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MONITORING THE SOLAR TEMPERATURE: SPECTROSCOPIC TEMPERATURE VARIATIONS OF THE SUN

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ABSTRACT

The C I λ5380 line in the solar flux spectrum was measured over the 1978–1992 interval. Analysis of the data shows seasonal and instrumental effects, but after allowance for these, the ratios of spectral line depths, C I λ5380 to Fe I λ5379 and to Ti II λ5381, are shown to be robust indicators of effective temperature. These data show the solar temperature to have varied systematically during the activity cycle and nearly in phase with other indicators of the cycle. The amplitude of the variation is 1.5 K $\pm$ 0.2 K, similar to but slightly less than the range implied by the variations of the sunspot-corrected irradiance. There is also evidence for a secular trend amounting to $\approx +0.014$ K per year.

Subject headings: Sun: activity — Sun: fundamental parameters

1. INTRODUCTION

The role of the Sun in climate change and the nature of the variations occurring in the Sun during its activity cycle form the backdrop of this study. Variations in the solar power reaching Earth (irradiance) raise the basic possibility of solar influence on terrestrial climate (Fröhlich et al. 1991; Pap et al. 1994a, 1994b). The remarkable correlation between the length of the solar cycle and Earth temperature (Friis-Christensen & Lassen 1991) is further evidence in this direction. Changes of solar irradiance might originate from at least three causes: (1) the effective temperature of the Sun might be changing (for example, through a changing distribution of faculae, and plage); (2) the size of the Sun might be changing (Ulrich & Bertello 1995); or (3) there might be a variation in irradiance with solar latitude, and this latitude dependence might change with phase in the solar cycle (Kuhn 1988, 1989). Studies of variations in temperature and related parameters for other solar-like stars have shown effective temperature to be the likely dominant variable (Gray et al. 1992, 1996a, 1966b; Gray & Baliunas 1995). But spectroscopic measurement of any variation in the solar temperature has proved to be elusive. Even in well–thought-out monitoring programs, results have been ambiguous, and we show below some of the problems that can arise.

In this paper, we analyze 14 years of spectroscopic data designed to monitor the Sun over activity cycle timescales. The weak line of neutral carbon at 5380 Å was chosen for this purpose. It has an equivalent width of some 22 mÅ, it is formed deep in the photosphere, coincident with the continuum-forming layers, and it is expected to be free of the changing effects of faculae and plage (Hill, Livingston, & Caudell 1977; Livingston & Steffen 1988). Direct observational evidence of its deep formation comes from the fact that the line diminishes and almost vanishes at the solar limb. In a previous paper (Gray & Livingston 1997), we looked into using the ratio of C I λ5380 to the adjacent lines, Fe I λ5379 and Ti II λ5381, as solar thermometers. Specifically, the ratios of the central depths of spectral lines proved to be more useful than other line parameters in delineating temperature changes in stars similar to the Sun (Gray 1994b, and references already noted above). For example, line depths turn out to be more dependable and to have smaller errors than the equivalent widths. Depths, as opposed to residual fluxes, hold certain advantages in dealing with scattered light, as shown below. We calibrated the temperature sensitivity of the line-depth ratios using a set of solar-like stars. The calibration stars were chosen to be similar to the Sun in surface gravity and effective temperature, spanning about $\approx$300 K around the solar value. The carbon line grows with increasing temperature, the iron line declines, and the titanium line is nearly constant. If we denote the change in line depth ratio by δr, the corresponding variation in temperature was found to be

$$\delta T = C_0 \frac{\delta r}{r}, \quad (1)$$

where $C_0 = 346$ for the C I/Fe I ratio and 468 for the C I/Ti II ratio. The first ratio is 1.4 times more sensitive than the second; that is, a given solar temperature change will produce a 1.4 times larger variation in the first ratio. Using expected observational errors, we estimated that we should be able to detect variations of a fraction of 1 K.

We discuss first the observations and the line depth measurements. Then we systematically consider several variations seen in the data, some caused by instrumental effects and some caused by solar variations.

2. THE OBSERVATIONS

Our observations with the 13.5 m double-pass spectrometer at the McMath-Pierce telescope on Kitt Peak began in the late 1970s. To obtain disk-integrated sunlight, a flat mirror was substituted for the normal concave focusing mirror of the telescope. The beam from this mirror was directed to the 0.5 mm wide entrance slit of the spectrograph, and this aperture acted as a pinhole camera, imaging the Sun on the grating. The double-pass feature is designed to eliminated scattered light and assure a good zero-level determination. Data were usually collected on 3–4 days near the beginning of each month. A single record consists

