Solar Activity and its Magnetic Origin
Proceedings IAU Symposium No. 233, 2006
Volker Bothmer, ed.

DOI: 00.0000/X000000000000000X

Partially-ejected flux ropes: implications for space weather

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Abstract. The structure and evolution of the sources of solar activity directly affects the nature of space weather disturbances that reach the Earth. We have previously demonstrated that the loss of equilibrium and partial ejection of a coronal magnetic flux rope matches observations of coronal mass ejections (CMEs) and their precursors.In this paper we discuss the significance of such a partially-ejected rope for space weather. We will consider how the evolution and bifurcation of the rope modifies it from its initial, source configuration. In particular, we will consider how reconnections and writhing motions lead to an escaping rope which has an axis rotated counterclockwise from the original rope axis orientation, and which is rooted in transient coronal holes external to the original source region.

Keywords. Sun: coronal mass ejections (CMEs), Sun: prominences, (Sun:) solar-terrestrial relations, Sun: magnetic fields

1. Introduction: tracing space weather back to its solar source

Solar-driven "space weather" can have significantly adverse consequences for the Earth and near-Earth environment. It is therefore important to link space weather perturbations to their sources at the Sun, in the hopes of understanding and ultimately predicting their origins. In particular, the space weather phenomenon known as a magnetic cloud [Klein & Burlaga (1982)] may be linked to coronal mass ejections (CMEs). Observations of both magnetic clouds [Burlaga *et al.* (1982), Burlaga (1988), Lepping *et al.* (1990), Mulligan & Russell (2001)] and CMEs [Dere *et al.* (1999), Plunkett *et al.* (2000), Cremades & Bothmer(2004)] are commonly interpreted as magnetic flux ropes. Comparisons of interplanetary and coronal observations thus are often done in the context of a flux rope, and correlations have been found between, for example, flux rope chirality, axis orientation, and magnetic flux [Rust *et al.* (2005) and references therein.] The success of such comparisons, however, relies on a clear understanding of how the coronal flux rope relates to the interplanetary flux rope. In this paper we will briefly describe the evolution of a flux rope which writhes and breaks in two during its eruption [Gibson & Fan (2006a)]. We will then discuss how properties of the escaping portion of the flux rope differ from the original, pre-eruption flux rope, and the significance of this for space weather.

2. A flux-rope model for a partially-ejected flux rope

Gibson & Fan (2006a, 2006b) presented results of a three-dimensional numerical MHD simulation in spherical coordinates, in which a flux rope quasistatically emerged into a pre-existing coronal arcade. As was the case in previous simulations [Fan & Gibson

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† The National Center for Atmospheric Research is sponsored by the National Science Foundation

