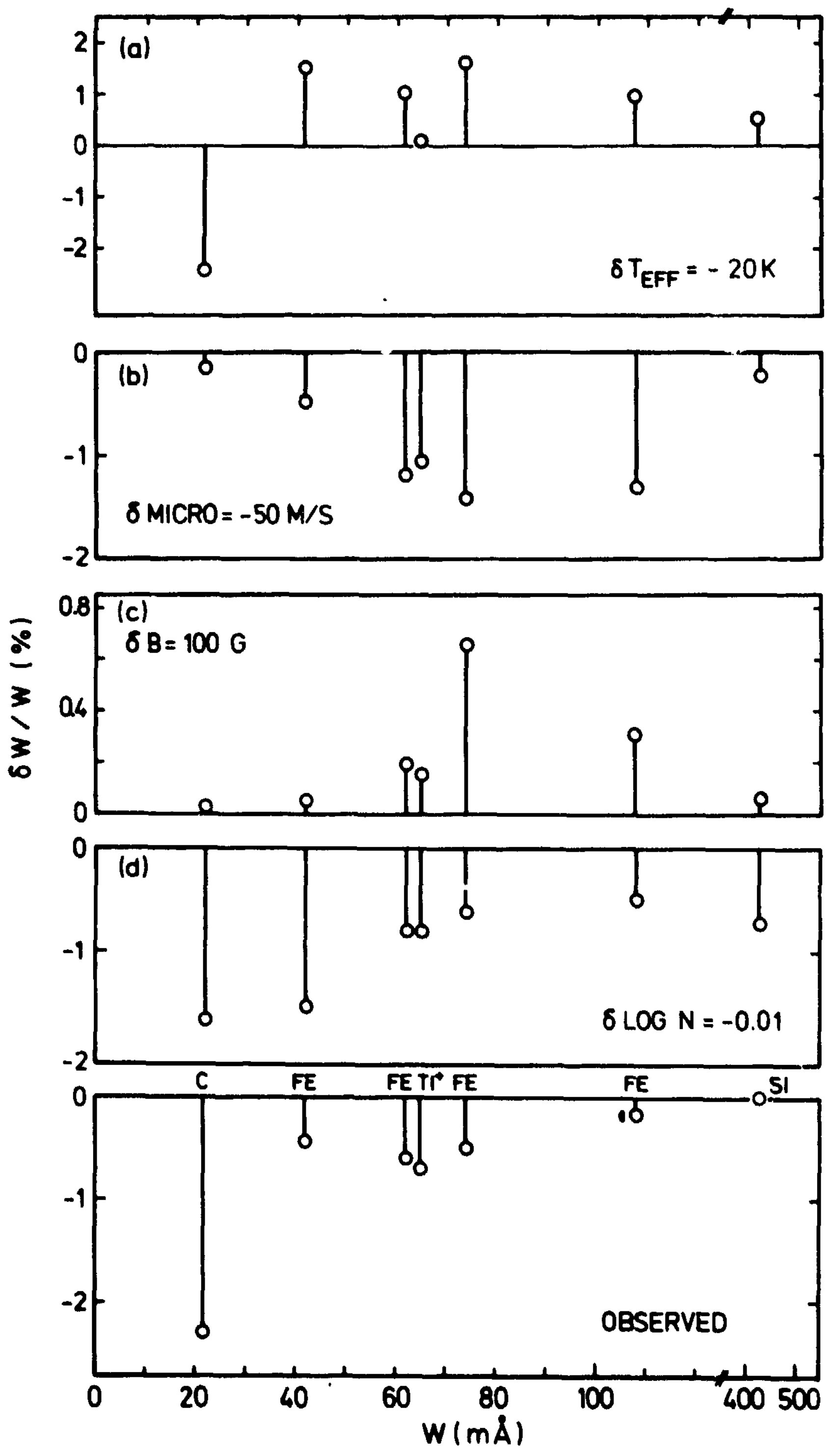

Figure 2. Predicted ΔW/W (%) compared with observed ΔW/W (%) for differing mechanisms: a) a step change of temperature, b) a change of microturbulence, c) introduction of a 100-gauss uniform magnetic field, and d) a 2.3% reduction in the abundance of observed species, and (bottom) the observations.

