Reports

Spectrum Line Intensity as a Surrogate for Solar Irradiance Variations

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Active Cavity Radiometer Irradiance Monitor (ACRIM) solar constant measurements from 1980 to 1986 are compared with ground-based, irradiance spectrophotometry of selected Fraunhofer lines. Both data sets were identically sampled and smoothed with an 85-day running mean, and the ACRIM total solar irradiance (*S*) values were corrected for sunspot blocking (S_c). The strength of the mid-photospheric manganese 539.4-nanometer line tracks almost perfectly with ACRIM S_c. Other spectral features formed high in the photosphere and chromosphere also track well. These comparisons independently confirm the variability in the ACRIM S_c signal, indicate that the source of irradiance is faculae, and indicate that ACRIM S_c follows the 11-year activity cycle.

THE ACTIVE CAVITY RADIOMETER Irradiance Monitor (ACRIM) on the Solar Maximum Mission (SMM) spacecraft has returned precision measurements of the total solar irradiance, *S*, with daily averages now available from March 1980 to March 1986. It was discovered early on that sunspots on the sun's visible disk block a noticeable fraction of the solar output (*1*). Hoyt and Eddy (*2*) compiled a sunspot blocking function, P_s, on the basis of daily sunspot areas and coordinates, and we have used this function to correct *S* for incremental depression produced by sunspots (*3*): $S_c = S + P_s \times S_0$, where S_0 is 1366.8 W/m^2. Apparently, *S* decreased from launch in 1980 to 1985 by about -0.02% per year. Instrumental drift cannot account for this decrease (*4*); the change in *S* has been tentatively identified with a parallel decline in solar activity over these years.

At Kitt Peak we have observed the equivalent widths and central depths of a variety of lines in the solar irradiance spectrum at monthly intervals, from 1976 to 1988 (*5*, *6*). Included are absorption lines originating in the low photosphere (for example, the C 538.0-nm line), temperature minimum lines in the midphotosphere (for example, the Mn 539.4-nm line and the CN molecular band head at 388.3 nm), and lines up through the chromosphere (Ca K 393.3 nm and He 1083.0 nm) (Table 1). Because line strength is determined relative to the local continuum, no correction for sunpsot blocking is needed to show any global variability. Depending on the weather, the duration of our observing runs lasted up to 4 days each month.

A correspondence is seen between ACRIM S_c and the equivalent width of the Mn 539.4-nm line for days in common (Fig. 1). Both data sets have been smoothed by an eight-point running mean (which on the average amounts to 85 days; see below). The correlation for solar maximum and the declining part of the cycle through to about March 1985 is excellent. Because Mn line strength is an entirely different kind of parameter from S_c, their detailed agreement lends credence to the validity of both data sets. Only linear drifts with time would escape notice. At solar minimum, however, this tight correlation fails and the CN band head becomes the better surrogate for S_c (Fig. 2). Because the line strength time series is known to follow the solar cycle (*7*), we infer that S_c will do the same in view of the tight correlation from solar maximum to minimum. This correlation indicates that the two features most likely have a common physical cause.

The strength of the chromospheric He 1083.0-nm line tracks solar maximum well but not as well as the strength of the Mn 539.4-nm line, and it is inferior to the CN band head as a surrogate at the minimum epoch (Fig. 3). The variation in the equivalent width of the low photospheric C 538.0-nm line (Fig. 3) does not follow the smoothed S_c values in either the decline from solar maximum or the shorter lived features of the plot characteristic of active

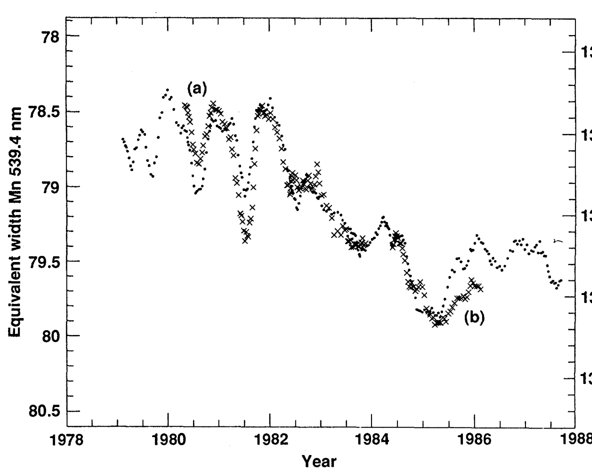

Fig. 1 (top). ACRIM S_c (crosses) and the equivalent width of the Mn 539.4-nm line in milliangstroms (dots). After editing for common dates and filtering with an eight-point running mean, we have normalized the line data and scaled them to a best fit of the two time series: (a) points to the start-up period of ACRIM S_c where the record is high; (b) points to a departure of correlation near solar minimum as explained in the text. When no ACRIM S_c data are available, we assume that $S_c = 0$ and these points are off the plot. **Fig. 2 (bottom).** ACRIM S_c (crosses) and the CN index in milliangstroms (dots). For this series the time intervals are slightly different than in Figs. 1, 3, and 4. Note the good correspondence at solar minimum.

