

REVIEW

Solar origins of solar wind properties during the cycle 23 solar minimum and rising phase of cycle 24

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Abstract The solar wind was originally envisioned using a simple dipolar corona/polar coronal hole sources picture, but modern observations and models, together with the recent unusual solar cycle minimum, have demonstrated the limitations of this picture. The solar surface fields in both polar and low-to-mid-latitude active region zones routinely produce coronal magnetic fields and related solar wind sources much more complex than a dipole. This makes low-to-mid latitude coronal holes and their associated streamer boundaries major contributors to what is observed in the ecliptic and affects the Earth. In this paper we use magnetogram-based coronal field models to describe the conditions that prevailed in the corona from the decline of cycle 23 into the rising phase of cycle 24. The results emphasize the need for adopting new views of what is 'typical' solar wind, even when the Sun is relatively inactive.

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Introduction

Most of us learn about the solar wind using the basic assumption that the coronal magnetic field has a dipolar configuration like that illustrated in Fig. 1. This makes the sources of solar wind a relatively organized mix of fast solar wind from the open magnetic fields of the polar regions, the polar coronal

holes, and slow, low latitude wind from the boundaries of the closed field regions of the helmet streamer belt (see Fig. 1). The helmet streamer belt source has moreover been recognized as having a non-steady or transient component. SOHO LASCO images revealed a constant occurrence of blobs of material being shed from both the boundaries and cusps of the streamer belt, the latter of which forms the base of the heliospheric current sheet separating the outward and inward-directed open magnetic fields in the solar wind. This transient slow wind component was shown by Wang et al. [1] to explain the average slow wind speeds, ion composition, and greater structural complexity of the slow wind observed in the ecliptic on spacecraft upstream of the Earth. The occasional excursions of fast wind in the ecliptic is often attributed to a varying tilt of the solar coronal dipolar configuration polar away from solar rotation axis alignment, allowing polar

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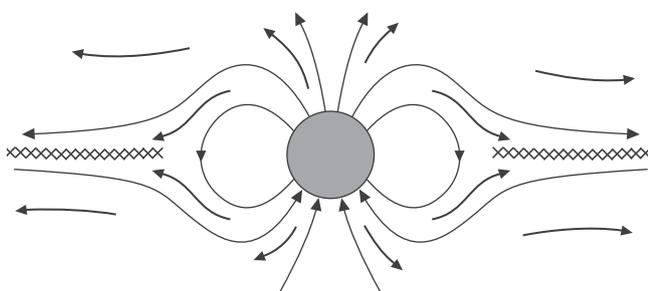


Fig. 1 Illustration of the idealized dipolar corona and solar wind concept that is often generally applied in spite of its frequent limitations compared to reality. In this picture the high speed wind comes from polar coronal holes (the open field regions here) while the low latitude low speed wind comes from the boundary between the open fields and the helmet streamer belt closed fields encircling the Sun.

coronal hole fast wind to dip into the ecliptic. However as detailed solar and coronal observations continue to accumulate, it has become increasingly clear that the dipole picture, even with the transient slow wind sources, is too simple to explain the solar wind most of the time. In this paper we describe what can be thought of as an updated picture of coronal sources of the solar wind, based on the accumulating observations and especially through the recent solar cycle.

The surface field of the Sun that is produced by the combination of the solar dynamo-produced active region field emergence and the redistribution and decay of those fields provides the boundary conditions for the coronal magnetic field structure and thus the solar wind sources. Fig. 2 illustrates the solar magnetic field appearance since 2006 as observed with the GONG magnetograph network. These observations are obtained as full-disk images where black and white indicate inward and outward directed fields at the solar surface that are combined using specialized procedures to obtain global ‘synoptic’ maps of the solar field. The images are obtained over the 27 day period of a solar rotation (referred to as Carrington Rotations if they follow a historically specified timing) and are thus not a snapshot, but at quiet times of the cycle when the field evolution is slow, they provide a good approximation. Synoptic maps are shown for several times through the recent deep solar minimum into the rise of new cycle 24. One can see that during solar minimum the maps are mostly gray, implying weak, polarity balanced, unresolved surface fields dominate – although at high latitudes close examination shows a prevalence of black or white pixels in the opposite polar regions. As the solar activity cycle progresses the active regions begin to emerge at latitudes of $\sim \pm 40^\circ$, after which the latitude band of new emergence slowly migrates to lower latitudes as time progresses through the cycle. The time history of this migration is what makes the well-known ‘butterfly diagram’ of sunspot occurrence versus time. The relative timing of the resulting cycles of active region and polar fields is not in phase. The active region field cycle is described by the sunspot cycle, while the polar fields are at their maximum strength during solar minimum when the decay products of most active regions have migrated to high latitudes. Note that not all active regions that appear on magnetograms have associated sunspots. Sunspots require a certain minimum field strength, while active regions can emerge or evolve in a way that never exceeds the sunspot threshold.

