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Long-Term Downward Trend in Total Solar Irradiance

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The first 5 years (from 1980 to 1985) of total solar irradiance observations by the first Active Cavity Radiometer Irradiance Monitor (ACRIM I) experiment on board the Solar Maximum Mission spacecraft show a clearly defined downward trend of −0.019% per year. The existence of this trend has been confirmed by the internal self-calibrations of ACRIM I, by independent measurements from sounding rockets and balloons, and by observations from the Nimbus-7 spacecraft. The trend appears to be due to unpredicted variations of solar luminosity on time scales of years, and it may be related to solar cycle magnetic activity.

The total solar irradiance of the earth is the primary determining factor of climate. Sustained variations from the present average value could alter the terrestrial environment. Systematic changes in irradiance of as little as 0.5% per century can cause the complete range of climate variations that have occurred in the past, ranging from ice ages to global tropical conditions (*1*). Knowledge of solar trends is important for understanding the interaction between solar variability and terrestrial climate-forcing phenomena, such as natural or man-made changes in atmospheric composition.

Our present knowledge of the interior of the sun does not allow for accurate predictions of solar luminosity (which we assume to be proportional to the total solar irradiance measured at the earth over long time scales). We must therefore depend on high-precision observations of the solar irradiance over time scales of climatological significance to understand the sun's role in climate variability. The secondary objective of compiling an irradiance database is to improve knowledge of solar physical processes that could provide a predictive capability for solar irradiance variations.

The modern high-precision database on solar total irradiance was started in 1980. It used data from the first Active Cavity Radiometer Irradiance Monitor (ACRIM I) experiment on the National Aeronautics and Space Administration's (NASA) Solar Maximum Mission (SMM) spacecraft (*2*). These observations have a precision of a few parts per million per day, based on the statistics of about 400 time-averaged samples per day. The ACRIM I observations now extend over a period of about one-half of a solar sunspot cycle.

Some observed irradiance variations have been related to known solar phenomena. The largest deviations from the mean are temporary decreases in irradiance of up to 0.25% on time scales of days, which have been shown to have a clear correlation with sunspots (*2–4*). A facular signal is also present at the level of +0.1% or less on time scales of weeks to months (*4–6*), but it is not as well understood, partly because of its smaller amplitude and the poor record of facular presence and properties.

Table 1. Results of sounding rocket and balloon solar irradiance reference experiments shown as the difference between their ratios, and SMM/ACRIM I observations taken on or near the same day.

Mission day*	ACRIM I (W/m^2)	ACR rocket (ppm)	PMOD balloon and rocket (ppm)
141	1368.5	−365	
1275	1367.4		−293
1437†	1367.5	−73	−585
1806	1367.0	73	−146
Average		−122	−341
SD		223	223

*SMM day count beginning with 1 January 1980. †The ACRIM I result from day 1434 was used since it was the nearest available.

On a shorter time scale the ACRIM I data reveal that solar global oscillations with a period near 5 minutes produce detectable irradiance variations with amplitudes for low degree modes of up to a few parts per million in the total irradiance (*7, 8*). These oscillations appear as resonance peaks in the power spectrum, superposed on a continuum of variation assumed to be due to the granulation and other atmospheric structures of the sun in the absence of significant solar magnetic activity (*9*).

This report focuses on the longest ACRIM I time scale, extending from the launch in February 1980 to the end of 1984, approximately one-half of an 11-year sunspot cycle. We provide a characterization of the slowest variations observed from the ACRIM I data. The longest time scales present the most difficulty for sustaining instrument calibration, but they are at the same time potentially the most important from the point of view of geophysical or astrophysical consequences.

The ACRIM I database used is essentially the same one published by the National Oceanic and Atmospheric Administration (NOAA) in *Solar-Geophysical Data* and described by Willson (*2, 4, 5*). The database derived from the observations consists of

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averages over the last half of individual shutter cycles. Shutters over active sensors open or close about every 65 seconds, producing solar observations separated by 131 seconds. About two-thirds of the orbital period of 96 minutes is useful for solar observations. Data reduction consists of making corrections for instrument temperatures, sun-satellite distance (*10*), and for relativistic effects of the sun-satellite velocity (*2*).

