Magnetic Field Intensity Modification to Force Free Model of Magnetic Clouds: Website of *Wind* Examples From Launch to July of 2015

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We describe a new NASA website that shows normalized magnetic field (\(B\)) magnitude profiles within *Wind* magnetic clouds (MCs) (i.e., observations versus basic model versus modified model) for 209 MCs observed from launch in late 1994 to July of 2015, where model modification is based on the studies of Lepping et al. (Solar Phys, 2017, 292:27) and Lepping et al. (Solar Phys, 2018, 293:162); the basic force free magnetic cloud parameter fitting model employing Bessel functions (Lepping et al., J. Geophys. Res., 1990, 95:11957) is called the LJB model here. The fundamental principles should be applicable to the \(B\)-data from any spacecraft at 1 AU. Earlier (in the LJB study), we justified why the field magnitude can be thought of as decoupled from the field direction within an MC, and further, we justified this idea in terms of actual observations seen over a few decades with examples of MCs from *Wind* data. The model modification is achieved by adding a correction ("Quad") value to the LJB model (Bessel function) value in the following manner: 

\[
\frac{B\text{(est)}}{B_0} \approx \left[ \text{LJB Model} + \text{Quad (CA, } u) \right],
\]

where \(B_0\) is the LJB-estimated field magnitude value on the MC’s axis, \(CA\) is the relative closest approach (See Supplementary Appendix A), and \(u\) is the distance that the spacecraft travels through the MC from its entrance point. In an average sense, the Quad technique is shown to be successful for 82% of the past modeled MCs, when Quality (\(Q_0\)) is good or excellent (see Supplementary Appendix A). The Quad technique is successful for 78% of MCs when all cases are considered. So \(Q_0\) of the MC LJB-fit is not a big factor when the success of the Quad scheme is considered. In addition, it is found that the Quad technique does not work better for MC events with higher solar wind speed. Yearly occurrence frequency of all MC events (\(N_{\text{Yearly}}\)) and those MC events with \(\Delta \sigma_{N_{\text{Yearly}}} / \sigma_{N_{\text{Yearly}}} \geq 0.5\) (\(N_{\text{MC}}/N_{\text{Yearly}} \geq 0.5\)) are well correlated, but there is no solar cycle dependence for normalizing \(N_{\Delta \sigma_{N_{\text{Yearly}}} / \sigma_{N_{\text{Yearly}}} \geq 0.5}\) with \(N_{\text{Yearly}}\).

Keywords: magnetic cloud, force free model, magnetic field intensity, solar wind, *Wind*-MC
1 INTRODUCTION AND BACKGROUND

A magnetic cloud (MC) is a solar wind region with the following features: enhanced magnetic field strength, a smooth change in magnetic field direction as observed by a spacecraft passing through the MC, low proton temperature compared to the ambient proton temperature, and low proton plasma beta (e.g., [1–3]). Also, we must require that the duration of the MC be 5 h or more, based on numerous observations. Many MC lists are available (e.g., [4–11]). Enhanced southward magnetic field of an MC will cause geomagnetic activity while the MC is passing by the Earth. Here, we call attention to a method of modifying a normalized magnetic field (B) magnitude profile within a Wind magnetic cloud (MC) (or for any spacecraft at 1 AU) by describing a new website that shows B-profiles (observations vs. model vs. modified model) for 209 cases of Wind MCs from launch (late 1994) to the end of 2015. The model modification is based on the studies of Lepping et al. [12] and Lepping et al. [10]: the basic MC parameter fitting (force free) model is that of Lepping et al. [13] (henceforth called the LJB model). The modification is based on the statistics of many actual MCs observed in the past by the Wind spacecraft. (For articles on the discovery of MCs and other relevant aspects see [1–3].)

The justification for separating the magnitude of B from its direction in the implementation of the LJB model results from the manner in which the model was posed in the first place and in what was shown to be the characteristics of hundreds of actual MCs from many different spacecraft. That is, the model always operated on the fundamental assumption that we could unit-normalize B (i.e., create B/|B| at all points) within the MC and carry out the least-square fitting of the model to the resulting data, being the unit normalized—B—not on the actual B. And only later do we adjust the B (model) profile to the average value of B across the MC; this leads to providing an appropriate |B₀| which is the estimated value for the magnetic field magnitude on the axis of the MC. In particular, this treatment for over 200 Wind MCs has generally provided a faithful reproduction of the profile of the direction of B within a MC for most cases (i.e., at least at 1 AU) and especially when considering the lower frequency components of B, that is, excluding what may be considered “noise.” But the model rarely gives a very good reproduction of the actual profile of the magnitude of B. The study by Lepping et al. [10] attempts to statistically correct for this shortcoming of the LJB model, as described below.

