Irradiance Observations of the Sun

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Measurements of the total solar irradiance during the last 14 years from satellites show variations over time scales from minutes to years and decades. The most important variance is in the range from days to several months and is related to the photospheric features of solar activity: decreasing the irradiance during the appearance of sunspots, and increasing it by faculae and the bright magnetic network. Long-term modulation by the 11-year activity cycle is observed conclusively with the irradiance being higher during solar maximum. The accuracy of the determined variability and its interpretation in terms of manifestations of activity related features on the photosphere is discussed. Besides the direct influence of the spots, faculae and magnetic network more profound changes in the thermal transport seem to influence the behaviour of the solar photospheric radiation on the solar cycle and longer time scales.

1. Introduction

The irradiance from the Sun at the mean Sun-Earth distance, integrated over all wavelengths, hence total irradiance, is traditionally called "solar constant" S although it has been shown to vary on time scales from minutes to decades (see e.g. Fröhlich 1993). 'All wavelengths' means essentially the energetically important range from 200 nm to 5μm containing 99.9 percent of S. The measurements from satellites discussed here (until the end of 1992) have been performed by the radiometer HF of the Earth Radiation Budget Experiment (ERB) on the NIMBUS-7 satellite since November 16, 1978 (Hoyt *et al.* 1992), by ACRIM I on the Solar Maximum Mission Satellite (SMM) from February 14, 1980 until June 1, 1989 (e.g. Willson & Hudson 1991), by ACRIM II on the Upper Atmospheric Research Satellite (UARS) since October 1991 (Willson 1994) and by PMO6/SOVA2 on the European Retrievable Carrier (EURECA) since August 11, 1992 (Romero *et al.* 1994). For comparison, the rocket and balloon experiments by JPL and PMOD/WRC are included in the discussion. These experiments were used in 1986 to prove that the downward trend of the solar irradiance during the declining phase of the cycle 21 was real and not instrumental (Willson *et al.* 1986). The selection of the experimental data is somewhat arbitrary and represents rather the author's familiarity with them than other criteria.

2. How accurate is the variability?

Time series of the measured irradiances are plotted in Figure 1 and illustrate the variability on all time scales. The differences among the experiments are due to their absolute calibrations which are accurate to 'only' about ±0.2% and do not reflect the precision and stability of the instruments which are obviously much better. The time series of the two ACRIM instruments demonstrate also the difficulty to bridge gaps; again due to the limited absolute accuracy: Willson (1994) has to adjust the ACRIM II measurements in order to get a homogeneous data set covering the whole period of ACRIM I and II. The HF time series is essentially uninterrupted and can be used as reference, although it cannot be proven that the sensitivity of HF has no long-term trend. The comparison between HF and ACRIM I and II is shown in Figure 2. There are obvious

