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Interchange Reconnection: Remote Sensing of Solar Signature and Role in Heliospheric Magnetic Flux Budget

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Abstract Interchange reconnection at the Sun, that is, reconnection between a doubly-connected field loop and singly-connected or open field line that extends to infinity, has important implications for the heliospheric magnetic flux budget. Recent work on the topic is reviewed, with emphasis on two aspects. The first is a possible heliospheric signature of interchange reconnection at the coronal hole boundary, where open fields meet closed loops. The second aspect concerns the means by which the heliospheric magnetic field strength reached record-lows during the recent solar minimum period. A new implication of this work is that interchange reconnection may be responsible for the puzzling, occasional coincidence of the heliospheric current sheet and the interface between fast and slow flow in the solar wind.

Keywords Coronal hole boundary · Reconnection · Stream interface · Heliospheric magnetic field

1 Introduction

In space physics applications, it is useful to describe magnetic field lines as either open or closed. Open field lines have one end rooted in the magnetized body and the other end extending out to infinity. Closed field lines form loops that have both ends rooted in the magnetized body. Since ultimately all field lines are closed, how infinity is defined for open fields can lead to misconceptions, as will be discussed in the last section. The subject of this paper, interchange reconnection, occurs when an open field line reconnects with a closed field line.

Although the term "interchange reconnection" is relatively new (Crooker et al. 2002), as a concept it has been invoked for some time to account for solar and solar wind

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phenomena and, more recently, for magnetospheric phenomena (see review in Merkin and Crooker 2008). Two properties of interchange reconnection are particularly relevant to this paper. First, interchange reconnection transports the foot of the open field line to the far footpoint of the closed loop. This transport has been invoked to explain the rigid rotation of coronal holes, the domain of open field lines on the Sun, in the face of differential rotation (e.g., Nash et al. 1988; Wang and Sheeley 2004). It has also been invoked to effect a global circulation of open flux on the Sun when the Sun's dipole axis is tilted with respect to the pattern of differential rotation (e.g., Fisk 1996; Fisk et al. 1999). The second property involves the exchange of flux between the Sun and the heliosphere. When the apex of the loop that participates in interchange reconnection at the Sun extends out into the heliosphere, the act of reconnection reduces the heliospheric flux from the two legs of the loop to one leg, and a new loop forms on the Sun (e.g., Gosling et al. 1995). The next section addresses the possibility of observing signatures of flux transport across the coronal hole boundary, and the following section addresses whether or not interchange reconnection can account for the dearth of magnetic flux in the heliosphere during the recent solar minimum.

2 Flux Transport at the Coronal Hole Boundary

Crooker et al. (2010) have recently reported on a possible remote signature of interchange reconnection on the Sun at the boundary between open field lines, which are concentrated in coronal holes, and closed field lines comprising the streamer belt that straddles the heliomagnetic equator. Here we review that work and suggest how it may support new ideas about the topology of the boundary as discussed in another paper in this volume.

If interchange reconnection occurs on the Sun across some boundary marked by a change in plasma characteristics, its signature at a spacecraft at 1 AU will be a separation between the plasma and suprathermal electron signatures of that boundary, as noted by Borovsky (2008). The reason for the separation is that suprathermal electrons streaming out from the Sun along magnetic field lines reach 1 AU within a matter of hours compared to days for solar wind plasma convecting radially outward. Crooker et al. (2010) applied that argument to the coronal hole boundary under the assumption (consistent, for example, with Fisk et al. 1999) that its signature in the heliosphere is the stream interface, the boundary between the fast flow emanating from coronal holes and the slow flow emanating from the streamer belt. With superposed epoch analysis they identified a suprathermal electron signature at the interface at 1 AU consisting of a strong peak in 250-eV flux integrated over pitch angle. In individual cases, however, this electron peak was often displaced from the well-known plasma signatures of the interface stemming from the pressure ridge there, where fast flow runs into slow flow. The displacements indicate that the electron flux peaks are not caused by local compression. Whatever the cause of the peaks (see discussion in Crooker et al. 2010 of relevant work by Gosling et al. 1978), the displacements may be signatures of interchange reconnection, as proposed by Borovsky (2008).

