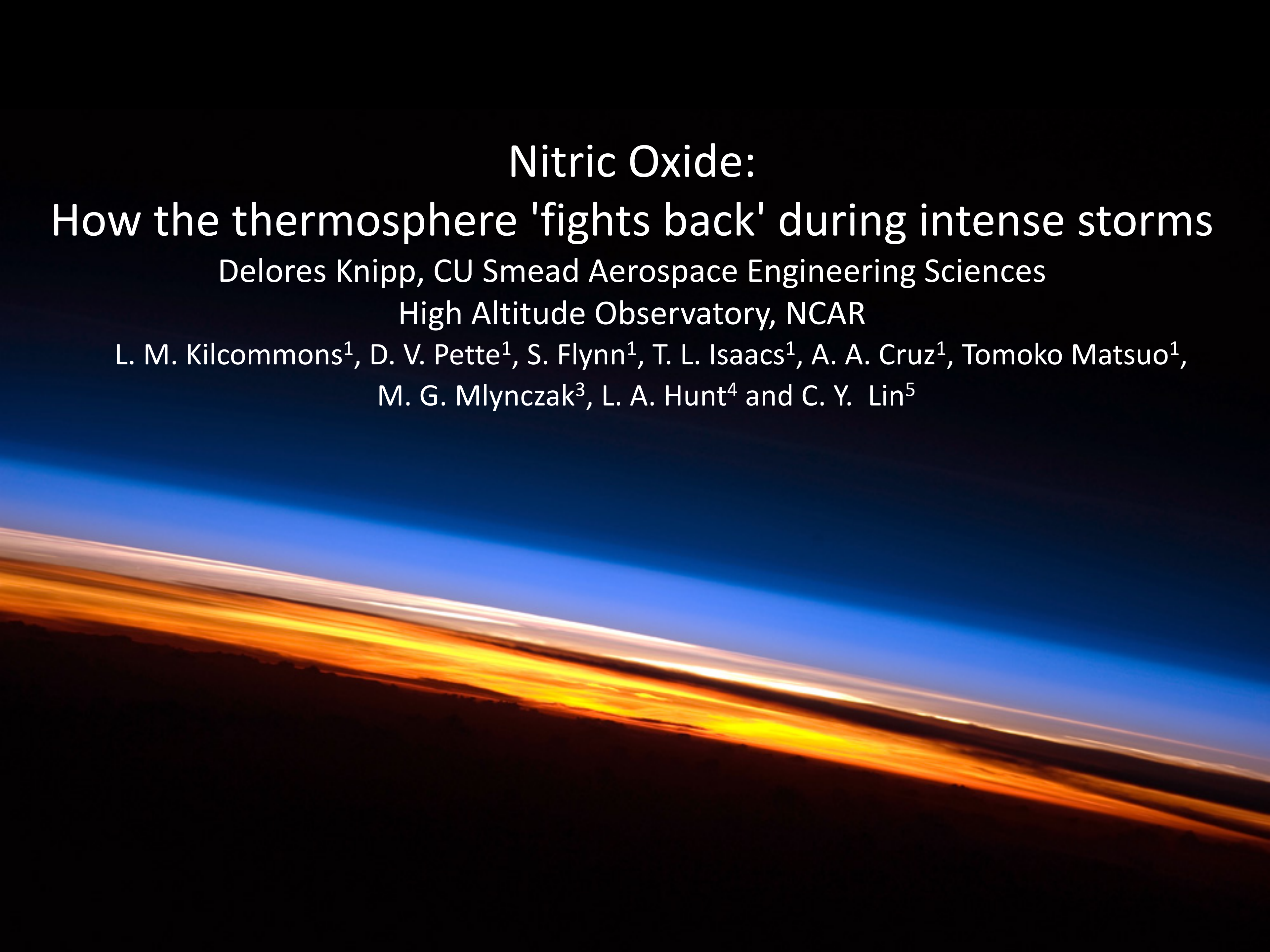
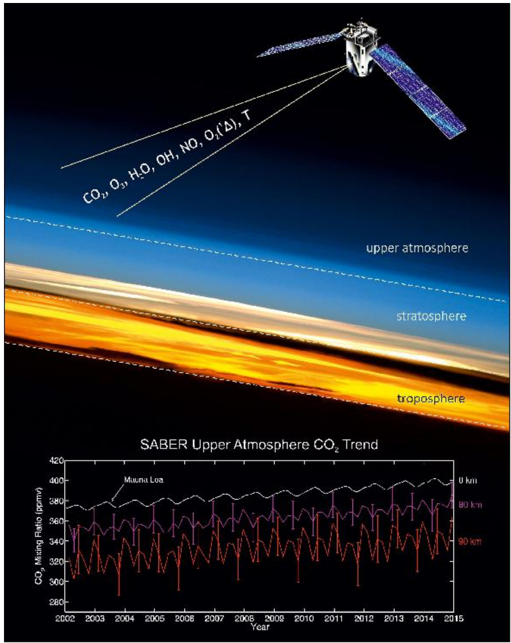


Nitric Oxide:
How the thermosphere 'fights back' during intense storms

Delores Knipp, CU Smead Aerospace Engineering Sciences
High Altitude Observatory, NCAR
L. M. Kilcommons[1], D. V. Pette[1], S. Flynn[1], T. L. Isaacs[1], A. A. Cruz[1], Tomoko Matsuo[1],
M. G. Mlynczak[3], L. A. Hunt[4] and C. Y. Lin[5]

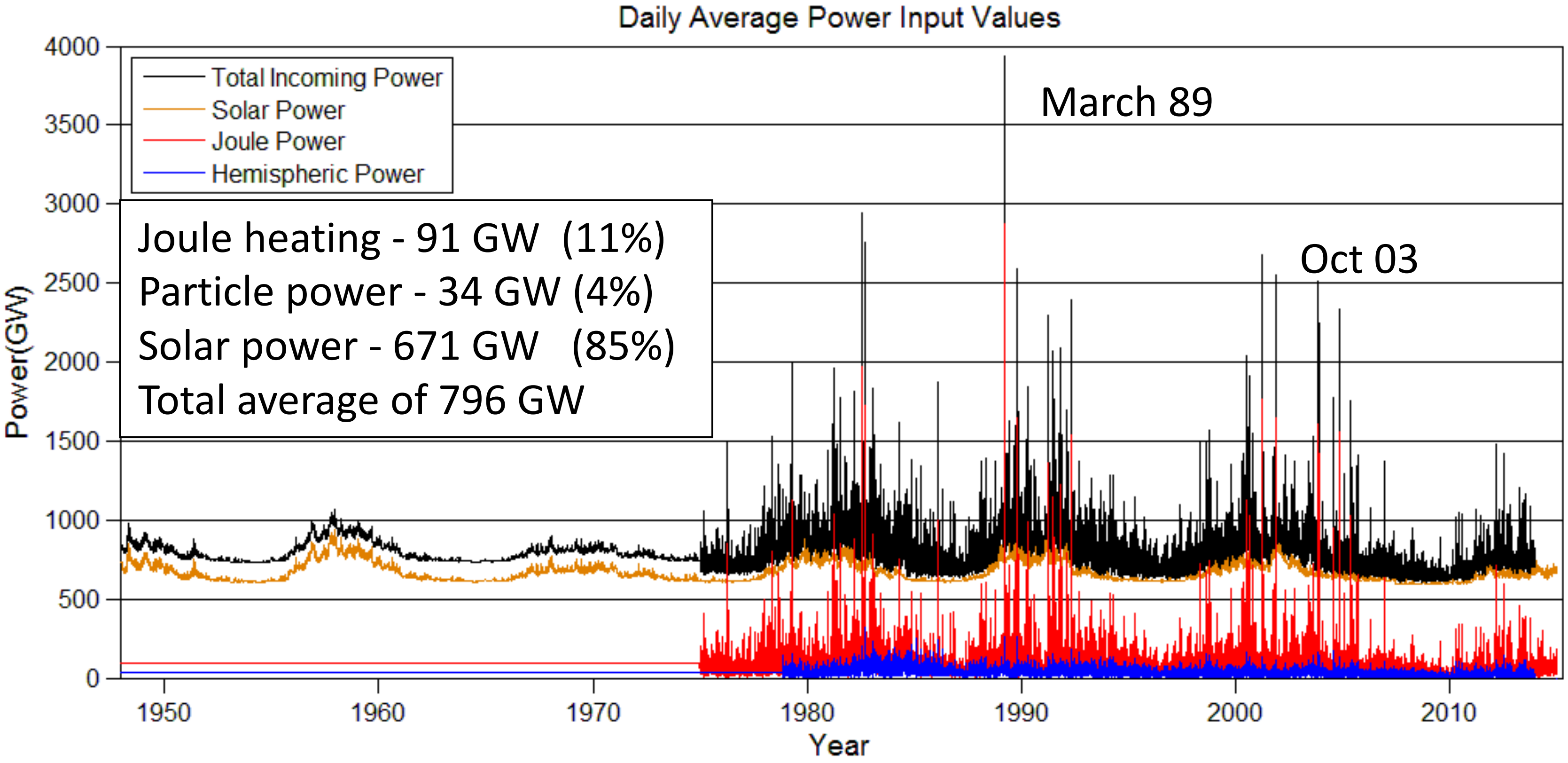
Overview

- Motivation
    - Balancing energy input and output
- Brief overview of atmospheric Nitric Oxide (NO)
    - Density and Emissions Distribution
- Storm time NO behavior—System Science
    - Thermospheric “thermostat”
- Solar wind influence on NO and cooling
- New results from near and far



Knipp, D. J., D. V. Pette, L. M. Kilcommons, T. L. Isaacs, A. A. Cruz, M. G. Mlynczak, L. A. Hunt, and C. Y. Lin (2017), Thermospheric nitric oxide response to shock-led storms, Space Weather, 15, doi:10.1002/2016SW001567.

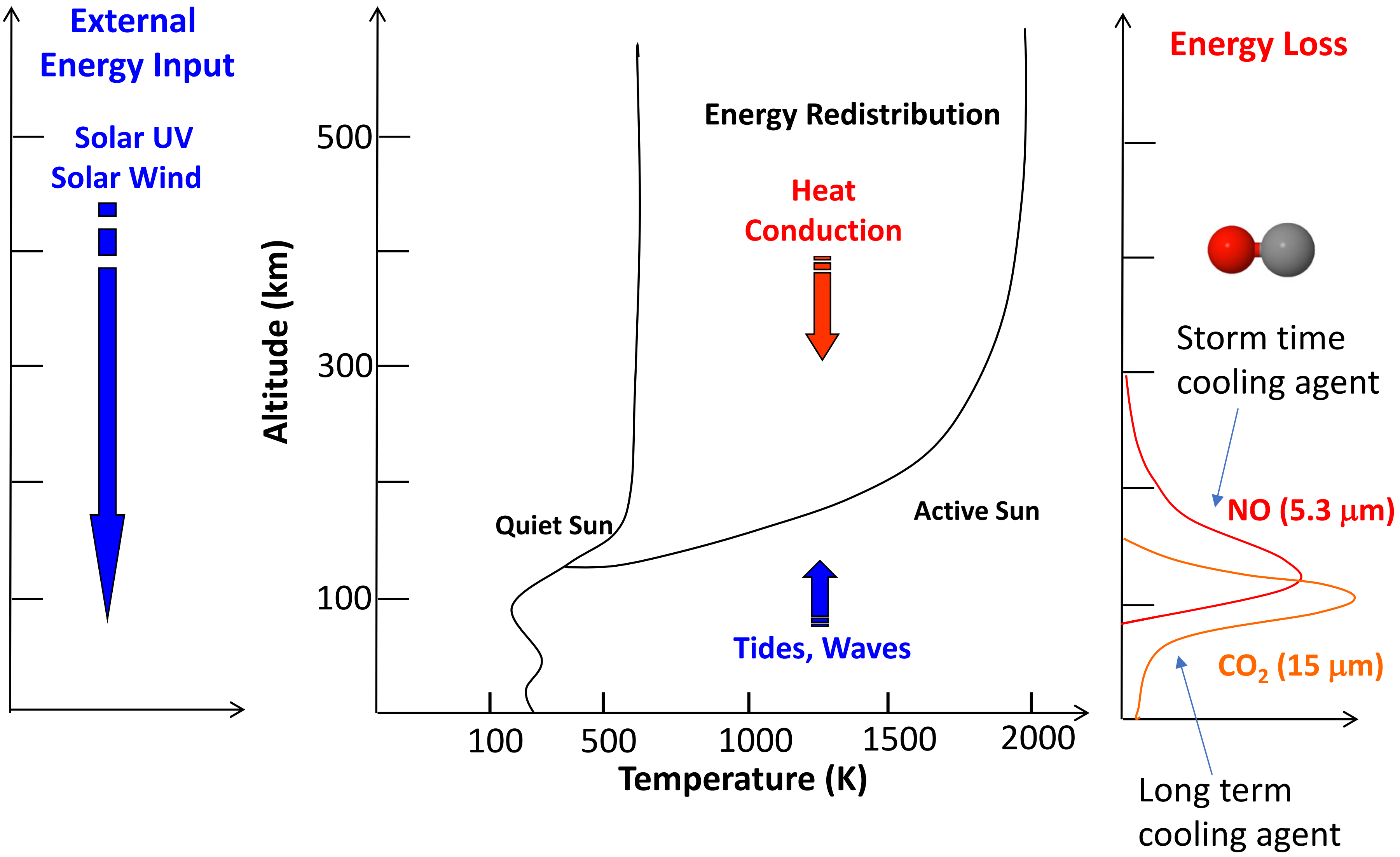
Power Input to the Upper Atmosphere



Joule heating - 91 GW (11%)
Particle power - 34 GW (4%)
Solar power - 671 GW (85%)
Total average of 796 GW

Extension of Knipp et al. (2004)

Thermosphere Energy Balance – Basic Elements



Provided by Martin Mlynczak, NASA Langley

NO—In the Atmosphere

- **Trace atmospheric constituent**
    - Mixing ratio varies from 10^{-8} to 10^{-4}
- **Sourced in energetic environments**
    - Created by solar protons and cosmic rays in the mesosphere
    - Created by solar Xray & EUV photons and protons in lower ionosphere
      Flares and Lyman-alpha emissions significant contributor to the D-region
    - Created by photo- and auroral electrons and possibly protons in the thermosphere
- **Highly variable density and emissions — factor of ten — 27 day and 11 year variation**
- **Density always larger in the auroral region (max at 65° geomagnetic latitude)**

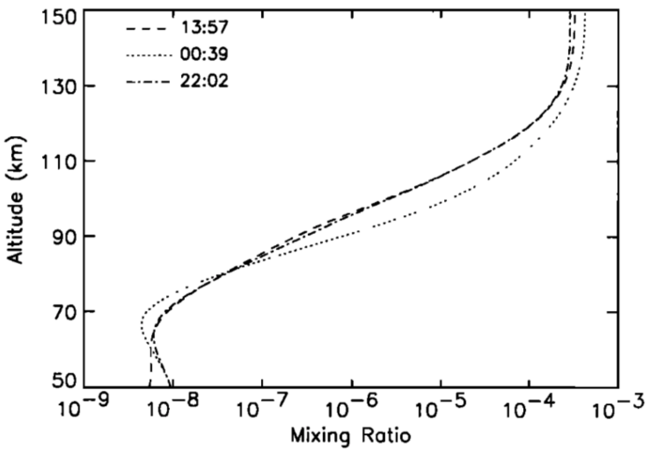


Figure 12. The mixing ratio of nitric oxide as calculated from the nitric oxide model for the conditions of the three ATMOS occultations.