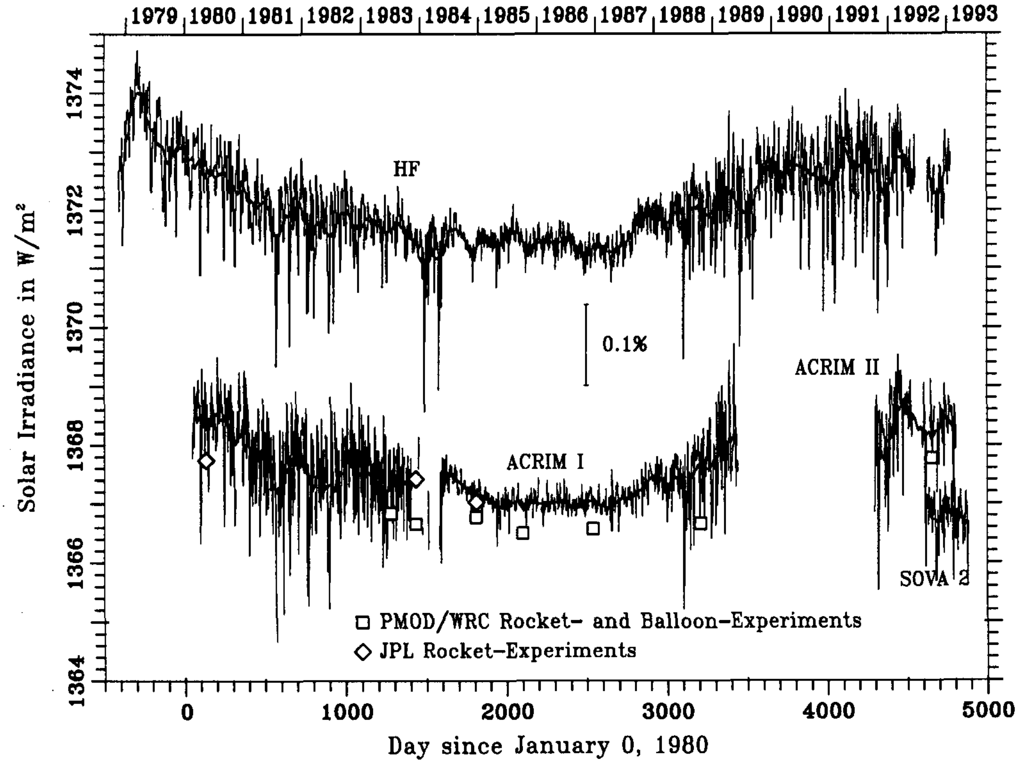

FIGURE 1. Time series of ACRIM I and II, HF and PMO6/SOVA 2 total solar irradiance measurements from November 1978 to beginning of 1993. The individual points represent daily mean values, the heavy line the 81-day running mean. Furthermore, the results of the rocket and balloon experiments of JPL and PMOD/WRC are plotted.

departures of up to 500 ppm (about half the solar cycle's amplitude) in these results which ask for explanation. During period from the end of 1980 until spring 1984 the SMM satellite was not pointing properly, thus ACRIM I had to be operated in a different mode and much less data have been acquired; this obviously increases the noise. During the solar minimum e.g. NIMBUS-7 shows much larger variations than ACRIM I (see also Figure 1). It is obvious from comparison of both time series that ACRIM (disregarding the 'non-pointing' period of SMM) shows much lower noise than HF; the latter is more noisy due to higher contributions from instrumental and operational effects, but also due to the fact that the observation time per orbit is much shorter. The modulation during the solar minimum, which is sensed by HF with a greater amplitude, is part of a more or less periodic signal with a period of about 300 days persisting throughout the measurement period. Besides the possibility that this is an interesting solar feature (see also Section 3), the ratio of its amplitude as measured by HF and ACRIM varies with time. This could be due to a modulation of the sensitivity by e.g. the distance change on the Earth' orbit around the Sun and a related temperature effect in one or both radiometers which is not fully accounted for by the applied corrections. The short observation and exposure time of HF may hide such an effect, whereas for ACRIM the 60 minutes of observation allow to analyze the orbital behaviour of the instrument in detail. There are other differences, especially during the period of ACRIM II where a gradual increase of the latter relative to HF is observed. These may still be due to some residuals of the 'inverse degradation' observed in ACRIM II (Willson 1994) but the applied correction would need to be increased by about 50% which seems unlikely. The decreasing ratio may also be due to a degradation of the HF cavity's absorptance during the high solar fluxes encountered before their rapid drop in spring 1992. These still not fully understood uncertainties underline the importance for having more than one and better three experiments simultaneously in space in order to cross-check the results and to tie new experiments into existing data basis.

The results of the rocket and balloon experiments were able to confirm the decrease of the solar radiation during the declining phase of cycle 21. A major drawback of these measurements is that they are rather short – a few minutes for a rocket and generally a few hours for a balloon flight – and a truly simultaneous comparison with an instrument on board an orbiting satellite may not be possible. The latter is a prerequisite for accurate comparison due to the short term variations of solar irradiance. Together with the limited accuracy of a radiometer working in a rapidly varying thermal environment during a rocket experiment or the limitations of the atmospheric corrections still needed for a balloon flight, an overall precision and repeatability of somewhat less than 0.1% can be achieved. This was sufficient for the downward trend, but is not enough to settle the above mentioned differences between space experiments or to assess solar irradiance variability over periods of more than a few years accurately. These uncertainties have to be kept in mind when the results of modelling solar variations are discussed.

