

# Solar Physics

## A Challenging Solar Eruptive Event of 18 November 2003 and the Causes of the 20 November Geomagnetic Superstorm. IV. Atypical Magnetic Cloud and Overall Scenario

--Manuscript Draft--

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<b>Corresponding Author:</b>	Victor Grechnev RUSSIAN FEDERATION
<b>Corresponding Author Secondary Information:</b>	
<b>Corresponding Author's Institution:</b>	
<b>Corresponding Author's Secondary Institution:</b>	
<b>First Author:</b>	Victor Grechnev
<b>First Author Secondary Information:</b>	
<b>Order of Authors:</b>	Victor Grechnev Arkadiy M. Uralov, Dr. Sc. Ilya M. Chertok, Cand. Sc. Anatoly V. Belov, Dr. Sc. Boris P. Filippov, Dr. Sc. Vladimir A. Slemzin, Dr. Sc. Bernard V. Jackson, Dr. Sc.
<b>Order of Authors Secondary Information:</b>	
<b>Abstract:</b>	<p>The geomagnetic superstorm on 20 November 2003 with <math>Dst = -422</math> nT, one of the most intense in history, escapes understanding. The superstorm was caused by a moderate solar eruptive event on 18 November, comprehensively studied in our preceding Papers I-III. The analysis has shown a number of unusual and extremely complex features, which presumably led to the formation of an isolated right-handed configuration. Here we analyze the interplanetary disturbance responsible for the 20 November superstorm, compare some of its properties with the extreme 28-29 October event, and reveal a compact size of the magnetic cloud (MC) and its disconnection from the Sun. Most likely, the MC had a spheromak configuration and expanded in a narrow angle of <math>&lt; 14</math> degree. A very strong magnetic field in the MC up to 56 nT was due to the atypically weak expansion of the disconnected spheromak in an enhanced-density environment constituted by the tails of preceding ICMEs. Additional circumstances favoring the superstorm were i) the exact impact of the spheromak on the Earth's magnetosphere and ii) the almost exact southward direction of the magnetic field, corresponding to the orientation in a probable region of its source near the solar disk center.</p>

We are grateful to both reviewer #1 and reviewer #2 for the attention to our paper, its favorable evaluation, cooperation in thinking about the issues in question, and useful remarks. We are pleased to see that the remarks on the previous version, SOLA2382R1, whose modifications were prompted by reviewer #1, are not related to the essence of the paper or its major outcome. We have carefully considered all of the remarks from both reviewers and made the corresponding changes in the present version, at least, endeavoring to follow their sense. The corrections in the manuscript are indicated with boldface. Below we respond to the reviewers' comments, which we mark with yellow boldface for convenience.

#### **Reviewer #1:**

**I have read the revised version. The authors revised some part of the paper in light of my previous comments, like the introduction part of the paper and discussion of Kumar et al (2011). This revision in introduction is acceptable for me.**

**However, they did not address all the points that I have suggested. Therefore, still I am not convinced to accept this paper as its present form. My further suggestions are as follows:**

**1. In the reply to my comments regarding the change of the title of the paper, the authors say 'The comparison with the 29 October magnetic cloud is not their specific purpose'. After reading the authors' previous papers (I-III) they have studied the event in great detail. Now in this paper IV they have studied and compared the geomagnetic superstorm of 18 November and 28 October events. Therefore, the comparison is one of the main aims of the paper. They should include the in-situ data of 29 October, 2003 and should compare them. Keeping this point in mind, I again suggest the authors to focus the paper on the comparison of the magnetic clouds of 20 November 2003 and 28-29 October 2003, and to change the title accordingly.**

– We have attentively considered this suggestion and come to the following.

Besides the reasons shown in our previous response, it is difficult to make a rigorous analysis of the 29–30 October ICMEs for the absence of the standard data on the solar wind, because the main detector on ACE did not operate normally for about 70 hours after the midday on 28 October, due to a large particle event. The analyses based on indirect data have already been published in several papers, some of which we cite.

We endeavor relating the title of our paper to its subject and aim. The title suggested by reviewer #1 characterizes a method. This title probably could be fine for a single, isolated paper, while our present paper completes a series of four companion papers devoted just to the 20 November superstorm and its solar source. The comparison between the 20 November and 29 October magnetic clouds, facilitating the readers reaching our major conclusions, is possibly most natural and conspicuous among our methods, whereas our major method is the analysis of the magnetic structure of the 20 November ICME. The attention paid to the 28–29 October event has already reached its upper allowable limit, as the impression of reviewer #1 shows. In principle, it would be more correct to compare the 20 November ICME not to a single 29 October ICME, but to many others. This has partially been done by, e.g., Yurchyshyn, Hu, and Abramenko (2005, *Space Weather*, 3, S08C02), and by Srivastava (2005, *Ann. Geophys.* 23, 2989). In particular, the major part of the paper by Yurchyshyn et al. (2005), ‘*Structure of magnetic fields in NOAA active regions 0486 and 0501 and in the associated interplanetary ejecta*’, presents exactly the comparison, which reviewer #1 is talking about. We show in our paper only few features of the 29 October magnetic cloud (adopted from other studies) that can be helpful for the readers to understand our considerations of the 20 November event. The presentation of a more complete compilation would be appropriate for a review paper that is not the case in our situation.

Proceeding from these circumstances, we have made the following changes.

1. Indeed, the previous title was somewhat vague; thus, we have changed it now to ‘*A Challenging Solar Eruptive Event of 18 November 2003 and the Causes of the 20 November Geomagnetic Superstorm. IV. Atypical Magnetic Cloud and Overall Scenario*’. This specific title is adequate to our subject and aim, as well as the completing character of our paper; and, implying a comparative analysis, it follows the sense of the recommendation from reviewer #1.

2. To reduce the apparent emphasis on the 29 October event, we have briefly mentioned on page 4 some other outstanding events (this addition is coherent with a remark (1) from reviewer #2, as mentioned below).

3. On page 11, just before Section 2.2, we have added a brief characterization of the 29 October magnetic cloud with a reference to Yurchyshyn et al. (2005).

**2. The authors have suggested some acknowledgements in the paper. It seems that the authors think all the previous studies have advanced the understanding of the 18 November 2003 event. Indeed I too believe these cited previous studies gave more opportunity to understand the 18 November event in more detail. Therefore, instead of putting some acknowledgements, I suggest the authors to put such**

a statement in the section of concluding remarks. It can be like: Various/many researchers contributed to the study of 18 November 2003 event and the 20 November 2003 magnetic cloud. These efforts certainly have advanced, step by step, our understanding of solar phenomena and their space weather outcome.

– Now these sentences are present in the first paragraph of Section 3.6 on page 22.

**Reviewer#2:**

The paper by Grechne et al. describes the biggest geomagnetic storms in solar cycle 23 (20 November 2003), and compares it with the events of 28-29 October 2003. Since this paper was reviewed by another referee and the authors have already taken care of the comments. Therefore I would only suggest the authors to add the following two points.

(1) It is an important topic for geomagnetic storms. The authors focused on the strength of the interplanetary magnetic field and the solar wind parameters. Since the topic of this paper is the biggest geomagnetic storm in cycle 23, the authors should compare their results (Nov.20,2003) with other storms of similar strength, with  $B > 50$  nT (For example, events listed below for items i,ii, iii).

i) July 15 2000  $B > 50$ nT (See Fig.6. in Lario et al, Space Weather, 6, S12001, 2008)

ii) Halloween 2003 has  $B \sim 50$  nT (See Figure 2 in Wu et al., 2005, JGR,110, A09S17)

iii)  $B \sim 50$  nT DOY 135, 2005, (See Fig. 7 in W.B. Manchester et al. 2014, Plasma Phys. Control. Fusion 56, 2014, 064006, 11pp).

– We have added brief information on these events (as well as corresponding references mentioned by reviewer #2) on page 4. Since the paper by Lario et al. (2008) mostly addresses SEP events, we have used a different reference. Also, we have looked at other events with  $|B|_{\max} > 50$  nT (including Halloween 2003):

Date	Dst <sub>min</sub> [nT]	$ B _{\max}$ [nT]	V <sub>sw,max</sub> [km/s]
1979.06.06	-40	54.4	655
2000.07.15	-301	51.9	1107
2001.11.06	-292	65.6	729
2001.11.24	-221	56.9	1040
2003.10.29	-353	47.5	1900
<b>2003.11.20</b>	<b>-422</b>	<b>55.8</b>	<b>703</b>
2005.05.15	-247	54.2	959
2005.08.24	-184	52.2	720

The table confirms that the 20 November 2003 magnetic cloud of a modest speed produced the largest Dst deviation among the events with  $|B|_{\max} > 50$  nT. It is difficult for various reasons to find other important parameters for all of these events, and therefore this table would not be very informative for the readers.

(2) It is well known that geomagnetic storms are associated with southward B field (e.g., Tsurutani and Gonzalez, 1997, Geophys. Monogr. vol. 98, pp. 77-89), and magnetic clouds are a good source for a long lasting southward field (e.g., Wu and Lepping, 2002. JGR 107, 1314).

There are many published studies for the formula of estimation for Dst. For example, the famous Dst formula made by Burton et al. (1975, JGR, 80, 4204); the Dst formula associated with magnetic clouds made by Wu and Lepping (2005, J. Atmos. Solar-Terr. Phys. 67, 283-291). I suggest the authors to use these formula to estimate the Dst values and compare them with their results.

– According to Wu and Lepping (2005), the  $B_z$ -based prediction gives  $Dst \approx -362$  nT, and the  $(VB_s)_{\max}$ -based prediction gives  $-372$  nT. Both values are acceptable by the order of magnitude, being underestimated relative to the actual one,  $-422$  nT. It is not clear what can be the reason for this; either the fact that the Wu and Lepping (2005) formulas were inferred from weaker geomagnetic storms, or the unusual magnetic configuration of the 20 November 2003 magnetic cloud. Similarly, a more complex technique of Burton et al. (1975), which allowed one estimating the evolution of Dst by solving an empirical equation, was based on considerably weaker events. Discussion of this issue in our paper would be inconclusive. Our paper does not pursue the practical forecast of geomagnetic disturbances. Our purpose is only to find the causes of the anomalously strong geomagnetic effect of an ICME, whose origin was a solar event of an ordinary power.