2 THE QUAD SCHEME FOR MODIFYING THE B-INTENSITY WITHIN THE MAGNETIC CLOUD

Recently, a scheme was developed by Lepping et al. [10] to provide a more realistic B/|B₀| profile of an MC, than that used in the LJB model, based on the results of 21 years of MCs studied from the Wind spacecraft (also, see Lepping et al. [10,12] for more detail on the foundation of the scheme). It was shown statistically that this scheme should improve MC profiles by about 82% of the time, when the highest quality (Q₀) MCs are considered. Q₀ can take one of three possible values: 1 (excellent), 2 (good/fair), and 3 (poor) (see Supplementary Appendix A, for a strict definition of Q₀). To provide differing examples, Figure 1 shows plots of B/|B₀| versus % of-time through the MC for three MCs (cases of #70, 71, and 62, all of Q₀ = 1), in terms of actual observations (101 averages across each MC, i.e., data averaged into 100 bins across each MC shown by the dot-dot-dashed curve; called the Obs curve), the original Bessel function model profile (the black solid-line curve, described by LJB), and the new statistically modified version (the red dashed curve, described generically by Lepping et al., 2018). MC #70 starts on 2002-03-24, #71 starts on 2002-04-18, and #62 starts on 2001-04-12; these dates are shown on the first line at the top of each panel of Figure 1. Also, within each panel of the figure are the start time (also on the first line at the top), and then the value of the relative closest approach in percentage (CA ≡ |Y₀|/R₀ in %), Q₀, the MC duration (τ), the average plasma speed within the MC (<VₘC>), and the estimated B₀, where Y₀ is the closest approach and R₀ is the estimated radius of the MC. Below the curves is the quantity Δσ₀/σ₀₂ described by Lepping et al. [10] as a good measure of how well the scheme is performing; when Δσ₀/σ₀₂ is above 0.5, it is doing very well (or exceptional when it approaches or exceeds 1.0); when it is between 0.5 and 0.5, it is acceptable; when it is negative, it is a failure. We give an abbreviated interpretation of Δσ₀/σ₀₂ here as follows:

The ratio Δσ₀/σ₀₂ is a relative measure of the improvement in the B/|B₀| fit to the MC’s profile by using a so-called Quad (CA,u) formula weighted by the “accuracy” of the final fit, for the LJB model, where σ₀₂ is a quantitative measure of how well the Quad equations fit the difference-profile between the observations and the model values: u is the distance measured as the spacecraft travels through the MC. Δσ₀ is a quantitative measure of the improvement in the fit of B/|B₀| after adding in the Quad modification (and Δσ₀ must be greater than or equal to 0.0 for a success), where B (est)/|B₀| = [LJB Model + Quad (CA,u)], developed for four possible CAs (in %), 12.5, 37.5, 62.5, and 87.5 (these are the center points of four equally spaced segments of the full span of CA (0–100%)). Quad is a quadratic fit to the difference-quantity [B/|B₀|(Observations)–LJB Model] for each point in the MC carried out statistically from 124 averaged (good quality, i.e., Q₀ = 1,2) MCs using Wind B-data (see Lepping et al. [10] for a more detailed explanation of the ratio Δσ₀/σ₀₂).

Concerning specifics of the three examples of Figure 1, we note the following:

- For case #70, we have a Δσ₀/σ₀₂ = −0.443, a poor (negative) case, with a CA of 8% and a long duration of 43.0 h. Since the Quad technique usually works best when B/|B₀|(Observations) is higher than the Bessel force free field in the early hours of the MC, which is not the case here, the “correction” field (red dashed curve in Figure 1) is too high in this case. This is a somewhat unusual case because of the low intensity field in these early hours, and therefore, it violates the assumptions on which the Quad technique was based and not surprisingly gives poor results, that is, the negative ratio for Δσ₀/σ₀₂ of -0.443, even though Q₀ = 1. In fact, there usually is not a good correlation between Δσ₀/σ₀₂ and Q₀ (see Figure 2 and related
text (Section 5) concerning this issue). And finally, notice that $B_0$ is 17.6 nT, a typical value for $B_\infty$ and $\langle V \rangle = 438$ km s$^{-1}$.