3. Influence of solar activity on irradiance variations

The dominant feature in the time series is the 'dip', a negative excursion of a few days' length and a depth ranging up to a few tenths of a percent of the irradiance. These dips result from sunspot groups rotating past the central meridian and have been noticed in data sets as early as in the ones from Mariner VI and VII. But only the prominent dips observed by ACRIM in April and May 1980 convinced the community that sunspots can produce such large depressions. Willson *et al.* (1981) described them in terms of the Photometric Sunspot Index, the *PSI* function, similar to the models of sunspot darkness noted earlier by Foukal & Vernazza (1979) and Hoyt & Eddy (1982). Hudson & Willson (1982) define this photometric index as the sum of the projected areas of the sunspots multiplied by a factor α taking into account the umbra/penumbra area ratio and the effective temperature of the sunspot relative to the photosphere, in the simplest way possible. An improved *PSI* calculation has been presented by Fröhlich *et al.* (1994). The major improvement is due to screening of the observations from outliers which improves the homogeneity of the data set substantially, at least for the period after December 1981 when NOAA started to report data from several stations instead of one to two stations only. Moreover, these calculations take into account the area dependence of the contrast α and calculate 'true' daily means for each observation using the latitude dependent surface rotation of the spots. The correlation between the newly calculated *PSI* and total solar irradiance using bi-variate spectral analysis yields a major improvement due to the screening of the data (an increase in coherence of about 5-10%) and a minor one due to the more sophisticated methods (1-2%) as shown by Fröhlich *et al.* (1994). Furthermore, this study has been performed for different phases of solar cycles 21 and 22. This analysis shows that the gain, the factor by which *PSI* has to be multiplied to yield the observed irradiance change, is time dependent. It changes from about 0.6 in 1980 to 1.1 in 1990 and cannot be interpreted by a change of the contrast relative to the quiet Sun (as it is normally defined and determined by direct photometry), but rather as a change of the contrast between the spots and their surrounding as seen in