Figure 1 illustrates the process of signature displacement at the stream interface before and after interchange reconnection occurs. To understand the diagram, it is best to focus first on the magnetic field lines emanating from the solar surface: They are the same in number and polarity in both views, but their connections change. The field line that has its origin at the coronal hole boundary, that is, the boundary between open field lines in the coronal hole and closed field lines in the streamer belt, is marked with a heavy curve in both views. In Fig. 1a it forms the stream interface between fast flow from the coronal hole, shaded gray,

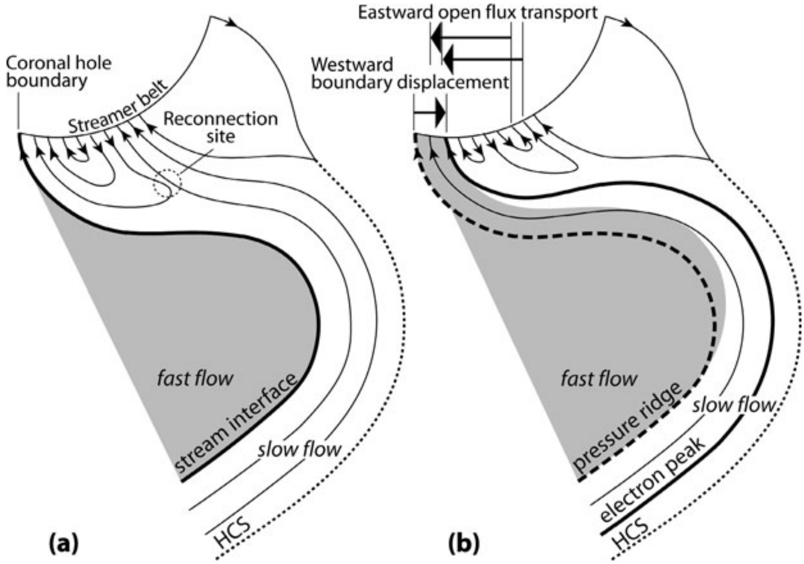

Fig. 1 Schematic illustration of the magnetic configuration (**a**) before and (**b**) after displacement of suprathermal electron and plasma signatures of the stream interface between fast and slow flow resulting from flux transport by interchange reconnection at the coronal hole boundary on the Sun (adapted from Crooker et al. 2010)

and slow flow from the streamer belt surrounding the heliospheric current sheet (HCS). Although with distance from the sun the fast flow slows and the slow flow speeds up near the interface owing to the dynamic interaction, in steady state the interface remains as the boundary between what was originally slow and fast flow.

Figure 1b illustrates a transitional state some time after interchange reconnection acts to displace the coronal hole boundary. In this case the heavy field line marking the coronal hole boundary maps out to the location of the peak suprathermal electron flux, which serves as a nearly instantaneous field-line tracer of the new coronal hole boundary location. The pressure ridge that forms the plasma signature of the stream interface in the heliosphere, however, remains at the original location of the interface, displaced from the electron signature. The field line threading the pressure ridge in the heliosphere is now marked by a heavy dashed curve instead of a solid curve because, closer to the Sun, it diverges from the boundary of the gray area marking the pressure ridge and, thus, no longer connects to the coronal hole boundary. Eventually the plasma at the newly displaced coronal hole boundary convects out into the heliosphere, and a steady state is reached in which a single field line lies along the interface between fast and slow flow, as in Fig. 1a.