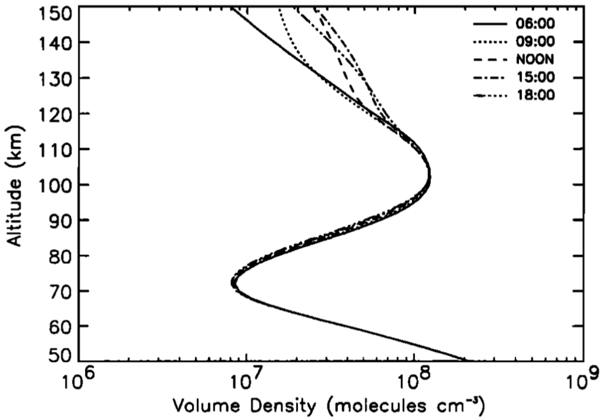


Figure 10. Calculations from the time-dependent model of the nitric oxide volume density every 3 hours from sunrise to sunset.

Barth et al. (1996) JGR
ATMOS Spacelab 3 mission 1985

Production and Loss of NO

Production:

$N_2 + e^* \rightarrow N(^2D) + N(^4S)$ **(R1)**

$N(^2D) + O_2 \rightarrow NO + O$ **(R2)** peaks at 105-110 km

Ionized atmospheric constituents also produce excited nitrogen atoms, $N(^2D)$:

$N_2^+ + O \rightarrow N(^2D) + NO^+$ **(R3)**

$NO^+ + e \rightarrow N(^2D) + O$ **(R4)**

Ionization of N_2^+ and NO^+ from energetic photons, electrons and protons

Particle, Joule and/or compressional heating drive a **temperature sensitive** reaction

$N(^4S) + O_2 \rightarrow NO + O$ **(R5)** peaks at 130-140 km

Loss :

$N(^4S) + NO \rightarrow N_2 + O$ **(R6)**

Reaction 6 is fed by photo-dissociation:

$NO + h\nu \rightarrow N(^4S) + O$ **(R7)**

And by the reaction

$N(^2D) + O \rightarrow N(^4S) + O$ **(R8)**

Both $N(^4S)$ and $N(^2D)$ are sources of NO.

Barth [1995, 2003]

General View of Thermospheric NO

- High latitudes NO created by auroral electrons (1-10 keV) and perhaps auroral protons
- Low latitudes NO created by solar produced photoelectrons
- Mid latitude NO is likely transported via meridional winds generated by auroral storm time heating

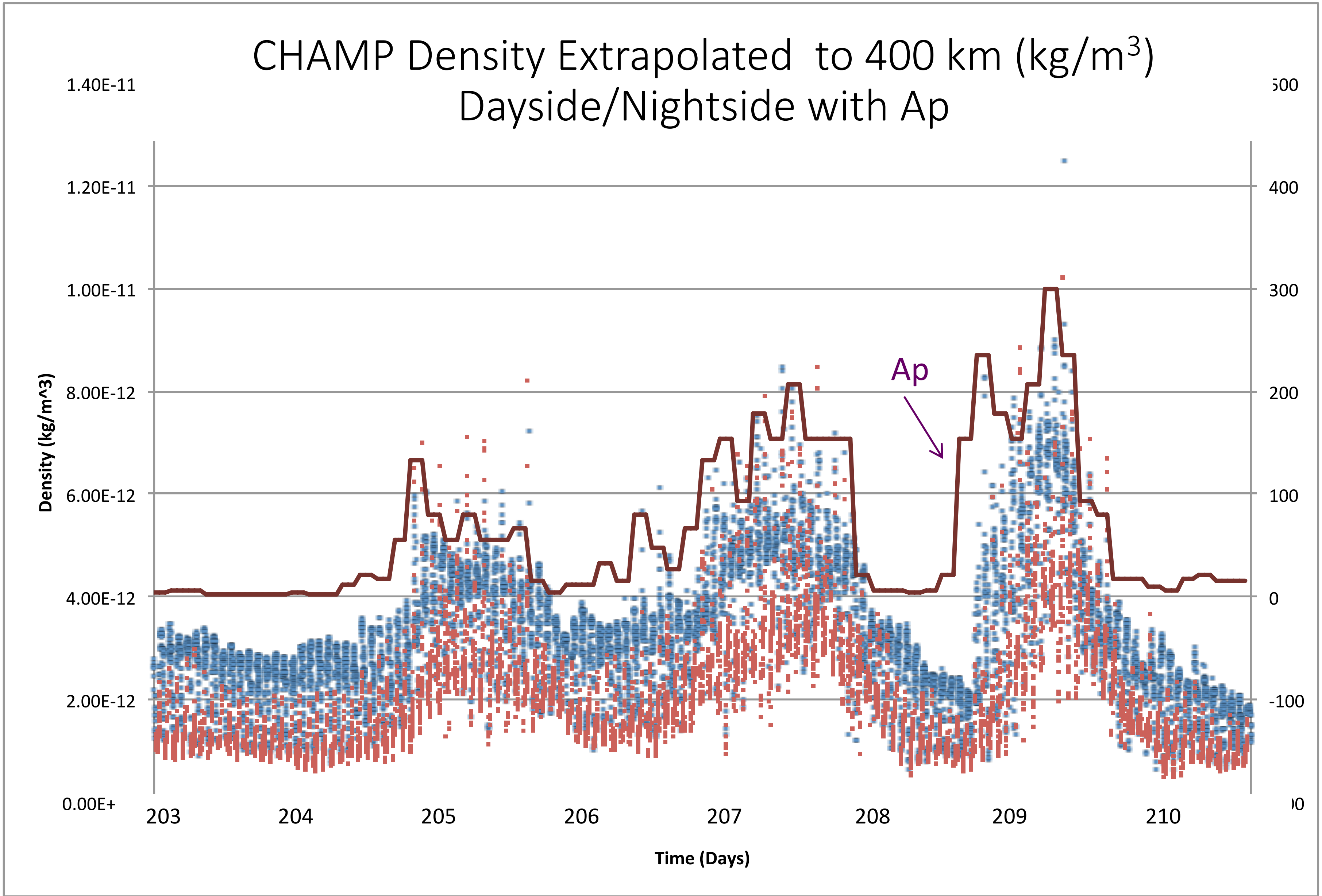
Why Do We Care About Atmospheric NO?

- **Destroys ozone in the stratosphere**
- **Exerts strong control of ionospheric D-region and associated radio propagation**
- **Controls temperature in the lower thermosphere**
    - **Regulates storm time behavior via a “thermostat effect”**
    - **Influences satellite drag**

- **Produced in the mesosphere and thermosphere**
    - Created by photoelectrons and auroral electrons and possibly energetic protons in the thermosphere
    - Strongly related to geomagnetic activity and solar flares
    - Storm-time Joule heating facilitates production of NO
- **So strongly related to storm-time behavior that NO emissions used as a proxy for energy input**

- **Created and excited by excess energy but also destroyed by excess energy**

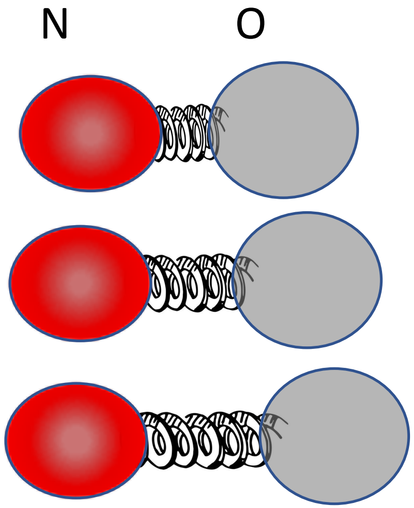
Why Do We Care About Atmospheric NO?

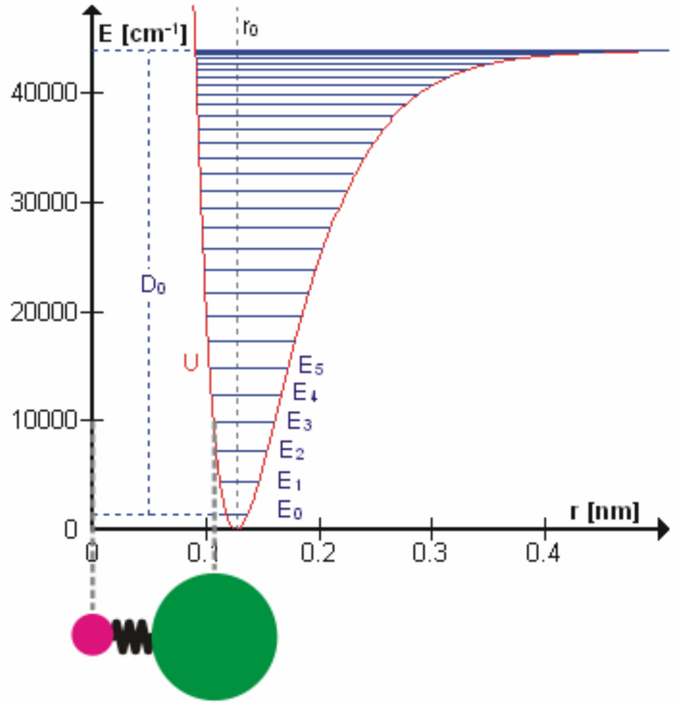


CHAMP Density Extrapolated to 400 km (kg/m³)
Dayside/Nightside with Ap

NO—The Molecule

Once created NO molecules can stretch and vibrate. In so doing they absorb and emit radiation (stretch = IR) and vibrate (radio). The sum of these creates emission bands that act as the thermospheric thermostat (Mlynczak et al. 2003)





The HCl molecule as an anharmonic oscillator wikipedia

- Heteronuclear, linear molecule
- Fundamental vibrational frequency

5.33 µm (infrared) due to stretching

- Permanent electric dipole moment
  bonding structure leaves 'exposed' electron on neutral nitrogen molecule

Abridged History: Observations and Models

- Solar spectral rocket experiment: mesospheric emissions between 220 nm -230 nm that Durand et al. (1949) speculate are related to NO emission.
- Nicolet (1955) estimates mesospheric NO density profiles
- Markov (1969) report of NO emissions between 4.5-8.5 μ from satellite observations
- Thermospheric NO discovered via UV spectroscopic rocket experiment; Barth (1964)
- NO UV airglow via OGO-4 satellite spectroscopic experiment; Rusch and Barth (1975)
- Global NO airglow observations on Atmos Explorer & Solar Mesosphere Explorer Sats
- Rees and Roble (1979) discuss the morphology of N and NO in auroral substorms
- Kockarts (1980) first discusses NO 5.3 μm cooling in the thermosphere
- Stratospheric & Mesospheric NO (Russell et al. 1988) measured by ATMOS (spectroscopy experiment) on board STS -51B (1985)
- Roble et al. (1988) coupled general circulation model with minor species
- Maeda et al. (1989) describe a Kp =7 storm with unusual cooling attributes
- Subsequently NO measurements by UARS, SNOE, TIMED SABER, SCIAMACHY, etc
- Growth of 3-D modeling

