The Open Flux Problem: The Need for High Latitude Observations

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Synopsis

The Sun's open magnetic field is a fundamental aspect of coronal and heliospheric physics. The primary source location of the open magnetic field is believed to be coronal holes, usually detected by the absence of EUV and/or X-ray emission. We have observed photospheric magnetic fields remotely and measured interplanetary magnetic fields in situ for over five decades. A long-standing issue is that models based on photospheric magnetic field observations significantly underestimate the open magnetic field inferred from interplanetary measurements, if their open field regions are compatible with coronal hole observations. This is not a model problem, but rather an observed open flux problem: When the open flux is estimated from coronal hole detections superimposed on observatory-based solar magnetic flux maps (entirely eliminating models), the deficit persists or is even larger. A major uncertainty is the strength of the polar magnetic fields, which are poorly observed from the ecliptic plane. Resolving the contribution of polar fields requires line-of-sight measurements of the photospheric field at high heliographic latitude (greater than 65°) with corresponding detection of coronal hole boundaries in a coronal emission line, at a time not too far from solar minimum (when polar fields are strongest), for at least a solar rotation. Regardless of the result (strong or weak polar fields), such measurements will have profound implications for our understanding of the structure of the solar corona and inner heliosphere, including CME and SEP propagation, and the formation and sources of the solar wind.

1 Introduction

The "open" magnetic field is that portion of the Sun's magnetic field that extends out into the heliosphere and becomes the interplanetary magnetic field (IMF). Open fields play a crucial role in heliophysics as the main driver of geomagnetic activity. They also determine where solar energetic particles (SEPs) propagate and shield the solar system from galactic cosmic rays. In the standard paradigm of coronal structure (e.g., Priest, 2014), the open magnetic field originates primarily in coronal holes (CHs), regions of low intensity emission in EUV and X-rays (Bohlin, 1977; Zirker, 1977). The regions that are magnetically closed trap the coronal plasma and give rise to the streamer belt that is prominent in coronagraph and eclipse images (e.g., Wang et al., 1997; Linker et al., 1999; Pasachoff et al., 2009; Rušin et al., 2010).

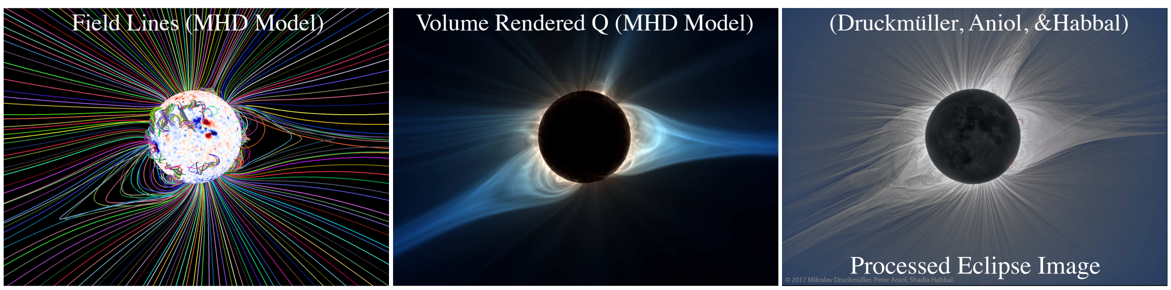

Figure 1: *Comparison between the corona predicted with an MHD model one week prior to the 21 August 2017 total solar eclipse and a digitally enhanced eclipse image taken in Mitchell, Oregon (©Druckmuller, Aniol, and Habbal). The volume-rendered squashing factor Q (Titov, 2007) emphasizes fine spatial scale structure in the magnetic field. See Mikić et al. (2018) for details.*

The distribution of the photospheric magnetic field on the solar surface has been observed for over five decades. Global magnetic maps, developed from full-disk magnetograms of the line-of-sight (LOS) photospheric magnetic field (inferred from the Zeeman splitting of measured spectral lines), are available from ground- and space-based observatories. Models, beginning with Potential Field Source Surface (PFSS, e.g., Altschuler & Newkirk, 1969; Altschuler et al., 1972) and the earliest magnetohydrodynamic (MHD) models (e.g., Mikić & Linker, 1996) have shown that they can reproduce key features of the large-scale corona and inner heliosphere, such as the location of CHs, the streamer belt, and the HCS, with a photospheric magnetic field map as the only direct observational input to the model. Figure 1 shows an example from a prediction of the structure of the solar corona prior to the August 21, 2017 total solar eclipse using the Magnetohydrodynamic Algorithm outside a Sphere (MAS) MHD model (Mikić et al., 2018). A magnetic map based on HMI measurements was used for the boundary condition. The model and observed large-scale streamer structure are very similar.

