Recent Voyager Evidence for Rapid Transport of Flare-Generated Disturbances by Polar Coronal Hole Streams

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Abstract. Disturbances observed by Voyagers 1 and 2 during the past five years or more may have been transported by plasma emitted from polar coronal holes, thereby having travelled much faster from the Sun to the termination shock than previously recognized. Estimating the average speed to the shock as 750 km/s has produced consistently good associations between solar flares, or groups of them, and dynamic pressure increases at Voyager 2 and plasma wave events at Voyager 1. Furthermore, magnetograph observations confirm that polar coronal holes were present around the times of the flares to which the events at the Voyagers have been attributed. These calculations also provide revised estimates of the transport of heliospheric current sheet fluctuations. We discuss the possibilities that extrapolations from past observations and simulations based on them may provide insight into currently challenging issues and possible future developments.

1. Introduction

Spacecraft observations obtained over the past fifteen or twenty years from regions of the heliosphere that formerly were solely the domains of guesswork and theoretical calculations have given a more definite view of the vast plasma bubble around the Sun and the planets than previously was ever possible. Nevertheless, these observations extend over such widely separated locations and long time intervals that many questions arise that can only be answered by comparing results from many spacecraft. These observations need to be combined with model calculations, and any other ground-based or inner solar system observations that can be applied.

In particular, the importance of understanding the propagation and interactions of the interplanetary disturbances generated by major solar flares has long been understood. However, it has been given additional urgency by Voyager 1 (V1) observations in recent years indicating that the strongest of these disturbances propagate all the way through the heliosheath and out into the local interstellar medium (LISM). Thus, the results we present here go substantially beyond our previously reported studies connecting solar events with observations in the heliosheath and LISM. We describe evidence that disturbances generated by solar flares that occurred from the summer of 2011 to early 2015 may have been convected to Voyager 2 (V2) and V1 in high-speed solar wind plasma emitted from polar coronal holes, producing phenomena observed at the Voyagers from the middle of 2012 to late 2016.

As we did last year, we concentrate on combining various in-situ observations from remote spacecraft with ground-based observations of the Sun, the heliosphere, the heliosheath, and the LISM.

2. A Consistency Question and a Transport Hypothesis

Our analyses in Intriligator et al. [1] reported the period of major solar flares in the first seven months of 2012 may be associated with phenomena observed at V2 in the middle months of 2013. In particular, a collection of powerful flares in early March, 2012, is associated with particle and plasma phenomena at V2 peaking around April 18, 2013. The even more powerful flares of July, 2012, are associated with particle and plasma phenomena peaking around August 19, 2013. These V2
observations were put into a larger context by Richardson, et al. in [2] as parts of a period of enhanced plasma dynamic pressure that they identify from magnetometer observations as a merged interaction region (MIR). It is the fourth of seven such pressure pulses (designated as pulses A through G as shown in Figure 1, which we adapted from Figure 4 of [2]) occurring in the V2 plasma observations from the middle of 2011 to late 2016. The last five of them (i.e., pulses C through G) are identified as MIRs. These regions are caused when shock waves resulting from closely spaced flares merge in propagating over the 100 or more AU from the Sun to the outer heliosphere. Thus, an obvious question is: whether the associations in [1] could be extended to associate the earlier and later MIRs with respectively earlier and later flares?

Figure 1. Smoothed history of plasma dynamic pressures at V2 in nanopascals. The Forward Shock (FS), Reverse Shock (RS), and the V1 Heliopause (HP) are indicated. The black bars are the times of the Plasma Wave System (PWS) events at V1. The onsets of the PWS events are shown in Figure 6.

