An Empirical Model of Total Solar Irradiance Variation Between 1874 and 1988
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estimates may relate only to the supersaturation, and there will also be an equilibrium background concentration of point defects in the material.

The proposed model for shear indicates that the stacking faults lie in the (010) [or the symmetry-related (100)] planes, bounded by partial screw dislocations with **b** = <(*a*/2), 0, (*c*/6)> or <0, (*b*/2), (*c*/6)>. Accurate analysis of the habit plane of the stacking faults was not possible because of limited tilt (±10°) in the TEM. The fault displacement vector **R** (by which the crystal above and below the fault is displaced) is of the type 1/2 [010]. Stacking fault contrast can be revealed with the use of appropriate

reflections so that **g** · **R** is not an integer (*8*), as shown in Fig. 3. The samples with *x* = 0.225 showed chemical inhomogeneity and no evidence for the line defects. The type of shear reported here could also be present in other Cu–O sheet, high-temperature superconductors, including those with the square pyramidal units.

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An Empirical Model of Total Solar Irradiance Variation Between 1874 and 1988

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An empirical model of variations in the total solar irradiance caused by observed changes in photospheric magnetic activity between 1874 and 1988 is presented. The model provides a remarkably good representation of the irradiance variations observed by satellite-borne radiometers between 1980 and 1988. It suggests that the mean total irradiance has been rising steadily since about 1945, with the largest peak so far at about 1980 and another large peak expected during the current solar cycle 22. But it is doubtful whether even this rise can contribute significantly to global warming, unless the temperature increase of about 0.02°C that it produces in current energy balance models seriously underestimates the sensitivity of climate to solar irradiance changes.

R ADIOMETRIC DATA FROM THE Solar Maximum Mission (SMM) and Nimbus-7 satellites have shown that the total solar irradiance declined by about 0.1% between solar activity maximum in about 1981 and minimum activity in 1986 and has since risen with increasing activity in the new sunspot cycle 22 (*1*). Most of this brightening of the active sun can be attributed to the irradiance effect of photospheric magnetic structures called faculae, whose areas increase at times of high sunspot number (*2*). Contributions from changes in the total irradiance not directly associated with photospheric magnetic activity have also been suggested (*3*).

The mechanism responsible for the total irradiance variation is of interest in examining possible influences of solar radiative output on climate. Climate models indicate that an irradiance variation of the magnitude observed over the last 11 years is too small

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to have significant impact on global temperature (*4*). However, a variation of this size occurring over many decades might contribute at an appreciable level to trends that may have occurred over the past century. We describe here an empirical model of total solar irradiance variation over the period from 1874 to 1988, developed from our understanding of the irradiance variation that has been directly observed since 1978.

In previous work (*2*), we have shown that after correction for the dimming caused by dark sunspots the total solar irradiance variations observed between 1981 and 1984 by the Active Cavity Irradiance Monitor (ACRIM) on SMM and the Earth Radiation Budget (ERB) radiometer on Nimbus 7 can be reconstructed from observed variations in facular area. The correction for sunspot dimming was computed from daily positions and areas of spots and from their photometric contrast. We used daily values of the He I index, a measure of the area of faculae on the entire disk including both magnetically active and quiet regions, as the basis for our reconstruction of the facular irradiance effect.
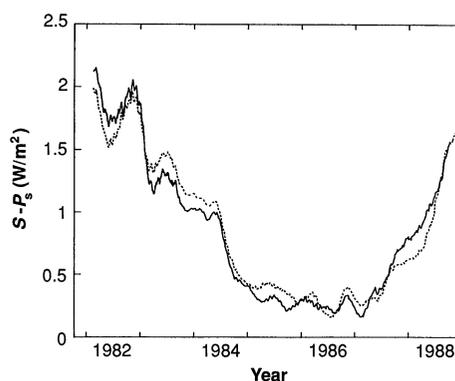
Fig. 1. A comparison of the ACRIM irradiance residuals (solid line) for 1982 to 1988 with a reconstruction of the irradiance residuals (dotted curve) based on the use of the linear regression given in the text. An 81-day smoothing has been applied to the data.

