Energetics of Large Geomagnetic Storms

Modeling the Disturbed Thermosphere as a Driven-Dissipative System

ISWI Workshop
Boston College
3 August 2017

William J. Burke
Boston College/Institute for Scientific Research
Energetics of Stormtime Thermosphere

Outline

• Historical Background:
  – Effects of the March 1989 storm
  – Solar wind & IMF coupling to Earth’s magnetosphere

• GRACE thermospheric density measurements during the November 2004 Storm
  – Clue #1 Similarities to polar cap potential and Sym H index

• Practical implications of J77 Model

• Application of First Law of Thermodynamics

• Energy responses when interplanetary drivers turns off
  – Clue #2: Stormtime thermosphere acts like a driven-dissipative system

• Comparison of driven-dissipative model predictions with measurements.

• Predicting thermospheric responses with the **Dst index alone**

• Summary and Conclusions
Historical Background:
Some Impacts of March 1989 Storm

**Great Storm of March 13 - 14, 1989**

- **Cause:** CME launched on March 9, oblique impact on 13 March

- **Effects:**
  - Created a new radiation belt in 5 minutes after impact.
  - Crippled Hydro Quebec for ~9 hours
  - Caused US Space Surveillance Network to lose ~3400 > 10 cm space objects it normally tracks.
  - Collision avoidance capabilities lost

- Subsequently, radiation belt physics was better understood and electric grid vulnerability was addressed and mitigated.

- Storm-induced tracking errors persist.
**Historical Background: Solar Wind/ IMF Coupling to Earth’s Magnetosphere**

- **Dessler-Parker-Sckopke Relation**: Dst directly proportional to the total energy of current-carrying particles in the magnetosphere

- **Burton-Russell-McPherron Relation**:
  (driven dissipative system)

- **Polar Cap Potential - IEF Relation**

\[
\Phi_I = \Phi_0 + \Lambda_G V_{SW} B_T \sin^2 \frac{\theta}{2} - \frac{D_{st}^* \Phi_{IEF}}{\tau}
\]

Define: \( \Phi_{IEF} = \frac{\Phi_{PC}}{2 R_E L_Y} \)

\( L_Y \approx 1.5 L_X \approx 14.4 / \sqrt{P_{SW} (nPa)} \)

- **Polar Cap Potential saturation during large storms**

\[
\Phi_{PC} = \frac{\Phi_I \Phi_S}{(\Phi_I + \Phi_S)}
\]

\[
\Phi_S = 1600 P_{SW}^{0.33} \text{ (nPa)} / \Sigma
\]

*Siscoe et al. (JGR, 2002)*
GRACE Accelerometer Measurements during the November 2004 Storms

GRACE satellites measured Thermospheric mass densities at ~ 500 km, during July & November 2004 storms.

- MSIS and J-70 use Ap index as disturbance-time driver but underestimated storm effects
- Missed fine structure in GRACE measurements
- Predicted density increases 4 to 6 hours too late
- Clue #1: $\Phi_{PC}$ and Sym H track centroids of GRACE density perturbation measurements.
- ACE data may predict thermospheric responses
J77: Parametric Relations

Exospheric temperature $T_\infty$ controls mass density profiles $\rho(h)$ via quadratic relations

$$T_\infty(K) = \sum_{i=0}^{2} a_i(h)\rho^i(h)$$

$$a_i(h) = \sum_{j=0}^{5} b_{ij}h^j(km)$$

$$\begin{pmatrix}
a_0(h) \\
a_1(h) \\
a_2(h)
\end{pmatrix} = \begin{pmatrix}
-28.1 & 2.69 & -2.03 \cdot 10^{-3} & 0 & 0 & 0 \\
-4.733 \cdot 10^{17} & 4.312 \cdot 10^{15} & -1.372 \cdot 10^{13} & 1.60 \cdot 10^{10} & 0 & 0 \\
3.2695 \cdot 10^{32} & -4.62 \cdot 10^{30} & 2.618 \cdot 10^{28} & -7.456 \cdot 10^{25} & 1.071 \cdot 10^{23} & -6.237 \cdot 10^{19}
\end{pmatrix} \begin{pmatrix}
1 \\
h \\
h^2 \\
h^3 \\
h^4 \\
h^5
\end{pmatrix}$$

Bottom Line: Knowing mass density at a given attitude we can calculate $T_\infty$, and through J77 tables, density, temperature and composition profiles.
**First Law of Thermodynamics:**

\[ dE_{th} = C_V \, dT + dW_G \]

\[ E_{th} = H_T + \Phi_G \]

- **Thermal energy:**

\[ H_T = \frac{4\pi}{A} \int_{R_e+h_0}^{R_e+1000} C_V(r)n(r)T(r)r^2\,dr \]

\[ C_V(r) = \frac{k_B A}{n(r)} \left\{ \frac{5}{2}(n[N_2] + n[O_2]) + \frac{3}{2}(n[O] + n[Ar] + n[He] + n[H]) \right\} \]