The interchange reconnection in Fig. 1 takes place at the encircled reconnection site in Fig. 1a between the outer two of the three nested loops and the two open field lines adjacent to the helmet streamer. (The presence of these open field lines in the purportedly closed-field region of the streamer belt is an approximation that is fully discussed below.) As a result of the reconnection, the footpoints of the two open field lines saltate (leap abruptly) eastward, across the distance originally spanned by the loops, and join the open fields in the coronal hole. To accommodate the transported flux, the coronal hole boundary shifts westward, although by a much smaller distance. The reverse sense of open-field-line transport, from the coronal hole to the streamer belt, is illustrated in Crooker et al. (2010). Their observational results, which apply only to those sections of the coronal hole boundary where the streamer belt lies west of the coronal hole, as in Fig. 1, suggest that flux transport can be in either direction there.

The lack of evidence for any systematic westward flux transport reported by Crooker et al. (2010) was surprising in view of predictions for the rigid rotation of equatorward extensions of coronal holes, illustrated by Wang and Sheeley (2004), and for the pattern of global footpoint circulation proposed by Fisk et al. (1999). Both of these concepts are specific about the direction of flux transport depending upon whether the coronal hole lies to the east or west of its boundary with the streamer belt. The most intriguing explanation for the lack of systematic transport lies in the recent work by S. Antiochos, J. Linker, and colleagues (e.g., Antiochos et al. 2011; Edmondson et al. 2010), as discussed in another paper in this volume. They propose that the coronal hole boundary can be highly irregular, with deep corrugations. Under these conditions, it seems reasonable to expect that while systematic flux transport may occur on a global scale, its signature may be overcome by the random signature of transport across the locally ragged boundary.

The concept of an irregular coronal hole boundary can be used to explain the presence of open field lines in the streamer belt in Fig. 1a. Strictly speaking, open field lines cannot exist in isolated islands separate from areas of other open field lines of the same polarity (Crooker and Siscoe 1990; Antiochos et al. 2007). If the coronal hole boundary is irregular, however, a cross-section passing from one side to the other may cut through a mix of volumes of open and closed fields, as in Fig. 1a. On the other hand, if we maintain the definition of the coronal hole boundary as the boundary between open and closed fields, then the configuration in Fig. 1 loosens the connection between the coronal hole boundary and the boundary between fast and slow flow. It suggests that the latter lies at the outer envelope of the irregular coronal hole boundary, consistent with the conclusions of the latest version of the Fisk model of global footpoint circulation (Zhao and Fisk 2010).

3 Heliospheric Flux Balance

Interchange reconnection may play a major role in the heliospheric magnetic flux budget. As solar activity increases during the rising phase of the solar cycle, magnetic loops expand into the heliosphere and increase the amount of flux there. Although from the perspective of potential field source surface modeling these loops merely become open flux, from the heliospheric perspective the loops are closed flux that can be detected by the presence of counterstreaming suprathermal electrons emanating from both footpoints on the Sun. Moreover, the loops are nearly always located within interplanetary coronal mass ejections (ICMEs) (e.g., Wimmer-Schweingruber et al. 2006), which implies that coronal mass ejections (CMEs) are nearly the sole source of flux added to the heliosphere. Since flux in the heliosphere does not continue to increase but waxes and wanes with the solar cycle, there must also be some mechanism for losing flux. Two possibilities have been proposed. One is interchange reconnection at the Sun, whereby a loop in an ICME opens through reconnection between one of its legs and an open field line (Gosling et al. 1995; Crooker et al. 2002). The other is disconnection at the Sun, whereby two open field lines reconnect to form a completely disconnected U-shaped field line (e.g., McComas et al. 1989). In both cases flux is returned to the Sun by the formation of a small loop there.

The recent, deep, extended solar minimum has prompted much discussion about whether interchange reconnection or disconnection is responsible for the record-breaking low values of interplanetary field strength (Owens et al. 2008; Connick et al. 2011; Schwadron et al.