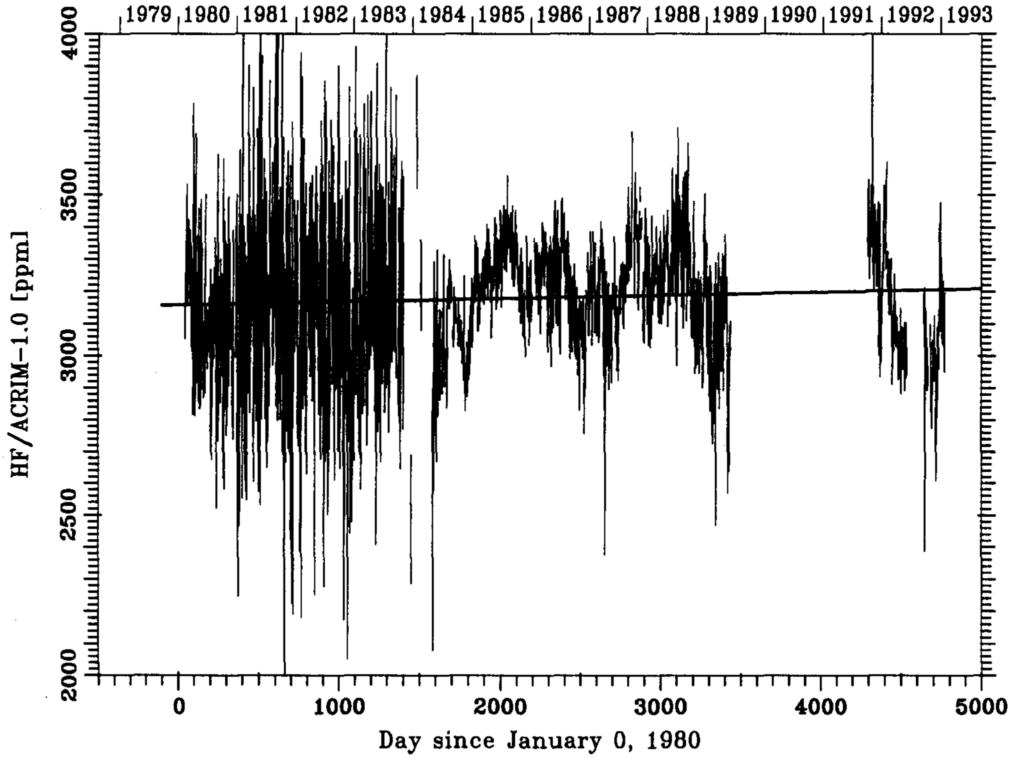

FIGURE 2. Comparison of ACRIM I & II and HF total solar irradiance measurements from February 1980 to end of 1992.

total irradiance (integrated over the solar disk). Part of this change is possibly due to a change in the spot to facular area ratio. But, independent of its interpretation, this time dependent factor can be used to calibrate the *PSI*, which then is used to subtract the effect of sunspots from the irradiance observations. The result of the subtraction of the calibrated *PSI* is shown in Figure 3 for both the ACRIM and HF data. The differences between the two data sets with a quasi-period of 300 days were already discussed in section 2 and Figure 2 and are clearly seen during the minimum and the rising part of cycle 22.

Several ideas and models have been put forward to explain these quasi-periodic variations and the solar cycle modulation. One approach is to account for the variations in terms of the effects that magnetic flux tubes seem to have on the radiation and convection in the relatively shallow photospheric layers that emit most of the Sun's luminosity. A relatively straightforward approach to both the 6 month and 300 days quasi-periodic and the 11-year variations has been proposed by Foukal & Lean (1988) and Willson & Hudson (1988). In these studies, it was shown that the residual irradiance variations of $S + PSI$ correlate quite well with the time-series of properly scaled He I index or the 10.7 cm radio flux. This is not surprising since facular area variations were previously shown to account also for shorter term variations in these residuals. Thus, one may conclude that the 6 and 10 month variations are caused by the tendency of major complexes of activity to persist for about this number of months or solar rotations. This time scale in persistence of solar activity episodes has been documented before in studies of the He I index time series by Harvey (1984). These variations are also found by the multivariate