We have added a comment at the onset of Section 3.3, bottom of page 19, continued on page 20.

With appreciation,

Victor Grechnev and the co-authors.



**Keywords:** Forbush Decreases; Geomagnetic Storms; Interplanetary Coronal Mass Ejections; Magnetic Clouds; Solar Wind, Disturbances

## 1. Introduction

A series of big eruptive flares in a complex of large super-active regions 10484, 10486, and 10488 occurred late in October 2003 (see, *e.g.*, Veselovsky *et al.*, 2004; Chertok and Grechnev, 2005; Gopalswamy *et al.* 2005a, 2005b; Grechnev *et al.*, 2005). The ‘Halloween 2003 events’ produced geomagnetic superstorms with  $Dst = -353$  and  $-383$  nT<sup>1</sup> on 29–31 October. A notable event on 18 November occurred in the decaying active region (AR) 10501 during the second passage across the solar disk of the former AR 10484. This event produced a still stronger superstorm on 20 November 2003 with  $Dst = -422$  nT, the largest one during the solar cycle 23 (*e.g.*, Yermolaev *et al.*, 2005; Gopalswamy *et al.*, 2005c; Yurchyshyn, Hu, and Abramenko, 2005; Ivanov, Romashets, and Kharshiladze, 2006; and others), and one of the severest storms in history (probably, among top ten in terms of the  $Dst$  index – see Cliver and Svalgaard, 2004).

A number of studies addressed the 18 November 2003 event and its interplanetary consequences, endeavoring to understand its extreme geoeffective impact, but its causes remain unclear. The major outcome of the studies is the oddness of the event, which strongly deviated from established correlations between solar and near-Earth parameters (Yermolaev *et al.*, 2005; Yurchyshyn, Hu, and Abramenko, 2005; Srivastava, 2005; Chertok *et al.*, 2013). In particular, the magnetic cloud (MC) near the Earth carried an exceptionally strong magnetic field of about 56 nT, while its velocity was modest.

The extreme geomagnetic disturbances on 29–30 October and on 20–21 November (Figure 3e) were produced by solar eruptions from nearly the same complex of active regions (which evolved in the meantime), and therefore one might expect the 18–20 November event to inherit the properties of the Halloween events. However, it looks instead like their antipode. For example, the 28 October solar event produced large and fast CME and very strong flare emissions in soft X-rays (exceeded the GOES saturation level of X17.2), hard X-rays, and gamma rays; huge radio bursts in microwaves (RSTN radiometers saturated) and up to submillimeters; strong SEP event (Figure 3a), and a ground-level enhancement of the cosmic ray intensity, GLE 65. The 29 October event was similar to the 28 October event. On the other hand, none of the listed extreme properties correspond to the 18 November event. It was medium in soft X-rays ( $\lesssim M5$ ), hard X-rays, and microwaves. The enhancement of the near-Earth proton flux was inconsiderable (but it could be reduced due to the easterly position of the active region on 18 November). The associated CMEs had a moderate speed, size, and brightness, and did not exhibit any extreme features. The time intervals between the solar eruptions and the geomagnetic storm onset/peak times were 19/38 h on 29 October and much longer on 20 November, 48/61 h.

<sup>1</sup>According to the Final data of the Kyoto  $Dst$  index service, <http://wdc.kugi.kyoto-u.ac.jp/dst.final/index.html>

The peculiarities are also related to the MC, which reached the Earth's magnetosphere on 20 November. The  $B_z$  magnetic component in the MC was pointed south (negative), although the MCs produced by the eruptions from AR 10484 in October had  $B_z > 0$ . The magnetic helicity of the MCs responsible for the Halloween superstorms (from AR 10486) was negative, but it was positive in the MC of 20 November. Moreover, the orientation and handedness of the magnetic field in the 20 November MC mismatched those in its presumable source region AR 10501 (Möstl *et al.*, 2008; Chandra *et al.*, 2010).

Thus, the 18–20 November extremely geoeffective event has offered four major problems: *i*) incomprehensible causes of its extremeness, *ii*) its enigmatic solar source, and perplexing *iii*) orientation and *iv*) handedness of the magnetic field in the MC. Despite several ideas proposed in the listed studies to address these issues, satisfactory explanations were still missing. This enigmatic event offers the challenge in predictions of geomagnetic disturbances, which can occur unexpectedly and be destructive for modern and future high-technology systems.

These circumstances were the major causes, which inspired us to undertake a comprehensive analysis of this event presented in our Paper I (Grechnev *et al.*, 2014a), Paper II (Grechnev *et al.*, 2014b), and Paper III (Uralov *et al.*, 2014). The analysis has revealed an extremely complex, unusual solar eruptive event. None of the observed CMEs was an appropriate candidate for the source of the MC, being only able to produce a glancing blow on the Earth due to their rather large angles with the Sun–Earth line. However, three different reconstructions of the MC (Yurchyshyn, Hu, and Abramenko, 2005; Möstl *et al.*, 2008; Lui, 2011) showed its central encounter with Earth.

On the other hand, indications were found of an additional eruption, which probably occurred rather far from AR 10501, but close to the solar disk center. The presumable erupted magnetic structure was a right-handed pair of linked tori moving away from the Sun, and slowly expanding with a radial (lateral) speed of  $\sim 100 \text{ km s}^{-1}$ , *i.e.*, within a narrow angle of  $\lesssim 14^\circ$  (Papers II and III). It is not completely clear into what structure the couple of tori evolved. Most likely, this structure was disconnected from the Sun and developed into a toroid or spheromak. Due to its weak expansion, the earthward direction, and a presumedly small mass, the probability to detect this eruption in coronagraph images was very low. Just this eluding structure could evolve into the MC, which reached Earth on 20 November.

We will not list all the ideas proposed previously and follow instead only those results and suggestions, which appear to be consistent with these findings and promising to shed light on the issues in question. The major reasons for the superstorm probably were the strongest magnetic field in the MC (close to a record value, while its speed was ordinary) and its orientation ( $\theta = -(49 - 87)^\circ$ , see Möstl *et al.*, 2008). Qiu *et al.* (2007) **demonstrated a quantitative correspondence between the magnetic fluxes in nine MCs and their solar source regions. Furthermore, Chertok *et al.* (2013) analyzed the major Solar Cycle 23 geomagnetic storms ( $\text{Dst} < -100 \text{ nT}$ ), whose sufficiently reliably identified solar source regions were located in the central part of the disk. They found that the intensity of the geomagnetic storms, as well as the ICMEs' Sun–Earth transit times, were mainly governed**

by the parameters of their solar sources, such as the total unsigned magnetic flux at the photospheric level within the post-eruption EUV arcades and dimming regions. For example, these magnetic fluxes in the solar sources of the strongest Solar Cycle 23 geomagnetic storms with  $Dst < -200$  nT, the near-Earth magnetic field  $|\mathbf{B}| > 50$  nT, and large southern  $B_z$  component, such as the 14–15 July 2000, 22–24 November 2001, 28–30 October 2003, and 13–15 May 2005 superstorms (see, *e.g.*, Wu *et al.*, 2005; Cerrato *et al.*, 2012; Manchester, van der Holst, and Lavraud, 2014) were very large,  $(240 - 870) \times 10^{20}$  Mx. The severity of the geomagnetic superstorm on 20 November 2003 appears to correspond to the near-Earth magnetic field of  $|\mathbf{B}|_{\max} \approx 56$  nT with a large southern magnetic component up to  $B_z \approx -45$  nT, while the total unsigned magnetic flux in the eruption region was as low as  $130 \times 10^{20}$  Mx, even including the flare arcade in active region 10501 and all dimmings. The only way to get an extremely strong magnetic field with a modest magnetic flux is a small size of the MC. This conjecture is consistent with the mentioned reconstructions of the MC, all of which showed both its dimensions in the ecliptic plane to be  $< 0.3$  AU ( $< 17^\circ$ ). One more indication is that the Forbush decrease on 20 November was much less than that after the 28 October event. Note also the idea about the compression of the MC due to the interaction of CMEs (Gopalswamy *et al.*, 2005c; Yermolaev *et al.*, 2005).

The mentioned reconstructions were based on the fitting of specific configurations such as a torus or cylinder (Yurchyshyn, Hu, and Abramenko, 2005; Möstl *et al.*, 2008; Lui, 2011; Marubashi *et al.*, 2012) to the observed rotating magnetic components in the MC. The fitted components more or less resembled the observed ones within some limited portions of the ICME, overlapping with each other, but covering somewhat different parts of the ICME in different reconstructions. On the other hand, considerations of the  $\phi_B$  and  $\theta_B$  angles led Kumar, Manoharan, and Uddin (2011) to the idea that the MC occupied a longer part of the ICME along the Sun–Earth line (see also Gopalswamy *et al.*, 2005c and Marubashi *et al.*, 2012). This possibility suggests that its magnetic structure might be different from those considered previously.

To verify these suggestions and shed further light on the enigmatic 18–20 November 2003 event, we address in this paper the corresponding ICME. In Section 2 we revisit *in situ* measurements of the interplanetary disturbance, analyze ground-based data on cosmic rays, and consider heliospheric 3D reconstructions made from the observations of the *Solar Mass Ejection Imager* (SMEI, Eyles *et al.*, 2003; Jackson *et al.*, 2004). Then we discuss the results and their implications in Section 3. In particular, we endeavor to understand the probable causes of the superstorm, to follow the whole presumable chain from the solar eruption on 18 November up to the encounter of the MC with the Earth on 20 November, and to outline possible ways to diagnose such anomalously geoeffective events.

