Comparative Magnetic Minima:
Characterizing quiet times in the Sun and stars
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Interplanetary conditions: lessons from this minimum

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Abstract. Interplanetary conditions during the Cycle 23-24 minimum have attracted attention because they are noticeably different than those during other minima of the space age, exhibiting more solar wind stream interaction structures in addition to reduced mass fluxes and low magnetic field strengths. In this study we consider the differences in the solar wind source regions by applying Potential Field Source Surface models of the coronal magnetic field. In particular, we consider the large scale coronal field geometry that organizes the open field region locations and sizes, and the appearance of the helmet streamer structure that is another determiner of solar wind properties. The recent cycle minimum had an extraordinarily long entry phase (the decline of Cycle 23) that made it difficult to identify when the actual miminum arrived. In particular, the late 23^{rd} cycle was characterized by diminishing photospheric fields and complex coronal structures that took several extra years to simplify to its traditional dipolar solar minimum state. The nearly dipolar phase, when it arrived, had a duration somewhat shorter than those of the previous cycles. The fact that the corona maintained an appearance more like a solar maximum corona through most of the quiet transitional phase between Cycles 23 and 24 gave the impression of a much more complicated solar minimum solar wind structure in spite of the weaknesses of the mass flux and interplanetary field. The extent to which the Cycle 23-24 transition will affect Cycle 24, and/or represents what happens during weak cycles in general, remains to be seen.

Keywords. solar wind sources, coronal field structure

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1. Introduction

The Cycle 23-24 solar minimum has generated considerable interest because of its distinctive behavior compared to the three previous cycles of the space age. As has been pointed out by many recent authors and speakers, the solar field has been both weaker overall and exhibits a lower axial dipole moment, resulting in several important consequences for solar irradiance and the interplanetary medium (e.g. see SOHO 23: Understanding a Peculiar Solar Minimum, ASP Conf. Ser. V.428, 2010). Emissions at EUV wavelengths were reduced to the point where the Earth's thermosphere practically disappeared (Solomon *et al.* 2011). Observations both in the ecliptic at 1 AU and at higher latitudes on the Ulysses spacecraft indicated that the interplanetary magnetic flux and the solar wind mass flux were each lower by ∼30% than their values in the previous solar minimum in 1995-6 (McComas *et al.* 2008, Smith & Balogh 2008). These parameters affected other heliospheric conditions including the galactic cosmic ray flux (e.g. Schwadron *et al.* 2010). The altered solar wind dynamic pressure also had significant impacts on planetary plasma interactions and geomagnetic activity. Here we focus on the coronal field topology that in part determined the interplanetary conditions during

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the Cycle 23-24 transition. In particular we use Potential Field Source Surface (PFSS) models to illustrate how the large scale coronal field features, including coronal streamer structure and ecliptic solar wind sources, compare to those during earlier solar minima.

2. Interplanetary Conditions at Cycle Minima

A review of interplanetary parameters over the previous three cycles through the Cycle 23-24 minimum can be found in the recent paper by Jian *et al.* (2011). These authors discuss the now well-documented weak interplanetary field strengths (reported by both Smith & Balogh 2008 and Lee *et al.* 2009, among others) and the low solar wind densities associated with the low solar wind mass flux mentioned above. The recorded high galactic cosmic ray fluxes are an expected result of the low interplanetary field, given past cycle correlations showing field strengths are anti-correlated with the fluxes (Cane *et al.* 1999). Of special interest here are the results of their analysis of solar wind structures through Cycle 23 including the bracketing minima. In particular, the stream interaction regions (SIRs) were examined for both their occurrence rates and average properties and found to be more numerous but weaker than in the previous minimum.

Figure 1 provides an overview of a selection of the interplanetary parameters analyzed by Jian *et al.*, from the OMNI 1 AU data base. The measurements shown are 27 day averages, which minimize variations introduced by corotating features. What is most notable from a cursory examination of these time series is the lack of clear solar cycle modulations in anything but the interplanetary magnetic field. The origin of the interplanetary field modulation during the minima on either side of Cycle 23, and in particular its relationship to the solar magnetic field, was explored in some detail by Lee *et al.* (2011) using complementary magnetograph observations. These authors demonstrated that the interplanetary field strength could be obtained from photospheric magnetic field maps by using the Potential Field Source Surface Model of the coronal field to estimate open flux, and then assuming that open flux was uniformly distributed over the heliosphere. Their analysis could explain the interplanetary flux magnitude difference between the previous (Cycle 22-23) and recent (Cycle 23-24) minima, but what about the greater number of weak SIRs? The answer may lie in the solar wind source distribution.