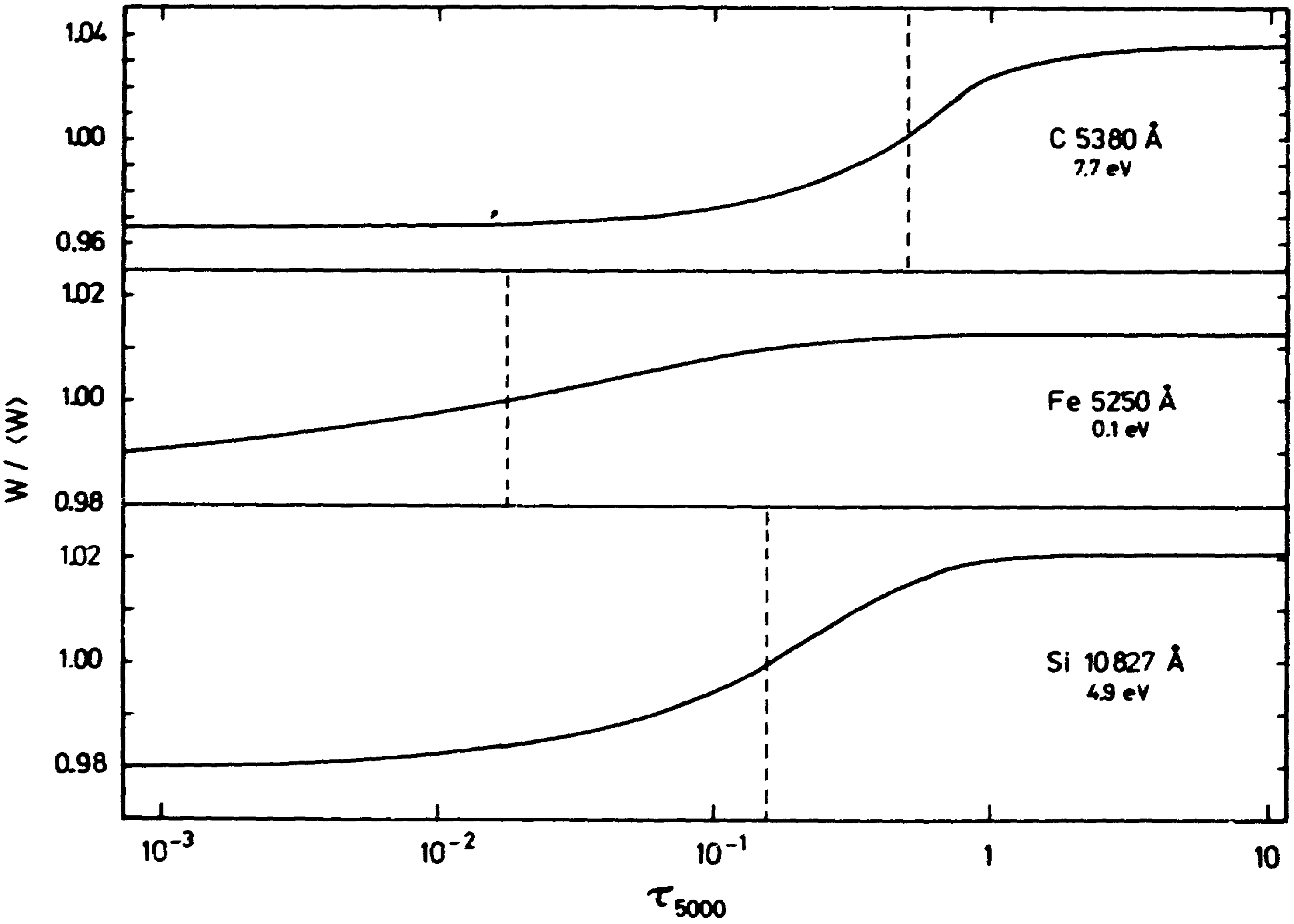

Figure 3. Contribution functions for the carbon, iron and silicon lines

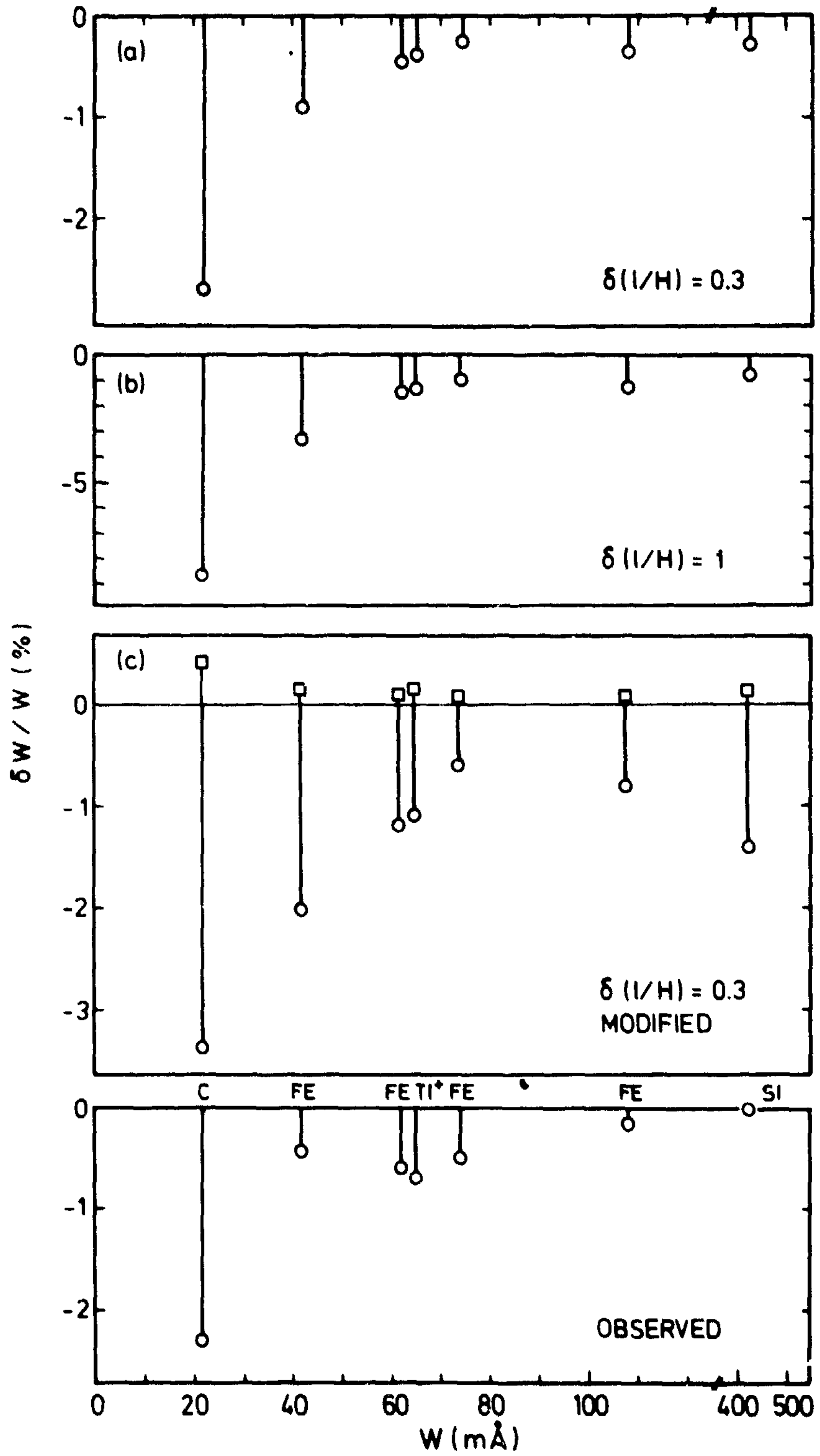

Figure 4. Equivalent width change in percent due to an increase of l/H a) from 2.0 to 2.3, b) 2 to 3, c) same as (a) but corresponding $\Delta T(\tau_{5000})$ shifted on τ scale by factor of two towards larger (squares), or smaller (circles) depths