We show here that our irradiance variation model successfully represents the radiometry over the interval from 1980 to 1988 covered by the available ACRIM data. In the present study we use the solar Lyman alpha (Lyα) flux (*5*) as an index of facular area instead of the He I index. The Lyα radiation of faculae arises from layers of the solar atmosphere relatively close to the photospheric layers that emit most of the sun's radiative output. The Lyα flux is less influenced than the He I emission by radiations from the very hot overlying coronal layers that contribute negligibly to the total solar irradiance. Also, we use the ACRIM radiometry alone in this paper to simplify the presentation, although the conclusions we reach are equally valid for a parallel analysis that we have carried out on the ERB data.

The irradiance residuals, $S - P_s$ (where S is the total irradiance measured by the ACRIM radiometer and P_s is the correction for sunspot dimming), are found to increase

linearly with the Lyα flux according to the relation $S - P_s = -3.3 + 855$ (± 9) Lyα, where both $S - P_s$ and Lyα are measured in watts per square meter. Thus, a strong positive linear relation exists between these total irradiance residuals and facular area.

We use this relation to reconstruct the total irradiance residuals for the period from 1982 to 1988, using daily Lyα flux values for this period. Remarkably good agreement is achieved between these reconstructed values and the residual variations measured by ACRIM (Fig. 1). This agreement holds both for the slope of the slow trend downward between 1982 and 1986 and for the slope of the subsequent upward rise. Perhaps most convincing is the model's ability to reproduce the variations of 4 to 9 months duration seen about this smooth trend, without any adjustment of parameters. The amplitude of these variations (as in 1983) approaches half of the full range seen in the smoother 11-year variation.

Figure 2 shows a comparison between the observed irradiance variations for 1980 to 1988, those computed from our model, and those calculated from another model based on photospheric activity (6). Some irradiance variation estimates based on recent ground-based observations by Kuhn et al. (3) are also plotted.

The alternate model shown in Fig. 2 for comparison with ours (6) predicts a significant phase advance of the total irradiance relative to the activity envelope traced by an index such as the sunspot number. The reason for the phase advance seems to be the equatorward drift of the solar polar faculae, whose irradiance contribution is an important term in that model. Because this phase advance is not seen in the radiometry at the onset of cycle 22, it appears that the importance of this effect of the polar faculae has

been overestimated, relative to those at lower latitudes.

The irradiance variations calculated in part from their ground-based photometry by Kuhn et al. (3) are not inconsistent with the interpretation that faculae cause the 11-year irradiance variation. However, only four data points have been published (Fig. 2), so it is not possible to determine whether the 4- to 9-month variations characteristic of the facular irradiance signal are present in this photometry until measurements with higher time resolution become available.

Neither the Lyα flux nor the He I index are available before 1975, so use of our model to reconstruct total irradiance variations before cycle 21 must rely on other facular indices. Lean and Foukal (7) used daily values of the 10.7-cm microwave flux ($F_{10.7}$) to extend the model back three solar cycles to 1954. The only facular index extending substantially earlier still are the areas of white-light faculae measured and compiled at Greenwich Observatory between 1874 and 1976. Unfortunately, these data exhibit evidence of an observational bias that makes them unreliable for our purpose (8).

However, we have found that monthly means of the sunspot number, R_z, provide a surprisingly good index of slow changes in facular behavior, as can be seen from Fig. 3. Figure 3A shows how well one can reproduce the solar cycle variation of $F_{10.7}$, using its regression on R_z and the monthly mean R_z values between 1947 and 1988 that are shown in Fig. 3B. Clearly, over this period, R_z is an excellent estimator of $F_{10.7}$ if we are interested in the relative cycle amplitudes rather than in details of the cycle shapes.