From the experience of the three previous solar cycle minimum periods in 1975-76, 1985-6 and 1995-6, and especially from the last one for which we have the comprehensive solar information from SOHO imagers available, certain expectations were established. The picture that emerged from the combination of observations and modeling was one in which the solar corona took on an approximately dipolar global appearance, with most of the ecliptic solar wind coming from the open fields near the low latitude boundaries of the polar coronal holes (e.g. Linker *et al.* 1999). Moreover, within the minimum there were periods when the coronal dipole equator was practically in the ecliptic plane. At other times it could be tilted with respect to the solar rotation axis, and/or have warps due to the presence of one or more active regions at lower latitudes, typically the last of the preceding cycle at the equatorward end of the butterfly diagram wings. The latter promoted the existence of sometimes large polar coronal hole extensions, an example of which was the elephant trunk feature of the first Whole Sun Month study campaign (Gibson *et al.* 1999). Both dipolar coronal tilting and polar coronal hole extensions bring higher speed polar hole wind into the ecliptic plane every solar rotation. The canonical solar minimum picture of interplanetary conditions dominated by corotating high speed streams from polar coronal holes and their stream interaction regions established by Hundhausen (1979; also Zhao and Hundhausen 1981) became the expected state for

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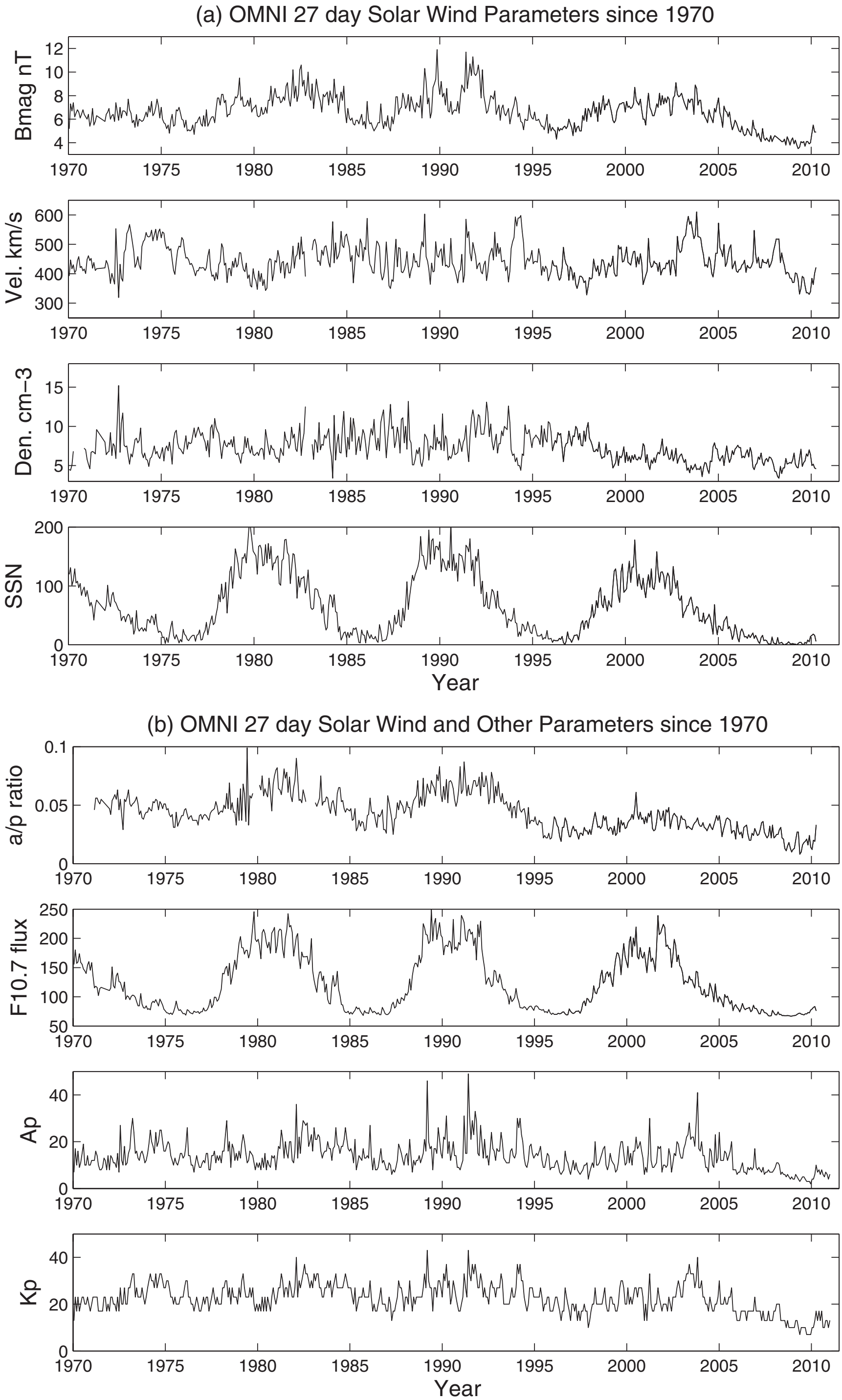