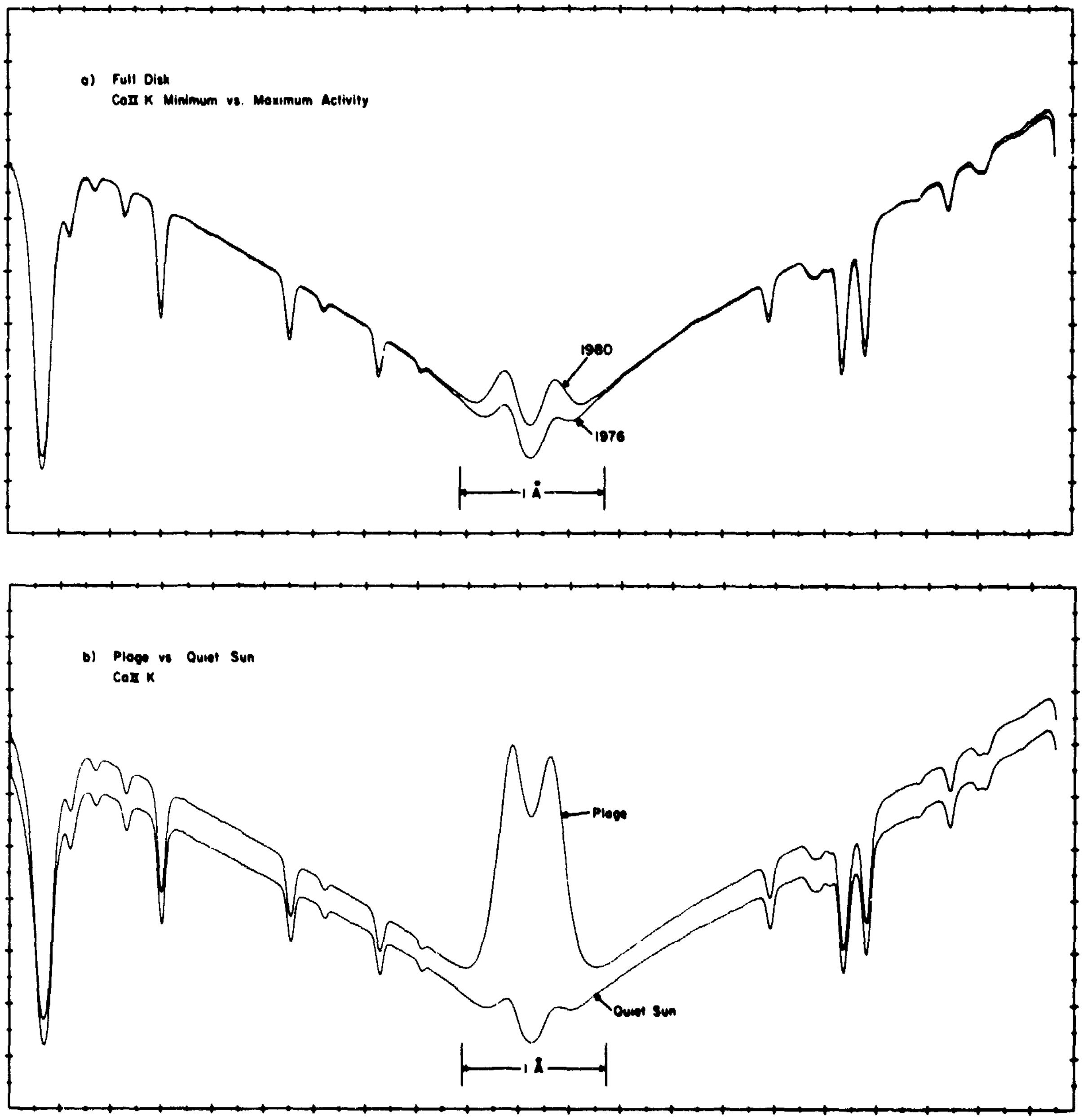

Figure 5. The variability of calcium K profiles: a) full disk K at minimum and maximum superposed and b) average profiles for an active region (plage) and a nearby quiet region at the same limb distance.