- **Gravitational Energy**

\[ \Phi_G = 4\pi \int_{R_e+h_0}^{R_e+1000} [\phi(r) - \phi(r_0)]r^2\,dr = 4\pi M_E G \int_{R_e+h_0}^{R_e+1000} \rho(r) \left[ \frac{1}{r} - \frac{1}{r_0} \right] r^2\,dr \]

\[ \phi_G(r) = \rho(r) M_E G / r \]

- **Thermal energy:**

\[ E_{th} = \frac{1}{2} \sum C_V n_i T_i + \frac{1}{2} \sum m_i v_i^2 + \frac{k_B}{2} \sum n_i T_i + \Phi_G \]

\[ E_{th} = \frac{1}{2} \sum m_i v_i^2 + \frac{k_B}{2} \sum n_i T_i + \Phi_G \]

- **Gravitational energy:**

\[ \Phi_G = G \int m_i \int \rho(r) \left[ \frac{1}{r} - \frac{1}{r_0} \right] r^2\,dr \]

\[ E_{th} = \frac{1}{2} \sum m_i v_i^2 + \frac{k_B}{2} \sum n_i T_i + \Phi_G \]

- **Total energy:**

\[ E_{th} = H_T + \Phi_G \]

- **Polar orbiting s/c sample about same average \( T_\infty \) independent of local-time plane**

\[ E_{th}(h \geq 100 \text{ km}) = 5.365 \times 10^{17} + 8.727 \times 10^{13} T_\infty \]
- Plot natural log of $E_{th}$ (J) and $\varepsilon_{VS}$ (mV/m) for days 24 – 31 July 2004
  $E_{th}$ represents the energy added to thermosphere above pre-storm levels
- Vertical lines mark rapid $\varepsilon_{VS}$ decreases
- Slanted lines show relaxation rate of ~6.5 hours in $E_{th}$ after $\varepsilon_{VS}$ terminates

• Assume independent UV & SW sources: $E_{th} = E_{th\ UV} + E_{th\ SW}$

$$\frac{dE_{th\ SW}}{dt} = \alpha_E \cdot \varepsilon_{VS} - \frac{E_{SW}}{\tau_1}$$

=> driven-dissipative equation

• Solve numerically using 1-hour time steps
• Best fits: $\alpha_E \approx 5.5 \times 10^{15}$ [(J/hr)/(mV/m)]
  $\tau_E \approx 6.5$ hr
Compare solutions of driven-dissipative equation predictions for $E_{SW}$ and $Dst$ with GRACE and U. Kyoto databases using $\varepsilon_{VS}$ from ACE during two storm periods.

$\alpha = 0.55$ GRACE

$E_{VS}$

Maximum $T_{\infty,SW} \approx 500^\circ K$

$\alpha = 0.55$ GRACE

$E_{VS}$

Julian Day: 2004
Predicting Stormtime Thermosphere Using Dst Driven-Dissipative Equation Alone

- Observed (red dots) vs modeled (blue lines) thermospheric energy $E_{SW}$ (top) and Dst index (bottom) during November 2004 storms.

- $E_{VS}$ derived from hourly-averaged ACE data acts as the driver for driven-dissipative $E_{th}$ and $Dst$ equations.

- Since $T_{\infty}^{SW}$ is directly proportional to $E_{SW}$, both it and $Dst$ obey driven-dissipative equations

\[
\frac{dT_{\infty}^{SW}}{dt} = \alpha_{T_{SW}} E_{SW} - \frac{T_{\infty}^{SW}}{\tau_{T}} \quad \text{and} \quad \frac{dDst}{dt} = \alpha_{D} E_{SW} - \frac{Dst}{\tau_{D}}
\]

- Combine equations, eliminate $E_{VS}$ and use $\Delta t = 1$ hr

\[
T_{\infty}^{SW}(t_{n+1}) = \left(1 - \frac{1}{\tau_{T}}\right) T_{\infty}^{SW}(t_{n}) + \alpha_{T} \left[ Dst(t_{n+1}) - \left(1 - \frac{1}{\tau_{D}}\right) Dst(t_{n}) \right]
\]

$\tau_{T} \approx 6.5$ hrs, $\tau_{D} \approx 7.7$ hrs and $\alpha_{T} / \alpha_{D} \approx 1.575$.

- Approximate interplanetary and thermospheric conditions during March 1989 storm

Note maximum $T_{\infty}^{SW} \approx 800^\circ$ K
This presentation outlined results of a renewed attempt to address a space weather effect encountered during the great magnetic storm of March 1989 when about 3400 tracked objects were lost.

The critical new element underlying this advance was the availability of precise thermospheric density measurements from the GRACE satellites during the magnetic storms of the last solar cycle.

Stormtime GRACE data were viewed in the light of:
(1) Established relations between the interplanetary electric field, the Dst index and the cross polar cap potential.
(2) Information implicit in the Jacchia 1977 thermospheric model.

Our analyses show globally-averaged exospheric temperatures \( T_\infty \), thermospheric energy \( E_{th} \) and Dst follow the equation for driven-dissipative systems.

Eliminating \( \varepsilon_{VS} \) from the combined equations shows the evolution of the stormtime thermosphere can be determined using the Dst index alone.

An independent study found stormtime tracking errors reduced by 65%


