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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: B (est)/$B_0 \approx$ [LJB Model + Quad (CA,u)], 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_{Yearly}) and those MC events with $\Delta\sigma_N/\sigma_{N2} \geq 0.5$ ($N_{\Delta\sigma N/\sigma N2 \geq 0.5}$) are well correlated, but there is no solar cycle dependence for normalizing $N_{\Delta\sigma N/\sigma N2 \geq 0.5}$ with N_{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 $\boldsymbol{B}$ 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 $\boldsymbol{B}$ (i.e., create $\boldsymbol{B}/|\boldsymbol{B}|$ at all points) within the MC and carry out the least-square fitting of the model to the resulting data, being the unit normalized-$\boldsymbol{B}$—not on the actual $\boldsymbol{B}$. 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 B_0, 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 $\boldsymbol{B}$ within a MC for most cases (i.e., at least at 1 AU) and especially when considering the lower frequency components of $\boldsymbol{B}$, 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 $\boldsymbol{B}$. 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/B_0 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 (Q_0) MCs are considered. Q_0 can take one of three possible values: 1 (excellent), 2 (good/fair), and 3 (poor) (see **Supplementary Appendix A**, for a strict definition of Q_0). To provide differing examples, **Figure 1** shows plots of B/B_0 *versus* %-of-time through the MC for three MCs (cases of #s 70, 71, and 62, all of Q_0 = 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 ($CA \equiv |Y_0|/R_0$ in %), Q_0, the MC duration (τ), the average plasma speed within the MC ($<V_{MC}>$), and the estimated B_0, where Y_0 is the closest approach and R_0 is the estimated radius of the MC. Below the curves is the quantity $\Delta\sigma_N/\sigma_{N2}$ described by Lepping et al. [10] as a good measure of how well the scheme is performing; when $\Delta\sigma_N/\sigma_{N2}$ is above 0.5, it is doing very well (or exceptional when it approaches or exceeds 1.0); when it is between 0.0 and 0.5, it is acceptable; when it is negative, it is a failure. We give an abbreviated interpretation of $\Delta\sigma_N/\sigma_{N2}$ here as follows:

The ratio $\Delta\sigma_N/\sigma_{N2}$ is a relative measure of the improvement in the B/B_0 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 σ_{N2} 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. $\Delta\sigma_N$ is a quantitative measure of the improvement in the fit of B/B_0 after adding in the Quad modification (and $\Delta\sigma_N$ must be greater than or equal to 0.0 for a success), where B (est)/B_0 ≈ [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/B_0(Observations)-LJB Model] for each point in the MC carried out statistically from 124 averaged (good quality, i.e., Q_0 = 1,2) MCs using *Wind* B-data (see Lepping et al. [10] for a more detailed explanation of the ratio $\Delta\sigma_N/\sigma_{N2}$).

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

- For case #70, we have a $\Delta\sigma_N/\sigma_{N2} = -0.443$, 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/B_0(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 $\Delta\sigma_N/\sigma_{N2}$ of -0.443, even though Q_0 = 1. In fact, there usually is not a good correlation between $\Delta\sigma_N/\sigma_{N2}$ and Q_0 (see **Figure 2** and related