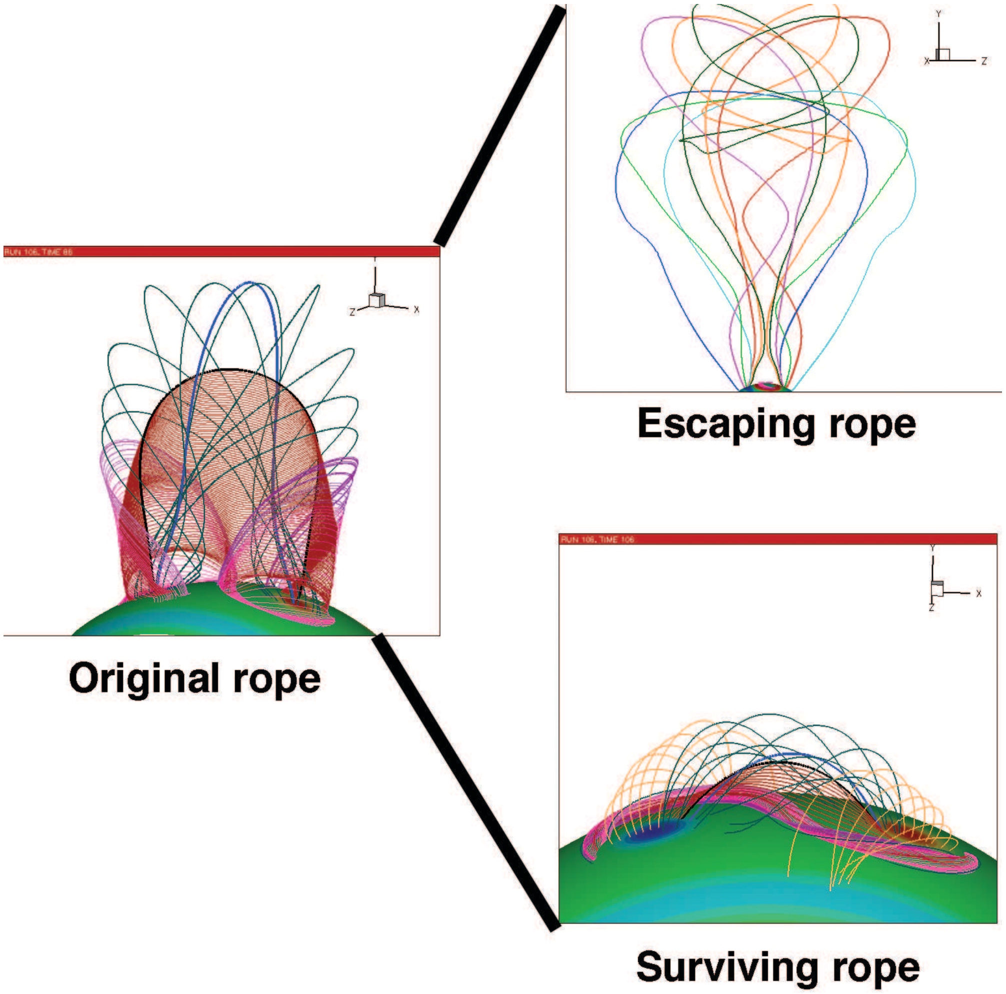

Figure 1. Gibson & Fan (2006a) model of a flux rope eruption that results in the rope breaking in two. The left image shows sample field lines for the pre-eruption flux rope. Red and black field lines are dipped field lines intersecting the central, vertical axis, pink-lavender are dipped field lines grazing the photosphere, and dark green and blue are additional rope field lines. Note that all of these field lines are rooted in the magnetic boundary of the "rope bipole", (red and blue circular poles, seen most clearly in "Surviving rope" image – see also Figure 4). Not shown in this image are the arcade field lines, which extend over the rope and which are rooted in an extended linear bipolar "arcade boundary" (the blue, negative pole of which can be seen as the extended linear structure to the front of the image – see also Figure 4). The right two images show the bifurcated rope at the final time step of the simulation. The top right image shows sample field lines of the escaping rope, which are rooted in the "arcade boundary". The bottom right image shows sample field lines of the surviving rope, color-coded in the manner of the original rope. The surviving rope is rooted in the "rope bipole", but some adjacent field lines (e.g., the orange ones in this image) have one footpoint in the rope-bipole boundary, and one in the arcade boundary. See Gibson & Fan (2006a, 2006b) for further discussion.

(2003), Fan & Gibson (2004), Fan (2005)], the emerging rope went through two distinct stages in its evolution. Initially, the rope's quasistatic emergence resulted in a series of equilibria, in which a coronal flux rope was contained within an overlying magnetic arcade. Once enough magnetic twist was emerged, however, equilibrium was lost as the magnetic kink instability set in, and the rope erupted.

The simulation described in Gibson & Fan (2006a) expanded upon previous analyses by extending long enough in time to demonstrate that the end-state of such an eruption was not the total eruption of the flux rope, but rather a rope that broke in two, with one part leaving, and the other staying behind (see figure 1) The significance of such a partially-ejected flux rope for coronal observations was explored in detail by Gibson & Fan (2006b). In particular, it was shown that simulated observables matched observations of partly and non-erupting filaments, quiescent cavities erupting as 3-part CMEs followed by the reformation of the cavities, and sigmoids transitioning to cusps above reformed sigmoids.

3. Space weather implications of partially-ejected rope

A partially-ejected flux rope is of significance to space weather for several reasons. First of all, not all of the twist is lost in such an eruption, so that the source region may still possess substantial magnetic energy. With the injection of further twist, either through flux emergence or footpoint motions, the region may erupt again soon. This is important for space weather prediction and interpretation, since multiple CMEs from the same region have been shown to lead to particularly strong solar energetic particle (SEP) events [Gopalswamy *et al.* (2004)]. We plan in future to continue our simulation with the emergence of additional twist, in order to demonstrate that such repeating eruptions may occur.

