FROM SOLAR MINIMUM TO SOLAR MAXIMUM: CHANGES IN TOTAL AND SPECTRAL SOLAR IRRADIANCE

Giuliana de Toma\textsuperscript{1} and Oran R. White\textsuperscript{2}

\textsuperscript{1}LASP, University of Colorado, Boulder, COLORADO, USA
\textsuperscript{2}HAO, National Center for Atmospheric Research, Boulder, COLORADO, USA

ABSTRACT

The rising phase of solar cycle 23 from the time of minimum in 1996 to its high activity phase in 2000, is significantly different from the previous two cycles. Cycle 23 is magnetically weaker with sunspot and facular area almost a factor of two lower than in cycle 22. The evolution of total solar irradiance (TSI) relative to solar magnetic flux and activity indices is different for the rising phase of this cycle. While most activity indices are consistently lower for cycle 23, current measurements of TSI from SOHO/VIRGO and UARS/ACRIMII indicate an increase similar to the one observed during the past solar cycle. Models of TSI based on facular excess and sunspot photometry gave good TSI estimates for cycle 22, but they give TSI estimates below the observed values for cycle 23. This difference raises questions about TSI observations themselves, TSI estimates based on ground–based observations and the sources of solar radiative variability. We review the recent measurements of solar magnetism, solar activity and radiative variability from both ground–based and space observatories to give a comprehensive overview of the rising phases of both solar cycle 22 and 23.

Key words: Sun: activity, Sun: irradiance, Methods: data analysis.

1. INTRODUCTION

The solar activity cycle has been observed in sunspots for centuries, but measurements of solar irradiance and solar magnetic flux cover only two and a half cycles, i.e. cycles 21–23. Solar cycles 21 and 22 were very active cycles, but cycle 23 has been a weak cycle so far. Other cycles, such as solar cycles 9 and 17, similar to cycle 23 existed in the past, but this is the first time that a relatively weak cycle is observed with a modern array of instruments. In this paper, we analyze the rising phase of solar cycle 23, from the time of solar minimum in 1996 into its maximum phase in summer of 2000. We will describe the evolution of the solar irradiance and magnetic flux during this time and compare it to the analogous period for cycle 22. In particular, we will discuss the measurements of total solar irradiance (TSI) during the two cycles and their relationship to magnetic flux observations. Since its beginning in 1996, solar cycle 23 has been magnetically less active, with sunspot area and total magnetic flux systematically below the values for the two previous cycles. In contrast, the SOHO/VIRGO and UARS/ACRIMII experiment show an increase in TSI in 1999 larger than expected from empirical models based on sunspot and facular observations. If this “anomalous” behavior of TSI is real, it raises the question if magnetic activity in the form of sunspots, faculae, and enhanced network is the only source of solar radiative variability. Given the importance of variations in the Sun’s radiative output for the Earth’s environment, this question is relevant not only to understand the solar activity cycle, but also the solar influence on the Earth’s system.


Solar minimum between solar cycle 22 and 23 occurred in 1996. Minimal solar activity was reached in the spring and fall of 1996. These two periods had equally low solar activity and were separated by a small burst of activity of the declining cycle 22. The time of solar minimum is not a single point in time, but rather an extended period, usually lasting a couple of years, when the old and new cycles coexist and the average level for magnetic activity remains low. It is often useful for practical purposes to define the onset of a new cycle more precisely. The time of minimum for solar cycle 23 was chosen in October 1996 (Joselyn et al., 1997; de Toma, White, & Harvey, 2000). Activity remained very low until the summer of 1997, when, in two solar rotations, there was an increase in the emergence of magnetic flux in the solar atmosphere. Several new active regions appeared between August and September 1997, and there was a relatively small, but clear, increase in most indices of solar activity (Figures 2–3). Activity continued to rise in the years 1997–1999, but the
Figure 1: Evolution of the solar corona (SOHO/LASCO) and of the photospheric magnetic field (NSO/Kitt Peak) during the rising phase of solar cycle 23. At the time of solar minimum in the Spring of 1996, there are no active regions on the solar disk and only the magnetic network is visible. At the same time, the corona is weaker and coronal streamers are confined at equatorial latitudes. In March 1998, the cycle has reached a moderate activity level. We notice an increase in the coronal emission, and two bands of active regions associated with the new cycle 23 which have formed at mid-latitudes. As the cycle evolves, there is an increase in the magnetic flux emergence, and the corona assumes a more symmetric shape. The November 1999 images are at high activity: the corona is very symmetric, with streamers visible at many latitudes, and large activity complexes are seen in the Northern hemisphere of the Sun. The LASCO image on July 14, 2000 shows a coronal mass ejection (CME) event which was preceded by a large flare. The CME induced an interplanetary shock wave and caused a large (class G5) geomagnetic storm the following day. This was the largest solar particle event so far in cycle 23.
Table 1. Solar Activity Indices and Total Solar Irradiance: Yearly Values

