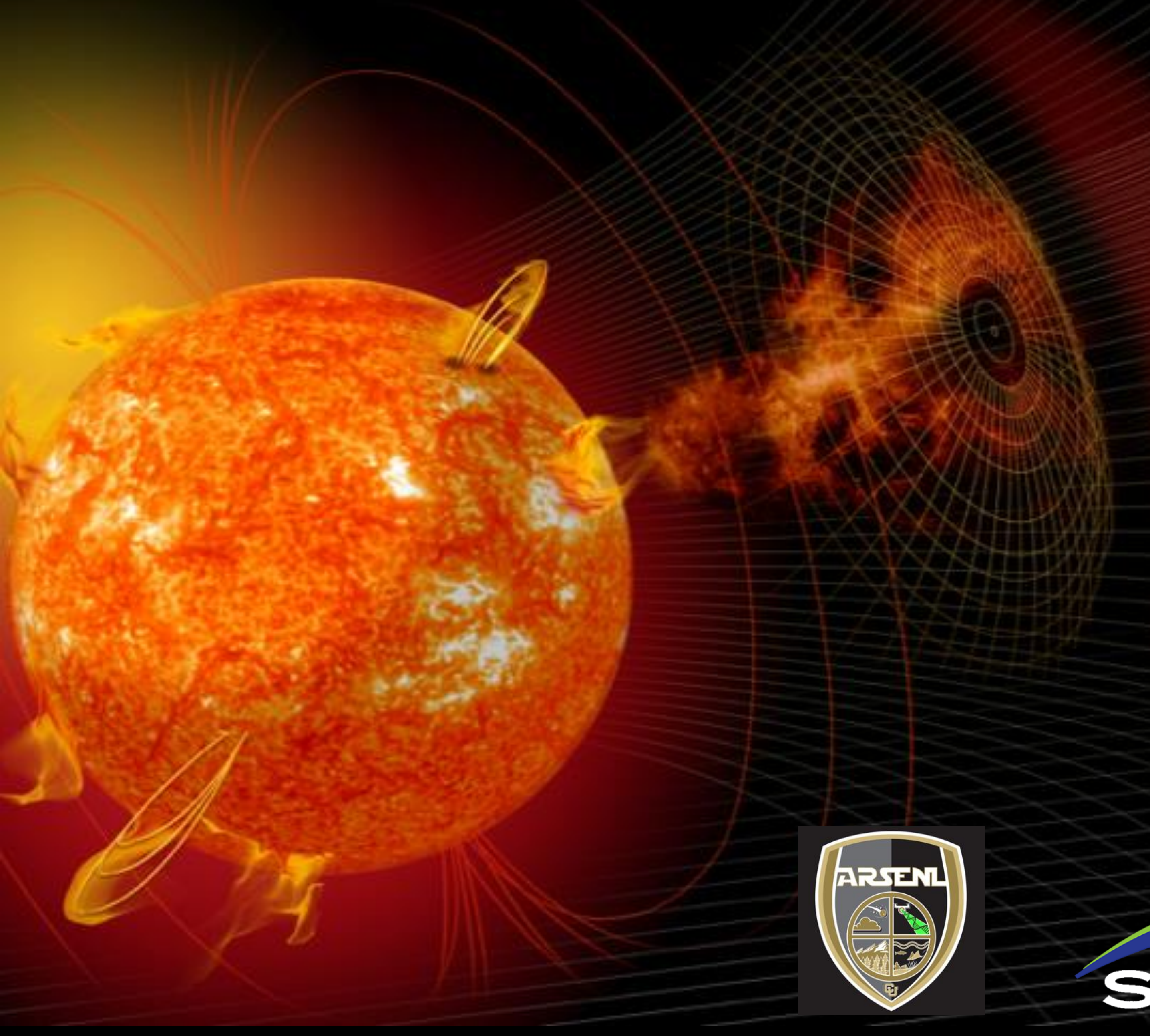
Our Entangled Thermosphere-Ionosphere System



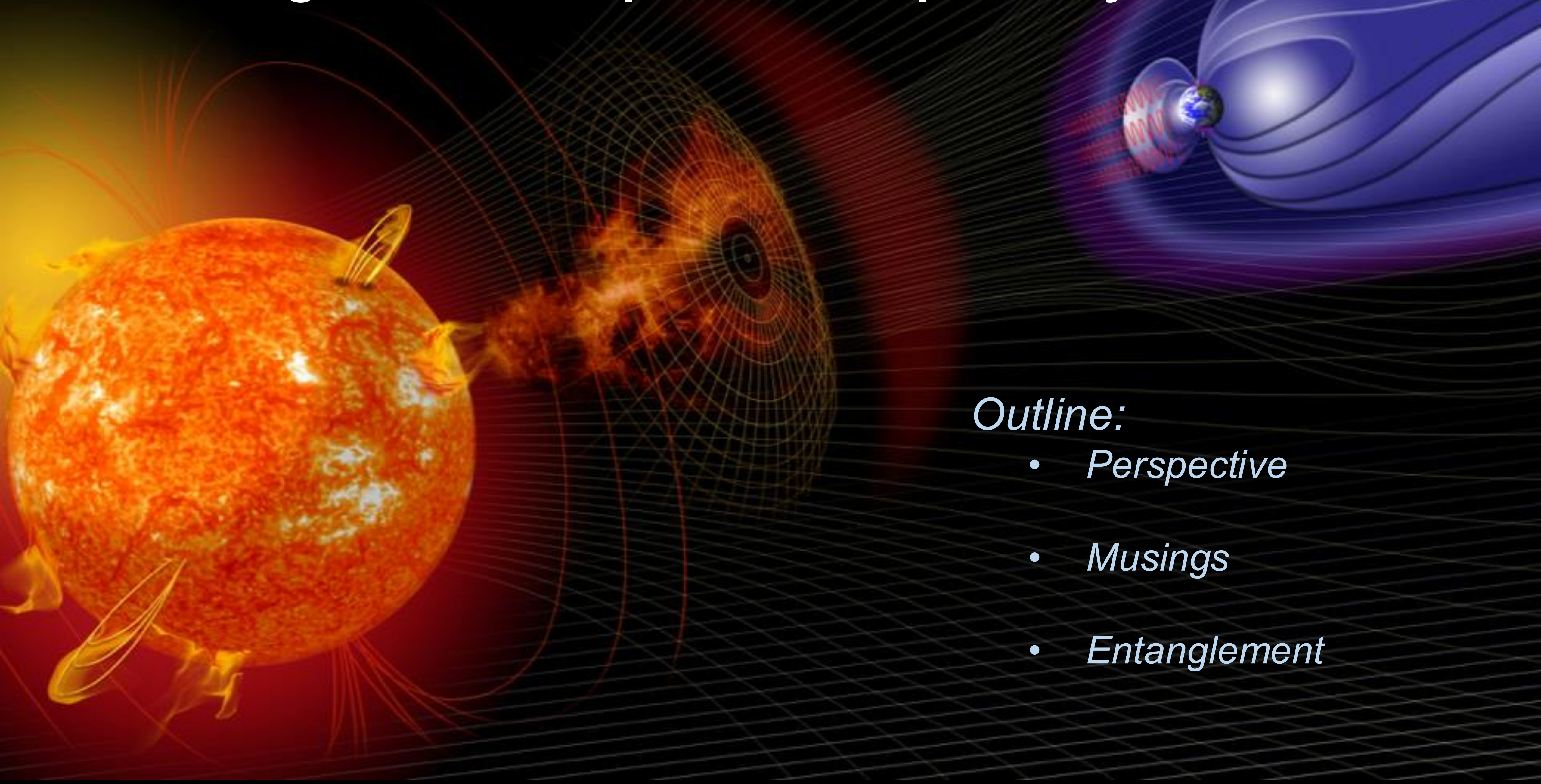
Professor Jeff Thayer, Aerospace Engineering Sciences Department, University of Colorado at Boulder

ARSENL

SWx TREC

CCAR

Our Entangled Thermosphere-Ionosphere System



Outline:

- *Perspective*
- *Musings*
- *Entanglement*

HIGH ALTITUDE OBSERVATORY
NATIONAL CENTER FOR ATMOSPHERIC RESEARCH
P. O. Box 3000; Boulder, Colorado 80307
Telephone: (303) 497-1500; Telex: 989764

June 3, 1987

MEMO TO: J. Thayer

FROM: Kathryn Drake, HAO/NCAR, (303) 497-1502

SUBJECT: Registration for the Second Summer CEDAR Workshop, June 29-July 2, 1987, in Boulder, Colorado

Thank you for your registration form and the fee indicated below. We look forward to your participation in the workshop.

$40.00 registration fee: ________

$50.00 registration (late) fee: ✓

$10.00 registration fee for those attending June 29 only: ________

$20.00 Flagstaff barbecue guest fee: ________

$25.00 NCAR dinner guest fee: ________

Other: ________

Please note that, to date, we have received registration from 140 people, many more than can be accommodated in the NCAR Main Seminar Room. A video camera will be set up in the Main Seminar Room with a couple of monitors in the Damon Room. If you are assigned a late registration number below, we ask that you view the invited talks from the Damon Room monitors. We are sorry for the inconvenience.

Late Registration # 137

Since the NCAR parking area will be crowded too, please car pool whenever possible. Thank you.

Tuesday, June 22, 1993 - NIST Auditorium

Chairman: R. Robinson, National Science Foundation

8:30 - 9:00	NSF/CEDAR Issues - R. Behnke
9:00 - 9:45	Tutorial Lecture #2 R. Meier - UV Spectroscopy
9:45 - 10:00	Break

Chairman: R. Behnke, National Science Foundation

10:00 - 12:30	CEDAR 10th Anniversary Celebration A light-hearted look at: Conception - M. Biondi Early Days - G. Romick NSF Perspective - R. Behnke Growth of Program - T. Killeen From Student to CEDAR Awardee - J. Thayer LTCS Campaigns - J. Salah GISMOS Campaigns - O. De la Beaujardiere GTMS ETS GTS GITCAD CADITS CAT Campaigns - A Retrospective of Collaborative Thermospheric Studies - M. Hagan AIDA Campaigns - J. Meriwether Present Days - M. Kelley
12:30 - 1:30	Lunch
1:30 - 5:30	Workshops at Foothills
	Extra-Curricular Extra-Fare Activity
5:11 - 6:16	Buses leave Boulder bus terminal for Stadium
7:05 - ?	Colorado Rockies vs Cincinnati Reds Baseball Game

CEDAR and Students

- Develop a sense of community
- Develop transferrable skills for the changing marketplace
- Have total access to researchers in their field
- Have the opportunity to present their research at various stages of their graduate career
- Are essential for the future direction of CEDAR

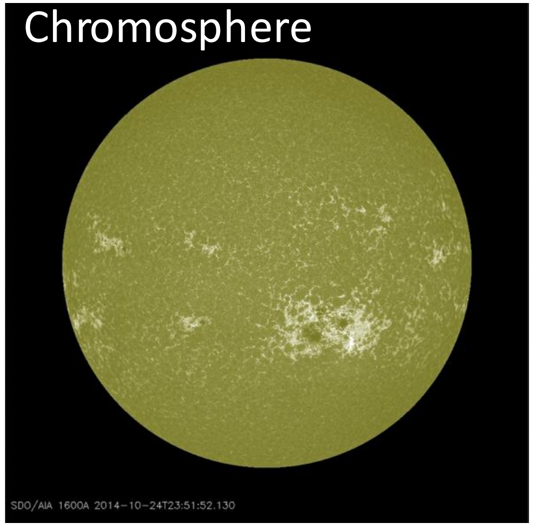
Perspective

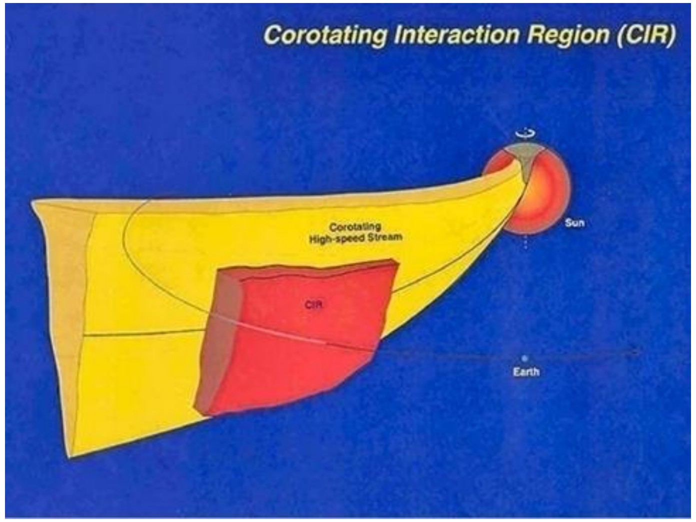
Wiener Quote

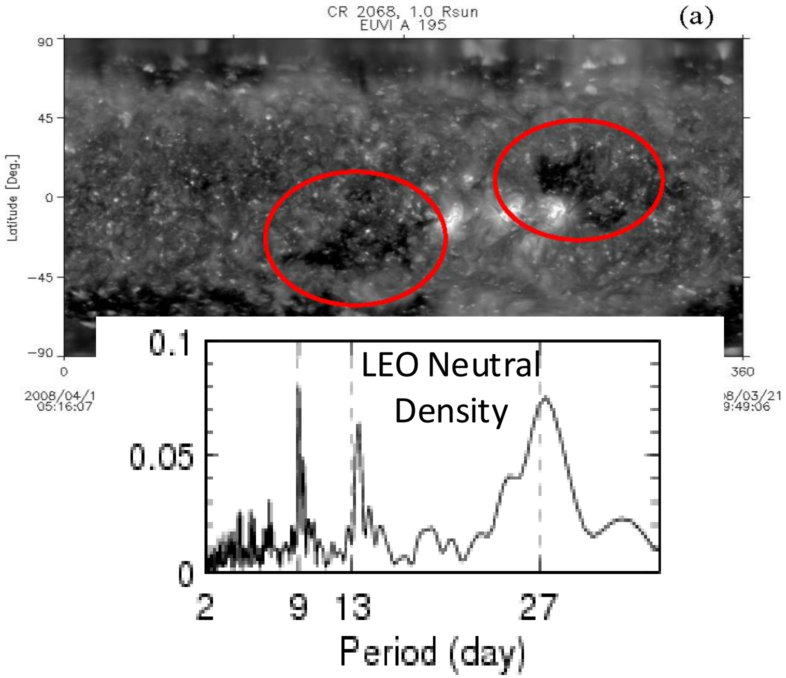
The most fruitful areas for growth of the sciences are those between established fields. Science has been increasingly the task of specialists, in fields which show a tendency to grow progressively narrower. Important work is delayed by the unavailability in one field of results that may have already become classical in the next field. It is these boundary regions of science that offer the richest opportunities to the qualified investigator.

– *Norbert Wiener*

From Sun to Mud

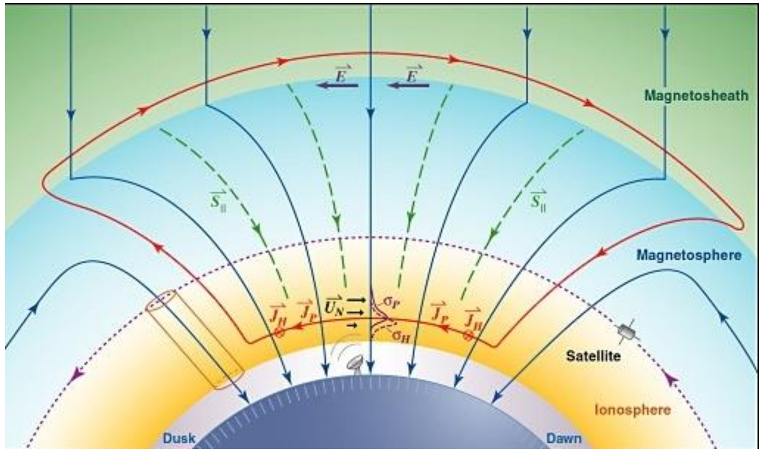


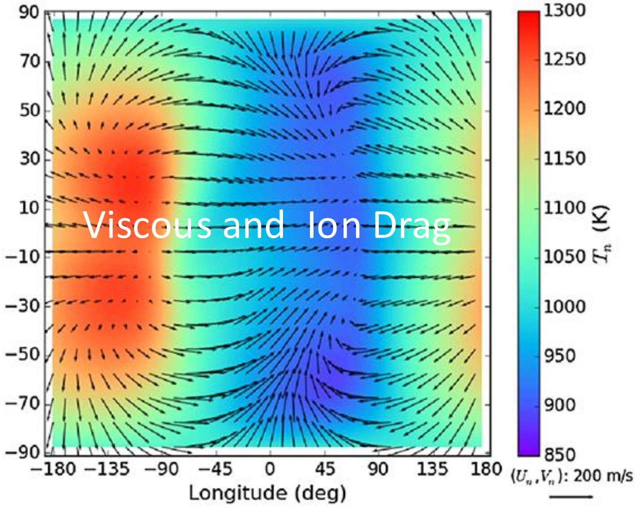


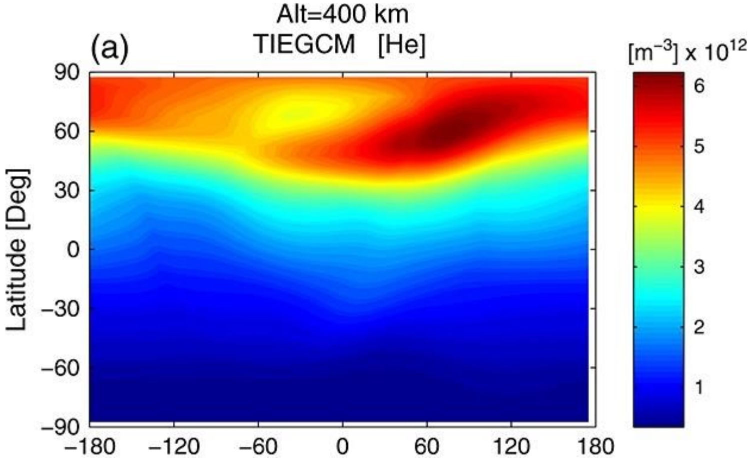


- Leake, J. E.; DeVore, C. R.; Thayer, J. P.; Burns, A. G.; Crowley, G.; Gilbert, H. R.; Huba, J. D.; Krall, J.; Linton, M. G.; Lukin, V. S.; Wang, W. (2014), Ionized Plasma and Neutral Gas Coupling in the Sun's Chromosphere and Earth's Ionosphere/Thermosphere, Space Science Reviews, Volume 184, Issue 1-4, pp. 107-172, doi: 10.1007/s11214-014-0103-1.
- Thayer, J. P., J. Lei, J. M. Forbes, E. K. Sutton, and R. S. Nerem, Thermospheric density oscillations due to periodic solar wind high-speed streams, J. Geophys. Res., 113, A06307, doi:10.1029/2008JA013190, 2008.
- Lei J., J. P. Thayer, J. M. Forbes, Q. Wu, C. She, W. Wan, W. Wang, Ionosphere response to solar wind high-speed streams, Geophys. Res. Lett., 35, L19105, doi:10.1029/2008GL035208, 2008.