However, the effort to do this raised a question of mathematical consistency. As we noted in [3], the period of great solar flares around Halloween, 2003, produced an MIR that reached V2 in late April, 2004, in which the peak convection speed (as of the middle of May, 2004) was about 560 km/s, and during most of the MIR the speed was around 500 km/s or less. Also, Richardson, et al. report in [2] that the convection speed of the heliosheath plasma was between about 90 and 120 km/s during MIR F, and in many other publications of the V2 PLS team they have reported heliosheath speeds of between 100 and 150 km/s. Assuming a speed of 500 km/s between the Sun and the termination shock (TS) at 84 AU (in 2007), and a speed of 150 km/s from the TS to V2, at 101.4 AU gives a predicted travel time of 493 days. This was three months longer than the 404 days from March 10, 2012 to April 18, 2013 shown in [1] in the table of delays. An even bigger discrepancy arises for the phenomena observed by V2 in August, 2013.

Richardson et al. may have recognized that difficulties are raised if the speed for the MIRs is only modestly above the observed plasma speeds, because they hypothesize a 320 km/s shock speed in the heliosheath which is more than twice as high as the presumed bulk plasma speed. This would bring the predicted delay times for the 2012 flares into much closer agreement with the actual delays at V2 observed in 2013.

An alternative hypothesis is provided by recalling that by the second half of 2012, when MIR C was observed, V2 was at an HGI latitude of 30 degrees south. In the model calculations of Usmanov, et al. [4] the solar wind at latitudes of 30 degrees or more is dominated by high-speed plasma flowing from the polar coronal holes. This raises the question: what results would be obtained from assuming that during the period of MIR observations from late 2012 to late 2016 V2 was in heliosheath plasma that the TS had decelerated from a higher speed than 500 km/s?
Simply assuming that flare disturbances travel 750 km/s from the Sun to a TS at 84 AU yields the travel time to the TS as a constant 194 days. Then a heliosheath speed of 150 km/s gives an additional time in days of \((r_{V2} - 84)^{1/2} \times 1,000,000/86,400\), where \(r_{V2}\) is the V2 distance, for a total time of \(194 + 11.574(r_{V2} - 84)\) days, as shown in Table 1.

**Table 1.** V2 associations with events in Figure 1

| MIR | Peak day   | V2 Distance (AU) | Estimated delay (days) | Flare date(s)          | Delay(s) (days) |
|-----|------------|------------------|------------------------|------------------------|-----------------|
| C   | Aug. 28, 2012 | 99.4            | 373                    | Aug. 9, 2011<br>Sept. 6, 2011 | 385<br>357      |
| D (early) | Apr. 18, 2013 | 101.42          | 396                    | Mar. 10, 2012         | 404             |
| D (late) | Aug. 19, 2013 | 102.48          | 408                    | Jul. 12, 2012<br>Jul. 23, 2012 | 403<br>392 |
| E   | Feb. 10, 2014 | 104.00          | 426                    | Dec. 14, 2012         | 423             |
| F   | Oct. 17, 2015 | 109.32          | 488                    | Jun. 10, 2014         | 494             |
| G (early) | Apr. 30, 2016 | 111.02          | 507                    | Dec. 13, 2014<br>Dec. 17, 2014 | 504<br>500 |
| G (late) | Jul. 20, 2016 | 111.72          | 515                    | Feb. 21, 2015         | 515             |

3. Solar Cycle Effects and Actual Coronal Hole Observations

We obtained excellent agreements in the arrival times in Table 1 with the simple assumption that solar flare disturbances had been transported to the TS in fast polar coronal hole plasma (specifically, from the south polar coronal hole for the pressure pulses at V2). Thus, the next step was to try to determine whether the agreements were merely fortuitous or whether a south polar coronal hole was actually present and large enough to be a plausible source of high-speed plasma around latitude 30 south. Actually, such a southern (high-latitude) polar coronal hole was directly observed by Ulysses during two solar minima and one solar maximum. This can be seen in Figure 2 (in which each top panel shows the spacecraft’s distance from the Sun in AU, the middle of its heliographic inertial (HGI) latitude, and the bottom the solar wind speed in km/s). Ulysses found that during the Solar Cycle (SC) 23 maximum there was very little high-speed solar wind from the south polar region and only a small region of fast plasma at the highest latitudes in the north polar region.