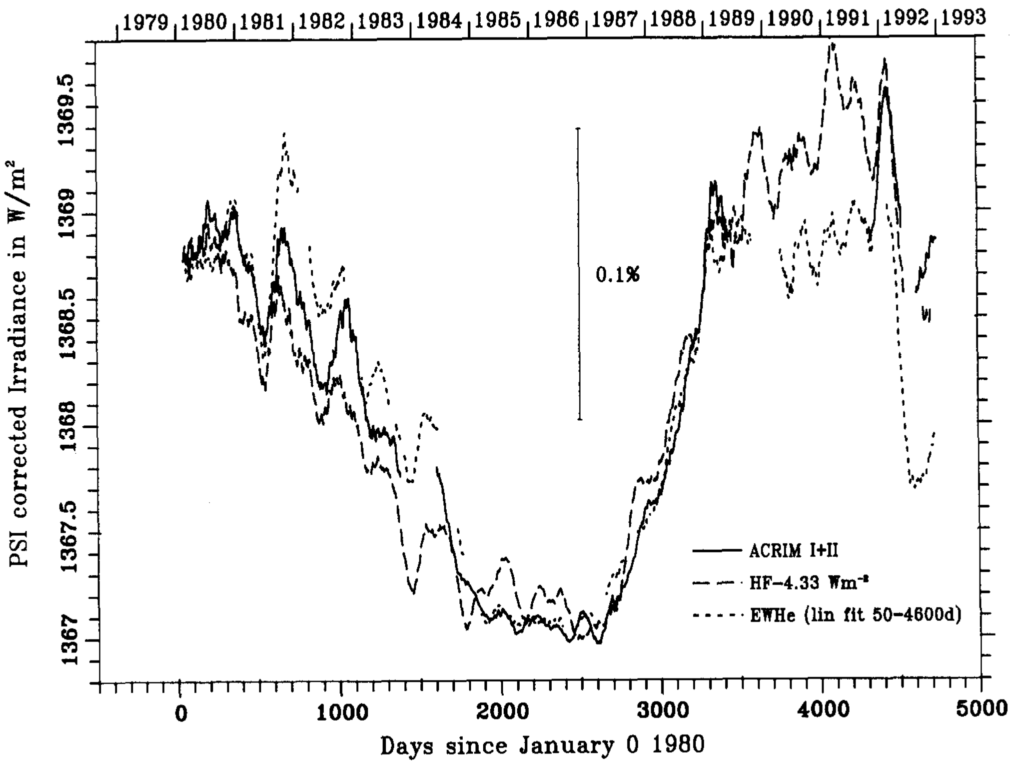

FIGURE 3. Solar irradiance measured by ACRIM (full line) and HF (long dashed line) with the effect of the sunspots removed ($S + PSI$, 81-day running mean). The short dashed line represents the result of the linear regression of the He I index with ($S + PSI$) for the time period Feb. 1980–Aug. 1992.

spectral analysis of the 9 year time series of ACRIM with PSI and He I (Pap & Fröhlich 1992; Fröhlich 1993). The part of the power density explained by He I has a large peak of about 80% at a period of 190 days and a broader peak with about 65% between periods of 250–450 days. This indicates that the 6 month and the 300 day quasi-periodic modulation is indeed due to the bright network and faculae. The solar cycle modulation has to be associated with some kind of a slow change in the solar atmosphere. The simplest explanation is a slow variation in the amount of the bright magnetic network outside active regions as shown by e.g. Foukal *et al.* (1991). This was mainly supported by the success of the modelling of $S + PSI$ by the He I index until about 1989, the end of the ACRIM I record (see e.g. Figure 6 of Fröhlich 1993). But, when the fit is either performed over the full period (1980–1992) or limited to the period of the declining phase of cycle 21 and the result used for the whole period, the model values fall short of the irradiance by as much as 25% around 1991. In the case of the fit over the whole period the model further overestimates the irradiance during the declining phase of cycle 21, as shown in Figure 3.

4. More detailed analysis of the solar cycle variation

In order to get more insight in the behaviour of the relationship between irradiance and He I the full period has been divided into the following intervals: 6 Feb 1980 – 13