From Sun to Mud

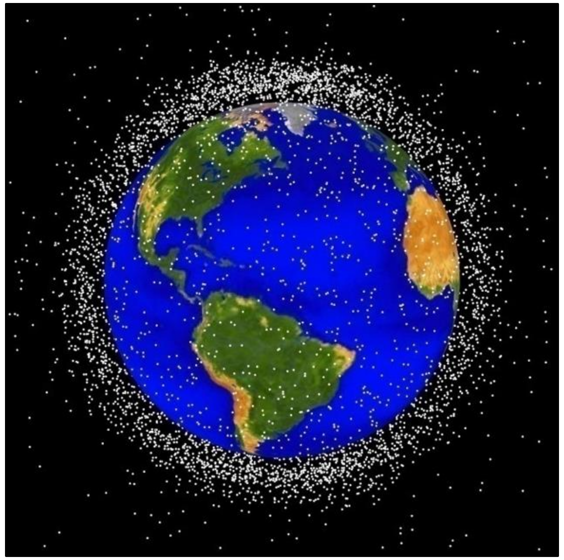


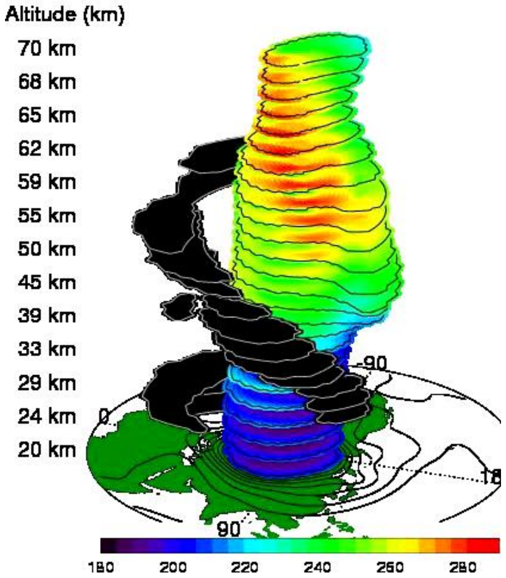


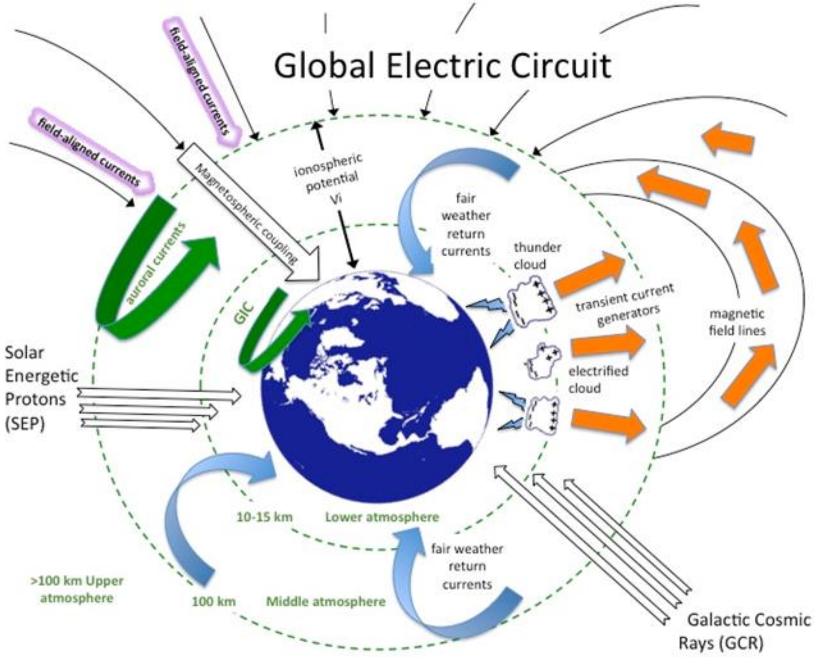


- Thayer, J. P. and J. Semeter, "The convergence of magnetospheric energy flux in the polar atmosphere," doi: 10.1016/j.jastp.2004.01.035, 66, 10, pp. 805-822, 2004.
- Hsu, V. W., J. P. Thayer, W. Wang, and A. Burns (2016), New insights into the complex interplay between drag forces and its thermospheric consequences, J. Geophys. Res. Space Physics, 121, 10,417–10,430, doi:10.1002/2016JA023058.
- Thayer, J. P., X. Liu, J. Lei, M. Pilinski, and A. G. Burns (2012), The impact of helium on thermosphere mass density response to geomagnetic activity during the recent solar minimum, J. Geophys. Res., 117, A07315, doi:10.1029/2012JA017832.

From Sun to Mud





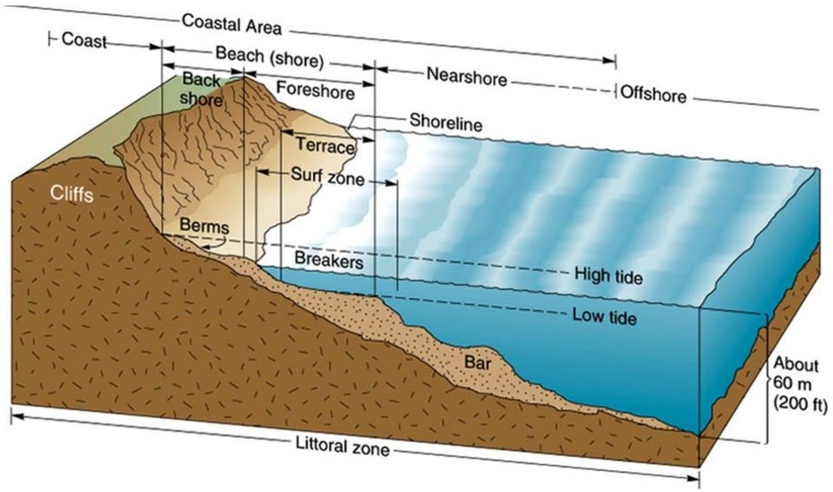


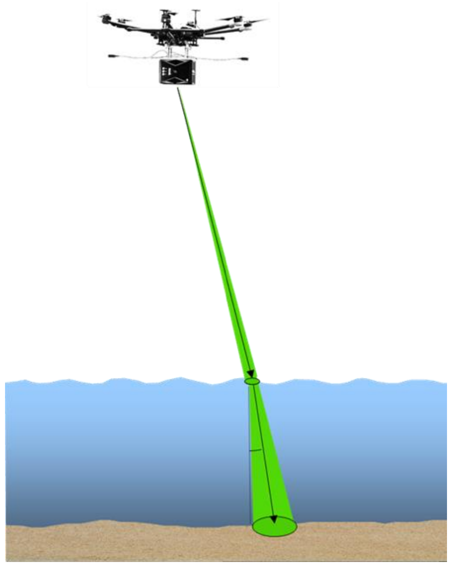
- Thayer J. P., W. K. Tobiska, M. Pilinski, and E. K. Sutton (2020) "Remaining Issues in Upper Atmosphere Satellite Drag." In Space Physics and Aeronomy, Volume 5, Space Weather Effects and Applications, eds. A. J. Coster and P. J. Erickson.
- Greer, K., J. P. Thayer, and V. L. Harvey (2013), A climatology of polar winter stratopause warmings and associated planetary wave breaking, J. Geophys. Res. Atmos., 118, 4168–4180, doi:10.1002/jgrd.50289
- Lucas, G. M., Baumgaertner, A. J. G., Thayer, J. P. (2015), A global electric circuit model within a community climate model, J. Geophys. Res. Atmos., 120, 12,054–12,066, doi:10.1002/2015JD023562.

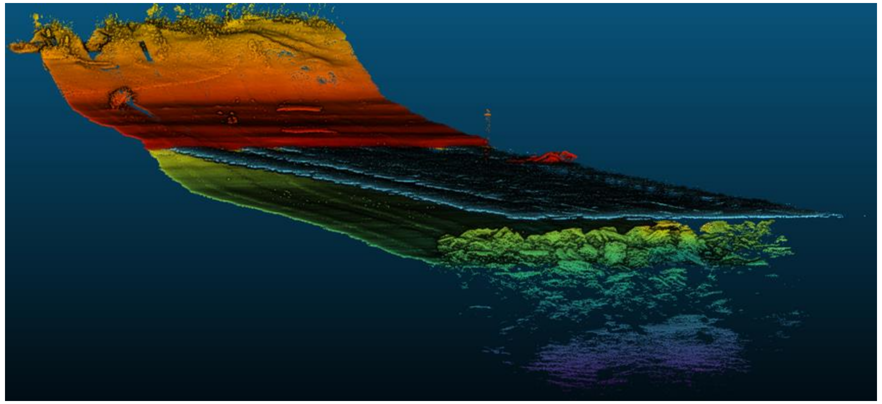
From Sun to Mud

- Neely, Ryan R., Matthew Hayman, Robert Stillwell, Jeffrey P. Thayer, R. Michael Hardesty, Michael O'Neill, Matthew D. Shupe, Catherine Alvarez, (2013): Polarization Lidar at Summit, Greenland, for the Detection of Cloud Phase and Particle Orientation. J. Atmos. Oceanic Technol., 30, 1635–1655
- Barton-Grimley, R. A., R. A. Stillwell, and J. P. Thayer (2018), High resolution photon time-tagging lidar for atmospheric point cloud generation, Optics Express, Vol 26., No. 20, doi10.1364/OE.26.026030.
- Stillwell, R. A., R. R. Neely III, J. P. Thayer, M. D. Shupe, and D. D. Turner (2018), Improved cloud-phase determination of low-level liquid and mixed-phase clouds by enhanced polarimetric lidar, Atmos. Meas. Tech., 11, 835-859, doi.org/10.5194/amt-11-835-2018.

From Sun to Mud







LiteWave TECHNOLOGIES

- Mitchell, S. E. and J. P. Thayer (2014) Ranging through Shallow Semitransparent Media with Polarization Lidar. J. Atmos. Oceanic Technol., 31, 681–697. doi: http://dx.doi.org/10.1175/JTECH-D-13-00014.1
- Thayer, J. P., S. E. Mitchell, and M. Hayman, Invention Title: Remote Measurement of Shallow Depths in Semi-Transparent Media, U.S. Patent No. 9,476,980 Issued 10/25/2016.
- Gisler, A., and J. P. Thayer (2021) Setting a New Standard for Topobathymetric Surveys, Lidar magazine, Volume 11, Issue 1

University of Colorado Active Remote Sensing Lab (ARSENL)


Ryan Neely


Matt Hayman

Other PhDs:
- Jason Reimuller
- Xianjing Liu
- Katrina Bossert
- Vicki Hsu
- Greg Lucas
- Matt Tooth

