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

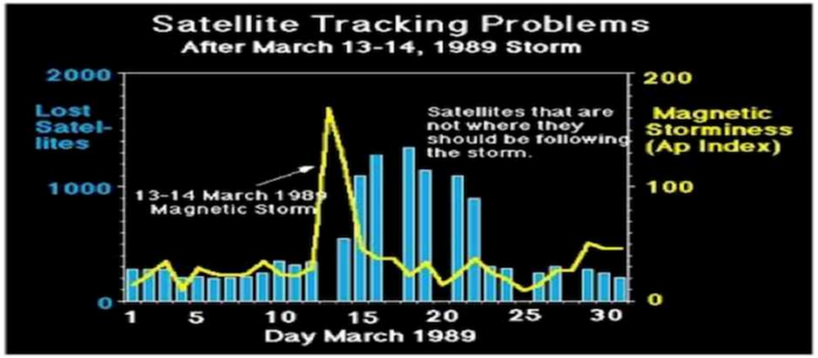
Outline

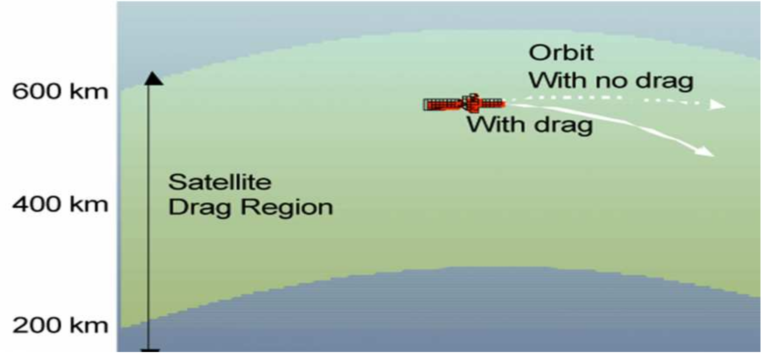
- **Historical Background:**
  - **Effects of the March 1989 storm**
  - **Solar wind & IMF coupling to Earth's magnetosphere**
- **GRACE thermospheric density measurements during the November 2004 Storm**
  - **Clue #1 Similarities to polar cap potential and Sym H index**
- **Practical implications 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**

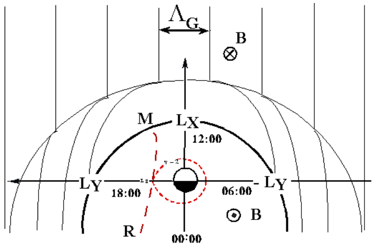
- *Burton-Russell- McPherron Relation*: **(driven dissipative system)**

$$\frac{dDst^*}{dt} = \alpha_D \varepsilon_{IEF} - \frac{Dst^*}{\tau}$$

- *Polar Cap Potential - IEF Relation*

$$\Phi_I = \underbrace{\Phi_0}_{\text{Residual}} + \underbrace{\Lambda_G}_{\text{SW gate}} V_{SW} \underbrace{B_T Sin^2 \frac{\theta}{2}}_{\text{IEF}}$$

1 mV/m ≈ 6.4 kV/R_E



Define: $\varepsilon_{VS} = \Phi_{PC} / 2 R_E L_Y$

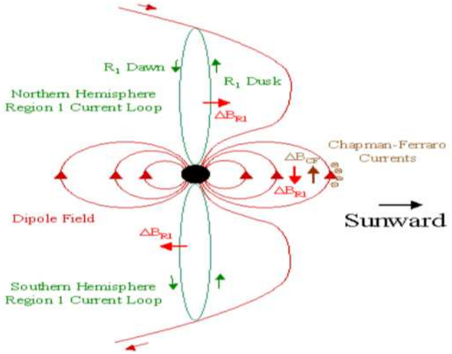
$$L_Y \approx 1.5 L_X \approx 14.4 / \sqrt[6]{P_{SW}} (nPa)$$

- *Polar Cap Potential saturation during large storms*

$$\Phi_{PC} = \Phi_I \Phi_S / (\Phi_I + \Phi_S)$$

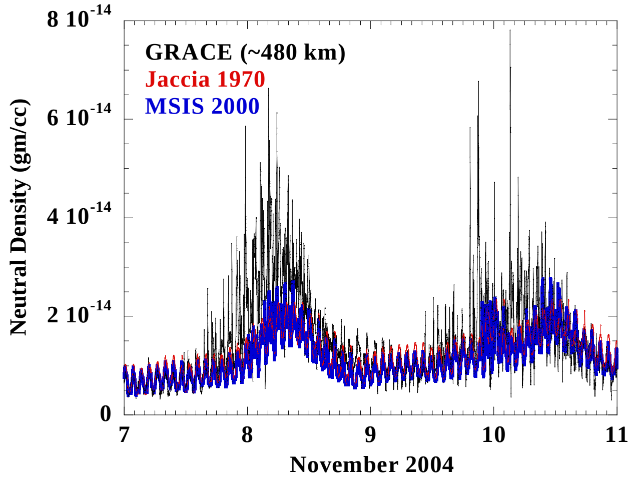
$$\Phi_S = 1600 P_{SW}^{0.33} (nPa) / \Sigma$$