NO

Distribution Thermosphere

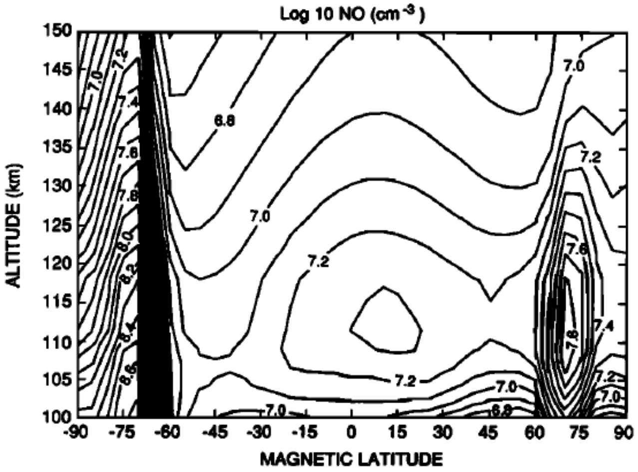
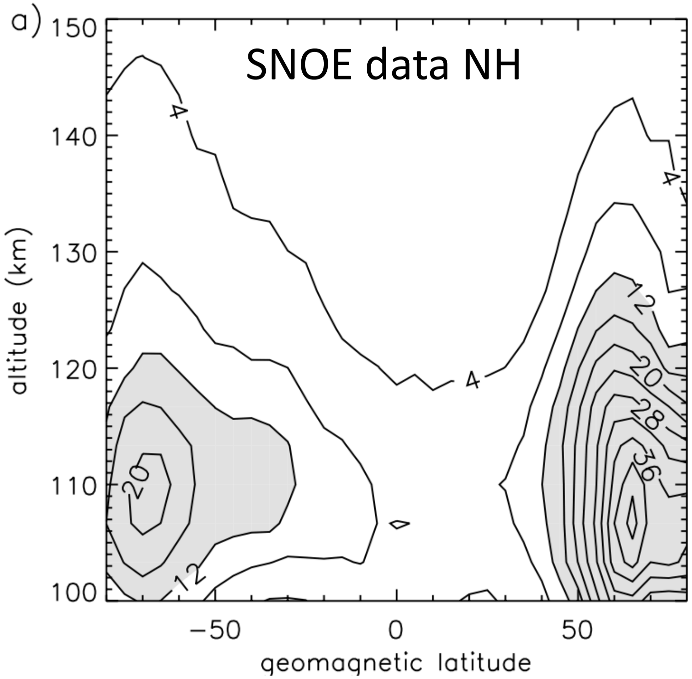
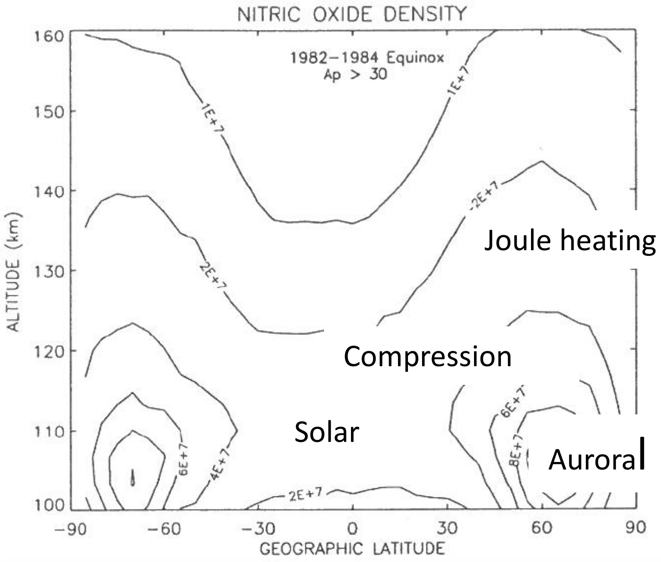


Fig. 1. Two-dimensional calculations of $\log_{10}$ zonally averaged nitric oxide concentrations (cm^{-3}) for June solstice and solar minimum conditions, F10.7 = 80. The eddy diffusion coefficients from *Garcia and Solomon* [1985] and a quenching coefficient of 5 x 10^{-13} cm^3 s^{-1} for $N(^2D)$ by O are adopted.

Gerard et al. (1990) JGR

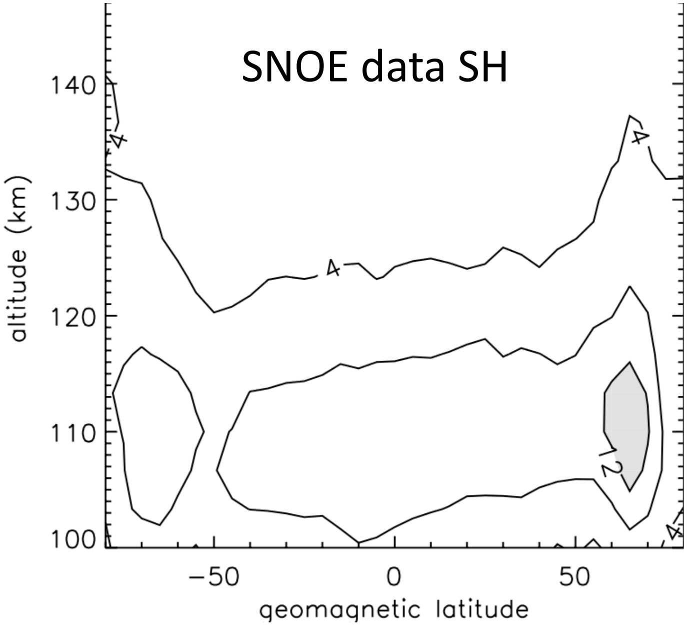
Zonally averaged latitudinal cross sections from UV spectroscopy





Barth, 1996 AGU Monograph

Density larger in the auroral region (max at ~65° geomagnetic latitude)

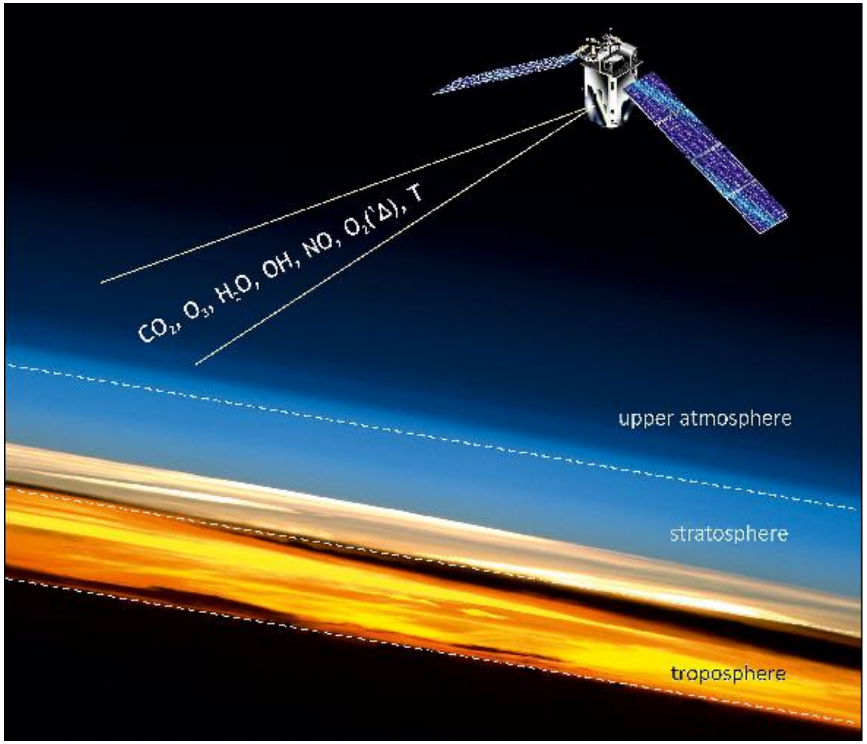


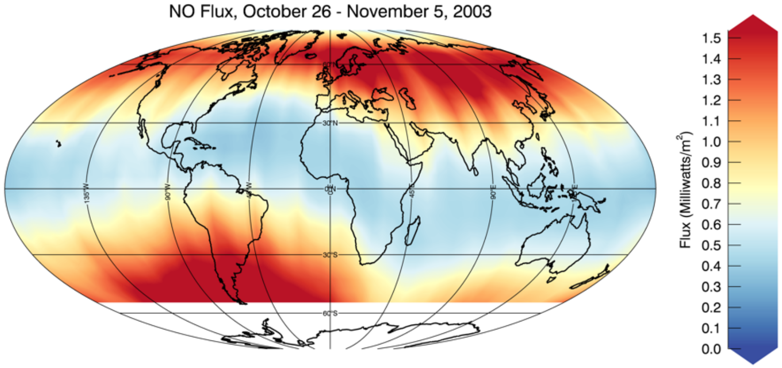
Marsh et al (2004) GRL

TIMED-SABER Emissions Measurements

Sounding of the Atmosphere using Broadband Emission Radiometry

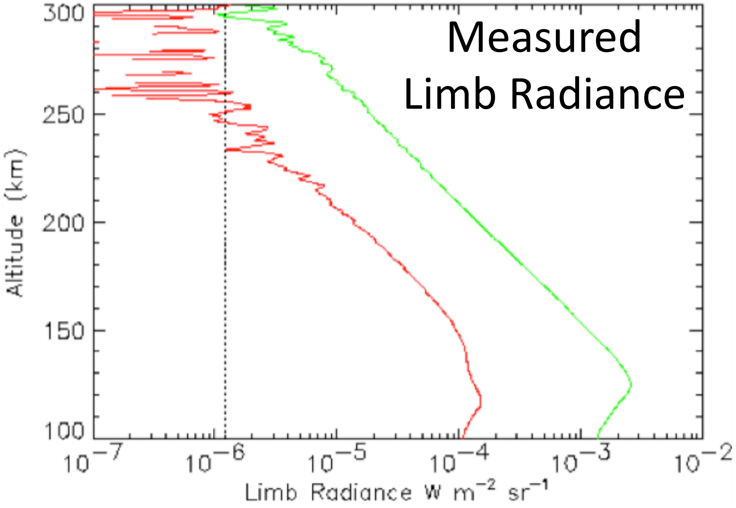
- **Limb viewing, 400 km to Earth surface**
- **Ten channels 1.27 to 16 μm**
- **Over 30 routine data products including energetics parameters**
- **8.3 million radiance profiles – per channel!**
- **Cryo-cooler operating excellently at 77 K**
- **Noise levels at or better than measured on ground**
- **Now in 16th year of on-orbit operation**



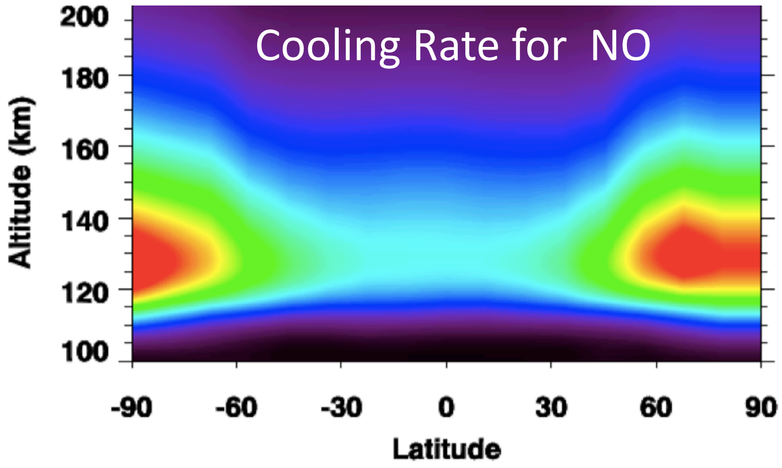


October26-November 5 2003

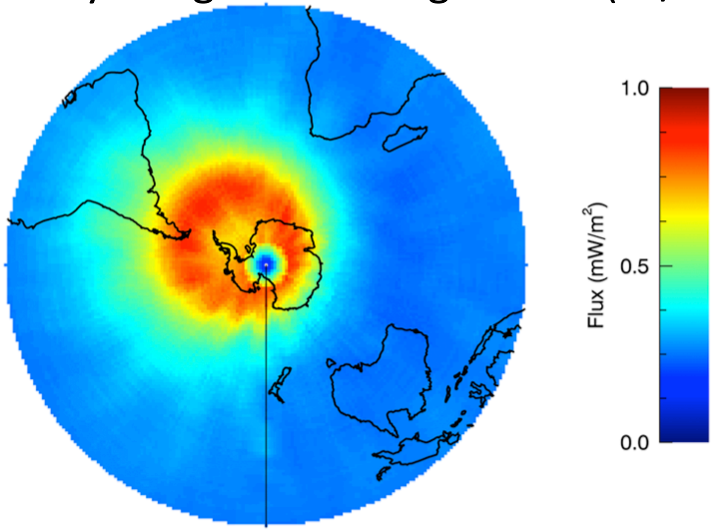
NO and CO_2 Cooling Parameter Derivations by SABER



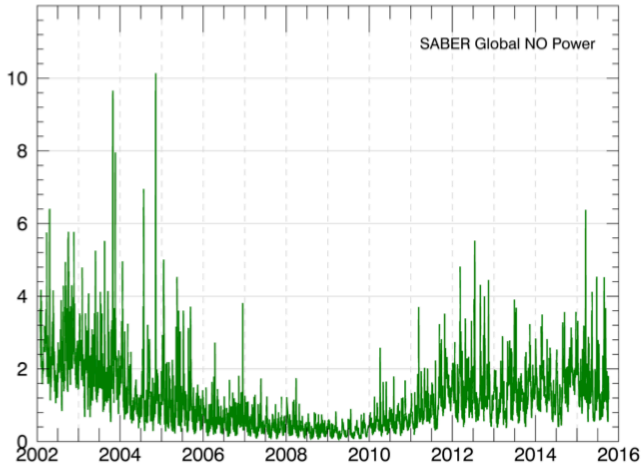
Abel Inversion to Cooling Rate (W/m^3)



Vertically Integrate Cooling to Flux (W/m^2)



Area integrate to get global power (GW)