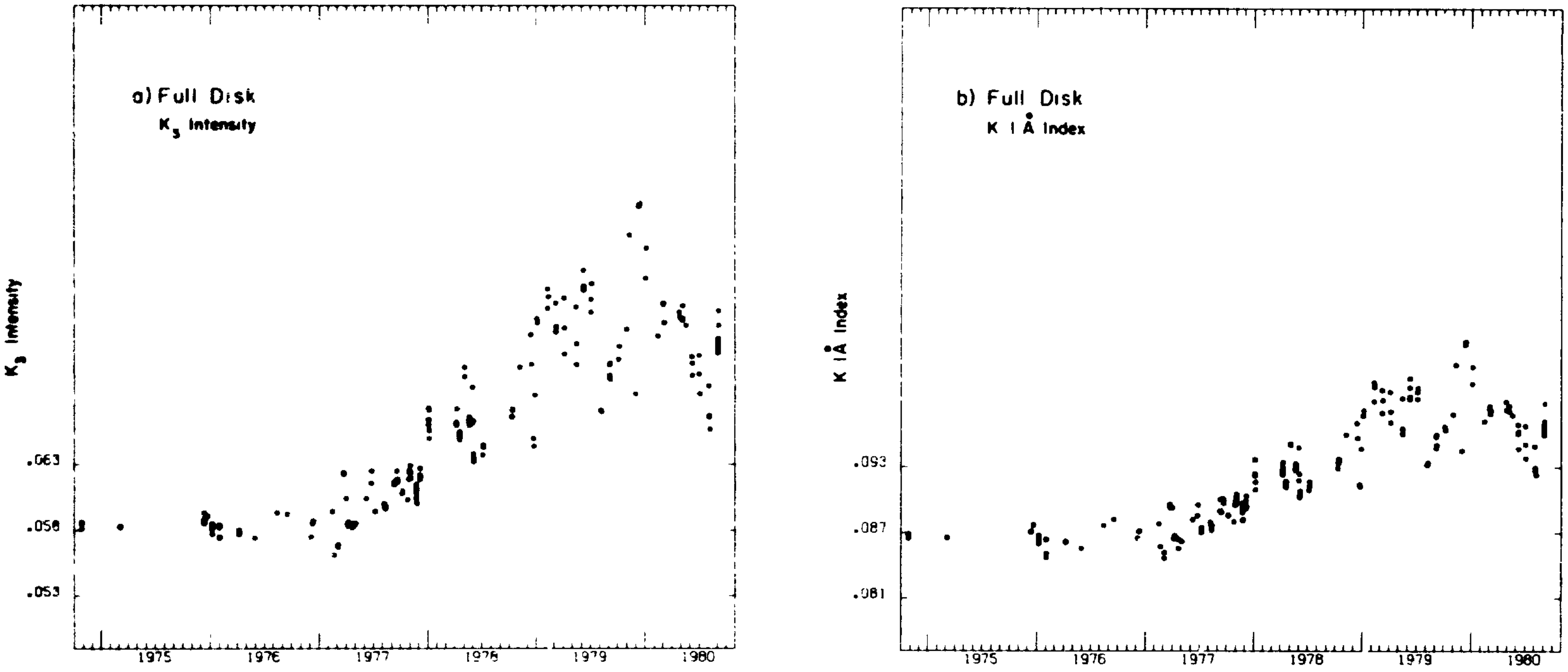

Figure 6. The cycle variation for K parameters: a) full disk K_3-intensity and b) full disk 1A K-index

