The peculiar solar cycle 24 — where do we stand?

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Abstract. The minimum that preceded solar cycle 24 was unusual in its depth and duration. It was the quietest minimum recorded in the era of detailed data. Cycle 24 started off extremely slow and has continued to be weak. We review the conditions of the minimum that preceded cycle 24. We discuss ignored or missed signs that cycle 24 would not be normal, and finally comment on the behaviour of the cycle thus far.

1. Introduction
Solar cycle 24 has been very weak so far. It was preceded by an extremely quiet and long solar minimum. Data from the solar interior, the solar surface and the heliosphere all show that cycle 24 began from an unusual minimum and is unlike the cycles that preceded it.

We begin this review of where solar cycle 24 stands today with a look at the antecedents of this cycle, and examine why the minimum preceding the cycle is considered peculiar (§ 2). We then examine in § 3 whether we missed early signs that the cycle could be unusual. § 4 describes where cycle 24 is at today.

2. The peculiar minimum
The minimum that preceded solar cycle 24 was unusual in its depth — the 10.7 cm flux was the lowest recorded, while there were sunspot free days than have been recorded among recent cycles. The minimum was also of a much longer duration than any other minimum in recent history.

The minimum preceding the cycle showed other unusual characteristics. For instance, the polar fields were lower than those of previous cycles. In Fig. 1 we show the polar fields as observed by the Wilcox Solar Observatory. It is very clear that the fields were much lower than those at the minimum before cycle 22 and also smaller than the fields during the minimum before cycle 23. Unfortunately, the data do not cover a period much before cycle 21 maximum so we cannot compare the polar fields during the last minimum with those of even earlier minima. Other, more recent data sets, such as the Kitt Peak and MDI magnetograms, and they too also show that the polar fields were weak during the cycle 24 minimum compared with the cycle 23 minimum (de Toma 2011; Gopalswamy et al. 2012).

The structure of the solar corona was also quite different from what is expected during a normal minimum. As can be seen from the LASCO images shown in Fig. 2 the solar corona has the canonical solar-minimum structure during the cycle 23 minimum, but the coronal did not have a simple configuration of streamers in an equatorial belt as it was during the previous minimum in 1996.
Figure 1. The variation of the polar magnetic fields as observed by the Wilcox Solar Observatory. The thick lines are the smoothed values.

Figure 2. LASCO C2 images showing the solar corona in January 1996 (the minimum before cycle 23; left) and December 2009 (minimum before cycle 24; right). Note that the coronal structures are quite different, with the corona being confined to the equatorial plane during the cycle 23 minimum but with considerable latitudinal structure during the cycle 24 minimum. (Images courtesy of NASA.)

The above examples are just some of the unusual characteristics of the minimum that have been documented in the proceedings if the SOHO 23 workshop entitled “Understanding a Peculiar Solar Minimum” (ASPCS Vol, 428). Other noteworthy differences include the fact that the fast solar winds were confined to higher latitudes — using interplanetary scintillation measurements Manoharan (2012) showed that at 125 R⊙ fast (> 600 km s⁻¹) winds were seen at latitudes > 30° at the cycle 23 minimum, but these were confined to much higher latitudes during the cycle 24 minimum (see Fig. 3). De Toma (2011) showed that the speed distribution of solar winds at earth was also different. While during the cycle 23 minimum in 1996, the speed-distribution had a peak at 370 km/s, in 2009 the distribution peaked at 340 km/s. In 2007 and 2008 the distribution was bimodal with peaks at 350 and 600 km/s in 2007 and 330 and 600 km/s in 2008.

The differences between the cycle 24 minimum and the previous ones were not confined to phenomena exterior to the Sun, dynamics of the solar interior showed differences too. For instance, Basu & Antia (2010) showed that the nature of the meridional flow during the cycle 24
minimum was quite different from that during cycle 23. This is significant because meridional flows are believed to play an important role in solar dynamo models (see e.g., Dikpati et al. 2010, Nandy et al. 2011, etc.). The main difference was that the meridional flow in the immediate sub-surface layers at higher latitudes was faster during the cycle 23 minimum than during the cycle 24 minimum. The difference can be seen in Fig. 3 of Basu & Antia (2010). Since the solar cycle is almost certainly driven by a dynamo, the differences in meridional flow between the last two minima, and between cycle 23 and the first part of cycle 24, may be important factors in creating the cycle differences, which extend into the corona and even cosmic rays (Gibson et al. 2009). Differences were also seen in the solar zonal flows (Howe et al. 2009; Antia & Basu 2010 etc.), and it was found that the equator-ward migration of the prograde mid-latitude flow was slower during the cycle 24 minimum compared with that of cycle 23.