Second, Gibson & Fan (2006b) described in detail how multiple, three-dimensional reconnections occur during the eruption. Indeed, all of the escaping rope field lines undergo some degree of reconnection, as is clear from the fact (see figures 1 and 3) that they are no longer rooted in the original flux rope's magnetic bipole boundary (referred to as "rope bipole" from here on), but rather in the original arcade field's boundary (referred to as "arcade boundary" from here on). This may be significant for interpreting the magnetic charge states of material entrained in magnetic cloud, which are "frozen in" at coronal temperatures. Magnetic cloud material identified with originally-cool filaments often include enhanced charge states implying hot coronal temperatures [Skoug *et al.* (1999), Gloeckler *et al.* (1999)]. Since Reinard (2005) showed that enhanced charge states correlate with flares in the corona, it is possible that a partially-ejected rope would result in some filament-carrying fieldlines heated by reconnections during eruptions. See Gibson *et al.* (2006) for further discussion.

Finally, the reconnections and writhing motions of the rope during eruption mean that the escaping rope differs in important ways from the original, pre-eruption rope. This has the potential to mislead analysis and prediction of magnetic cloud properties, if the source region is considered without taking into account evolution of the erupting structure. We will consider this now in some detail, with regards to transient coronal holes and rope axis orientation.

3.1. *Transient coronal holes*

Transient coronal holes are associated with CMEs, and appear as dimmings in soft X-ray [Hudson *et al.* (1998)] and extreme ultraviolet [Thompson *et al.* 1998; 2000] and brightenings in ultraviolet [De Toma *et al.* (2005)]. They have been identified as open field regions, and proposed to be the footpoints of magnetic clouds [Webb *et al.* (2000)]. Figure 2 shows the results of a model of a totally erupting flux rope model (three-dimensional and analytic) [Gibson & Low (2000)], and demonstrates that the footpoints

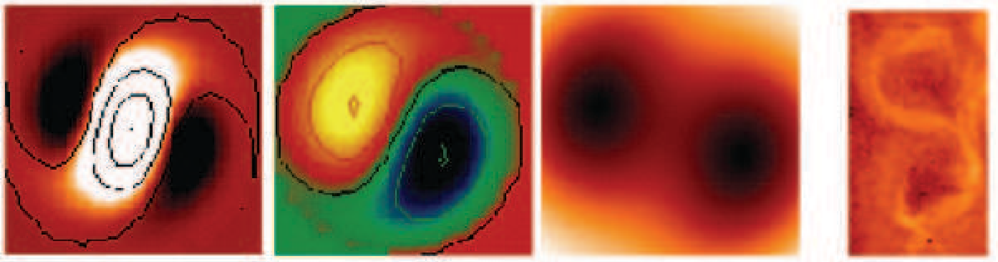

Figure 2. Left three images: Gibson & Low (2000) model of a totally-ejected rope. (From left to right): slice of density at lower boundary, slice of normal magnetic field at lower boundary, and soft-X-ray emission integrated along the line of sight. Right image: Yohkoh SXT observation of transient coronal holes, lying within sigmoid emission.