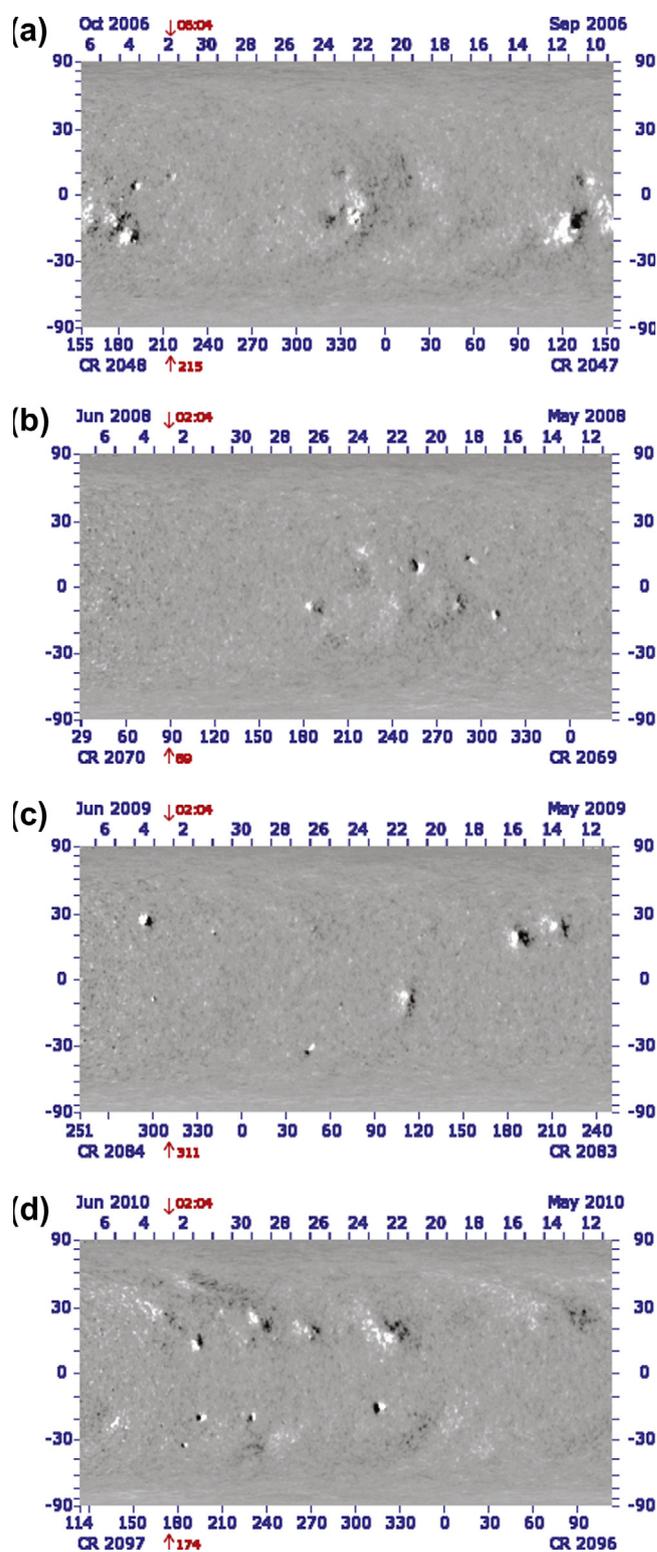


Fig. 2 Examples of synoptic maps constructed from full-disk magnetograms from the GONG Observatory, showing how the solar magnetic field looked from 2006 through 2010. *Source:* <http://gong.nso.edu/data/magmap/>

The coronal magnetic field geometry associated with the evolving solar surface fields can be approximated using models. One of these is the relatively simple potential field source

surface (PFSS) model (see the review by Wang and Sheeley [2]), which assumes the coronal field is current free within a spherical surface of several solar radial, outside of which the solar wind makes the field radial. The PFSS model does not tell us anything about the plasma in the corona but over years of applications it has been shown to do a remarkable job of describing the general topology of the coronal magnetic fields, e.g. seen in both eclipse images and spacecraft coronagraph images. Because the solar wind is assumed to flow from coronal open field regions (e.g. fields that connect to the source surface in the PFSS models), it can also be used to infer coronal hole footprints and interplanetary magnetic field polarity. More physically complete magnetohydrodynamic (MHD) models can be used to provide both the magnetic field structure and consistent coronal densities and solar wind properties [3]. Here we use some results from such models to illustrate the realities of coronal geometry and resulting solar wind sources during the previous cycle including the deep minimum of cycle 23. We focus on the complex structure that is often present in the large scale coronal fields and its effects on solar wind sources. We also mention the limitations of steady state assumptions that the current models make. However, while they are not intended to capture coronal transients they can give a good idea of the global interconnections of the fields at times between them, or at the times of slow coronal evolution. The goal is to provide an updated perspective to those

who work with solar wind concepts and observations, with applications to space weather or related problems.