The IMF has also been measured in situ for many years. Ulysses measurements demonstrated that the magnitude of the radial IMF is nearly independent of heliographic latitude (Smith & Balogh, 1995, 2008), implying that currents in the heliosphere are primarily confined to the heliospheric current sheet (HCS) and that the field is nearly potential everywhere else. The consequence of these measurements is that the open magnetic flux of the Sun can be inferred from suitably averaged single point in situ measurements of the radial IMF (e.g., Owens et al., 2008).

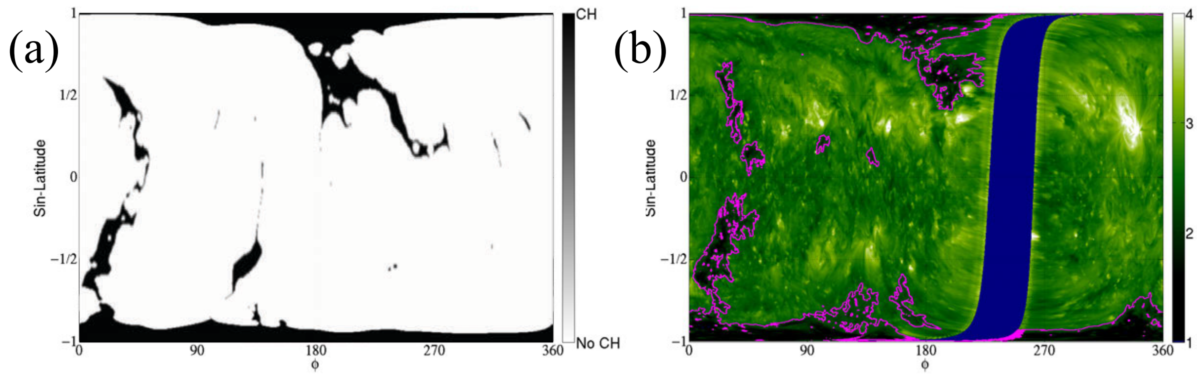

Figure 2: *Comparison of modeled open field regions and detected coronal holes (adapted from Linker et al., 2017). (a) Open field regions (black) from a PFSS model using an NSO SOLIS (VSM) synoptic map. (b) Synchronic EUV map for July 8, 2010 at 18:00, compiled from STEREO A & B EUVI 195Å and SDO AIA 193Å images. The magenta lines show the coronal hole detections from Caplan et al. (2016). The sector near 270°, indicated by the blue swath, was not observed. The modeled open field regions are roughly similar to the detected coronal holes, but the modeled open flux was ∼1.8-2.3 times smaller than that inferred from interplanetary measurements for this time period.*

Two basic properties can be predicted by all models: the magnitude of the open magnetic flux, and the open field regions at the solar surface. If the basic paradigm of coronal structure is correct, then the magnitude of the open magnetic flux predicted by the combination of a coronal model and an observatory map should match that inferred from in situ spacecraft measurements (e.g. suitable averages taken over a solar rotation). We would expect this approach to work reasonably well near solar minimum, when the large-scale underlying structure of the corona often varies slowly. Accuracy could be more problematic near solar maximum, when the Sun's magnetic flux is rapidly evolving.