The resulting time series, shown in Fig. 1, has 1520 daily averages in a total span of 1781 days over the 5-year period (from 1980 to 1985). During normal satellite operation with precise solar pointing, up to 2×10^5 samples of primary sensor data per day were acquired from each of the three ACRIM I detectors (*11*). The SMM satellite experienced a period of spin stabilization (spin mode) between the failure of three-axis stabilization in November 1980 and its repair by the NASA space shuttle in April 1984, during which an average of only 100 samples per day were acquired. Reduced sampling is responsible for the increased scatter between adjacent daily mean values during this interval (shown in Fig. 1). The data sampling returned to 2×10^5 samples per day in April 1984 after repair of the SMM satellite. The data quality and quantity at the beginning and end of the database are sufficient that measurement errors are essentially negligible. The scatter seen in these points is due almost entirely to intrinsic solar variations.

The SMM/ACRIM I spin-mode data have a different sampling pattern as well as a different frequency. In the spin mode, shutters over active sensors were opened at orbit sunrise and closed at sunset. The satellite, not designed for spin stabilization, rotated and precessed slowly about the solar line of sight, occasionally allowing the sun to pass through ACRIM I's field of view (*12*). Sufficient time for acquisition of data occurred when the sun crossed near ACRIM I's optical axis. Differences in both duration of solar exposure and in sensor thermal response to off-axis irradiance produced a systematic offset of +0.12% (±0.02%) in the solar irradiance results derived from the spin mode, relative to the solar-pointed mode (*13*). This offset has been removed from the results shown in Fig. 1.

As shown in Fig. 1, a downward trend exists in the results. Since the ACRIM I measurements are absolute observations, they are susceptible to drifts, so the possibility of an instrumental effect causing the trend must be explored.

The ACRIM I instrument contains three nominally identical sensors, each an absolute detector in its own right, with independently operated shutters. Sensor A is the continuously observing detector. The shutters of sensors B and C are normally closed except for infrequent intercomparisons that are designed to calibrate optical degradation of sensor A.

Figure 2 shows the ratios of simultaneous readings from two or more ACRIM I sensors during the data-collecting period. The results depicted are the change in ratios relative to the initial baseline comparison of all three sensors conducted 17 days after launch. They show a relative reproducibility for the reference sensors (B and C) on the order of a few parts per million (root-mean-square) over the time span studied. The B/C ratios have been used to correct sensor A's results for the slow degradation of its absorbing surface (caused by prolonged exposure to the space environment) and to eliminate the degradation as a possible cause of the trend.

The other potential instrumental cause of an apparent trend is a drift in the analog-to-digital conversion electronics. The long-term behavior of two precision reference voltages in ACRIM I's electronic system indicates that the analog-to-digital conversion process was at least as stable as the optical properties of the reference sensors over the same time period.

The results from these two internal reference systems provide strong evidence against an instrumental cause of the drift. Although the probability of an instrumental cause is small, the possibility of common degradation of the optical properties of all three sensors or the two reference voltages