Coronal field geometry

PFSS coronal field models can be found on several websites operated by solar observatories and other research institutions. In particular the results for conditions since late 2006 can be accessed at the GONG observatory pages at <http://gong.nso.edu/data/magmap>. We make use of that archive here. Fig. 3a–c illustrates a set of GONG PFSS model displays from a particularly dipole-like period in late 2009. These show the footprints on the solar surface of the coronal model open field (red and green for the outward and inward open magnetic field polarities) and the largest scale closed magnetic field line arcade (blue) called the Helmet Streamer Belt. The Helmet Streamer Belt is the feature that is illuminated by the trapped, hot plasma visible in eclipse and coronagraph images, where it forms the base of the main coronal rays. This relatively simple coronal field geometry illustrates the classical solar wind source picture (e.g. as in Fig. 1), dominated by the open fields of polar coronal holes. Tracing open magnetic field lines from the ecliptic plane intersection with the source surface at 2.5 solar radii back to the solar surface (described later in this Discussion) allows one to infer solar wind source locations

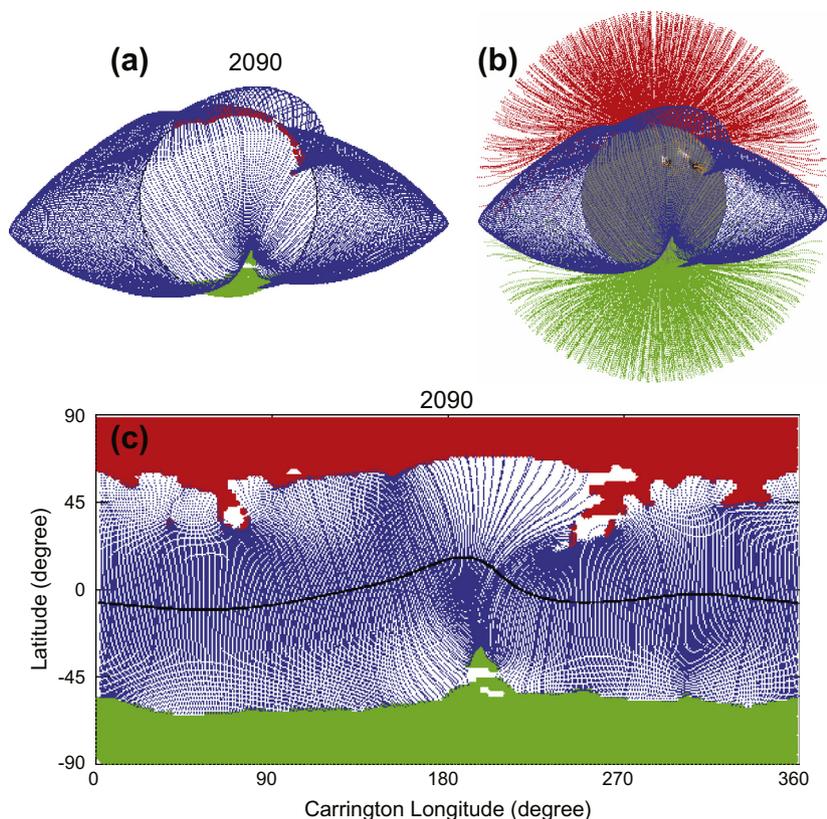


Fig. 3 GONG synoptic map-based PFSS model field lines from Carrington Rotation 2090 in late 2009, when the solar corona resembled an axial dipole corona for a few months. (a) The closed field lines of the near-equatorial helmet streamer belt (blue) from one viewpoint. The inferred coronal holes, the footprints of the open coronal fields, are shown by the red and green areas on the solar surface indicating inward or outward magnetic polarity. (b) Same model with the open field lines and surface field map added. (c) Synoptic map view of the model.

relevant to Earth. In this case the ecliptic solar wind would originate primarily from the polar open field region borders. However this is an exceptional case for the period covered by the GONG observations and of interest here.

A more typical PFSS model result for the period of the GONG magnetograms is shown in Fig. 4. The displays shown are analogous to those in Fig. 3, but for a different Carrington Rotation. Here the coronal field geometry is significantly distorted from the dipolar field geometry. It is not simply described as a tilted dipole as is often assumed. In particular, the open field areas of coronal holes (red and green) are no longer confined to the polar regions. Instead there are numerous coronal holes at mid to low latitudes [4,5]. In addition, the Helmet Streamer Belt is highly warped, leaving large areas of the surface map (white) outside of its closed field arcades (blue). These areas that are not part of the coronal holes or covered by the Helmet Streamer Belt arcade are occupied by closed field loops that are topologically distinct. These are the so-called pseudostreamers [6], closed field structures that also contain the hot dense plasmas found in the main streamer belt but are separate from it and more localized. These can be seen in coronal images as additional coronal rays similar to but separated from the main streamer belt rays. In this case there is one additional prominent streamer as seen in the PFSS model comparisons with SOHO LASCO images displayed in Fig. 5a

and b. In fact the coronal images obtained since 2006 generally exhibit more than the two opposite coronal rays associated with a dipolar appearance. An illustration of an even more highly structured coronal field example is shown in Fig. 6a and b. These coronal field configurations more closely resemble what is expected around solar maximum. The reason why they occur during relatively inactive times is due to the higher order harmonic content of the solar surface field routinely present through the cycle 23–24 minimum. While this recent minimum has overall weaker surface fields [7], the fields that are present also have smaller polar field contributions [7], making the decayed active region fields at low to mid latitudes more important in controlling the large scale coronal magnetic field topology.