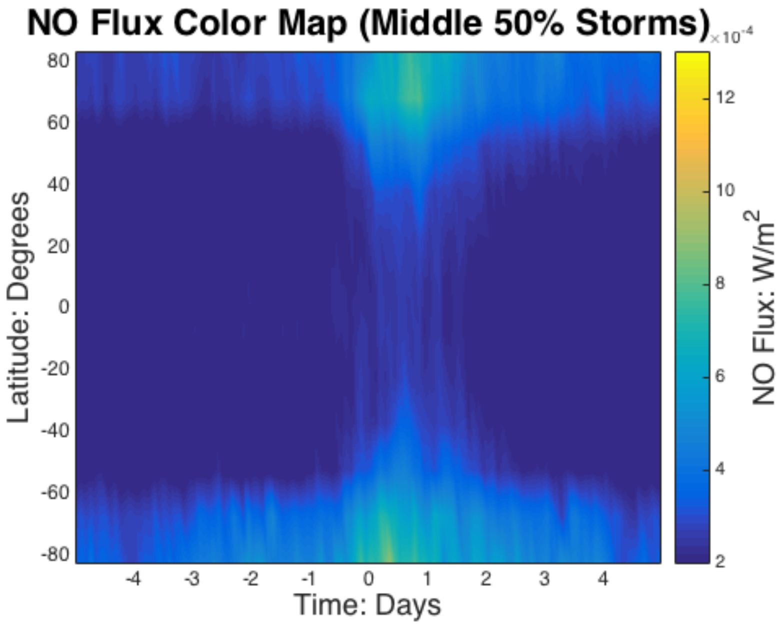


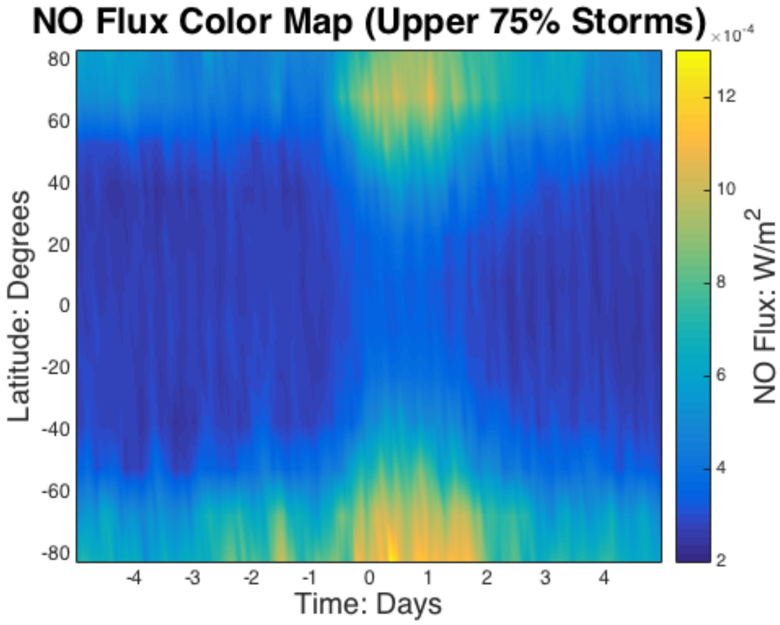
Courtesy of Marty Mlynczak

Nitric Oxide — Temporal Variations

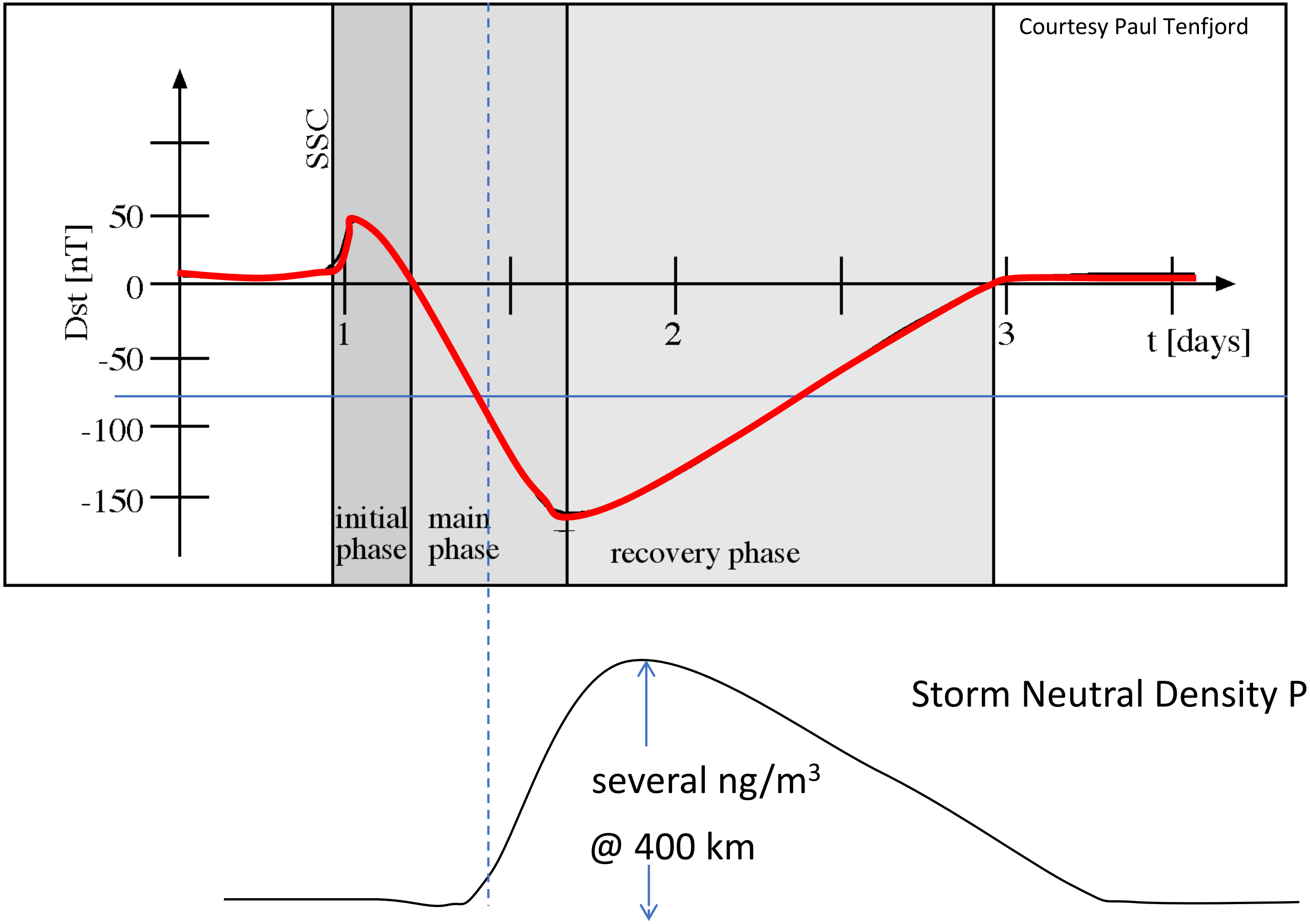
- **NO emissions are highly variable — during storm time**

Superposed Epoch Analysis (SEA) of SABER Data for Isolated Geomagnetic Storms 2010-2014





Dst Index and Neutral Density Perturbation



Courtesy Paul Tenfjord

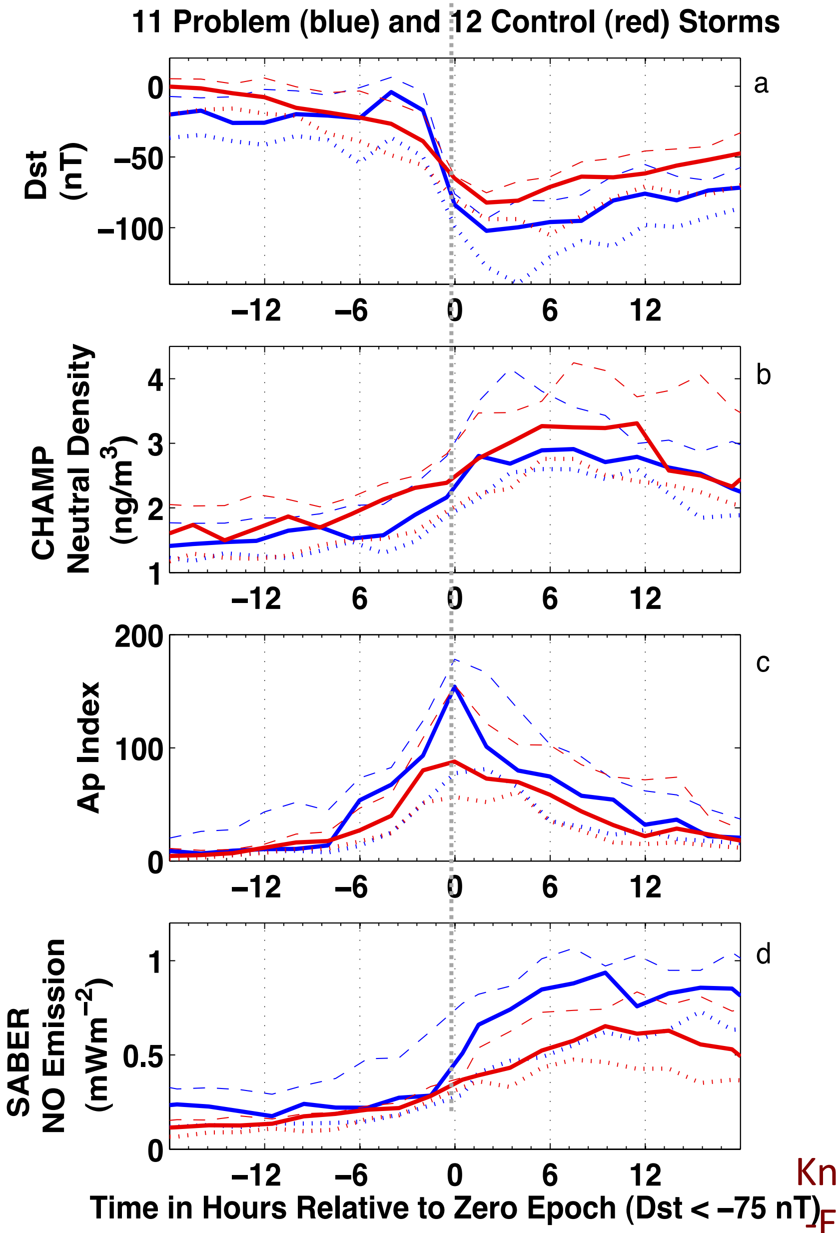
Storm Neutral Density Profile

several ng/m^3

@ 400 km

Bowman et al., 2008, Burke et al. 2009

Superposed Epoch Analysis



Problem-storm Dst has compression effect and larger negative perturbation*

Problem-storm neutral density has delayed, fast rise and then a sudden plateau

Problem-storm Ap Index is much higher

Problem storm Nitric Oxide Emission is much larger

Knipp et al., Thermospheric Damping Response to Sheath-Enhanced Geospace Storms, GRL 2013

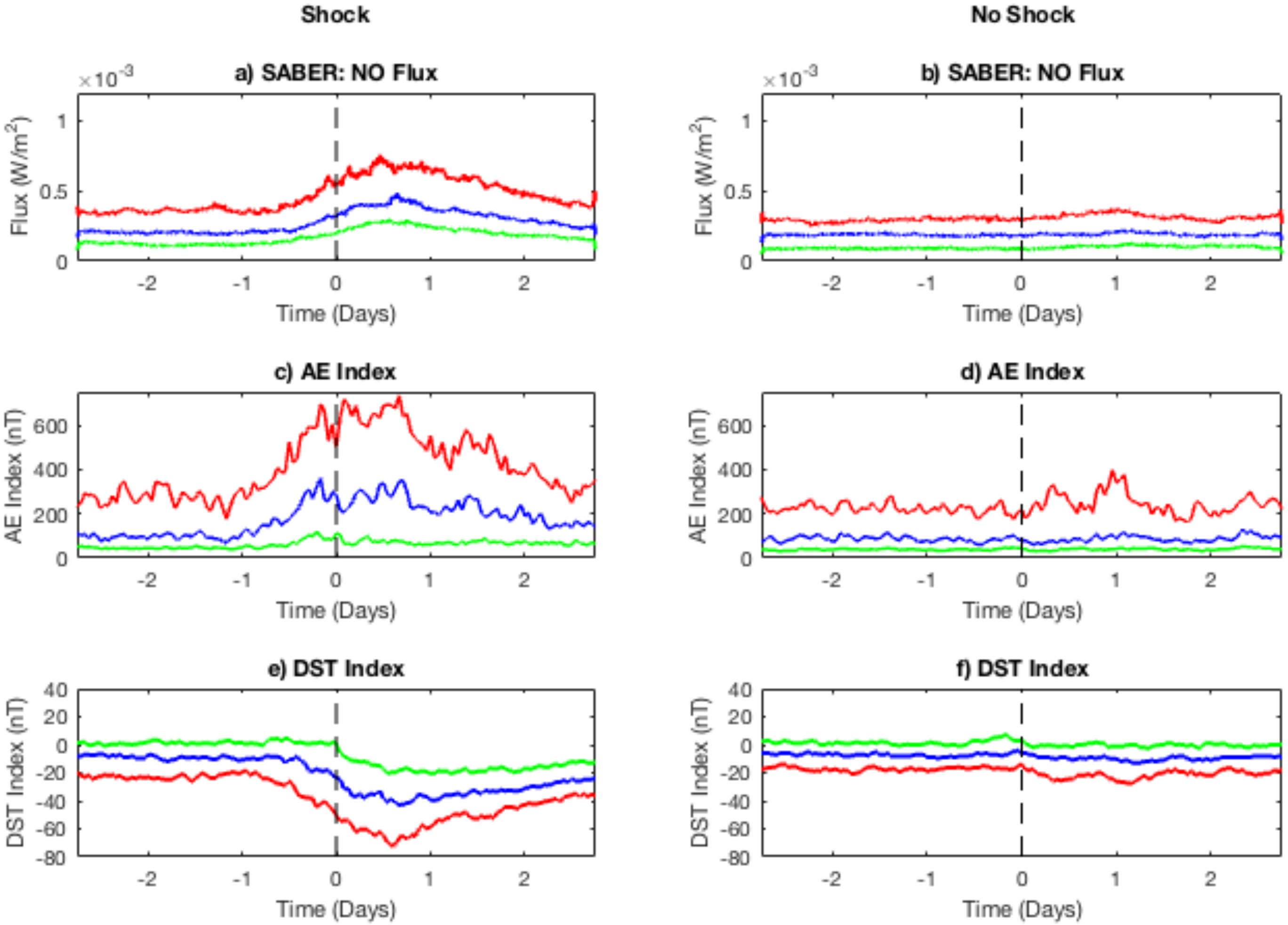
Superposed Epoch Analysis of CME 193 storms (2002-2014)

