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Global Circulation of the Open Magnetic Flux of the Sun

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Abstract

The global circulation of the open magnetic flux of the Sun, the component of the solar magnetic field that opens into the heliosphere, and the consequences of the global circulation were proposed by Fisk and coworkers in the early 2000s. The Parker Solar Probe, on its initial encounters with the Sun, has provided direct confirmation of both the global circulation and the physical mechanism by which the circulation occurs, transport by interchange reconnection between open magnetic flux and large coronal loops. The implications of this confirmation of the global circulation of open magnetic flux and the importance of interchange reconnection is discussed.

Unified Astronomy Thesaurus concepts: Solar magnetic fields (1503); Solar wind (1534); Solar coronal loops (1485)

1. Introduction

In 1995, the Ulysses spacecraft orbiting over the south pole of the Sun observed 26 day increases in the intensity of a few hundred keV electrons and 0.5 MeV protons, which gave every evidence of having originated from corotating interaction regions that lie within 30° of the solar equatorial plane (Simnett et al. 1995). These observations were a surprise. Low-energy electrons in particular follow field lines, and the Parker spiral magnetic field, lying on cones of constant heliographic latitude, provides no means for electrons to be transported from low to high latitudes. The implication of these observations is that the Parker spiral is not correct, and the heliospheric magnetic field must also include a systematic polar component, along which the low-energy particles can propagate.

The heliospheric magnetic field is the component of the solar magnetic field that opens into the heliosphere, the so-called open magnetic flux of the Sun. To impart a polar component into the heliospheric magnetic field, the open magnetic flux must be in motion in heliographic latitude in the solar corona, in addition to being attached to the rotating Sun. In 1995, the Sun was at solar minimum, and the open magnetic flux observed by Ulysses originated from the coronal hole at the south pole of the Sun. The polar coronal holes are offset from the rotation axis of the Sun; the solar wind that originates from the polar coronal hole undergoes a super-radial expansion; and the poles differentially rotate relative to the solar equator. Putting all these effects together, Fisk (1996) showed that the magnetic field from the polar coronal hole moves systematically in latitude, downward on one side of the Sun and upward on the other side, thereby imparting a polar component to the heliospheric magnetic field.

The work of Fisk (1996) was obviously of interest to studies of the heliosphere. However, it shortly became evident that the transport of the heliospheric magnetic field in latitude had profound consequences for basic solar processes, such as the acceleration of the solar wind, the formation of coronal holes, even potentially the solar dynamo.

The heliosphere contains a single current sheet, separating two hemispheres of open magnetic flux of opposite magnetic polarity. During solar minimum conditions the heliospheric current sheet lies near the solar equatorial plane. Under these circumstances, open magnetic flux can be eliminated only if two oppositely directed open magnetic field lines reconnect at the current sheet, inside the Alfvén point, thereby forming two U'-shaped loops, one that remains attached to the Sun, and the other that is carried outward with the solar wind, eliminating open flux from the heliosphere. There is little evidence that this process occurs at all, and certainly as the open magnetic flux from the polar coronal hole is transported downward in heliographic latitude from the polar coronal hole, across a broad range of heliographic longitudes, it cannot all reconnect and be eliminated at the current sheet, nor on the other side of the Sun can open flux be generated and transported upward in heliographic latitude. Nor can the open flux accumulate on one side of the Sun. The magnetic field pressure in the corona is dominant, and substantial variations in magnetic pressure do not occur. The only possibility then is that open magnetic flux is transported in a band that surrounds the heliospheric current sheet, from one side of the Sun to the other, thereby creating a continuous circulation pattern of open magnetic flux, downward and upward in heliographic latitude at the higher latitudes, and parallel to the current sheet at lower latitudes.

Fisk & Schwadron (2001) and Fisk (2005) specified the mechanism by which open magnetic flux is transported at lower latitudes. The open magnetic flux moves through the corona to maintain magnetic pressure balance. It remains attached to the solar surface. The open flux is thus dragged through overlying large coronal loops present at lower latitudes during solar minimum, reconnects, in a process usually referred to as interchange reconnection, and is displaced. The displacements result in a diffusion of open flux along the solar surface, with the displacements oriented preferentially in the direction of motion required to maintain magnetic pressure balance in the solar corona.