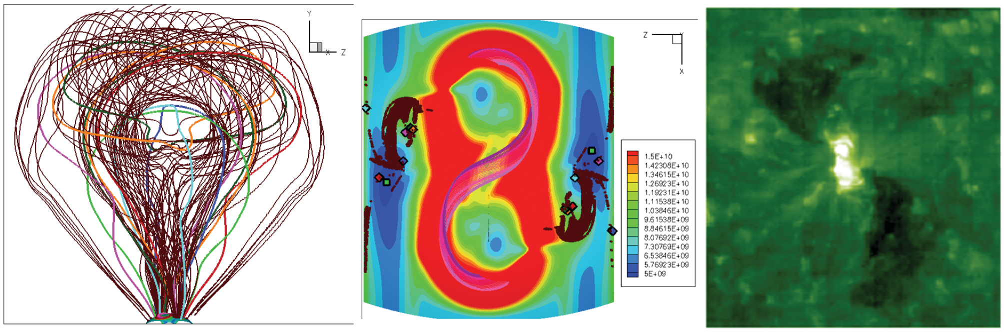

Figure 3. Gibson & Fan (2006a) model of partially-ejected rope. (Left) Escaping flux rope: colored field lines are the same sample field lines shown in figure 1, and brown field lines are examples of field lines that intersect the upper boundary of simulation. (Middle) surviving rope (pink/lavender fieldlines) and footpoints corresponding to escaping fieldline footpoints in image to left (brown points and colored diamonds). Colored isocontours show density, showing that the escaping flux rope footpoints lie outside the original rope bipole, but in regions of depleted density. (Right) SOHO/EIT 195 Angstrom observations of transient coronal holes of May 12, 1997 [Thompson *et al.* (1998)].

of such a flux rope would indeed appear dim in soft-X-ray intensity. A subset of transient coronal holes might be well-described in this manner, in that they: (1) occur as a pair of dimmings, and (2) overlie strong-field regions within the bend of the source region's neutral line [Kahler & Hudson (2000)]. The soft-X-ray dimmings shown to the right in figure 2 show a nice example of this, where the dimmings lie inside the concavities a bright soft-Xray "sigmoid" [See also Sterling & Hudson (1997)].

However, not all transient coronal holes are of this type. In many cases, one dimming is much larger than the other, or indeed there is only one apparent dimming [Thompson *et al.* (2000), Kahler & Hudson (2000), De Toma *et al.* (2005)]. Kahler & Hudson (2000) also found cases where the transient coronal holes appeared overlying weak field regions adjacent to the associated (often flaring) active region. In such cases, the transient coronal holes may occupy significantly larger area than the associated flaring active region. The right-hand image of figure 3 shows a case where, although the dimmings are twin and highly symmetric, they extend well above and below the flaring active region, and are not concentrated in the concavities of the associated sigmoid [Thompson *et al.* (2000)].

The partially-ejected rope simulation discussed above describes this second type of transient coronal holes well. As the rope writhes, it reconnects with the surrounding arcade as well as internally at a central, vertical current sheet, resulting in an escaping rope rooted in the original arcade boundary (see Gibson & Fan (2006b) and figure 3). Thus the escaping rope's footpoints lie outside the original rope-bipole boundary, in a region of relatively weak magnetic flux. Figure 3 also demonstrates that the escaping rope's footpoints are rooted in relatively dim regions that extend along the arcade-boundary.

We note that both the initial, emerging flux rope and the overlying arcade in our simulation are very symmetric. For this reason, the reconnections between the two magnetic systems lead to a symmetric escaping rope with twin, symmetric dimmings at its feet. If, on the other hand, the overlying arcade were asymmetric or generally more complicated, we would expect the footpoints of the escaping rope and associated dimmings to likewise be asymmetric andpatchy. Indeed, given large enough asymmetries, an effectively solo dimming might occur. We plan in future to study this by varying our simulation setup.

3.2. *Rope axis orientation*

The original, pre-eruption rope is left-handed (negative chirality), and has an eastward axis orientation. If it had erupted without writhing or reconnection, its interplanetary magnetic cloud would have been classified as SEN in the notation of Bothmer & Schwenn (1997). That is, the magnetic field vector of the magnetic cloud would be southward-directed field in its leading portion, then turn eastward near cloud center, and finally turn northward in its trailing portion. This can be deduced from the "BOTTOM" vector magnetic field plot of figure 4. The overlying arcade field, which would be at the front of the cloud, can be seen to be oriented southward. The rope axis direction, which would dominate at the center of the cloud, is eastward (pointing from the positive pole on the right to the negative pole on the left). The magnetic field vectors at the rope bipole's neutral line indicate an inverse configuration (field pointing from negative to positive), and so represent the dips at the back of the rope, which angle northward.