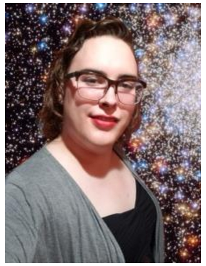

Katelynn Greer

Steve Mitchell


Robert Stillwell


Rory Barton-Grimley

Future PhDs



PhD: Allie Wise

PhD: Kevin Sacca

PhD: Vicki Herde

PhD: Matt van den Heever

PhD: Anton Buynovskiy

PhD: Alex Medema

PhD: Sarah Luettgen

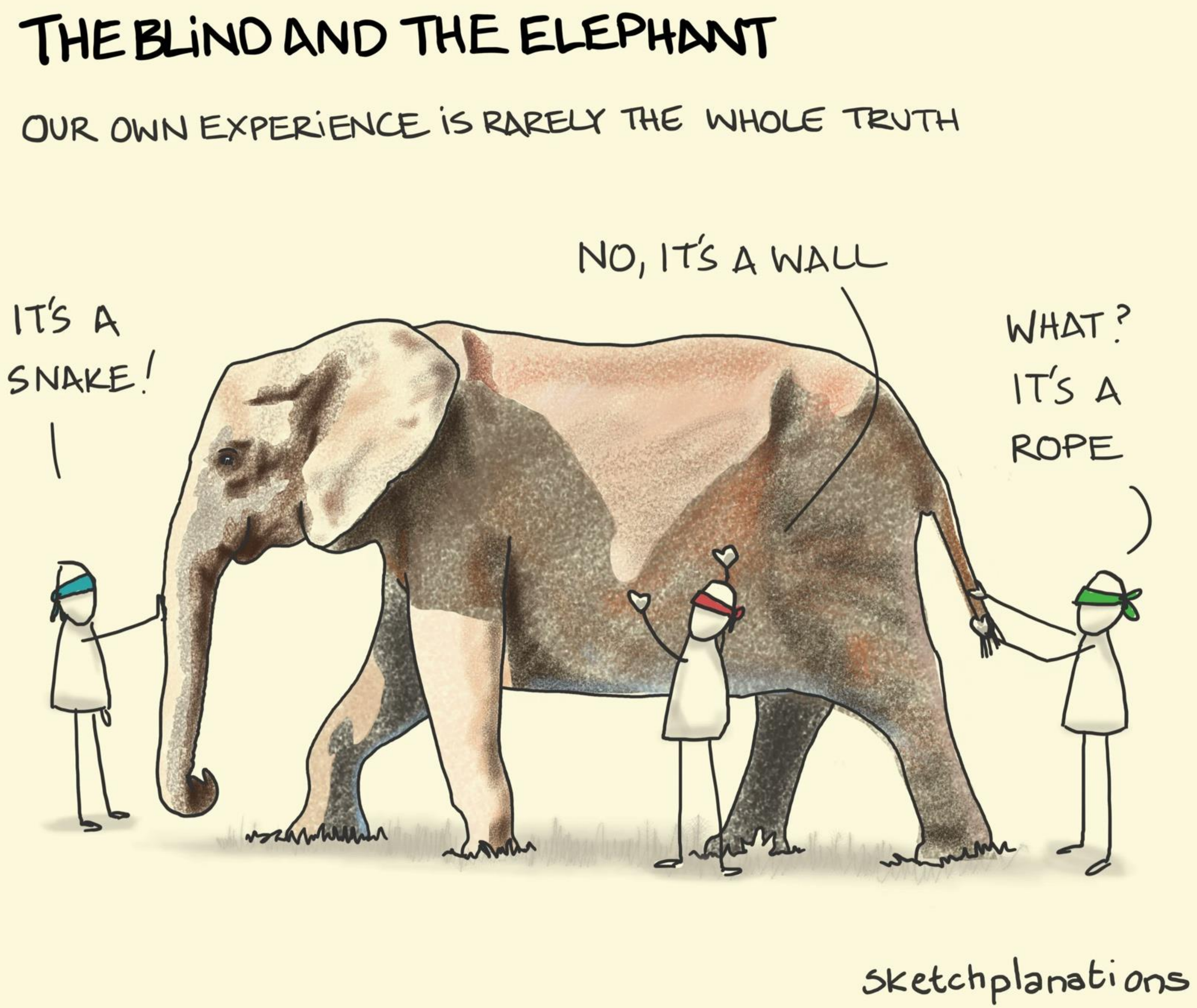
PhD: Grant Kirchhoff

PhD: Austin Coleman

PhD: Arunima Prakash

PhD: Bryce Garby

PhD: Robert Sewell



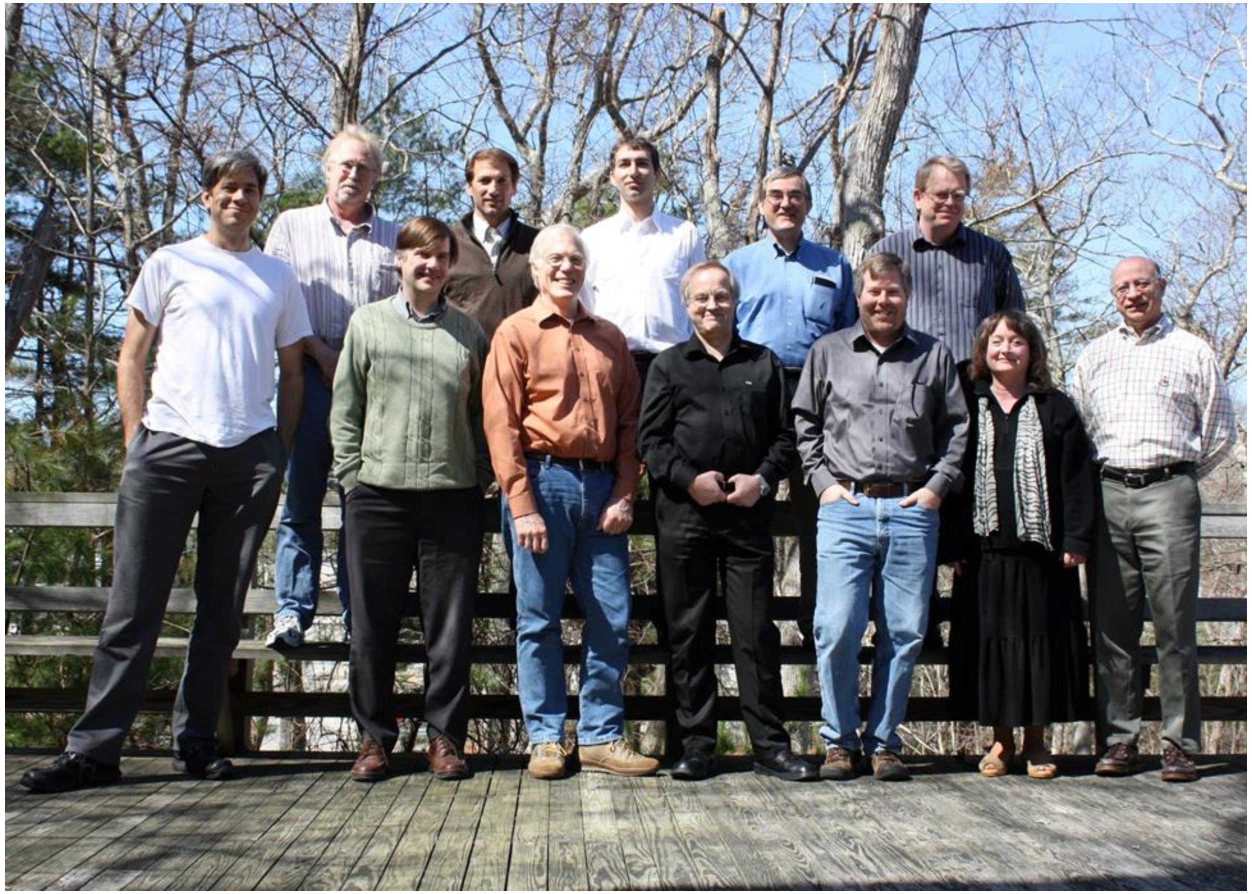
"It ain't what you don't know that gets you in trouble. It's what you know for sure that just ain't so." – Mark Twain

CEDAR Strategic Plan

The New Dimension

Man must rise above the Earth – to the top of the atmosphere and beyond – for only thus will he fully understand the world in which he lives. *–Socrates*

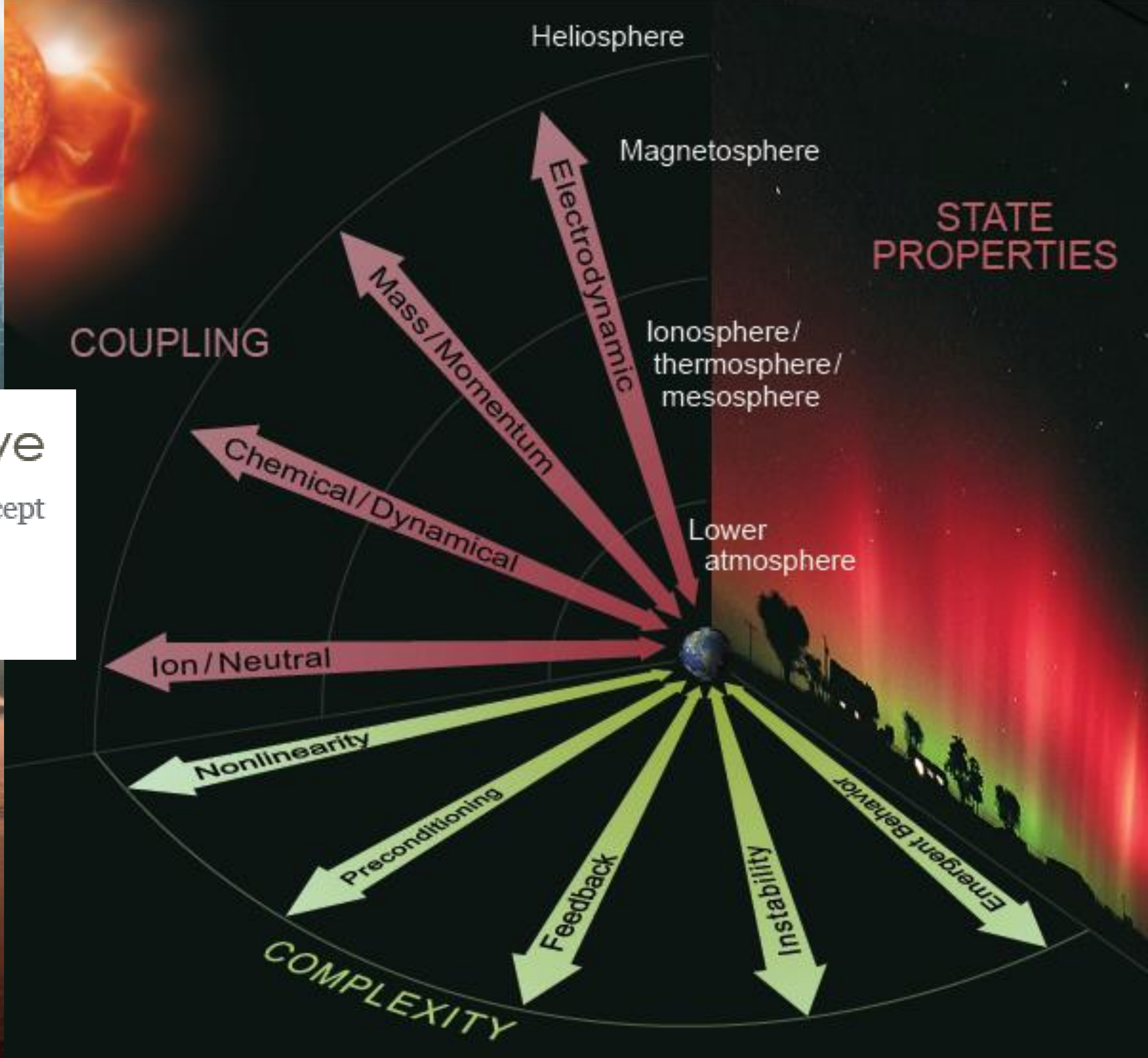
Acknowledgements



- 2007-2011 CSSC Committee Members
- WHOI writing team: Drs. Susan Avery, Anthony van Eyken, John Foster, Dave Hysell, Robert Kerr, Janet Kozyra, Larry Paxton, Aaron Ridley, Joshua Semeter, Jeff Thayer, Lara Waldrop
- Graphic Illustrator: Vicki Moore, SRI International
- NSF Upper Atmosphere Research Section: Rich Behnke, Robert Robinson, Robert Kerr and Farzad Kamalabadi

3 The Systems Perspective

The systems approach transcends the concept of scale, enabling the characteristics of a complex system to be generally applied to many problems in the Sun-Earth system.



Musings

(contemplative, meditative, pensive, pondering, reflective, ruminative, careful thought)

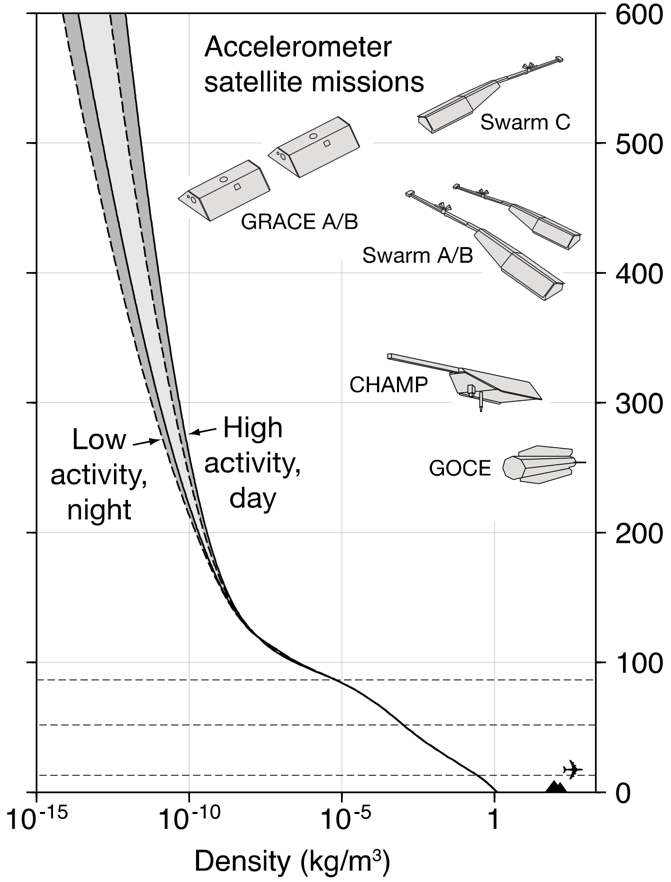
Signals of Opportunity

The Thermopause

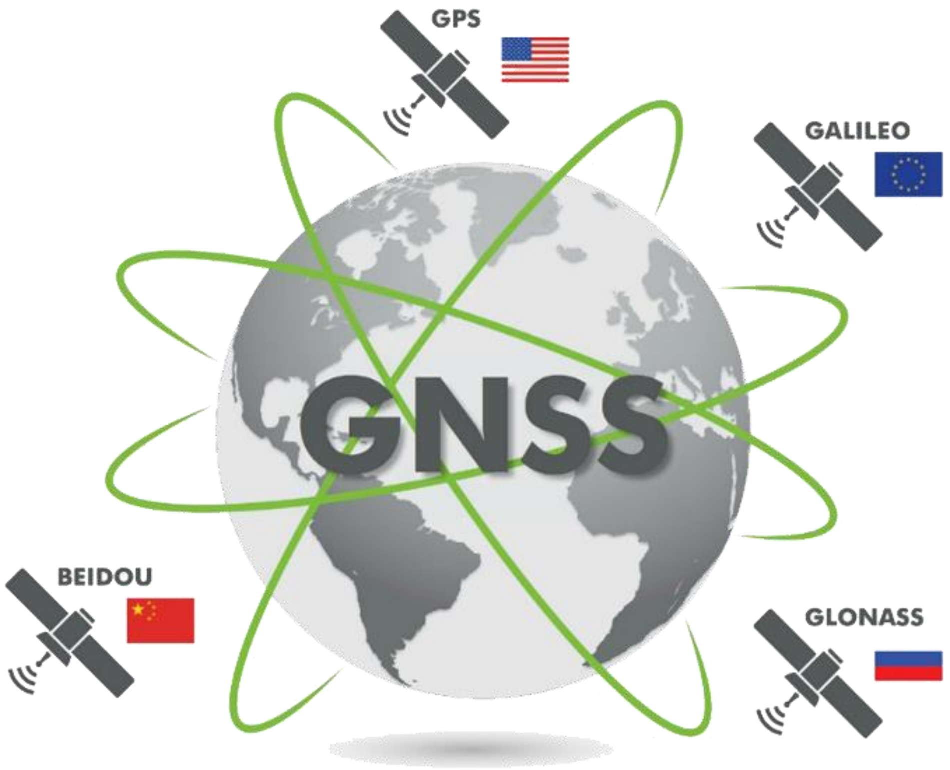
Electromagnetic Energy

Musings: Signals of Opportunity

Science-Grade Accelerometers



GNSS

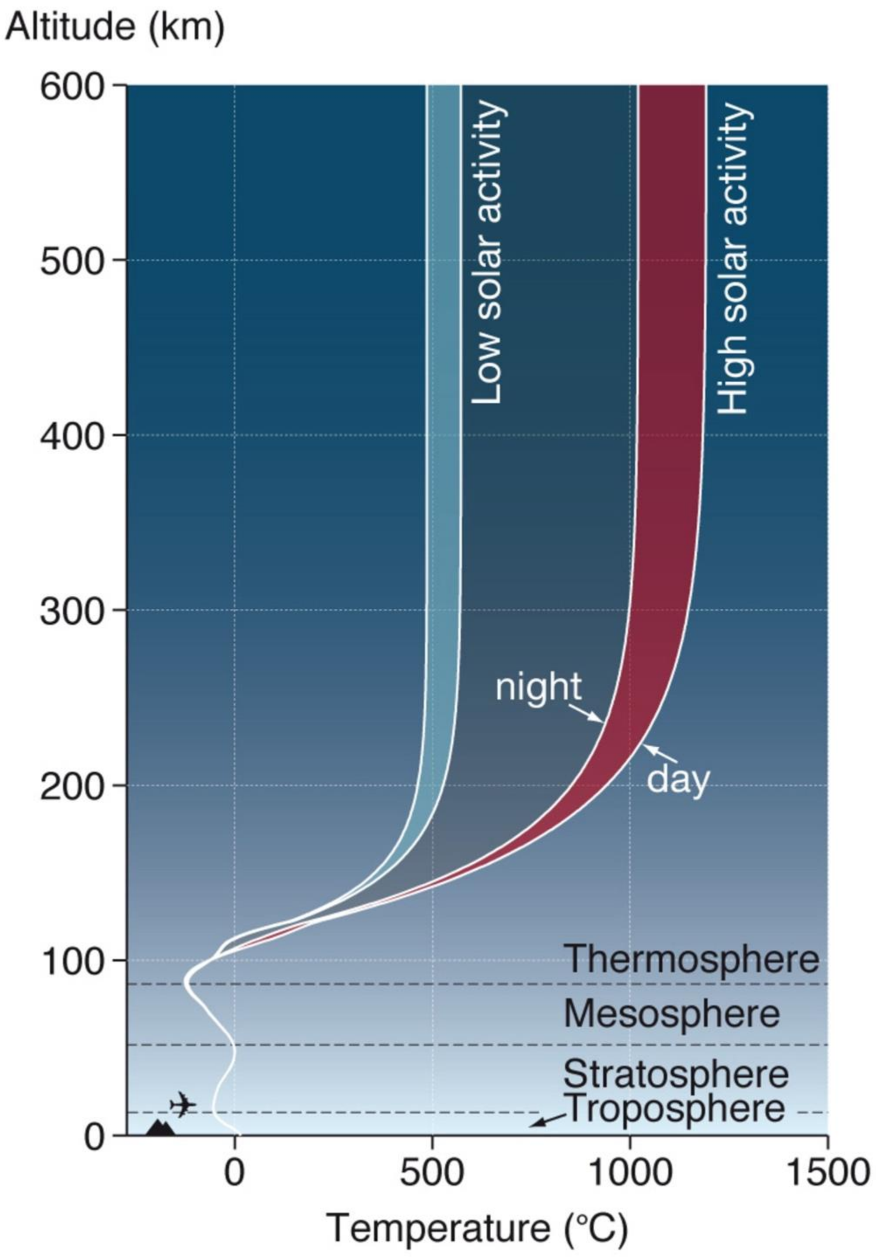


Musings: Signals of Opportunity

In addition, we must pursue **comprehensive** I-T measurements to advance the field

Musings: The Thermopause

- Outermost protective layer of our "Sensible Atmosphere"
- Where the sidewalk ends (above which particle kinetics abound)
- Hottest region (thermally, scientifically, and operationally)
- Distinctly different characteristics and processes from the lower thermosphere
  - Highly viscous
  - Highly forced by a mobile plasma
  - Highly responsive to energy input (local and distant)
  - Highly diffusive, dissipative, and conductive
  - Unique chemical activity - beta plasma chemistry
  - Horizontally structured and variable