Shown in Figure 1 is a simple schematic of the transport mechanism of Fisk & Schwadron (2001) and Fisk (2005). The red curves represent open magnetic field lines and the blue curves, large coronal loops. The open magnetic field lines are undergoing global circulation in the overlying corona, while still being attached to the solar surface. In illustration A, the open field line and the loop are separate. In illustration B, the open field line is dragged through the loop, and undergoes interchange reconnection, creating a smaller loop, and an open field line with a large

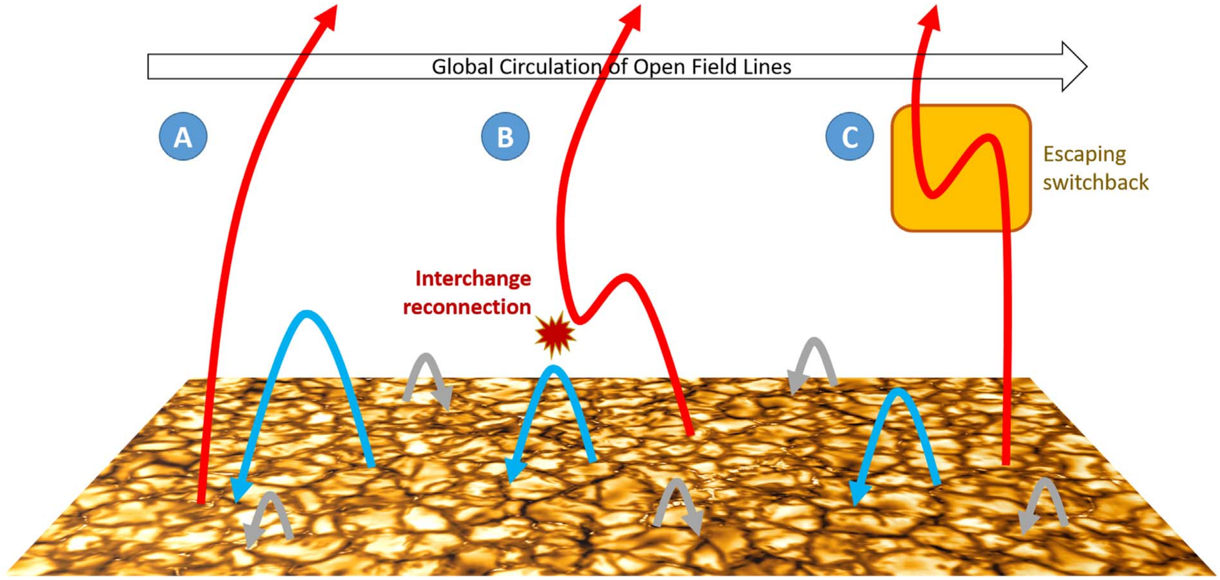

Figure 1. Illustration of global magnetic field circulation enabled by interchange reconnection. In this scenario an open magnetic field line is (A) dragged against a large coronal loop, by global circulation in the corona, (B) undergoes interchange reconnection, and (C) effectively jumps the approximate width of the originally closed loop, launching an *S*-shaped switchback in the magnetic field into the corona.

S-shaped switchback (C) that propagates outward into the corona at the Alfvén speed.

In the original work by Fisk & Schwadron (2001) and Fisk (2005) the *S*-shaped switchbacks were not expected to survive in the corona; rather, the open magnetic field line would simply relax so as to maintain constant magnetic pressure in the corona. The remarkable observations from the Parker Solar Probe (PSP), which we will now discuss, not only show that the *S*-shaped switchbacks survive, they validate that open magnetic flux is transported by interchange reconnection, that systematic interchange reconnection is an essential process for understanding the dynamics of the solar corona and the solar magnetic field, and that the global circulation of open magnetic flux predicted by Fisk & Schwadron (2001) and Fisk (2005) exists.