## 2. Properties of the ICME

As mentioned, the 20 November geomagnetic superstorm was a conspicuous exception to almost all established statistical correlations (see, *e.g.*, Yurchyshyn,

Hu, and Abramenko, 2005; Srivastava, 2005; Chertok *et al.*, 2013). Being surprising, this fact also promises an opportunity to find hints at causes of the superstorm from its particularities. By comparing the 28 October event and related interplanetary disturbances with those on 18–20 November, we hope to understand the incomprehensibly large geomagnetic effect of the 18 November eruption.

## 2.1. Interplanetary Data

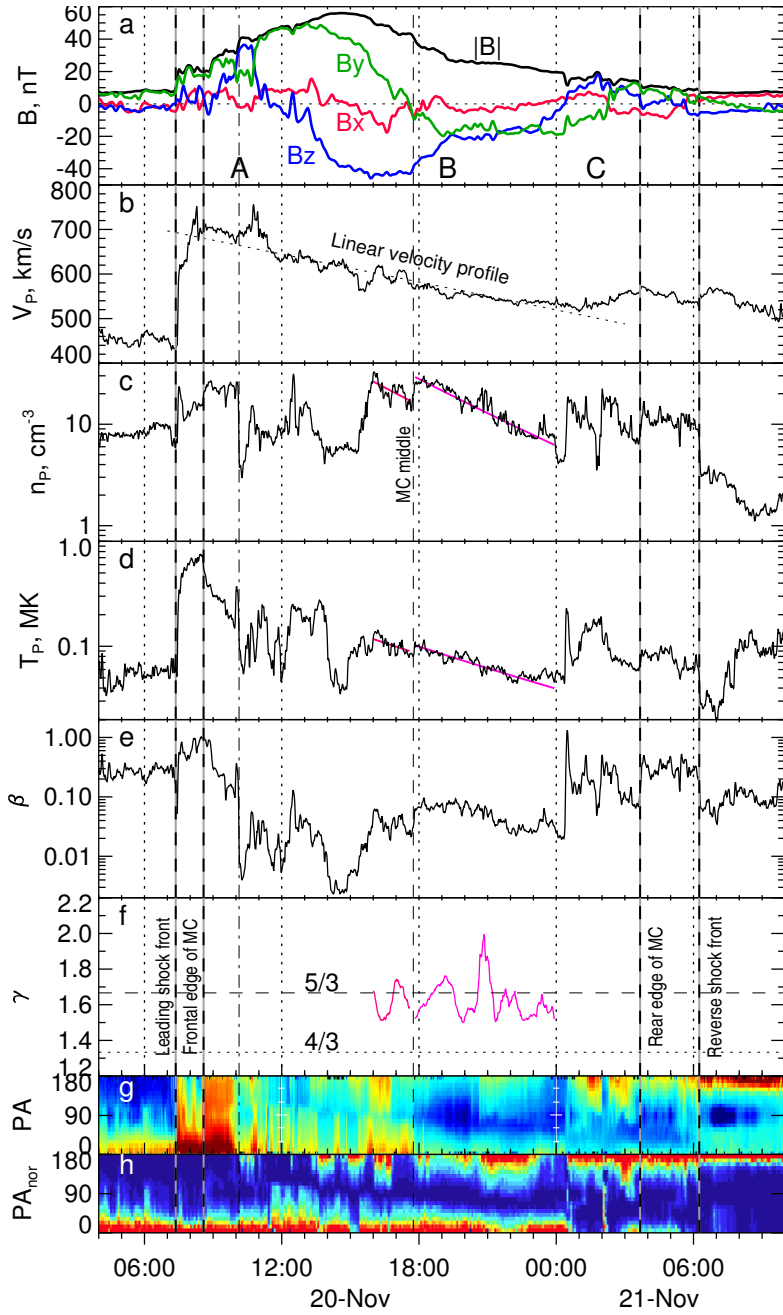
Data on *in situ* measurements of the interplanetary disturbance have been addressed in several studies (*e.g.*, Yurchyshyn, Hu, and Abramenko, 2005; Yermolaev *et al.*, 2005; Gopalswamy *et al.*, 2005c; Möstl *et al.*, 2008; Kumar, Manoharan, and Uddin, 2011; and Marubashi *et al.*, 2012). Nevertheless, some significant particularities were not discussed previously. Here we consider the near-Earth ICME observations made with Solar Wind Electron Proton Alpha Monitor (SWEPAM, McComas *et al.*, 1998) and Magnetometer Instrument (MAG, Smith *et al.*, 1998) on *Advanced Composition Explorer* (ACE). Figure 1 shows records of the magnetic field components  $B_x$ ,  $B_y$ , and  $B_z$  along with a magnitude  $|\mathbf{B}|$  (a), solar wind velocity (b), proton temperature (c) and density (e), and plasma  $\beta$  inferred from the above parameters. The reasons for our identification of the boundaries of the magnetic cloud are as follows.

After arrival of the shock front at about 07:20 on 20 November, the plasma velocity kept on increasing up to the contact surface that is typical of a bow shock. This fact suggests significance of the aerodynamic drag. The thick dashed line at 08:35 and the thin dash-dotted line at 10:08 in Figure 1 mark possible arrival times of the MC frontal edge that is rather uncertain. The earlier thick line roughly corresponds to the position of the highest plasma velocity. Such a situation occurs at the forward stagnation point of a supersonic body with fixed shape and size. The later thin line approximately corresponds to the position where the plasma beta and density underwent a seemingly sharpest drop. This situation is expected for a typical MC. It is difficult to choose between the two options of the MC leading edge for the following reasons. On the one hand, the MC expanded with a velocity of the order of  $100 \text{ km s}^{-1}$  which was appreciably higher than the fast-mode speed in an undisturbed solar wind that prevented a stationary flow around the ICME. On the other hand, the nearly self-similar expansion of a MC that is often employed implies conservation of the profile of the plasma beta formed at the MC creation. As Paper III showed, the MC hitting the Earth was probably formed from magnetic structures with considerably different temperatures, densities, and possibly plasma beta. Therefore, sharp changes of beta without significant variations of  $|\mathbf{B}|$  in Figure 1 might correspond to these different parent structures.

We consider the first thick dashed line as the leading edge of the MC because of *i*) equality of the  $B_z$  flux in a closed magnetic structure (see below), *ii*) a sharp density increase of suprathermal electrons (Figure 1g) discussed later; *iii*) sharp changes of the proton temperature and density. The conditions *i*) and *iii*) were also used in identifying the rear edge of the MC.

One more feature deserving attention is a weak reverse shock in Figure 1 at 06:10 on 21 November. Its presence as well as the presence of the forward shock





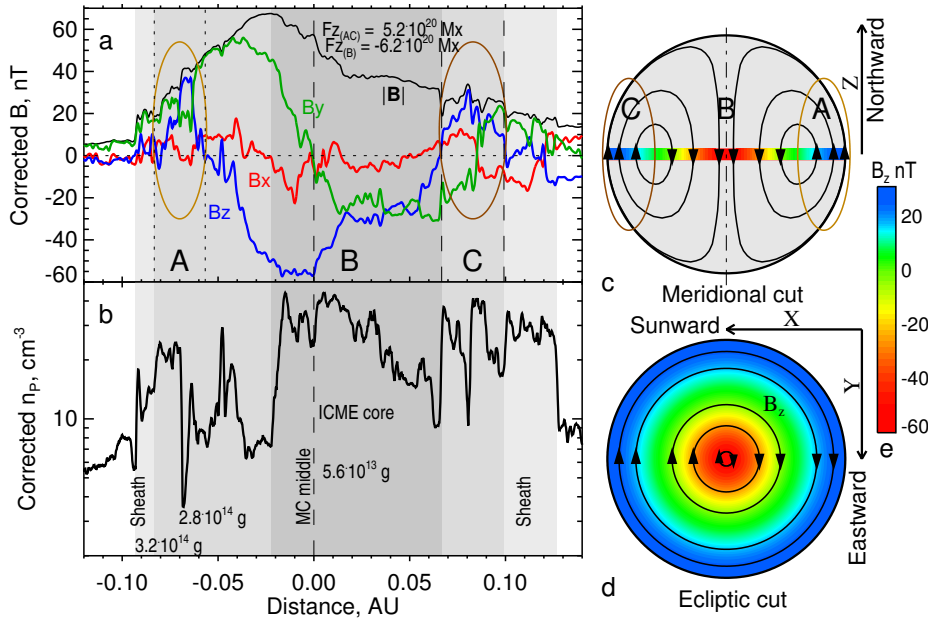
**Figure 1.** ACE data. a)  $B_x$ ,  $B_y$ , and  $B_z$  components of the magnetic field and its magnitude  $|B|$ . Parameters of the ejecta: velocity (b), proton density (c) and temperature (d), and plasma  $\beta$  (e). f) Polytropic index  $\gamma$  inferred from the density and temperature in two intervals marked with the pink and purple lines. g) Pitch angle distribution of 272 eV electrons (minimum blue, maximum red). h) Same as (g) but with a moving normalization (adopted from Marubashi *et al.*, 2012).