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<tbody>
<tr>
<td>Magnetic Flux</td>
<td>7.200</td>
<td>18.898</td>
<td>21.057</td>
<td>6.743</td>
<td>15.014</td>
<td>17.075</td>
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<tr>
<td>He I 1083nm index</td>
<td>46.139</td>
<td>76.578</td>
<td>74.960</td>
<td>42.732</td>
<td>68.773</td>
<td>74.231</td>
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<tr>
<td>Mg II 280nm index</td>
<td>264</td>
<td>282</td>
<td>279</td>
<td>264</td>
<td>274</td>
<td></td>
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<tr>
<td>F10.7 radio flux</td>
<td>74.0</td>
<td>213.4</td>
<td>189.8</td>
<td>72.0</td>
<td>153.5</td>
<td>181.3</td>
</tr>
<tr>
<td>Sunspot Number</td>
<td>13.4</td>
<td>157.6</td>
<td>142.6</td>
<td>8.6</td>
<td>93.3</td>
<td>118.8</td>
</tr>
<tr>
<td>Sunspot Area</td>
<td>73.5</td>
<td>1828.07</td>
<td>1333.83</td>
<td>55.25</td>
<td>862.30</td>
<td>1425.08</td>
</tr>
<tr>
<td>Facular Area</td>
<td>28552.0</td>
<td>23369.2</td>
<td>1444.5</td>
<td>12496.6</td>
<td></td>
<td>13275.7</td>
</tr>
<tr>
<td>TSI (Nimbus 7/ERB)</td>
<td>1371.414</td>
<td>1372.299</td>
<td>1372.041</td>
<td>1365.634</td>
<td>1366.608</td>
<td></td>
</tr>
<tr>
<td>TSI (SOHO/VIRGO v2.5)</td>
<td></td>
<td>1366.038</td>
<td>1366.850</td>
<td>1366.918</td>
<td></td>
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<tr>
<td>TSI (SOHO/VIRGO v3.0)</td>
<td></td>
<td>1366.162</td>
<td>1366.976</td>
<td>1367.241</td>
<td>1367.241</td>
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*Averages for the year 2000 are based on the period January–June 2000, and are still preliminary.

rise was fairly slow, characterized by small, simple, and short-lived sunspots and sunspot groups and by a relatively low flare activity. The highest values for sunspot number and the 10.7 cm radio flux were reached in November of 1999 and again in March and July 2000. The first half of 2000, as we approached solar maximum, was characterized by higher solar activity and an increasing number of CMEs and flare events, often associated to geomagnetic storms like the storms on April 7, June 8 and July 15, 2000. The latter was a very strong geomagnetic storm, which followed an intense flare eruption and full–halo CME on July 14 (Figure 1), and has been the largest solar radiation storm so far in cycle 23. Geomagnetic storms have also been associated to coronal holes at equatorial latitudes, as on February 24 and August 28, 2000. In the spring–summer of 2000 sunspot number and 10.7 cm radio flux fluctuated a lot going from relatively high values, as on May 16 (sn = 189 and F10.7 = 264.5) and on July 18 (sn = 228 and F10.7 = 270.5), to low values, as on May 6 (sn = 50 and F10.7 = 129.1). However, the average values for sunspots, radio flux, as well as magnetic flux remain moderate and systematically below the values observed in the two previous cycles, as illustrated by Table 1 and Figures 2–3.

As the cycle progresses, the distribution of photospheric magnetic fields and the shape of the solar corona change significantly (Figure 1). A number of observations, such as the distribution of coronal streamers and of coronal holes, the topology of the unipolar magnetic fields in the polar regions, and the latitudinal distribution of sunspot regions, all indicate that in summer of 2000 we are reaching the maximum phase of solar cycle 23. Observations of the solar corona from SOHO/LASCO (Figure 1) and MLSO/MK4 show the corona has an almost symmetric configurations, typical of solar maximum. Coronal holes and helmet streamers, have been reaching equatorial latitudes since winter of 2000. In summer of 2000, the unipolar magnetic field in the polar region is weak, i.e. about 0.2 x 10^22 Mx in the North and -0.2 x 10^22 Mx in the South, according to NSO/Kitt Peak data, but has not reversed yet. Sunspots are appearing over a large range of latitudes from about 3 to 38 deg. in both hemispheres.