Musings: Electromagnetic Energy

Plasma-Neutral Heating

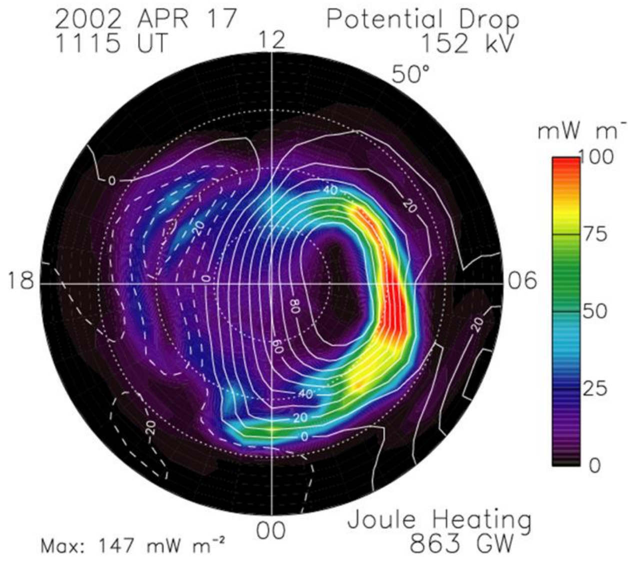
Poynting Flux

Joule Heating

Ohmic Heating

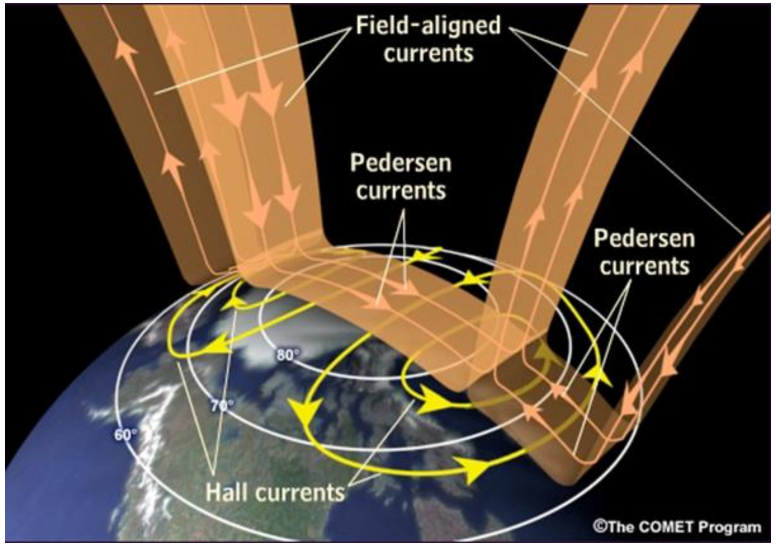
Frictional Heating

Momentum Transfer



View Thayer 2017 CEDAR Tutorial

Plasma-Neutral Electrodynamics



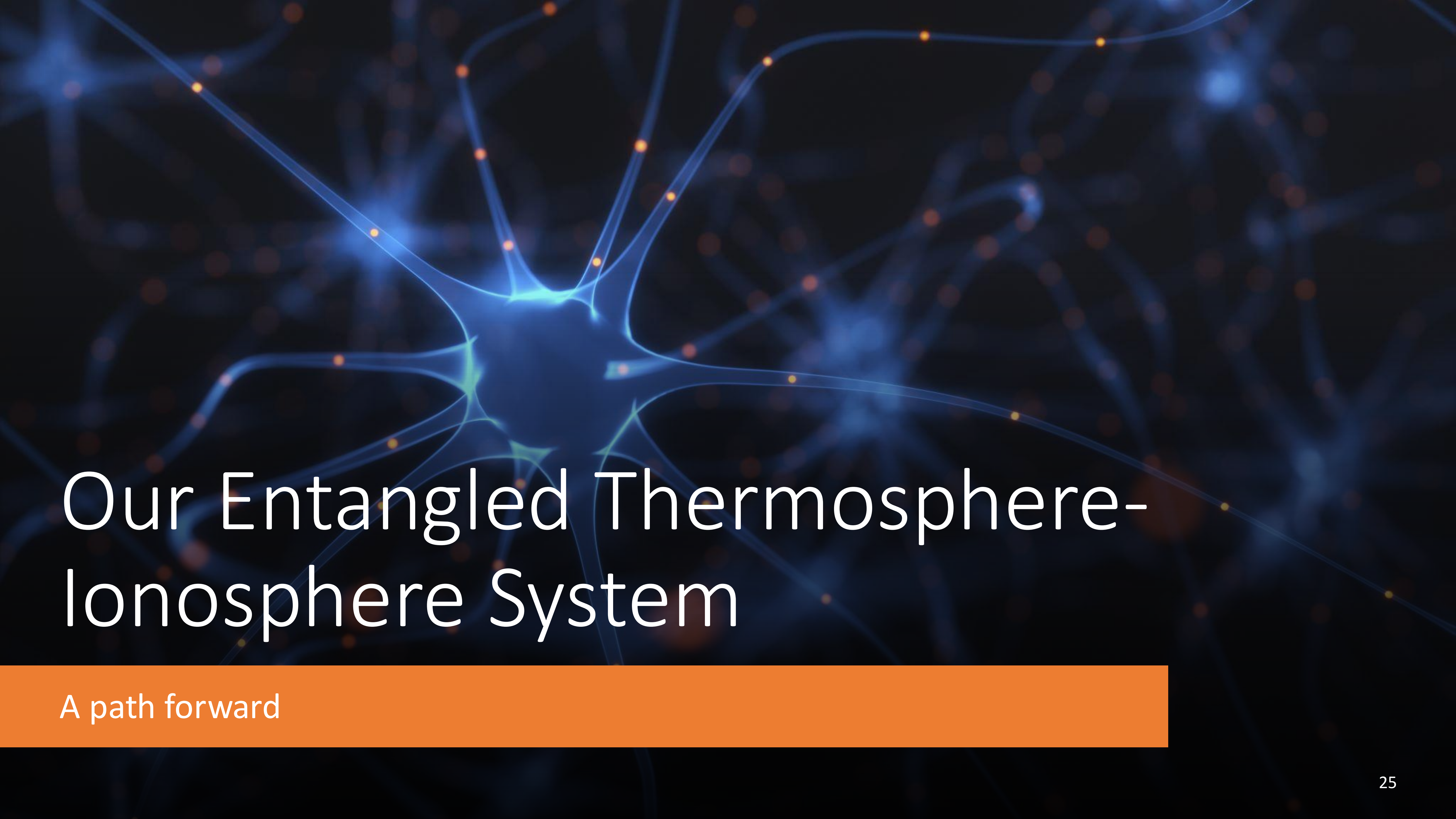
Musings: Electromagnetic Energy

<u>M-I coupling</u>

"Missing" Electromagnetic Energy Flux

<u>I-T Entanglement</u>

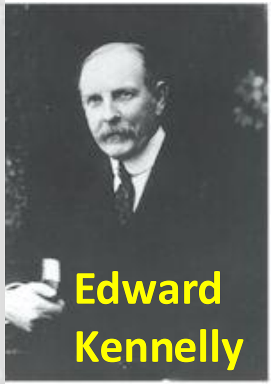
"Transforming" Electromagnetic Energy Flux

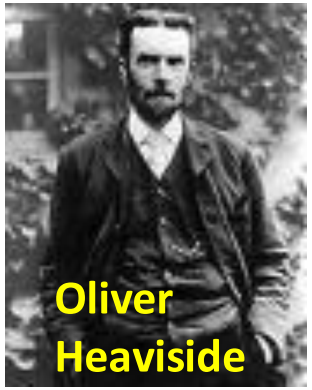


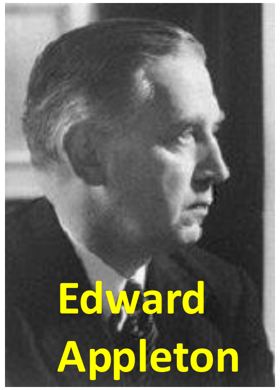
Our Entangled Thermosphere-Ionosphere System

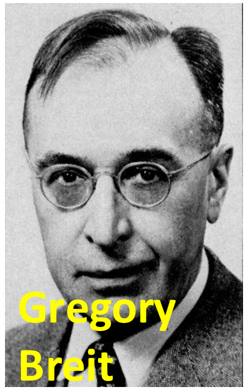
A path forward

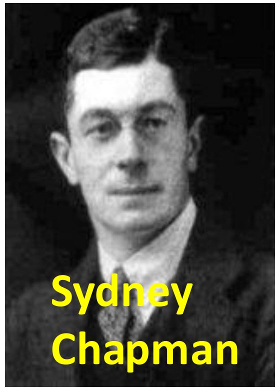
History of Ionosphere-Thermosphere Science







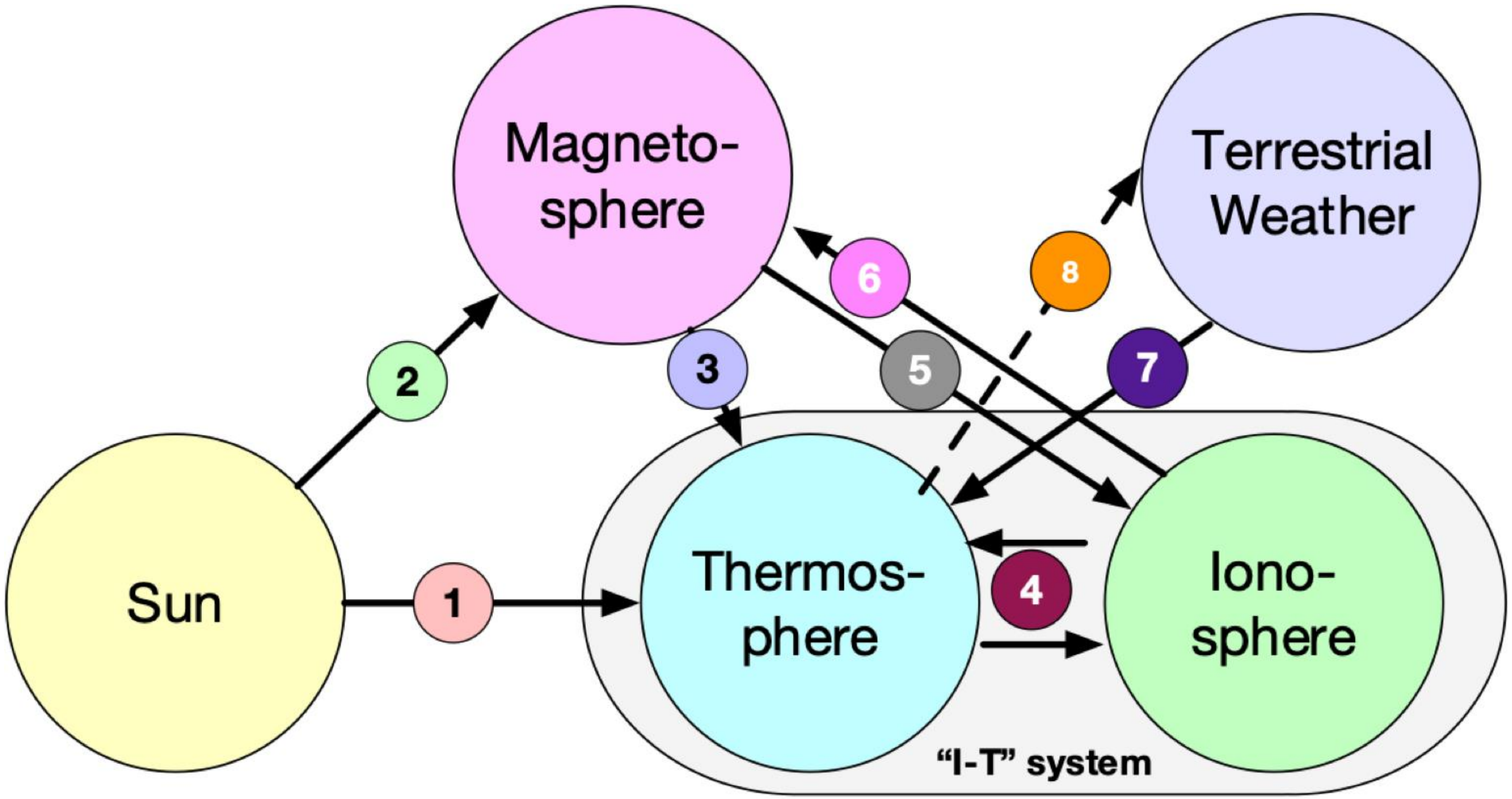




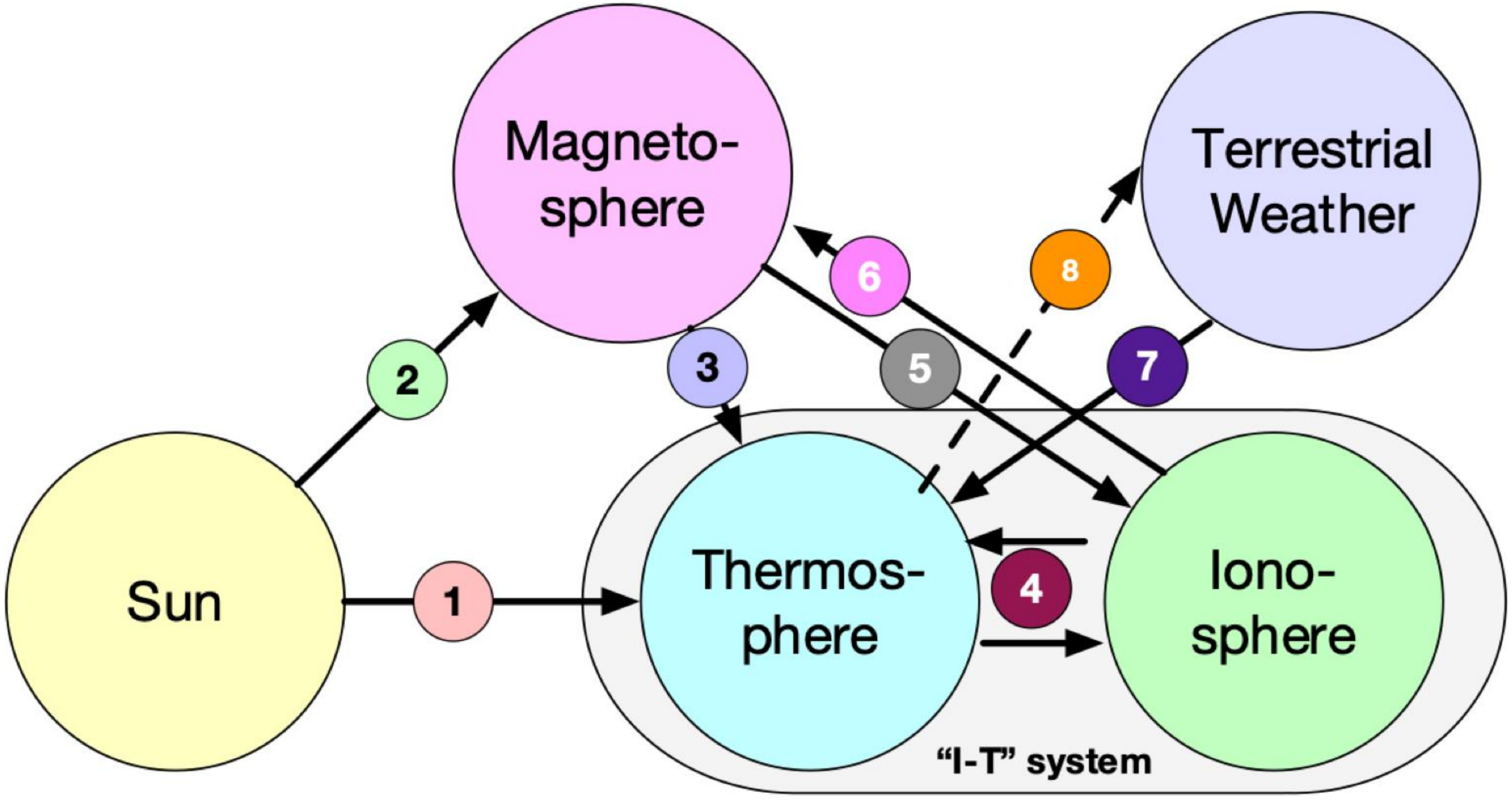
ERA	Science
Discovery 1925-1960	Discovery of the I-T via radio, rockets, and start of space age
Connections 1960-1990	Identification of the coupled nature of the I-T via ground-based, rockets, and satellite systems
Characterization 1990-2020	Characterization through climatologies, correlations, and patterns from broader data sets
Causation Needed Now	Realization of I-T entanglement
Comprehensive Future needs	Prediction of global I-T “weather” at high fidelity and resolution

Your Picture Here

I-T is a strongly driven, nonlinear system dependent on flux convergence of external drivers but also the transformations that occur within