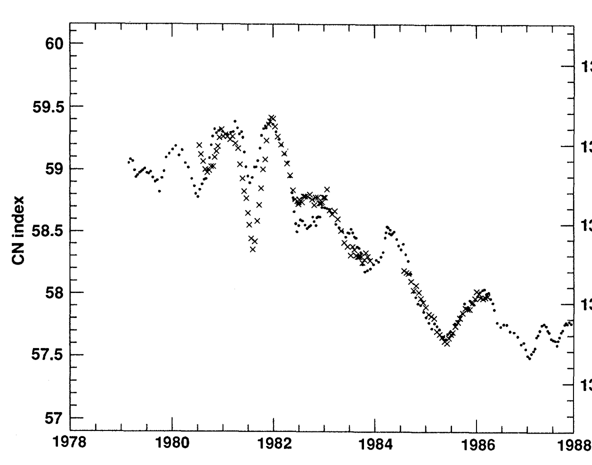

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Table 1. Deduced relation between ACRIM S_C and line strength if ACRIM $S_C = A + B \times$ (line variable).

Line	Height (km)	A (W/m^2)	B*	Parameter†	Period of agreement (years)
He 1083.0 nm	+1500	1422.5	−58.9	Central depth	Variable
Ca K 393.3 nm	1500	1352.6	163.13	0.1-nm index	1982.0–1986.3
CN 388.3 nm	600	1279.1	1.509	0.0285-nm index	1982.5–1986.3
Mn 539.4 nm	200	1512.2	−1.818	Equivalent width	1981.5–1985.1
C 538.0 nm	0			Equivalent width	None

*B has units of W/m^2 for the He line and 10^{13} W/m^3 for the other lines. †Central depth is intensity; the other parameters are in units of milliangstroms.

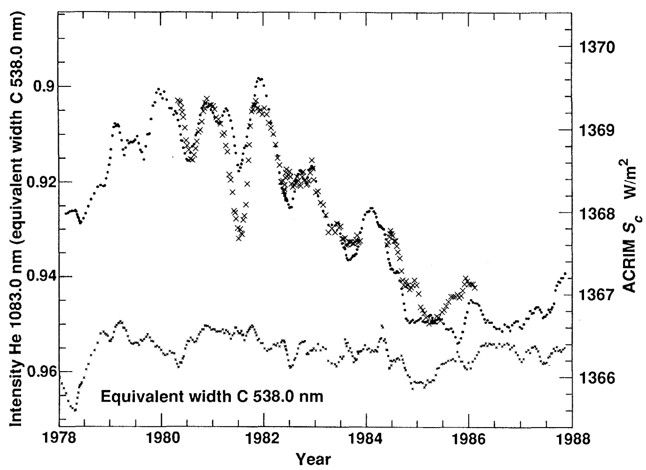

Fig. 3. ACRIM S_c (crosses) and intensity of the He 1083.0-nm line (dots). The correlation is inferior to those for the Mn and CN lines, but daily measurements are available for the He line (Fig. 4). At the bottom is the time series for the C 538.0-nm line treated in the same way. For the C 538.0-nm line: mean equivalent width = 0.0022 nm; peak variability is 0.00003 nm. Except for the two lowest dips, no correlation with ACRIM S_c is apparent.

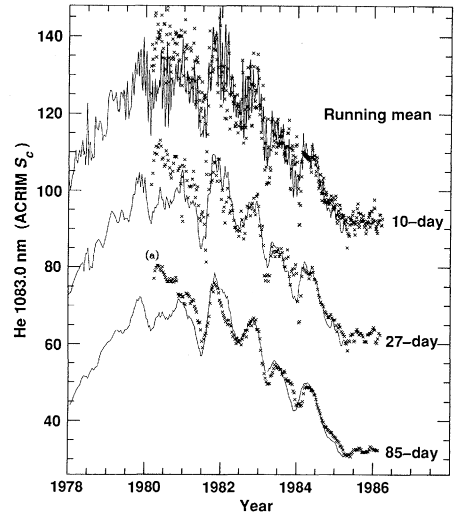

Fig. 4. Daily ACRIM S_c (crosses) and coincident He 1083.0-nm line strength measurements in milliangstroms (lines) made with the 512-channel magnetograph at Kitt Peak. The line data have been normalized and scaled to a best fit of the two time series. The top series has been smoothed by a 10-day running mean, the next lower by a 27-day mean, and the bottom by an 85-day mean. As in Fig. 1, (a) points to an early departure of the two series which rapidly disappears. Note the rotational modulation that shows up in the 10-day mean series. The lower two plots have been shifted down.