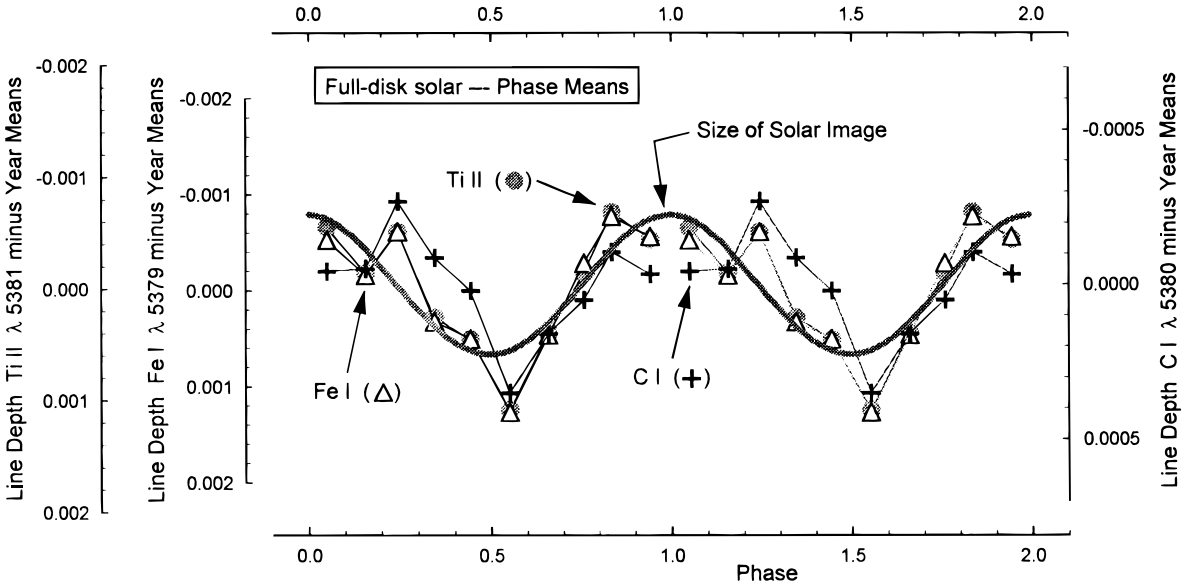


FIG. 1.—Means of line depths are shown phased to the tropical year to reveal seasonal variations. They are compared to the apparent angular size of the solar disk, which changes because of the 0.017 orbital eccentricity of the Earth's orbit. Ordinates have been scaled arbitrarily to obtain similar amplitudes for all three line depths.

of 52 rapid scans across ≈ 4 Å, and typically six of these records are averaged to form a day's observation. The whole series, from 1978 July 6 to 1992 September 4, consists of 553 days of data. During this time, there were no changes in the equipment, i.e., the telescope, spectrometer, grating, detector, filter, or slits.

Scintillation noise on a single record is about 0.1%; photon noise in the continuum is 4 times smaller. Day-to-day observations, however, show somewhat larger variation. We do not know the source of this excess scatter, but it could be related to nonuniformity in scanning, or possibly the variations in scattered light postulated in § 5 below.

3. MEASUREMENTS OF SPECTRAL LINES

Line depths and equivalent widths were measured relative to a quadratic polynomial put through the three high points within the scan window. There is no perfect continuum, and all lines are blended to some degree. But for our task of determining variations in temperature, consistency is what is needed. Especially important are ubiquitous water vapor blends. The total column amount of water vapor was measured each day of the observing runs using a calibrated water line at 10832.2 Å, and appropriate corrections were applied. The improvement in the data following

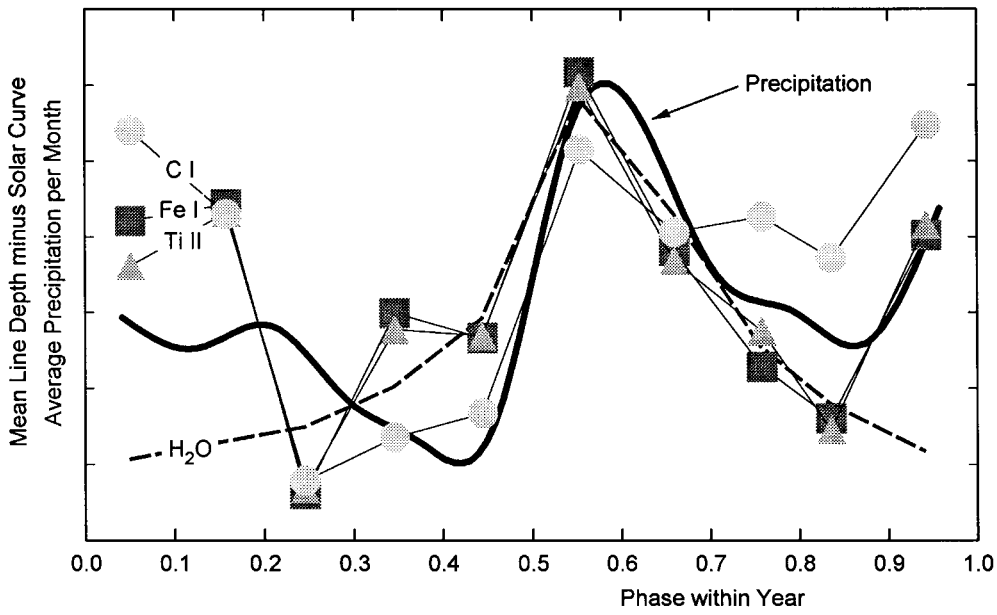


FIG. 2.—The residuals of the line depths from the solar image curve shown in the previous figure are compared to the seasonal precipitation at Kitt Peak. The average seasonal corrections originally made for telluric water vapor are also shown (H_2O).