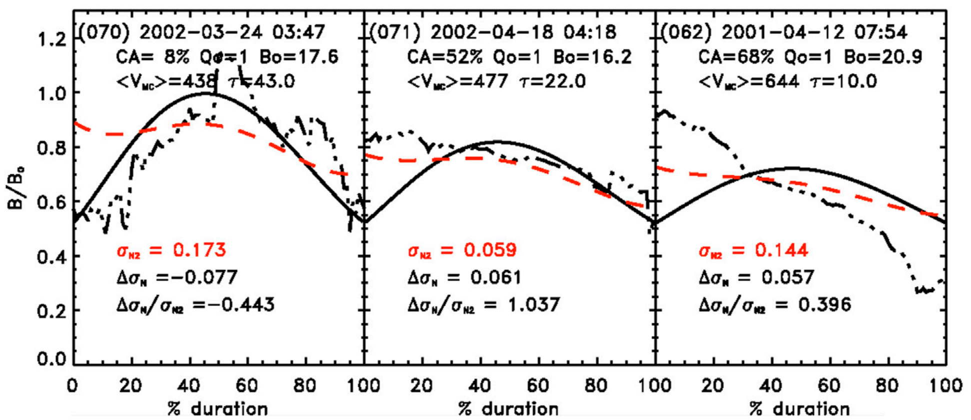

FIGURE 1 | Three examples (the cases of #s 70, 71, and 62 of *Wind* MCs; see the associated starting dates of these MCs on the first line at the top of each panel) of plots of B/B_0-profiles: B_0-normalized *B observations* (black dash-dot-dot), force free model values (black solid curve) and modified-model values (red dashed curve from Lepping et al. [10]—all as a function of percent passage through the MC (i.e., *u* in %); each profile has 101 points across. In each panel the following are shown: TOP OF EACH PANEL: the start time (year-month-day of month) hour:minute (UT), *CA* (= $|Y_0|/R_0$ in %), Quality (Q_0), B_0 (in nT), average plasma speed within the MC ($<V_{MC}>$, in km s^{-1}), and duration (τ, in hours), BOTTOM OF EACH PANEL: the values of the quantities $\Delta\sigma_N$,σ_{N2}, and $\Delta\sigma_N/\sigma_{N2}$ (see text) that are described by Lepping et al. [10]. The ratio $\Delta\sigma_N/\sigma_{N2}$ in particular is shown to be a good measure of how well the scheme is performing in general.

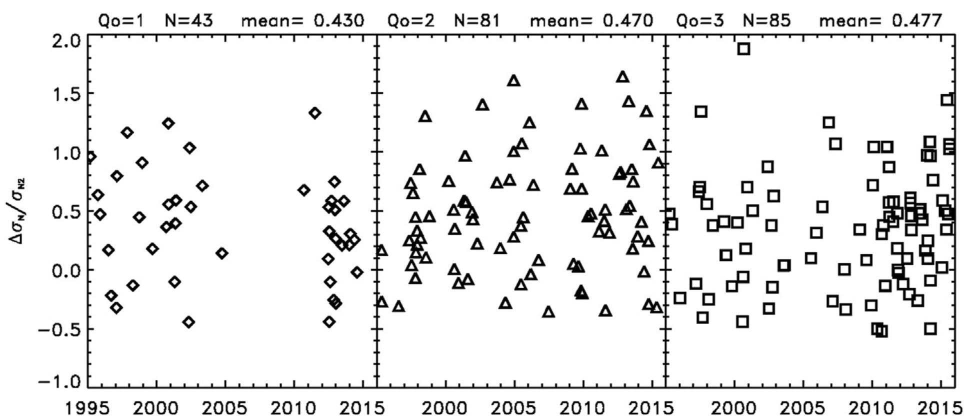

FIGURE 2 | A plot of $\Delta\sigma_N/\sigma_{N2}$ *versus* time for the family of Q_0, showing almost the same average of $\Delta\sigma_N/\sigma_{N2}$ for each Q_0 (the averages are given above each panel), where Q_0 = 1 set is represented by diamonds, Q_0 = 2 by triangles, and Q_0 = 3 by squares, with a large spread in values in each case.

text (**Section 5**) concerning this issue). And finally, notice that B_o is 17.6 nT, a typical value for B_o, and $<V>$ = 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_o is 16.2 nT, another typical value for B_o, and finally, $<V>$ = 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_o is 20.9 nT, a somewhat high value for B_o, and finally, a moderately high $<V>$ = 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_o 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.