2. New Observations by PSP

Launched in 2018 August, PSP has completed four encounters with the Sun, three into 35 solar radii and one into 28 solar radii. Initial results from the first two encounters have been reported (Bale et al. 2019; Kasper et al. 2019). Based on the in situ observations, numerical simulations (Van der Holst et al. 2019), and extrapolations of photospheric magnetic field maps (Badman et al. 2020), the spacecraft is thought to have spent the entire interval inside 0.25 au (54 solar radii), just below the heliospheric current sheet (HCS) in the southern magnetic hemisphere of the Sun (Szabo et al. 2020). Given the phase of the solar cycle, if PSP was in the southern magnetic hemisphere, the solar wind magnetic field should always have had a magnetic polarity oriented inward toward the Sun. Instead, PSP observed thousands of intervals, ranging in duration from seconds to tens of minutes where the speed of the solar wind flow suddenly jumps and the magnetic field orientation rotates by nearly 180° in the most extreme cases, before returning just as quickly to the original solar wind conditions. These events have been termed switchbacks, when referring to the change in magnetic field direction, or velocity spikes, when referring to the sharp increase in solar wind speed (Bale et al. 2019; Kasper et al. 2019).

2.1. S-shaped Structures

A reversal of the field could be due to a traveling fold in the magnetic field in the solar wind, a small patch of open coronal magnetic field with the opposite polarity of the southern magnetic hemisphere overall, a closed magnetic loop, a disconnected *U*-shaped loop, or a flapping motion of the global HCS causing it to move rapidly across the spacecraft. Measurements of the direction of the electron heat flux and the cross-helicity conclusively show that these events are of the first kind, folds in the magnetic field that travel past the spacecraft (Kasper et al. 2019; McManus et al. 2020). If both ends of the field line were connected to the Sun, a heat flux would be seen traveling in opposite directions along the field simultaneously, and if the events were *U*-shaped disconnections of field near the HCS, the heat flux would drop out. If the HCS were somehow dynamically flapping across the spacecraft the heat flux would continue to travel away from the Sun as the field polarity flipped. Instead, PSP always observes the heat flux to remain constant in intensity and to rotate with the magnetic field. It is unphysical for an electron heat flux to flow back toward the Sun, and instead the only remaining conclusion is that the switchbacks are local folds in the magnetic field.

The simplest three-dimensional shape of the folds is an *S*-shaped structure, the same as is illustrated in Figure 1. This conclusion is additionally supported by the observation that the perturbed magnetic field within each event tends to rotate in one direction in a 2D plane, and then return to the original quiet orientation afterward (Kasper et al. 2019; Horbury et al. 2020). The relative amplitudes of the perturbed magnetic field and velocity within each spike are consistent with them being stable, nonlinear, and large amplitude Alfvén waves (Kasper et al. 2019). While there may be some evidence of instability and dissipation at the boundaries of the spikes, to first order they are steady, non-evolving *S*-shaped folds in the magnetic field produced closer to the Sun and flowing faster than the solar wind at approximately the local Alfvén speed (Mozer et al. 2020).