Figure 3C shows the variation of sunspot areas for the same period represented by the sunspot dimming function P_s. The ampli-
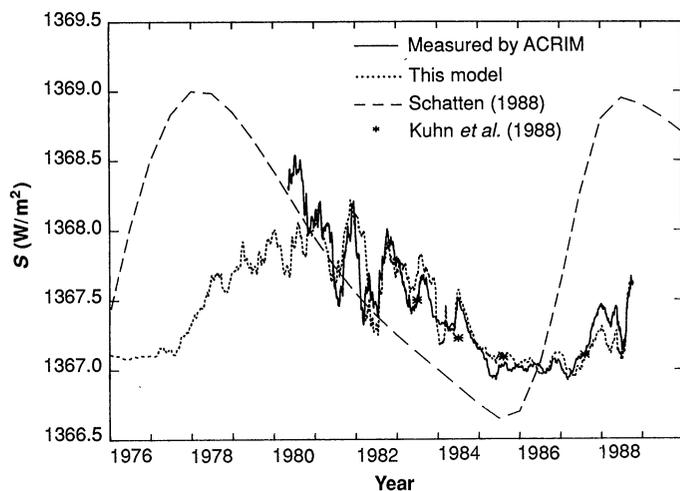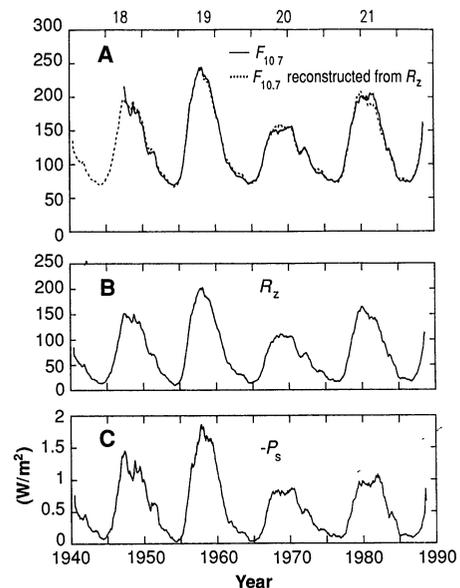
Fig. 3. (A) Observed values of $F_{10.7}$ and reconstruction of $F_{10.7}$ based on the use of values of R_z between 1947 and 1988 shown in (B). (C) The variation of sunspot areas given by the function $-P_s$ for the same period. These monthly data are smoothed with a 12-month running mean. Values of R_z, $F_{10.7}$, and daily sunspot areas and coordinates were obtained from the NOAA World Data Center, Boulder, Colorado.

tude of cycle 21 is much less in the index P_s than in R_z or in $F_{10.7}$. Examination of data on other indices indicates that during cycle 21 it was the mean area of a spot (rather than the number of spots) that was anomalously low (9).

This discussion indicates that P_s, which is an objective measure of sunspot area on the solar hemisphere, can behave quite differently from the index known as the "sunspot number." This is not too surprising, since the definition of sunspot number in terms of the number of spots and the number of groups is somewhat arbitrary. In our model, P_s provides a direct estimate of sunspot dimming and the value of R_z is used to estimate the facular contribution to total irradiance. Thus, the solar cycle irradiance variation estimated by our model is largest when a cycle's amplitude (measured in R_z) is relatively large as compared to its amplitude in the sunspot area. This was the case during cycle 21.

Having established R_z as a viable index of the facular contribution to 11-year irradiance variation, we calculate the regression of the irradiance residuals, $S - P_s$, against R_z for the period from 1980 to 1988. This regression, shown in Fig. 4, is used together with monthly mean values of R_z, to reconstruct the facular contribution to irradiance variation for the period from 1874 to 1988. This variation is shown as the function $S - P_s$ in Fig. 5B. Figure 5A shows the

Fig. 2. A comparison of the ACRIM radiometry for 1980 to 1988 with our model of the irradiance variations between 1976 and 1988, with the model of Schatten (6), and with the results of Kuhn et al. (3).
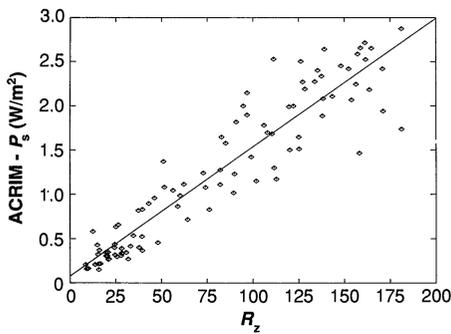
Fig. 4. Regression of ACRIM irradiance residuals, $S - P_s$, against R_z. Monthly averaged data are used for the period from March 1980 to December 1988. ACRIM $-P_s = 0.078 + 0.0146\ R_z$; uncertainty (SE) in slope = 0.0006.

function $-P_s$ calculated for the period from 1874 to 1988 (10). Figure 5C shows the total irradiance variation found from our model, obtained by adding the negative P_s function to $S - P_s$ and using a quiet sun irradiance value of $S_0 = 1366.81$ W/m^2.