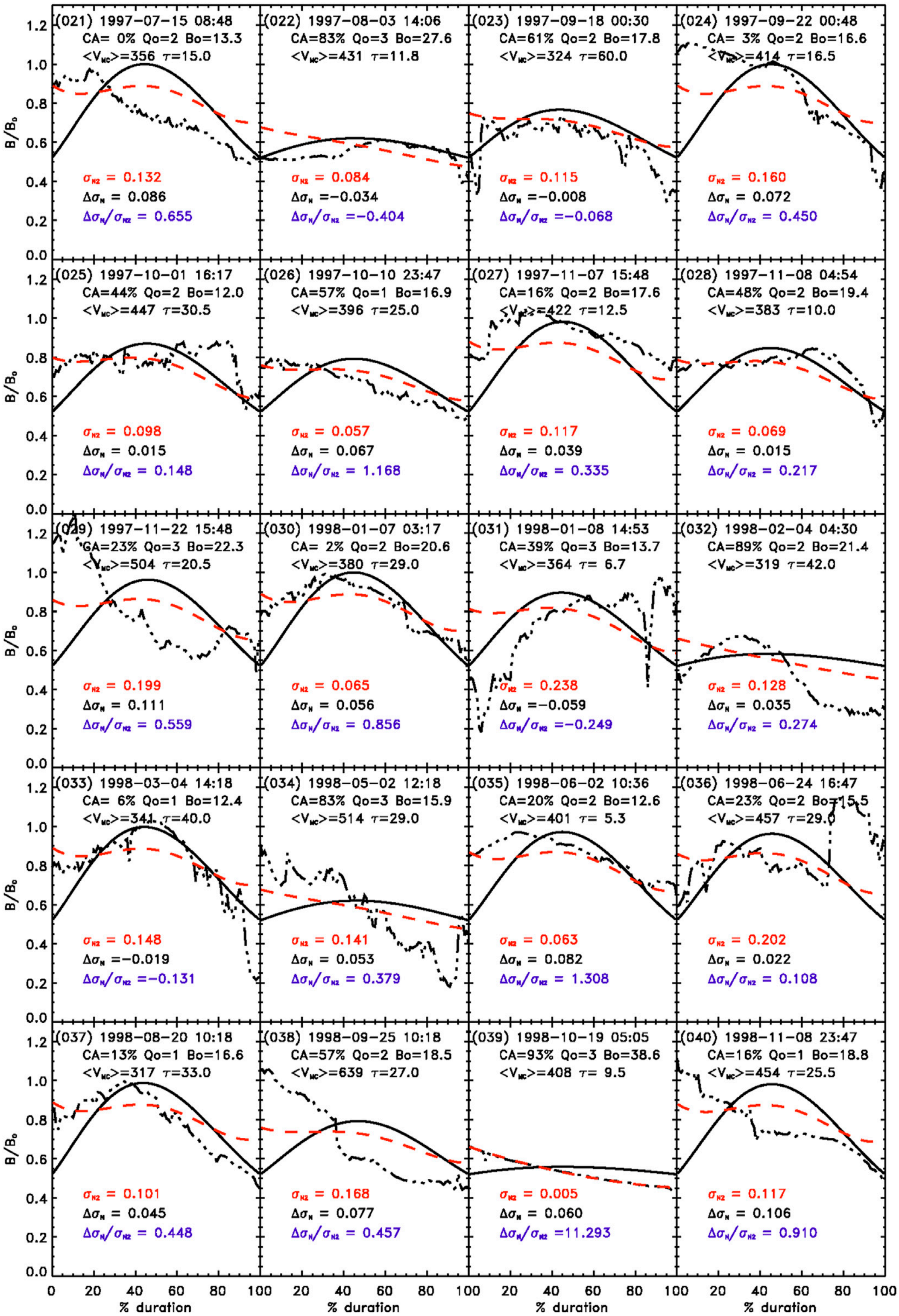

FIGURE 3 | Example page (p. 2) of set of 11 pages (20 panels each) of the same quantities as shown in **Figure 1**, and in the same format, of *Wind* MCs from launch to July of 2015.

TABLE 1 | Summary of number of MC failures and number of those with $\Delta\sigma_N/\sigma_{N2} \geq 0.5$

Page No.[a]	No. of failures	No. of $\Delta\sigma_N/\sigma_{N2} \geq 0.5$
1	6[b] (1)[c]	7[b] (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 [%]	46 [22%][b] (22 {18%})[c]	84 [40%][b] (54 {44%})[c]

[a]*Page number out of 11 pages (initially) of 20 MCs each, except for page 11 which has 9 events.*
[b]*For all cases, that is, MCs of Q_0 = 1, 2, and 3. There were a total of 209 such cases for the mission.*
[c]*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* MCs 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 figure shows that the force free Bessel fields (solid black lines) at the start and end times, for all cases, give the same B/B_o 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 σ_{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_o) magnitude profiles within *Wind* MCs in terms of observations *versus* the basic-LJB model *versus* the Quad-modified model for 209 MCs 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

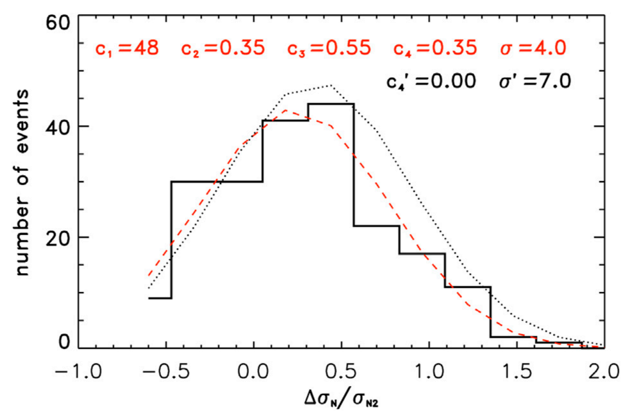

FIGURE 4 | A histogram of frequency of occurrence of the observed ratio $\Delta\sigma_N/\sigma_{N2}$ (black solid curve) with a superimposed skewed normal (Gaussian)-distribution, f(*Z*) (red dashed curve), where $Z \equiv \Delta\sigma_N/\sigma_{N2}$; c_1, c_2, c_3, and c_4 are the coefficients shown in **Eq. 1**. The black dotted curve is for the same Gaussian (i.e., the same values of c_1, c_2, and c_3), except now c_4 is set equal to zero. σ gives a measure of how well the fit-curve approximates the observed histogram and is given by **Eq. 2**. The red coefficients hold for the red dashed skewed Gaussian and the black coefficients are for the simple Gaussian (second line at the top), where c_1, c_2, and c_3 are the same in both cases. Note that both black and red curves are approximately Gaussian.