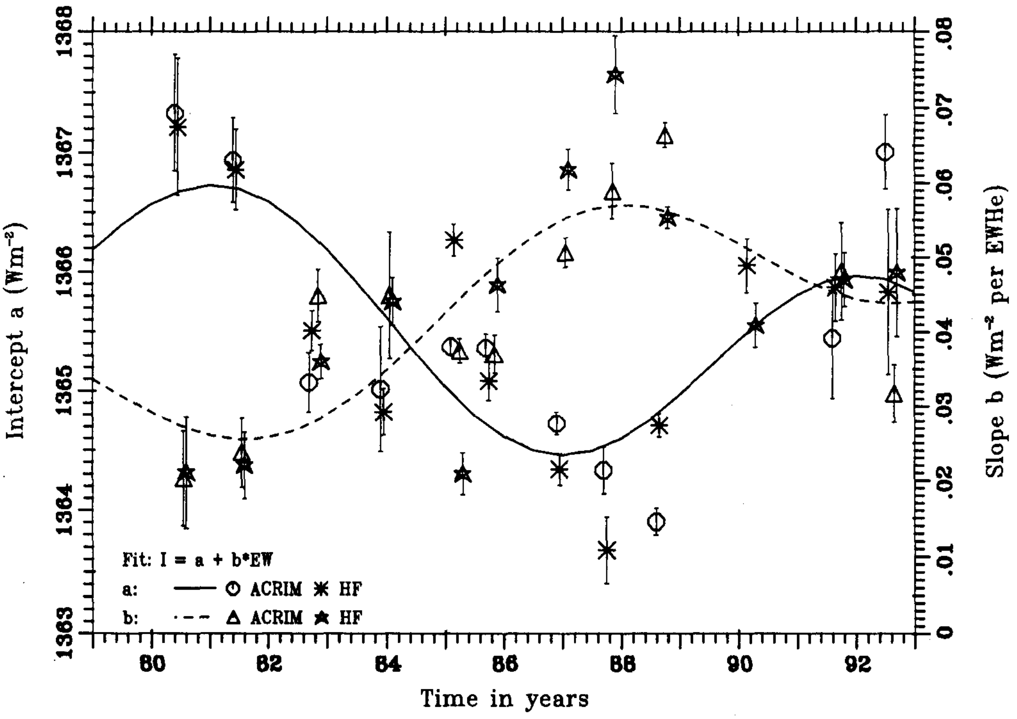

FIGURE 4. Linear regression analysis of irradiance against He I for different time intervals with $\pm 1\sigma$ error bars: the full line represent the results for the intercept a (left hand scale); the broken line the ones for the slope b (right hand scale).

Nov 1980; 1 Jan 1981 – 31 Dec 1981; 1 Jan 1982 – 30 Jun 1983; 1 Jul 1983 – 30 Jun 1984; 1 Jul 1984 – 31 Dec 1985; 1 Feb 1985 – 31 Mar 1987; 1 Jan 1986 – 31 Dec 1987; 1 Apr 1987 – 31 Mar 1988; 1 Jan 1988 – 31 May 1989; 1 Jun 1989 – 31 Dec 1990; 1 Jan 1991 – 1 May 1992; 1 Jan 1992 – 25 Feb 1993. The choice of these intervals is mainly dictated by the availability of data in the sense that gaps are excluded and they coincide with the periods analyzed for the PSI analysis (Fröhlich *et al.* 1994). A linear regression analysis between irradiance I and He I EW is performed according to $I = a + b \cdot EW$. The results for the slope b and the intercept a are shown in Figure 4 for each interval. The full and broken lines represent a fit of the slope and intercept respectively with an 11 year period sine-wave superimposed on a linear trend. Interesting enough, the slope b is increasing with time in a very similar manner as the contrast in the PSI representation of the spot influence: it is low in 1980/81, increasing until 1988 and slightly decreasing towards 1992 (PSI contrast has a much lesser decrease). The intercept does the opposite and weakens the slope effect to some extent. As we are dealing with a factor of 3.5 between minimum and maximum slope, however, the weakening due to the out-of-phase change of the intercept does not influence the net effect very much. It is interesting to note, that Harvey (1994) has observed a similar difference between magnetic flux from the disk outside sunspots and He I. This may indicate that the He I index should be replaced by the more direct surrogate: the magnetic flux outside spots. Further investigations in this direction are planned. The irradiance reconstructed using the fitted slope and intercept is shown in Figure 5. The fit is quite good although some discrepancy seem

