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Time scale of the largest imaginable magnetic storm

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Abstract. The depression of the horizontal magnetic field at Earth's equator for the largest imaginable magnetic storm has been estimated (Vasyliūnas, 2011a) as $-\mathrm{Dst} \sim 2500$ nT, from the assumption that the total pressure in the magnetosphere (plasma plus magnetic field perturbation) is limited, in order of magnitude, by the minimum pressure of Earth's dipole field at the location of each flux tube. The obvious related question is how long it would take the solar wind to supply the energy content of this largest storm. The maximum rate of energy input from the solar wind to the magnetosphere can be evaluated on the basis either of magnetotail stress balance or of polar cap potential saturation, giving an estimate of the time required to build up the largest storm, which (for solar-wind and magnetospheric parameter values typical of observed superstorms) is roughly between ~ 2 and ~ 6 h.

1 Introduction

The current interest in extreme space weather events such as the occasional geomagnetic "superstorms" (e.g. Tsurutani et al., 1992, 2008; Dal Lago et al., 2006; Echer et al., 2008; Gonzalez et al., 2011) and in particular the historic "Carrington" storm of September 1859 (Tsurutani et al., 2003) has led to the concept of the largest imaginable magnetic storm: "the largest depression of the geomagnetic field that could possibly occur" as the result of interaction with the solar wind, in the formulation by Vasyliūnas (2011a), who estimated the maximum depression as $-\mathrm{Dst} \sim 2500$ nT by postulating some (unspecified) super-effective plasma transport process that can enhance the total pressure up to maximum value everywhere in the magnetosphere. The purpose of this paper is to seek an answer to the question mentioned but left open by Vasyliūnas (2011a): how much time would be needed to build up the largest imaginable storm by supplying energy from the solar wind?

2 Energy content in the magnetosphere

The upper limit on $-\mathrm{Dst}$ was derived by assuming the energy content U_K of the magnetosphere to be limited ultimately by compression against the Earth's magnetic dipole field and applying the Dessler–Parker–Sckopke theorem, to obtain

$$\mu \cdot \mathbf{b}(0) \simeq 2U_K < \frac{2}{27}\,\frac{\mu^2}{{R_\mathrm{E}}^3} \tag{1}$$

($\mu =$ dipole moment, $R_\mathrm{E} =$ Earth radius). The calculated maximum $2U_K$ is simply a fraction ($\sim 2/27$) of the energy in the geomagnetic field above the Earth's surface, and $-\mathrm{Dst}$ is the corresponding fraction of the equatorial surface geomagnetic field B_E (the origin of the factor 2/27 is explained in Vasyliūnas, 2011a). To first approximation, these values are independent of solar-wind parameters; the lowest-order corrections to Eq. (1) are $\mathrm{O}(R_\mathrm{E}/R_\mathrm{CF})^3$, where R_CF is the Chapman–Ferraro distance defined by

$${R_\mathrm{CF}}^3 \equiv \frac{2\mu}{\sqrt{8\pi\rho V^2}} \simeq (7.3\,R_\mathrm{E})^3 \left(\frac{10\ \mathrm{nPa}}{\rho V^2}\right)^{1/2} \tag{2}$$

with $\rho =$ solar-wind mass density and $V =$ bulk velocity (Gaussian units are used throughout this paper). The question investigated in this paper can now be stated quantitatively: what is the time τ required to supply the energy content

$$U_K \sim \frac{1}{27}\,\frac{\mu^2}{R\,{R_\mathrm{E}}^3} = 9.2 \times 10^{16}\ \mathrm{J} \tag{3}$$

to the magnetosphere from the solar wind?