1  
2 indicates that expansion of the MC was not free for all directions. A reverse  
3 shock can be due to two reasons. One is overexpansion of a MC if its earthwards  
4 bulk velocity is less than velocity of its own expansion. This is not the case  
5 here. The second possibility for the development of the reverse shock appears if  
6 a MC is pressed from behind by the faster flow of the disturbed solar wind. The  
7 latter situation is favored if a MC is disconnected from the Sun. In this situation  
8 the MC is not protected from lateral disturbances such as shocks and related  
9 high-speed flow which could come from expanding CME1, CME2, and CME3.  
10 If a magnetic flux rope is connected to the Sun, then the extended magnetic  
11 structure protects the top of the MC from such lateral disturbances.  
12

13 The trend of the velocity in the MC (region B in Figure 1a) is close to a linear  
14 one (dotted line), which is an attribute of a self-similar expansion (Low, 1984).  
15 Such expansion occurs if all forces affecting an ejecta (magnetic forces, plasma  
16 pressure, and gravity; so far we neglect the aerodynamic drag, whose effect is  
17 not self-similar) reduce with distance by the same factor (Low, 1982; Uralov,  
18 Grechnev, and Hudson, 2005). This condition is satisfied if the polytropic index  
19  $\gamma = 4/3$ . Its actual value in the MC interior can be estimated from the proton  
20 density and temperature (Figure 1c, d) as  $\gamma = n/T (dT/dt) / (dn/dt) + 1$  as  
21 shown in Figure 1f. This expression is valid if the entropy distribution inside the  
22 MC is uniform. Averaging of values obtained in this way provides an average  
23  $\gamma$  inside the MC. To bypass fluctuations in computations of the derivatives, we  
24 fitted the trends within two intervals with smooth functions (pink and purple).  
25 The actual  $\gamma$  varies around  $5/3$ ; the difference from  $4/3$  does not seem to be  
26 significant, because  $\beta \leq 0.1$  within this interval. [According to Farrugia, Os-  
27 herovich, and Burlaga (1995), the estimated value of  $\gamma$  supports the spheromak  
28 configuration *vs.* a flux rope.] These circumstances allow us to calculate an  
29 expansion-corrected ‘snapshot’ of the ICME assuming its expansion to be exactly  
30 self-similar. We infer the time-dependent expansion factor  $\xi(t)$  from the linear  
31 fit of the velocity profile. The correction factor for the magnetic field strength in  
32 the snapshot related to the  $t_0$  moment is  $[\xi(t_0)/\xi(t)]^2$  (from the magnetic flux  
33 conservation), and the correction factor for the density is  $[\xi(t_0)/\xi(t)]^3$ .  
34

35 Figures 2a and 2b show such ‘snapshots’ for the magnetic field and density  
36 distributions in the ICME along the Sun–Earth line corresponding to the first  
37 contact with ACE spacecraft. The expansion factor evaluated from the linear  
38 velocity profile in Figure 1b was used in the second power for the magnetic field  
39 strength and in the third power for the density. The total length of the ICME in  
40 the Sun–Earth direction was  $\approx 0.22$  AU and, according to the reconstructions of  
41 the MC (Yurchyshyn, Hu, and Abramenko, 2005; Möstl *et al.*, 2008; Lui, 2011),  
42 its axis passed close to ACE spacecraft.  
43

44 The behavior of the  $B_x$  component, which alternately reached significant  
45 positive and negative values within the MC (see also Figure 12 in Lui, 2011),  
46 rules out a glancing blow of a flux rope connected to the Sun; otherwise, the sign  
47 of  $B_x$  would not change in the MC. Variations of the magnetic components in  
48 regions A and C outlined with the brown ovals in Figure 2a look like their regular  
49 continuations from region B rather than pile-up fluctuations in the sheath. To  
50 verify this conjecture, we estimated the total magnetic fluxes of the  $B_z$  compo-  
51 nent in region B, on the one hand, and the corresponding sum in regions A and  
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**Figure 2.** A ‘snapshot’ of the magnetic field (a) and density (b) distributions in the ICME along the Sun–Earth line according to expansion-corrected ACE data. The ICME size corresponds to the first contact with ACE. c, d) A magnetic configuration of a perfect spheromak with its axis shown perpendicular to the ecliptic plane for simplicity. The brown ovals outline the regions presumably belonging to the leading (A) and trailing (C) parts of the MC. e) The color scaling of the  $B_z$  component in a perfect spheromak shown in panels (c) and (d) and roughly corresponding to  $-B_z$  in Figure 15 of Lui (2011).

C, on the other hand, assuming the ICME cross section to be circular. To take account of the ICME asymmetry in the Sun–Earth direction, the two estimates for each ICME half were averaged. The result shown in Figure 2a demonstrates that the difference between the magnetic fluxes in regions B ( $-6.2 \times 10^{20} \text{ Mx}$ ) and A+C ( $5.2 \times 10^{20} \text{ Mx}$ ) does not exceed 20%. These values are close to the estimate of  $5.5 \times 10^{20} \text{ Mx}$  obtained by Möstl *et al.* (2008), despite the coarseness of our approach. Hence, the magnetic field variations in regions A and C were, most likely, not sporadic.

The presence of the opposite magnetic  $B_z$  components and the equality of their fluxes together with the same situation for  $B_y$  (while  $B_x$  was rather small) indicates their balance in the ICME, *i.e.*, a closed magnetic field in the MC. This is only possible if the MC was not connected to the Sun, so that its configuration was either an isolated toroid or a spheromak. In either case, the angle between the MC axis and the ecliptic plane must be large. We adopt the spheromak configuration and later confirm this assumption by different indications considered in Section 2.

A simplest 2.5-dimensional configuration which satisfies the equality of magnetic fluxes is an infinitely long cylinder with a linear force-free magnetic field inside:  $B_z = J_0(\alpha r)$ ,  $B_\varphi = \sqrt{(B_x^2 + B_y^2)} = J_1(\alpha r)$  where  $J_n$  is a cylindrical Bessel function of the first kind of order  $n$ . The boundary of the cylinder is determined

by the first root of the equation  $J_1(\alpha r) = 0$ . The total magnetic flux through a normal cross section of such a magnetic flux rope is zero. A 3-dimensional analog of this situation is a spheromak whose total magnetic flux equals to zero in both equatorial and meridional cross sections. The boundary of a spheromak is determined by the first root of the equation  $j_1(\alpha r) = 0$  where  $j_1$  is a spherical Bessel function of the first kind. A transformation of a long cylindrical flux rope into a thin toroid does not significantly change the inherent situation for an infinitely long flux rope. A force-free flux rope whose small radius is determined by the condition  $J_1(\alpha r) = 0$  cannot have bases frozen in the solar surface. If it were so, then the total magnetic flux in each photospheric base of the flux rope would be zero that obviously disagrees with observations of eruptive coronal flux rope structures. Thus, the MC was more probable a force-free self-closed magnetic structure rather than that closed to the Sun, and the total magnetic flux in its cross section was zero.

It is important to note that usually the boundary of a MC is considered as a surface, at which the axial magnetic field of either a loop-like flux rope or toroid is zero. To the linear force-free approximation in this situation corresponds the equation  $J_0(\alpha r) = 0$  whose first root determines the boundary of a rope. In this case, the total flux of the axial magnetic field in the flux rope's cross section is maximum but not zero. At present this scheme is a basis of the technique to fit the internal magnetic structure of many observed MCs (see, *e.g.*, Marubashi and Lepping, 2007; Romashets and Vandas, 2003). Marubashi *et al.* (2012) also employed this technique to determine geometry of the 20 November 2003 MC. However, this technique does not permit the presence of the opposite magnetic  $B_z$  components with the equality of their fluxes that we emphasize. The fitting technique usually employed is not usable in the 20 November 2003 event exactly for this reason.

A quite different Grad–Shafranov reconstruction technique was used by Yurchyshyn, Hu, and Abramenko (2005), Möstl *et al.* (2008), and Lui (2011). This technique allows one to reconstruct a two-dimensional cross section of an MC and to evaluate the inclination of its axis only if the MC is a nearly straight portion of a magnetic flux rope with the curvature, plasma pressure, and magnetic field slowly varying along the flux rope axis. Regrettably, the reconstruction intervals in these papers did not fully cover all the three intervals A, B, and C shown in Figure 2. Möstl *et al.* (2008) considered a large portion of interval B starting from its left boundary. Yurchyshyn, Hu, and Abramenko (2005) included the same portion and a half of interval A. Lui (2011) considered the whole interval B and almost the whole interval C. Nevertheless, Figure 15 from Lui (2011) shows that the direction of the  $\mathbf{B}_x + \mathbf{B}_y$  vector is practically constant in the motion from the flux rope center to its periphery despite the change of sign of  $B_z$ . The ecliptic cut of the spheromak in Figure 2d shows the same situation. A cut of a force-free magnetic cylinder with a boundary determined by the condition  $J_1(\alpha r) = 0$  is similar. However, one should be aware of the fact that the results of the Grad–Shafranov reconstruction of outer parts of a MC can be distorted if all the MC dimensions are comparable which is the case for a spheromak. Possibly, this circumstance was responsible for the appearance of an X point in the reconstruction of Yurchyshyn, Hu, and Abramenko (2005).

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Figures 2c and 2d show two views of a perfect non-distorted spheromak with its axis perpendicular to the ecliptic for simplicity. The regions outlined with the ovals correspond to regions A (dark brown ovals) and C (bright brown ovals) in Figure 2a. The pass of the spheromak across ACE spacecraft is expected to produce a response, which is close to the observed one. The actual front/tail asymmetry of the magnetic field indicates compression of the leading half of the MC and stretch of the trailing one suggesting a significant role of the aerodynamic drag. Note that the toroidal (Figure 2d) and poloidal (Figure 2c) magnetic fluxes in the spheromak are transposed with respect to a torus (connected to the Sun or disconnected).

For a spheromak configuration it is possible to estimate the total mass of the ICME. We consider a simple three-layer spheroid consisting of *i*) a central core inside *ii*) the ICME surrounded by *iii*) a sheath. The ICME cross section is assumed to be an oval extended along the Sun-Earth line with an eccentricity of 2 according to Möstl *et al.* (2008). The estimates for the leading and trailing half of the MC are averaged. The results are shown in Figure 2b for the three layers separately. The total ICME mass is estimated to be  $\lesssim 10 \times 10^{14}$  g and, since the sheath was acquired by the ejecta on the way to the Earth, the initial mass of the CME was, most likely,  $\lesssim 5 \times 10^{14}$  g. This estimate is consistent with the conclusion of Paper I that the major part,  $(2 - 4) \times 10^{15}$  g, of the initial mass of the eruptive filament of  $(4 - 6) \times 10^{15}$  g remained on the Sun.