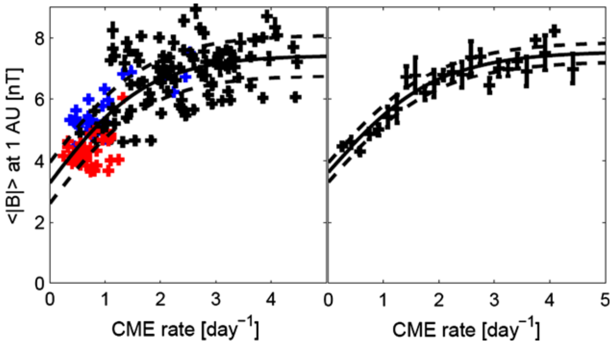

Fig. 2 Scatter plots of Carrington-Rotation averaged CME rate against magnetic field strength in the heliosphere at 1 AU, updated from Crooker and Owens (2010) to include points through the end of 2009. In the *left panel*, points from the recent solar minimum are *red* and points from the previous solar minimum are *blue*. In the *right panel*, points are binned by CME rate. The *solid curves* are tanh fits bracketed by *dashed curves* at the 95% confidence level

2010; Crooker and Owens 2010; Zhao and Fisk 2010). While interchange reconnection has the attractive property of conserving open flux, since reconnection with loops transports but does not destroy the participating open flux, disconnection can proceed ad infinitum, independent of the presence of closed loops. Disconnection is thus capable of reducing the flux to zero, whereas interchange reconnection can proceed only until all of the closed flux opens, leaving the conserved open flux to supply a floor value to heliospheric field strength.

Possible evidence for a floor value to heliospheric field strength has been presented by Svalgaard and Cliver (2007, 2010) using long-term historical records and by Owens et al. (2008) and Crooker and Owens (2010) using measured CME rates over the past solar cycle. An update of the results presented in the latter two papers is shown in Fig. 2. Carrington-Rotation-averages of CME rate and heliospheric field strength are plotted against each other covering the period from the last solar minimum in blue to the recent minimum in red in the left panel. If the loss of flux is accomplished by opening closed loops in ICMEs through interchange reconnection, then the heliospheric field strength should depend upon how many CMEs are fed into the heliosphere. The points in the left panel of Fig. 2 are consistent with this view, although the scatter is broad. When binned by CME rate, in the right panel, a clearer pattern emerges. Evidence for a floor value to the heliospheric field strength is the fact that the hyperbolic tangent curve fit to the points intersects the B axis at a finite value for zero CME rate. That value is $\sim$3.8 nT, comparable to the lowest averages plotted in the left panel.

The origin has been included in this updated version of the plots in order to obtain a sense of the likelihood that a fitted curve could pass through it, as it would if there were no floor value to the field. While the curve on the right clearly could not pass through the origin, one can imagine a curve with some functional form other than tanh running up from the origin through the unbinned values on the left, owing to the large degree of scatter. Thus at most one can say that the data do not preclude the possibility that interchange reconnection is the primary means of reducing flux in the heliosphere and that open flux is conserved. On the other hand, making this statement may come as a surprise to those who have noted the steady, prolonged decline in heliospheric field strength during the recent minimum.

4 Discussion and Conclusions

Two aspects of interchange reconnection have been addressed primarily from an observational point of view—its possible signature at the coronal hole boundary and its role in the heliospheric flux budget. Here we discuss some relevant points about flux budget models, the expected locations of source and loss processes on the Sun, and how those locations might map to the heliosphere.

Models of the heliospheric flux budget that assume interchange reconnection as the sole means of flux loss (e.g., Owens and Crooker 2006), or, more generally, that flux loss depends upon the amount of closed flux, overestimate the heliospheric field strength during the recent minimum (Owens et al. 2011). The reason may be owing to the simplifying assumption that the rate of interchange reconnection is constant. If it varies, instead, with the degree to which higher order fields dominate the solar configuration, as they did during the recent minimum compared to the previous minimum, then the model can provide a good fit to the observations (Owens et al. 2011). Why the reconnection rate should vary in this way is discussed further below.

