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On the relaxation of magnetospheric convection when B_z turns northward

M. C. Kelley

School of Electrical and Computer Engineering, Cornell University, Ithaca, NY, USA

Correspondence to: M. C. Kelley (mck13@cornell.edu)

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Abstract. The solar wind inputs considerable energy into the upper atmosphere, particularly when the interplanetary magnetic field (IMF) is southward. According to Poynting's theorem (Kelley, 2009), this energy becomes stored as magnetic fields and then is dissipated by Joule heat and by energizing the plasmasheet plasma. If the IMF turns suddenly northward, very little energy is transferred into the system while Joule dissipation continues. In this process, the polar cap potential (PCP) decreases. Experimentally, it was shown many years ago that the energy stored in the magnetosphere begins to decay with a time constant of two hours. Here we use Poynting's theorem to calculate this time constant and find a result that is consistent with the data.

Keywords. Electromagnetics (Electromagnetic theory) – Interplanetary physics (Interplanetary magnetic fields) – Magnetospheric physics (Magnetospheric configuration and dynamics)

1 Introduction

Figure 1 shows the polar cap potential (PCP) for several hours after B_z turned northward and after it had been southward for a long time (Wygant et al., 1983). The decay time constant of the PCP is about two to three hours. Our goal is to predict this time constant using Poynting's theorem. Poynting's theorem (PT) is not usually thought to apply to slowly varying systems, but only to wave phenomena. This is not a requirement of the theory, however. A few papers have been written using PT for low-frequency magnetospheric and ionospheric phenomena (Kelley et al., 1991; Richmond, 2010). For reference, an excellent discussion of auroral physics is presented in Paschmann et al. (2003) and references therein.

2 Calculations

Our tool is Poynting's theorem, which states that

$$\frac{d}{dt}\left[\iint \frac{B^2}{2\mu_0} dV\right] = \iint (\boldsymbol{E} \times \boldsymbol{H}) \cdot d\mathbf{A} \qquad (1)$$
$$-S[V \cdot (\boldsymbol{J} \times \boldsymbol{B})]\, dV - \iint (\boldsymbol{J} \cdot \boldsymbol{E})\, dV,$$

where $\boldsymbol{B}$ is the magnetic field in the magnetosphere, $\boldsymbol{E} \times \boldsymbol{H}$ is the Poynting flux across the magnetopause for B_z north, and $\boldsymbol{J} \cdot \boldsymbol{E}$ is the Joule heat being dissipated (Kelley, 1989, 2009; Wygant et al., 2000). For the magnetosphere, $\boldsymbol{B} = \mu_0 \boldsymbol{H}$ and we use $\boldsymbol{B}$ below. In the final state after the stored energy is dissipated, the Poynting flux across a closed magnetosphere (for viscous interaction) plus energy input due to the cusp connection (Wygant et al., 1983) equals the Joule heating associated with the final electric field, $\boldsymbol{E}_f$. Since our goal is to predict the relaxation to the final state, we may ignore these balancing terms and relate the left-hand side of Eq. (1) to the $\boldsymbol{J} \cdot \boldsymbol{E}$ term.

We integrate both sides of this equation over time. The change in magnetic field energy is estimated from the total magnetic field in the stretched magnetosphere. We take the average magnetic field in this region to be 10 nT and the magnetosphere volume, V_m, to be $(10\,R_E)\,(10\,R_E)(L)$, where R_E is one earth radius and $L \approx 100\,R_E$ is the average length of the last closed magnetic field line. The stored magnetic energy in the Eq. (1) bracket on the left-hand side is then 10^{15} J. Exact values of these parameters are not necessary to estimate the time constant within a factor of two or so. During the decay of the electric field with time constant τ, the Joule heating term on the right-hand side of Eq. (1) is due to horizontal ionospheric electric fields, E_I, and parallel currents, $J_{||}$, linking the two regions. We assume the decay time

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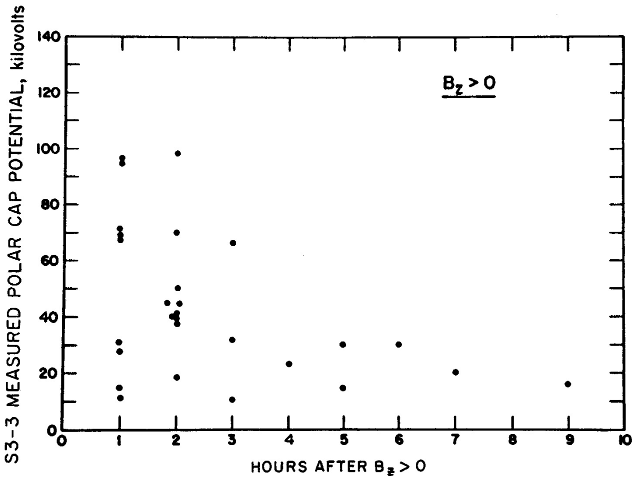

Fig. 1. The polar cap potential decreases slowly after the IMF turns northward. It finally reaches a value between 20 and 15 kV that is perhaps attributable to the viscous interaction process. [After Wygant et al. (1983). Reproduced with permission of the American Geophysical Union.]

constant, τ, is the same for $E_{\rm I}$ and $J_{||}$. The energy, W, dissipated by Joule heating is

$$W = \tau \left(\Sigma_{\rm p} E_{\rm I}^2 A_{\rm I} \right) + \frac{J_{||}^2}{\sigma_0} A_{\rm I} L_{||}, \qquad (2)$$

where $\Sigma_{\rm p}$ is the sum of the field-line-integrated Pedersen conductivity in the two polar caps and $E_{\rm I}$ is the initial electric field. $A_{\rm I}$ is the area of the auroral oval, σ_0 is the parallel conductivity, and $L_{||}$ is the length of the magnetic field line. As noted above, the Poynting flux and $\boldsymbol{J} \cdot \boldsymbol{E}$ term for B_z north cancel. We take $E_{\rm I} = 0.01\,{\rm V\,m^{-1}}$, $\Sigma_{\rm p} = 10\,{\rm S}$, $L_{||} = 10\,R_{\rm E}$, $J_{||} = 10\,\mu{\rm A\,m^{-2}}$, and $\sigma_0 = 10\,{\rm S\,m^{-1}}$. Then, the second term in Eq. (2) is negligible. The first term is about 100 GW. Substituting, we find that $\tau = 10^4\,{\rm s} = 2.8\,{\rm h}$, which is in good agreement with the data.

3 Conclusions

When B_z turns northward after a long time southward, the energy stored in the distorted magnetic field decays, with a two to three-hour time constant. Here we show this is consistent with the Joule dissipation term in Poynting's theorem as applied to the magnetosphere. Although this calculation is made for B_z north, it has applications for B_z south, since a major balance to the input of energy in that case is the Joule heating term, for which we now know the time constant. The fact that the potential does not go to zero is due to the Poynting flux term for B_z north, which is due to a viscous interaction, cusp reconnection, or a combination of both.

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