The peculiar solar minimum has been followed by a rather weak activity cycle, and of course the question is what will happen next. Predictions of the behaviour of cycle 24 spanned across a wide range of cycle-strengths (see Pesnell, 2012 for a compilations of cycle 24 predictions), but only a handful predicted the weak cycle that we are tending towards.

While there is enough evidence to show that the cycle 24 minimum was very different when compared with that of cycle 23, it is not completely clear that the minimum was peculiar compared with minima that occurred in the early part of the 20th century or late in the 19th century. The biggest problem in making such a comparison is that very little data exist before the 1950s. The only data available are the sunspot numbers, and some observations of the solar corona during eclipses.

As discussed by Sheeley (2010), looking at the historic record of sunspot numbers we find that there were sun-spot free solar minima in the early part of the 20th century (the minima
Figure 5. The solar corona as seen during solar eclipses. Left: A photograph of the solar eclipse over Sumatra in 1901 (the minimum before cycle 14) processed with modern image-processing techniques, and Right: Solar eclipse in 2009 over the Marshall Islands. Note that the configuration of the solar corona was quite similar during the two minima. (Images courtesy of Miloslav Druckmüler and the HAO historical eclipse database [Judge et al. 2010].)

of 1900 and 1910), going even further back, we see a lot of other minima that were as deep at the cycle 24 minimum, at least as far as sunspot numbers are concerned. This can be seen in Fig. 4. Note that plotting the logarithm of the sunspot numbers accentuates the deep minima and shows that the last minimum was not unique in its depth.

Another issue is that of the configuration of the solar corona during the last minimum. As Judge et al. (2010) pointed out, there are eclipse records that show that the solar corona during the solar minimum circa 1901 was very similar to that of 2009 as seen in eclipse photographs (see Fig. 5). Thus it is quite possible that the ‘anomalous’ and ‘peculiar’ solar minimum was not so anomalous after all, and the seeming anomaly is simply the result of not having enough data from earlier cycles for a proper comparison.

3. Did we miss signs of an unusual cycle?
There is evidence coming to light that the Sun had started behaving unusually (at least unusually compared to other epochs for which we have good data) during the cycle 23 maximum and perhaps even earlier. For instance Janardhan et al. (2011) published studies of inter-planetary scintillation that showed that solar wind turbulence has been decreasing steadily from about the time of the minimum before cycle 23 (Fig. 6).

There were signs from the solar interior too that something unusual was going on inside the Sun. Data on solar oscillation frequencies that can be used to deduce conditions inside the Sun (see e.g. Christensen-Dalsgaard 2002). Solar oscillation frequencies are known to change with solar activity (Woodard & Noyes 1985; Elsworth et al. 1990; Libbrecht & Woodard 1990; and more recently Basu 2002; Howe et al. 1999). These solar-cycle related changes are also correlated with solar activity indices (Jain & Bhatnagar 2003). The solar cycle-related change in the frequency of a given mode is known to be a function of the frequency of that mode. High-frequency modes have larger shifts than lower-frequency modes. and this implies that solar-cycle related changes in the solar structure occur predominantly in a thin sub-surface layer of the Sun (Nishizawa & Shibahashi 1995). The Birmingham Solar Oscillation Network (BiSON) has been
collecting solar oscillation data for over thirty years. Its observations cover cycles 22 and 23 in their entirety and of all cycle 24 to date. The data also cover a few epochs of cycle 21. Basu et al. (2012) showed that the frequency-dependence of solar-cycle related shifts was different during cycle 23 compared to cycle 22. The correlation of the different solar activity indices with the frequency shifts was affected, and in particular, they showed that while the International Sunspot Number (ISN) and the 10.7 cm flux was correlated with the change frequencies during cycle 22, this correlation was lost after the maximum of cycle 23 (Figures 2 and 3 of Basu et al. 2012). Had this change in behaviour been detected in a timely fashion, it would have alerted us to the fact that the Sun was going through an unusual phase. The correlation between frequency-change and activity indices was regained for the high-frequency modes ($\nu > 2400 \mu$Hz) in cycle 24, but not for modes with lower frequencies.

Basu et al. (2012) also found that the change of modes an intermediate frequency range ($2400 < \nu \leq 2920 \mu$Hz) as a function of the change in higher frequencies ($2920 < \nu \leq 3450 \mu$Hz) was the same during cycles 22 and 23, the change in the low frequency modes ($1860 < \nu \leq 2400 \mu$Hz) was very different during cycle 23 compared with cycle 22, in fact there was very
little change in the low frequency modes during cycle 23 (see Fig. 7). This can be interpreted as the layer of magnetic field had effectively become thinner after cycle 22. Thus there seem have been early indications that the Sun was behaving in a manner that was different from its earlier behaviour.