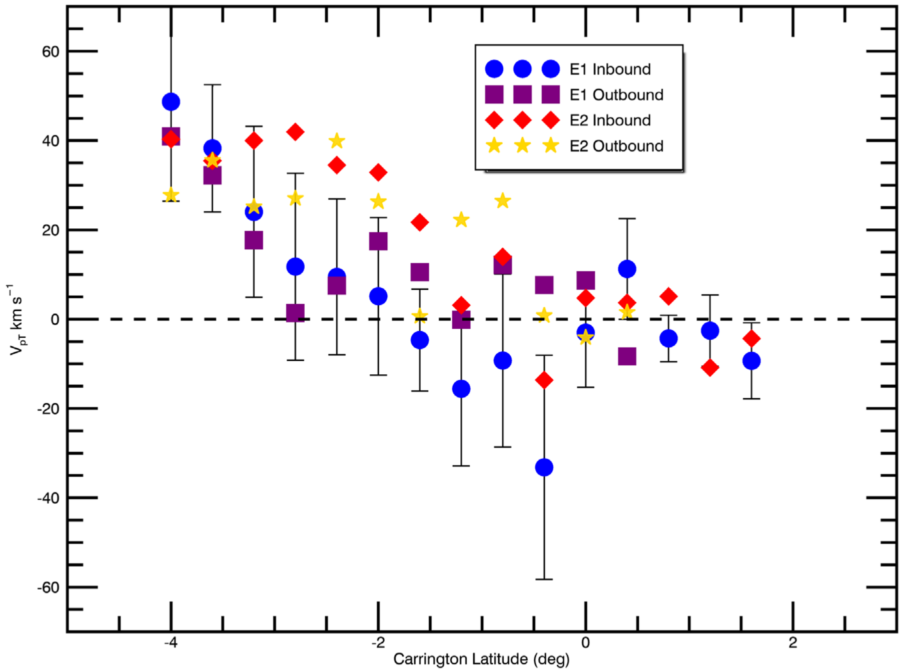

Figure 2. Mean transverse proton flow V_{pT} with latitude. Data are organized by latitudinal distance from the heliospheric current sheet. Symbols correspond to the inbound and outbound phases of encounters one (E1) and two (E2).

While switchbacks and spikes have been seen in the solar wind before (Gosling et al. 2009; Horbury et al. 2018), the events discovered by PSP exhibit an important new set of characteristics. There are many of them and they occur in all types of solar wind, such as regular slow solar wind, highly Alfvénic slow solar wind near the boundary of a coronal hole, and fast wind emerging from a midlatitude coronal hole, suggesting that the process that created them occurs in all types of solar wind and their source regions in the corona (Bale et al. 2019; Badman et al. 2020; Rouillard et al. 2020).

Thousands of individual events with durations greater than several seconds are seen in the 11 days below 0.25 au, allowing for preliminary studies of their statistical properties. Remarkably, over periods of hours to days the deflection of the magnetic field within larger switchbacks tends to deflect in a similar direction (Horbury et al. 2020). A persistent orientation of the switchbacks, along with statistical studies of the time between switchbacks and their durations, all strongly suggest that they originate close to the Sun (Dudok de Wit et al. 2020), a possibility supported by initial simulations that the switchbacks could survive intact from the lower corona to PSP (Tenerani et al. 2020). While naturally evolving turbulence in the expanding solar wind could also produce switchbacks (Vasquez & Hollweg 1996; Squire et al. 2020), local turbulence is not able to produce the organized deflections and persistence in occurrence rates lasting for hours to days observed by PSP for the larger events.

In summary, the most compelling explanation for the switchbacks in the magnetic field, and their accompanying spikes in the solar wind velocity, is that the switchbacks and spikes are the remnants of the interchange reconnection process in the lower corona proposed by Fisk & Schwadron (2001) and Fisk (2005), and illustrated in Figure 1.

2.2. The Global Circulation of Open Magnetic Flux

Kasper et al. (2019) also reported that the solar wind develops a substantial flow component transverse to the radial direction below 0.25 au that increased more than linearly with distance as the spacecraft approached the Sun. The transverse flow had roughly the same dependence on distance for the inbound and outbound phases of the first two encounters, even though the solar wind source was different for each phase and the speed of the wind varied by more than a factor of three from nearly 200 km s^{-1} to over 600 km s^{-1}. At closest approach the transverse flow reached 50 km s^{-1}, or 25% of the radial speed of the wind, with no sign that it was a maximum.

Recall that PSP sweeps through a range of solar latitudes as it approaches the Sun, reaching a maximum distance from the solar equator at closest approach. In Figure 2 we replot the same data from Figure 4 of Kasper et al. (2019) for the overall transverse flow V_{pT} of protons, but as a function of the heliographic latitude of the spacecraft instead of radial distance from the Sun. The 1σ error bars shown are dominated by the natural variance of the wind and not the much smaller uncertainties in the measurements as described in Kasper et al. (2019) and in Case et al. (2020). Several trends are immediately apparent. The dependence of the transverse flow on latitude is just as strong as the dependence on radial distance, suggesting that distance from the heliospheric current sheet or the midlatitude coronal hole could be a factor in setting the amplitude of the circulation.

The observed transverse flows are consistent with the global circulation of open magnetic flux predicted by Fisk & Schwadron (2001) and Fisk (2005). At solar minimum, open magnetic flux is transported downward and upward in heliographic latitude at the higher latitudes, and parallel to the current sheet at lower latitudes, driven by the need to maintain magnetic pressure balance in the corona. The open magnetic flux is attached to the rotating Sun, and thus particularly near the current sheet, any transverse flow in the corona that is different from the solar rotation rate requires that the open flux is also transported at the base of the corona at a speed comparable to that of the excess between the transverse flow speed and the rotation rate.