Figure 1 shows that the standoff distance between the ICME piston and the shock ahead was  $\approx 0.02$  AU, significantly less than a typical value of 0.1 AU (Russell and Mulligan, 2002). According to the formulas from this paper, the radius of curvature of the ICME nose in this case must be  $\lesssim 0.1$  AU for each of the X and Y ICME dimensions with any Mach number  $M > 1$ . This radius of curvature is consistent with the ICME geometry discussed in the preceding paragraph and the conclusion of Vandas *et al.* (1997) related to a spheromak.

The spheromak configuration of the MC addresses the suggestions of its small size mentioned in Section 1. The length of the MC along the Sun-Earth (the X direction) line was about 0.2 AU (see Figure 2). The Y size was close to the X size, as the reconstructions of the MC presented by Yurchyshyn, Hu, and Abramenko (2005), Möstl *et al.* (2008), and Lui (2011) showed indeed. Considering all the facts, we have to conclude that the whole spheromak-shaped ICME expanded within a narrow cone of  $\leq 14^\circ$ . Therefore, the corresponding CME could appear from behind the occulting disk of LASCO/C2 at distances  $\geq 16R_\odot$ , where the Thomson-scattered light was meager. Such a CME could only be detected with LASCO if its mass were very large, which was not the case. It is therefore not surprising that nobody has succeeded in detecting this CME in LASCO images.

We have concluded that the magnetic configuration of the MC was closed, *i.e.*, the MC must be a trap for charged particles. This suggestion can be verified by considering pitch-angle distributions of suprathermal electrons. Manifestations of bidirectional streams in pitch-angle maps are sometimes considered as a support of the connection of a MC to the Sun, as Möstl *et al.* (2008) did. However, the argument of bidirectional particles does not seem to certify their reflections from bases of a magnetic flux rope anchored on the Sun being only an indication of a magnetic trap. For example, closed isolated torus or spheromak

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2 configurations are perfect magnetic traps, and therefore bidirectional particles  
3 can also be present in such configurations. Thus, we agree with the approach of  
4 Marubashi *et al.* (2012), who revealed the presence of counterstreaming electrons  
5 during more than half a day on 20–21 November and considered them among  
6 indications of a MC structure. The pitch angle distribution of electrons in the 272  
7 eV channel calculated by Marubashi *et al.* (2012) as 5-min averages normalized  
8 to the maximum flux value in each time bin is shown in Figure 1h. To understand  
9 the nature of the bidirectional electron flows, let us consider the records of the  
10  $B_x$  and  $B_y$  components in Figures 1a and 2b (see also Figure 12 of Lui, 2011).

11 Before the arrival of the MC, the signs of these magnetic components were  
12  $B_x < 0, B_y > 0$ , and after the departure of the MC  $B_x > 0, B_y < 0$  suggesting  
13 that the MC passed ACE spacecraft when it crossed a sector boundary of the  
14 heliospheric magnetic field (anti-sunward before the MC and sunward after-  
15 wards; see also Ivanov, Romashets, and Kharshiladze, 2006). This orientation  
16 corresponds to small pitch angles of electrons flowing away from the Sun before  
17 the MC and those close to  $180^\circ$  after the MC pass as Figure 1h confirms.  
18 The bidirectional electron flows might appear due to reconnection of the MC  
19 with environment magnetic fields that is supported by a nearly linear trend  
20 separating the electron pitch-angle distribution. The trend implies a gradual  
21 change of predominant reconnection at one MC edge to the opposite one as the  
22 MC passed through the sector boundary. Thus, the bidirectional electron flows  
23 might be absent in the MC without reconnection and therefore should not be  
24 considered in favor of the connection of the MC to the Sun.

25 An additional indication of the trap-like behavior of the MC can be revealed  
26 from the pitch-angle distribution<sup>2</sup> of the 272 eV electrons with an overall nor-  
27 malization presented in Figure 1g. As we saw, region A of the ICME presumably  
28 belonged to the MC. Indeed, the SWEPAM-E plot shows a sharp increase of  
29 the electron density at the leading MC boundary, which we identified, and no  
30 drastic changes afterwards.

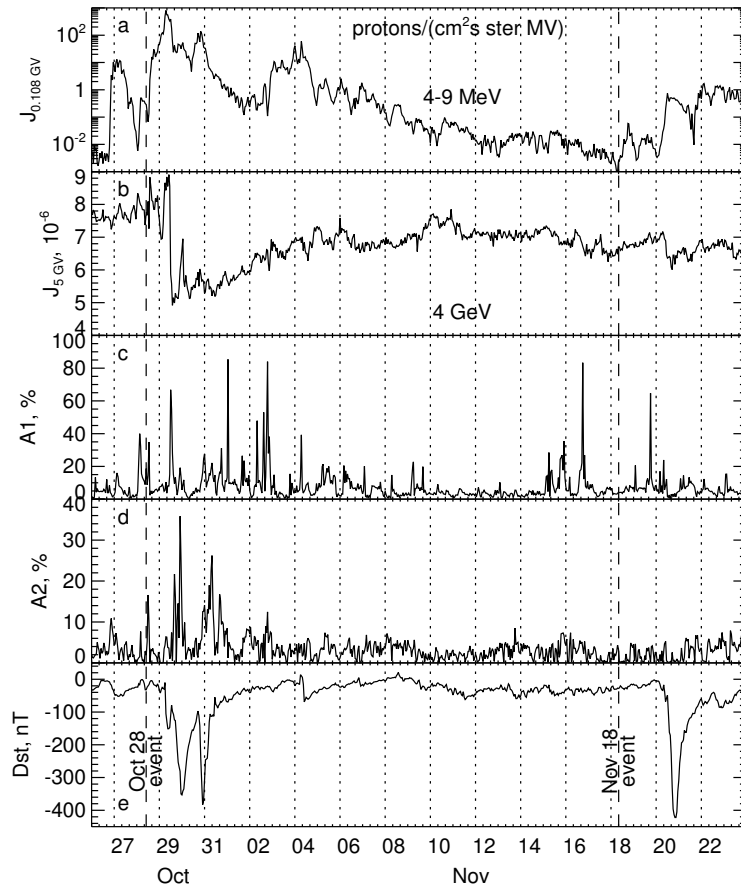
31 **In contrast to the considered indications of the unusual spheromak**  
32 **configuration of the 20 November 2003 MC, the Halloween 2003 MC**  
33 **showed the properties typical of a classical croissant-like flux rope.**  
34 **The latter event and its solar source were addressed by Yurchyshyn,**  
35 **Hu, and Abramenko (2005).**

## 36 2.2. Data on Heavy Relativistic Particles

37 The intensity of geomagnetic storms is known to strongly depend on the param-  
38 eters (the sign and value of the  $B_z$  component, speed) in a relatively local ICME  
39 part interacting directly with the Earth's magnetosphere (see, *e.g.*, Tsurutani  
40 and Gonzalez, 1997), while the depth of a Forbush decrease (FD) is determined  
41 by global characteristics of an ICME, particularly such as its magnetic field  
42 strength, size, and speed (see, *e.g.*, Belov, 2009). Figure 3e shows that the  
43 geomagnetic effect from the 18 November event (in terms of the Dst index) was  
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45 <sup>2</sup><http://www.srl.caltech.edu/ACE/ASC/DATA/level3/swepam/index.html>



**Figure 3.** Solar protons (a), galactic cosmic ray data (b–d, Courtesy V. Sdobnov), and geomagnetic disturbances (e) during the late October through November interval. The spherical harmonics of the galactic cosmic ray pitch-angle anisotropy are shown in panel c (first,  $A1$ ) and d (second,  $A2$ ). The dashed lines mark the 28 October and 18 November solar events.

stronger than that of the 28 October event, but the FD from the 20 November interplanetary disturbance was incomparably moderate with respect to the huge Halloween one (Figure 3b). However, the correctness of the comparison of FDs in the two events does not seem to be obvious. In particular, the 29 October FD was a largest one ever observed with neutron monitors (Belov, 2009) and could acquire its value only due to an extremely rare combination of circumstances.

For comparison with other events we have used a data base on interplanetary disturbances and Forbush decreases created in IZMIRAN (Belov *et al.*, 2001; 2009). The density variations of cosmic rays in the data base refer to cosmic rays of 10 GV rigidity, which is close to the effective one for the majority of ground-based neutron monitors, so that cosmic ray variations around this rigidity can be evaluated with a highest accuracy. The FD magnitude determined in this way was 28.0% for 29 October FD and 4.7% for 20 November. The latter effect is probably underestimated and needs correction for the following reason. An un-

usually large magnetospheric variation of the cosmic ray intensity observed over ground-based detectors on 20 November (Dorman, 2009) resulted in a decrease of the geomagnetic cutoff rigidities at observation stations (Belov *et al.*, 2005) that decreased the FD depth evaluated over the whole World's neutron monitor network. Thus, the real magnitude of the 20 November FD was most likely 6–7% (this has been really confirmed by the most recent estimate of 6.6% by taking account of the magnetospheric effect). This effect is generally large (Belov *et al.*, 2001), but does not seem to correspond to the parameters of the associated ICME. With a strength of the total interplanetary magnetic field  $|\mathbf{B}|$  of up to 55.8 nT (hourly averages), one might expect a considerably larger FD, because such a strong magnetic field was additionally observed only two times over the whole history of the solar wind observations. The two extra events occurred in November 2001, while the corresponding FDs were considerably larger, 9.2% and 12.4%. All but one (31 March 2001) events with strongest magnetic field exceeding 45 nT caused FDs larger than that on 20 November (pronouncedly larger, as a rule).