3 Energy input rate from the solar wind

The time scale τ can be estimated as

$$\tau \simeq \frac{U_K}{\mathcal{P}} \tag{4}$$

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where U_K is the energy content given by Eq. (1) and $\mathcal{P}$ is the energy input rate from solar wind into magnetosphere. Unlike U_K, which to first approximation depends on terrestrial parameters only, $\mathcal{P}$ depends sensitively on solar-wind, magnetospheric, and terrestrial parameters. A scaling law for $\mathcal{P}$ can be derived by dimensional analysis (Vasyliūnas et al., 1982; Vasyliūnas, 2009):

$$\mathcal{P} = \frac{1}{2}\rho V^3 \pi\, R_{\mathrm{CF}}^2\ \Psi \tag{5}$$

$$\simeq 3.4\times 10^{13}\,\mathrm{W}\left[\frac{V}{10^3\,\mathrm{km\,s^{-1}}}\right]\left[\frac{\rho V^2}{10\,\mathrm{nPa}}\right]^{2/3}\Psi$$

where

$$\Psi = \Psi\left(\frac{B}{\sqrt{4\pi\rho V^2}}, \frac{4\pi\,\Sigma_{\mathrm{P}} V}{c^2}, \theta\right) \tag{6}$$

is a dimensionless function of dimensionless arguments ($B =$ magnitude and $\theta =$ direction of interplanetary magnetic field, $\Sigma_{\mathrm{P}} =$ Pedersen conductance of ionosphere). Ψ represents the magnetospheric energy input normalized to the flow of solar-wind kinetic energy through a cross-sectional area of radius R_{CF}; equivalently, $\pi\, R_{\mathrm{CF}}^2\,\Psi$ is the effective cross-section of the magnetosphere for extracting energy from solar-wind flow.

For evaluating the time scale of the largest imaginable storm, the maximum value that Ψ may assume and its dependence on the dimensionless parameters of Eq. (6) needs to be estimated. The fact that intense storms occur when the interplanetary magnetic field is directed predominantly southward for prolonged periods (Gonzalez et al., 1994) defines the condition on θ required for maximum Ψ. The dependence on the other parameters and the numerical value of $\Psi_{\max}$ can be roughly estimated, by a combination of theoretical and empirical arguments, in several ways. Magnetotail stress balance (Appendix A) gives

$$\Psi_{\max} \sim \frac{1}{4}\,, \tag{7}$$

a constant, independent of other parameters. Polar cap potential saturation (Appendix B) gives

$$\Psi_{\max} \sim \frac{1}{7}\left[\frac{10^3\,\mathrm{km\,s^{-1}}}{V}\right] \tag{8}$$

from the observed saturation level, or

$$\Psi_{\max} \sim \left(\frac{1}{6}\ \ \text{to}\ \ \frac{1}{10}\right)\left[\frac{10^3\,\mathrm{km\,s^{-1}}}{V}\right]\left[\frac{10\,\mathrm{mho}}{\Sigma_{\mathrm{P}}}\right] \tag{9}$$

from theoretical models. Since these are estimates of the maximum values, expected under extreme conditions, it is not surprising that they are somewhat larger than the values (usually ~0.05 to 0.1) found in empirical determinations (e.g. Gonzalez et al., 1989; Gonzalez, 1990; Weiss et al., 1992; Koskinen and Tanskanen, 2002, and many others).

4 Estimate of time scale

Combining Eqs. (1), (4), and (5) gives the time scale required to build up the largest imaginable magnetic storm as

$$\tau \simeq \frac{1}{27}\,\frac{\mu^2}{R_{\mathrm{E}}^3}\left[\frac{1}{2}\rho V^3 \pi\, R_{\mathrm{CF}}^2\,\Psi_{\max}\right]^{-1} \tag{10}$$

or, noting that $\mu^2 \equiv (B_{\mathrm{E}}\, R_{\mathrm{E}}^3)^2 = 2\pi\, R_{\mathrm{CF}}^6\,\rho V^2$,

$$\tau \simeq \frac{4}{27}\,\frac{1}{\Psi_{\max}}\left(\frac{R_{\mathrm{E}}}{V}\right)\left(\frac{R_{\mathrm{CF}}}{R_{\mathrm{E}}}\right)^4 \tag{11}$$

$$\simeq \frac{0.373}{\Psi_{\max}}\left(\frac{R_{\mathrm{E}}}{V}\right)\left(\frac{B_{\mathrm{E}}^2}{8\pi\rho V^2}\right)^{2/3}. \tag{12}$$