**Figure 2a.** Ulysses HGI distance and latitude and solar wind speed from 19920101 to 19971231
Correspondingly, as shown in Figure 3, for early October and late November, 2003 (after Ulysses had completed its polar pass), our HHMS program used inputs from the Wang-Sheely-Arge model (based on magnetograms extending up to high solar latitudes) to calculate that there were only small regions of solar wind with speeds as high as 700 km/s, as indicated by the pink and purple blobs in the left and right rectangular regions of the figure. These are indicative of the recurring high speed stream structures before and after the flares were launched.

On the other hand, since the 2012-2014 period of peak sunspot activity of SC 24 was notably weaker than the SC 23 peak observed by Ulysses in 2000-2003, this raised the possibility that the polar
Coronal holes in SC 24 might have been bigger, even at the peak of the SC, than the polar coronal holes during SC 23.

**Figure 4a.** Coronal holes in August and September, 2011 (CR 2113 and 2114) [5]

**Figure 4b.** Coronal holes in March and July, 2012 (CR 2121 and 2126) [5]

**Figure 4c.** Coronal holes in December, 2012 and June, 2014 (CR 2131 and 2151) [5]
As shown in Figures 4a - 4d, it was possible to resolve these questions using synoptic coronal hole maps prepared by the National Solar Observatory Integrated Synoptic Program (NISP) [5]. They show that large southern coronal holes were present during all the Carrington rotations (CR) during which the flares listed in Table 1 occurred. The lack of events during 2013 may be connected with the rapid change in the solar magnetic field at the end of 2012 and during the first months of 2013, so that in Carrington rotations 2133 - 2137 the polar coronal holes were almost completely closed. In these images the blue lines represent closed magnetic field lines, while the red regions are coronal holes in which the polarity is toward the Sun, and the green regions are holes with polarity away.

4. Comparisons with Voyager 1 Plasma Wave System Events

As V1 is now in the LISM, some 24.1 AU (as of early April, 2017) farther from the Sun than V2, and more than 60 degrees of heliographic latitude north of V2, so that they are more than 100 AU apart, they are approximately as far from each other as either is from the Sun. Thus, there are obvious questions of how to compare their observations and environments, and some differences are already known. For example, V1 crossed the TS at about 94 AU from the Sun, and emerged into the LISM after traveling about 27.6 AU through the heliosheath. By contrast, V2 crossed the TS at a little less than 84 AU from the Sun and after traveling more than 30 AU through the heliosheath has not yet emerged. If Roelof, et al (2012) and Krimigis et al. (2016) [6] are correct, V2 probably may not emerge for several more years at the earliest. This is because they combine the Voyager LECP observations and energetic neutral atom data from Cassini to conclude that the heliosheath along V2’s trajectory may be 40 - 70 AU thick.

However, MIRs are expected to spread out very widely both in longitude, as suggested in Figure 5 from Intriligator et al., (2014) [7], and in latitude from the locations of the flares that produced them. Thus, an obvious question is whether the PWS events observed at V1 (see Figure 1) are associated with the pressure pulses observed at V2 and hence with the flares listed in Table 1?

Since V1 is a few degrees farther from the heliographic equator than V2 is, at about 34 degrees north, the success of the high-latitude assumption for the V2 calculations suggested trying the same approach for V1. Specifically, the assumption is a speed of 750 km/s from the Sun to the TS at 94 AU, then 150 km/s for 27.6 AU through the heliosheath, and finally a speed of around 40 km/s through the LISM to V1. The times predicted by this approach were compared with the onset dates of the 3 kHz (green) PWS events as shown in Figure 6. We obtained these values from the Univ. of Iowa [8]. (Note that the readings in the 1000 Hz (blue) and 1780 Hz (red) channels visible in the plots for May, 2014, and to a lesser extent in the plots for September, 2015, are caused by spacecraft roll maneuvers to calibrate the magnetometer (or “magrols”) that happened to be in progress at the times these PWS events started. Thus, unlike the 3 kHz signals, these lower-frequency readings do not represent detections of physical phenomena external to the spacecraft. The nearly silent purple channel is 5620 Hz.)
The results in Table 2 of the calculations for the three PWS events in 2013, 2014, and 2015 and the forward shock in August, 2014, show fairly good agreement with predictions made by assuming that the shock speed through the LISM is 43 km/s with respect to the heliosphere. Since the agreement is very close for the onsets of the PWS events, but associating the forward shock with either of the listed July, 2012 flares implies that it arrived significantly sooner than the prediction, this is consistent with the expectation that the shock would propagate through the plasma faster than the bulk convection speed of the CME plasma that formed the MIRs.