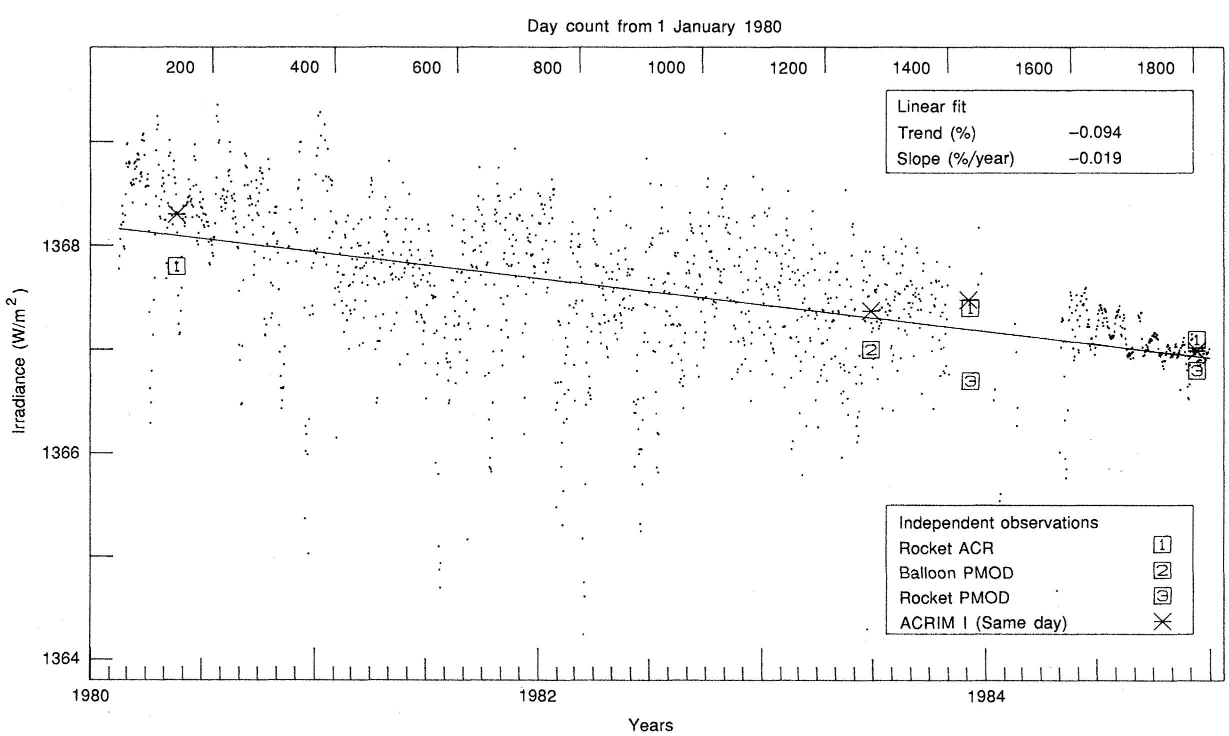

Fig. 1. Time series of SMM/ACRIM I daily mean results for the period from 1980 to 1985. Standard errors of the daily means increased from 0.0001 to 0.0005% from 1981 through 1983 due to a much lower rate of data acquisition during this period of "wobbly" spin stabilization of the SMM spacecraft. The linear least-squares fit shown has a slope of −0.019% per year. Independent total irradiance observations by sounding rocket and balloon experiments show generally good agreement with the ACRIM I results (with a linear least-squares fit slope of −0.014% per year). PMOD, Physikalisch-Meteorologisches Observatorium, Davos.

Table 2. Comparison of the trend computed by linear least-squares fits to total solar irradiance results from the SMM/ACRIM I, Nimbus-7/ERB, and sounding rocket and balloon reference experiments.

Experiments	Trend (% year)	No. of samples	SD (% year)
SMM/ACRIM I	−0.019	1520	0.0009
Nimbus-7/ERB	−0.015	1370	0.0009
Rocket and balloon	−0.014	6	

cannot be excluded. Therefore, a search for other, independent data relevant to the trend was conducted.

The need to periodically calibrate the SMM/ACRIM I experiment was addressed by a NASA sounding rocket program in which flight experiments that used another Active Cavity Radiometer (ACR) instrument were conducted in 1980, 1984, and 1985. In addition, a Swiss solar total irradiance experiment *(14)* developed by the World Radiation Center at Davos was flown on a high-altitude balloon in 1983 and was included on the payload of the NASA rocket flights in 1984 and 1985. The rocket flights provided between 5 and 8 minutes of solar data at altitudes between 200 and 300 km, obviating the need for atmospheric attenuation corrections. The 1983 balloon flight provided several hours of solar data above 40 km with in situ measurements of overlying ozone, the major attenuating atmospheric component at that altitude.

Results from the set of six reference flights are shown in Fig. 1 and summarized in Table 1. The 1984 and 1985 rocket results are the most precise and reproducible of the set. A linear least-squares fit to the six reference observations yields a slope of −0.014% per year, similar in magnitude and direction to those computed for ACRIM I and Nimbus-7/Earth Radiation Budget (ERB) experiments. The small number of samples precludes meaningful statistical analysis of the rocket and balloon trend.

We conducted an experimental effort to obtain independent, quantitative evidence of the relative precision of the rocket and balloon experiments over the period from 1980 to 1985. For this approach we used pre- and postflight ground calibration experiments at the Jet Propulsion Laboratory's Table Mountain Solar Test Facility. In these experiments the relative performance of the flight sensors and of an international set of reference sensors was compared. The results of these tests have provided a reproducibility of the rocket flight sensors over the 5-year period of ±0.05%, a precision apparently inferior to that of the reproducibility of the flight experiments themselves *(15)*.

To search for other correlative evidence for the trend, we intercompared the ACRIM I results and those of another satellite solar irradiance experiment, the Hickey-Frieden solar total irradiance sensor, part of the NOAA Nimbus-7/ERB experiment.