Figure 1. OMNI 27-day averaged solar wind plasma and field data are shown for the 3+ cycles of the space age, together with sunspot number, F10.7cm radio flux (a solar EUV proxy), and the Ap geomagnetic index. Of all of the interplanetary parameters, the magnetic field and solar wind alpha-to-proton (a/p) ratio are the only ones that show a clear solar cycle modulation.

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solar quiet periods. However the recent minimum period seems to require a somewhat modified picture.

3. Sources of the Solar Minimum Interplanetary Conditions

A number of previous authors have noted the unusually wide coronal streamer belt (e.g. McComas *et al.* 2008) and the ubiquity of low latitude coronal holes during the Cycle 23-24 minimum (Abramenko *et al.* 2010, deToma, in this proceedings). The reasons for these can be found in the weakening solar polar magnetic fields relative to the mid-to-low latitude magnetic fields of decayed active regions. Luhmann *et al.* (2009) discussed how this combination produces a large scale coronal field that has significant higher order multipole contributions compared to the axial dipole influence. Instead of a single, wide helmet streamer belt overlying essentially all the smaller scale closed coronal fields, the corona includes large topologically distinct pseudostreamers (e.g. Wang *et al.* 2009). The cartoon in Figure 2 (top) illustrates the major features the large scale field structure. The formation of pseudostreamers can be understood as the result of two effects. One is the location of the source surface, the provisional radial distance at which the coronal fields are opened by the solar wind. A smaller source surface will always produce a more structured coronal hole pattern than a large source surface (e.g. see Lee *et al.* 2011 for an illustration). The other effect is the existence on the solar surface of sufficiently large and strong dipolar magnetic regions with surface dipole moments having a direction opposite to the polar dipole moment and its overlying large scale field. As Luhmann *et al.* (2003) illustrated, the opposing surface dipole moment allows a part of the helmet streamer to essentially break away from the main streamer belt. The weak polar fields and inferred small source surface of Cycle 23 (see Lee *et al.* 2011) conspired to regularly produce pseudostreamers. Thus the multi-rayed coronal field that prevailed throughout the long Cycle 23 decline more closely resembled a solar maximum configuration than a dipole, even though the photospheric field was weak overall. Figure 2 (bottom) displays a sampling of large scale coronal field pictures contructed using GONG magnetogram-based Potential Field Source Surface (PFSS) models for Carrington Rotations in and around the Cycle 23-24 minimum.

PFSS models have been shown to reproduce coronal hole geometries and streamer features during quiet to moderately active solar conditions (e.g. Levine *et al.* 1977). The average polarity of the interplanetary magnetic field can also be inferred to remarkable accuracy by assuming the source surface neutral line separates outward and inward going fields (Hoeksema 1984, Wang *et al.* 2009). Lee *et al.* (2011) and also deToma (this proceedings) modeled coronal holes for Cycle 23 Carrington Rotations that generally capture their locations, shapes and sizes seen in EUV images. In the above mentioned paper by Luhmann *et al.* (2009) a numerical experiment was done with the PFSS model to demonstrate that weakened polar fields relative to the same mid-to-low latitude fields produced a situation where the ecliptic solar wind source mapping (via open field lines) that usually connects to polar coronal hole boundaries instead connects to low to mid latitude coronal holes. Riley & Luhmann (2012) further show that part of this source mapping change involves frequent ecliptic connections to the ubiquitous pseudostreamer boundaries in the years ∼2006-9. Although these latter authors use an MHD model, their results can also be seen in the PFSS versions of the solar wind source mapping. This combination of successful long-term and recent applications of PFSS models suggests that we can further apply them toward comparing solar minima.