The PSP observations of the switchbacks also provide compelling evidence that the required transport of open flux at the base of the corona is by interchange reconnection between open magnetic field lines and large coronal loops, as illustrated in Figure 1 and predicted by Fisk & Schwadron (2001) and Fisk (2005). The larger switchback events have a statistically significant clustering of the orientations of their magnetic field deflections away from the quiet radially inward direction (Horbury et al. 2020). This preferred orientation can persist for days at a time. For example, in the several days surrounding the first encounter with the Sun, all switchbacks with a rotation of the magnetic field greater than 45° had the rotation in the field and the correlated increase in velocity pointed in the solar equatorial plane in the same direction as the transverse flow from the global circulation (Kasper et al. 2019; Horbury et al. 2020). Since the durations of the switchback follow power-law distributions, it is difficult to assess the mean properties of a switchback, but each 100 s switchback with a 10 km s^{-1} jump in the transverse flow of the solar wind can be thought of as transporting a field line approximately 10,000 km transverse to the radial, and should yield average transverse speeds consistent with observations.

In the classic Weber–Davis model (Weber & Davis 1967), the lower corona is assumed to rotate rigidly at the mean rotational period of the Sun and to force the solar wind to develop a transverse flow component as it expands outward. The angular momentum carried by the solar wind and accelerated in the transverse direction by magnetic torques is predicted to reach its maximum at the Alfvén point, after which the angular momentum causes the solar wind transverse velocity to decrease inversely with distance, with some enhancement as the development of the Parker spiral converts magnetic angular momentum into particle angular momentum, which is then lost to the Sun.

The observed level of global circulation is more than 25 times larger than the Weber–Davis model, which predicts flows of about 2 km s^{-1} at PSP distances from the Sun for an Alfvén point at 10 solar radii, implying much higher rates of angular momentum loss by the solar wind and resulting spindown of solar rotation. The global circulation of open flux in the corona resolves this problem because it removes the assumption that the coronal field lines must rigidly rotate with the surface of the Sun. Instead, the large transverse flows observed by PSP are a result of transverse flows in the corona. Moreover, the large observed transverse flows are part of a closed global circulation pattern, and within a closed system, angular momentum is conserved. The closed global circulation flows of open flux can neither add nor subtract angular momentum, and indeed, to within our limited observations of the global flow patterns, there are both positive and negative flows. It is conceivable that there could be a change in angular momentum loss to the solar wind, if the solar wind originates preferentially from a region with either enhanced or reduced angular momentum in the circulating open magnetic flux.

3. Concluding Remarks

The observations presented in the previous section provide confirmation that there is global circulation of open magnetic flux, which is made possible by interchange reconnection between open magnetic flux and large coronal loops, as predicted by Fisk & Schwadron (2001) and Fisk (2005). These observations also make clear that interchange reconnection is a ubiquitous process in the solar corona, and as a result many of the ideas and concepts that have served as the basis for our understanding of the solar magnetic field and the solar wind require some reconsideration.

The clear observation that open magnetic flux is undergoing interchange reconnection with coronal loops in all forms of solar wind invalidates any model in which there is not open magnetic flux embedded throughout closed magnetic field regions, as, for example, would be predicted by the commonly used potential field source surface models for calculating the distribution of open magnetic flux. There are also models in which interchange reconnection between open magnetic flux and coronal loops, the Poynting flux it creates, and the displacement from equilibrium of the coronal magnetic field that it causes can accelerate the solar wind (Fisk et al. 1999; Fisk 2003). With the confirmation that there is interchange reconnection on every open magnetic field line embedded in a closed field region, models for the acceleration of the slow solar wind in particular need to be revisited. There are also models in which interchange reconnection between open magnetic flux and loops results in open flux accumulating in regions where the emergence of new magnetic flux is a local minimum, which can provide an explanation for the formation of coronal holes (Fisk 2005; Abramenko et al. 2006). The global circulation pattern of open flux may also have implications for the solar dynamo. We should recall that the polar magnetic field that begins a new magnetic cycle of the Sun is the magnetic field in the polar coronal holes, open magnetic flux, not the magnetic field of active regions that migrate to the poles, and it is necessary to transport the open flux to the poles.

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