If vector magnetic fields such as shown in the "BOTTOM" plot of figure 4 were observed at the photosphere in conjunction with a filament, that filament would also be determined to be left-handed [Rust (1997)]. Bothmer & Rust (1997) found that when magnetic clouds were identified with filament disappearances, the magnetic clouds and pre-eruption filaments had the same direction chirality in 24 out of 27 cases. Rust *et al.* (2005) obtained similar results, in that in four cases of five studied, the chirality of flux ropes was maintained from pre-eruption filament to magnetic cloud. Since magnetic helicity should be preserved during reconnection, we would expect this also to be the case in our partially-ejected rope. Indeed, we find that, despite the reconnections and writhing motions, the chirality is preserved: the escaping rope is still left-handed. However, it has rotated counterclockwise from the original rope, and at least a central portion of it can be identified as now having essentially a WSE orientation (see "TOP" images in figure 4).

Filaments are sometimes observed to writhe during eruption (Rust and Labonte (2005) and figure 5a). Moreover, Rust *et al.* (2005) found that axis orientation was slightly less likely to agree between pre-eruption filament and magnetic cloud: in 2 out of 6 cases where axial direction could be compared, the direction differed by approximately 130 degrees. The authors of that paper pointed out that writhing motions during eruption might be the cause of these discrepancies. Figure 5b-c shows our erupting rope at two time steps: the first shows that our rope writhes counterclockwise (we find the axis writhes approximately 145 degrees before it reconnects), and the second, later time plot shows that reconnections with the external arcade field have led to an escaping rope rooted in the arcade boundary. As figure 5c and the "TOP" images of figure 4 show, these three-dimensional reconnections (discussed in detail in Gibson & Fan (2006b)) lead to an escaping flux rope that is more complex than the pre-eruption rope. Moreover, we note

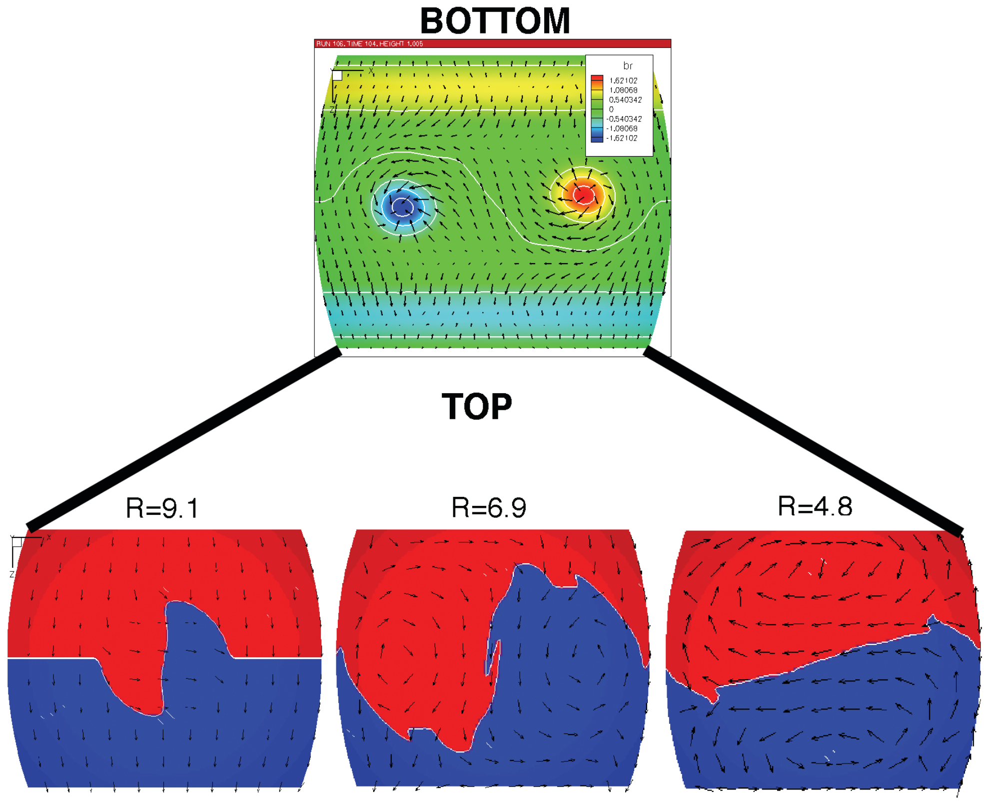

Figure 4. Vector magnetic fields at different heights during simulation time step 104. The image labelled "BOTTOM" shows the slice at the bottom of the simulation box, which we identify with the solar photosphere – note that since emergence was stopped at time step 86, this lower boundary is essentially unchanged during the eruption. The images labelled "TOP" show slices in the order, from left to right, in which they would be viewed in a magnetic cloud.

that the overlying field which could precede the escaping rope in a magnetic cloud is still southward (although significantly weaker than the flux rope fields that follow it), so that the magnetic cloud field rotation might appear as S-WSE, or perhaps something even more complicated. We are presently undertaking a detailed examination of the escaping rope's magnetic structure, with an emphasis on how it might manifest in a magnetic cloud.