Synoptic map-based 3D MHD models, such as the MAS model [3], include more of the physics of the corona and allow the consistent description of the coronal density, velocity and temperature as well as the magnetic field. Simulated coronal images obtained using MAS model density results for the same Carrington Rotation as the PFSS model results in Figs. 5 and 6a are shown in Fig. 5 and 6c. The comparisons with the real images in Fig. 5 and 6b are remarkable in their ability to capture both the main helmet streamer appearance and the split-off pseudostreamer ray. Many other examples can be found in the MAS coronal modeling website at

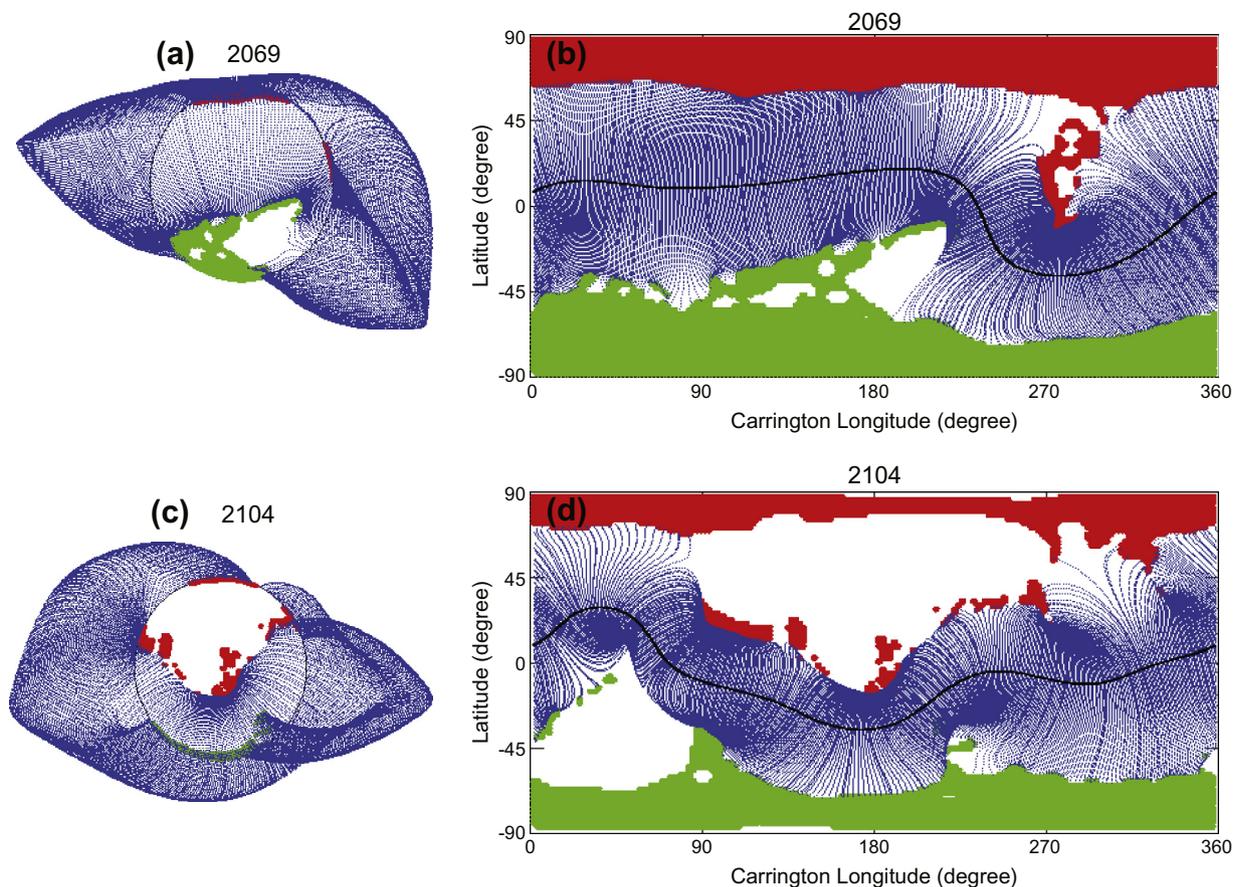


Fig. 4 Further examples of PFSS models like those in Fig. 3a and c but for times other than late 2009 (Carrington Rotation 2069 in panels a and b and 2104 in c and d). These illustrate the common nondipolar appearance of the large scale coronal magnetic field and the associated open field regions outside the polar caps. The fields on the solar surface have generally produced complicated coronal field geometries and their associated non-polar coronal hole sources of solar wind during the cycle 23–24 transition.