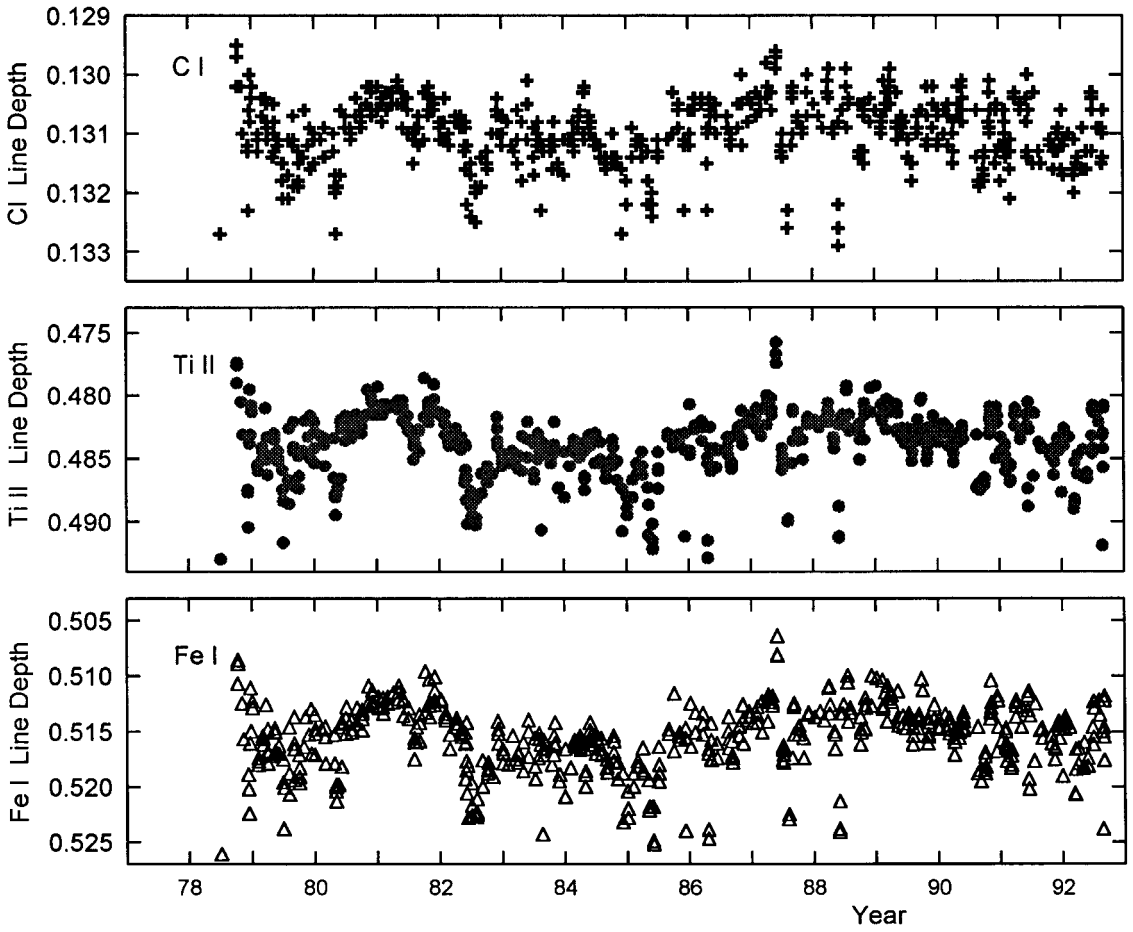


FIG. 3.—Line depths for the C I line and the line next to it on either side are shown as a function of time. Essentially identical patterns are seen in each panel.

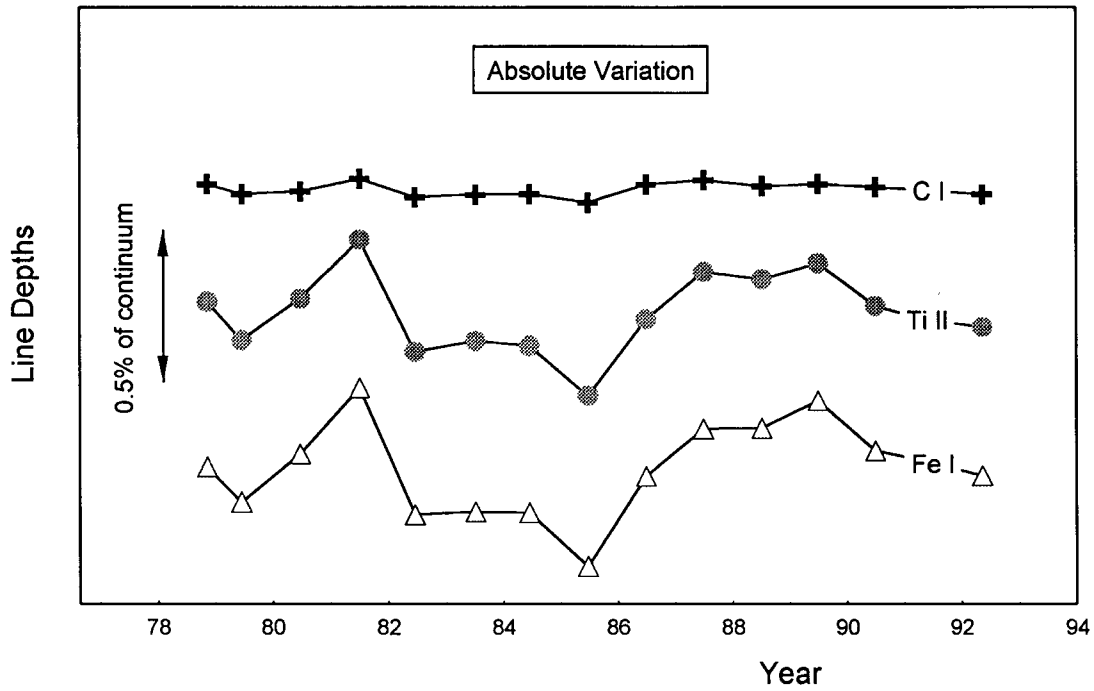


FIG. 4.—Year mean line depths are shown here on the same continuum scale. The lines are ordered by strength, and one sees that weaker lines have markedly smaller amplitudes, but they do not scale with the line strength.