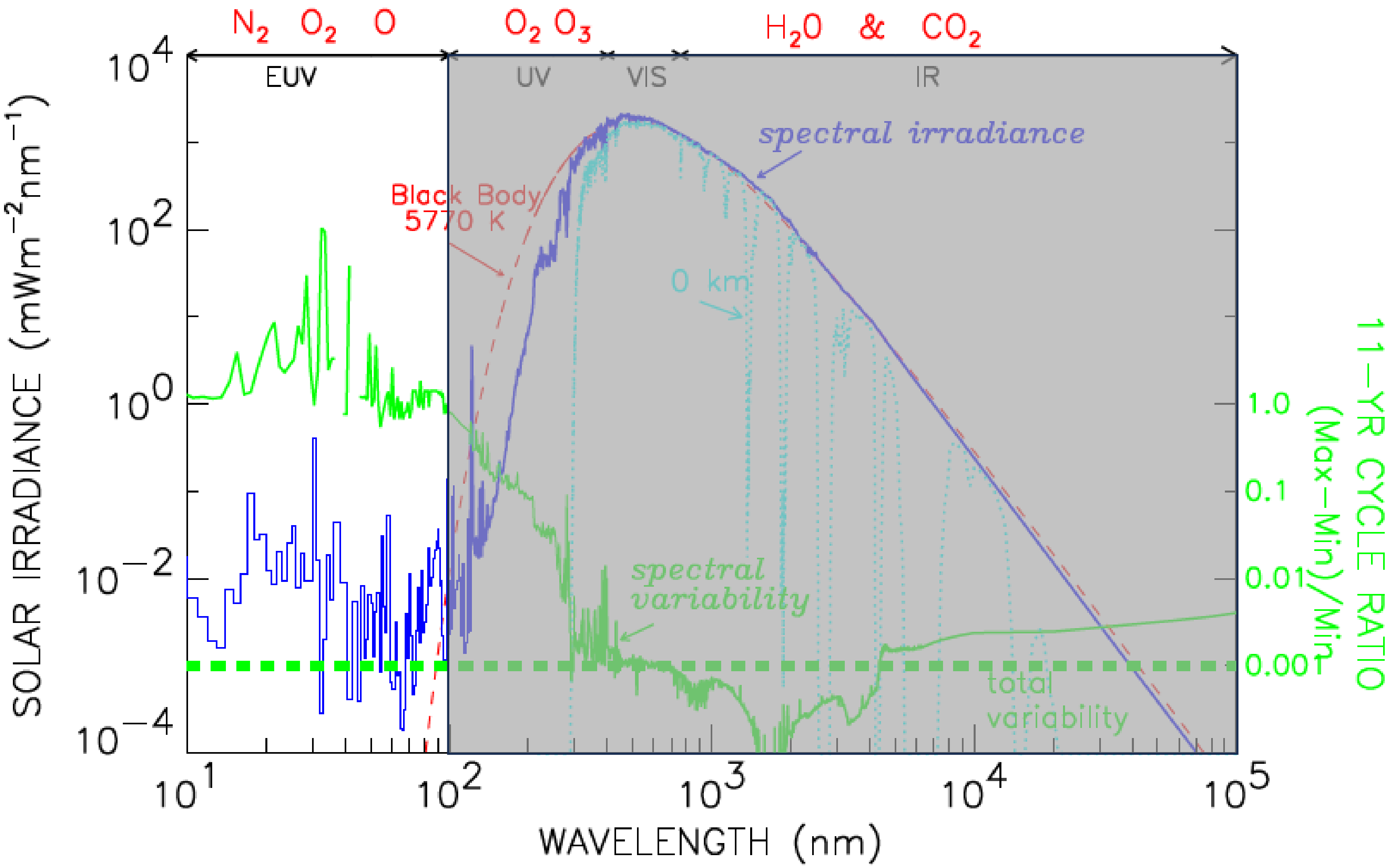
Flux Convergence and Transformations



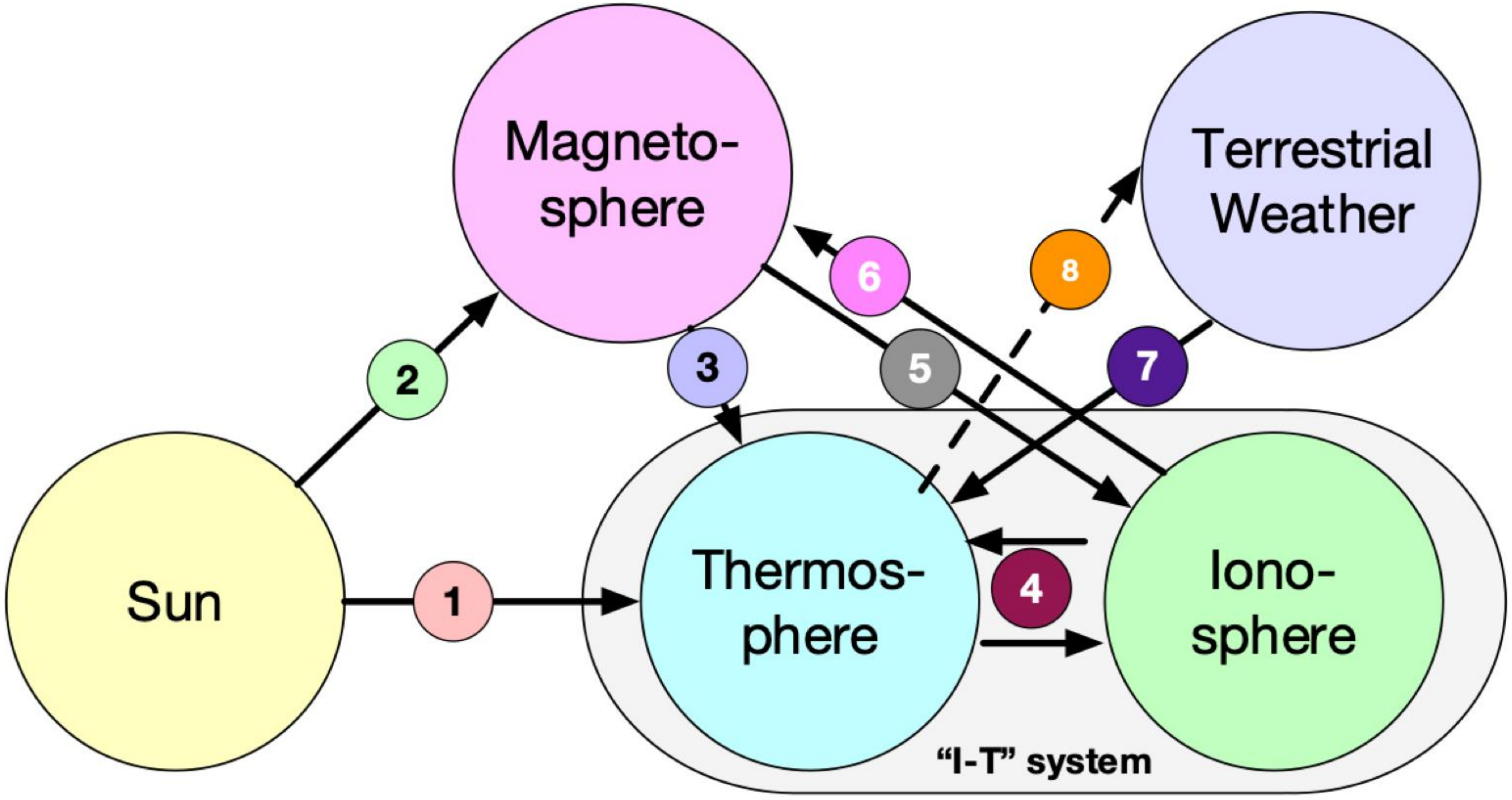
1. Solar photon influx
2. Solar wind energy influx
3. Particle energy influx
4. Transformation of flux
5. E&M energy influx
6. Mass outflux
7. Wave energy influx
8. Species outflux

$$\frac{\partial \psi}{\partial t} + \vec{\nabla} \cdot \vec{F} = P - L \quad [Quantity / s]$$

Solar Spectral Irradiance



Flux Convergence and Transformations

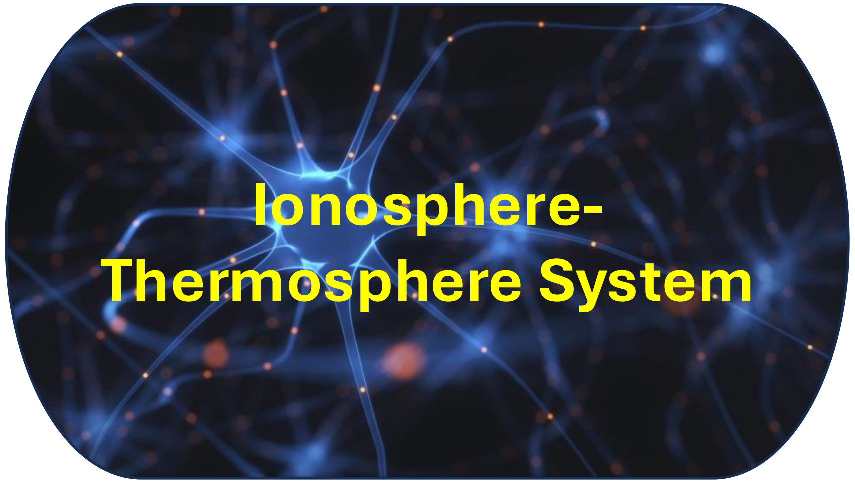


1 Solar photon influx
2 Solar wind energy influx
3 Particle energy influx
4 Transformation of flux
5 E&M energy influx
6 Mass outflux
7 Wave energy influx
8 Species outflux

$$\frac{\partial \psi}{\partial t} + \vec{\nabla} \cdot \vec{F} = P - L \quad [Quantity / s]$$

Causation Needed Now

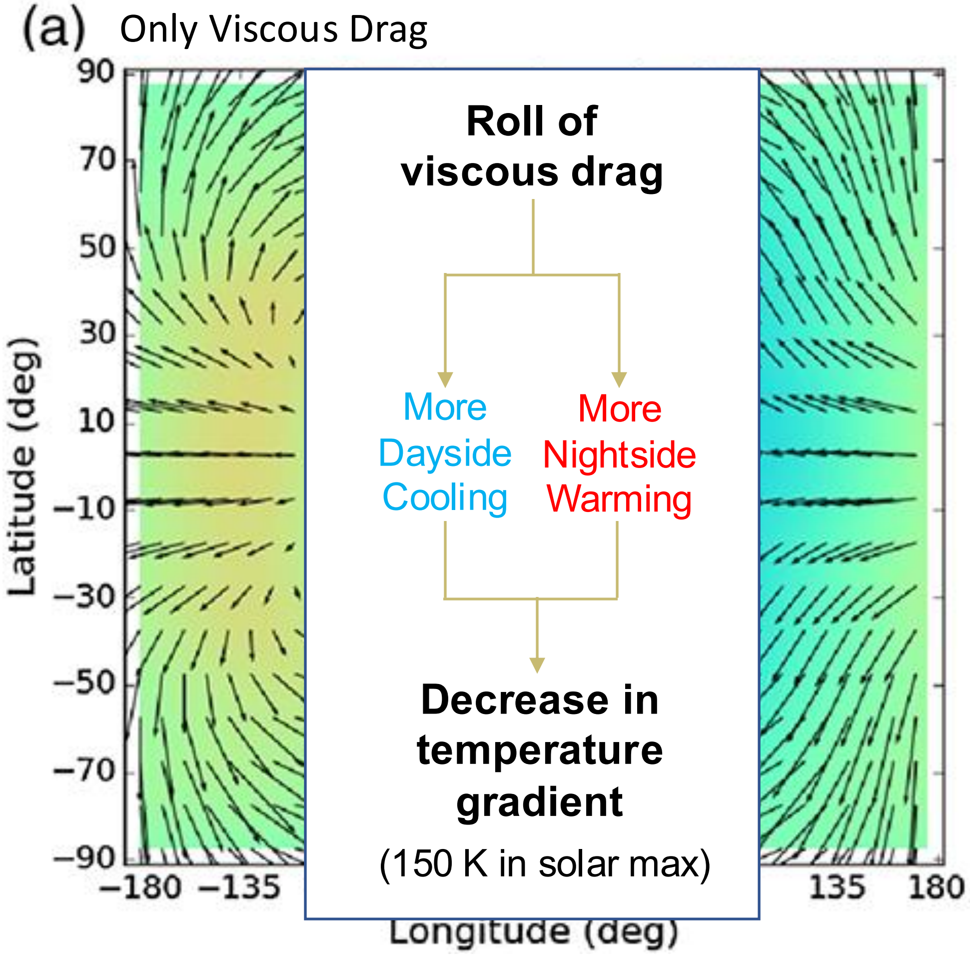
Realization of I-T entanglement



I-T Entanglement: A collection of neutral and charged particles interacting and sharing spatial proximity in such a way that the state of one group cannot be described independently of the state of the other, including when spanning large distances.

Entanglement: NCAR-TIEGCM Numerical Experiment

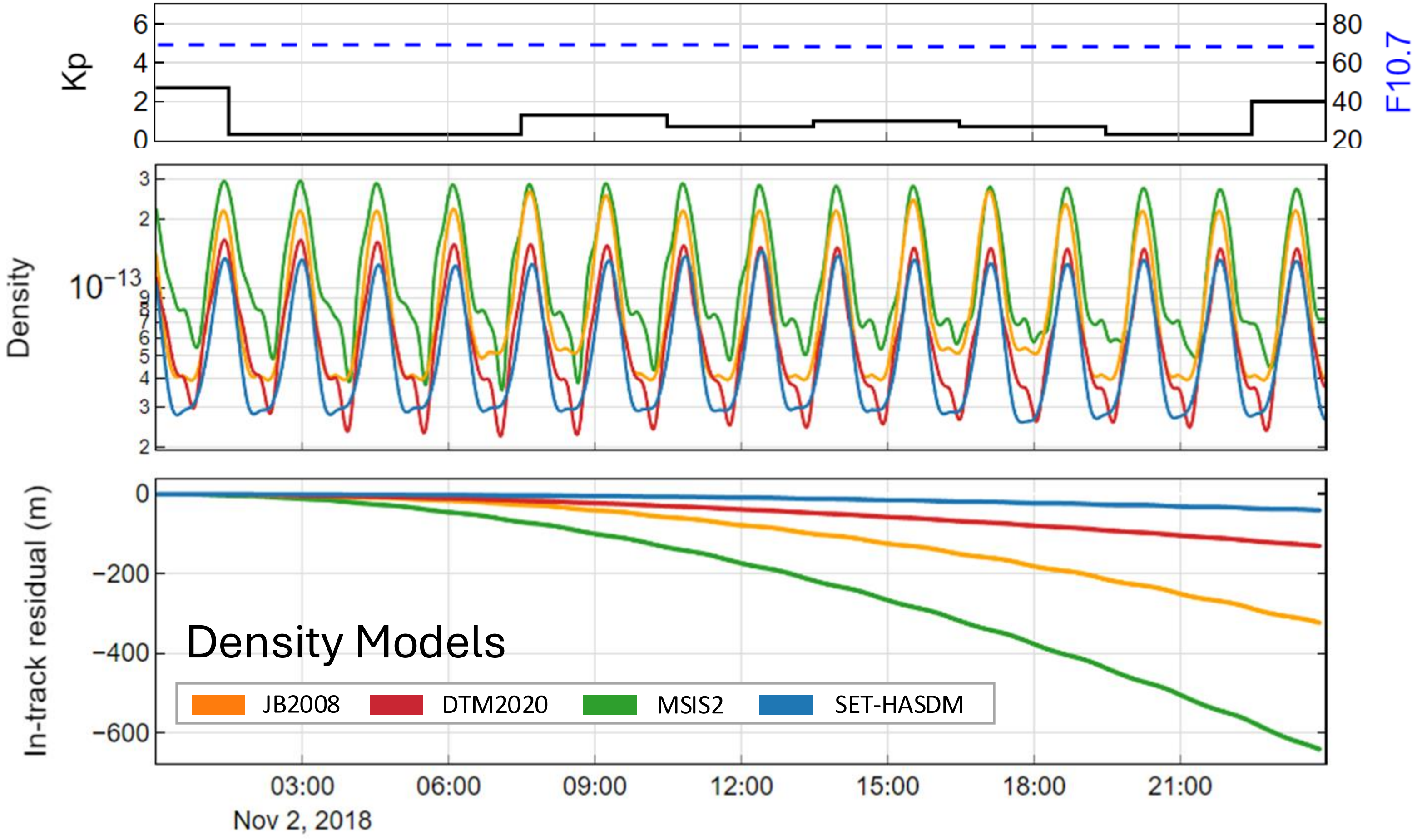
Neutral temperature T_n and horizontal wind vectors (U_n, V_n)
solar maximum conditions ~400 km at UT = 0.0, low activity

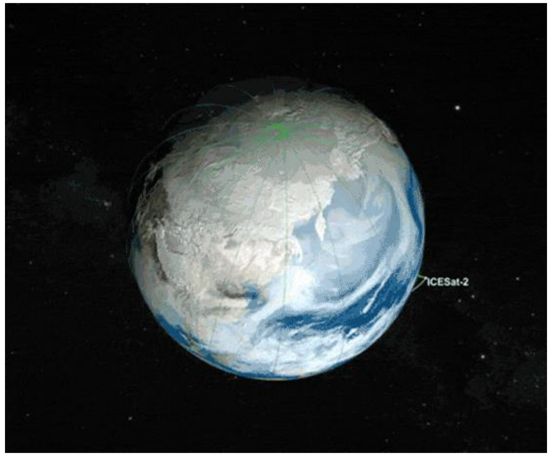


Hsu, V. W., J. P. Thayer, W. Wang, and A. Burns (2016), New insights into the complex interplay between drag forces and its thermospheric consequences, J. Geophys. Res. Space Physics, 121, 10,417–10,430, doi:10.1002/2016JA023058

Orbit Propagation Assessment

Evaluate ICESAT-2 orbit trajectory over a 24-hour period using different thermosphere density models.



