Comparison of Two Solar Minima: Narrower Streamer Stalk Region and Conserved Open Magnetic Flux in the Region Outside of Streamer Stalk

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Abstract. To explore the difference between the most two recent solar minima, we analyze the in-situ ACE and ULYSSES observations and examine the distributions of the three types of solar wind (streamer-stalk-associated wind, wind from outside the streamer stalk that can be associated, in part, with coronal holes, and interplanetary coronal mass ejections). We use the taxonomy provided by Zhao et al. (2009) to identify the three types of solar wind. We then map the in-situ observations to the 2.5 solar radii surface. With the aid of the potential-field-source-surface model (PFSS), we calculate the normal distance from the solar wind "foot point" to the local heliospheric current sheet on that surface. We find that the source region of the streamer stalk wind is narrower ($15^\circ \sim 20^\circ$) compared to the previous minimum ($\sim 40^\circ$). The area outside the streamer stalk is accordingly larger, but the magnetic field strength is observed to be lower, with the result that the total amount of the magnetic open flux from the outside of streamer stalk region is conserved in the two successive solar minima. The implications of the conservation of open magnetic flux for models of the behavior of the solar magnetic field are discussed.

1. Introduction

There are three distinct types of solar wind identified by Zhao et al. (2009). First, there is relatively high coronal electron temperature wind originating from loops in the streamer stalk region (Woo & Martin 1997). Second, there is solar wind from the outside of this region. This wind includes coronal hole wind that has relatively low coronal electron temperatures and high wind speeds, as well as slower solar wind with lower coronal electron temperatures than the streamer stalk region. The third type of solar wind is the transient interplanetary coronal mass ejections (ICMEs) which are caused by the coronal mass ejections (CMEs) (Richardson & Cane 1995; Zurbuchen & Richardson 2006; Burlaga et al. 2002; Zurbuchen 2006).

The streamer stalk region is the narrow region in the middle of the streamer belt, which has the highest density fluctuations and the lowest solar wind speeds (Borrini et al. 1981; Gosling et al. 1981). Woo & Martin (1997) provide observational evidence that the streamer stalks can be the coronal sources of the slow solar wind. Wang (1994) suggests that slow solar wind originates from regions of rapidly expanding flux-tubes located above small coronal holes and at the boundaries of the large polar holes. Based on a comparison of solar remote and in-situ observations, Liewer et al. (2004) suggests that low-speed wind with
higher \(O^{7+}/O^{6+}\) ratios may originate from open fields in or near active regions. Fisk and collaborators (e.g. Fisk et al. 1999; Fisk 2003) suggest that reconnection between open and closed field lines releases material to form the solar wind. This model provides a reasonable explanation for the differences between fast and slow solar wind.

The distribution of the three types of wind varies with the solar cycle. At solar minimum, the coronal holes concentrate at both poles and high latitude coronal hole wind is observed (Phillips et al. 1995). The heliospheric current sheet is flat and lies near the equatorial plane, and the streamer belt stalk wind occurs in a band around the current sheet (Gosling et al. 1997; Feldman et al. 1981). The ICME rate is roughly proportional to the solar activity levels and therefore is very low at solar minimum (Owens & Crooker 2006). At solar maximum, the current sheet tilts to high latitudes, and the streamer-stalk wind, which still occurs in a band around the current sheet, now can reach high latitudes. The solar coronal holes shrink, resulting in less coronal hole wind in the heliosphere. The increasing rate of ICMEs can temporarily enhance the open magnetic flux of the Sun. Subsequently, interchange reconnection between the large ICMEs loops and the open field of the Sun eliminates the increased magnetic flux (Gosling et al. 1995; Fisk & Schwadron 2001; Crooker et al. 2002). Further, there is no compelling observational evidence to suggest that disconnection of open magnetic flux occurs at the heliospheric current sheet (Fisk & Schwadron 2001). Hence, the expectation was, prior to this solar minimum, the open magnetic flux would return to a constant background level, as it had in previous minima (Svalgaard & Cliver 2007).