- Sorted by shock/non shock class

-- Top75%

-- Median

-- Bottom 25%



Knipp et al. (2017) submitted

- Shock-led storms have a distinct Nitric Oxide (NO) response
- Excess Nitric Oxide production alters storm energetics
    - May alter dynamics and temporal response profile

Superposed Epoch Analysis of 104 CME storms (2002-2010)

- All isolated and ejecta-driven
- Sorted by shock/non shock cloud/non cloud
- Shock-led magnetic storms show distinct NO emission and neutral density patterns
- Response to magnetic clouds is stronger

Magnetic Cloud

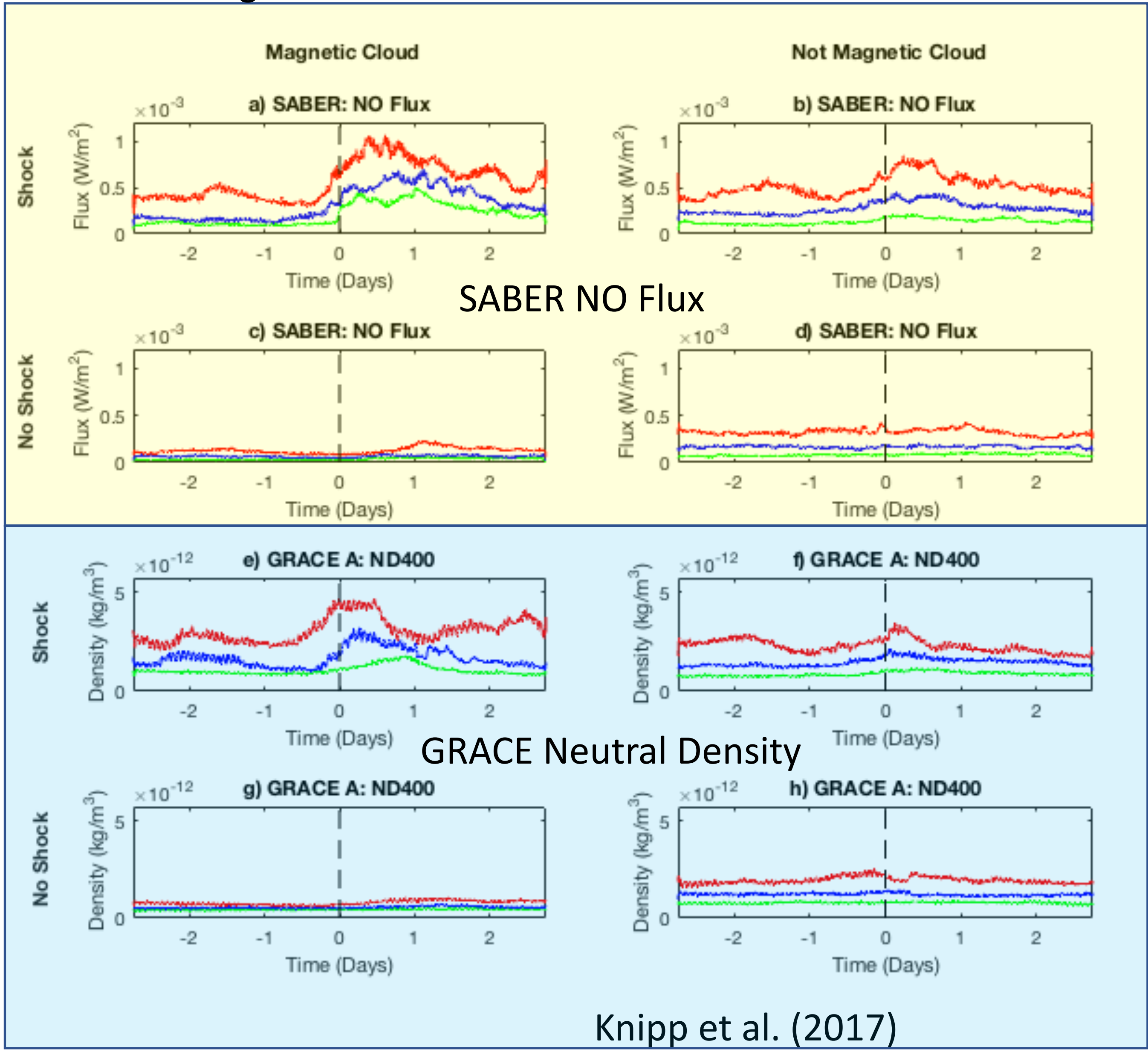
Non Cloud Ejecta

Shock

No shock

Shock

No shock



SABER NO Flux

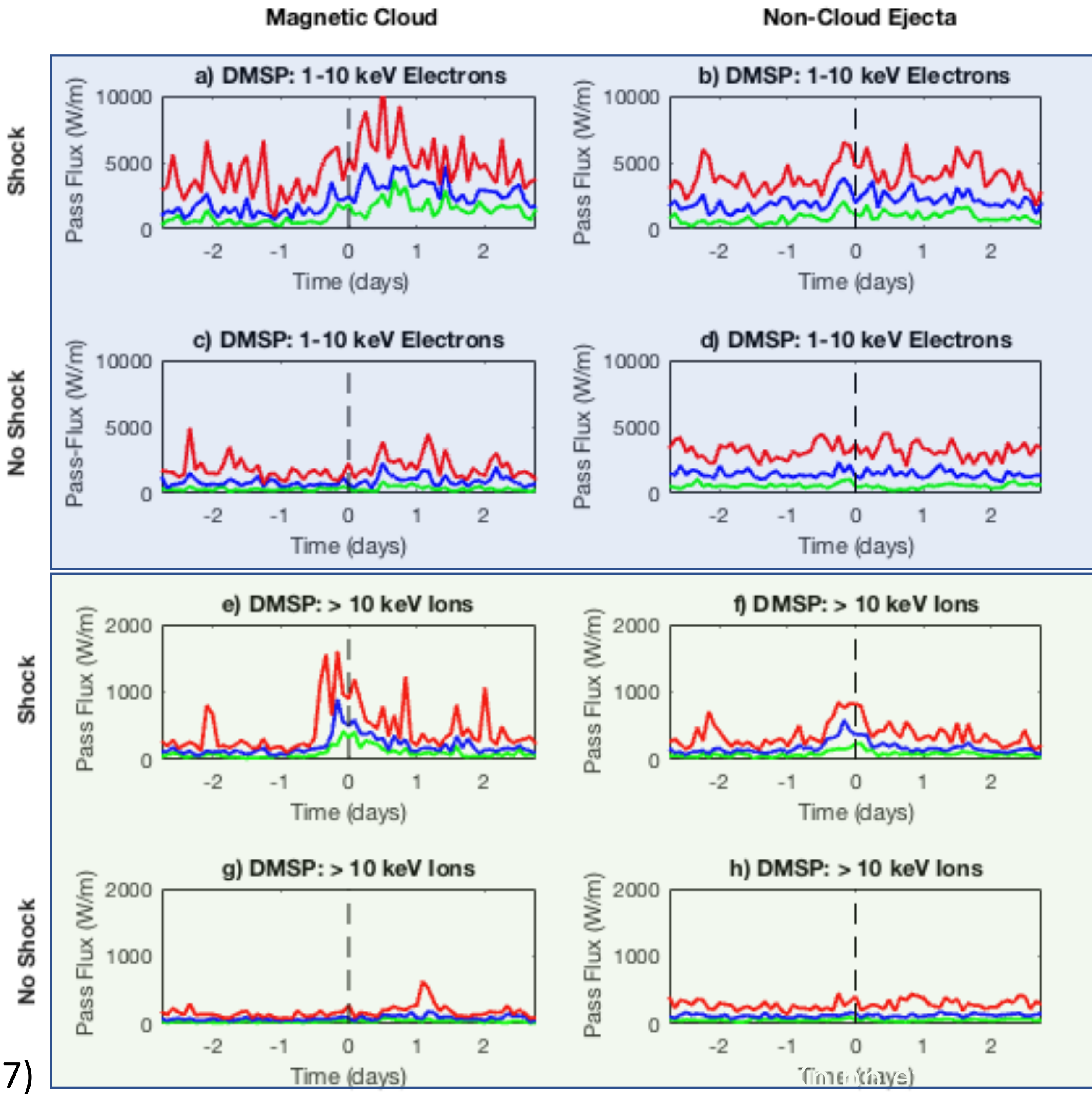
GRACE Neutral Density

Knipp et al. (2017)

Superposed Epoch Analysis of 104 CME storms (2002-2010)

Auroral Particles
Sorted by

Shock-led magnetic cloud
Shock-led ejecta
No shock magnetic cloud
No shock ejecta



Shock-led magnetic clouds have strongest response

Knipp et al. (2017)

Superposed Epoch Analysis of 104 CME storms (2002-2010)

Further sorted by

Shock-led magnetic cloud
Shock-led ejecta
No shock magnetic cloud
No shock ejecta