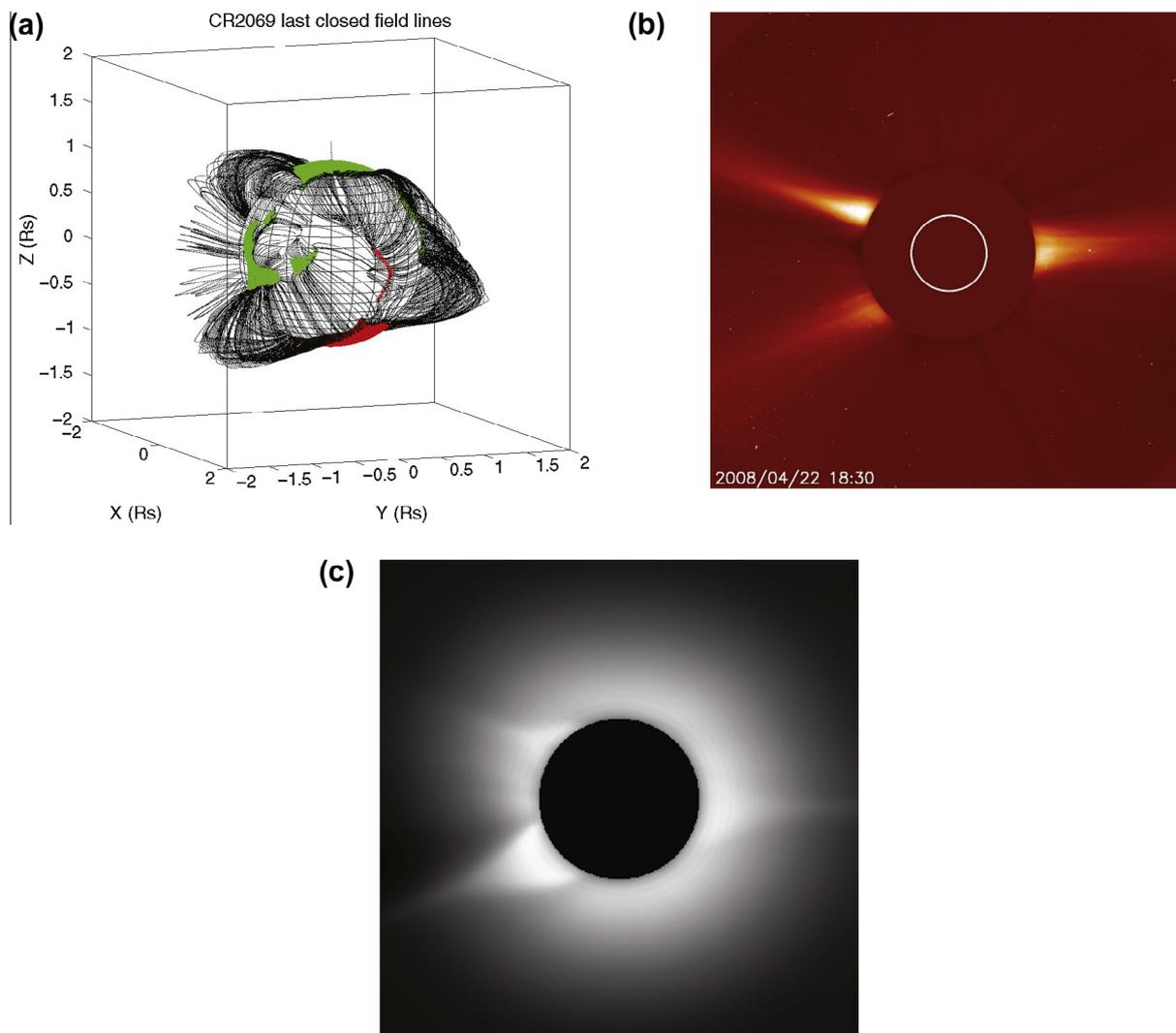


Fig. 5 Illustration of a pseudostreamer in both the PFSS model large scale coronal closed fields (a) and in the corresponding coronagraph image (b) for the Carrington Rotation shown in Fig. 4a and b. These additional coronal streamers have been common during the cycle 23–24 transition. In the SOHO LASCO C2 images (<http://sohowww.nascom.nasa.gov>) they appear as extra coronal rays. In the PFSS model they appear as closed field regions on the limb that are split away from the main helmet streamer belt. These closed field lines of the pseudostreamers are not generally shown in the on-line GONG PFSS model field plots. However their footprints can be seen as the areas on the solar surface that are left white (see Fig. 4a and b) and are outside the main helmet streamer belt arcade (blue). Panel (c) shows a corresponding simulated coronagraph image from an MHD model.

<http://www.predsci.com/stereo/>. These MHD model results further support the picture of a nondipolar corona like that exhibited in the observed images and PFSS coronal field models through most of the cycle 23–24 minimum, and into the cycle 24 rise. The implications for the solar wind are considered below.