4. Cycle 24 thus far

As can be seen from Fig. 8, solar cycle 24 started slowly compared with the previous three cycles. Also slow in rising was the number of flares. Biesecker (2011) showed that while in the first 27 months of the cycle the number of M class flares per sunspot was comparable with those of cycle 21-23, the number if X class flares was much smaller, with only 1 X-class flare compared with 18, 20 and 17 for cycles 21, 22 and 23 respectively. The behaviour of the polar fields (Fig. 1) appears to show that we are very close to the solar maximum, if not there already, making this one of the weakest cycles in recent history.

![Figure 8. The rise of the monthly averaged smoothed sunspot number for different solar cycles. Note that the rise of cycle 24 is the slowest among all recent cycles.](image)

This solar cycle is showing a number of other differences compared to previous cycles. For instance the poleward migration of magnetic fields is weaker (Hathaway 2013). This poleward movement is believe to be a precursor of the next cycle, and could indicate that the next cycle will be weak too. Altrock (2011, 2012) also commented the absence of this poleward movement (which he dubbed “the rush to the poles”) in coronal Fe XIV emission. Flows on the solar surface are also different. Hathaway & Upton (private communication) find that the meridional flows as obtained by tracking of magnetic elements observed by the MDI and HMI instruments are faster now compared with cycle 23 maximum. Doppler measurements of the solar surface also show large variations in the meridional flows (Ulrich 2010 and private communication).

The dynamics of the solar interior is quite different from what has been seen before. Of course one has to keep in mind that we only have 16 years of data on solar interior dynamics, and this allows us to compare this cycle only with cycle 23. As can be seen in Antia & Basu (this volume), the latitude independent part of the solar rotation rate is slower during this cycle than it was in cycle 23. The zonal flows are different too, in particular, the poleward flow is very weak. Plots of the zonal flow seen at different latitudes plotted at a function of radius and time show other differences between the flows during cycles 23 and 24, as can be seen in Fig. 3 of Antia & Basu (this volume). In fact the poleward flow is so weak, it was at first believed to be absent and led to the speculation that cycle 25 may not occur at all and that we may be delayed or that we may be headed towards a Maunder-type minimum (Hill et al. 2011). What Antia & Basu (this volume) also find is that while the zonal flows at all latitudes in cycle 23 can be fitted with three harmonics of an 11.7 year period, one cannot simultaneously fit the mid-latitudes of cycle 24.

It is too early to be able to say whether or not solar-cycle dependent change in solar structure is the same during this cycle as it was in cycle 23. Structure changes during cycle 23 were so
Figure 9. LASCO C2 images showing the solar corona in March 2001 (cycle 23 maximum; left) and January 2013 (almost cycle 24 maximum; right). Note that the coronal structures are quite similar in terms of the latitudinal extent; the current coronal emission however, seem weaker. (Images courtesy of NASA.)

5. What comes next?
Cycle 24 has raised a number of questions and the observations gathered over the next few years will be crucial in answering these. Among the important questions is what cycle 25 will be like. E.g., will the rush to the poles remain weak, or will that strengthen? This could affect what the beginning of the next cycle will be like. While the weakness of the rush to the poles and the poleward branch of the zonal flows appear to indicate a delayed cycle 25, the higher speeds of the meridional flows appear to indicate otherwise.

Another issue is the strength of the sunspot magnetic fields. Penn & Livingston (2011) had claimed that the maximum field strength in sunspots shows a gradual decrease over the last several years and that sunspots may completely disappear in the not-so-distant future. This led Pevtsov et al. (2011) to look into historic data and claim that the Penn & Livingston conclusions are based on limited data collected over just the descending part of cycle 23. Looking into data over several solar cycles they found that the maximum field strength of sunspots is dependent on the phase of the solar cycle. However, in a follow-up paper, Nagovitsyn et al. (2012) claimed that the magnetic field strength data show a solar cycle variation when only sunspots with
the strongest magnetic fields are included; they also found a negative correlation between the numbers of small and large sunspots and that during the the period of 1998-2011, the number of large sunspots gradually decreased, while the number of small sunspots steadily increased.

Of course, since it is believed that sunspots need a minimum strength to emerge, the question will be whether the trend of decreasing numbers of large sunspots will continue over the current cycle, and hence make a spotless cycle possible. The long-term trends in the strength and size of sunspots will perhaps be a better indicator than solar flows as to whether the Sun is moving towards a magnetically quiet phase. How the Sun behaves in 2013 will be exciting to observe.

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