Shock magnetic cloud
have strongest response

Shock

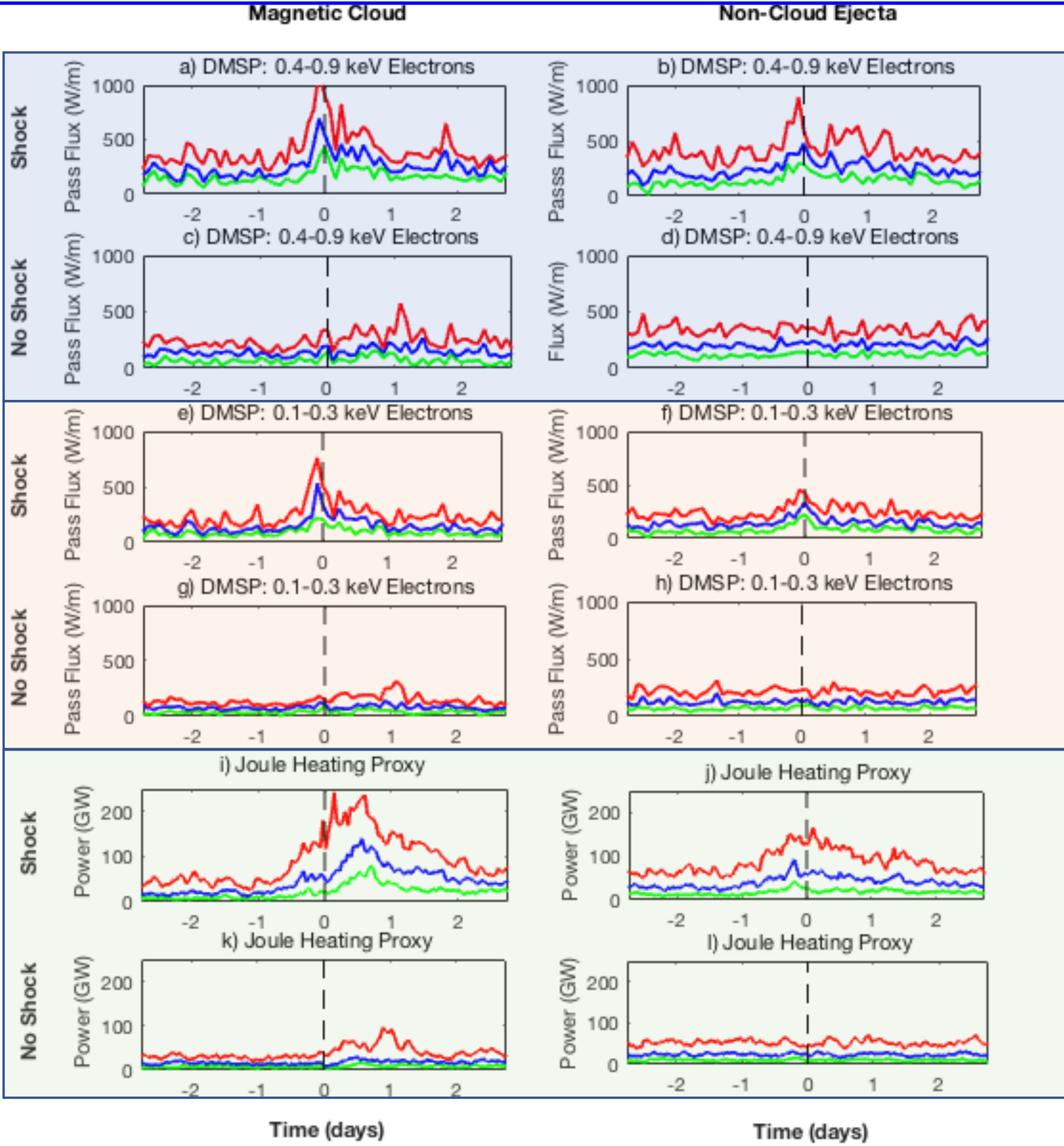
No shock

Shock

No shock

Shock

No shock



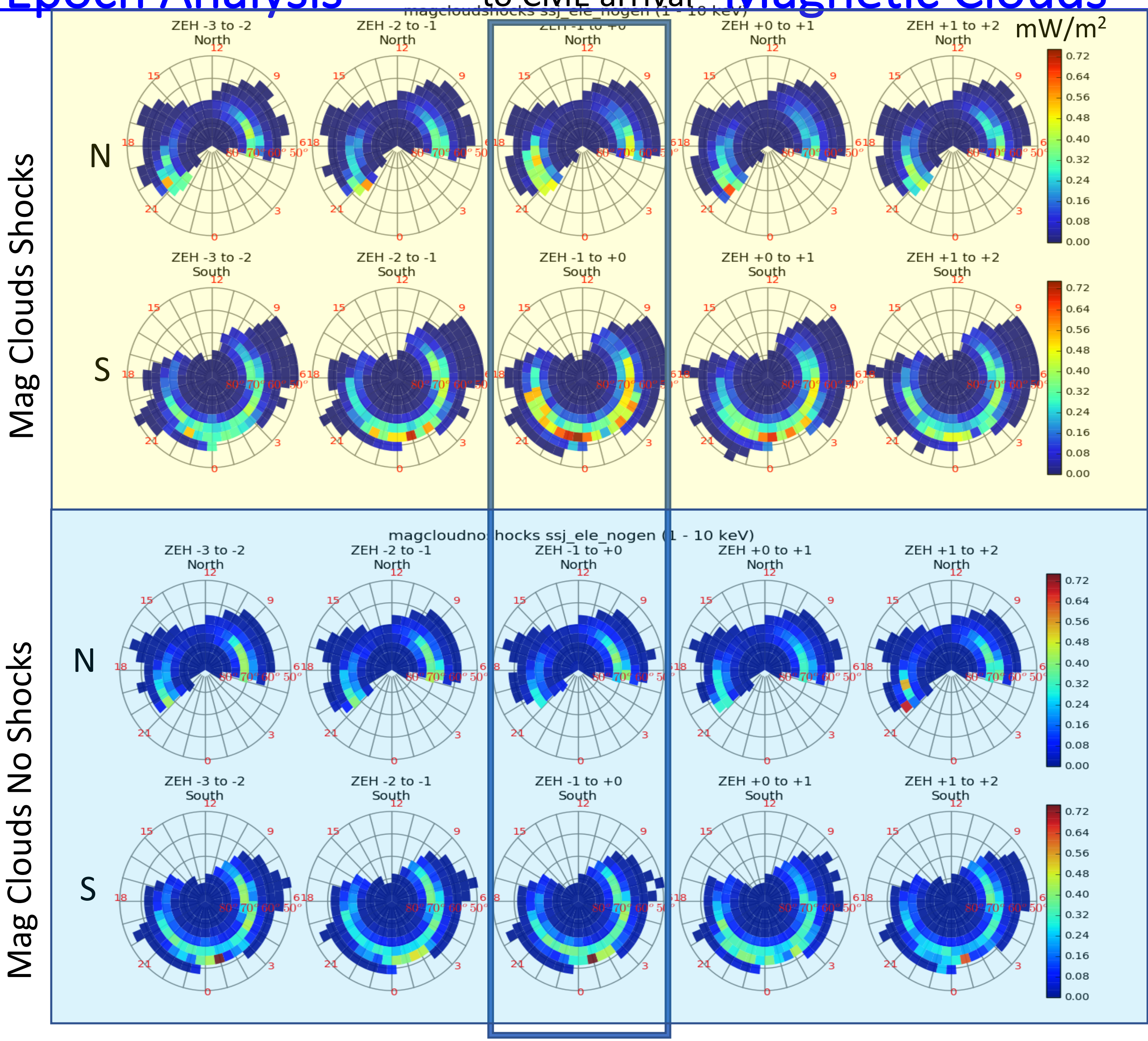
Knipp et al. (2017)

Superposed Epoch Analysis

Magnetic Clouds

1-10 keV electrons measured by DMSP 2002-2015

With shocks: Most intense particle precipitation 24 hr prior to cloud arrival



0-24 hr prior to CME arrival

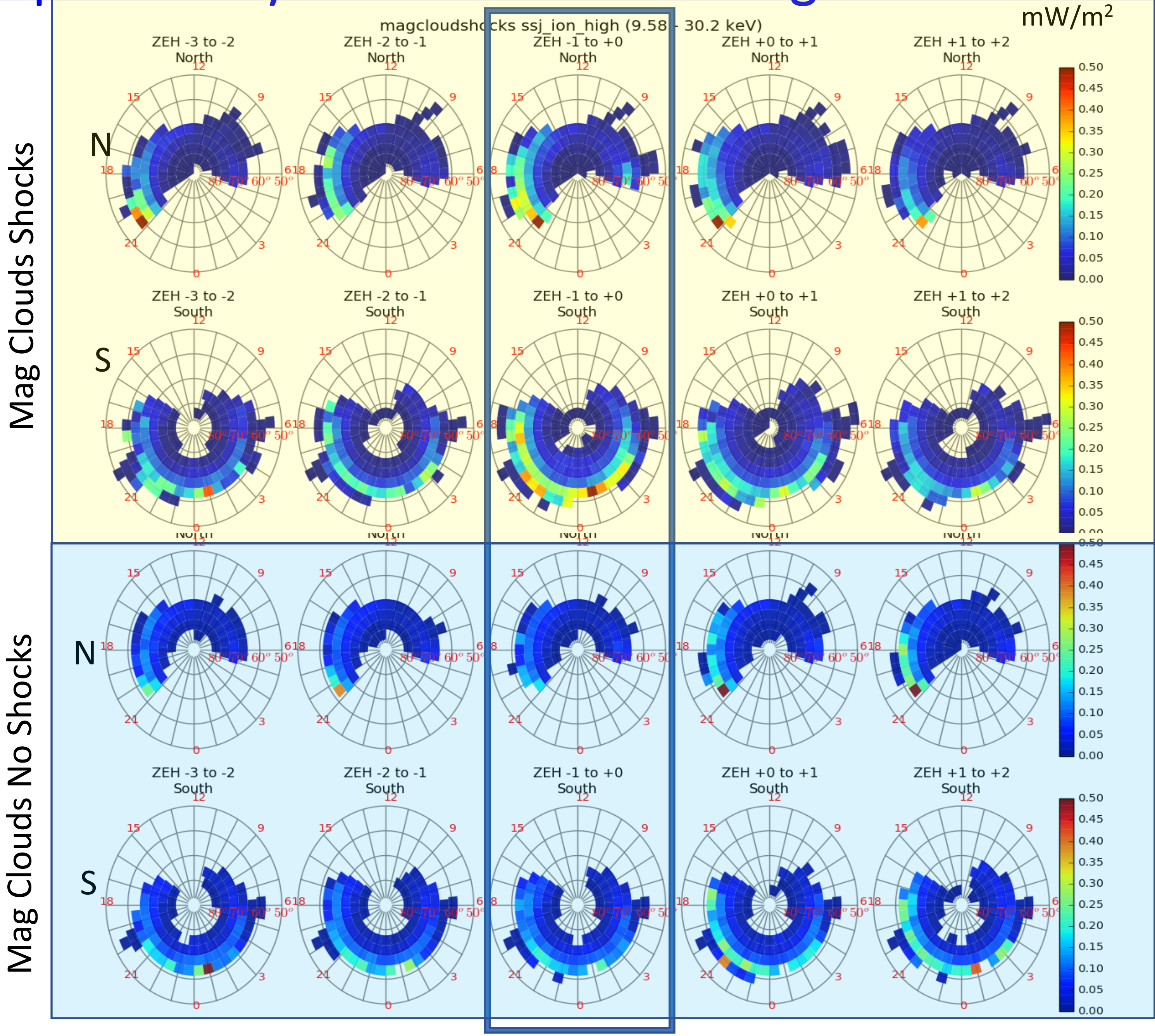
Mag Clouds Shocks

Mag Clouds No Shocks

Superposed Epoch Analysis Magnetic Clouds

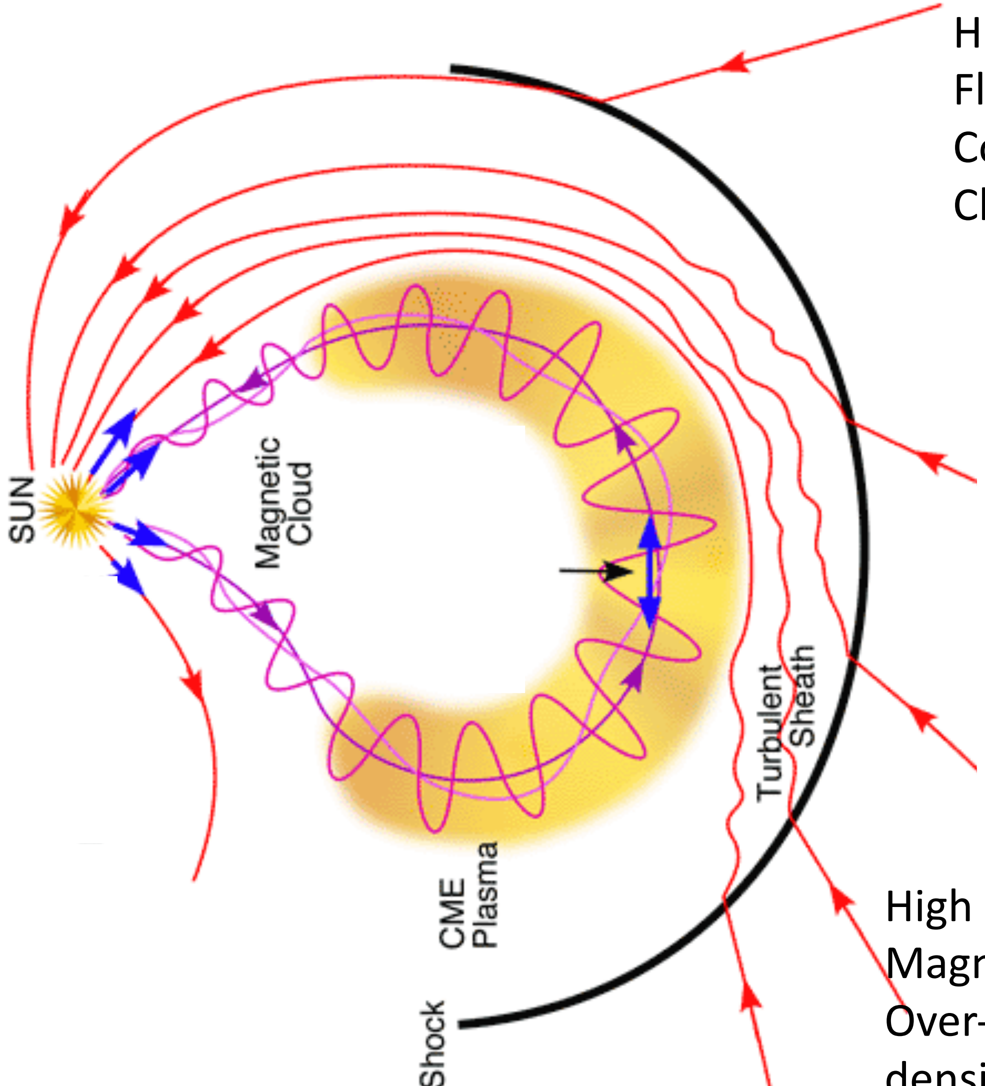
10-30 keV ions measured by DMSP 2002-2015

With shocks: Most intense particle precipitation 24 hr prior to cloud arrival



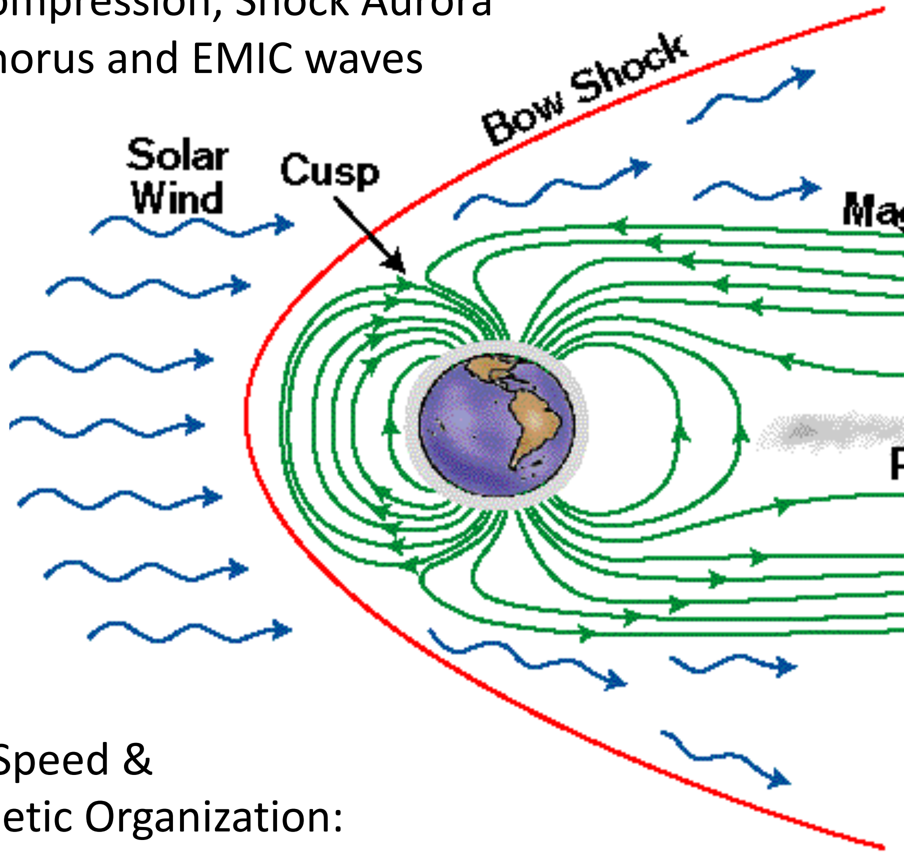
0-24 hr prior to CME arrival

Why are shock-led magnetic clouds so effective in producing NO emissions?



Courtesy of Deborah Eddy and Thomas Zurbuchen.