In the current solar minimum, both the open magnetic flux and the mass flux of the solar wind are reduced compared to any previous solar minimum for which there are good space observations. In this paper, we offer a possible explanation for the decrease in open magnetic flux in the current minimum. We point out that the streamer-belt-stalk-associated wind originates from a narrower region in the current solar minimum compared to the previous one, and thus the region outside the streamer belt stalk region is larger. When we calculate the increase in area outside the stalk region, we find it is equal and opposite to the decrease in open magnetic flux, suggesting that the total magnetic flux in the region outside the stalk region remains constant in each solar minimum. The implication for the transport models of open flux developed by Fisk and colleagues is then discussed.

2. Observations at the Current Solar Minimum

2.1. The Changes of the Magnetic Field and Solar Wind Composition

The ULYSSES 18-year mission started in 1991 (Balogh et al. 1992) and terminated in 2009, providing sufficient data to compare the different conditions in the two minima. Here we use the data from the year of 1995.07-1998.2 (Carrington rotation 1892-1933) at last minimum and 2005.83-2008.96 (Carrington rotation 2036-2077) at the current minimum and compare the difference. As shown in Figure 1, the radial component of the heliospheric magnetic field, the so-called open magnetic flux of the Sun \((B_r r^2)\), decreases by 35.4%; \(O^{7+}/O^{6+}\),
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$C^{6+}/C^{5+}$, and Fe/O all decrease by 61.5%, 66.2% and 10.1%, respectively. Especially, when considering the region outside of the streamer stalk (as identified later), we find the open magnetic flux decreased by 30%.

![Figure 1](image)

**Figure 1.** Histograms of $B_r r^2$, $O^{7+}/O^{6+}$, $C^{6+}/C^{5+}$, and Fe/O at the previous (black) and the current (dotted) minimum from *ULYSSES*.

| Table 1. In-situ signatures of three types of solar wind |
|---|---|---|
| Signature | $V_{sw}$ Relationship | Criterion For |
| 1 | $O^{7+}/O^{6+}$ | $O^{7+}/O^{6+} \geq 6.008 \exp(-0.00578 V_{sw})$ | ICMEs |
| 2 | $O^{7+}/O^{6+}$ | $0.145 < O^{7+}/O^{6+} < 6.008 \exp(-0.00578 V_{sw})$ | Streamer-stalk wind |
| 3 | $O^{7+}/O^{6+}$ | $O^{7+}/O^{6+} < 0.145$ | Non-streamer-stalk wind |

2.2. The Narrower Streamer Belt Stalk Region

We repeat the analysis of Zhao et al. (2009) for ACE observation to determine the three types of solar wind: wind associated with the streamer belt stalk; wind from outside this regions; and ICMEs. First, we identified the three-type solar wind for the last solar maximum and the current solar minimum using the criteria shown in Table 1. Then, we map the in-situ observations back to 2.5 solar radii to have a synoptic map for each Carrington rotation showing the distribution of the solar wind coronal sources, i.e., Figure 2a. As expected, ACE observes streamer-stalk wind (orange) when it crosses the current sheet. In Figure 2a, the polarities of magnetic field from observation match the PFSS model very well. Based on these maps, we can calculate the normal distance from the each of the "foot points" of the solar wind to the local current sheet. Those normal distances are portions of great circle arcs and can be expressed as an angle relative to the current sheet.
From Figure 2(b and c), in the current solar minimum, the width of the streamer-stalk wind relative to the heliospheric current sheet is only $\sim 10^\circ$ on one side, or $20^\circ$ on both sides. In the previous solar minimum, the width is $40^\circ \sim 50^\circ$ (Phillips 1995). Not surprisingly, the normal distances from the streamer stalk wind foot points to the heliospheric current sheet are more scattered at solar maximum than minimum.