Solar wind source mapping

The classical solar wind flows out into the heliosphere along open coronal field lines. This picture of the solar wind has been built upon over the last decade to include a related solar wind speed that depends on either the divergence of the open flux tubes and/or proximity to the open field/coronal hole boundary [8]. In short, faster (> 500 km/s) wind comes from close to the centers of larger area coronal holes, while slower wind

(~ 250 – 350 km/s) comes from the edges. However its open field origins have been a persistent paradigm that has endured. It has been shown that both PFSS and MHD coronal model field mapping to the ecliptic, together with these approximations regarding wind speed versus coronal hole mapped location, often provides a reasonable approximation to observed time series of solar wind streams and interplanetary field polarity [3,8]. This approach is expected to be most accurate around solar minimum, when the solar surface boundary fields are steadiest over a solar rotation, an assumption of both global models.

Fig. 7 shows some results of solar wind source mapping with the MHD model for a Carrington Rotation in the period of interest. Model time series of solar wind velocity (Fig. 7 upper panel) and interplanetary field polarity (Fig. 7 lower panel) at the 1 AU location of the STEREO-B (Behind) spacecraft for Carrington Rotation 2096 are compared

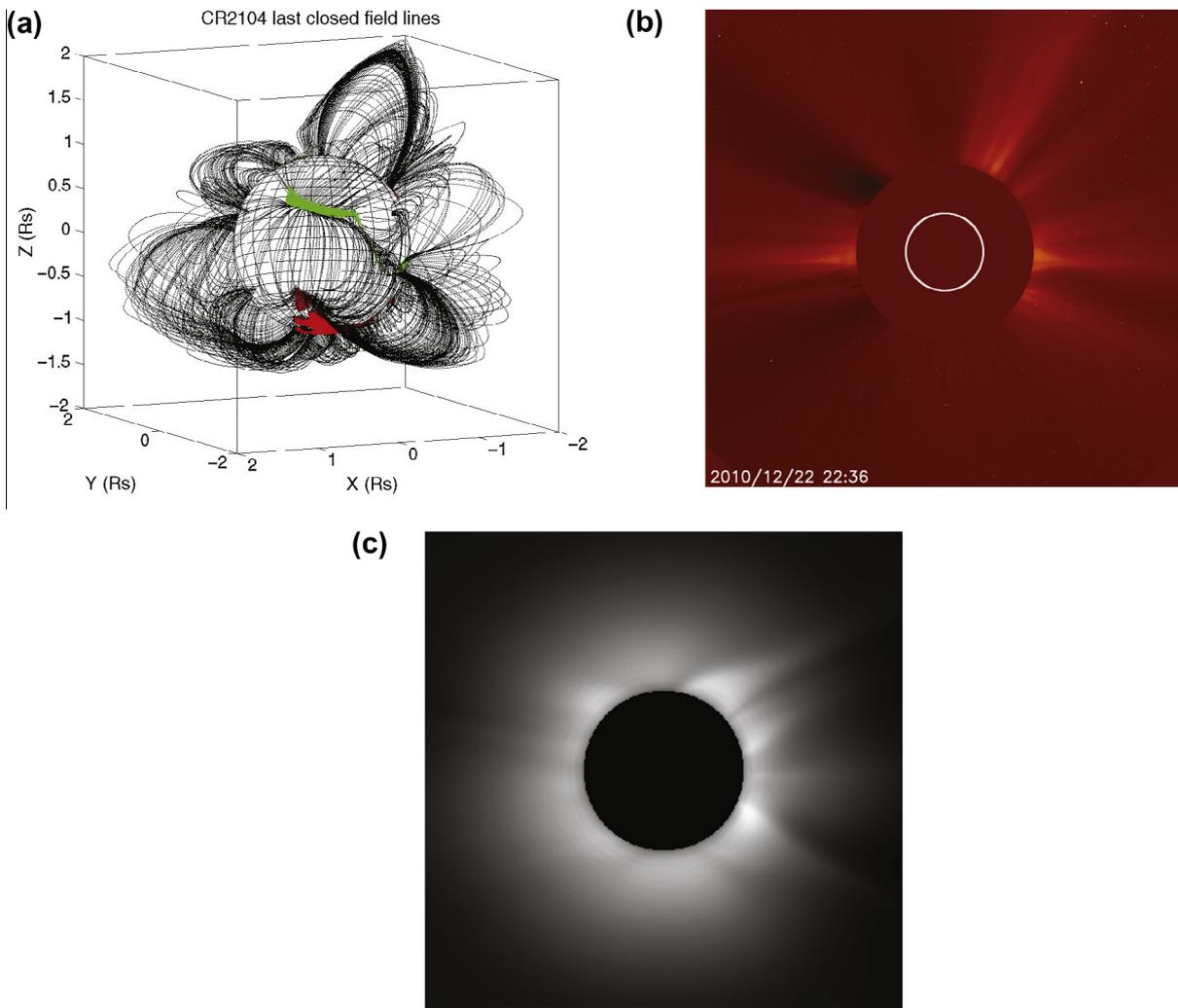


Fig. 6 The PFSS model field lines (a) and a coronagraph image (b) for the Carrington Rotation in Fig. 4c and d. These show a particularly complicated coronal field with many closed loops and fragmented open field areas. The SOHO LASCO C2 image shows the related complexity of streamers around the limb. Panel (c) shows a corresponding simulated coronagraph image from an MHD model.