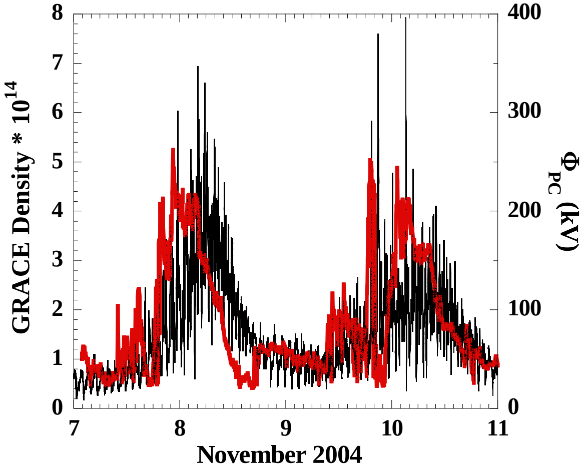
Siscoe et al. (JGR, 2002)

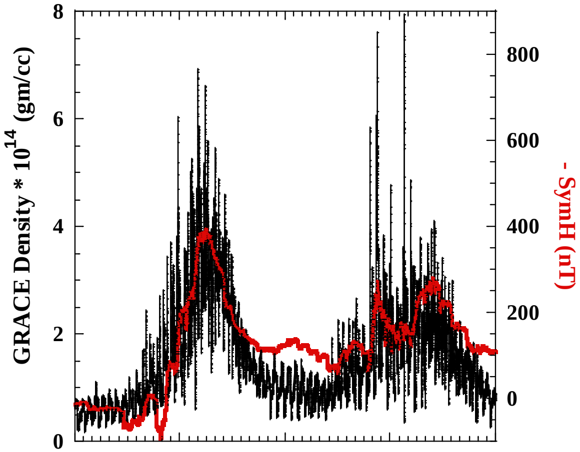


GRACE Accelerometer Measurements during the November 2004 Storms

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**

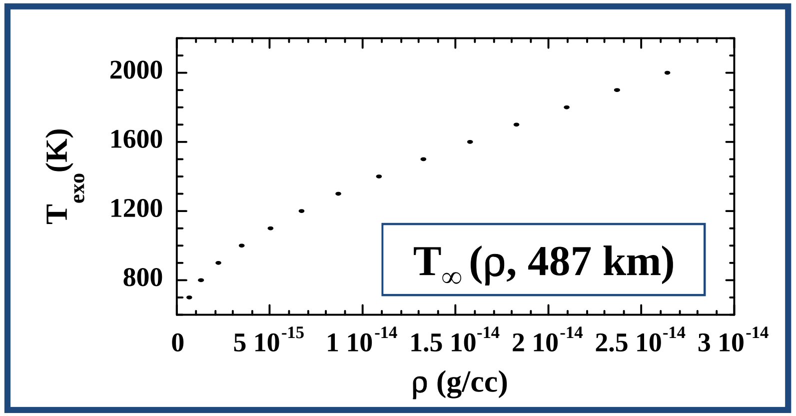
- **Clue #1: Φ_{PC} *and* - Sym H track centroids of GRACE density perturbation measurements.**

- **ACE data *may* predict thermospheric responses**

Practical Implications of the J77 Model

J77: Parametric Relations

Exospheric temperature T_∞ controls mass density profiles ρ(h) via quadratic relations



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

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

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

<u>Bottom Line</u>: Knowing mass density at a given attitude we can calculate T_∞ , and through J77 tables, density, temperature and composition profiles