- For case #71 we have a $\Delta \sigma_N/\sigma_{N2} = 1.037$, an excellent case, with a CA of 52% and a fairly typical duration of 22.0 h. Here the observations are higher than the Bessel force free field (red dashed curve in Figure 1) in the early hours, which, as stated above is typical, and, in fact, this is an excellent example of such front-end enhancement in the field. Also $Q_0 = 1. B_0$ is 16.2 nT, another typical value for $B_\infty$, and finally, $\langle V \rangle = 477$ km s$^{-1}$.

- For case #62 with a $\Delta \sigma_N/\sigma_{N2} = 0.396$, we have an acceptable (intermediate) case, that is, a positive ratio but less than 0.500—and a short duration of the MC of 10 h. Here CA was moderately large (68%) and again $Q_0 = 1. B_0$ is 20.9 nT, a somewhat high value for $B_\infty$ and finally, a moderately high $\langle V \rangle = 644$ km s$^{-1}$.

All three cases were deliberately chosen to be in the $Q_0 = 1$ category so that Quality would not be an obvious determinate in the value of the ratio $\Delta \sigma_N/\sigma_{N2}$ (see comments in the Conclusions and Discussion (Section 5) about $\Delta \sigma_N/\sigma_{N2}$ versus $Q_0$).

3 WIND WEBSITE TO OBTAIN THE FULL SET OF FIELD INTENSITY PLOTS

The Website to obtain the MC $B/B_0$ profiles is within the Wind/MFI Website, which is https://wind.nasa.gov/mfi/mag_cloud_pub1.html.

The link at that Website to the Field Intensity plots, based on the Quad scheme, is http://lepmfi.gsfc.nasa.gov/mfi/mag_cloud_B_magnitude.html.
FIGURE 3 | Example page (p. 2) of set of 11 pages (20 panels each) of the same quantities as shown in Figure 1, and in the same format, of Wind MCs from launch to July of 2015.
TABLE 1 | Summary of number of MC failures and number of those with $\Delta \sigma_{N}/\sigma_{N2} \geq 0.5$

| Page No. | No. of failures | No. of $\Delta \sigma_{N}/\sigma_{N2} \geq 0.5$ |
|----------|----------------|----------------------------------|
| 1        | 6b  (1)c       | 7b  (4)c                         |
| 2        | 4 (2)          | 7 (5)                            |
| 3        | 5 (2)          | 7 (4)                            |
| 4        | 4 (2)          | 10 (8)                           |
| 5        | 3 (3)          | 7 (7)                            |
| 6        | 6 (3)          | 9 (5)                            |
| 7        | 3 (0)          | 8 (5)                            |
| 8        | 6 (3)          | 6 (4)                            |
| 9        | 3 (2)          | 10 (9)                           |
| 10       | 5 (3)          | 6 (2)                            |
| 11       | 1 (1)          | 7 (1)                            |

Sum [%] 48 [22%]a 22 [18%]a 84 [40%]b 64 [44%]b

| Page No. | No. of failures | No. of $\Delta \sigma_{N}/\sigma_{N2} \geq 0.5$ |
|----------|----------------|----------------------------------|
| 1        | 6b  (1)c       | 7b  (4)c                         |
| 2        | 4 (2)          | 7 (5)                            |
| 3        | 5 (2)          | 7 (4)                            |
| 4        | 4 (2)          | 10 (8)                           |
| 5        | 3 (3)          | 7 (7)                            |
| 6        | 6 (3)          | 9 (5)                            |
| 7        | 3 (0)          | 8 (5)                            |
| 8        | 6 (3)          | 6 (4)                            |
| 9        | 3 (2)          | 10 (9)                           |
| 10       | 5 (3)          | 6 (2)                            |
| 11       | 1 (1)          | 7 (1)                            |

Sum [%] 48 [22%]a 22 [18%]a 84 [40%]b 64 [44%]b

*Page number out of 11 pages (initially) of 20 MCs each, except for page 11 which has 9 events.

*For all cases, that is, MCs of $Q_0 = 1, 2,$ and $3$. There were a total of 209 such cases for the mission.