Whether it is interchange reconnection or disconnection that reduces flux in the heliosphere once loops have passed beyond about 10 AU is a question that cannot be addressed by suprathermal electron observations (Owens and Crooker 2007; Connick et al. 2011). The counterstreaming signature of a loop is lost at 1 AU once the apex of the loop is so far out that electrons cannot stream out from the Sun and back to the observer along the far leg owing to scattering. All that remains is unidirectional streaming from the Sun along the leg encountered by the observer. Any interchange reconnection between that loop and an open field line will give the signature of disconnection, which is a dropout of electrons, called a "heat flux dropout" (McComas et al. 1989; Crooker and Pagel 2008). These are observed frequently enough that flux budget models can accommodate either interchange reconnection or disconnection as a loss mechanism (Owens and Crooker 2007). Owens et al. (2011) use the term "pinching" for either process at the Sun and generalize the models so that the distinction between the processes is not important, aside from the issue of whether or not open flux is conserved.

Evidence for pinching can be found in white light observations at the Sun and plasma observations in the heliosphere. The location of pinching for disconnection is expected to be at the base of the heliospheric current sheet, where open fields of opposite polarity meet at the tips of helmet streamers, and the location of pinching for interchange reconnection is expected to be at the coronal hole boundary, which can be in the same vicinity. For example, Wang et al. (2000) ascribe the release of blobs from the tips of coronal streamers, as seen in white light images, to either process. Also seen in white light near the current sheet are downflows ascribed to loops returning to the Sun as the result of disconnection (e.g., Sheeley and Wang 2001), although these could as well result from pinching by interchange reconnection. The downflows occur preferentially where the current sheet is highly inclined to the heliographic equator, that is, when the dipole component of the field is strong and tilted or when higher order fields dominate the configuration and produce a highly warped current sheet. Presumably the preferred site for downflows reflects higher rates of reconnection there, driven by differential rotation. It is this property of downflows which motivated Owens et al. (2011) to vary the flux loss rate with the degree of current sheet tilt/warp in the flux budget model. In the heliosphere, the expected site for signatures of interchange reconnection on the Sun is at the stream interface, as illustrated in Fig. 1, and the expected site for signatures of disconnection on the Sun is at the heliospheric current sheet. Heat flux dropouts, which take the form of high-beta plasma sheets, are a likely signature of either, and these occur at and near the heliospheric current sheet, possibly the heliospheric counterpart of the blobs observed near the Sun (Crooker et al. 2004a). The high degree of variability in measurements of plasma sheets near and at the heliospheric current sheet is consistent with the new concept of a ragged coronal hole boundary that continually changes its configuration through reconnection, as Fig. 1 illustrates.

The Fig. 1 view also offers an explanation for a longstanding question regarding the position of the stream interface relative to the heliospheric current sheet. While at 1 AU it usually takes about 10 hours for a spacecraft to pass from the heliospheric current sheet to the stream interface (Gosling et al. 1978), that distance is highly variable, and sometimes the two features coincide (e.g., Siscoe and Intriligator 1993; Crooker et al. 1999). Antiochos et al. (2011) point out similar variability in related MHD model parameters. Figure 1 shows how the variability could be the result of interchange reconnection, which, at times, might locally remove all open flux between the interface and the current sheet. The view in the right panel shows a reduced space between the features, implying some remaining open flux between them, but the features could as well have been drawn as coincident.