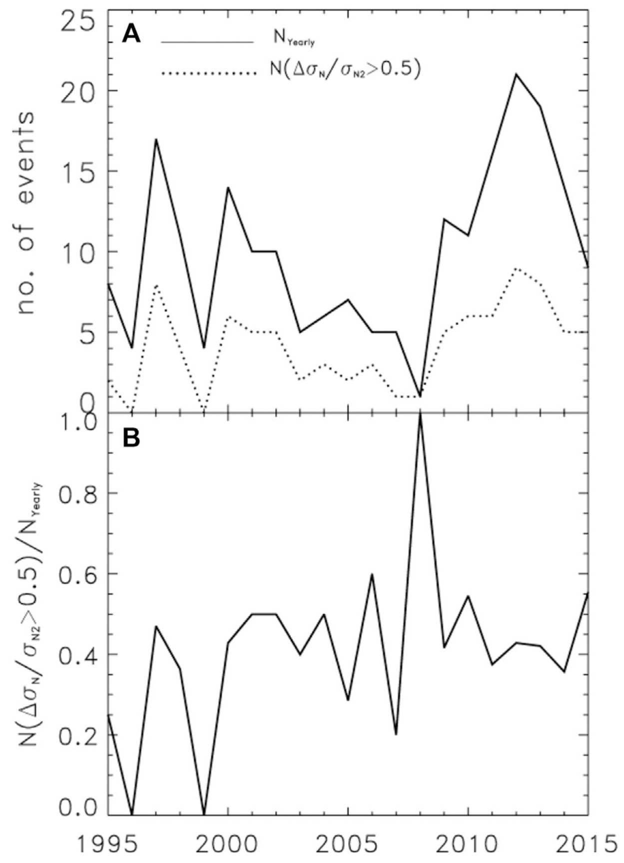

FIGURE 5 | (A) Yearly occurrence frequency of all MC events, N_{Yearly} (solid-lines), and MC events with $\Delta\sigma_N/\sigma_{N2} \geq 0.5$, $N_{\Delta\sigma N/\sigma N2 \geq 0.5}$ (dotted line). **(B)** Normalized yearly $N_{\Delta\sigma N/\sigma N2 \geq 0.5}$ with N_{Yearly}.

small number of events greater than 1.0. It appears to be a slightly modified normal distribution. Since the histogram peaks near $\Delta\sigma_N/\sigma_{N2} = 0.5$, we choose it as a separator of "acceptable" from "very good" values of $\Delta\sigma_N/\sigma_{N2}$. In fact, the curve f (obs) appears to be quite well fitted with a simple skewed Gaussian distribution (called f(Z) here):

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

where $Z \equiv \Delta\sigma_N/\sigma_{N2}$, for $c_1 = 48$, $c_2 = 0.35$, and $c_3 = 0.55$ (see [14]); the skewness factor is ($1—c_4Z$), 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 σ as follows:

$$\sigma = \sqrt{\left(\sum_i \left[f(\text{obs})_i - f(Z)_i\right]^2/N\right)}, \tag{2}$$

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 σ = 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 σ′ = 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 σ′′ = 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 σ = 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 will be added to this website, and, of course, they may alter the optimum f(Z) fit curve.

Finally, we discuss **Figure 2** which is a plot of $\Delta\sigma_N/\sigma_{N2}$ *versus* time for a family of Q_0 (1, 2, and 3) showing almost the same average of $\Delta\sigma_N/\sigma_{N2}$ (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 $\Delta\sigma_N/\sigma_{N2}$ and Q_0. In other words, better values of $\Delta\sigma_N/\sigma_{N2}$ 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 $\Delta\sigma_N/\sigma_{N2} \geq 0.5$.

Concerning the issue of solar cycle dependence, solid and dotted lines of **Figure 5A** show yearly occurrence frequency of all MC events, N_{Yearly} and MC events with $\Delta\sigma_N/\sigma_{N2} \geq 0.5$, and $N_{\Delta\sigma N/\sigma N2 \geq 0.5}$. The correlation coefficient between them is 0.94; that is, they correlate very well. Both N_{Yearly} and $N_{\Delta\sigma N/\sigma N2 \geq 0.5}$ vary with solar activity. **Figure 5B** shows clearly that there is no solar cycle dependence for normalized $N_{\Delta\sigma N/\sigma N2 \geq 0.5}$ with N_{Yearly}.

Speed is also an important input parameter for the LJB model. We separate 209 MCs into two groups: 1) $\Delta\sigma_N/\sigma_{N2} < 0.5$ and 2) $\Delta\sigma_N/\sigma_{N2} \geq 0.5$. There are 123 MCs with $\Delta\sigma_N/\sigma_{N2} < 0.5$ and 86 MCs with $\Delta\sigma_N/\sigma_{N2} \geq 0.5$. 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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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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