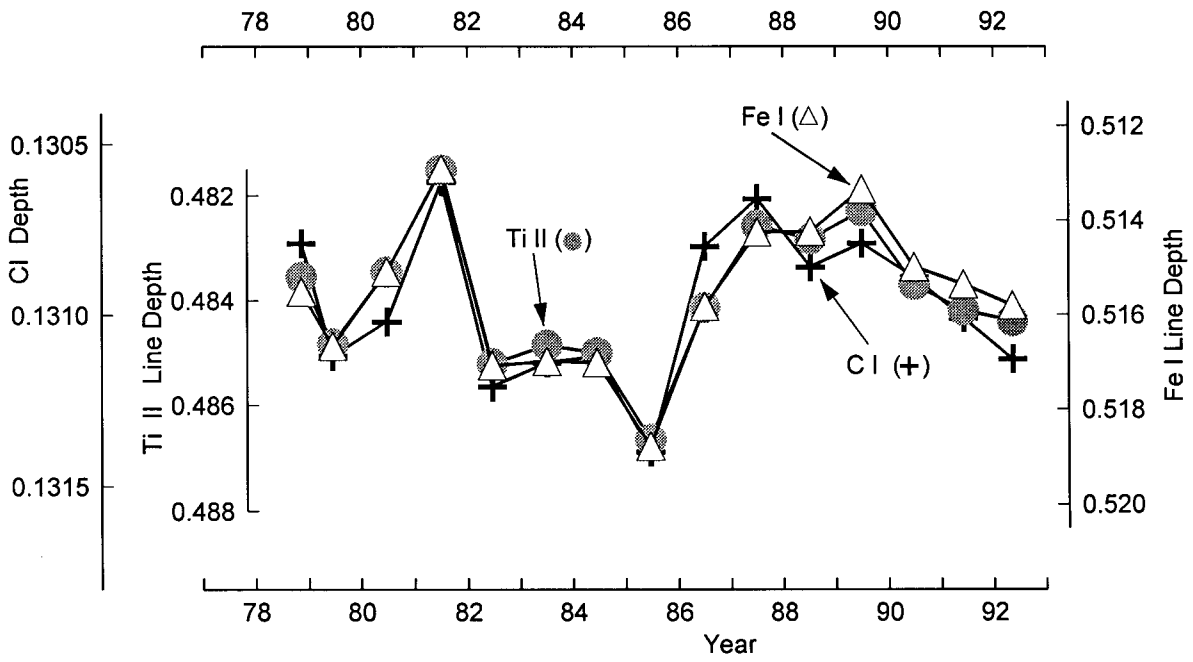


FIG. 5.—The year mean line depths from Fig. 4 are shown here scaled in ordinate so they match each other. Scaling from this plot is used in the discussion of scattered light.

these corrections is obvious, with the scatter being reduced threefold (but see § 4 below).

We determined the depths of the three lines of interest: C I λ5380.3, Ti II λ5381.0, and Fe I λ5379.6. The carbon line is weakest, and the iron line is strongest (see graphs below). Their excitation potentials are 7.68, 1.57, and 3.69 eV, and their Landé g factors are 1.0, 0.9, and 1.0, respectively.

4. ANNUAL VARIATIONS

As explained in § 2 above, the entrance-slit pinhole was used to obtain a flux image of the Sun. Since the image of the solar disk on the grating is only a few centimeters across, the effective size of the grating is then a few centimeters and is a significant factor in limiting the spectral resolving power of the instrument to $\approx$75,000. Furthermore, because the Earth's orbit is eccentric with $\epsilon = 0.017$, the angular size of the Sun changes, and the resolution of the spectrograph is expected to have an annual variation of $\leq$1.7%. Weaker, narrower lines will be affected more than stronger, wider lines.

We binned the line depth observations in 0.1 yr intervals and computed means. The annual signal is shown in Figure 1. where the ordinates are scaled to give similar amplitudes for all three lines. Given the small size of the variation, $\approx$1