With numerical values for $\Psi_{\max}$ from Sect. 3, the estimated time scale becomes the following: from Eq. (7) (magnetotail stress balance)

$$\tau \simeq \left[\frac{10^3\,\mathrm{km\,s^{-1}}}{V}\right]\left[\frac{10\,\mathrm{nPa}}{\rho V^2}\right]^{2/3}\ 140\ \mathrm{min}, \tag{13}$$

Eq. (8) (polar cap potential saturation, empirical)

$$\tau \simeq \left[\frac{10\,\mathrm{nPa}}{\rho V^2}\right]^{2/3}\ 240\ \mathrm{min}, \tag{14}$$

and Eq. (9) (polar cap potential saturation, theoretical)

$$\tau \simeq \left[\frac{10\,\mathrm{nPa}}{\rho V^2}\right]^{2/3}\left[\frac{\Sigma_{\mathrm{P}}}{10\,\mathrm{mho}}\right]\ 210\text{–}350\ \mathrm{min}. \tag{15}$$

For solar-wind parameters typical of observed very large storms, the time scale is about 2 to 6 h (shorter if the solar-wind dynamic pressure significantly exceeds 10 nPa).

5 Conclusions

The rate of energy input from the solar wind, under conditions expected for extreme storms, appears to be sufficient (albeit not by an overwhelming margin) to supply the energy content of the largest imaginable magnetic storm within a reasonable time (several hours).

Not considered here is one remaining open question concerning the largest imaginable magnetic storm: can the postulated super-effective transport process, capable of filling the magnetosphere with plasma pressure up to the maximum possible value everywhere, actually occur, and if so, under what conditions?

Appendix A

Energy input estimated from magnetotail stress balance

The net magnetic tension force in the magnetotail (Siscoe, 1966), exerted ultimately on the Earth, is applied from the solar wind, predominantly along open magnetic field lines. The work done by solar-wind plasma flow against this force is the primary source of energy supply to the magnetosphere, as proposed by Siscoe and Cummings (1969) (see also Siscoe and Crooker, 1974). The quantitative stress-balance relation is (Siscoe, 1966; Vasyliūnas, 1987; Vasyliūnas, 2009)

$$\frac{{B_T}^2}{8\pi}(1-\delta)\,A_T - S\Delta V_x \simeq 0 \tag{A1}$$

where B_T = magnetotail (lobe) field, A_T = cross-sectional area of magnetotail at its Earthward boundary, S = total plasma mass flow through region of interaction with solar wind (e.g. plasma mantle), and ΔV_x = average slowdown of antisunward flow; δ = correction term for plasma sheet and for tail flaring (Siscoe, 1972a,b; Carovillano and Siscoe, 1973; Vasyliūnas, 1987). The corresponding energy input rate is, quite generally (e.g. Vasyliūnas, 2009, 2010), $\mathcal{P} = SV\Delta V_x$, which combined with Eq. (A1) gives

$$\mathcal{P} = SV\Delta V_x = \frac{1}{2}\rho V^3 A_T(1-\delta)\,\frac{2{B_T}^2}{8\pi\rho V^2} \tag{A2}$$

or, comparing with Eq. (5),

$$\Psi \simeq \frac{2\,A_T(1-\delta)}{\pi\,{R_{\mathrm{CF}}}^2}\,\frac{{B_T}^2}{8\pi\rho V^2}\,. \tag{A3}$$