An enduring problem, and one that is seen across a wide range of models, is that the modeled strength of the IMF, that is, the open magnetic flux, is underestimated, often by a significant factor of 2-3 (Riley et al., 2012; Linker et al., 2017; Wallace et al., 2019), if the open field regions of the model are compatible with CH boundaries inferred from observations. Figure 2, adapted from Linker et al. (2017), illustrates the problem. Open field regions computed with a PFSS model using an NSO SOLIS synoptic magnetic map and a source-surface radius (R_{SS}) of 2.0 are similar to detected coronal holes, but the modeled open flux is about 1/2 of the inferred interplanetary flux for this time period. For an $R_{SS} = 1.3$, the modeled open flux with this map was compatible with the interplanetary flux, but then the open field areas of the model were much larger (68%) than observed. Recent observations from PSP indicate that this problem persists, even with interplanetary measurements much closer to the Sun (Riley et al., 2021).

This is fundamentally not a model problem, but rather an observed open flux problem: When the open flux is estimated from coronal hole detections superimposed on observatory-based solar magnetic flux maps (entirely independent of models, but the features models attempt to match), the discrepancy with IMF measurements is generally the same or even larger (Linker et al., 2017; Lowder et al., 2017; Linker et al., 2021). Figure 3 shows the combination of an SDO HMI LOS synoptic map (a) combined with (b) coronal holes detected in EUV with the Minimum Intensity Disk Merge (MIDM, Linker et al., 2021) to produce an estimate of the open flux (c). The resulting estimate of open flux ($B_r \approx 0.68$nT scaled to 1 AU) was 2.5 times less than the open flux estimated from interplanetary measurements (≈ 1.71nT). MIDM produced the largest open field areas and fluxes of the detection schemes compared in Linker et al. (2021).

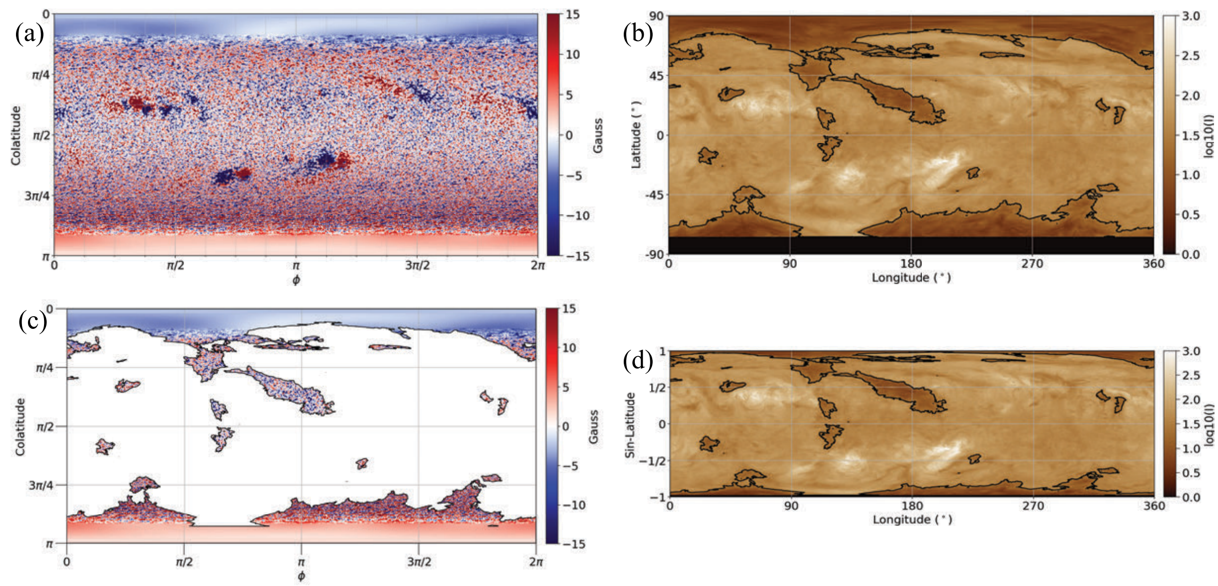

Figure 3: *(a) Synoptic map of B_r from HMI LOS measurements (using HMI pole-filled maps, Sun, 2018) for CR2101 (9/5 -10/3/2010). (b) EUV map and detected CHs for the same time period as (a) using MIDM (Linker et al., 2021) with SDO AIA 193Å images. This technique employs EUV images at multiple times to minimize obscuration and maximize the detected CHs. At this time period, a portion of the southern pole was not visible and was assumed to be open. (c) B_r combined with the detected CHs to estimate the open magnetic flux The solar open flux estimated in this way was 2.5 times less than the inferred interplanetary flux. (d) The same as (b) but in an equal-area format (sine-latitude vs. longitude), the actual geometry of ecliptic observations.*