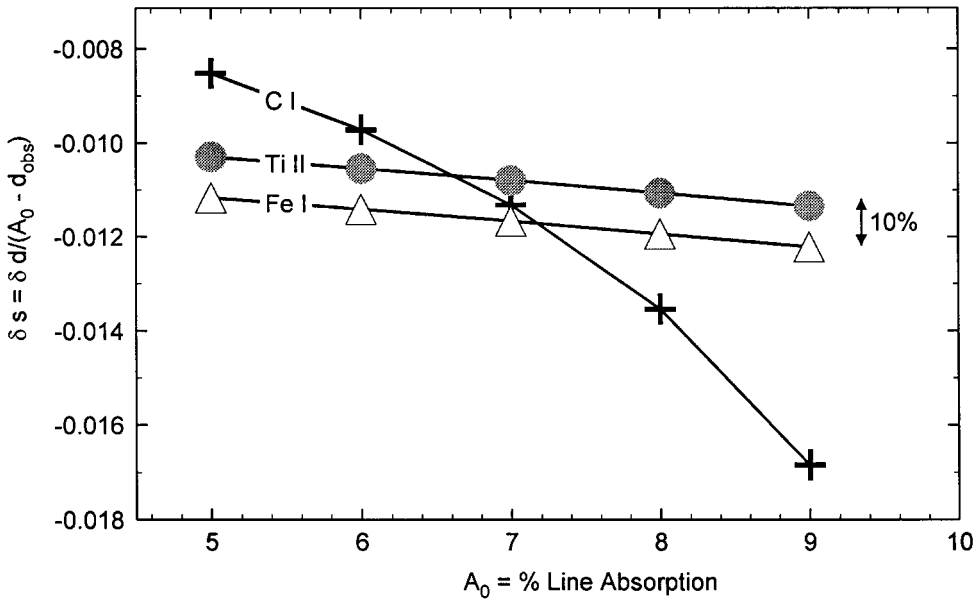


FIG. 6.—Equation (4) is plotted for the three lines as a function of assumed line absorption. A solution is where they cross near $A_0 = 7\%$. The uncertainty in the scaling of line depth variation, δd, from Fig. 5 is approximately the 10% indicated, and therefore the curves for the iron and titanium lines are the same within errors.

part per 1000 of line depth, the agreement among the three lines is very good.

There are, however, systematic deviations from the calculated angular size of the Sun in Figure 1. These deviations from the solar curve are plotted in Figure 2 as a function of annual phase. Although the noise level is significant, the residuals of all three lines do show a similar pattern with a broad dip in the second quarter followed by a steep rise through a peak in the third quarter. We show also in this figure the monthly average precipitation from the years immediately preceding the observations (Kitt Peak 1982; we could not obtain data for the exact years of the observations). The agreement is remarkable, and it would appear that normally undetectable telluric lines still affect the line depths even after careful allowance was made for all known telluric features.

These annual effects were removed by approximating them with a sixth-order polynomial and subtracting the correction from the line depths. As it turns out, the corrections are too small to make a significant difference in the overall analysis, although the scatter about the annual means is reduced 4.4%.

A periodogram analysis (based on Gray & Desikachary 1973) showed only two other periods in the data. One corresponds to the monthly sampling spacing, and the other is at the very low frequencies of the 11 year activity cycle. No rotational modulation is seen.

5. SYSTEMATIC ERRORS: THE SCATTERED-LIGHT HYPOTHESIS

The long-term variations of the three lines are shown in Figure 3. All three of them show a similar pattern that we believe does *not* arise from temperature changes in the Sun. This basic conclusion is based on the simple fact that the excitation and ionization of the three species are sufficiently different to cause real temperature variations to show up as different, not similar, variations in the lines. In fact, the variations track each other so well, it seems most likely that we are dealing with some kind of systematic error in the observations. Although the amplitudes of this pattern are smaller for weaker lines, as illustrated in Figure 4, they do not scale with the depth of the line. The relative amplitudes were determined from Figure 5, where the ordinates were adjusted until the best match was judged to exist. Uncertainty in this scaling is a few percent. From this plot, we read the amplitudes of variation to be 0.000690 for C I, 0.00447 for Ti II, and 0.00520 for Fe I.

What can possibly account for this unusual scaling? Variations in scattered light is one possibility. From the basic statement of scattered light, where the observed and true fluxes are related by

$$F_{\rm obs} = F_{\rm true} - sF_{\rm true} + s\langle F_{\rm true}\rangle \,, \tag{2}$$

with the fractional scattered light denoted by s and the average flux available for scattering in the spectral region of interest being denoted by the term in angle brackets. Typically this last term can be expressed in terms of the fraction of light lost to spectral lines, A_0, also called the line absorption, i.e., $\langle F_{\rm true}\rangle = (1 - A_0)F_{\rm true}^{\rm cont}$. Or, since we are working with the line depths, defined in the usual way as $d = (F_{\rm cont} - F_{\rm core})/F_{\rm cont}$, the observed line depth is

$$d_{\rm obs} = d_{\rm true}\,\frac{1 - s}{1 - sA_0} \,. \tag{3}$$

And in this instance, we need the variation in line depth arising from a variation in scattered light,

$$\delta d_{\rm obs} = \delta s\,\frac{A_0 - d_{\rm true}}{1 - sA_0} \,. \tag{4}$$

Here we see that the mapping of scattered light variations into line depth variations depends on the depth of the line compared to the line absorption, and it even reverses sign when the line is weaker than A_0. The question is, does this explain the strange scaling of the variations in line depths for the three lines in Figures 4 and 5? We have the mean observed values of the depths which we use as approximations to $d_{\rm true}$. We take a range of values for A_0, and the amplitudes from Figure 5, although we must remember that these are uncertain by several percent. The results of the calculation is given in Figure 6. Because the iron and titanium lines are similar in strength, they show nearly identical behavior in the figure, especially given the uncertainty in the scaling. The carbon line, on the other hand, shows quite a different behavior. We see that a unique solution exists if the line absorption amounts to 7% $\pm$ 0.5%. Is this a reasonable value for this spectral region? The line absorption was measured for 5380 Å $\pm$ 10 Å, $\pm$15 Å, and $-11/+32$ Å to test this point. The values are 6.8%, 7.1%, and 8.3%, i.e., virtually perfect agreement.

As shown in Figure 6, the actual variation in scattered light required to give the solution is 1.1% with an uncertainty of 0.1%. That, of course, implies a scattered light ranging up to at least 1.1% from zero, or larger. We do not understand how this can be possible with the double-pass system used to collect the observations (in particular, see Brault et al. 1971). Nevertheless, this scattered-light hypothesis does explain the observations remarkably well.