In general, the irradiance variation we show in Fig. 5C follows the behavior of the sunspot number, R_z. That is, for most of the 114-year period, the relative amplitude of cycles measured in R_z and P_s is similar. Cycle 21 is an important exception; its small amplitude in P_s relative to its amplitude in R_z produced the largest irradiance variation of any cycle since 1874. Thus, if our model is correct, precise spaceborne measurements of S became available at just the time when the sun produced the largest 11-year irradi-
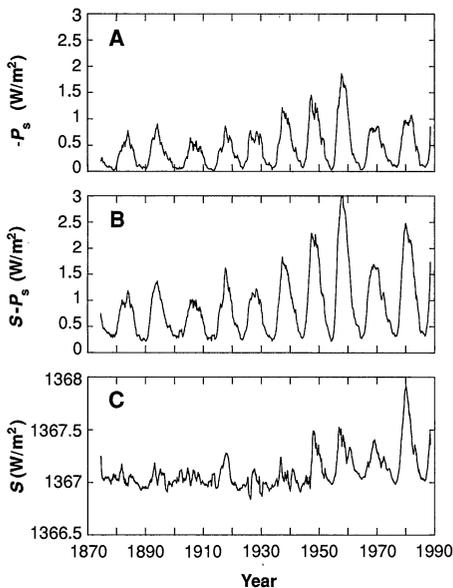
Fig. 5. Reconstruction of (**A**) the sunspot dimming function, P_s (plotted positively), (**B**) the facular contribution, $S - P_s$, to total irradiance reconstructed from R_z, and (**C**) the total irradiance, S. All the (monthly) data were smoothed with a 12-month running mean.

ance variation in at least the past 114 years.

Perhaps the most important result seen in Fig. 5C is the gradual increase in total irradiance beginning about 1945 when the general activity level began to rise, extending through cycle 21, and continuing to the present. The likelihood of slow changes in total irradiance that follow the envelope of solar activity over the past century has been suggested before (11). However, the prediction of our model that cycle 21 produced the largest irradiance jump in over a century makes a clearer case that the smoothed total irradiance over the past 45 years has risen steadily and achieved its highest levels so far, at about 1980.

The increase in S calculated from this model for the rising phase of the present cycle is already comparable to that seen during any previous cycle in the past 114 years, except for cycle 21. Thus it appears that cycle 22 will continue the irradiance rise of the last four decades.

It is of interest to test the influence of our computed irradiance variation on climate models, to study its effects on global temperature over the past century. Two such tests have been run so far. In one, a function similar to that shown in Fig. 5C was used as input to a box-diffusion, energy-balance climate model (12). Runs of the climate model were carried out by Wigley and Raper over accepted ranges of the parameters that determine equilibrium temperature sensitivity, oceanic vertical diffusivity, mixed layer depth, and upwelling rate. The transient response to even the largest 11-year variation (cycle 21) was only about 0.02°C. The response to the general rise of irradiance over roughly the past 45 years would be expected to be larger because it is not as severely damped by the oceanic heat reservoir. But this slow irradiance increase is sufficiently smaller than that of cycle 21 that its amplitude of about 0.02°C is again a small perturbation to the global warming of about 0.3°C expected to be caused by the 25% increase of carbon dioxide measured between 1850 and the present. Similar results were obtained from runs of a climate model that incorporates latitudinal transports (13).

To summarize, solar irradiance variations of the magnitude below 0.1% expected from photospheric activity are unlikely to have had significant influence on climate over the past century unless the sensitivity of climate to solar irradiance variation is seriously underestimated by currently accepted energy balance models. For instance, neglect of cloud feedbacks in these models is an obvious concern.

Much larger variations in solar luminosity could be caused by global solar changes not associated with photospheric sunspots and faculae. A secular variation approaching even 1% over the past century cannot strictly be ruled out, given the low precision of pyrheliometry, until modern data became available from satellites beginning in 1978. The theory of the solar radiative interior and convection zone is also insufficiently accurate to rule out luminosity variations of such amplitude. Only a determined effort to measure the behavior of S over many decades can increase our understanding of this potentially important climate parameter.

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