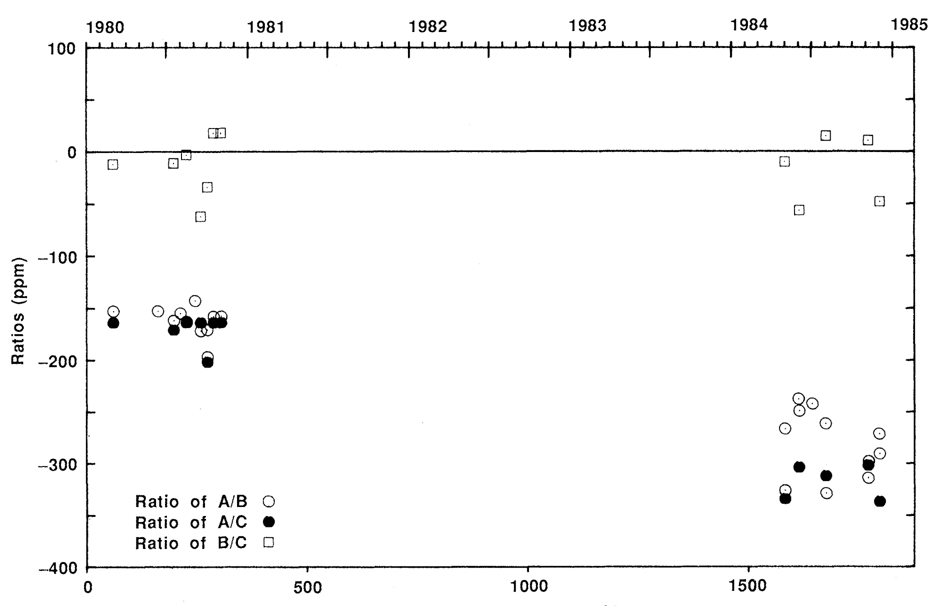

Fig. 2. Results of SMM/ACRIM I self-calibration by periodic comparisons of irradiance data acquired by its three independent ACR sensors. Ratios are shown relative to initial comparisons conducted shortly after launch. Sensor A has operated almost continuously throughout the interval. Sensor B is compared with A about once per month. Sensor C is used less frequently to minimize its exposure to solar UV. Sensor A exhibits degradation of about 300 ppm over the 5-year period, whereas sensors B and C show no significant degradation. The results in Fig. 1 have been corrected for sensor A's degradation.

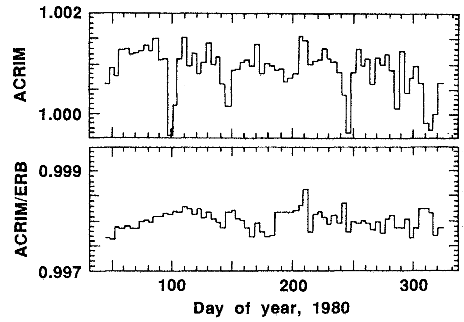

Fig. 3. Comparison of 4-day means of ACRIM I observations in 1980 (upper panel, ratio to 1367 W/m^2) to simultaneous data from the Nimbus-7/ERB total irradiance experiment (lower panel). For the ERB data, we took a weighted mean over sets of three consecutive observation days and then matched this mean with the three simultaneous ACRIM I daily means. No apparent trend occurs in the ratio, which implies that the early ACRIM I data did not experience special conditions shortly after the instrument was turned on.

The long-term ERB results show a trend over the same period of −0.015% (±0.001%) per year, close to the observed ACRIM I trend *(16)*.

To further evaluate the quality of agreement between the SMM/ACRIM I and Nimbus-7/ERB experiments, their results for 1980 were compared (since overlapping data are available for this period of maximum quality for both experiments). Weighted 4-day means were used to minimize bias arising from the difference between ACRIM I and ERB observing patterns (ERB is operated only during 3 out of 4 days). The results (Fig. 3) demonstrate remarkable consistency, even though the absolute values of their means differ by about 0.2%. The scatter of the ratios between ACRIM I and ERB results during 1980 remained within 100 ppm peak-to-peak, supporting the internal calibration results of the ACRIM I experiment.

Comparison of SMM and Nimbus-7 data indicates that neither ultraviolet (UV)-induced nor vacuum-induced instrument degradation explains the observed trend. The close agreement of ACRIM I and Nimbus-7 results rules out instrument degradation due to UV exposure as an explanation of the trend, since Nimbus-7 observes the sun on a far smaller duty cycle. This agreement and the constant ratio (Fig. 3) over the first 250 days of ACRIM I operation strongly indicate that there is no significant residual of uncorrected degradation in the ACRIM I results that is caused by exposure to vacuum.

The above arguments support a solar source of the trend seen by the SMM/ACRIM I experiment. We approach this conclusion with caution since the observed effect is comparable to the absolute errors of measurement and the independent reference flight data (Table 1) are undersampled and not fully supported by pre- and postflight ground testing observations of adequate precision.