6. SCATTERED LIGHT AND LINE DEPTH RATIOS

Although it may be obvious, we note explicitly that the ratio of line depths is independent of the amount of scattered light. Scattered light appears primarily as a change in the zero level, while line depths are measured downward from the continuum and depth ratios are therefore unaffected. This can be expressed more formally using equation (3), and then one can see the limitations imposed by the factors we expect to cancel. Namely, the factors containing s cancel provided s and A_0 are indeed the same for both lines. This is likely to be true when the two lines are close together as ours are, but it cannot necessarily be assumed to hold in more general cases.

Consequently, although it was necessary and informative to consider all known variations in the spectral line depths in order to understand the data, and variation in scattered light appears to cause the most obvious of these, the changes in solar temperature we discuss next depend only on the ratio of line depths and are independent of scattered light.

7. SOLAR TEMPERATURE VARIATIONS

The individual line depth ratios, C I λ5380 to Fe I λ5379 to C I λ5380 to Ti II λ5381, are shown in Figure 7, along with the variations of other related parameters. Before a detailed comparison is made, we should note the extremely small size of the variation in the line depth ratio; we are looking at variations in the third decimal place. The fact

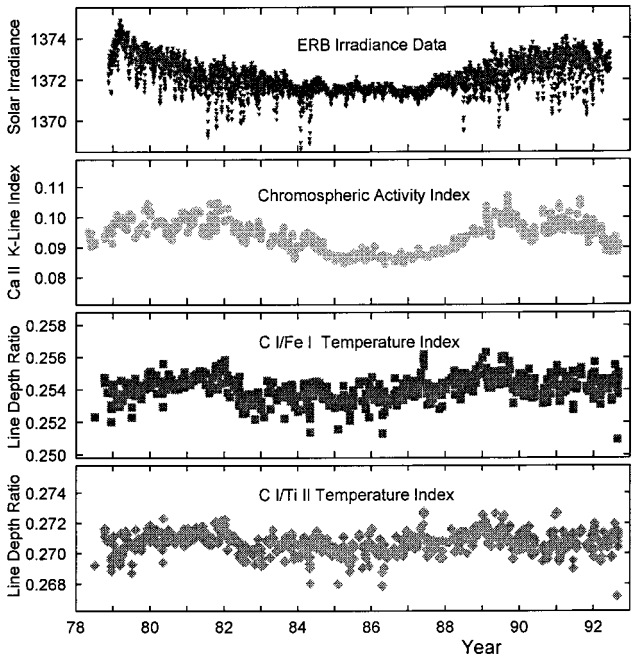


FIG. 7.—The activity cycle signal is seen in the irradiance, the chromospheric K-line index, and the temperature through the two line depth ratios.

that the signature of the magnetic cycle in these data is somewhat noisy is therefore to be expected. All three parameters vary approximately in phase: coolest temperatures come with the least power output and the lowest magnetic activity. The amplitude for the C I/Ti II ratio is noticeably smaller than the amplitude of the C I/Fe I ratio, in agreement with equation (1).

We notice also, in addition to the activity-cycle modulation of temperature, an underlying rise with time. Although this is uncertain because of the relatively short time base of 14 yr, we nonetheless explored the situation by placing a least-squares line through the data. Figure 8 shows the case for one of the line depth ratios; the other is similar. If this is physically real, then we have separated a secular rise in temperature from the variations in temperature associated directly with the activity cycle. This secular component is discussed further in § 9 below.

Smoothed values are compared in Figure 9. Here we use only the cyclic component of the line depth ratios. The smoothing is done using a locally weighted linear regression with the number of points per regression chosen to give smoothing comparable to taking means over 1 year. The temperature scale of the line depth variations is determined from equation (1). The full amplitude amounts to ≈ 1.5 K. Notice the consistency of the results for the two line depth ratios. This is more proof, in addition to that already given in the previous paper (Gray & Livingston 1997), that the variations in our line depth ratios are valid temperature indicators and are not influenced by changes in photospheric temperature gradients or variations of faculae and plage, which would be expected to affect each line in a different way.

Also shown in this figure are the variations in the calcium H and K magnetic signature and the irradiance. The measured irradiance includes the deficit caused by sunspots, as is evident in the top panel of Figure 7, where sharp drops are seen when spot groups transit the solar disk. The contribution of light from sunspots to the flux or disk-integrated light is very small, since a typical spot is an order of magnitude fainter than surrounding surface and total spot area is $\leq 0.3\%$. Consequently, our spectroscopy is based on light arising basically from the nonspotted portion of the solar disk. The fact that we see no rotational modulation in our spectroscopic data (§ 4) indicates also that there is minimal light contributed from spots. Therefore, we plot for the comparisons in Figure 9 the *spot-corrected* irradiance. This irradiance plot was converted to temperature variation