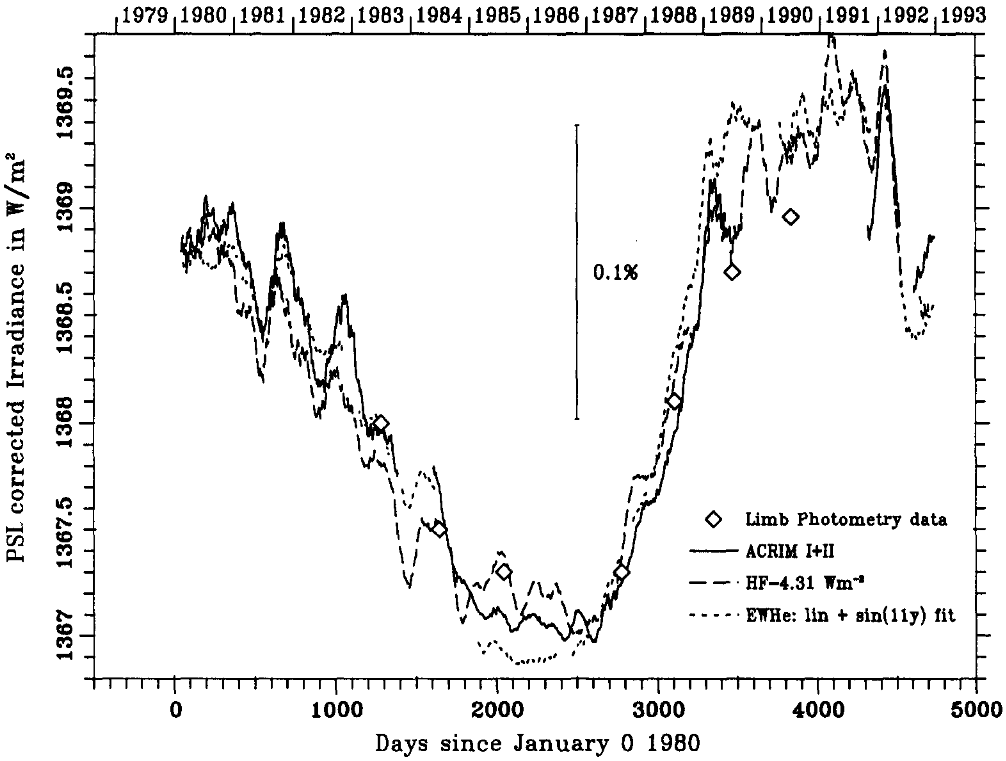

FIGURE 5. Solar irradiance measured by ACRIM (full line) and HF (long dashed line) with the effect of the sunspots removed ($S + PSI$, 81-day running mean). The short dashed line represents the result of the linear regression of He I line with ($S + PSI$) using the time varying regression parameters from Figure 4.

to be too large to be accounted for by uncertainties in the index or irradiance. Major discrepancies occurred at solar minimum and around and after the maximum of cycle 22. The discrepancy in 1980, noted earlier by Foukal & Lean (1988) has disappeared.

Kuhn *et al.* (1988) and Kuhn & Libbrecht (1991) have reported observations of the limb brightness which can be used to explain the total irradiance variation of the solar cycle. The observations are broad-band, two-color photometric measurements of the brightness distribution in a narrow annulus 20 arcsec wide, just inside the solar limb. The solar limb flux, observed as a function of latitude, can be divided into a 'facular' and 'temperature' part based on the assumptions that the 'temperature' part is constant over the 4-month observing summer period and that the 'facular' part shows up as intermittent bright regions. The component of excess brightness moves toward the equator between 1983 and 1985, and then reappears at relatively high latitudes in 1987 and again moves to the equator while it becomes brighter. The excess brightness responsible for the limb flux is due to features which are not resolved by this observation, and it could be due to the bright network in and outside active regions. The contribution of the limb flux (including the facular component) can account for the total irradiance decrease after 1983, and its increase since 1987 (Kuhn & Libbrecht 1991) as shown in Figure 5. However, there are systematic differences as e.g. the solar cycle amplitude which is smaller from the limb data than the observed one in irradiance. This could be corrected by using a slightly different limb darkening function for the translation of the limb data to full disk observations. This point should be investigated further as it may give a hint of what features are producing the solar cycle irradiance variation.

5. Conclusions

The past 15 years have seen the introduction of radiometers with sufficient precision to measure a variety of small variations of the total solar irradiance. These variations are interesting to solar physicists in several ways. In addition, the presence of a distinct 11-year modulation of total irradiance suggests that longer-term variations may be significant for the Earth's climate.

It is also important to note that the available time series is based on at least one instrument covering the full period of 14 years. Without this instrument the other time series might have been in trouble to fit new to old data with gaps of several years. The lesson learned from this is that at least one instrument should be in space to monitor the solar irradiance accurately. The understanding of the underlying physics can only be improved by comparing models with reliable continuous data.

For most of the variations physical explanations are available by e.g. Hudson & Willson (1982), Spruit (1988), Schatten & Mayr (1992). In order to better understand the reasons for the observed temporal changes of the model parameters for sunspots and other magnetic influences, however, more simultaneous studies of the detailed features on the solar disk from ground and space together with continued solar constant observations from space are needed. The Solar Heliospheric Observatory, SOHO, the next ESA/NASA solar mission, will certainly yield a major contribution to this issue. However, for the time between now and SOHO's launch in 1995 it is hoped that the existing measurements of ACRIM II will last long enough to have at least some time overlap for direct comparisons.

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