Figures 3 and 4 illustrate the overall solar cycle evolution of coronal holes and their near-ecliptic connections since the early 1970s according to PFSS models. This is an

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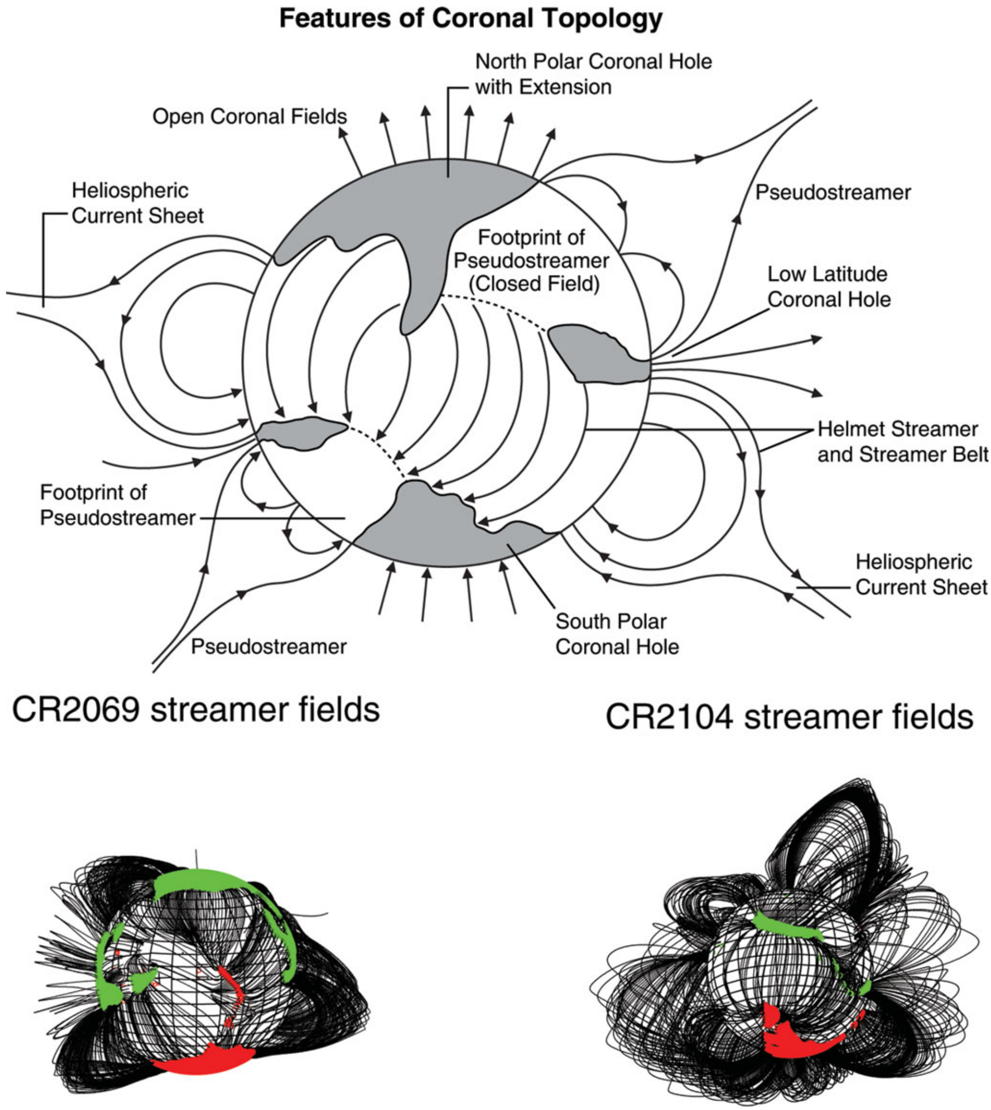

Figure 2. (top) Illustration of the main features of the large scale coronal field. Frequently occurring departures from dipolar topology including numerous coronal holes at mid-to-low latitudes and pseudostreamers separate from the helmet streamer belt. (bottom) A sampling of magnetogram-based PFSS models of large scale coronal fields for the Cycle 23 declining phase and the Cycle 23-24 minimum.

update of similar plots presented in Luhmann *et al.* (2002), where the ability of the ecliptic mapping results to mimic the solar cycle trends in average solar wind parameters observed upstream of Earth was demonstrated. These updated plots display the results of Mt. Wilson Observatory (MWO) magnetogram-based models up to 2007, transitioning to GONG magnetogram-based models thereafter (e.g. after Carrington Rotation (CR) 2050). Carrington Rotations are used as the time coordinate for consistency with the synoptic map origins of the results. For overall perspective and context, Figure 3 (top) shows the sunspot number for the periods of the modeled open field footprints in Figure 3 (bottom). Here one sees how the coronal hole distributions evolve over the solar

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cycle (with greatest model accuracy around solar minima). The polar coronal holes and their extensions persist except around solar maximum, when they disappear for several rotations as polar field reversal takes place. One also sees the band of mid-to-low latitude coronal holes and polar hole extensions associated with the active region belt. These features follow the butterfly diagram of the Hale Cycle, which reaches its midpoint in equatorward drift at solar maximum when the polar coronal holes disappear. It is important to note that the polar holes do not tilt toward low latitudes as many cartoons suggest, but instead shrink and then disappear (sometimes not exactly at the same time in both hemispheres), leaving the mid-to-low latitude coronal holes associated with active regions to dominate the solar maximum period.