with the in situ measurements. While the model does not capture all of the observed details, many gross features of the measurements are reproduced by the model mappings. A comparison of the inferred solar wind sources from the MHD model mapping with the PFSS open field line mapping for this same case (with the actual open field line segments for the PFSS model) is shown in Fig. 8. Both models suggest similar pictures of the solar wind source locations for the example shown, suggesting that either model can be used to obtain a first order picture of what solar wind sources are prevailing at a particular time and location in the ecliptic at 1 AU. The exception, of course, is if transients from Coronal Mass Ejections are occurring. This example is typical of the cycle 23–24 transition and backs up the earlier discussion concerning the non-polar sources of much of the solar wind observed at Earth’s orbit.

One caveat that must be introduced relates to the increasing appreciation that the solar wind is not generally steady or quasi-steady as both of these models assume. This may partially explain the disagreements found from model comparisons with

in situ data, although there are many other details (including synoptic map construction procedures and extrapolations to 1 AU) that can also contribute. The SOHO LASCO coronagraph observations were a main reason for the general acceptance of the idea that the slow solar wind in particular may have its origins partially in small (non-coronal mass ejection) transients that appear to arise at the boundaries and cusps of the coronal streamers in the images [1,9]. These transient ‘blobs’ are ubiquitous, occurring at solar minimum as well as more active times of the cycle. The tracking of the blobs suggest they accelerate and move outward at what are considered slow solar wind speeds of ~ 300 km/s. The extent to which the slow solar wind is made up of these transients rather than steady coronal hole boundary wind continues to be an area of investigation. Nevertheless, it is worth pointing out that if there are more streamers and coronal hole boundaries in the coronal field topology, such transient contributions to the slow solar wind should increase. It follows that for this recent period of complex coronal topology the slow solar wind could have a particularly large transient component as perhaps

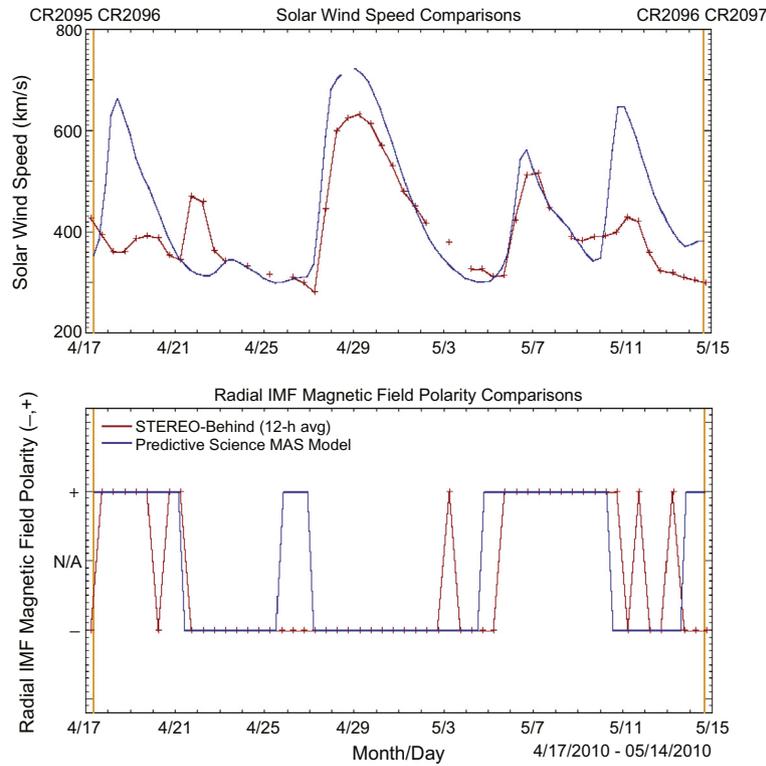


Fig. 7 Examples of field polarities and solar wind velocities at 1 AU inferred from the MAS MHD model results (here for Carrington Rotation 2096). (top panel) Model velocities (blue) compared to the STEREO-B measurements (red) at 1 AU for this period. (lower panel) Model interplanetary field polarities (blue) compared to the measurements (red).