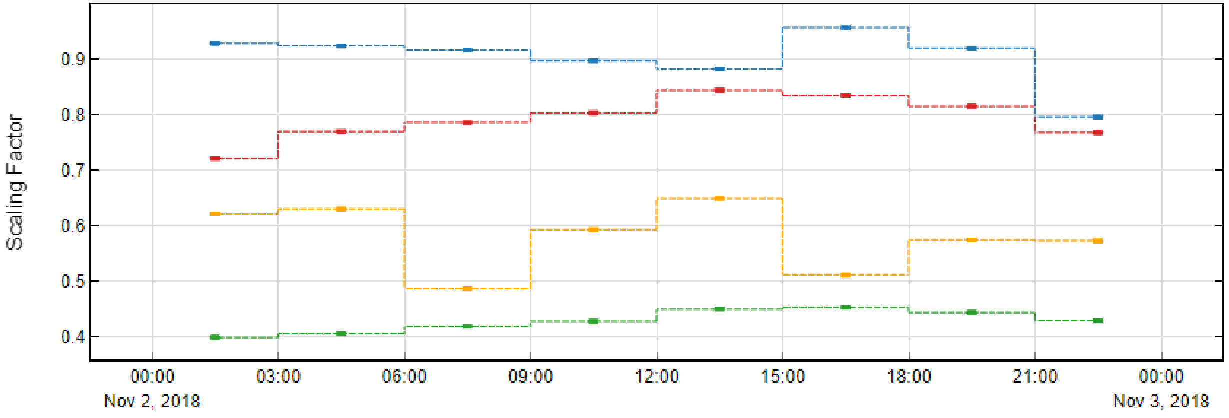


Courtesy of Zach Waldron

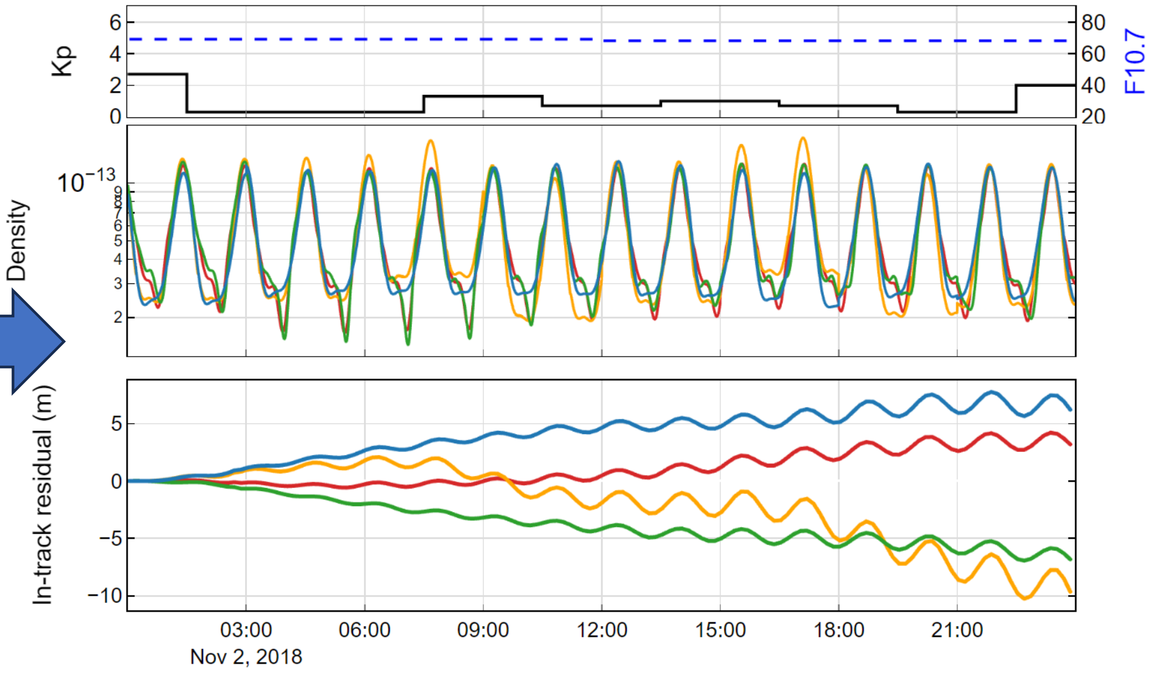
Orbit Propagation Assessment Revised

Re-evaluate trajectory solution over a 24-hour period using scaled updates every 3 hours.

Scaling factor for best orbit fits



Scaled Density Solution



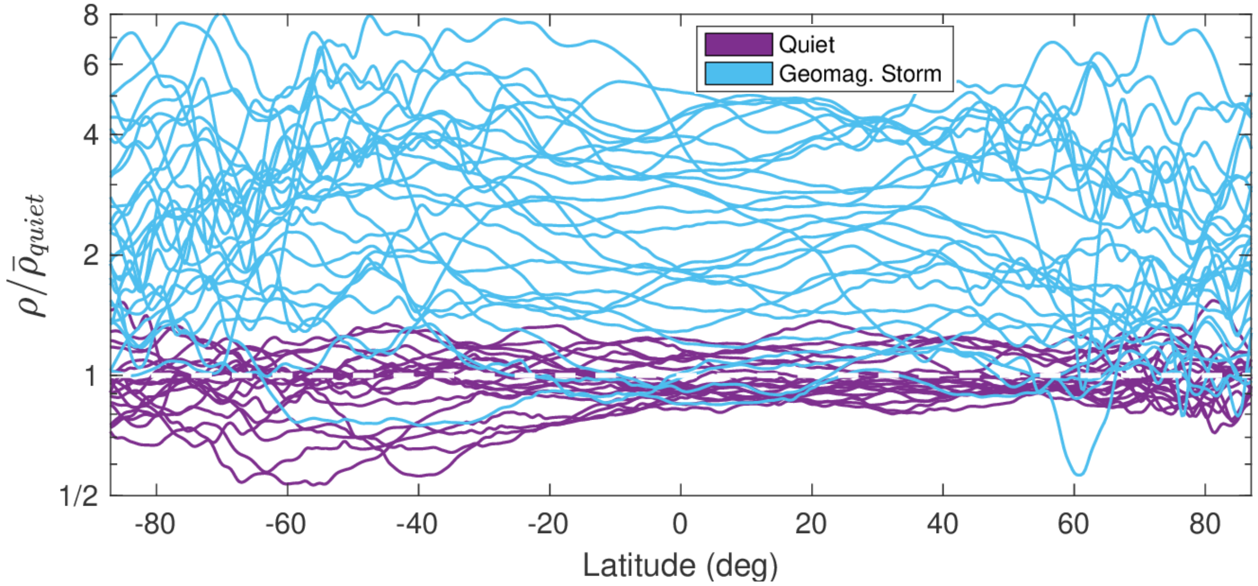
Density Models

JB2008	DTM2020	MSIS2	SET-HASDM

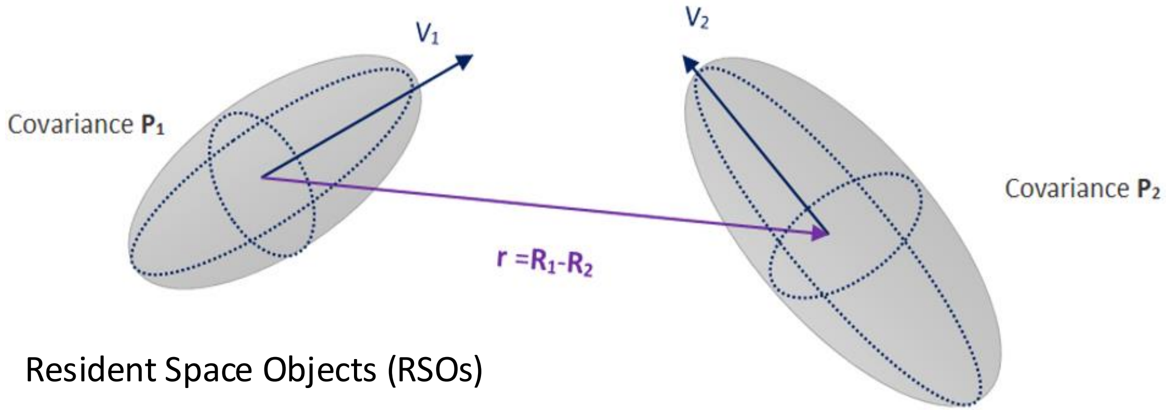
Courtesy of Zach Waldron

Entanglement: Energy Injection Events, Variable I-T Response, and LEO Consequences

Neutral Density Variability @ 400 km



"Error Bubbles" around LEO RSOs are large due primarily to density variations caused by SWx



Resident Space Objects (RSOs)

NASA Collision Avoidance Risk Assessment (CARA) program

Courtesy of Eric Sutton

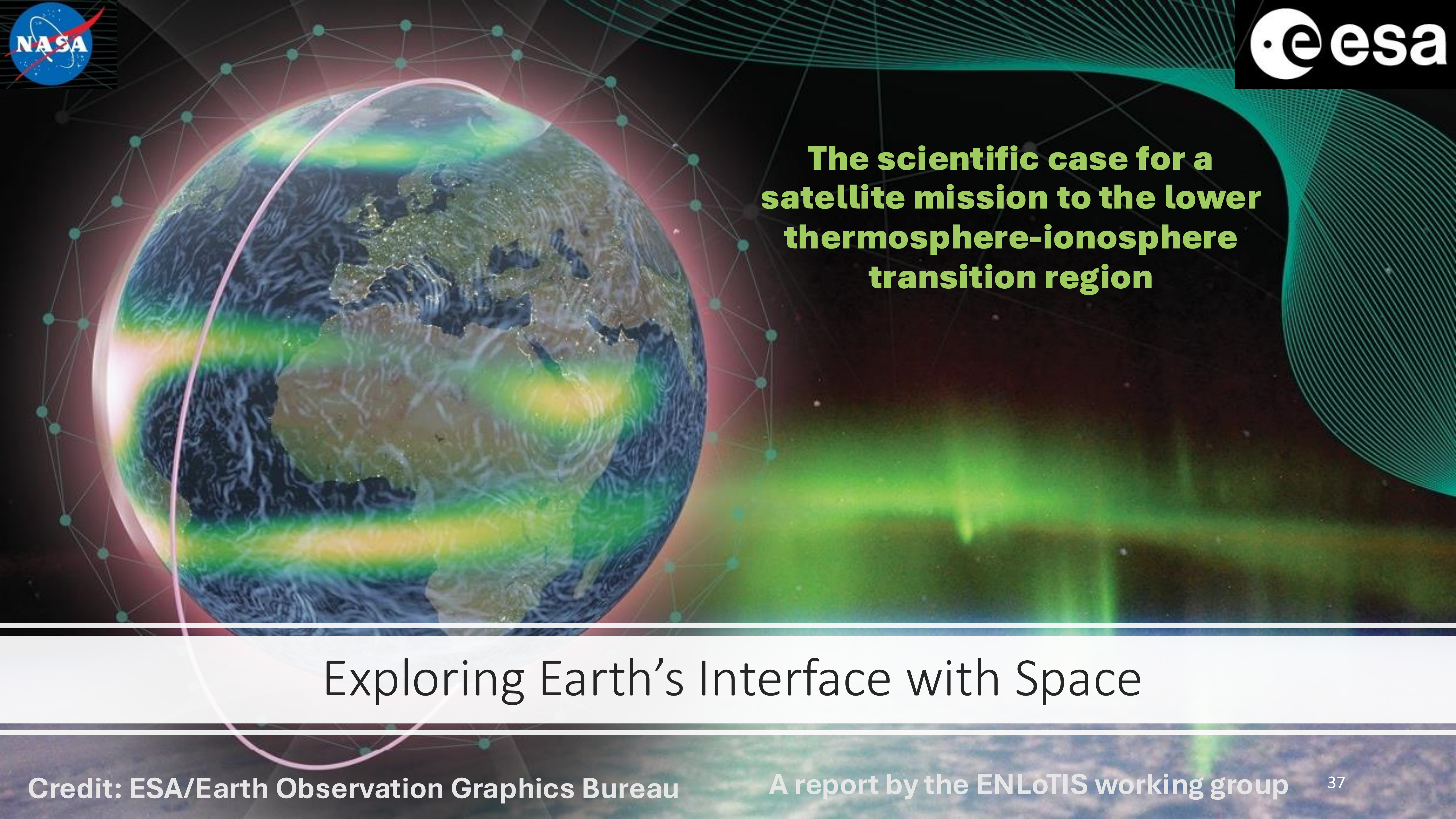
Comprehensive Future Needs

Global Prediction of I-T System

- Because of this entanglement realization, observing and interpreting the I-T system requires multi-property, multi-point measurements at the same time to capture the true state of the system.
- GDC and DYNAMIC are future NASA I-T missions designed to meet this realization.

GDC
GEOSPACE DYNAMICS CONSTELLATION
Exploring Our Connected Atmosphere

The scientific case for a satellite mission to the lower thermosphere-ionosphere transition region



Exploring Earth’s Interface with Space

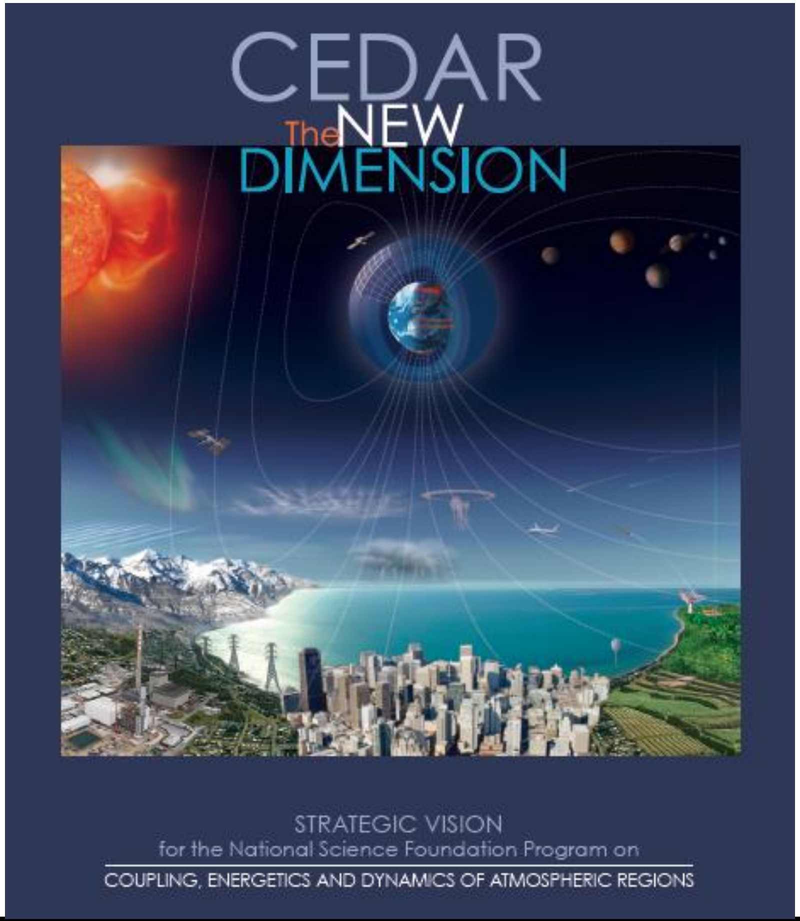
Credit: ESA/Earth Observation Graphics Bureau