As identified by Linker et al. (2017), there are two general categories of resolutions for this underestimate of the open flux: (1) Either the magnetic maps derived from observations are underestimating the magnetic flux, or (2) a significant portion of the open magnetic flux is not rooted in regions that appear dark in emission. In the following sections, we describe how observations of the Sun's poles are key to providing a resolution.

2 Implications of Stronger Polar Fields

For resolutions in category (1), suspicion naturally falls on measurements of the polar magnetic fields, which are poorly observed from the ecliptic plane. Far from disk center, the radial magnetic field (B_r) is transverse to the LOS, so the LOS signal of B_r near the poles is dominated by noise. In principle, B_r can be obtained from the transverse field in vector magnetograms (e.g. HMI). However, this component is far noisier than the LOS field (Hoeksema et al., 2014), and it is difficult to obtain reliable transverse field measurements outside of active regions. Attempts to measure the polar magnetic fields with the much higher resolution Hinode SOT gave tantalizing indications of kilogauss concentrations of vertical fields and stronger polar magnetic flux at the southern pole

(Tsuneta et al., 2008), but the features were likely still under-resolved, and interpretations of the contribution to the overall magnetic flux were highly dependent on assumptions about the filling factor.

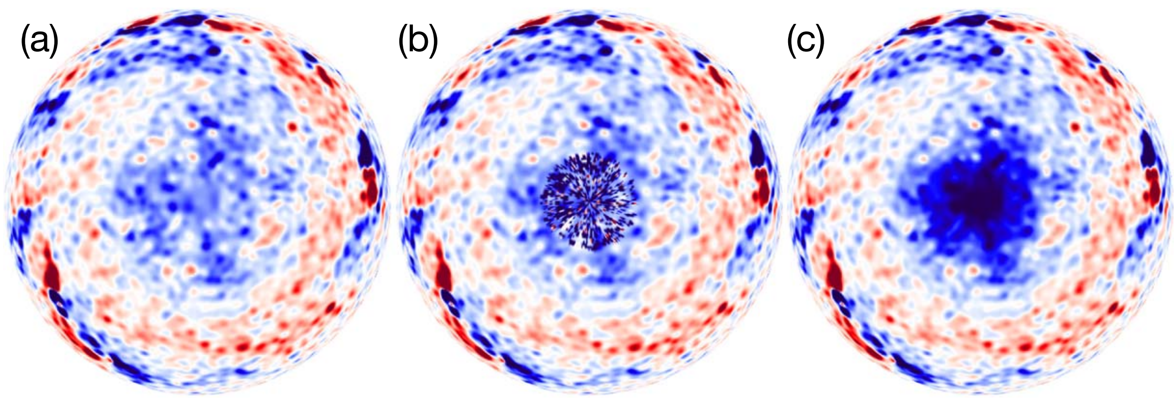

Figure 4: *Polar view of the radial component of the photospheric magnetic field for the CR 2097+2098 time period, from SOHO MDI LOS measurements (Riley et al., 2019). (a) Polar field derived from standard processing techniques. (b) The same as (a) but with small-scale polarities (biased toward the sign of the existing field) added to the polar regions. (c) A smoothed version of (b).*