4. Conclusions

We have demonstrated that a model for a partially-ejected flux rope can explain a subset of space weather phenomena. In particular, reconnections and writhing motions lead to an escaping portion of the rope which varies in field orientation from the original pre-eruption rope. This is important to space weather prediction, since the properties of the source region are often used to identify field orientation and thus estimating the potential geoeffectiveness of eruptions [Presentation by Zhukov, this conference: NOTE TO EDITOR – if Zhukov has a paper on this subject in this Proceedings, it would be good to reference it here]. The escaping rope is also rooted external to the original source region. This has significance for studies of transient coronal holes, where, for example, a comparison of magnetic flux depends on identifying the rope's footpoints

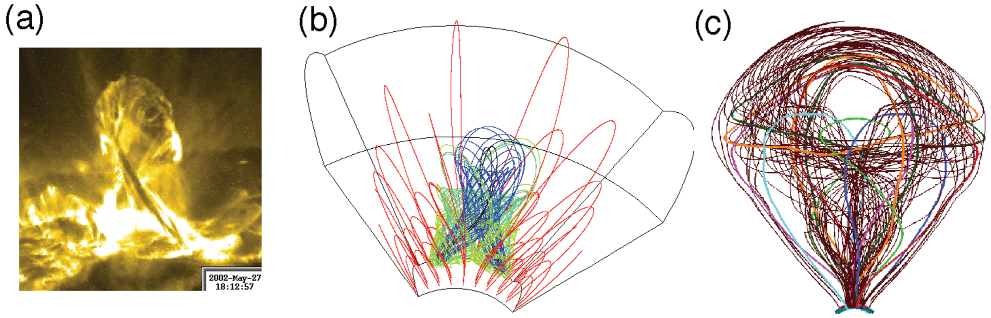

Figure 5. (a) TRACE 171 Angstrom image of writhing filament. (b) Writhing flux rope (blue and green fieldlines), before most of the reconnections with external arcade (red fieldlines) have occurred (simulation timestep 86). (c) Escaping flux rope (timestep 106), as in figure 3.

properly [Webb *et al.* (2000), Kahler & Hudson (2000)]. The large amount of three-dimensional reconnections and possible associated energetics and heating, in combination with the fact that the surviving rope may well erupt again, are additional reasons why such partially-ejected ropes are significant to space weather analyses. In general, allowing for the possibility of flux rope bifurcation opens a window onto new interpretations of the links between coronal and interplanetary manifestations of solar activity.

Acknowledgements

We thank Giuliana de Toma for internal HAO review of this manuscript, and B. C. Low and Joan Burkepile for interesting discussions. We thank the organizers of the IAU Symposium 233 for an excellent conference, and Dave Webb in particular for the invitation to speak at it. The Transition Region and Coronal Explorer, TRACE, is a mission of the Stanford-Lockheed Institute for Space Research (a joint program of the Lockheed-Martin Advanced Technology Center's Solar and Astrophysics Laboratory and Stanford's Solar Observatories Group), and part of the NASA Small Explorer program. SOHO is a project of international cooperation between ESA and NASA. The Soft X-Ray Telescope (SXT) was prepared by the Lockheed Palo Alto Research Laboratory, the National Astronomical Observatory of Japan, and the University of Tokyo with the support of NASA and ISAS.