*Numbers in parentheses are for the better quality cases, that is, where the MCs are of quality $Q_0 = 1$ or 2 only. There were a total of 124 such cases for the mission.

Each MC has a case number (#) that is given (in parentheses) in the upper left-hand corner of each panel, as we saw in the three examples of Figure 1. We give below an example of a single page in the initial set.

4 EXAMPLE OF A PAGE OF 20 CASES OF WIND MCS

Figure 3 shows a single example page, that is, page 2, of a set of pages (20 panels each page, with one MC per panel) of the same quantities as shown in Figure 1 of Wind MCSs from launch to July of 2015. A full set of 11 figures is shown in Supplementary Appendix B. Initially, there are 11 such pages in the Website described above, to cover the 209 MCs that are believed to exist over that period. Notice that the example page shows that the force free Bessel fields (solid black lines) at the start and end times, for all cases, give the same $B/B_0$ value of about 0.52, as expected. The upper left-hand corner of each panel shows the case number (#) of the MC.

First, case #039 shows a value of $\Delta \sigma_{N}/\sigma_{N2}$ of 11.29, which is unusually high (indicating a good result, even though $Q_0 =$ 3), because the value of $\sigma_{N2} = 0.005$ is unusually small. We will not see many odd cases like this. Now consider good cases like #035 and #040, where $\Delta \sigma_{N}/\sigma_{N2}$ is 1.31 (with $Q_0 = 2$) and 0.91 (with $Q_0 = 1$), respectively; both are well above 0.5. In both cases, we see the dramatic difference between the ability of the Quad scheme (dashed curve) to almost reproduce the observed values in the early part of the MC and the inability of the Bessel function (solid black curve) to do so in that part of the MC. Notice that #026 is similar to #035 in that they give similar values of $\Delta \sigma_{N}/\sigma_{N2}$ (1.17 and 1.31, respectively) even though the first one has a somewhat long duration of 25.0 h and the second one has a rather short duration of only 5.3 h, and both of a quality that differs from $Q_0 = 3$. Now we consider a very poor case, #022, that is, where $\Delta \sigma_{N}/\sigma_{N2}$ is negative and rather large in the absolute value, where $\Delta \sigma_{N}/\sigma_{N2}$ is -0.40 (with $Q_0 = 3$). Case #033 is interesting in that the Quad scheme does well in the early part of the MC but not in the middle or latter regions, i.e. not as well as the Bessel field, so $\Delta \sigma_{N}/\sigma_{N2}$ is negative, −0.13; notice that this is a very long duration MC of 40.0 h, and $Q_0 = 1$. Those cases where the observed field is significantly lower in relative intensity than the Bessel function field, early in the MC, will usually produce the poorest results, such as in cases #022 and #031. This does not occur very frequently.

5 CONCLUSION AND DISCUSSION

Here, we describe a new NASA Website (see Section 3) that provides normalized magnetic field ($B/B_0$) magnitude profiles within Wind MCSs in terms of observations versus the basic-LJB model versus the Quad-modified model for 209 cases that cover the period from launch (late 1994) to July of 2015. The model-modification is based on the studies of Lepping et al. [12] and Lepping et al. [10]. The basic force free MC parameter fitting model that is modified is that of LJB. The statistics of both the number of MC-modified failures and the number of (very good) cases where $\Delta \sigma_{N}/\sigma_{N2} \geq 0.5$ given by this new website to this point (July 2021) is provided in Table 1.

For all cases (i.e., MCs of $Q_0 = 1, 2,$ and $3$), Table 1 shows that the percentage of failures is 22%, and for the cases where $Q_0 = 1$ and 2, only (values in parentheses) the percentage slightly improves to 18%. However, considering all cases, we find that 40% have $\Delta \sigma_{N}/\sigma_{N2} \geq 0.5$, but the percentage slightly increases to 44% when the cases are restricted to $Q_0 = 1$ and 2 only.