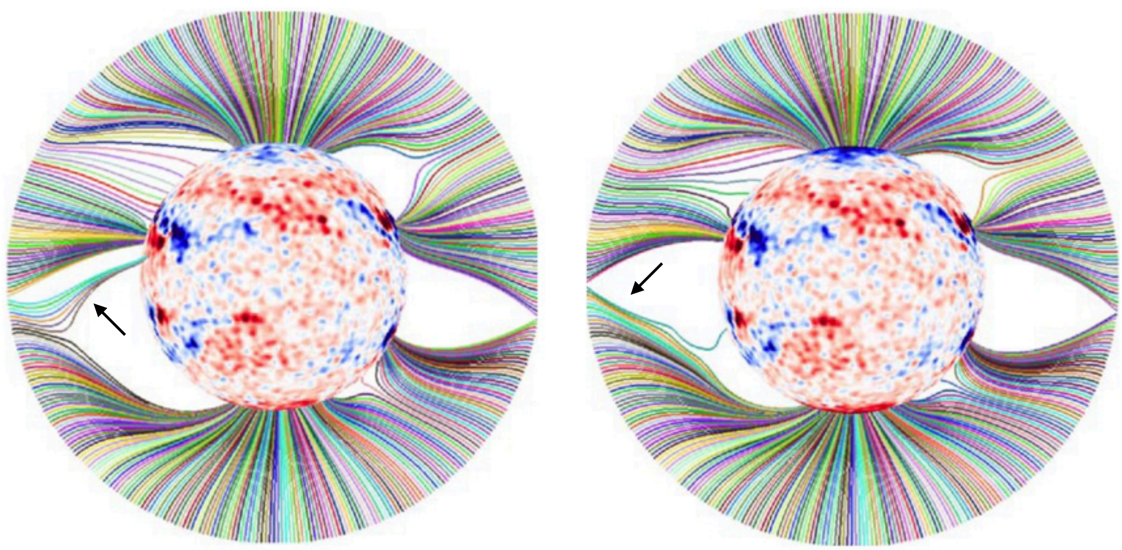

Figure 5: *Magnetic field lines in a PFSS model for standard and enhanced polar fields (Riley et al., 2019). On the left, field lines for the magnetic map in Figure 4(a), and on the right, for the map in Figure 4(c). The connectivity of solar wind field lines back to the Sun can change significantly between the two models (arrows indicate one example).*

Riley et al. (2019) investigated the consequences of unobserved magnetic flux concentrations at high latitudes using PFSS and MHD models. Figure 4, adapted from that paper, shows three possible scenarios for polar fields in July 2010: (a) is derived from MDI observations; (b) has flux added in the polar region in small concentrations, and (c) is a smoothed version of (b). These different cases are largely indistinguishable when observed from the ecliptic plane, but the cases with stronger polar fields have open flux compatible with interplanetary measurements. Riley et al. (2019) showed that model solutions that lack this additional flux systematically produce streamers lying at higher helio-latitudes than is inferred from observations, and solutions that include the additional flux do not substantially change the location or size of the modeled coronal holes. Stronger polar fields have important implications for coronal and heliospheric structure. Figure 5 shows significant differences in magnetic connectivity for solutions with and without additional polar flux. This, in turn, impacts our understanding of dynamic phenomena. For example, advanced simulations of CME events are initiated from background coronal models. The CME-driven shock parameters and magnetic connectivity differ in models that start from maps with different polar fields (Jin et al., 2022), leading to different conclusions about the origin and acceleration of SEPs. The magnetic fields in the CME that are propagated to 1 AU combine the erupting fields with the overlying fields in the streamer belt that are carried outward in the eruption (e.g., Török et al., 2018). The overlying fields are, therefore, a critical input for models attempting to predict the geoeffectiveness of CMEs, and their structure and field strength depend on the polar fields.

3 Implications for Weak Polar Fields

What if measurements show that the polar fields are not stronger than what we infer from ecliptic observations? The consequences are equally striking. Could all magnetographs be systematically underestimating the large-scale photospheric magnetic field? This possibility has been raised previously (Wang & Sheeley, 1995) and has recently been renewed with similar arguments (Wang et al., 2022). This argument relies on alternative interpretations of the saturation factor in older measurements, which are a subject of controversy (Svalgaard et al., 1978; Riley, 2007; Riley et al., 2014) and raises the question of why subsequent instruments (e.g. MDI, HMI, NSO GONG, NSO SOLIS) also lead to open flux underestimates (Linker et al., 2017). If this is true, then inferences from all past and currently operating magnetographs will have to be re-examined.