References

Bothmer, V. & Rust, D. M.. 1997, *Geophys. Monogr.* 99, 137

Bothmer, V. & Schwenn, R. 1997, *Annales Geophysicae* 16, 1

Burlaga, L. F., Klein, L., Sheeley, N. R. Jr., Michels, D. J., Howard, R. A., Koomen, M. J., Schwenn, R., & Rosenbauer, H. 1982, *Geophys. Res. Lett.,* 9, 1317

Burlaga, L. F. 1988, *Journ. of Geophys. Res.* 93, 7217

Cremades, H. & Bothmer, V. 2004, *Astron. and Astrophys.* 422, 307

Dere, K. P., Brueckner, G. E., Howard, R. A., and Michels, D. J. 1999, *Astrophys. Journ.*, 516, 465

de Toma, G., Holzer, T. E., Burkepile, J. T., and Gilbert, H. R. 2005, *Astrophys. Journ.*, 621, 1109

Fan, Y. 2005, *Astrophys. Journ.* 630, 543

Fan, Y. & Gibson, S. E. 2003, *Astrophys. Journ. Lett.* 589, 505

Fan, Y. & Gibson, S. E. 2004, *Astrophys. Journ.* 609, 1123

Gibson, S. E., Fan, Y., Toeroek, T., & Kliem, B. 2006, in: von Steiger *et al.* (eds.), *Solar dynamics and its effects on the heliopshere and earth* (Springer), in press

Gibson, S. E. & Fan, Y. 2006, *Astrophys. Journ. Lett.* 637, 65

Gibson, S. E. & Fan, Y. 2006, *Journ. Geophys. Res.* submitted

Gibson, S. E. & Low, B. C. 2000, *Journ. Geophys. Res.* 105, 18187

Gloeckler, G.; Fisk, L. A.; Hefti, S.; Schwadron, N. A.; Zurbuchen, T. H.; Ipavich, F. M.; Geiss, J.; Bochsler, P.; Wimmer-Schweingruber, R. F. 1999, *Geophys. Res. Lett.* 26, 157

Gopalswamy, N., Yashiro, S., Krucker, S., Stenborg, G., & Howard, R. A. 204, *Journ. Geophys. Res.* 109, A12105, doi:10.1029/2004JA010602

Kahler, S. W. & Hudson, H. S. 2000, *Journ. Geophys. Res.* 106, 29239

Hudson, H. S., Lemen, J. R., St. Cyr, O. C., Sterling, A. C., & Webb, D. F. 1998, *Geophys. Res. Lett.* 25, 2481

Klein, L. W. & Burlaga, L. F. 1982, *Journ. of Geophys. Res.* 87, 613

Lepping, R. P., Burlaga, L. F., & Jones, J. A. 1990, *Journ. of Geophys. Res.* 95. 11957

Mulligan, T. & Russell, C. T. 2001, *Journ. of Geophys. Res.* 106. 10581

Plunkett, S. P., Vourlidas, A., Simberova, S., Karlicky, S. M., Kotrc, P., Heinzel, P., Kupryakov, Yu. A., Guo, W. P. & Wu, S. T. 2000, *Solar Phys.* 194, 371

Reinard, A. 2005, *Astrophys. Journ.* 620, 501

Rust, D. M.. 1997, *Geophys. Monogr.* 99, 119

Rust, D. M., Anderson, B. J., Andrews, M. D., Acuna, M. H., Russell, C. T., Schuck P. W. & Mulligan, T. 2005, *Astrophys. Journ.* 621, 524

Rust, D. M. & Labonte, B. J. 2005, *Astrophys. Journ. Lett.* 622, L69

Skoug, R. M., Bame, S. J., Feldman, W. C., Gosling, J. T., McComas, D. J., Steinberg, J. T., Tokar, R. L., Riley, P., Burlaga, L. F., Ness, N. F., Smith, C. W.1999, *Geophys. Res. Lett.* 26, 161

Sterling, A. C. & Hudson, H. S.1997, *Astrophys. Journ.* 491, L55

Thompson, B. J., Cliver, E. W., Nitta, N., Delannee, C., Delaboudiere, J.-P. 1998, *Geophys. Res. Lett.* 25, 14, 2461

Thompson, B. J., Plunkett, S. P., Gurman, J. B., Newmark, J. S.,St. Cyr, O. C., Michels, D. J., Delaboudiniere, J.-P. 2000, *Geophys. Res. Lett.* 27, 10, 1431

Webb, D. F., Lepping, R. P., Burlaga, L. F., DeForest, C. E., Larson, D. E., Martin, S. F., Plunkett, S.P., Rust, D. M. 2000, *Journ. Geophys. Res.* 105, 27251