**Figure 5a.** Our HAFSS ecliptic plane plot [7] of the B field from the Sun to 140 AU.

**Figure 5b.** Our HAFSS ecliptic plane simulation plot of the plasma density [7] from the Sun to 140 AU.

**Figure 6a.** V1 for the 3 kHz plasma wave system event onset April 9-10, 2013
Table 2. V1 associations with events in Figure 1 and Table 1

| MIR? | V1 PW event onset | V1 Dist. (AU) | Estimated delay (days) | Flare date(s) | Delay(s) (days) |
|------|-------------------|--------------|-------------------------|---------------|-----------------|
| C    | April 10, 2013    | 123.82       | 627                     | Aug. 9, 2011  | 610             |
|      |                   |              |                         | Sept. 6, 2011 | 582             |
| D    | May 8, 2014       | 127.66       | 783                     | Mar. 10, 2012 | 789             |
| (early) |                   |              |                         |               |                 |
| D (late) | Aug. 22, 2014 (FS) | 128.70       | 824                     | Jul. 12, 2012 | 771             |
|      |                   |              |                         | Jul. 23, 2012 | 760             |
| E    | Sept. 4, 2015     | 132.40       | 974                     | Dec. 14, 2012 | 994             |
| F    | (pred.) Apr. 1, 2018 | 140.87       | (pred.) 1314            | Jun. 10, 2014 | (pred.) 1314    |
|      |                   |              |                         |               |                 |

The last line of Table 2 shows that extrapolating the calculation to MIR F, which was unusually powerful at V2, implies that it could reach V1 and set off another PWS event in January of 2018. This may be a little sooner than the “early 2018” prediction of Richardson, et al. [2], since they assume a propagation speed through the LISM of 40 km/s with respect to the heliosphere. (A matter for future consideration is that since the IBEX and Ulysses observations have been reconciled to conclude that the heliosphere is moving 26 km/s with respect to the rest frame of the LISM [9], shock or MIR speeds of 40 and 43 km/s with respect to the heliosphere correspond to speeds of 66 and 69 km/s through the LISM.)

These associations in Table 2 suggest that the apparently unusual length of the 2014 PWS event (from early May to early November, much longer than the other two) may be attributable, at least in part, to the prolonged period of large flares in 2012 [1, 7]. It began with large flares in late January,
continued with several larger ones in early March, and ended with still more in July, culminating in the
great flare of July 23. Correspondingly, MIR D at V2 is broader with respect to its height (as depicted
in Figure 1) than most of the other pressure pulses.

5. Additional Flare Contributions to the MIRs and Plasma Wave System Events

As each of MIRs C through G is likely to have formed as CMEs from several flares merged on their
way outward from the Sun, Table 3 lists additional information [10] about the more important flares
that may have contributed to each MIR, including many that were not listed in Table 1.