Figure 4 (top) shows only those open field footpoints that map to within ∼10 degrees of the equator, color coded by magnetic polarity (radially outward or inward field). These indicate the sources of the near-ecliptic solar wind according to the PFSS model. The corresponding magnetic neutral line on the source surface, approximating the latitude of the heliospheric current sheet at its origin at a few solar radii, is displayed in Figure 4 (bottom) as a complement to Figure 4 (top). These plots collectively illustrate the differences in the Cycle 23-24 solar minimum solar wind sources compared to the preceding few cycle minima. What is most striking is the long duration of the decline into the Cycle 23-24 minimum. Whereas in the previous few cycles a significant fraction of the transition between solar cycles was occupied by polar hole dominated conditions, in the Cycle 23-24 minimum the mid-to-low latitude active region related coronal holes do not disappear except for a few Carrington Rotations in late 2009. The consequences this has had for interplanetary conditions over the last ∼5 years are considered below.

4. Implications

It is now generally-agreed that the boundaries of coronal streamers, which are also the boundaries of coronal holes, produce mainly slow solar wind including a transient component. In addition, analyses of the ion composition of the slow solar wind suggests it may have at least two main sources (Wang 2012, Kasper *et al.* 2007), perhaps the polar hole boundaries and the low-to-mid latitude coronal holes discussed above. Do the coronal conditions in the Cycle 23-24 minimum favor either polar coronal hole boundary or mid-to-low latitude coronal hole mappings more than in the previous cycle minima? To address this question we use the PFSS model results in Figure 4a to obtain statistics of near-ecliptic mapped footpoint field latitudes for the ∼3+ solar cycles shown. We distinguish between polar hole boundary and low-to-mid latitude coronal hole boundary sources by separately counting the points at latitudes above and below 50 degrees. As each Carrington Rotation in our model plots involves the same number of source points mapped from a source surface equatorial band, this produces a consistent picture of the comparative ecliptic mappings from cycle to cycle. The results in Figure 5 (top) more quantitatively illustrate what is inferred from looking at Figure 4a. By comparing the fraction of the total near-ecliptic mappings that go to the polar hole boundaries (latitudes >50 degrees) with the fraction going to mid-to-low latitudes, one can see how much of each cycle is invested in one or the other source. Interestingly, the duration of the period when polar hole boundary sources dominates is similar for all the cycle minima shown, including the Cycle 23-24 minimum. However, Cycle 23 was distinguished by its markedly longer (by several years) declining phase, during which the low-to-mid latitude mapping dominance persisted. These results suggest that our perception of the Cycle 23-24 minimum solar wind structure is affected more by the long decline of Cycle 23 than