J77: Total Energy of Stormtime Thermosphere

First Law of Thermodynamics:

$$\boxed{dE_{th} = C_V dT + dW_G}$$

$$\boxed{E_{th} = \mathrm{H}_T + \Phi_G}$$

- **Thermal energy:**

$$\mathrm{H}_T = \frac{4\pi}{A}\int_{R_E+h_0}^{R_E+1000} C_V(r)n(r)T(r)r^2dr$$

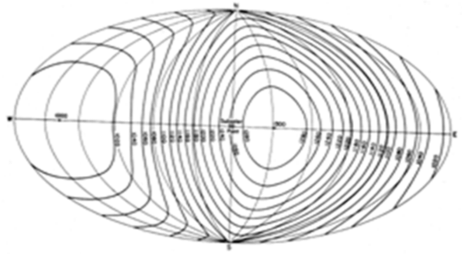
$$C_V(r) = \frac{k_B A}{n(r)}\left\{\frac{5}{2}\left(n[N_2]+n[O_2]\right)+\frac{3}{2}\left(n[O]+n[Ar]+n[He]+n[H]\right)\right\}$$

k_B = Boltzmann constant   A = Avagadro number

- **Gravitational Energy**

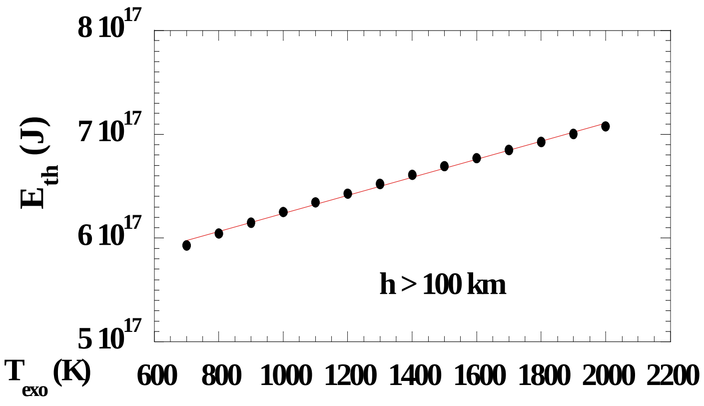
$$\Phi_G = 4\pi\int_{R_E+h_0}^{R_E+1000}[\phi(r)-\phi(r_0)]r^2dr = 4\pi M_E G\int_{R_E+h_0}^{R_E+1000}\rho(r)\left[\frac{1}{r}-\frac{1}{r_0}\right]r^2dr$$

$$\phi_G(r) = \rho(r)M_E G/r$$



J77: Isothermal T_∞ contours

Polar orbiting s/c sample about same average T_∞ independent of local-time plane



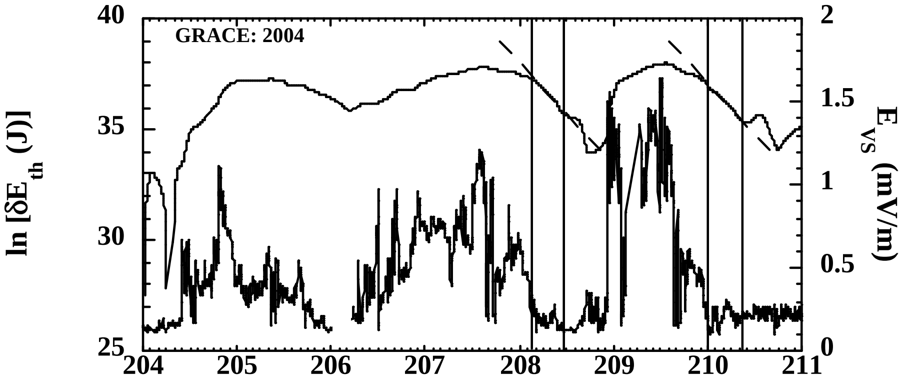
$$E_{th}(h \geq 100\ \mathrm{km}) = 5.365\ 10^{17} + 8.727\ 10^{13}\ \bar{T}_\infty$$

BOSTON COLLEGE ISR

Stormtime Thermosphere: A Driven-Dissipative System

- Plot natural log of E_{th} (J) and ε_{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 ε_{VS} decreases
- Slanted lines show relaxation rate of ~6.5 hours in E_{th} after ε_{VS} terminates