| Table 3a. Possible Flares for MIR C |
| Date, 2011 | Time (UT) | Lat. | Earth Lon. | HGI Lon. | X-ray Imp. | CME (km/s) |
|-----------------|------------|------|------------|-----------|------------|------------|
| August 4        | 0415       | N19  | W36        | 274       | M9.3       | 1315       |
| August 8        | 0820       | N17  | W69        | 312       | X6.9       | 1610       |
| September 6     | 0200       | N14  | W07        | 277       | M5.3       | 782        |
| September 6     | 2230       | N14  | W18        | 288       | X2.1       | 575        |

| Table 3b. Possible Flares for MIR D (early) |
| Date, 2012 | Time (UT) | Lat. | Earth Lon. | HGI Lon. | X-ray Imp. | CME (km/s) |
|-----------------|------------|------|------------|-----------|------------|------------|
| January 23      | 0400       | N28  | W21        | 67        | M8.7       | 2175       |
| January 27      | 1830       | N27  | W71        | 121       | X1.7       | 2508       |
| March 5         | 0400       | N17  | E52        | 36        | X1.1       | 1531       |
| March 7         | 0100       | N17  | E27        | 63        | X5.4       | 2684       |
| March 10        | 1755       | N15  | W24        | 117       | M8.4       | 1296       |

| Table 3c. Possible Flares for MIR D (late) |
| Date, 2012 | Time (UT) | Lat. | Earth Lon. | HGI Lon. | X-ray Imp. | CME (km/s) |
|-----------------|------------|------|------------|-----------|------------|------------|
| July 6          | 2310       | S13  | W59        | 268       | X1.1       | 1828       |
| July 12         | 1645       | S15  | W01        | 216       | X1.4       | > 885      |
| July 19         | 0530       | S13  | W88        | 316       | M7.4       | 1631       |
| July 23         | 0230       | S17  | W132       | 1         | ? on far side | > 2003 |

The coronagraph underestimated the CME speeds for both the July 12 flare, because it was at the solar
centerline, and the July 23 flare, because it was on the far side.

| Table 3d. Possible Flare for MIR E |
| Date, 2012 | Time (UT) | Lat. | Earth Lon. | HGI Lon. | X-ray Imp. | CME (km/s) |
|-----------------|------------|------|------------|-----------|------------|------------|
| Dec. 14         | 0100       | N07  | W120 - 140 | 126 - 146 | ? on far side | > 1000 |

No Type II radio burst is recorded for this flare, but it was identified from the GSFC daily plot of
CMEs for December 14, 2012 [11], which also shows that it was associated with a modest rise at the
Earth in the count rate for particles in the energy range of 10 - 50 MeV. The COHO website hourly
average data for the STEREO spacecraft [12] also shows that substantial particle counts from this
event were observed at STEREO A, about 110 degrees ahead of the Earth, but not at STEREO B,
about 120 degrees behind. This implies (consistent with evidence from the GOES x-ray data that an
active region rotated out of view a day or two earlier) that this flare occurred beyond the west limb of
the Sun as seen from the Earth.

| Table 3e. Possible Flares for MIR F |
| Date, 2014 | Time (UT) | Lat. | Earth Lon. | HGI Lon. | X-ray Imp. | CME (km/s) |
|-----------------|------------|------|------------|-----------|------------|------------|
| May 8           | 0321       | S09  | W108       | 258       | ? on far side | > 847     |
| May 9           | 0240       | S11  | W122       | 273       | ? on far side | > 1099    |
| May 10          | 0432       | S11  | W136       | 288       | ? on far side | > 1086    |
| June 10         | 1258       | S17  | E82        | 100       | X1.1       | 1469       |
**Table 3f.** Possible Flares for MIR G (early)

| Date, 2014 | Time (UT) | Lat. | Earth Lon. | HGI Lon. | X-ray Imp. | CME (km/s) |
|------------|-----------|------|------------|----------|------------|------------|
| Dec. 13    | 1427      | ?    | W90        | 94       | ? at limb  | 2222       |
| Dec. 17    | 0409      | S11  | E33        | 335      | M1.1       | 869        |
| Dec. 17    | 0500      | S20  | E09        | 359      | M8.7       | 587        |
| Dec. 18    | 2231      | S11  | E15        | 354      | M6.9       | 1195       |

**Table 3g.** Possible Flare for MIR G (late)

| Date, 2015 | Time (UT) | Lat. | Earth Lon. | HGI Lon. | X-ray Imp. | CME (km/s) |
|------------|-----------|------|------------|----------|------------|------------|
| February 21| 0430      | S20  | W87        | 162      | C1.5       | > 1000     |

No Type II radio burst is recorded for this flare, but it was identified from the GSFC daily plot of CMEs for February 21, 2015 [11], which also shows that it was associated with a modest rise at the Earth in the count rate for particles in the energy range of 10 - 50 MeV.