Two principal impediments occur when characterizing trends. First, there is a spectrum of variations on shorter time scales whose root-mean-square amplitudes are comparable to the magnitude of the 5-year trend. The variance of the data is not Gaussian and therefore normal statistical inferences cannot be made. Second, the pointed-mode and spin-mode data have different systematic and random uncertainties, so a common, in-depth statistical analysis for the combined set is of questionable value. The most straightforward approach to abstracting the trend is to find the best straight-line fit to the data. We have done this for the ACRIM I experiment, balloon and sounding rocket flights, and Nimbus-7/ERB results, as summarized in Table 2.

The general agreement among the slopes of the three data sets supports a solar rather than instrumental explanation for the trend. Although failure of the ACRIM I and Nimbus-7/ERB slopes to agree within the bounds of their mutual standard errors, and the lower slope value of the rocket and balloon results, do not add credibility to the actual value of the slope derived from the ACRIM I experiment, the statistical uncertainties in Table 2 do not precisely describe the quality of agreement. The six rocket and balloon results are insufficient to support a meaningful statistical argument. Although the statistics for the ACRIM I and ERB results are based on sufficient samples, the simple statistics do not address the more fundamental issue of long-term accuracy of these databases. The ACRIM I observations of 1980 and 1984 onward can be related with a precision equal to the results of intercomparisons of ACRIM I sensors (10 ppm, root-mean-square). No comparable data are available for the ERB database during this period since no internal comparisons are possible with its single sensor.

The ACRIM I data now extend over nearly one-half of the 11-year solar cycle. These data give an accurate and precise view of the variations of total solar irradiance. Over the 5 years of daily mean values analyzed, the total irradiance systematically decreased, and its average value was reduced by about 0.1%.

The trend may be a luminosity dependence on the solar magnetic cycle of activity: either the 11-year sunspot cycle, the 22-year full magnetic cycle (*17*), or longer variations related to solar magnetic effects. The rate of variation observed thus far is not inconsistent with the currently accepted theory of solar interior structure.

Past climate variability would seem to preclude a lengthy continuation of the present downward trend of solar luminosity. Even for solar cycle time scales, however, the present database is so short that one can only speculate on the nature of the variation. But if the trend is related to the solar cycle, the positive relation between total flux and sunspot activity appears to agree with that inferred from the maunder minimum (*1*). Sunspots also exhibit a strong inverse correlation with the total irradiance on short time scales (*2, 3*), and if this effect were incorporated into our analysis, it would increase the magnitude of the observed trend.

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Pertussis Toxin–Sensitive Pathway in the Stimulation of c-*myc* Expression and DNA Synthesis by Bombesin

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The bombesin-like peptides are potent mitogens for Swiss 3T3 fibroblasts, human bronchial epithelial cells, and cells isolated from small cell carcinoma of the lung. The mechanism of signal transduction in the proliferative response to bombesin was investigated by studying the effect of *Bordetella pertussis* toxin on bombesin-stimulated mitogenesis. At nanomolar concentrations, bombesin increased levels of c-*myc* messenger RNA and stimulated DNA synthesis in Swiss 3T3 cells. Treatment of the cells with pertussis toxin (5 nanograms per milliliter) completely blocked bombesin-enhanced c-*myc* expression and eliminated bombesin-stimulated DNA synthesis. This treatment had essentially no effect on the mitogenic responses to either platelet-derived growth factor or phorbol 12,13-dibutyrate. These results suggest that the mitogenic actions of bombesin-like growth factors are mediated through a pertussis toxin–sensitive guanine nucleotide–binding protein. Furthermore they indicate that bombesin-like growth factors act through pathways that are different from those activated by platelet-derived growth factor.

IN RECENT YEARS, SEVERAL GROWTH factors for mesenchymal and epithelial cells have been identified. Included among these factors are bombesin and related peptides that are potent mitogens for cultured Swiss 3T3 cells (*1*), human bronchial epithelial cells (*2*), and several cell lines derived from human small cell lung carcinomas (SCLC) (*3–5*). These peptides, which are normally found only in neuroendocrine cells of the central nervous system and the gastrointestinal tract (*6–10*) and in the mucosal endocrine cells of fetal and neonatal lung (*11*), have been found in a number of human tumors including SCLC (*12–15*). Antibodies to bombesin inhibit the growth of these transformed cells in cell culture and block tumor progression in whole animals (*5*). Taken together, these data suggest that bombesin-like peptides participate in the regulation of cell proliferation and act as autocrine growth factors for human SCLC.

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