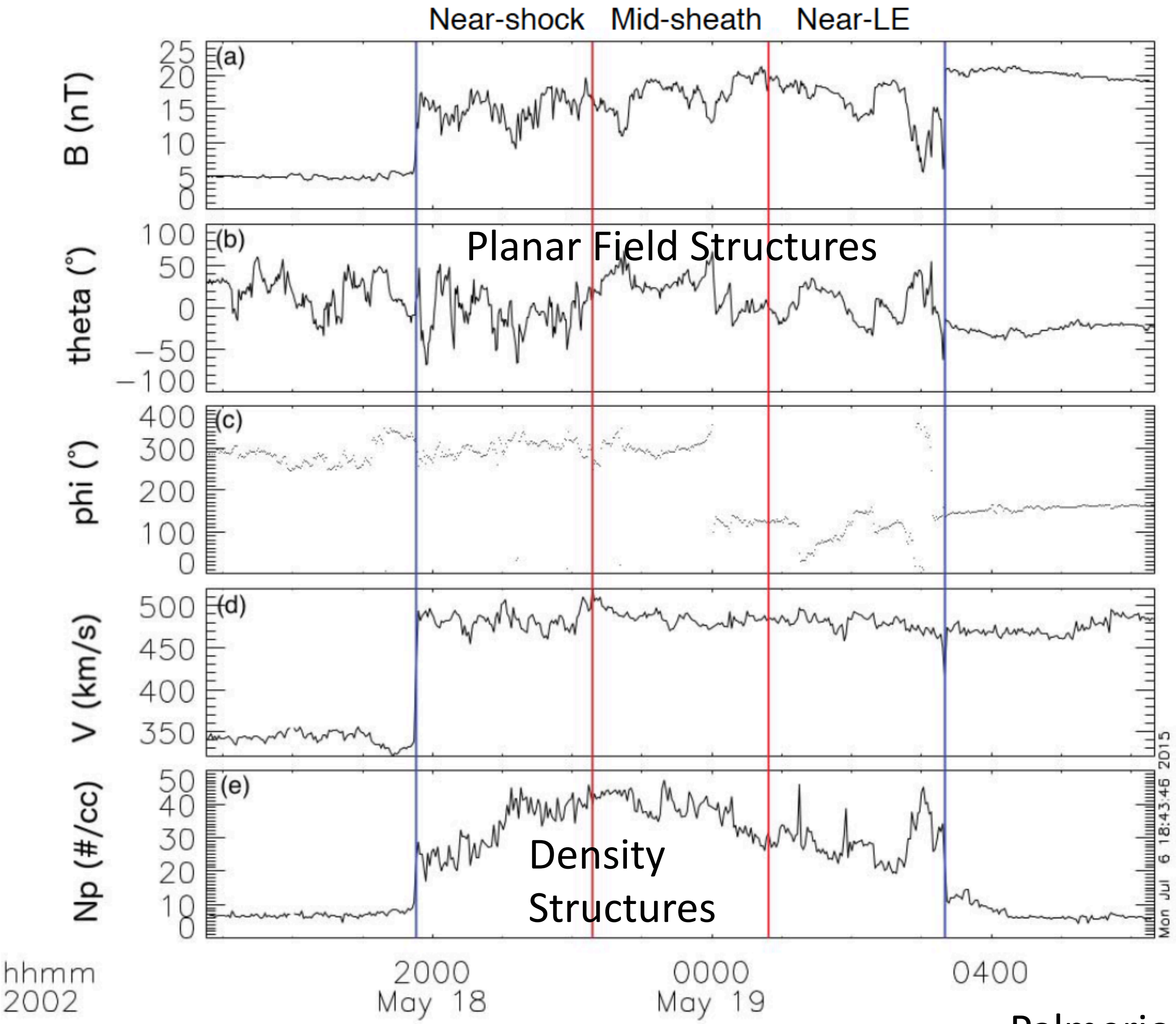
High SW Speed and Density and Fluctuations: Magnetopause Compression, Shock Aurora Chorus and EMIC waves



High Speed & Magnetic Organization: Over-draped field and density enhancements

Shock-Sheath

Undisturbed ← Sheath → ICME



Planar Field Structures

Density Structures

The sheath region between the CME edge tends to have organized magnetic and density structures that enhance geoeffectiveness of flow in advance of fast CMEs

Palmerio et al., 2017

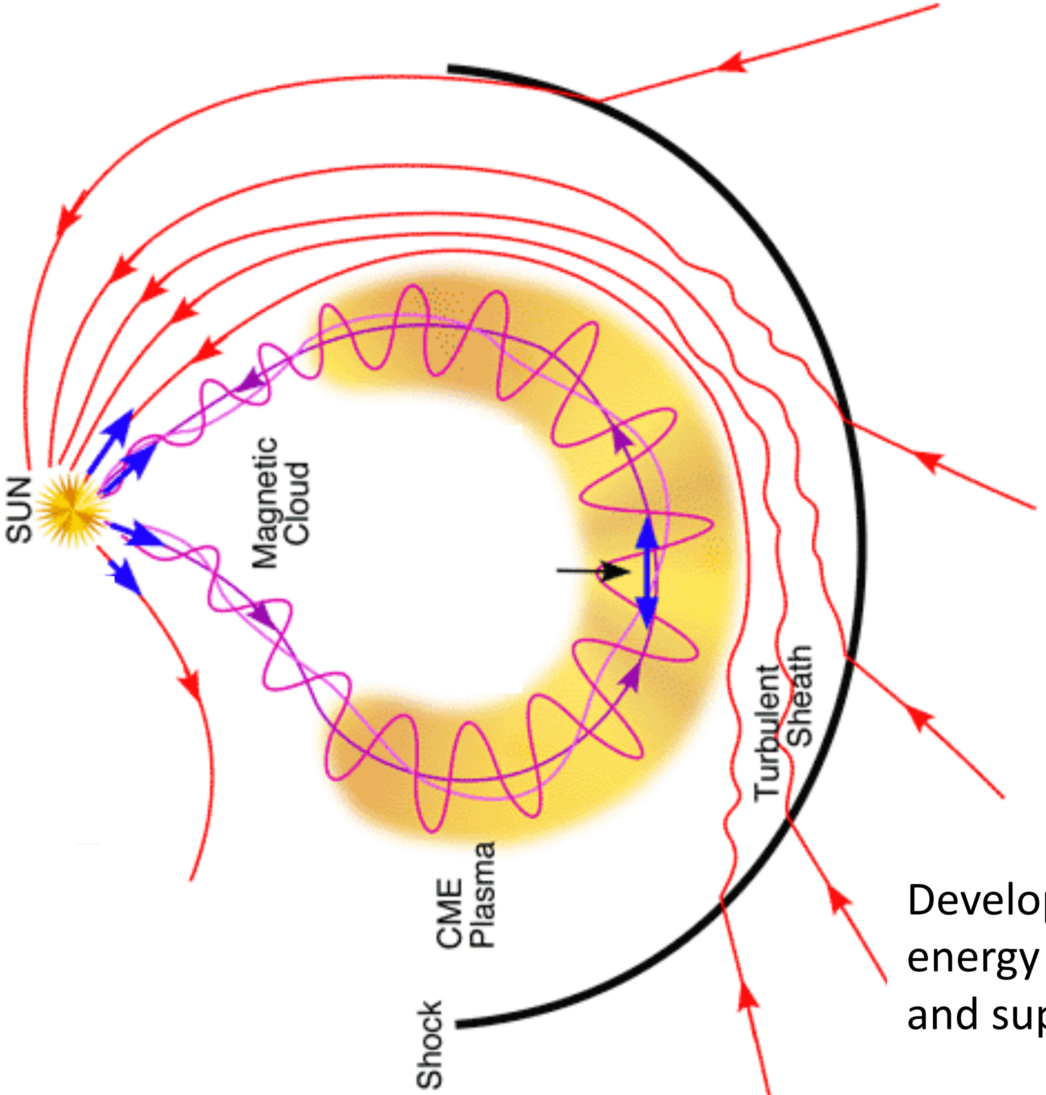
Inside the Magnetosphere

- Fast moving ICMEs tend to accumulate the ambient IMF within the sheath structure, building up of enhanced and draped magnetic field ahead of the ICME proper.
- Preexisting structures in the solar wind are swept up and compressed inside the sheath producing highly variable magnetic fields that tend to align as 2-D planar magnetic structures [Nakagawa et al., 1989; Palmerio et al., 2017, and references therein].
- Solar wind density variations in sheath produce discrete, global magnetospheric oscillations (Kepko and Spence, 2003, Li et al., 2011)
- Chorus and EMIC wave enhancement of 1-10 keV electrons and > 10 keV ions from convective and substorm processes?
- These particles along with enhanced Joule heating produce and facilitate NO emissions

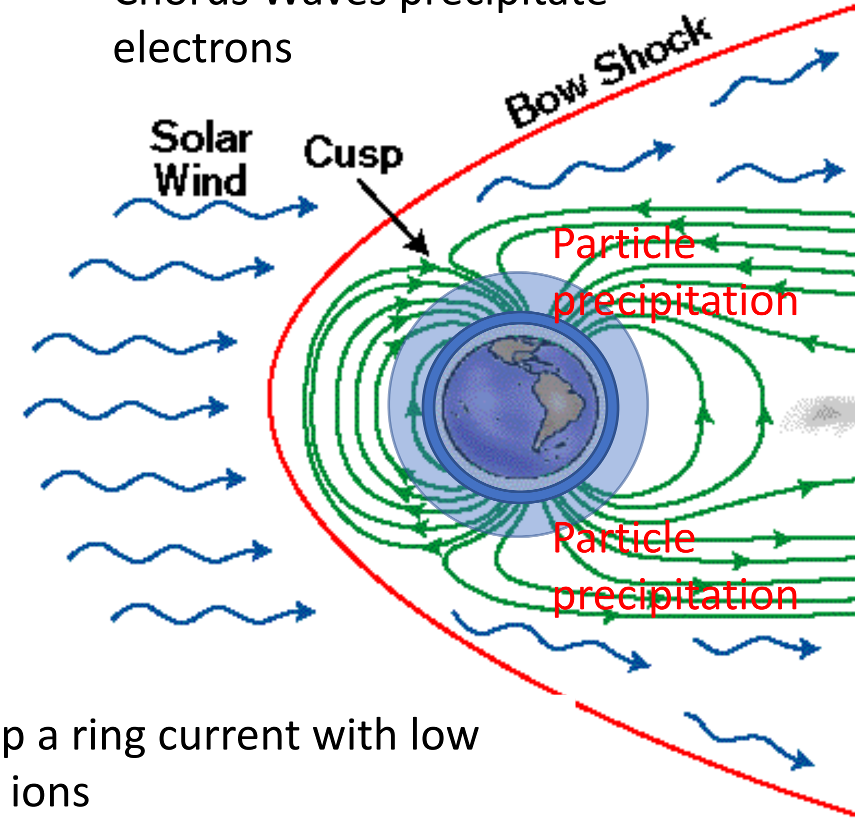
Shock-Sheath (details)

- Sheath: Compressed plasma with a high P_{dyn} and regions of large amplitude, |B|
- Fast moving ICMEs tend to accumulate the ambient IMF within the sheath structure, building up of enhanced and draped magnetic field ahead of the ICME proper.
- Faster CMEs: more IMF draping ahead of the ejecta & faster ICME speed and expansion rate. Gosling and McComas [1987]
- For situations with |B|>18 nT in the sheath, nearly 90% of the sheaths had stronger fields than those found in the ICME bodies. According to Owens and Cargill [2002]
- Ambient solar wind flow deflects around the leading edge of fast ICMEs, creating nonradial components of the plasma velocity in the sheath region [Owens and Cargill, 2004], which further enhance geoeffectiveness.
- Preexisting structures in the solar wind are swept up and compressed inside the sheath. These produce highly variable magnetic fields that tend to align as 2-D planar magnetic structures [Nakagawa et al., 1989; Palmerio et al., 2017, and references therein].
- Planar fields in ~85% of ICME sheaths, usually with stronger Bz field than the nonplanar parts, suggesting that planar sheaths are more likely to drive stronger magnetospheric activity. Palmerio et al. [2016]
- Badruddin and Singh [2009] investigate 150 MCs and note that shock-led MCs produce the largest geomagnetic disturbances.
- Gopalswamy [2009] reported that the MCs and NCEs seem to represent “head-on” and “glancing blows” by ICMEs, respectively.. Intercepting the shock front away from the nose, where the standoff distance is greater, produces a sheath that is less compressed [Owens et al., 2005].

Why are shock-led magnetic clouds so effective in producing NO emissions?



EMIC waves precipitate
>10 keV ions
Chorus Waves precipitate
electrons



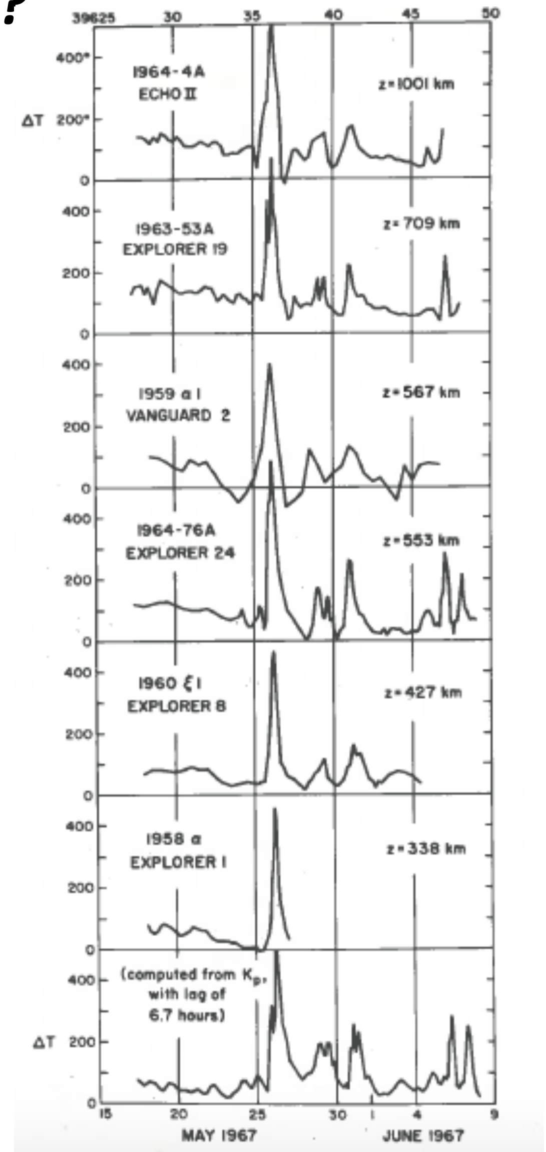
Develop a ring current with low energy ions
and support Joule heating

Courtesy of Deborah Eddy and Thomas Zurbuchen.