The second category of resolutions involves open flux not appearing dark in emission. This raises the question of the uncertainties associated with automated CH detection, recently studied by Linker et al. (2021) and Reiss et al. (2021). Both studies compared several CH detection methods on a reasonably well-observed low latitude CH, and found substantial variation in the detected areas (a factor of $\sim$2.4 in Linker et al. (2021), and 4.5 in Reiss et al. (2021)). Linker et al. (2021) used the standard deviation from the mean to estimate the uncertainty and obtained a value of $\approx$26%. MIDM, the detection method that produced the largest areas and open fluxes, was used to estimate the total open flux for the entire Sun, and found values substantially lower than the inferred interplanetary open flux (see Figure 3(c)). However, the detection of polar CHs observed from the ecliptic plane suffers from the same foreshortening issues as the measurement of the magnetic field, as shown in Figure 3(d). Understanding the structure of polar CHs requires EUV observations from high latitudes.

Linker et al. (2021) tested the same CH detection methods on simulated AIA images from a thermodynamic MHD model for this time period, finding that the full-Sun detections on the simulated corona underestimate the model open flux, but by factors well below what is needed to account for the missing flux in the observations. They concluded that under-detection of open flux in coronal holes may contribute to the open flux problem, but is unlikely to be the primary source.

Other explanations for the open flux deficit depart from the standard paradigm for coronal structure. They include the possibility that a significant portion of the open flux is rooted at the Sun, but continually undergoes interchange reconnection, and the mixture of open and closed field lines is not obviously dark in emission. While interchange reconnection has been advocated as an explanation for the origin of the slow solar wind (e.g., Fisk et al., 1998; Antiochos et al., 2011), it is not clear what emission properties the plasma on these field lines would possess. Another possibility is that the disparity between observed coronal and heliospheric open flux is not related to solar observations, but to the behavior of the interplanetary magnetic field. The discovery of "switchbacks" in the interplanetary magnetic field from PSP (Bale et al., 2019; Kasper et al., 2019) suggests that folded flux could be more ubiquitous than previously thought, and lead to increases in the magnitude of B_{R} measured in-situ at increasing distance (i.e., 1 AU) from the Sun (Macneil et al., 2020). However, comparisons of PFSS and MHD models with PSP observations (Badman et al., 2021; Riley et al., 2021) suggest that the models significantly underestimate the field strength even at the perihelion distances that PSP has reached thus far. Finally, large amounts of disconnected flux in the heliosphere could also account for the missing open flux, although this has generally been considered unlikely (Crooker & Pagel, 2008). All of these explanations face formidable observational obstacles, e.g. why would all magnetographs have systematic errors in the same direction? Why do even simple coronal/empirical models (e.g. WSA/PFSS) do reasonably well in predicting heliospheric properties? Why do we measure largely unidirectional heat flux in the background solar wind?

4 Required Measurements

To definitively resolve the polar fields, we need to observe the entire polar region for an extended period of time at sufficiently high latitude. For LOS magnetograms, the measured fields must be sufficiently close to disk center that the LOS field provides a reasonable approximation to the radial field. At an orbit above 65° heliographic latitude for at least a solar rotation (longer is better), an LOS magnetograph can be expected to provide reasonable estimates of the magnetic flux. For this orbit, the instrument need not be very high resolution: spatial pixel size equivalent to the MDI instrument aboard SOHO should be sufficient. With a LOS measurement, resolving the magnetic elements is not crucial to measuring the magnetic flux, as the flux distributed over a pixel will be adequately measured. In conjunction with the magnetic flux measurements, identifying CH boundaries at high latitudes is required. EUV measurements in a coronal line (e.g. 171Å, 193Å, or similar) at a spatial pixel size similar to SOHO EIT should be adequate, although resolution closer to STEREO EUVI is desirable. Accompanying in situ measurements at high latitude from a magnetometer would be highly desirable for relating the remote observations to interplanetary magnetic flux. These measurements should occur not too far from solar minimum, when the polar fields are strongest. Possible polar mission concepts have been discussed by Gibson et al. (2018). The Solaris MIDEX mission (Hassler et al., 2021) underwent a Phase A study and is being expanded to a Discovery/New Frontiers-class mission in a White Paper to this Decadal Survey (Hassler et al., 2022). It is an example of a mission that could provide definitive observations for resolving the contribution of polar open flux. Figure 6(a) shows the number of days that all longitudes of the south polar region would be observed simultaneously.