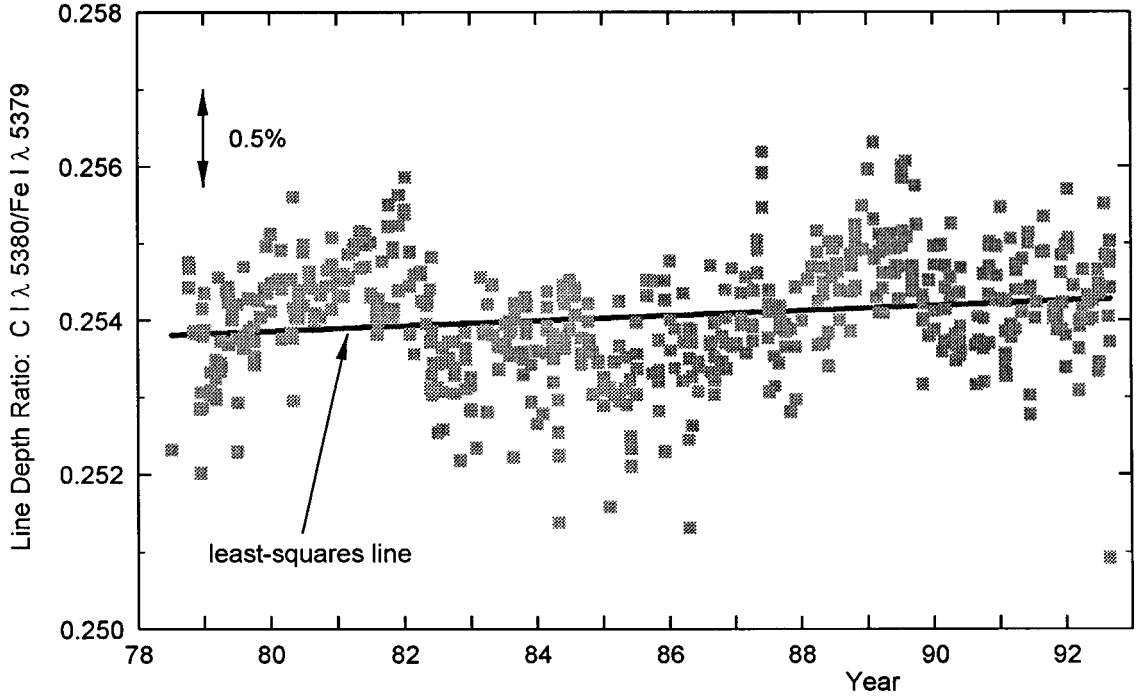


FIG. 8.—There is a secular rise in the temperature according to the line depth ratios. The C I/Fe I ratio is shown here. The least-squares line is used as the best approximation for the rise.

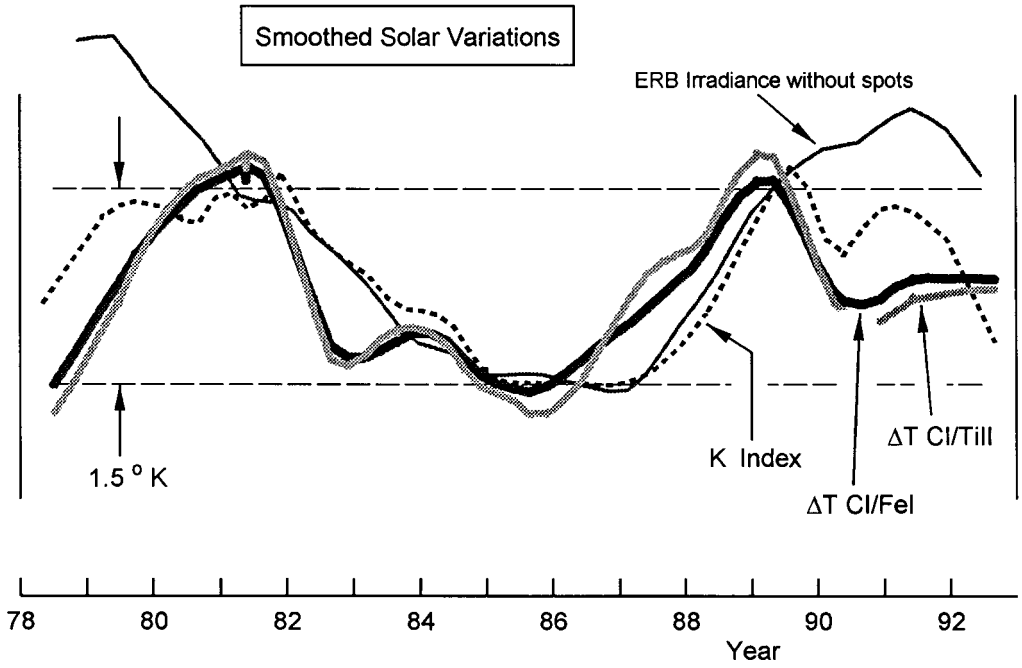


FIG. 9.—Smoothed variations in irradiance, K index, and temperature from the line depth ratios are compared here. The ordinates of the irradiance and the spectroscopic temperature curves are scaled so that the 1.5 K interval applies to both. The scaling of the K index was adjusted arbitrarily to be consistent with the other curves.

assuming a negligible variation of solar radius, an assumption supported by recent balloon experiments (Sofia 1996; but see Ulrich & Bertello 1995). The irradiance ordinate was scaled to match the one for our spectral line results; the 1.5 K span indicated in the figure therefore applies to both the irradiance and spectroscopic plots. As we see, the amplitudes of the temperature variations deduced from the irradiance are roughly consistent with that found from the spectral lines. We note the color-temperature measurements of Kuhn & Leibrecht (1991) that indicated a temperature change similar to ours during the same time period. In addition, variations in *p*-mode oscillations seen during the solar cycle are explained successfully if the temperature variation occurs below the photosphere (Kuhn 1989; Fröhlich et al. 1991).

On the other hand, there are also apparent differences in detail among the variables to which we now turn our attention.

8. DISCREPANCIES

Anomalous behavior in the line depth ratis occurred in the 1982 season, during which the temperature appears to have dropped abruptly without an obvious parallel in the other two parameters. We note, however, that this deviation is no larger than discrepancies seen between ACRIM (not shown; see Willson & Hudson 1991) and ERB (Kyle et al. 1993) data or between irradiance and calcium H and K index.