Clue # 2 ➡



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

Critical Conclusion ➡

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

=> driven-dissipative equation

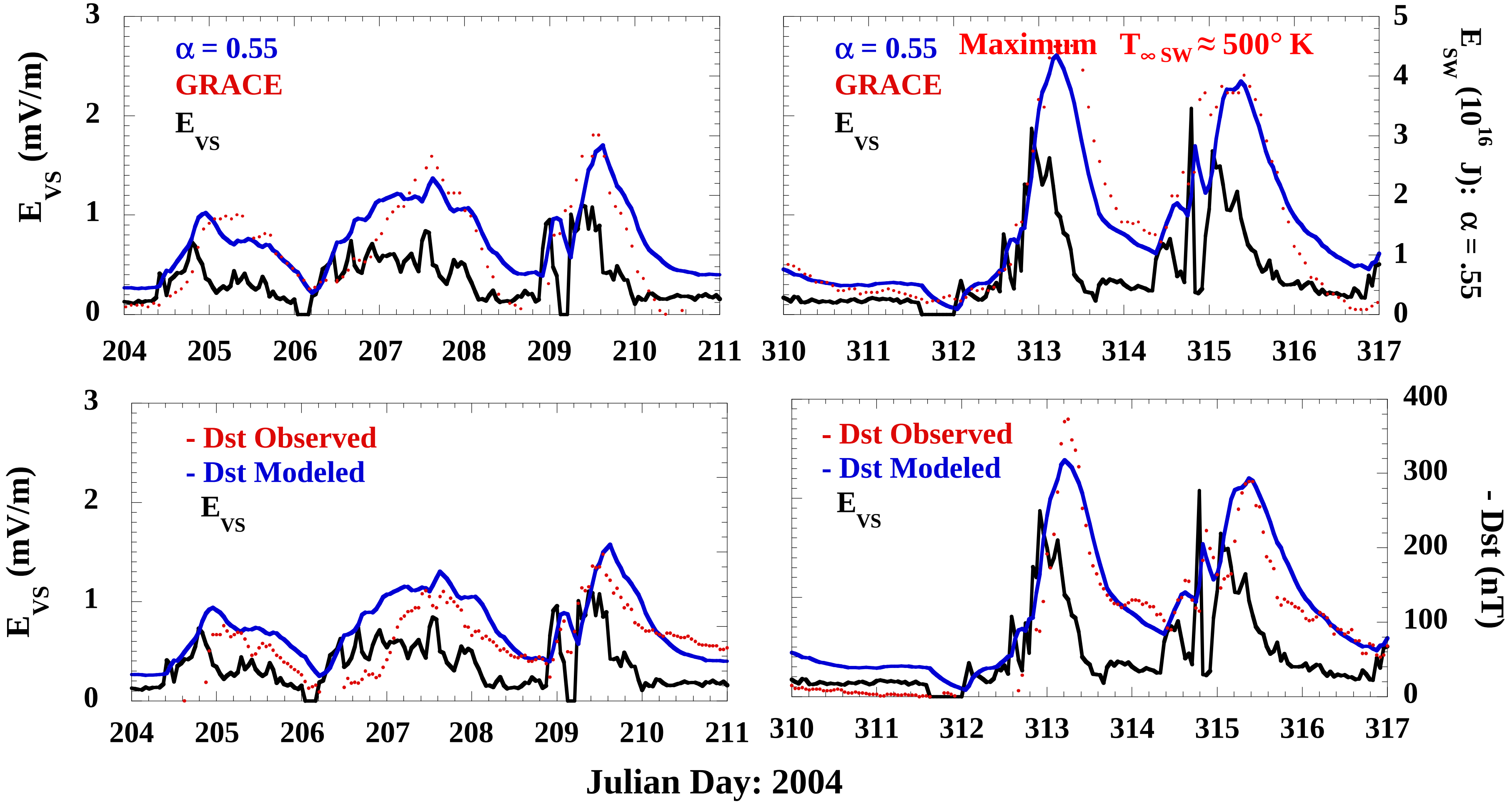
- Solve numerically using 1-hour time steps
- Best fits:

$$\alpha_E \approx 5.5 \square 10^{15}\ [(\mathrm{J/hr})/(mV/m)]$$

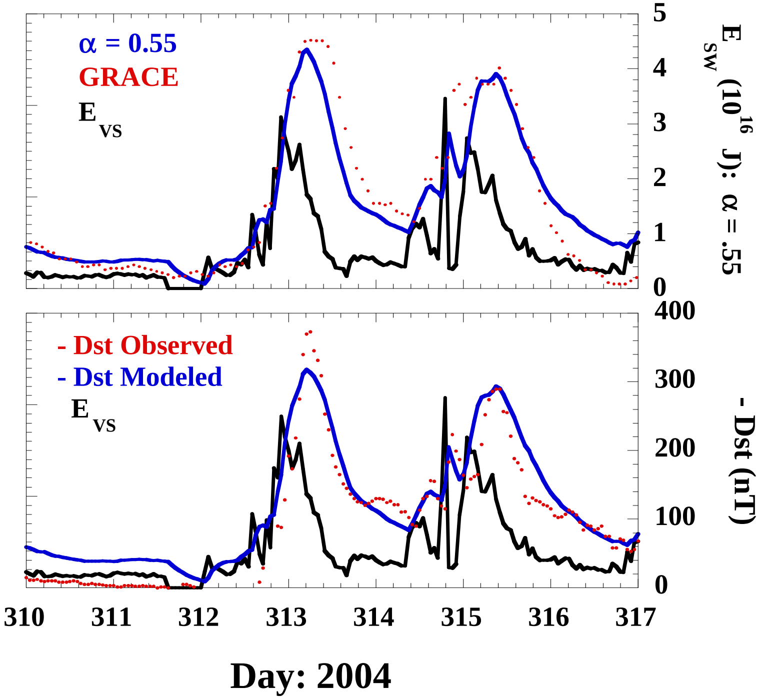
$$\tau_E \approx 6.5\ \mathrm{hr}$$

Driven-Dissipative System Applications to July and November 2004 Storms

Compare solutions of driven-dissipative equation predictions for E_{SW} and *Dst* with GRACE and U. Kyoto databases using ε_{VS} from ACE during two storm periods.



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

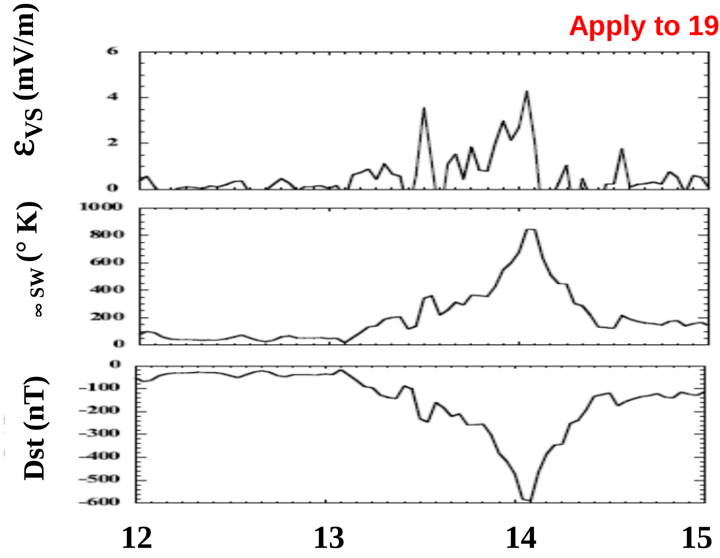
- **Since $T_{\infty SW}$ is directly proportional to E_{SW}, both it and *Dst* obey driven-dissipative equations**

$$\frac{dT_{\infty SW}}{dt} = \alpha_{TSW}\varepsilon_{SW} - \frac{T_{\infty SW}}{\tau_T} \quad \text{and} \quad \frac{dDst}{dt} = \alpha_D \varepsilon_{SW} - \frac{Dst}{\tau_D}$$

- **Combine equations, eliminate ε_{VS} and use Δt = 1hr**

$$T_{\infty SW}(t_{n+1}) = \left(1 - \frac{1}{\tau_T}\right) T_{\infty SW}(t) + \frac{\alpha_T}{\alpha_D}\left[Dst(t_{n+1}) - \left(1 - \frac{1}{\tau_D}\right) Dst(t_n) \right]$$

$\tau_T \approx$ 6.5 hrs, $\tau_D \approx$ 7.7 hrs and $\alpha_T / \alpha_D \approx$ 1.575.



Apply to 1989 storm

- **Approximate interplanetary and thermospheric conditions during March 1989 storm**

Note maximum $T_{\infty SW} \approx 800°$ K

Energetics of the Stormtime Thermosphere

Summary and Conclusions

- **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_∞), thermospheric energy (E_{th}) and Dst follow the equation for driven-dissipative systems.**

- **Eliminating ε_{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%

Energetics of the Stormtime Thermosphere

Short Bibliography

Bowman, B. R., et al., A new empirical thermospheric density model JB2008 using new solar and geomagnetic indices, AIAA 2008 6438, *AIAA/AAS Astrodyn. Specialist Conference*, Aug. 2008.

Burke, W. J., Solar-cycle dependence of solar-wind energy coupling to the thermosphere, *J. Geophys. Res.*, 116, A06302, doi:10.1029/2011JA016437, 2011.

Burke, W. J. et al.,, The stormtime global thermosphere: A driven-dissipative thermodynamic system, *J. Geophys. Res., 114*, A06306, doi:10.1029/2008JA013848, 2009.

Jacchia, L. G., Thermospheric temperature density and composition, A new model. SAO Special Rpt. 375. 1977

Siscoe, G. L. et al., Hill model of transpolar potential saturation: Comparison with MHD simulation, J. Geophys. Res., 107, (A6) , doi: 10.1029/2001JA000109.

Wright, D., Space Debris, *Physics Today*. 60, 10, 35-40. 2007.