Figure 4 gives a histogram (called f (obs) and shown by a solid black curve) representing the frequency of occurrence of the observed ratio $\Delta \sigma_{N}/\sigma_{N2}$ for the full Wind mission (i.e., from launch to July 2015), and for $Q_0 = 1, 2,$ and $3$, and showing some key features, such as having a peak at about 0.5, a relatively
small number of events greater than 1.0. It appears to be a slightly modified normal distribution. Since the histogram peaks near $\Delta \sigma /\sigma_{N2} = 0.5$, we choose it as a separator of “acceptable” from “very good” values of $\Delta \sigma /\sigma_{N2}$. In fact, the curve $f(\text{obs})$ appears to be quite well fitted with a simple skewed Gaussian distribution (called $f(Z)$ here):

$$\text{Freq of occurrence} = f(Z) = c_1 \times (1 - c_2 Z) \times \exp\left[\frac{-1}{2}(Z - c_3 Z)^2/c_4^2\right],$$

where $Z \equiv \Delta \sigma /\sigma_{N2}$, for $c_1 = 48$, $c_2 = 0.35$, and $c_3 = 0.55$ (see [14]); the skewness factor is $(1-c_4 Z)$, where $c_4 = 0.35$. $f(Z)$ is shown in Figure 4 as the red dashed curve. For a measure of how well this modified normal distribution fits the actual histogram, we define a $\sigma$ as follows:

$$\sigma = \sqrt{\frac{\sum f(\text{obs}) - f(Z)^2}{N}},$$

where $i$ goes from 1 to 11, and therefore, $N$ in this case is 11 (but recall that the total number of MCs employed in this analysis is 209). The value of $\sigma = 4.0$ is shown in the upper right-hand corner (first line in red) of Figure 4. For comparison, for the same set of coefficients, except with no skewness (i.e., $c_4' = 0.0$), we get a larger $\sigma' = 7.0$ seen on the second line; this simple Gaussian is the black dotted curve in Figure 4. And for a set of coefficients of $c_1 = 45$, $c_2 = 0.35$, $c_3 = 0.55$, and $c_4' = 0.0$, we get an intermediate value for $\sigma' = 6.0$ (not shown in Figure 4); this is an attempt to lower the peak in the black dotted curve in the figure. The set of coefficients giving $\sigma = 4.0$, where only two-place accuracy is needed, is probably the best set possible, or very close to it. As new MCs are found in future Wind data, they may alter the optimum $f(Z)$ fit curve.

Finally, we discuss Figure 2 which is a plot of $\Delta \sigma /\sigma_{N2}$ versus time for a family of $Q_0$ (1, 2, and 3) showing almost the same average of $\Delta \sigma /\sigma_{N2}$ (which goes from 0.43 to 0.48) regardless of the value of $Q_0$ but with large scatter in each case. This means that there is a very poor correlation between $\Delta \sigma /\sigma_{N2}$ and $Q_0$. In other words, better values of $\Delta \sigma /\sigma_{N2}$ should not necessarily be expected, just because the MCs are of better Quality (based on the LJB model). However, as Table 1 shows, the better $Q_0$ is we might expect statistically slightly better results in both the success rate and in the degree of excellence, that is, in the percentage of cases where $\Delta \sigma /\sigma_{N2} \geq 0.5$.

Concerning the issue of solar cycle dependence, solid and dotted lines of Figure 5A show yearly occurrence frequency of all MC events, $N_{\text{Yearly}}$, and MC events with $\Delta \sigma /\sigma_{N2} \geq 0.5$, $N_{\text{Yearly} \geq 0.5}$ (dotted line). For comparison, for the same set of coefficients, except with no skewness (i.e., $c_4' = 0.0$), we get a intermediate value $\Delta \sigma /\sigma_{N2} \geq 0.5$. The correlation coefficient between them is 0.94; that is, they correlate very well. Both $N_{\text{Yearly}}$ and $N_{\text{Yearly} \geq 0.5}$ vary with solar activity. Figure 5B shows clearly that there is no solar cycle dependence for normalized $N_{\text{Yearly} \geq 0.5}$ with $N_{\text{Yearly}}$.

Speed is also an important input parameter for the LJB model. We separate 209 MCs into two groups: 1) $\Delta \sigma /\sigma_{N2} < 0.5$ and 2) $\Delta \sigma /\sigma_{N2} \geq 0.5$. There are 123 MCs with $\Delta \sigma /\sigma_{N2} < 0.5$ and 86 MCs with $\Delta \sigma /\sigma_{N2} \geq 0.5$. The average and median speed are 440 and 405 km/s, respectively, for group (1). The average and median speed are 433 and 408 km/s, respectively, for group (2). This implies that the Quad technique does not work better for the MC events with higher speed.