![Figure 2. Comparison of the observed values of the 10.7 cm radio flux for solar cycle 23, with the NOAA/NASA solar prediction made in 1997, and with the previous cycle. Solar cycle 22 data have been shifted to match the time of minimum between cycle 21 and 22 in September 1996 with the recent minimum in October 1996.](image)

Some active regions are occurring below 10 deg. and a few within 5 deg. from the equator. Solar cycle 23 has been so far much weaker than expected by the NOAA/NASA predictions made in September 1997 shown in Figure 2. Cycle 23 has shown a relatively slow rise during his ascending phase in 1997–1999, and has not reach the level of activity seen in cycle 22 and 21 yet.

2.1. Comparison of Solar Cycle 22 and 23

In Figure 3, we present the time series for the composite TSI (Fröhlich & Lean, 1997), the NSO/Kitt Peak magnetic flux data, and some common indices of solar activity. They include chromospheric indices such as the MgII core–to–wing ratio at 280 nm and He I equivalent width at 1083 nm, the coronal 10.7 cm radio flux, and the sunspot number. Average values during low and high activity for cycles 22 and 23 are given in Table 1, where we report annual averages at solar minimum and two and three years after minimum. Analysis of these observations shows that cycle 23 has been less vigorous magnetically than
cycles 21 and 22. The photospheric magnetic flux, most activity indices, as well as UV irradiance have lower values for this cycle. In particular, we note the lower values for sunspot number and area for this cycle. Observations at San Fernando Observatory of sunspot and facular area are a factor of two lower than in solar cycle 22 (Figure 4, and Table 1). This is consistent with the magnetic flux measured at NSO/Kitt Peak, and with the weaker effect of sunspot passages on TSI. However, the relative increase in TSI from minimum to maximum is about the same for both cycle 22 and 23.

3. TOTAL SOLAR IRRADIANCE

In Figure 5, we note the decrease in the effect of sunspot disk passages on TSI during the rise of cycle 23 compared to the corresponding phase of cycle 22, as expected from the photometric observations of sunspots which indicate a decrease in the number of large spots and spot groups. Despite the weaker effect of sunspots on TSI, the relative increase in TSI in 1999–2000 is similar to the one observed during the maximum phase of cycle 22. Empirical models based on sunspots and faculae, which well represented TSI observations during the last solar cycle, fail to explain completely the observed rise in TSI during the present cycle.

3.1. Observations and Models

Measurements of TSI from SOHO/VIRGO v2.5 showed an early increase in TSI starting at the end of 1996 and continuing in 1997. At the end of 1999, the observed increase in TSI was already 1 Wm$^{-2}$, and comparable to the increase observed in TSI by Nimbus-7/ERB during the maximum of solar cycle 22 (Figure 5). UARS/ACRIMII observations, currently available up to 1999, seemed to confirm the trend in the SOHO/VIRGO observations. In contrast, the magnetic flux remained low until September 1997, and only in the fall of 1997 started to show the effects of increased solar activity. Observations of chromospheric irradiances also showed very little
or no increase until the summer of 1997, in agreement with the magnetic flux evolution.

To better understand the TSI observations, we have used empirical model of TSI based on the photometric indices derived at San Fernando Observatory (Chapman, Cookson, & Dobias, 1996; Chapman et al., 1997). Images in the Ca II K line at 393.4 nm are used to estimate bright features in the form of plages/faculae and network, while images in the red continuum at 672.3 nm are used to estimate the photospheric contribution of sunspots. The indices are derived from the residual images, i.e. after the quiet Sun center-to-limb variation has been subtracted, and the intensity is normalized to the disk center intensity (Walton & Preminger, 1999). All the pixels are added together with the appropriate contrast and therefore, include both dark and bright features. The Ca II index is dominated by bright structures and the red continuum index by sunspots. These indices, which give the contrast pixel by pixel, are superior to other commonly used photometric indices, which assume the contrast for spots and faculae, i.e. PSI (Fröhlich, Pap, & Hudson, 1994) and PFI (Lean et al., 1988 and references therein).