A more significant difference is the higher value of irradiance through the 1990–1992 interval compared to the spectroscopic temperature. (The high irradiance at the start of the data, 1978–1981, might result from instrumental changes; see Foukal & Lean 1988 and Pap et al. 1994b.) One source of difference might lie with our assumption of a constant solar radius. From the discrepancy in Figure 9, we estimate that the radius associated with irradiance would have to be $\approx 0.02\%$ larger during the cycle maximum. This is not far from the radius behavior deduced by Ulrich & Bertello (1995). At the same time, some caution should be used here because the depth of formation, and hence the effective solar radius, can vary significantly across strong spectral lines and from one spectral region to another, all of these radii being part of the solar power output. In addition, the preliminary results of Sofia et al. mentioned above indicate variations in solar radius to be an order of magnitude smaller than we are considering.

Another source of the difference might be that the spectroscopic temperatures are limited explicitly to the deep photospheric layers in which these weak spectral lines are formed, while the irradiance includes power from all atmospheric layers. Indeed, the outer layers are well known to show markedly larger *fractional* variations in power output (e.g., Lean 1991; White 1994; Withbroe & Kalkofen 1994), and so one might expect irradiance to show larger variation than photospheric temperature. However, the absolute contribution of these outer atmospheric layers to the total irradiance is actually very small and therefore cannot account for the large size of the excess irradiance amplitude shown in Figure 9. Furthermore, this same discrepancy has been seen repeatedly in other comparisons, for example, with helium $\lambda 10830$ or radio 10.7 cm flux (Pap et al. 1994b; Brandt, Stix, & Weinhardt 1994), and these radiations do arise from higher layers. This point clearly needs more study, but that lies beyond the scope of our current investigation.

Going back to basics, one might imagine the irradiance variation stemming from an angular dependence of the solar power output, i.e., a nonisotropic emission, that varies during the activity cycle. In effect, the Sun would be "beaming" more power in the Earth's direction at some phases; less at others. To the extent that the temperature variations deduced from irradiance and from spectroscopic

monitoring agree, we have evidence that the globally averaged solar radiation is isotropic. The counterpoint is that nonisotropy cannot yet be ruled out as the source of the discrepancy between irradiance and spectroscopic temperature variations.

9. THE SECULAR RISE IN TEMPERATURE

If the small secular rise shown in Figure 8 is real, then during the 1978–1992 epoch the Sun was growing hotter at the rate of ≈ 0.012 K yr^{-1}. The value for the less sensitive ratio using Ti II is 0.016 K yr^{-1}. The main uncertainty here comes from the short time base. Ideally, we need continuous observations over many cycles. Assuming that solar variations do play a central role in determining terrestrial climate change, then a comparison of solar to terrestrial warming rates gives an empirical determination of the amplification factor introduced by the Earth. Modeling the amplification factor is difficult at best (see, for example, Ghil 1991; Lean et al. 1994; Lean, Beer, & Bradley 1995) and involves numerous physical processes and interactions, along with nonlinear feedback. Empirical measurement is therefore a basic and vital aid to the modeling. Spectroscopic measurements like ours could supply this information independent of irradiance measurements.

10. COMPARISON WITH OTHER STARS

Compared to many stars, the temperature excursions of the Sun in the 1978–1993 interval are small (Gray et al. 1992, 1996a, 1996b; Gray & Baliunas 1995). Whether or not this small variation is typical behavior for the Sun is an important question for terrestrial climate and dynamo physics. In the stellar studies, temperature variations deduced from line depth ratios show a lag behind the calcium H and K variations (Gray 1994a). This lag appears to be dependent on spectral type, with the G0 dwarf β Comae showing a lag of 2.9 ± 0.3 yr compared to the K0 dwarf ϵ Eri, which shows a lag of only 0.3 ± 0.3 yr. Other stars fall in between. According to this relation, the Sun should show a lag of some 2 yr. Some evidence of a 1–2 yr lag was found by Kuhn & Leibrecht (1991), but our results here (e.g. Figs. 7 and 9) show essentially *no* lag. Why the Sun should differ from other stars is an important open question. The Sun might currently be in a transient phase of superstability. Or it might have aged sufficiently to have entered a pattern of magnetic activity different from those stars showing the time lag (Radick, Lockwood, & Baliunas 1990).

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ERRATA

In the paper "Monitoring the Solar Temperature: Spectroscopic Temperature Variations of the Sun" by David F. Gray and William C. Livingston (ApJ, 474, 802 [1997]), equation (4), giving the variation in observed line depth, is incorrect. It should read

$$\delta d_{\rm obs} = \delta s \, \frac{(A_0 - 1) d_{\rm true}}{(1 - s A_0)^2} \, .$$

The remainder of § 5 following equation (4) stems from the incorrect equation and should be disregarded. These changes do not affect the results of the paper, except that a possible explanation for the nearly synchronized variation of the central depths of all three spectral lines no longer obtains.

The authors note that an error in setting the continuum level is farthest from explaining the scaling behavior of the line depths shown in Figures 4 and 5 of the original paper. Continuum errors affect weaker lines proportionately more than stronger lines, which is just the opposite of what is observed. An error in zero level, which is close to the effect of scattered light, causes line depths to scale proportional to their depth. This is closer to what is observed, but does not go far enough in this direction, since the percent variation in the weaker C I line (depth 0.13) is only about half that of the Ti II (depth 0.48) and Fe I (depth 0.52) lines.