**Figure 7.** WSO limit estimates [1] for maximum HCS latitude, adjusted for delays to spacecraft. Stars are at times of sector boundaries observed at each spacecraft (V1 and V2).

**6. Solar Cycle Variations in the Extent of the Sectored Heliosheath**

Finally, we consider possible implications that these observations of temporally dependent latitudinal variations in the solar wind environment may have for the larger-scale structure of the heliosphere. Figure 7 provides a more comprehensive depiction of the indications in the plots in Figure 4 that during 2011 through 2014 (the period for which V2 magnetometer data are available to allow identifying sector boundaries) the heliospheric current sheet (HCS, the footprints of which are shown as the thick black lines in the Figure 4 plots) extended to high solar latitudes. This figure shows estimates of the northern and southern limits of the extent of the HCS made at the Wilcox Solar Observatory (WSO), with the times from the WSO dataset [13] adjusted for the delays to the spacecraft, using the formulas that made the predictions in Tables 1 and 2.

This approach to calculating the delays is similar to one used in Hill, et al [14], a paper written to propose that the regions of unipolar heliosheath in polar latitudes and their boundaries with the region of sectored heliosheath could explain the disparity between the nearly constant count rates of energetic particles in many energy bands observed at V1 and the much more variable count rates in the same
energies observed at V2. Thus, it may be significant that in the period shown in Figure 7 (which is mostly after the period covered by the data in [14]) the regions of unipolar heliosheath shrank nearly to vanishing and the southern boundary of the sectored heliosheath was far from V2.

The authors of [14] note that this paper was written before V1 emerged into the LISM (it was first submitted to the Astrophysical Journal at the end of June, 2012). It also does not address the arguments in [6] (which records information presented at a conference in March, 2010) that the heliosheath is likely to be thicker along the trajectory of V2 than for V1. However, since it now appears that in [6] Roelof, Krimigis, et al. may have been at least partially correct (though the total thickness along the V2 trajectory is still unknown), a more realistic depiction of the heliosheath than what appears in the figures in [14] would look more like a geological diagram. It would have a north-south asymmetry and thicker and thinner regions of sectored plasma from respectively more and less active phases of the SC, flowing at speeds of 100 - 150 km/s. Furthermore, as the IBEX experimenters estimate that the tail of the heliosphere extends for hundreds of AU downstream, this would imply that the downstream portion of the heliosheath contains fluctuations dating from a number of years or even more than one SC in the past. (However, the only foreseeable way to test this hypothesis would be if evidence could be found in additional IBEX observations or in the more comprehensive data expected from the planned IMAP mission, for which near the end of [15] the IBEX experimenters include a recommendation for a timely launch.)

As the Sun is now in a period of declining activity and the latitudinal extent of the HCS has substantially decreased from what it was during the maximum of SC 24, this raises a question of whether the unipolar heliosheath region will expand enough to once again come close to or even to reach V2. In their discussion of the magnetic field the authors of [14] state that they do not expect this to happen because of the deflection of the solar wind flow observed by the spacecraft. However, we note that the transmission of the dynamic pressure of the interstellar plasma through the heliosheath to cause the deceleration at the TS and the gradually increasing deflection of the plasma flow that V2 has been observing since entering the heliosheath [16] is likely to be occurring by interactions of the solar wind flux tubes with the interstellar magnetic field and with each other, since the densities of these plasmas are far below those of laboratory plasmas that are collisionless in terms of the interactions of their particles. Thus, the tangential orientation of the field, and hence of the flux tubes, is likely to account for at least part of the observation in [16] that the deflection of the solar wind during V2’s first several years in the heliosheath has been much more in the radial-tangential (RT) plane than in the radial-normal (RN) plane. As long as the deflection is more tangential than normal, this increases the chance that a more nearly equatorial HCS will bring the unipolar region close to the spacecraft again.