### 2.3. The Conservation of the Total Magnetic Flux in the non-Streamer-Stalk Region

We conclude above that in the current minimum the streamer stalk region is narrower, and the area outside the streamer stalk is larger, than the previous minimum. Consider, then, how the total open magnetic flux contained in the region outside the streamer stalk region varies between the two solar minima.

The total amount of the open magnetic flux is the product of the area or solid angle ($\sigma$) occupied by the non-streamer-stalk region and the magnetic strength ($B_r r^2$). From Table 2, the half-width of the streamer stalk region in the last minimum is $\sim 25^\circ$, and in this minimum it is reduced to $\sim 7.5^\circ \sim 10^\circ$. If we set the solid angle covered by the non-streamer-stalk region in last minimum as 1, then in the current minimum this solid angle increases to 1.43. The magnetic field strength outside the streamer stalk region is lower in the current minimum by $\sim 70\%$. Thus, the total amount of open magnetic flux in the region outside of the streamer stalk region remains the same in the two minima.
Table 2. Total amount of magnetic flux outside of streamer stalk

|                  | Streamer half-width (degree) | Non-streamer-stalk region solid angle | $B_r r^2$ | Total Magnetic flux |
|------------------|------------------------------|--------------------------------------|-----------|---------------------|
| Last minimum     | 25                           | 1                                    | 1         | 1                   |
| Current minimum  | 7.5~10                        | ~1.43                                | 0.7       | ~1                  |

3. A New Model for the Transport of Open Magnetic Flux on the Sun

Fisk and colleagues developed a model for the global transport of open magnetic flux on the Sun, which is illustrated in Figure 3a (Fisk 1996; Fisk et al. 1999; Fisk 2005; Fisk & Schwadron 2001). Differential rotation drives the open flux across the polar coronal hole and then into closed field regions where open flux does not disconnect at the current sheet, but rather the flow patterns turn as shown. The process by which the magnetic field is transported through the closed field region is diffusion due to reconnection with loops. This model accounts for a number of features of the observed behavior of open magnetic flux; e.g., the slow solar wind appears to come from large coronal loops outside of coronal holes, and be released by reconnection (Feldman et al., 2005).

![Figure 3](image.png)

Figure 3. (a) An illustration of the motions of the magnetic field on the Sun in the frame corotating with the equatorial rotation rate. The M-axis is the axis of symmetry for the expansion of the magnetic field from a polar coronal hole. The $\Omega$-axis is the solar rotation axis. P marks the open line (green) that connects to the pole. The curves with arrows (red) are the trajectories of the open field lines, and the yellow region is the streamer stalk region. (b) The open lines reconnects and diffuses outside the streamer stalk region.

This picture now needs to be revised, as shown in Figure 3b. The open magnetic flux in regions outside the streamer-stalk region is unable to penetrate into this region. Thus, disconnection of this component of open flux, which must occur at the heliospheric current sheet, is not possible. Rather, the turning of the flow patterns of open flux must occur outside the streamer stalk region, as shown. The total open magnetic flux outside of the streamer-stalk region, which cannot now disconnect, is conserved, as is observed to be the case.
4. Conclusion Remarks

There are several points worth emphasizing. The signature we use to identify our streamer-belt-stalk wind is the $O^{7+}/O^{6+}$ ratio, or the inferred coronal electron temperature, not the solar wind speed, as was used in other studies. Moreover, it is important to note that the streamer-stalk wind is not the entire slow speed solar wind. Rather, it is only the very slow, high coronal electron temperature wind, which we identify as originating from the streamer stalk underlying the heliospheric current sheet. There is a broader slow solar wind region (Tokumaru et al. 2009), as constrained by the black dotted line in Figure 3b.

The conservation of the total magnetic flux in the non-streamer-stalk region during the two solar minima suggests that the open magnetic field of the Sun in the current solar minimum is behaving as it did in previous minima, the only difference being the width of the streamer belt stalk region, which controls the magnetic field strength in the region outside the streamer belt stalk region.

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