Normally, the bulk of the energy input given by Eq. (A2) goes down the magnetotail and only a limited fraction goes into the inner magnetosphere (Vasyliūnas, 2010, 2011b). To obtain an estimate for $\Psi_{\max}$, I assume that (1) under appropriate conditions (and as a property of the postulated super-effective transport process that produces the largest imaginable magnetic storm), the energy input of Eq. (A2) can go predominantly into building up the energy content of the inner magnetosphere, (2) the magnetotail parameters in Eq. (A3) retain, within on order of magnitude, their typical empirically estimated values $A_T/\pi\,{R_{\mathrm{CF}}}^2 \sim 4$, $B_T/\sqrt{8\pi\rho V^2} \sim 1/3$, and $\delta \sim 0.5$ to 0.7 (Carovillano and Siscoe, 1973; Vasyliūnas, 1987). Assumption (2) appears reasonable for the first two parameters, which are determined largely by geometry and by pressure balance; less so perhaps for δ, which depends appreciably on the ratio (plasma sheet cross-sectional area)$/A_T$ (Carovillano and Siscoe, 1973) and hence on the ratio of closed to open magnetic flux in the magnetotail – but the increased amount of open flux expected for intense storms should lead rather to a decrease of δ compared to the average value quoted above. With these two assumptions, Eq. (A3) then gives the estimate for $\Psi_{\max}$ in Eq. (7).

Appendix B

Energy input estimated from polar cap potential saturation

An intuitively obvious estimate of the energy input rate is

$$\mathcal{P} = \Phi_{\mathrm{PC}} I_{\mathrm{M}}\,, \tag{B1}$$

the product of Φ_{PC}, the (so-called) cross-polar-cap potential (actually the potential across much of the magnetosphere and magnetotail) times I_{M}, the total current flowing across this potential in the magnetosphere (not just in the polar cap). From dimensional analysis

$$\Phi_{\mathrm{PC}} = \frac{1}{c}\,VB\,R_{\mathrm{CF}}\Psi_{\mathrm{PC}}\,, \tag{B2}$$

$$I_{\mathrm{M}} = \frac{c}{4\pi}\sqrt{8\pi\rho V^2}\,R_{\mathrm{CF}}\Psi_I\,, \tag{B3}$$

where Ψ_{PC} and Ψ_I are dimensionless functions of the same dimensionless variables as Ψ in Eq. (6). Comparison of Eqs. (5) and (B1) gives the relation

$$\Psi = \Psi_{\mathrm{PC}}\Psi_I\,\frac{B}{\sqrt{4\pi\rho V^2}}\,\frac{2\sqrt{2}}{\pi}\,. \tag{B4}$$

There are diverse theoretical models for Φ_{PC} and Ψ_I (e.g. Gonzalez and Mozer, 1974; Kan and Lee, 1979; Kan et al., 1980, and others), but more relevant for the purposes of this paper are the upper limits on both quantities. The total magnetospheric current is limited by global stress balance between magnetic field and solar-wind dynamic pressure and by the size of magnetosphere. The limiting current I_{M} calculated from a simple hemispherical model of the magnetopause, combined with the Newtonian approximation for the exterior pressure, is given by Eq. (B3) with $\Psi_I \leq 4$; numerically,

$$I_{\mathrm{M}} \leq 2.35\times 10^7\,\mathrm{A}\left[\frac{\rho V^2}{10\ \mathrm{nPa}}\right]^{1/3}\,. \tag{B5}$$

The transition, during intense storms, from pressure balance to dissipative tangential stress is discussed by Siscoe (2006, 2011).

The cross-polar-cap potential Φ_{PC} is observed to become saturated, i.e. independent of VB (for fixed solar-wind dynamic pressure ρV^2) when VB becomes sufficiently large; see review by Shepherd (2007) and references therein. Equation (B2) can be rewritten as

$$\Phi_{\mathrm{PC}} = \left[\frac{1}{c}\sqrt{4\pi\rho V^2}\,R_{\mathrm{CF}}\right]\left[V_{\mathrm{A}}\,\Psi_{\mathrm{PC}}\right] \tag{B6}$$

($V_{\mathrm{A}} = B/\sqrt{4\pi\rho}$ = Alfvén speed in the solar wind), where all the factors that depend on solar-wind dynamic pressure (only) have been collected into the first pair of brackets (easily shown to vary as $[\rho V^2]^{1/3}$); if saturation occurs, the quantity in the second pair of brackets ($V_A \Psi_{PC}$) must therefore be independent of VB. This can be used to infer Ψ_{max} in two different ways.