7. Concluding Remarks

In seeking to compare the discussion in this paper with the extensive explicit computations of Washimi et al. [17] and references therein about the heliospheric boundary and termination shock, we note that their computations start with interstellar medium conditions and extend to 65 AU with generic latitudinal backgrounds. The previous sections have described our fundamentally different approach of estimating how solar flare coronal mass ejections form merged interaction regions affecting the Voyager observations of the boundary and shock. Combining these approaches is beyond the scope of this work, but might be useful in the future. The contrast between the transport speed estimates in this paper and the results of the simulations in [17] is not a direct contradiction because those simulations were for 2001-2009, while the flares and spacecraft observations here are from late 2011 through 2016, during weak SC 24. Observations by the Voyagers and various other spacecraft are gradually providing a comprehensive understanding of the effects of solar activity on phenomena in the front half of the heliosphere during the past decade or more. In particular, we have evidence that from the summer of 2011 to early 2015 solar flares produced disturbances that may have been convected to V2 and V1 in high-speed solar
wind emitted from polar coronal holes, producing phenomena observed at the Voyagers from the middle of 2012 to late 2016. The time may now be right for more detailed efforts of modeling and analysis, as in [17], to see how MIRs from these events have migrated out to the TS, how they have affected the heliosheath and the LISM, and what is likely to happen as solar activity declines. Furthermore, our description of this whole region may also evolve as we gain more understanding of the basic physics involved.

8. References
[1] Intriligator D S, et al., 2016, 15th AIAC, “The Science of Ed Stone Celebrating his 80th Birthday:” Journal of Physics Conference Series, 761, 012013
[2] Richardson J D, et al., 2017, Astrophys. J., 834, 190
[3] Intriligator D S, et al., AGU Fall Presentation, 2015
[4] Usmanov AV, et al., 2014, Astrophys. J., 788, 43
[5] NSO Integrated Synoptic Program (NISP) Integral PFSS model synoptic coronal hole plot http://gong2.nso.edu/archive/patch.pl?menutype=z
[6] Roelof E C, et al., 2012, AIP Conf. Proc., 1436, 239. updated by Krimigis S M, et al., AGU Fall Presentation, SH23A-04, 2016
[7] Intriligator D S, et al., 2014, 13th AIAC, Journal of Physics Conference Series, 577, 012013
[8] PWS Gurnett and Kurth, http://www-pw.physics.uiowa.edu/das/voyager-pws-sa-list
[9] Moebius E, et al., AGU Fall Presentation, SH11C-4060, 2014
[10] Wind/WAVES type II bursts and CMEs list https://cdaw.gsfc.nasa.gov/CME_list/radio/waves_type2.html
[11] GSFC daily CME list: https://cdaw.gsfc.nasa.gov/CME_list/daily_plots/sephtx/2015_02/sephtx_20150221.png
[12] COHO websites for STEREO data: https://omniweb.gsfc.nasa.gov/coho/form/stereoa.html and https://omniweb.gsfc.nasa.gov/coho/form/stereob.html
[13] Wilcox Solar Observatory (WSO) http://wso.stanford.edu courtesy of J T Hoeksema
[14] Hill M E, et al., 2014 Astrophys. J., 781, 94
[15] McComas D H, et al., 2014, Astrophys. J. Sup. 213, 20
[16] Richardson J D, 2015, 14th AIAC, Journal of Physics Conference Series, 642, 012022
[17] Washimi H, et al., 2011, Mon. Not. R. Astron. Soc., 416, 1475

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