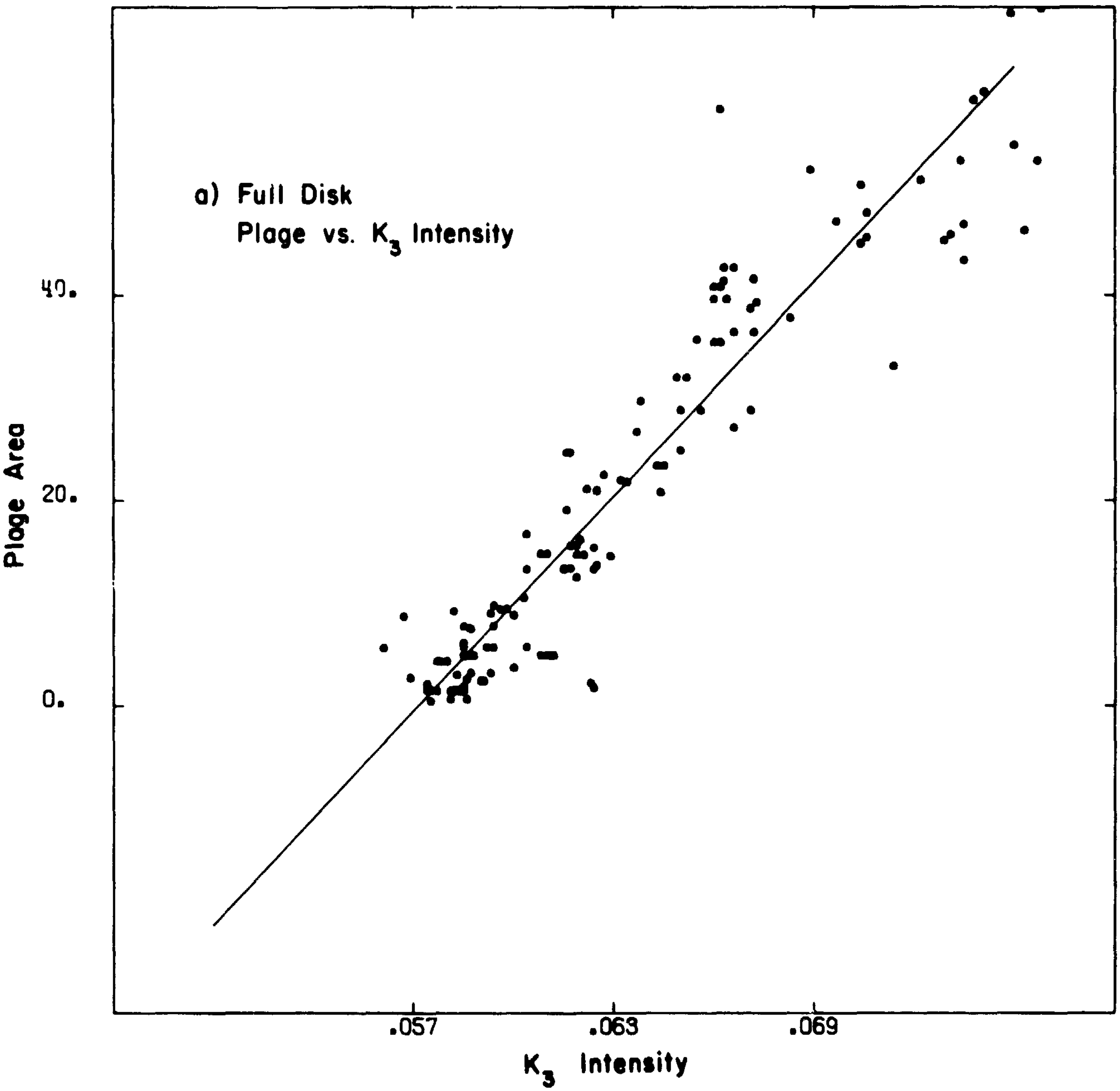

Figure 7. Correlation between K_3-intensity and the Mt. Wilson plage area index