Besides the magnetic field strength in an ICME, the solar wind speed should be taken into account in these comparisons. Unlike the magnetic field, the solar wind speed on 20 November was ordinary and increased only up to 703 km s<sup>-1</sup> (hourly data). The FD magnitude is known to correlate well with a product of observed maximums of the magnetic field strength  $|\mathbf{B}|_{\max}$  and the solar wind speed  $V_{\max}$  (*e.g.*, Belov, 2009). In the 20 November 2003 event, the  $|\mathbf{B}|_{\max}V_{\max}$  product normalized to 5 nT and 400 km s<sup>-1</sup> is 19.6, while the whole range of the product over the data base is from 0 to 29.6. We have considered all the events with  $|\mathbf{B}|_{\max}V_{\max} > 15$  that were not influenced by preceding events. Almost all the events (except for the mentioned 31 March 2001 event) produced deeper FDs than the 20 November 2003 one, with an average value of  $10.1 \pm 1.8\%$ . This value is probably underestimated, because data on the solar wind were incomplete or absent during several largest FDs. Due to this reason, our sample does not include such FDs as those in August 1972 (25%) and in October 2003 (28%).

Thus, the ICME parameters observed on 20 November 2003 suggested expectations of a larger FD. This fact implies that a smaller size and/or an unusual structure of the CME in question can be a reason for its lowered ability to modulate cosmic rays. It is possible that two kinds of powerful CMEs/ICMEs exist whose probably different structure and other properties determine the difference between their influence on cosmic rays even with equal parameters of the plasma velocity and magnetic field strength.

Both the geomagnetic effect and FD of an ICME are considered to depend on parameters of a MC with the FD depth being independent of  $B_z$ ; thus, the inconsistency between the geomagnetic effect and the FD depth provides further support to the small size of the 20 November MC. Indeed, its extent along the Sun–Earth line was about three-times less than that of the Halloween MC, and reconstructions of the MC (Yurchyshyn, Hu, and Abramenko, 2005; Möstl *et al.*, 2008; Lui, 2011) show its perpendicular size in the ecliptic to be even less than the Sun–Earth extent. Thus, the area of the 20 November MC cross-section was about one order of magnitude smaller than that of the 28 October MC.



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3 An additional indication can be revealed from the pitch-angle anisotropy of  
4 relativistic protons. Their gyroradius is larger than that of suprathermal elec-  
5 trons by a factor of  $\sim 10^5$ , which considerably reduces effects on their pitch-angle  
6 anisotropy due to factors irrelevant to trapping. Therefore, anisotropy of rela-  
7 tivistic protons promises still more reliable indication of a large-scale magnetic  
8 trap connected to the Sun than low-energy electrons do. Anisotropy appears  
9 in ground-level enhancements of cosmic ray intensity (GLE events) and due to  
10 modulation of galactic cosmic rays by magnetic clouds and corotating interacting  
11 regions in the solar wind.

12 The spherical harmonics of the pitch-angle anisotropy computed by Dvornikov,  
13 Kravtsova, and Sdobnov (2013) from the data of the worldwide neutron monitor  
14 network using the method of Dvornikov and Sdobnov (1997, 1998) are shown in  
15 Figures 3c (first harmonic, A1) and 3d (second harmonic, A2). The percentage in  
16 the figure shows the excess of the cosmic ray intensity over the opposite direction  
17 (100% correspond to a two-fold excess). The second harmonic of the pitch-angle  
18 distribution of 4.1 GeV protons indicating their trapping was absent just before  
19 20 November, while the first harmonic was well pronounced, unlike the end of  
20 October, when both harmonics were distinct.

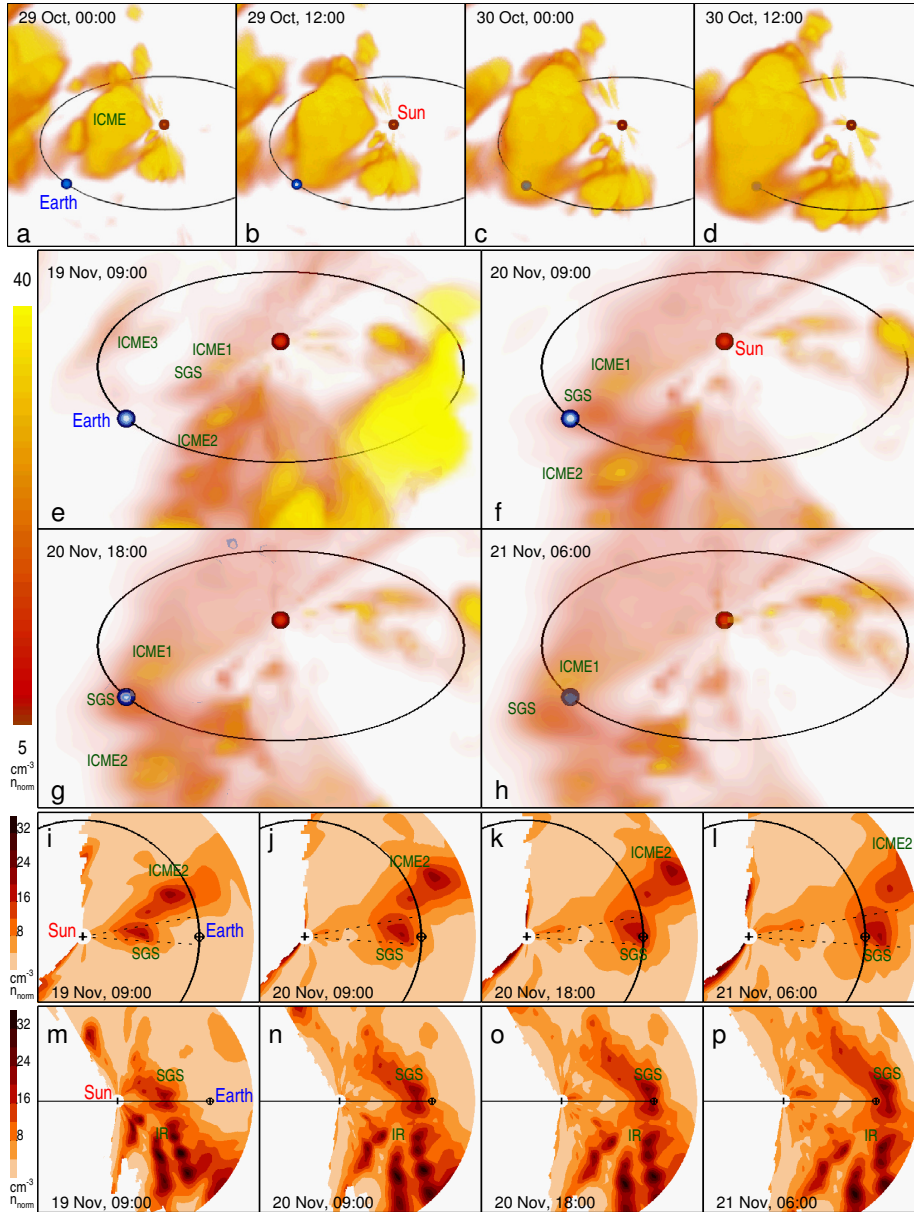
21 Richardson *et al.* (2000) showed that significant increases of the second har-  
22 monic of the cosmic ray anisotropy corresponding to bidirectional particle flows  
23 are typical of MCs of large ICMEs. An example is shown by the ICMEs of 29  
24 and 30 October in Figure 3. In addition to the incompatibly moderate FD with  
25 respect to very large Dst, the absence of any increase in the second harmonic on  
26 20 November clearly indicates that this ICME was atypical.

### 27 2.3. Heliospheric 3D Reconstructions from SMEI observations

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29 While the CME of interest is not detectable in SOHO/LASCO images, now  
30 we consider 3D reconstructions of heliospheric disturbances made from white-  
31 light Thomson scattering observations with SMEI. Three SMEI cameras allow  
32 to achieve a combined  $\approx 160^\circ$  wide field of view at a sufficiently high spa-  
33 tial resolution. The tomographic reconstructions have been made by the Cen-  
34 ter for Astrophysics and Space Sciences in University of California, San Diego  
35 (CASS/UCSD).  
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38 Figure 4 presents 3D reconstructions from SMEI data of the heliospheric  
39 response for two ICMEs ejected on 28 October (upper row) and 18 November  
40 2003, which we want to compare. The images show heliospheric plasma density  
41 distributions as viewed from 3 AU  $30^\circ$  above the ecliptic plane and  $\sim 45^\circ$   
42 west of the Sun–Earth line. The location of the Earth is indicated by a blue circle  
43 with the Earth’s orbit viewed in perspective drawn as an ellipse. The Sun is indicated  
44 by a red dot. An  $r^{-2}$  density gradient is removed.

45 Figure 4a–d adopted from Jackson *et al.* (2006) shows four successive times  
46 of the heliospheric response to the 28 October CME. The images reveal a large  
47 croissant-shaped ICME expanding from the Sun and suggest connection of the  
48 flux rope to the Sun. The overall picture shows a presumable typical scenario:  
49 a large expanding flux rope reached the Earth on 29 October and caused (with  
50 its southern  $B_z$ ) a severe geomagnetic storm.  
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**Figure 4.** SMEI 3D reconstructions made by the CASS/UCSD team. a–d) Large croissant-shaped ICME observed on 29–30 October suggesting a flux rope connected to the Sun (from Jackson *et al.*, 2006). e–h) Ejecta observed on 19–21 November: ICME1, ICME2, ICME3, and a probable compact source of the geomagnetic storm (SGS). i–l) ecliptic and m–p) meridional cuts corresponding to the remote views (e)–(h). ‘IR’ is a probable intrusion region of CME2 into CME1. The scale bars on the left quantify the densities in the corresponding rows.