The Quad modification is derived from the difference in field magnitude between the actual field profiles and the fields derived from the LJB (Bessel function) model where many cases are considered, to develop quadratic correction functions. We have shown that in general, the LJB model with the Quad modification is expected to provide more accurate MC fitting, and it should be useful particularly for those studies where the spatial variation of the B-field magnitude across a MC is important, especially in comparison to the basic LJB model.

**DATA AVAILABILITY STATEMENT**

The original contributions presented in the study are included in the article/Supplementary Material; further inquiries can be directed to the corresponding author.

**AUTHOR CONTRIBUTIONS**

C-CW, RL, and DB contributed to conception and design of the study. C-CW organized the database. RL and C-CW performed...
the statistical analysis. RL wrote the first draft of the manuscript. RL, C-CW, and DB wrote sections of the manuscript. All authors contributed to manuscript revision, reading, and approved the submitted version.

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REFERENCES
1. Burlaga L, Sittler E, Jr., Mariani F, and Schwenn R Magnetic Loop Behind an Interplanetary Shock: Voyager, Helios, and IMP 8 Observations. J Geophys Res (1981) 86:6673–84. doi:10.1029/ja086ia08p06673
2. Burlaga LF Magnetic Clouds and Force-Free Fields with Constant Alpha. J Geophys Res (1988) 93:7217–24. doi:10.1029/ja093ia07p07217
3. Burlaga LF Interplanetary Magnetohydrodynamics. New York: Oxford Univ. Press (1995). p. 89–114.
4. Cane HV, and Richardson IG Interplanetary Coronal Mass Ejections in the Near-Earth Solar Wind during 1996–2002. J Geophys Res (2003) 108:1156. doi:10.1029/2002ja009817
5. Jian L, Russell CT, Luhmann JG, and Skoug RM Properties of Interplanetary Coronal Mass Ejections at One AU during 1995–2004. Solar Phys (2006) 239:393–436. doi:10.1007/s11207-006-0133-2
6. Chi Y, Shen C, Wang Y, Xu M, Ye P, Wang S, et al. Statistical Study of the Interplanetary Coronal Mass Ejections from 1995 to 2015. Solar Phys (2016) 291:2419–39. doi:10.1007/s11207-016-0971-5
7. Lepping RP, Berdichevsky DB, Wu C-C, Szabo A, Narock T, Mariani F, et al. A Summary of WIND Magnetic Clouds for Years 1995–2003: Model-Fitted Parameters, Associated Errors and Classifications. Ann Geophys (2006) 24:215–45. doi:10.5194/angeo-24-215-2006
8. Lepping RP, Wu C-C, Berdichevsky DB, and Szabo A Magnetic Clouds At/ near the 2007 - 2009 Solar Minimum: Frequency of Occurrence and Some Unusual Properties. Sol Phys (2011) 274:345–60. doi:10.1007/s11207-010-9646-9
9. Lepping RP, Wu C-C, Berdichevsky DB, and Szabo A Wind Magnetic Clouds for 2010 - 2012: Model Parameter Fittings, Associated Shock Waves, and Comparisons to Earlier Periods. Sol Phys (2015) 290:2265–90. doi:10.1007/s11207-015-0735-3
10. Lepping RP, Wu C-C, Berdichevsky DB, and Kay C Magnetic Field Magnitude Modification for a Force-free Magnetic Cloud Model. Solar Phys (2018) 293(19):162. doi:10.1007/s11207-018-1383-5
11. Lepping RP, Wu C-C, Berdichevsky DB, and Szabo A Model Fitting of Wind Magnetic Clouds for the Period 2004 – 2006. Solar Phys (2020) 295:83. doi:10.1007/s11207-020-01630-2
12. Lepping RP, Berdichevsky DB, and Wu C-C Average Magnetic Field Magnitude Profiles of Wind Magnetic Clouds as a Function of Closest Approach to the Clouds’ Axes and Comparison to Model. Solar Phys (2017) 292(2):27. doi:10.1007/s11207-016-1040-9
13. Lepping RP, Jones JA, and Burlaga LF Magnetic Field Structure of Interplanetary Magnetic Clouds at 1 AU. J Geophys Res (1990) 95:11957. doi:10.1029/ja095ia08p11957
14. Freund JE Mathematical Statistics. Englewood Cliffs, NJ: Prentice-Hall (1962). p. 127–8.

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SUPPLEMENTARY MATERIAL
The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fphy.2021.712599/full#supplementary-material

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