regions (*8*). This suggests that the solar cycle variation in S_c has its root cause high in the solar atmosphere, a region that is sampled by our other measures (Ca K, CN, and Mn lines). Faculae may therefore be the source of increased total irradiance at solar maximum rather than a uniform global change in the low photosphere. The linear regressions between S_c and line strength are given in Table 1.

Why have we used an eight-point running mean, and what are the consequences of its use? The line strength observations were made on one to four consecutive days once a month. This monthly cadence is unfortunately close to the 27-day rotation period for the sun. As a result, any rotational modulation is not resolved because it is badly aliased. We chose an eight-point running mean because it is the shortest average that produces empirically a reasonable, smooth time series. The average number of days per monthly run is 2.89 for the Mn time series; therefore, an eight-point average covers 2.8 months or three solar rotations (85 days). White (*9*) showed that correlations between spectral irradiance time series improve if fluctuations with periods of less than 85 days are suppressed by numerical filtering. As an approximate description, then, the smoothed curves in Figs. 1 to 3 were produced by a running mean covering three solar rotations.

We caution the reader not to overinterpret the plots in Figs. 1 to 3. Because of the irregular spacing of the data points in our measurements, the time scale has been corrupted by numerical filtering, but the mixing of data points at different time separations is the same for both ACRIM S_c and line strengths. Consequently, these three plots illustrate only the similarity between the two types of data, and they are not intended as accurate time histories of solar variation.

Foukal and Lean (*3*) recognized that there is a close relation between S_c signals and He 1083.0-nm line strength. We have shown that the 85-day mean is a filter to eliminate variations due to rotational modulation, and that the strengths of other spectrum lines are also surrogates, particularly at solar minimum. We have applied the 85-day running mean to the same daily data set that Foukal and Lean studied (Fig. 4). The 10-day and 27-day running means reduce the scatter, but the 85-day mean is most effective in producing a smooth record. We conclude that much of the variability between S_c and our line-strength measurements occurs in time spans that are less than 85 days and most likely arises from both rotational modulation and random noise.

Several inferences about the solar source of S_c variability can be drawn from line-strength correlations. Sheeley (*10*) showed that the weakening of the CN band head spatially corresponds to weak magnetic fields on the resolved disk. Mount *et al.* (*11*) determined that the CN band head is formed around 300 to 400 km. The Mn 539.4-nm line originates in the midphotosphere at 200 km. The He 1083.0-nm line and the core of the Ca K line at 393.3 nm are formed much higher (~1500 km) in the chromosphere (Table 1).

At solar maximum, magnetic fields loop upward above the sun and penetrate equally the layers where the Mn, CN, Ca K, and He lines are formed. Cospatial with these fields is the facular brightening in the continuum, which increases S and S_c (*12*). Faculae form in the high photosphere. Some departure between ACRIM S_c and line strength suggests that active plage and less dense, quiet faculae act in ways unaccounted for in this simple model (a in Figs. 1 and 4).

There are other complications. The strength of the He 1083.0-nm line is subject to nonthermal equilibrium effects through a coupling of the He transition ground state to coronal He emission at 30.4 nm (*13*), and this can account for a certain amount of variance at any time of the cycle. At solar minimum, faculae are few and the associated compact bipoles do not reach upward to the heights where the He 1083.0-nm line originates, accounting for a poorer correlation between this line and S_c at that epoch than for the other lines.

The Mn 539.4-nm line strength fails to track well at solar minimum (b in Fig. 1). We hypothesize that beginning in the spring of 1985 seedlings of new cycle flux emerged which weakened the strength of the Mn 539.4-nm line but did not reach high enough to affect the CN band head and cause faculae. Possibly for this reason, the CN band head appears to report more accurately on the solar minimum facular layers. Our best surrogate for the entire cycle is a combination of Mn 539.4- and CN 388.3-nm line strengths.