The SMEI 3D reconstructions for the 18–20 November event in Figure 4e–h present a very different picture, which is more complex (see also the movie `SMEI-19-20.11.2003.mpg` accompanying the electronic version of the paper). To make it clearer, Figure 4i–l also shows the corresponding ecliptic cuts, and Figure 4m–p shows the meridional cuts. Comparison of the heliospheric disturbances within a sector of  $\sim 120^\circ$  embracing the Earth, on the one hand, with the CMEs observed by LASCO on 18 November by taking account of their directions and speeds (see Paper II), on the other hand, allows one to presumably identify visible ICMEs with the southeast CME1 and southwest CME2 addressed in Paper II. They are labeled ICME1 and ICME2. An extended density enhancement labeled ICME3 in Figure 4e appears to correspond to the fastest far-east CME3.

A far-west Y-like feature resembles in shape the darkening observed with CORONAS-F/SPIRIT at  $304 \text{ \AA}$  (see Paper I). However, the speed of the  $304 \text{ \AA}$  darkening was only  $\lesssim 100 \text{ km s}^{-1}$  that rules out their association.

A large inhomogeneous density enhancement IR south of the ecliptic visible in meridional cuts (Figure 4m–p) as a multitude of small blobs appears to correspond to the region where CME2 intruded into CME1 (see Paper II). The intrusion region appears to have missed the Earth being south of it.

A feature of our major interest is a rather compact blob exactly impacting the Earth. This is a moderate density enhancement presumably associated with a source of the geomagnetic storm (SGS). The pass of the blob across the Earth temporally corresponds to the ACE measurements (Figure 1c). The maximum density in the lower-resolution SMEI two-dimensional cuts passed through the Earth at about 00 UT on 21 November (*i.e.*, between Figures 4k and 4l) that reasonably corresponds to the weighted center of the expansion-corrected higher-resolution ACE record in Figure 2b (before the density minimum at the end of the ICME core, *cf.* Figure 1c). The SGS dimensions correspond to expectations: the dotted lines in Figure 4i–l delimit a sector of  $14^\circ$ , where the bulk of the ICME mass was concentrated. The images do not leave any doubt that just this blob was associated with the MC responsible for the geomagnetic disturbance.

The density in the blob was moderate, peaking at  $22 \text{ cm}^{-3}$  according to the SMEI tomography that it close to the ACE measurements. The blob was surrounded by a larger enhanced-density cloud suggesting a possible influence from the southwestern ICME2 and southeastern ICME1 as well as the southern intrusion region. As all the three representations of the SMEI reconstructions show, the shape of the blob does not suggest either a larger isolated torus nearly perpendicular to the ecliptic plane or a croissant connected to the Sun. The spheromak configuration appears to be most appropriate. Thus, the SMEI data put the last missing point in hunting out the mysterious source of the 20 November superstorm.

### 3. Discussion

All the observational facts and indications considered in Section 2 lead to a conclusion that the 20 November MC was a spheromak of a small size disconnected from the Sun. These particularities of the 20 November ICME must be reflected

in its propagation between the Sun and Earth. Let us compare the corresponding properties of the 18 November and 28 October ICMEs.

### 3.1. Propagation of the 18 November and 28 October ICMEs

The average velocity of the 18–20 November ICME between the Sun and Earth was about  $865 \text{ km s}^{-1}$ , while its velocity at the first contact of the ICME body with ACE was  $v_1 \approx 700 \text{ km s}^{-1}$ . This suggests its considerable deceleration. Assuming that the disconnected 18–20 November ICME moved almost in the free-fall regime, it is possible to estimate its initial velocity  $v_0$  from energy conservation,  $v_0 = \sqrt{v_1^2 + 2GM_\odot [1/R_\odot - 1/(1 \text{ AU})]} \approx 930 \text{ km s}^{-1}$  (the initial velocity could be still higher, if the aerodynamic drag was efficient). Conspicuous deceleration of the 20 November ICME supports its disconnection from the Sun.

The situation was different for the ICME which erupted on 28 October at about 11 UT and whose body reached ACE on 29 October at about 08 UT according to the ACE/SWICS and ACE/MAG data (ACE/SWEPAM did not operate because of a large particle event). The average transit velocity of the ICME was  $\approx 1980 \text{ km s}^{-1}$ , while the frontal speed of the ICME body slightly exceeded  $1900 \text{ km s}^{-1}$  (ACE/SWICS,  $\text{He}^{++}$  bulk speed). Thus, deceleration of the 28–29 October ICME was inconspicuous as if it also moved in the free-fall regime (in this case,  $v_0 \approx 2000 \text{ km s}^{-1}$ ) despite its huge size and a much higher speed relative to the 18–20 November ICME. With such a high speed the gravitational deceleration is as small as 5% of the speed so that it is not possible to reveal it reliably. However, significant deceleration of the 28–29 October ICME due to strong aerodynamic drag could be expected. This seemingly inconsistency can be accounted for by a toroidal propelling force of the 28–30 October flux rope connected to the Sun. The toroidal propelling force dramatically decreased in expansion of the ICME, but its influence probably was able to ensure the observed velocity of the ICME, while the actual  $v_0$  was probably higher.

Some properties of the 20 November MC were atypical of magnetic clouds. The inhomogeneous temperature distribution in the MC (Figure 1d) provides a hint that the MC was possibly formed from different-temperature structures, as we have concluded in Paper III.

The inclination of the 20 November MC axis to the ecliptic estimated by different authors ranged within  $\theta = -(49-87)^\circ$  [see Möstl *et al.* (2008)], which is reasonably close to the orientation of the dipole at the eruption site,  $\alpha = -80^\circ$ , evaluated in Paper III. Thus, the orientations of the dipole on the Sun, from which the spheromak was formed, and the MC near the Earth were close to each other, and no significant rotation of the ejecta was required (which was among the problems discussed by Möstl *et al.*, 2008).

The magnetic flux conservation along with the almost exactly southwards orientation of the magnetic axis determined the extreme geomagnetic effect of the atypically slowly expanding MC in the ICME. The causes of the unusually slow expansion of the ICME deserve further study. We assume they might be due to the following reasons.

- The major condition for the slow own expansion of the ICME was its disconnection from the Sun. Otherwise, at least, two of ICME dimensions must be  $\geq 1 \text{ AU}$  near the Earth.

- The maximum magnetic field strength in a spheromak is  $\approx 20\%$  higher than in a cylinder or thin torus under the same outer pressure at their boundaries.
- The own ICME expansion could be restrained by the enhanced-density environment, almost fourfold with respect to nominal conditions. This dense environment could be due to combined effects of the tail of the preceding CMEs, the lateral pressures from the ICME2 and ICME1 (including the intrusion region) and, possibly, from the flank of the shock ahead of ICME3.
- The orientation of the magnetic axis of the spheromak nearly perpendicular to the direction of its motion determined the drag pressure at its surface to preserve the spheromak configuration and to prevent its transformation into a toroid expected for a freely expanding spheromak (Vandas *et al.*, 1997).

The combined effect of the last two factors disfavored a free expansion of the ICME.

### 3.2. Why the 18–20 November 2003 Event Escaped Understanding?

The analysis presented in our Papers I–IV appears to reconcile all the challenges of the 18–20 November 2003 event. Moreover, now it seems to be strange that some important aspects of the event were not revealed previously. For example, there were several indications of the small size of the MC: incomparable Dst value and the depth of the Forbush decrease; the extremely strong magnetic field *vs.* suggestions of an ordinary magnetic flux (*cf.* Qiu *et al.*, 2007); the small reconstructed cross section of the MC (Yurchyshyn, Hu, and Abramenko, 2005; Möstl *et al.*, 2008; Lui, 2011). Note that the reduced MC size also corresponds to the initial idea of Yermolaev *et al.* (2005) and Gopalswamy *et al.* (2005c) about compression of the MC from other CMEs.

The spheromak configuration could be understood if the magnetic field distribution were considered entirely, without ignoring the positive  $B_z$  portions in the leading and trailing portions of the ICME. The orientation of the spheromak nearly perpendicular to the ecliptic significantly favored its identification from the magnetic field records, while the spheromak configurations of MCs have been extensively considered for a long time (*e.g.*, Ivanov and Kharshiladze, 1985; Farrugia, Osherovich, and Burlaga, 1995; Vandas *et al.*, 1997; Shiota *et al.*, 2010; Zhou *et al.*, 2012; and many others). One of lessons of the 20 November MC is that an idealized consideration of an MC as a smooth ‘magnetic reservoir’ of low-proton-temperature plasma is not always justified.

Comparison of the 3D reconstructions from SMEI white-light observations in Figure 4f, g with those made from Ooty observations of interplanetary scintillations (IPS) presented by Kumar, Manoharan, and Uddin (2011) in their Figure 16 leaves an impression that important ICMEs could be also recognized in those images, although they look not as clear as the SMEI reconstructions. The IPS Ooty images also show suggestions of a compact blob hitting the Earth, a tail of the southwestern ICME2 and, possibly, the southeastern ICME1 as well as the intrusion region IR in the velocity images. The conclusion of the authors were possibly different from the idea about the two merged CMEs, if the authors paid

more attention to the indications of a small size of the MC (3D reconstructions for a longer time interval would be probably also useful).

Möstl *et al.* (2008) suspected the mismatch between the handedness of the MC and the presumed solar source region AR 10501. Chandra *et al.* (2010) have convincingly confirmed this conjecture. This mismatch, along with the conclusion of Grechnev *et al.* (2005) that the eruptive filament had not left the Sun, seems to be sufficient to warn against a simple scenario, in which the MC is considered as a stretched magnetic rope initially associated with the pre-eruption filament in AR 10501. However, this circumstance was not noticed. Instead, Chandra *et al.* (2010) proposed a right-handed eruption from a small part of AR 10501, although the CME onset times estimated by Gopalswamy *et al.* (2005c) did not support this conjecture. The cautious suggestion of Chandra *et al.* (2010), ‘*Should this injection [of the positive helicity flux] occur over six days at the same rate an accumulated helicity of the order of  $10^{26}$  Wb<sup>2</sup> will be injected, enough to explain the helicity carried by the positive MC*’, was exaggerated up to an established fact. It was not noticed that one of the severest storms in history was attributed to a partial eruption from a minor region.