Finally, we consider the question of whether the sources and losses in the flux budget are related, as assumed for the model invoking interchange reconnection to open all of the loops added by CMEs, or not, as assumed for disconnection. Recent findings that bear upon this question concern how CMES, which commonly arise near active regions, can be related to losses at the distant coronal hole boundary. Cohen et al. (2009, 2010) have simulated CME events that are accompanied by coronal waves and confirm the view of Attrill et al. (2007) that the footpoints of these CME loops rapidly saltate laterally through reconnection with other loops until they reach the coronal hole boundary. Thus the loops are rapidly exposed to the site of flux loss by interchange reconnection. Suprathermal electron data suggest that about half of the loops in CMEs open in this manner shortly after ejection (Shodhan et al. 2000; Crooker et al. 2004b). The remaining loops are expected to open over timescales on the order of 40 days (Owens and Crooker 2006). Over these long timescales, however, the observational distinction between interchange reconnection and disconnection becomes moot, as discussed above. Loss by either process might cease when the dominance of higher order fields disappears and the heliospheric current sheet aligns with the heliographic equator, as noted by Owens et al. (2011), in which case it is not clear how the amount of flux lost might match the amount that was added. It is also important to note that interchange reconnection with loops that have not left the solar atmosphere, as pictured in Fig. 1, act only to transport open field lines and does not reduce the flux in the heliosphere.

In conclusion, interchange reconnection may be responsible for a ragged coronal hole boundary, a variable distance between stream interfaces and the heliospheric current sheet, and reducing flux in the heliosphere.

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References

S.K. Antiochos, C.R. Devore, J.T. Karpen, Z. Mikić, Astrophys. J. **671**, 936–946 (2007). doi:10.1086/522489

S.K. Antiochos, Z. Mikic, R. Lionello, V. Titov, J. Linker, Astrophys. J. (2011, submitted)

G.D.R. Attrill, L.K. Harra, L. van Driel-Gesztelyi, P. Demoulin, Astrophys. J. **656**, L101–L104 (2007). doi:10.1086/512854

J.E. Borovsky, J. Geophys. Res. **113**, A08110 (2008). doi:10.1029/2007JA012684

O. Cohen, G.D.R. Attrill, W.B. Manchester, M.J. Wills-Davey, Astrophys. J. **705**, 587–602 (2009). doi:10.1088/0004-637X/705/1/587