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Deuterium on Mars: The Abundance of HDO and the Value of D/H

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Deuterium on Mars has been detected by the resolution of several Doppler-shifted lines of HDO near 3.7 micrometers in the planet's spectrum. The ratio of deuterium to hydrogen is $(9 \pm 4) \times 10^{-4}$; the abundance of H_2O was derived from lines near 1.1 micrometers. This ratio is enriched on Mars over the telluric value by a factor of 6 ± 3. The enrichment implies that hydrogen escaped more rapidly from Mars in the past than it does now, consistent with a dense and warm ancient atmosphere on the planet.

THE GEOMORPHOLOGY OF THE MARtian surface indicates that running water was present in the distant past, but the total amount of water and the periods of its activity are still uncertain (*1*–*3*). Estimates of the total quantity of volatiles that have been outgassed by the planet are consistent with the formation of the dense, warm, ancient atmosphere that would have been required for the presence of slow-moving water (*4*), but nongeological evidence for an early warm and wet climate on Mars has been lacking. The present ratio of deuterium to hydrogen, D/H, in the martian atmosphere can help constrain models for the near-surface reservoir of water and the loss of H_2O by photodissociation and escape. Accordingly, we decided to search for HDO on Mars and compare the resulting abundance with that of H_2O to determine D/H.

Using the Fourier transform spectrometer with the Canada-France-Hawaii 3.6-m telescope at Mauna Kea, we detected many lines of the *P*- and *Q*-branches of the ν_1 fundamental of HDO near 3.7 μm (Fig. 1). The observations were made on 10 January 1987 UT, when the Doppler shift for martian lines relative to their broader telluric counterparts was 0.125 cm^{-1}. At our unapodized resolution of 0.030 cm^{-1}, the two sets of lines were unambiguously separated. Eight separate scans of 16 min each were recorded with 5-arc-s apertures in a beam-switched mode, for a total integration time in excess of 2 hours. The co-added and apodized spectra yielded a final spectrum with a signal-to-noise ratio of approximately 200 in the continuum and a spectral resolution of 0.036 cm^{-1}. Our ability to detect the martian lines was aided by the low amount of precipitable water in Earth's atmosphere above Mauna Kea (about 0.3 mm) at the time of our observations.

We have analyzed these data using room-temperature line strengths (*5*) that we adjusted to an average atmospheric temperature of 200 K (*6*, *7*). We derived the total, integrated line-of-sight column density of HDO on Mars by first taking the ratio of the apodized martian spectrum to a lunar spectrum that was recorded during the same night, and then fitting this ratioed spectrum with a synthetic spectrum of Mars in which we could vary the amount of HDO. For the calculation of the synthetic spectrum, we assumed that the spectrum followed a simple reflecting-layer model. Jakosky and Farmer (*7*) showed that the water-vapor abundances they derived were unaffected by dust, except during global dust storms, as long as their viewing angle was less than 60°. In the 3 months before our observations, a period that normally corresponds to the dust-storm season on Mars, no global dust storms were observed (*8*). Furthermore, we easily observed albedo contrasts on the disk of Mars during the nights of our observation, which supports the clear atmosphere assumption to the extent that we require it.

The contribution of thermal radiation from Mars was estimated in the computation of the synthetic spectrum by the following method. We adopted a geometric albedo of 0.17 with an infrared phase function of 0.5 (*9*), which corresponds to the 40° phase angle of our observations. Assuming an average ground temperature of 245 K (*10*), we estimated that the thermal flux contributed about 12% of the total martian flux that was recorded near 2720 cm^{-1}. As an additional check, we compared several solar lines that were also observed in our martian spectrum in this region with the same lines in a solar spectrum that was recorded with the ATMOS spectrometer on the Shuttle-based Space Lab (*11*). The solar lines in the martian spectrum were generally weaker than in the direct solar spectrum. The difference can be accounted for by a martian thermal flux that is, on the average, about 11% of the total flux, which is in good agreement with our first estimate. Correction for this thermal flux changed the calculated abundance of HDO by only 5%.

Twenty-two lines of HDO were analyzed, eleven in each of the *P*- and *Q*-branches. Additional lines of HDO were detected, but they were either too weak to be useful or blended with lines of CO_2 isotopes in the martian atmosphere. Our best fit was obtained for a total, integrated line-of-sight column density of 3.6×10^{-2} precipitable micrometers of HDO (Fig. 2). The uncertainty in this column density is derived from three major sources. First, the random error associated with a signal-to-noise ratio of 200 in the continuum of the HDO spectrum

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