This is also related to the study by Marubashi *et al.* (2012), who presented an undoubtedly valuable method aimed at a general understanding how the encounter of an MC with the Earth occurs. Their consideration of the whole sequence of events starting from the solar eruption on 18 November was based, in particular, on the assumptions of *i*) the correspondence between the MC and the eruption region in AR 10501 in handedness and orientation of the magnetic field, *ii*) the constancy of the direction of the axial magnetic field in the MC, and *iii*) the association of the MC with CME2 or, less probable, CME1. None of these assumptions was confirmed. Moreover, because the authors ignored the positive- $B_z$  regions in the MC (like all other researchers), their consideration of its magnetic configuration could not be perfect.

The solar eruptive event on 18 November was extremely complex and unusual, so that it was very difficult to reveal its features, which were important for understanding the actual solar source of the geomagnetic superstorm. (Even being aware of the spheromak configuration of the MC, it was difficult to understand how such an exotic object could form on the Sun.) One more lesson of the 18 November solar event is that simplified considerations of observations can be unsuccessful. The analysis, which allowed us to approach a plausible consistent picture of the event and to reconcile its various aspects, has required the four papers to present the results. These results agree with a number of those obtained in preceding studies; otherwise, incorrectness of previous conclusions has been revealed. These circumstances emphasize the importance of the attention to various observational facts and even indirect indications, especially if an event or phenomenon in question is challenging.

### 3.3. Expansion Factor

**The fact that the geomagnetic superstorm on 20 November 2003 was produced by the ICME with a total magnetic field up to  $|\mathbf{B}|_{\max} \approx 56$  nT and a southern  $B_z$  up to  $-45$  nT does not contradict well-known**

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patterns (*e.g.*, Burton, McPherron, and Russell, 1975; Wu and Lepping, 2005). Other Solar Cycle 23 geomagnetic superstorms mentioned in Section 1 were also caused by the ICMEs with magnetic field strengths of  $|\mathbf{B}|_{\max} > 50$  nT. The 20 November 2003 ICME had even a considerably lower speed ( $\approx 700$  km s<sup>-1</sup>) than the other ICMEs responsible for the superstorms (up to 1900 km s<sup>-1</sup>). Therefore, the key to the extremeness of the 18–20 November event was primarily related to the retention of the strongest magnetic field up to the Earth orbit.

Thus, one more important outcome of our analysis is a significant role of the expansion factor for a geomagnetic effect, along with the strength and orientation of the magnetic field in a MC as well as its speed (as follows from the results of Chertok *et al.*, 2013, the magnetic field and speed of a MC are largely determined by the magnetic flux in the eruption region; see also Qiu *et al.*, 2007). The magnetic flux conservation leads to an estimate of the total magnetic field in a MC of  $|B_{\text{MC}}| \sim B_0/(L_{\text{MC}}/L_0)^2$  where  $L$  is a size and the ‘0’ indices are related to a solar source region. While the sign and value of the  $B_z$  component can reduce the geomagnetic effect relative to an utmost possible situation of  $B_z \approx -|B|$ , an atypically small expansion factor can considerably strengthen the geomagnetic impact. The expansion factor can be reduced due to either larger  $L_0$  (typical of quiescent filaments) or smaller  $L_{\text{MC}}$ , which most likely was the case on 20 November 2003. The whole range of variations of the squared expansion factors  $(L_{\text{MC}}/L_0)^2$  can probably exceed one order of magnitudes.

We considered a large intensity of the geomagnetic storm along with a moderate Forbush decrease as an indication of a small size of the MC that turned out to be justified in the 20 November 2003 event. A similar anomaly was also the case in the major geomagnetic storms of 31 March 2001 (Dst = -387 nT, FD of 4.1%) and of 8 November 2004 (Dst = -374 nT, FD of 5.2%). The latter storm was followed by another one on 10 November 2004 (Dst = -263 nT, FD of 8.3%), for which the Dst *vs.* FD anomaly was not as challenging. It is possible to check the conjecture about the small size of the ICME for the November 2004 events by looking at SMEI reconstructions (SMEI observed during 2003–2011) available at <http://smei.ucsd.edu/smeidata.html> and <http://smei.ucsd.edu/test/index.php?type=smei3drecons>. Indeed, on 8–10 November 2004 they show two earthward ICMEs of a moderate size following each other and do not suggest their connection to the Sun.

The implication of the expansion factor in the geomagnetic importance of a solar eruption can probably be responsible for an additional significant scatter in loose correlations between parameters of solar eruptions and space weather disturbances (see, *e.g.*, Cliver and Svalgaard, 2004; Yurchyshyn, Hu, and Abramenko, 2005; Chertok *et al.*, 2013). The expansion factor, which can be especially reduced for disconnected MCs, might be probably implicated in such abnormal events as the 13–14 March 1989 superstorm (Dst = -589 nT) and that one after the Carrington event on 1 September 1859 (Carrington, 1859; Tsurutani *et al.*, 2003; estimated Dst on the order of -850 nT according to Siscoe, Crooker, and Clauer, 2006). Previous studies of such events (*e.g.*, Tsurutani *et al.*, 2003; Cliver and Svalgaard, 2004) did not consider such a possibility, while it seems to be qualitatively clear what could occur if an event similar to the 18 November 2003

one involved an eruption in much stronger magnetic fields like the 28 October 2003 event. Such a possibility should also be considered.

### 3.4. Overall Scenario of the Event

Although the whole event was extremely complicated, a key to its overall scenario seems to be comprehended now. The eruption of the left-handed main filament from AR 10501 was followed by a collision with a topological discontinuity in a coronal null point (whose projection was close to the solar disk center) on its way that resulted in *i*) disintegration of the filament, which transformed into an inverse-Y-like cloud flying along the solar surface and probably eventually landed on the Sun, *ii*) a forced eruption of CME2, and *iii*) reconnection of the filament's portion with a static closed coronal structure that led to formation of a right-handed isolated couple of grappled tori slowly expanding in its motion away from the Sun exactly earthward. The couple of tori then evolved into a spheromak, whose expansion was probably restrained by an enhanced-density environment due to combined effects of neighbor CMEs. The earthward direction of this ejecta along with its weak expansion and a small mass prevented its detection with LASCO. Due to the unusually slow expansion, the disconnected spheromak preserved very strong magnetic field. In addition, this strong field was pointed almost exactly south. As a result, its interaction with the Earth's magnetosphere caused the surprisingly strong geomagnetic storm on 20 November.

The source region of a compact ICME hitting the Earth obviously must be close to the solar disk center. This was really the case. The toroidal magnetic component of the MC was formed from the axial magnetic field of the eruptive filament. The toroidal magnetic flux of a perfect spheromak is about 3.5 larger than its poloidal flux. The poloidal flux of the spheromak was  $\approx 5.5 \times 10^{20}$  Mx according to Möstl *et al.* (2008), and their estimate of the complementary magnetic flux of  $(11 - 44) \times 10^{20}$  Mx is surprisingly consistent with the expectation for a spheromak, although it was obtained for a flux rope geometry. The large negative  $B_z$  in the MC was due to its poloidal magnetic field formed from the formerly static coronal structure, while the inherited magnetic field of the filament was mainly responsible for the  $B_y$  component, which most likely was not crucial for the extreme geomagnetic effect (although  $B_y$  is implicated in the Akasofu's  $\epsilon$  parameter).

### 3.5. Is It Possible to Forecast Such Superstorms?

The outlined scenario along with complications of the solar event considered in Papers I–III leave a pessimistic impression of an erratic combination of accidental circumstances that is impossible to predict. However, there are some promising circumstances.

- As the magnetic field extrapolation in Paper III shows, the pre-eruption filament was pointed exactly to the coronal null point. Thus, the topological catastrophe was inevitable and therefore predictable in principle.



- An outer manifestation of the topological catastrophe was an anomalous eruption. Such eruptions are manifest in the HeII 304 Å line (Paper I; Grechnev *et al.*, 2011b) and can be indicators of potentially dangerous processes on the Sun.
- The dangerous compact earthward CME was not detected by LASCO but could be detected from a vantage point far from the Sun-Earth line. Such a compact CME/ICME can be probably registered with STEREO imagers.
- The 3D reconstructions from SMEI data were very helpful in recognizing the compact earthwards ICME. The SMEI observations have been terminated in 2011, while the state-of-art would not allow such reconstructions to be made in the near-the-real-time regime. The fruitful employment of the SMEI data confirms that the method of tomographic reconstructions of heliospheric disturbances from white-light observations with a wide field of view deserves further elaboration and implementation in future missions.

The major challenge of the 18–20 November event was its incomprehensibly large geomagnetic effect. Once a key to the enigma has been found, investigations into its features could hopefully make clearer its different manifestations.

### 3.6. Concluding Remarks

**Several researchers contributed to the study of the 18 November 2003 event and the 20 November magnetic cloud. These efforts certainly have advanced, step by step, our understanding of solar phenomena and their space weather outcome.**

Various observations reveal that the magnetic cloud responsible for the 20 November 2003 superstorm was, most likely, a compact spheromak disconnected from the Sun. We do not think that our analysis puts a final point in the study of the 18–20 November 2003 event. The analysis has revealed several particularities of different aspects of the event that were not noticed previously. Our main purposes were to understand the overall scenario of the event and to answer the major question, why this seemingly ordinary eruptive event gave rise to the MC with a very large southern magnetic component near Earth,  $B_z \approx -45$  nT, and eventually caused the strongest geomagnetic storm. In this way our analysis has revealed, for example, an anomalous eruption with a catastrophe of the filament in a coronal null point; the transformation of the handedness of a pre-eruption structure; the necessity to take account of the expansion factor of an ICME that can be significantly different; possible considerable differences of a real magnetic cloud from an idealized concept, and others. These issues appear to deserve further investigation, and we hope that our results would highlight some ways for future studies to address them.

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