O. Cohen, G.D.R. Attrill, N.A. Schwadron, N.U. Crooker, M.J. Owens, C. Downs, T.I. Gombosi, J. Geophys. Res. **115**, A10104 (2010). doi:10.1029/2010JA015464
D.E. Connick, C.W. Smith, N.A. Schwadron, Astrophys. J. **727** (2011). doi:10.1088/0004-637X/727/1/8
N.U. Crooker, M.J. Owens, in *SOHO-23: Understanding a Peculiar Solar Minimum*, ed. by S. Cranmer, T. Hoeksema, J. Kohl. ASP Conf. Proc., vol. 428, pp. 279–283 (Astronomical Soc. Pacific, San Francisco, 2010). Also as arXiv:1004.2238v1 [astro-ph.SR]
N.U. Crooker, C. Pagel, J. Geophys. Res. **113**, A02106 (2008). doi:10.1029/2007JA012421
N.U. Crooker, G.L. Siscoe, J. Geophys. Res. **95**, 3795–3799 (1990)
N.U. Crooker, J.T. Gosling et al., in *Corotating Interaction Regions*, ed. by A. Balogh, J.T. Gosling, J.R. Jokipii, R. Kallenbach, H. Kunow. ISSI Space Sci. Ser. (Kluwer Academic, Dordrecht, 1999), pp. 179–220. Also, Space Sci. Rev. **89**, 179–220 (1999)
N.U. Crooker, J.T. Gosling, S.W. Kahler, J. Geophys. Res. **107**(A2), 1028 (2002). doi:10.1029/2001JA000236
N.U. Crooker, C.-L. Huang, S.M. Lamassa, D.E. Larson, S.W. Kahler, H.E. Spence, J. Geophys. Res. **109**, A03107 (2004a). doi:10.1029/2003JA010170
N.U. Crooker, R. Forsyth, A. Rees, J.T. Gosling, S.W. Kahler, J. Geophys. Res. **109**, A06110 (2004b). doi:10.1029/2004JA010426
N.U. Crooker, E.M. Appleton, N.A. Schwadron, M.J. Owens, J. Geophys. Res. **115**, A11101 (2010). doi:10.1029/2010JA015496
J.K. Edmondson, S.K. Antiochos, C.R. DeVore, B.J. Lynch, T.H. Zurbuchen, Astrophys. J. **714**, 517–531 (2010). doi:10.1088/0004-637X/714/1/517
L.A. Fisk, J. Geophys. Res. **101**, 15,547–15,553 (1996)
L.A. Fisk, N.A. Schwadron, T.H. Zurbuchen, J. Geophys. Res. **104**, 19,765–19,772 (1999)
J.T. Gosling, J.R. Asbridge, S.J. Bame, W.C. Feldman, J. Geophys. Res. **83**, 1401–1412 (1978)
J.T. Gosling, J. Birn, M. Hesse, Geophys. Res. Lett. **22**, 869–872 (1995)
D.J. McComas, J.T. Gosling, J.L. Phillips, S.J. Bame, J.G. Luhmann, E.J. Smith, J. Geophys. Res. **94**, 6907–6916 (1989)
V.G. Merkin, N.U. Crooker, J. Geophys. Res. **113**, A00B04 (2008). doi:10.1029/2008JA013140
A.G. Nash, N.R. Sheeley, Jr., Y.-M. Wang, Sol. Phys. **117**, 359–389 (1988)
M.J. Owens, N.U. Crooker, J. Geophys. Res. **111**, A10104 (2006). doi:10.1029/2006JA011641
M.J. Owens, N.U. Crooker, J. Geophys. Res. **112**, A06106 (2007). doi:10.1029/2006JA012159
M.J. Owens, N.U. Crooker, N.A. Schwadron, T.S. Horbury, S. Yashiro, H. Xie, O.C. St. Cyr, N. Gopalswamy, Geophys. Res. Lett. **35**, L20108 (2008). doi:10.1029/2008GL035813
M.J. Owens, N.U. Crooker, M. Lockwood, J. Geophys. Res. (2011, submitted)
N.A. Schwadron, D.E. Connick, C.W. Smith, Astrophys. J. **722**, L132–L136 (2010)
N.R. Sheeley Jr., Y.-M. Wang, Astrophys. J. **562**, L107–L110 (2001)
S. Shodhan, N.U. Crooker, S.W. Kahler, R.J. Fitzenreiter, D.E. Larson, R.P. Lepping, G.L. Siscoe, J.T. Gosling, J. Geophys. Res. **105**, 27,261–27,268 (2000)
G. Siscoe, D. Intriligator, Geophys. Res. Lett. **20**, 2267–2270 (1993)
L. Svalgaard, E.W. Cliver, Astrophys. J. **661**, L203–L206 (2007)
L. Svalgaard, E.W. Cliver, J. Geophys. Res. **115**, A09111 (2010). doi:10.1029/2009JA015069
Y.-M. Wang, N.R. Sheeley Jr., Astrophys. J. **612**, 1196–1205 (2004)
Y.-M. Wang, N.R. Sheeley Jr., D.G. Socker, R.A. Howard, N.B. Rich, J. Geophys. Res. **105**, 25,133–25,142 (2000)
R.F. Wimmer-Schweingruber, N.U. Crooker et al., in *Coronal Mass Ejections*, ed. by H. Kunow et al. ISSI Space Sci. Ser. (Springer, Dordrecht, 2006), pp. 177–216. Also, Space Sci. Rev. **123**, 177–216. doi:10.1007/s11214-006-9017-x
L. Zhao, L. Fisk, in *SOHO-23: Understanding a Peculiar Solar Minimum*, ed. by S. Cranmer, T. Hoeksema, J. Kohl. ASP Conf. Proc., vol. 428 (Astronomical Soc. Pacific, San Francisco, 2010) pp. 229–234. Also as arXiv:1003.4336v1 [astro-ph.SR]