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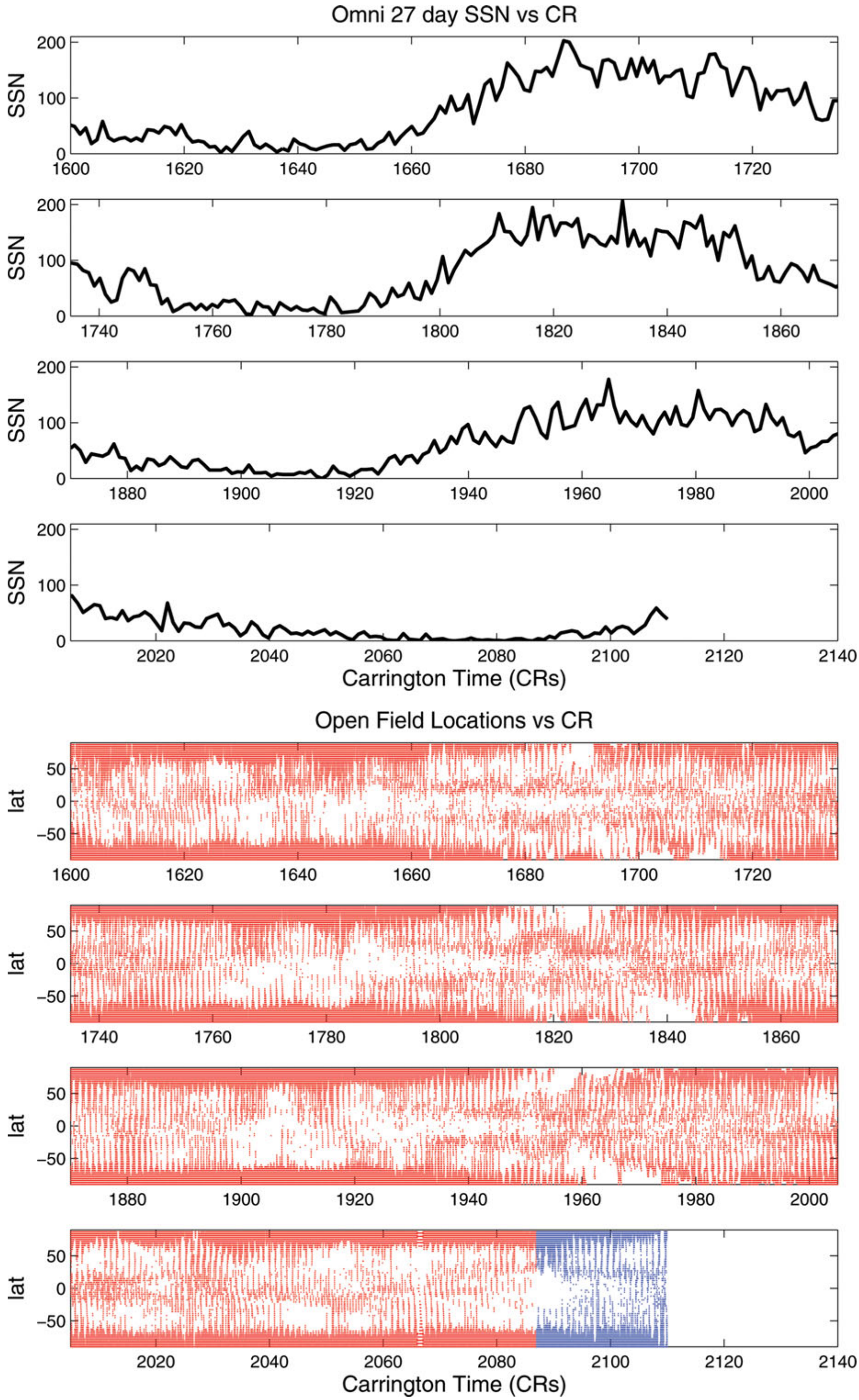

Figure 3. (top) Sunspot number and (bottom) footpoint locations of open coronal magnetic fields on the photosphere according to PFSS models. The models are MWO magetogram based prior to Carrington Rotation 2050, and GONG magnetogram based thereafter. See the text for a discussion of the features in the open field patterns and the online version for color figures.

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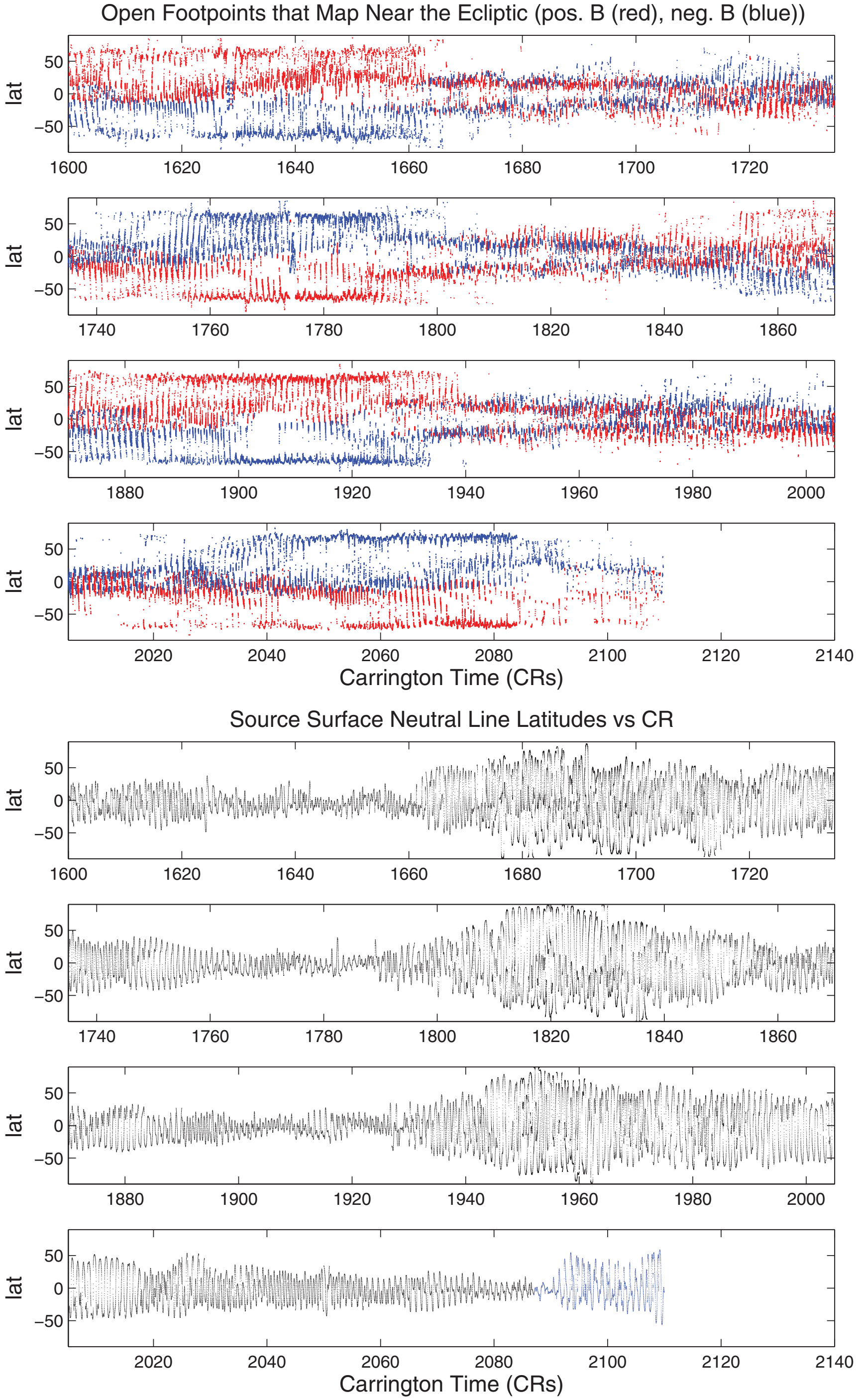