A report by the ENLoTIS working group

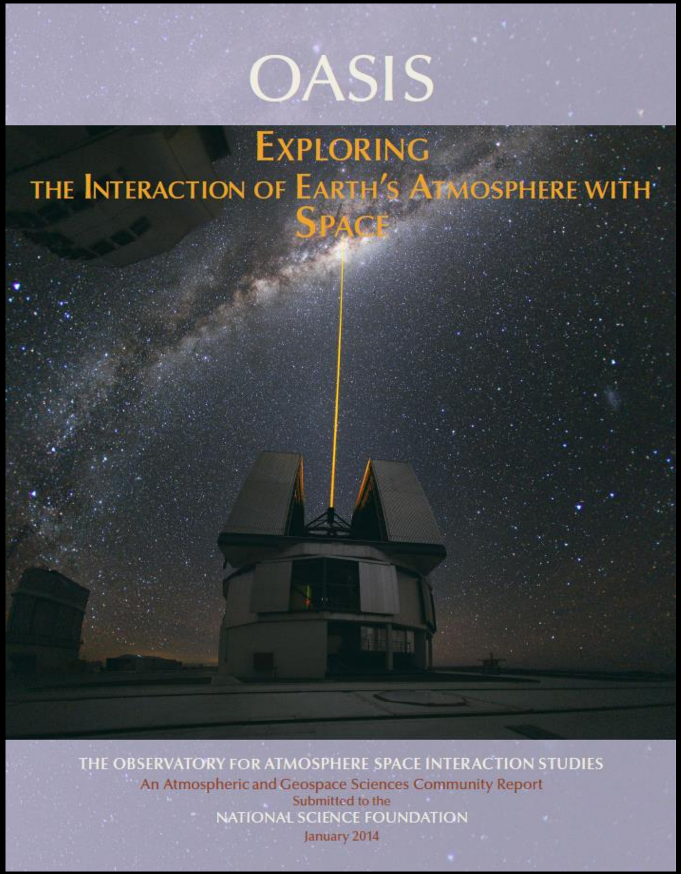
Closing Remarks

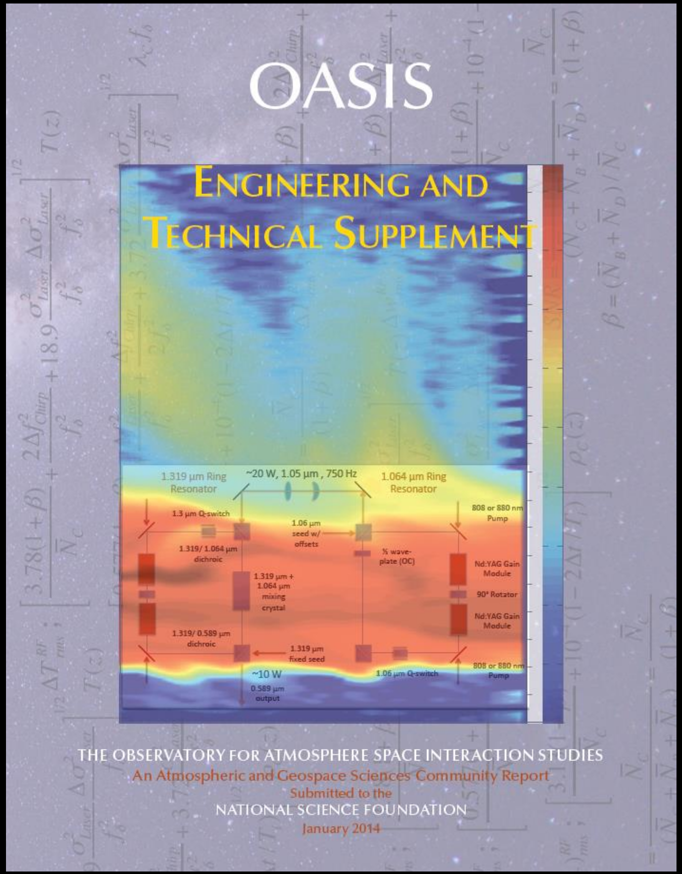
Stay one step ahead

Planning is Everything



OASIS Workshop Reports





University Club of Chicago - 16 May 2012

I ♥ CEDAR

Community – grass roots

Equity – fair and sweat

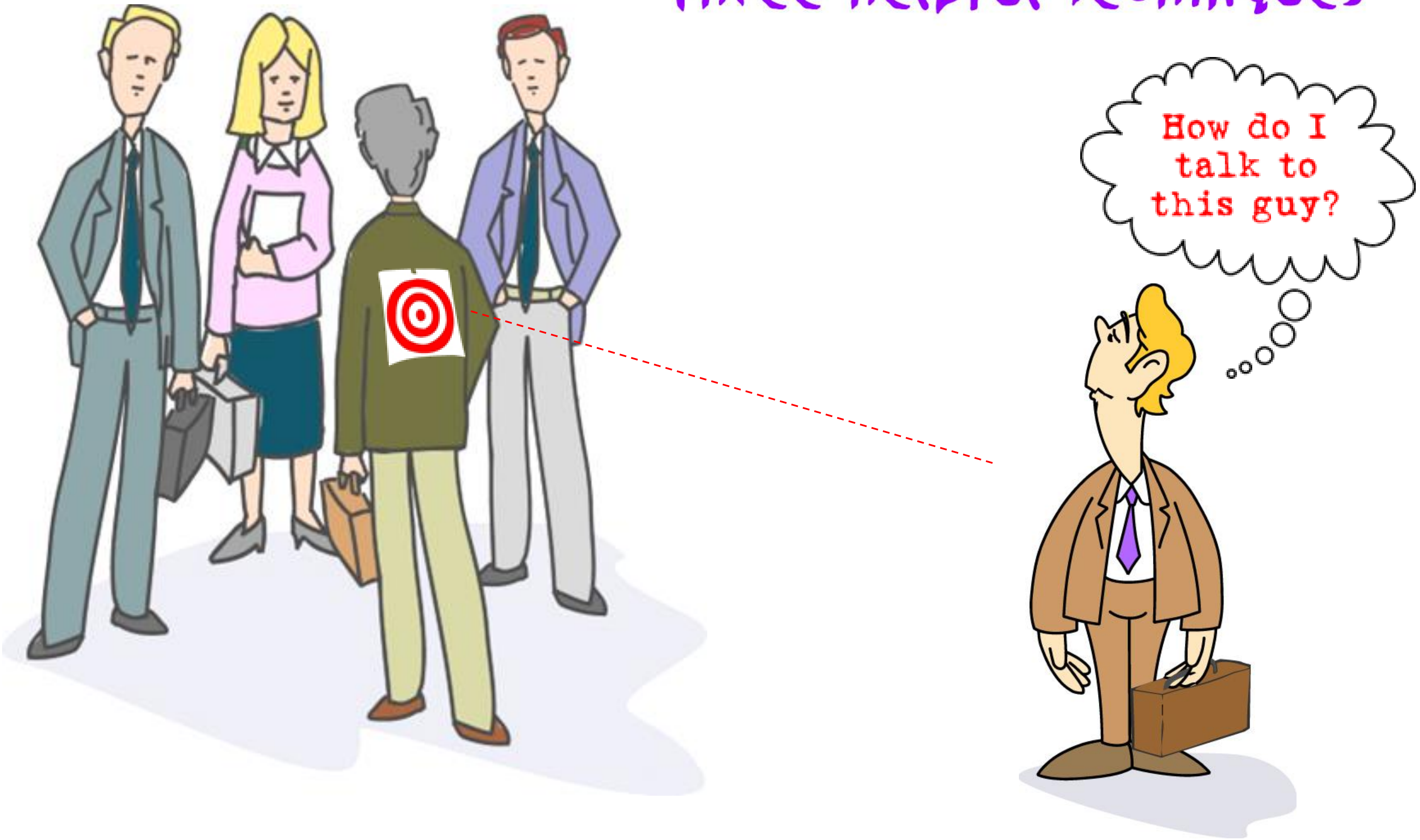
Diversity – identity and thought

Altruism – charity and sacrifice

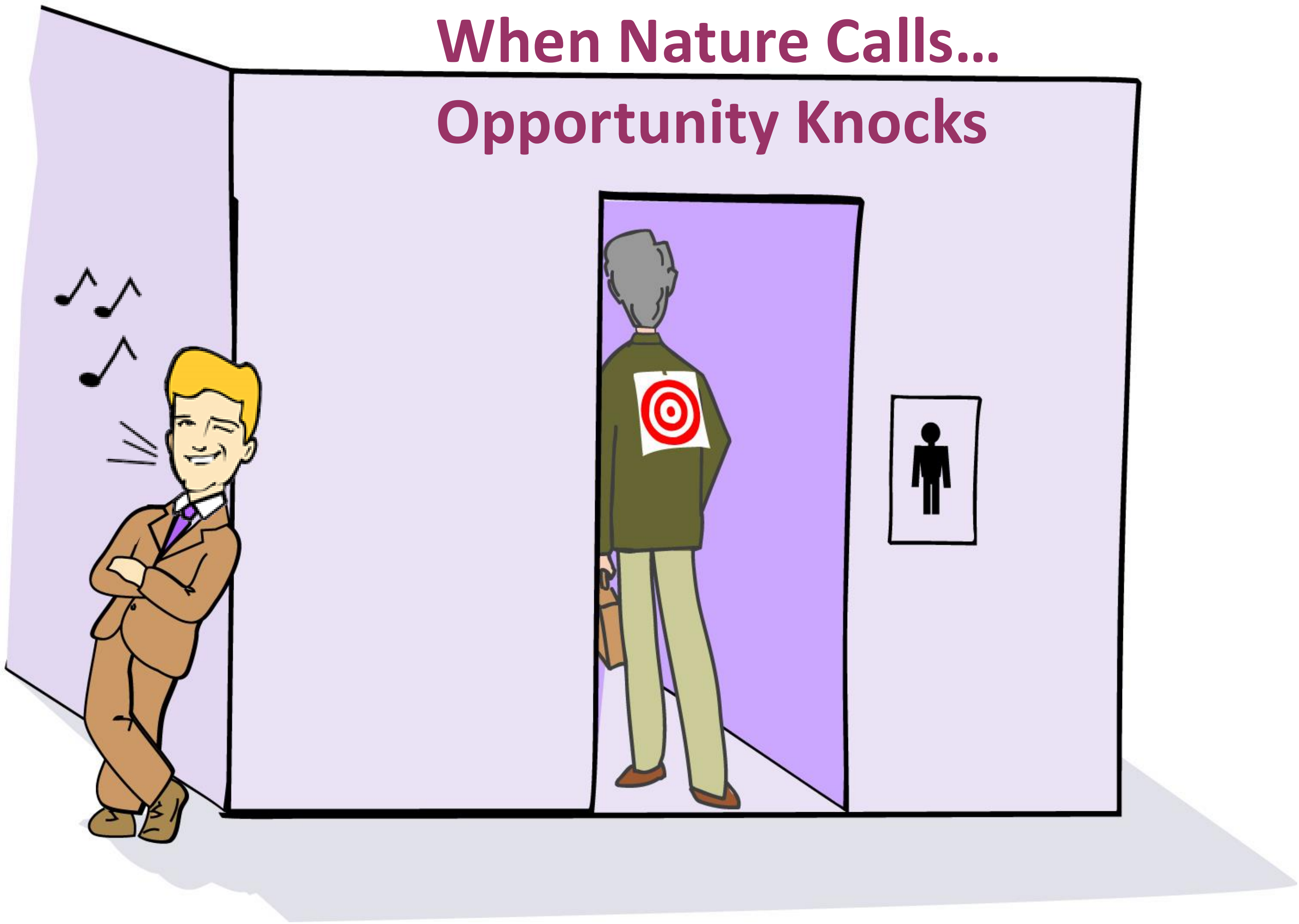
Respect – thoughtfulness and admiration

How to Generate Interest in Your Research

Three helpful techniques

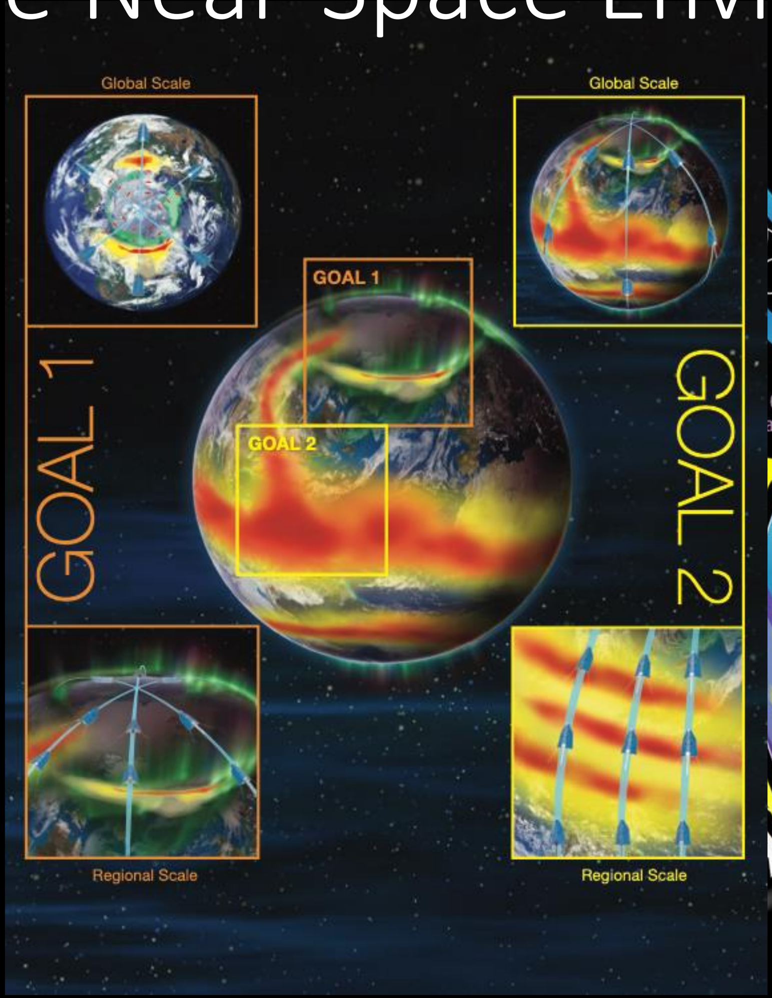


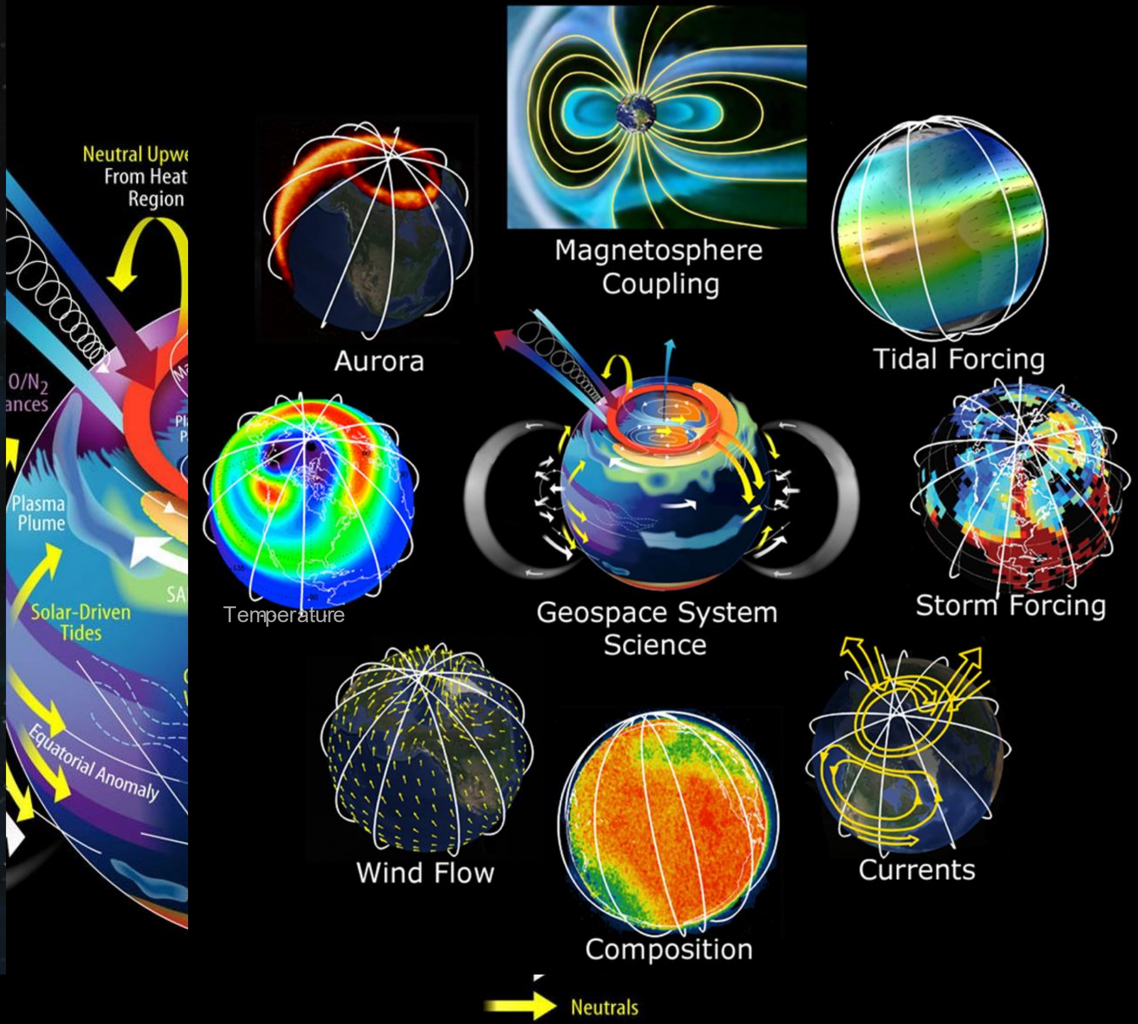
The Planned Coincidence



V03-023

GDC Mission: Discover Missing Energy, Explore System Response, and Transform Understanding of the Near-Space Environment