In Figure 6, we present the TSI model based on the San Fernando photometric indices and its fit to observations. The model is computed for the period 1988–1996 and extrapolated forward in time. Models estimates are in excellent agreement with observations for solar cycle 22: the correlation coefficient is 0.935 and accounts for 87% of the variance of the data. The model predicts an increase of about 0.5 Wm$^{-2}$ from 1996 to the end of 1999, and underestimates the observations from SOHO/VIRGO v2.5 by about a factor of two. The disagreement between model estimates and SOHO/VIRGO v2.5 starts in 1996 and continues to the present time (de Toma et al., 2000b). Results similar to ours have been obtained by Fröhlich (1999) using an empirical model based on different facular and sunspot proxies. The disagreement between observations and models of TSI has led to a revision of the SOHO/VIRGO observations. VIRGO data are the weighted average of measurements from two radiometers, PGO6 and DIARAD (Fröhlich & Anklin, 2000) on board the SOHO spacecraft. Anomalies have been found in both radiometers after the instruments are powered off. A new version of the VIRGO data, v3.0, have been released on September 4, 2000. The VIRGO v3.0 data (Figure 5) are significantly different from the v2.5 data. For version v3.0, the increase from minimum to maximum is reduced from 1 Wm$^{-2}$ to 0.8 Wm$^{-2}$. A different sensitivity correction from the one used in VIRGO v3.0 is applied to the DIARAD data from the DIARAD team. The latest DIARAD data also show a TSI increase in late 1999 of 0.8 Wm$^{-2}$, in agreement with VIRGO version v3.0 (Table 1). A comparison between SOHO/VIRGO v3.0 observations and the model estimates is shown in the bottom panel of Figure 6. Models estimates and observations have an higher correlations in 1996–2000 for the VIRGO data v3.0 than for v2.5 and there is very good agreement up to 1997. However, starting in 1998 the observations show a faster increase. In figure 7, we present a second set of models for the rising phase of cycle 22 and 23, where we fit Nimbus–7/ERB and SOHO/VIRGO v3.0 separately during the period 1986–1999, and 1996–1999. In this case, we used the Mg II index to estimate facular and network contribution, since the San Fernando Ca II K images we used before to estimate

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faculae and network started only in 1988 and does not cover the rising phase of cycle 22. We find very good agreement between models and observations for both Nimbus-7/ERB and SOHO/VIRGO data, with correlation coefficients of 0.91 and 0.93, respectively. However, to account for the faster rise in TSI during this cycle, the coefficient in the linear regression for our facular index, in this case the Mg II index, is almost 33% larger for cycle 23 than for cycle 22. Empirical models based on sunspots and faculae have been largely used in the past to model TSI (Foukal & Lean, 1988; Chapman et al., 1996; Lean et al., 1998). Results for solar cycle 22 have given very good fits to observations, leading to the assumption that “dark” spots and “bright” faculae and network are responsible for most of the observed variability in TSI (Chapman et al., 1996; Lean et al., 1998). We now find that this is not possible to fit cycle 22 and 23 with the same model. It is very important to determine if the current measurements of TSI are correct, and if the difference between the two cycles is real. We emphasize the challenge to measure TSI with an accuracy of 200 ppm, which is necessary to understand the TSI differences we see.

4. CONCLUSIONS

We are now in the maximum phase of solar cycle 23. This is usually an extended period of time, that lasts 2 or 3 years. The periods of highest activity during the rise of cycle 23 were in November 1999, and July 2000. So far, cycle 23 has been magnetically weaker than the two previous cycles, this is confirmed by a number of observations including: sunspot area and number, magnetic flux, coronal 10.7 cm radio flux, and the chromospheric Mg II and He I indices.

TSI evolution during this cycle is not completely consistent with magnetic flux and the other indices of solar activity. TSI values in late 1999 are larger than expected by empirical models based on cycle 22 observations. To fit TSI observations well during cycle 23, an increase in the facular contribution to TSI of about 33% relative to cycle 22 is necessary, according to our model estimates.

If the measures of TSI are correct, the faster increase in TSI suggests that the sources of radiative variability may be different for this cycle. It is very important to investigate this discrepancy between the two cycles further to better understand the sources of TSI variability. This is crucial not only to the understanding of the Sun itself, but to the understanding of the solar influence on the Earth's atmosphere and climate. However, measurements of one complete cycle (cycle 22) and parts of cycles 21 and 23 are not enough to understand fully if and how the solar atmosphere may have changed between cycles 22 and 23. It is thus very important to continue the TSI measurement programs through cycle 23 and in the future.

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