Figure 4. (top) A subset of the open fields shown in Figure 3 (bottom) that corresponds to locations that map to the low heliolatitudes near the ecliptic. These are in principle the source regions for the interplanetary conditions prevailing around each cycle minimum. The points are color coded (see the online version) according to the solar field polarity at the open field footpoints (red=outward, blue=inward). (bottom) Magnetic neutral line latitude on the source surface for the PFSS models used in Figure 4 (top)

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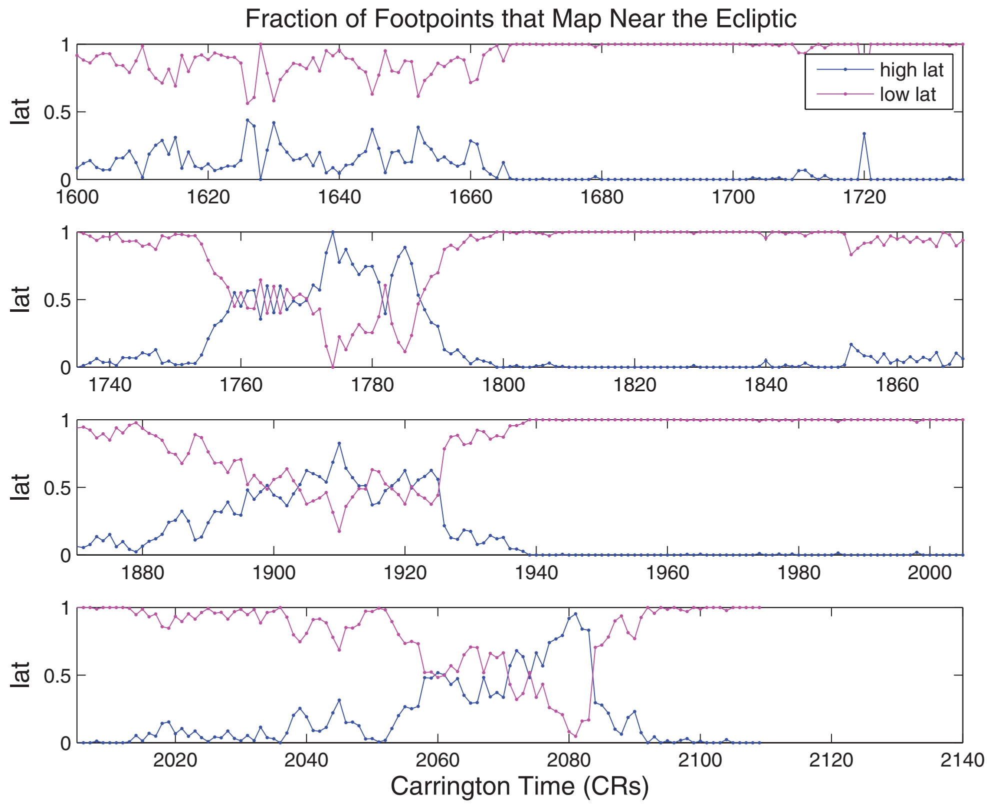