Historical Context

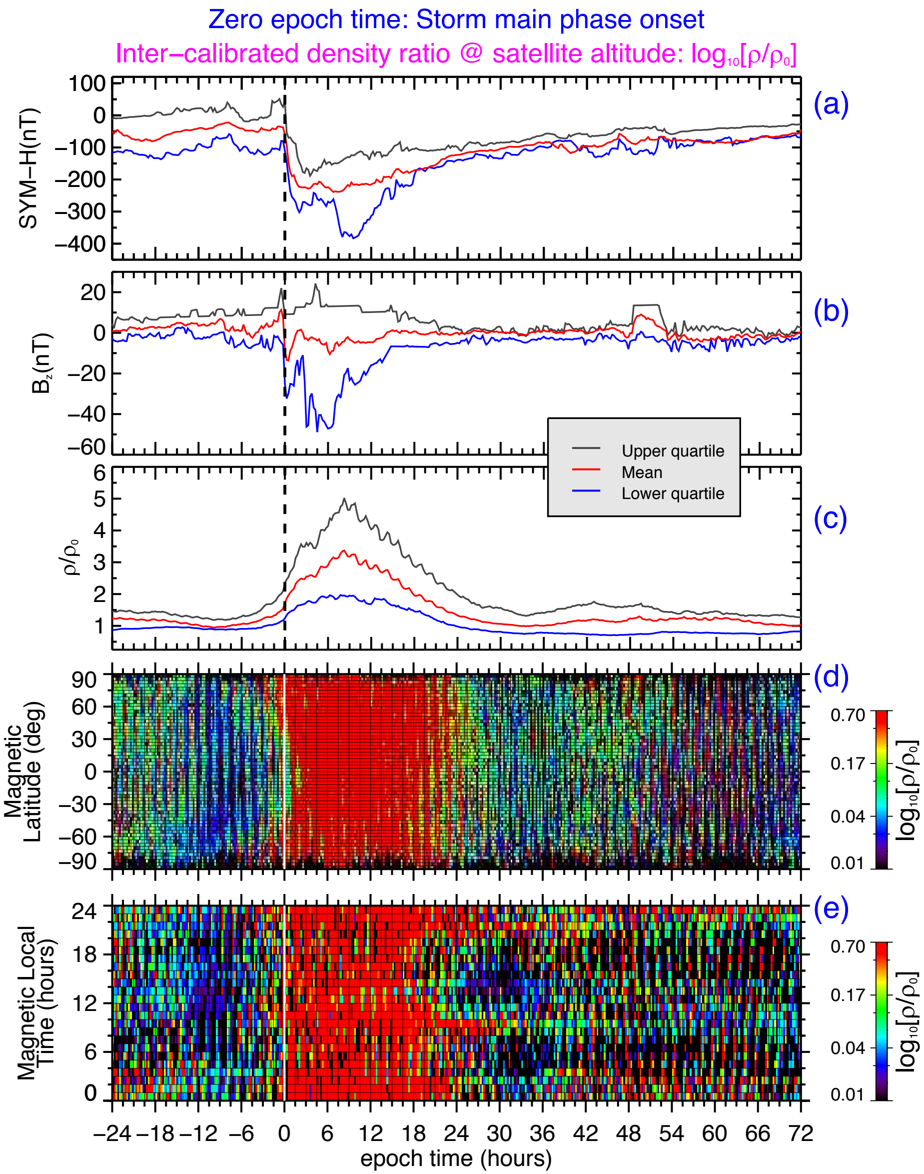
Unusual cooling events related to Nitric Oxide?

- *Jachiaa (1970) showed an extreme overcooling event*
  - *Thermospheric temperatures rise 400K*
  - *and then fall 500 K in a matter of hours*
- *Maeda et al. (1989) describe a*
  - *Kp =7 storm with unusual cooling attributes*
- *Liu et al.* (2007) data suggest an density damping
  - in July 2004 events
- *Lei et al., (2011, 2012) describe overdamping in the*
  - *October 2003 storms*
- *Knipp et al. (2013) suggested cooling/damping*
  - *as source of a dozen problem density storms*
- *Zesta et al. and Oliviera et al. (2017 submitted) Show fast density recovery for storms with Dst < -250 nT*



- ***Is there a pattern?***

Corroborating Evidence



Zesta, E., D. M. Oliveira, and H. K. Connor (2017), Observations of thermospheric response to extreme events, in Extreme Events submitted to Geospace: Origins, Predictabilty and Consequences, edited by N. Buzulukova, Elsevier, Philadelphia, PA.

Density variations for all magnetic storms 2001-2011 with CHAMP and GRACE data available, when possible

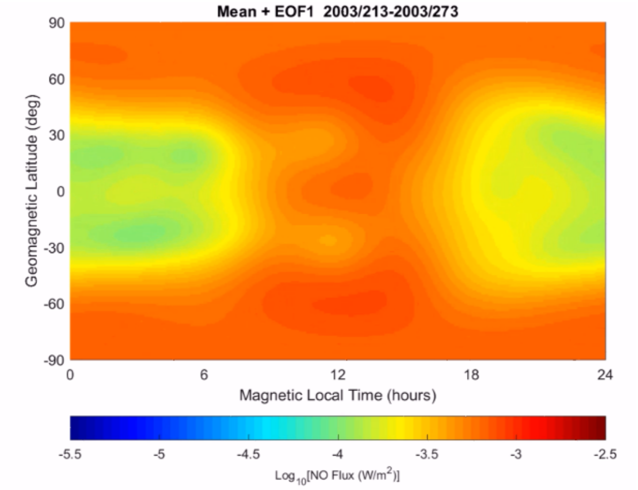
Density recovery 18-24 hours after storm main phase onset, but only 12 hours for storms with Dst < -250 nT

Epilogue

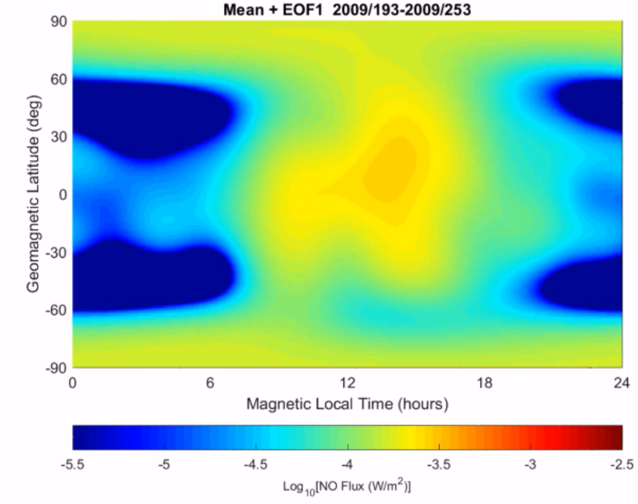
- Oberheide et al. (2013) show an impact of tropospheric tides on the nitric oxide 5.3 m infrared cooling of the low-latitude thermosphere during solar minimum conditions
- McGranaghan et al. (2014) report that even moderate storms show a pre-conditioning NO effect
- Zhang et al. (2014) illustrate storm-time behaviors of O/N_2 and NO variations from TIMED GUVI
- Weimer et al. (2016) create an empirical model relating NO emissions to solar and geomagnetic indices with very high correlation coefficients
- Oliveira et al (2017 submitted) show pre storm effects on neutral density
- Zheng et al. CEDAR (2017) Tue talk shows TIMED GUVI comparisons with TIEGCM model and discusses role meridional transport of NO during storm time
- Flynn et al. CEDAR (2017) Wed poster shows EOF analysis of SABER NO data and raises intriguing questions about role of solar active region emissions

New Results and New Views:
SABER NO Emissions 60-day Mean Patterns & EOFs
S. Flynn et al. Poster Wed night

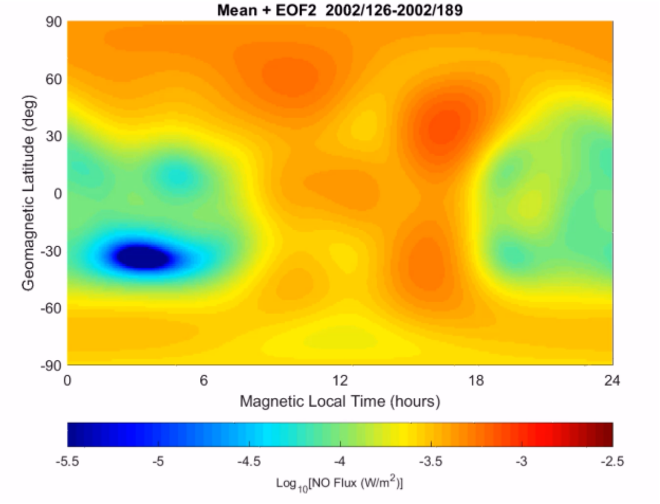
Solar Max



Solar Min



NH Summer



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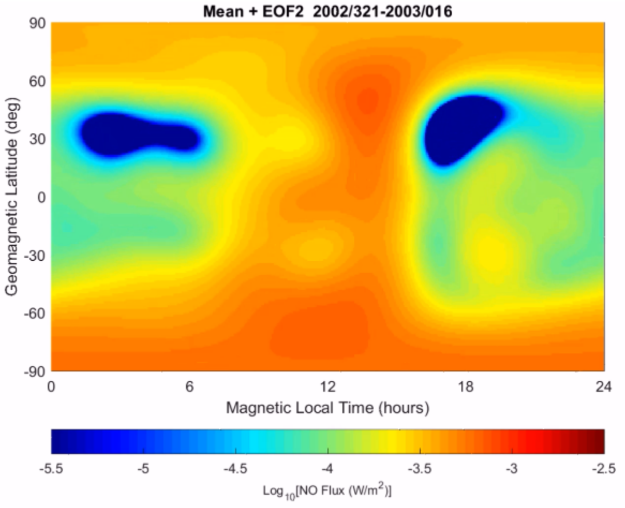

Solar input, Auroral input, seasonal variations, meridional transport, tides and more

Conclusions

- Shock-led storms produce more NO emissions
- Shock-led magnetic clouds tend to be the top producers
- The fastest CMEs (usually the largest) storms produce a condition where the thermospheric NO fights back to maintain energy balance in a strongly heated regime
- Some events may overcool (May 1967, Oct 2003, July 2004) making neutral density forecasting very challenging
- Only a full view of the Space Weather System explains this behavior

Knipp et al., Space Weather, 2017

Acknowledgements

- Many useful discussions with HAO colleagues
- Thanks to students who continue come up with intriguing results and questions
- Liam Kilcommons who tirelessly processes data for these studies
- David Berens, my husband, who listens to endless science discussions over breakfast, lunch and dinner
- NSF, AFOSR and NASA funding

Thank You!


Thermosphere
Mesosphere
Stratosphere
Troposphere
You are here

Abridged History: Global Observations and 3-D Models

- Siskind et al. [1989] NO density increases as a result of the temperature increase during the Joule heating event owing to the role played by the temperature-sensitive reaction between ground-state nitrogen atoms and molecular oxygen.
- Lou et al. (1993, GRL) factor of 3 increase in NO mixing ratio above ~115 km at 50◦N during 8-9 Nov 1991 storm observed by Upper Atmosphere Research Satellite HALOExperimet
- Marsh et al (2004) produced first Principle Component analysis of NO density from SNOE data
- Richards [2004, JGR] using Atmosphere Explorer C data and Dobbin and Aylward [2008, JASTP] use model results suggested that downward transport increases NO at lower altitudes during storms.
- Barth et al. (2010, JGR) increase in stormtime NO density equatorward of the auroral region during a Joule heating event is the result of the transport of heat equatorward by a gravity wave with the increase in NO taking place at midlatitudes
  - both the SNOE observations and the TIEGCM calculations show that the increase in NO density in the 150-km level is followed by downward transport of NO molecules to the 110-km level.
  - When the heated thermosphere was illuminated by solar radiation, the density of nitric oxide increased over this entire latitude region because of a temperature-sensitive reaction between ground state nitrogen atoms and molecular oxygen
- TIMED SABER measures NO 5.3 um emissions beginning in 2002

Thermospheric nitric oxide response to shock-led storms

- We present a multiyear superposed epoch study of the Sounding of the Atmosphere using
- Broadband Emission Radiometry nitric oxide (NO) emission data. NO is a trace constituent in the
- thermosphere that acts as cooling agent via infrared (IR) emissions. The NO cooling competes with storm
- time thermospheric heating resulting in a thermostat effect. Our study of nearly 200 events reveals that
- shock-led interplanetary coronal mass ejections (ICMEs) are prone to early and excessive thermospheric NO
- production and IR emissions. Excess NO emissions can arrest thermospheric expansion by cooling the
- thermosphere during intense storms. The strongest events curtail the interval of neutral density increase and
- produce a phenomenon known as thermospheric **“**overcooling.**”** We use Defense Meteorological Satellite
- Program particle precipitation data to show that interplanetary shocks and their ICME drivers can more than
- double the fluxes of precipitating particles that are known to trigger the production of thermospheric NO.
- Coincident increases in Joule heating likely amplify the effect. In turn, NO emissions are more than double.
- For some events, there may be an additional factor of early NO production due to solar flares. Perhaps a more potent combination of solar
- wind events involves a series of ICMEs, especially if the interplanetary path has been “cleared” for the second
- or subsequent ICME. We discuss the roles and features of shock/sheath structures that allow the thermosphere to temper the
- effects of extreme storm time energy input. Shock-driven thermospheric NO IR cooling likely plays an important role in satellite drag
- forecasting challenges during extreme events.