Empirically, $V_A \Psi_{PC}$ can be treated (in the saturation regime) as simply a number to be determined by a fit to observations; this provides a limiting potential which, together with the limiting current, allows Ψ_{max} to be estimated without further appeal to dimensional analysis. Hairston et al. (2005) report saturation values $\Phi_{PC} \sim 200$ kV during large storms, when $\rho V^2 \sim 10$ nPa. Multiplying this Φ_{PC} by I_M from Eq. (B5) and comparing with the numerical values in Eq. (5) yields Ψ_{max} given in Eq. (8).

Theoretically, $V_A \Psi_{PC}$ can be independent of VB only if Ψ_{PC} (a dimensionless function of dimensionless arguments) has the form

$$\Psi_{PC} \simeq \Psi_0 \frac{\sqrt{4\pi\rho V^2}}{B} \frac{c^2}{4\pi \Sigma_P V} = \Psi_0 \frac{c^2}{4\pi \Sigma_P V_A} \qquad \text{(B7)}$$

where $\Psi_0 =$ constant. The additional restriction $\Psi_{PC} < 1$ (from the observed fact that Φ_{PC} is at most a fraction of the solar-wind potential across the magnetosphere) implies that Eq. (B7) must be a limiting form, valid only for $4\pi \Sigma_P V_A / c^2 \gg 1$. Given the premise that polar cap potential saturation occurs, simple dimensional analysis thus suffices to establish Eq. (B7) and the corresponding expression for the saturated potential,

$$\Phi_{PC} \simeq \Psi_0 R_{CF} \sqrt{4\pi\rho V^2} \frac{c}{4\pi \Sigma_P} \simeq 416\,\text{kV}\, \Psi_0 \left[\frac{\rho V^2}{10\,\text{nPa}}\right]^{1/3} \left[\frac{10\,\text{mho}}{\Sigma_P}\right], \qquad \text{(B8)}$$

together with the consequence that saturation (at least in the strict sense of complete independence from VB) is possible only if the physical process involves a (sufficiently large) Σ_P. Dimensional analysis does not require any additional assumptions, but neither does it provide any further information about the physical process, and it does not determine the value of Ψ_0. Specific physical models for polar cap potential saturation have been proposed by Hill et al. (1976), Siscoe et al. (2002), and Kivelson and Ridley (2008); they all predict a dependence of the potential on Σ_P that, when expressed in dimensionless terms, gives

$$\Psi_{PC} = \frac{\Psi_0}{\Psi_0 + 4\pi \Sigma_P V_A / c^2} \qquad \text{(B9)}$$

which reduces to Eq. (B7) in the limit $4\pi \Sigma_P V_A / c^2 \gg 1$. Hill et al. (1976) simply assume $\Psi_0 = 1$; the others calculate $\Psi_0 = 0.608$ (Siscoe et al., 2002, from a semi-empirical fit to data/simulation) or $\Psi_0 = 0.344$ (Kivelson and Ridley, 2008, from theory). Inserting the limiting value Eq. (B7) into Eq. (B4) gives

$$\Psi_{max} \simeq \Psi_0 \frac{8\sqrt{2}}{\pi} \frac{c^2}{4\pi \Sigma_P V}. \qquad \text{(B10)}$$

With the above calculated values for Ψ_0, Eq. (B10) gives the estimates for Ψ_{max} in Eq. (9). (Rigorous application of Eq. (B9) implies the substitution

$$\left[\frac{10\,\text{mho}}{\Sigma_P}\right] \longrightarrow \left[\frac{\Sigma_P}{10\,\text{mho}} + \Psi_0 \frac{80\,\text{km s}^{-1}}{V_A}\right]^{-1} \qquad \text{(B11)}$$

in Eqs. (9), (15), and (B8), showing how upper limits that depend on ionospheric conductance can be produced by strong interplanetary magnetic fields typical of intense storms).

The method of estimating the energy input rate used here in Appendix B is fundamentally equivalent to that in Appendix A (Vasyliūnas et al., 1982) but yields lower values of Ψ_{max} (hence longer time scales) because it takes into account additional constraints imposed by the ionosphere, manifested in the phenomenon of polar cap potential saturation.

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