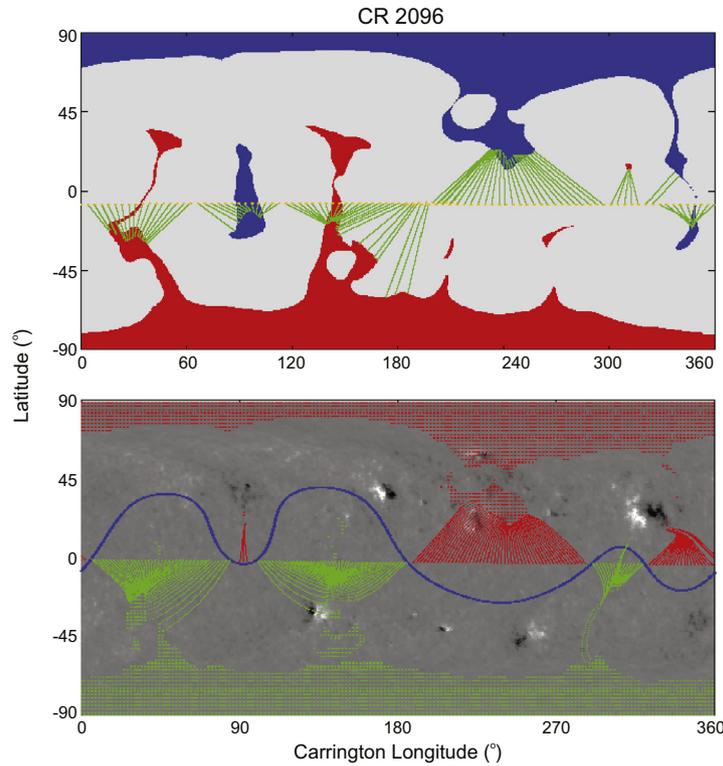


Fig. 8 Comparisons of MAS MHD model and PFSS model solar wind source mappings for Carrington Rotation 2096. (a) Coronal hole map showing the endpoints of the open field lines mapping to the ecliptic, connected by green lines. (b) PFSS model open field line mappings, color coded by the magnetic polarity of the solar wind source region.

suggested by the complex outflows in STEREO Heliospheric Imager images [10].

Discussion and concluding remarks

In this review we describe an updated view of solar wind sources based on combinations of modern observations and models. The picture now commonly applicable is not the dipolar coronal/polar coronal hole picture of early solar wind theory, although it retains certain elements. The modern solar wind still has its main source in open coronal magnetic field areas and velocities that depend on the location where the mapped field lines of interest originate within them. It still is expected to have transient contributions related to the boundaries and cusps of coronal rays. However the prevailing field geometries generally exhibit significant distortions from the dipole picture, including many mid-to-low latitude coronal holes outside the polar regions, and multiple streamers. The topologically distinct pseudostreamers produce coronal rays without field reversals at their cusps at locations apart from the main helmet streamer belt. This combination produces a more complex solar wind source map for the typical ecliptic solar minimum and increases the contribution of streamer boundary transients to the slow solar wind. The occurrence of these conditions results from the distribution of the solar surface fields which in the recent minimum have had weaker polar contributions. The result has been a solar maximum-like corona through much of the long period of quiet solar conditions during the cycle 23–24 transition. It remains to be seen if this solar wind source pattern persists through the new solar cycle. In any case solar wind researchers and students alike are encouraged to adopt this more correct, albeit challenging, perspective on what are now typical solar wind sources.

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References

- [1] Wang Y-M, Sheeley NR, Howard RA, Rich NB, Lamy PL. Streamer disconnection events observed with the LASCO coronagraph. *Geophys Res Lett* 1999;26:1349–52.
- [2] Wang Y-M, Sheeley Jr NR. On potential field models of the solar corona. *Astrophys J* 1992;392:310–9.
- [3] Riley P, Lionello R, Linker JA, Mikić Z, Luhmann J, Wijaya J. Global MHD modeling of the solar corona and inner heliosphere for the whole heliosphere interval. *Sol Phys Online First* 2011.
- [4] Abramenko V, Yurchyshyn V, Linker J, Mikić Z, Luhmann JG, Lee CO. Latitude coronal holes at the minimum of the 23rd solar cycle. *Astrophys J* 2010;712:813–8.
- [5] Lee CO, Luhmann JG, Zhao XP, Liu Y, Riley P, Arge CN, et al. Effects of the weak polar fields of solar cycle 23: investigation using OMNI for the STEREO mission period. *Sol Phys* 2009;256:345–63.
- [6] Wang Y-M, Sheeley Jr NR, Rich NB. Coronal pseudostreamers. *Astrophys J* 2007;658:1340–8.
- [7] Wang Y-M, Robbrecht E, Sheeley Jr NR. On the weakening of the polar magnetic fields during solar cycle 23. *Astrophys J* 2009;707:1372–86.
- [8] Arge CN, Pizzo VJ. Improvement in the prediction of solar wind conditions using near-real time solar magnetic field updates. *J Geophys Res* 2000;105:10465–80.
- [9] Wang Y-M, Sheeley NR, Socker DG, Howard RA, Rich NB. The dynamical nature of coronal streamers. *J Geophys Res* 2000;105:25133–42.
- [10] Rouillard AP, Sheeley NR Jr, Cooper TJ, Davies JA, Lavraud B, Kilpua EKJ, et al. The solar origin of small interplanetary transients. *Astrophys J* 2011;734, doi:<http://dx.doi.org/10.1088/0004-637X/734/1/7>.