We note that while Solar Orbiter may contribute substantially to our understanding of high-latitude fields, it is unlikely to resolve the polar field controversy. In the nominal phase of the mission, Solar Orbiter will reach latitudes of $\sim$17° latitude, which, while providing new polar information, is insufficient to definitively measure the polar field. At the end of the extended mission phase, it could reach latitudes above 30° degrees and observe the polar fields for short periods [$<$ 10 days, see Figure 6(b)]. This latitude is still too low to adequately measure the polar field magnetic flux from a LOS measurement. Polar field flux estimates would then rely on measurements of the transverse field. The transverse field in vector magnetograms is typically far noisier than the LOS field, and requires ambiguity resolution and estimates/assumptions about the filling factor to infer magnetic flux. Conclusively measuring the polar magnetic flux requires LOS measurements above 65° heliographic latitude for extended periods. While not required for measuring open flux, vector measurements at high latitude are desirable for discerning inclination of the polar fields.

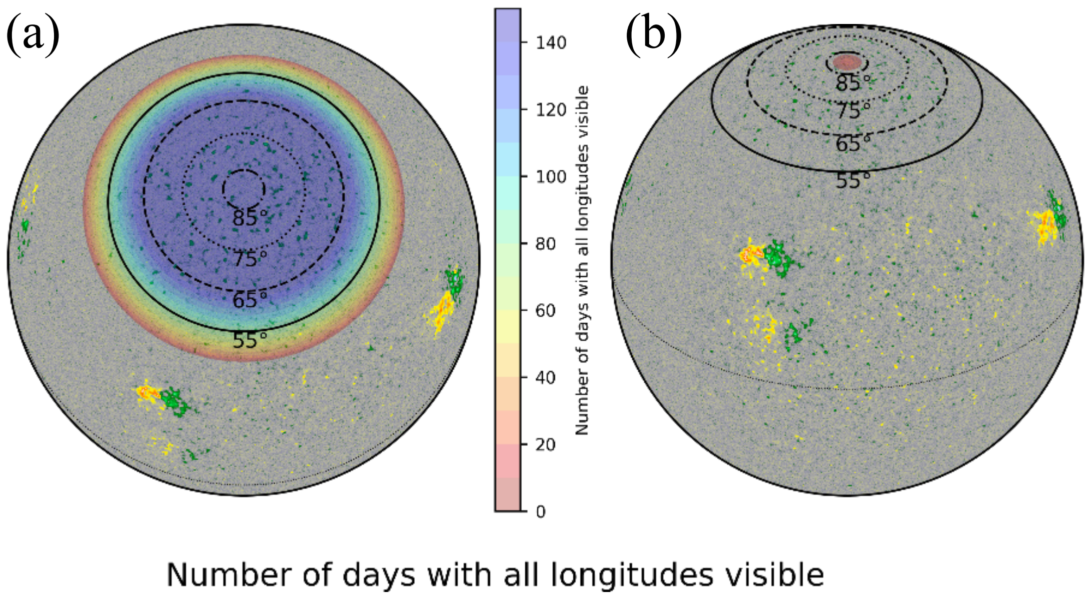

Figure 6: *Number of days where all longitudes are visible for a given latitude region near the southern pole for (a) Solaris and (b) Solar Orbiter. Solaris would provide viewing of the entire polar region for a significant time period, while in its extended mission Solar Orbiter would observe the entire pole only above 88° degrees heliographic latitude for 8 days (Hassler et al., 2022).*

5 Summary

The solar open magnetic flux is a central feature of the solar corona and heliosphere. After more than five decades of observations, we have not adequately explained why solar observations of the open flux significantly underestimate the observed interplanetary flux. **Resolving the poorly measured contribution of the Sun's polar magnetic fields to the open flux requires measurements of the LOS magnetic field above 65° heliographic latitude, with accompanying EUV detections of coronal holes, for at least a solar rotation.** Such measurements will profoundly influence our understanding of the solar corona and inner heliosphere.

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