Figure 5. Fraction of the open field footpoints in Figure 4 (top) that map to polar coronal hole boundaries (defined here as latitudes >50 deg.) compared to the fraction mapping to mid-to-low latitude sources. The periods where polar hole boundary mapping dominates can be viewed as the classical dipolar coronal phases of the solar minima. See color figure in the online version of the paper.

anything special about the dipolar phase. Of course the weak mass flux and interplanetary field are present throughout this period regardless of the coronal source complexity.

As some authors have suggested, the long, slow decline may have contributed to the relative weakness of the photospheric field, including the polar fields, at the end of Cycle 23. This long decline moreover maintained a complexity of the coronal field, and thus the solar wind sources, by limiting the polar field strength buildup. However observations also indicate that less flux emerged from the subphotospheric convection zone during Cycle 23 in the first place (Penn & Livingston 2010), leading to a chicken-egg situation. It may be that when flux emergence is weak, for reasons of either weak internal generation or weak delivery to the surface, the subsequent flux redistribution process –by association or as a consequence– further weakens the surface field, including the polar region fields. Moreover –if by association or as a consequence– it takes longer for the new cycle field emergence to get started, even more time is available for the previous cycle surface fields to diminish in strength. The result for the interplanetary conditions includes a long-lived period of weak but complex coronal field and related solar wind sources prior to the onset of the next cycle. What has happened on the Sun and in the interplanetary medium in the past decade is part of a highly interconnected evolutionary process. Will it affect the subsequent cycles? If some internal mechanism delivers a new cycle of emerged active

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region fields that are robust (e.g. not heavily influenced by what went on during the prior cycle), the next cycle could in principle evolve mainly according to its own dynamics, However, if the next cycle, perhaps through memory and recirculation of flux (e.g. Dikpati 2011), again produces weak emerged fields, the result could be a continuation of the present conditions of weak solar wind and interplanetary fields from weak but complex coronal sources. Whether the solar surface and interplanetary field and mass flux would be reduced yet further remains to be seen.

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Discussion

Arnab Choudhuri: The last minimum was not dipolar. If you try to model the streamer belt located farther South would it be correct?

Janet Luhmann: The problem is that a dipole with a planar neutral line just cannot fit most of the time. One needs to add the higher order harmonic contributions to get the observed warps and structures, it has to be more than a dipole translation to describe the corona during this recent minimum.

Jeffrey Linsky: Does the total mass flux integrated over all latitudes of the solar wind change between solar maximum and minimum and, in particular, was it lower during this minimum?

Janet Luhmann: Ulysses measurements suggested this minimum's mass flux was $\sim$30% lower than the previous minimum, as other speakers also noticed. This reduction seems to be mainly in the density, rather than in the velocity. Dave Webb and others have published estimates of solar cycle variations based on previous observations (as per comment by Dave Webb). I do not have those numbers handy.

Axel Brandenburg: Could you clarify what was plotted when you showed the fine structure of the solar wind? You mentioned HI intensity, but does black then mean a strong decrease against some finite mean value?

Janet Luhmann: The movie shown was made from difference images, so the contrasts indicate large increases (white) and decreases (black) in the densities detected in the white light of the HI images.

Margit Haberreiter: How does the unusual shape of the magnetic field affect the shielding from cosmic ray flux?

Janet Luhmann: The solar wind transients that result over a wide heliolatitude band probably merge with the stream interaction regions before they get far out into the heliosphere, so hard to say what effect these might have on galactic cosmic rays. It's usually merged interaction regions that seem to affect modulation form what I understand.

Eric Priest: What is the definition of a pseudo streamer?

Janet Luhmann: It is a closed coronal field structure outside of the main (circumsolar) streamer "belt". It can have a circular or elongated footprint, depending on the solar distribution.

Mark Giampapa: What is the origin of the dominance of higher order multipole moments in the field and does it have anything to do with the "blobby" turbulent-looking outflow?

Janet Luhmann: The Sun somehow did not produce polar fields (by the usual transport processes of convection plus diffusion) as strong as in the past. As a result, the decayed active region fields that dominate lower latitudes had a much greater influence over the global coronal field than in the previous minimum. The latitude extent of the wind "blobbiness" this minimum, as seen by HI, is one result.

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