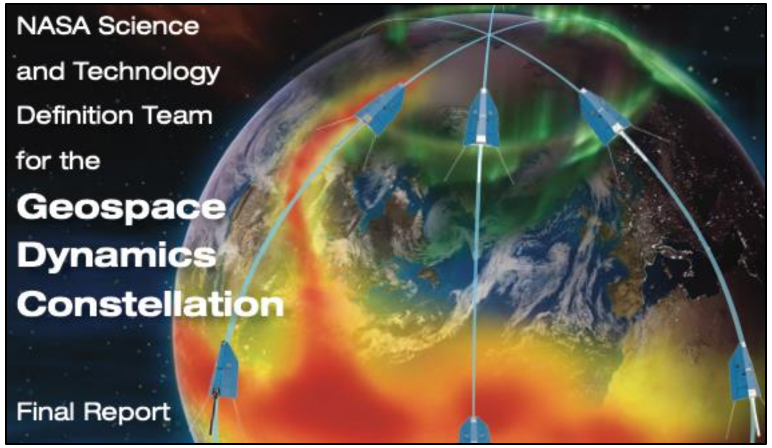




J. Grebowsky / NASA GSFC

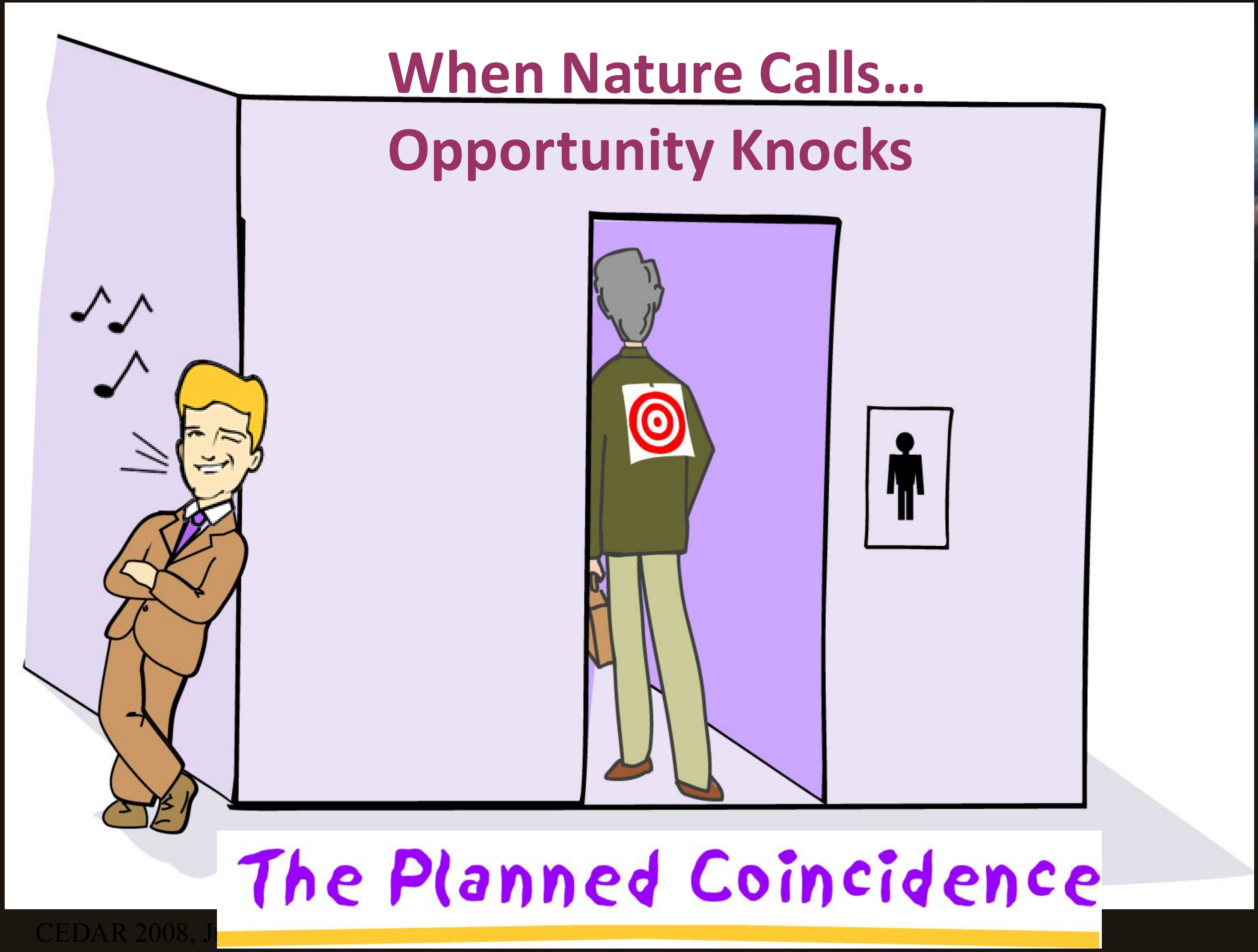
Smead Aerospace
UNIVERSITY OF COLORADO BOULDER

What is the Geospace Dynamics Constellation (GDC)?



GDC is a 2013 Decadal Survey-recommended Strategic Mission being developed for the Living With a Star program in the NASA Heliophysics Division.

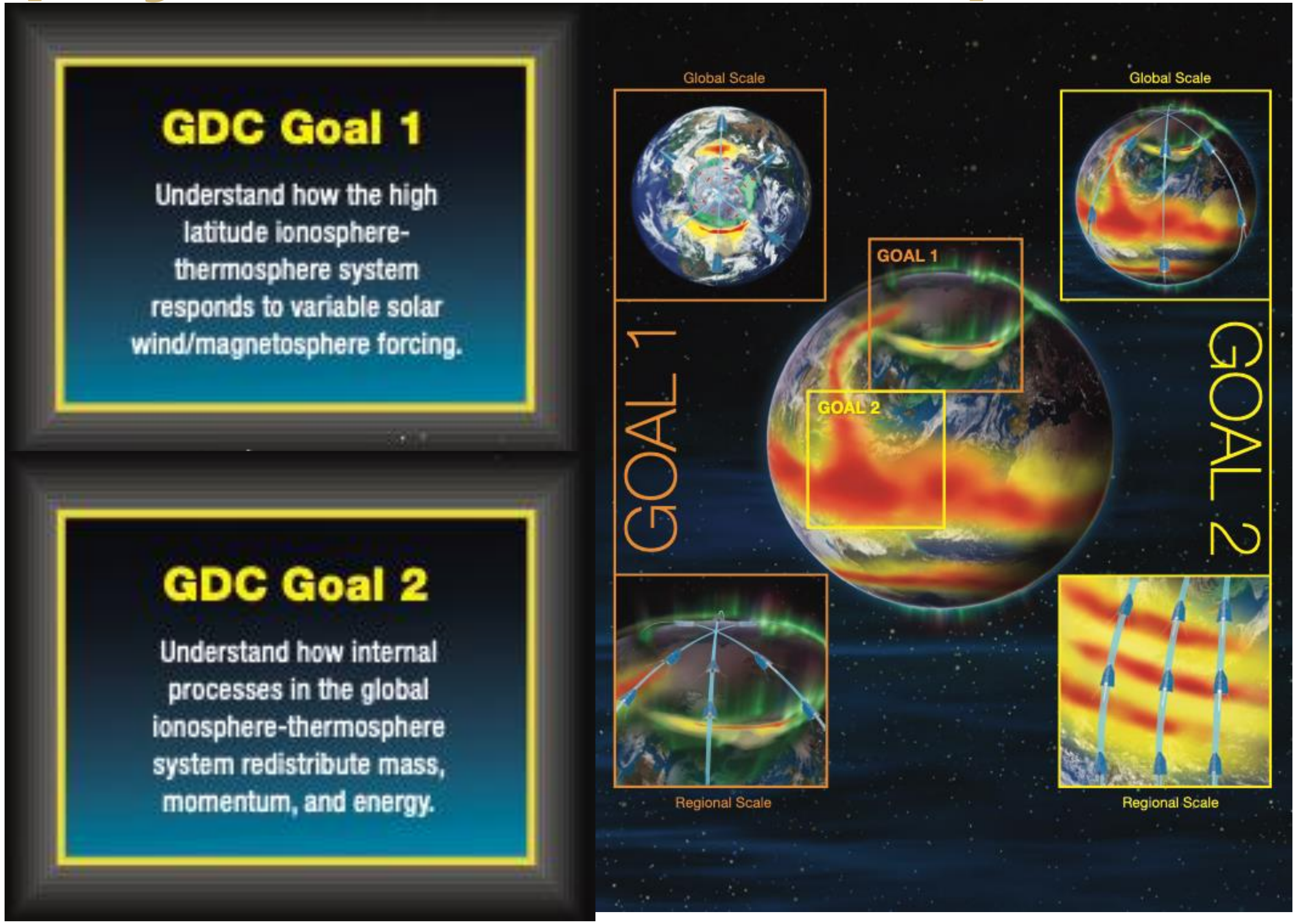
The nominal mission is a low-earth orbit constellation of six satellites (350-400 km, high inclination ~82 deg) that will provide a comprehensive study of the upper atmosphere and its responses to forcing from the magnetosphere


When Nature Calls…
Opportunity Knocks
The Planned Coincidence

CEDAR 2008, J

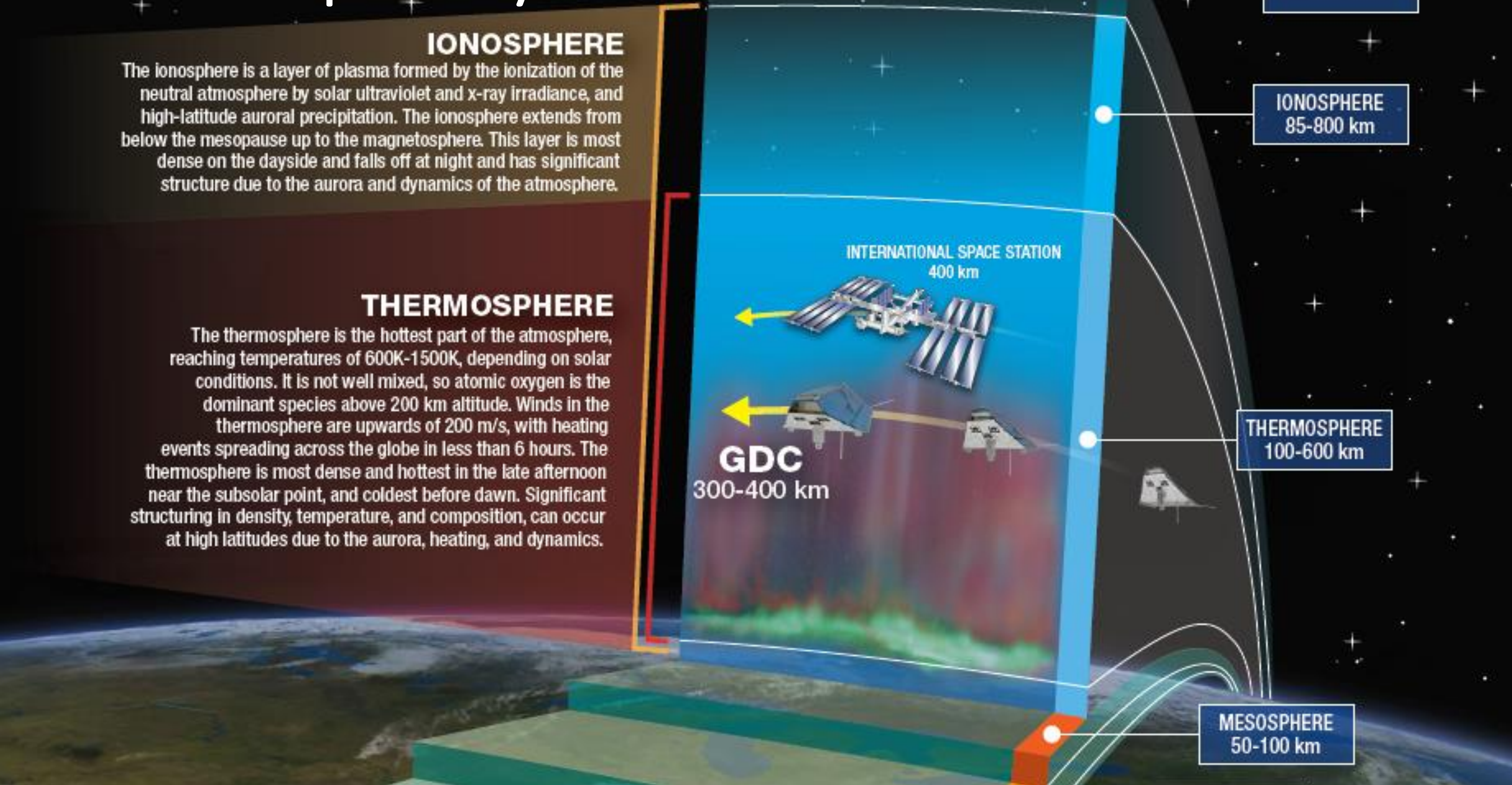
University of Colorado Active Remote Sensing Lab (ARSENL)

GDC Science Goals are focused on the physics of the ionosphere/thermosphere



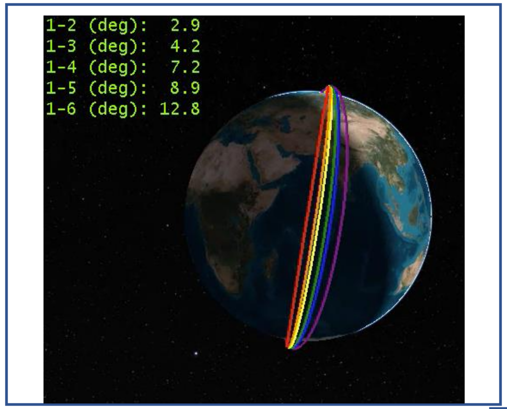
- Pathways of energy and momentum transport, especially across boundaries (e.g. across the magnetic field, as well as vertically)
- Importance of cross-scale coupling
- Development of feedback mechanisms (ionosphere/thermosphere as an “active” load for the magnetosphere)
- Broadening our perspective to the first truly global picture of the ionosphere-thermosphere system

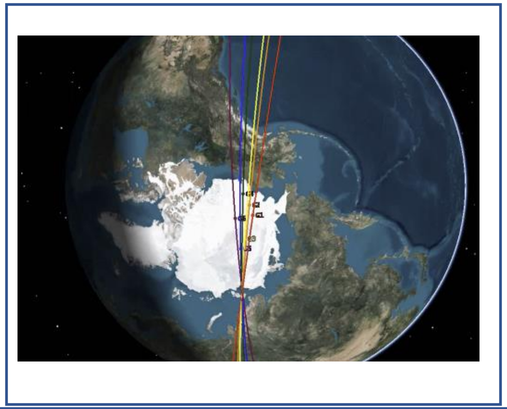
NASA Geospace Dynamics Constellation



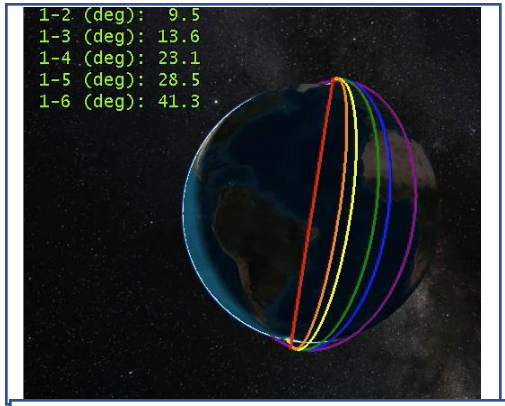
GDC samples at all scales, local times, and seasons over its 3-year mission

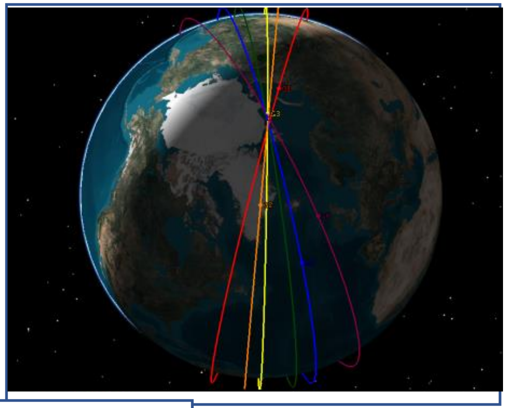
”Local” phase



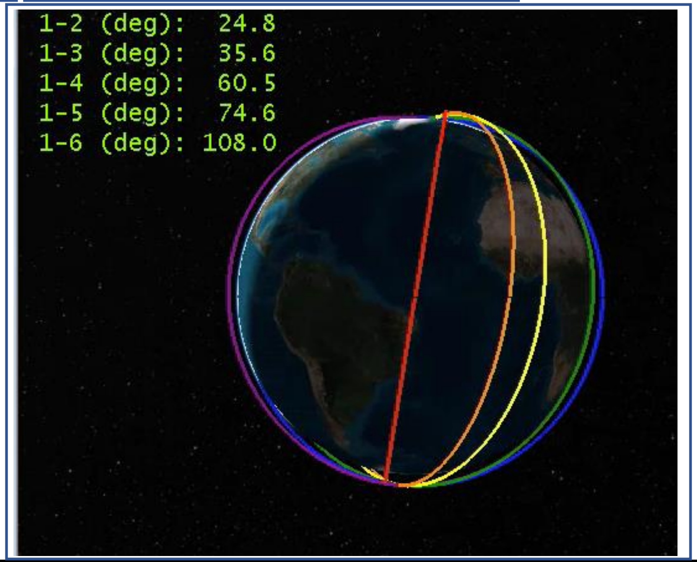


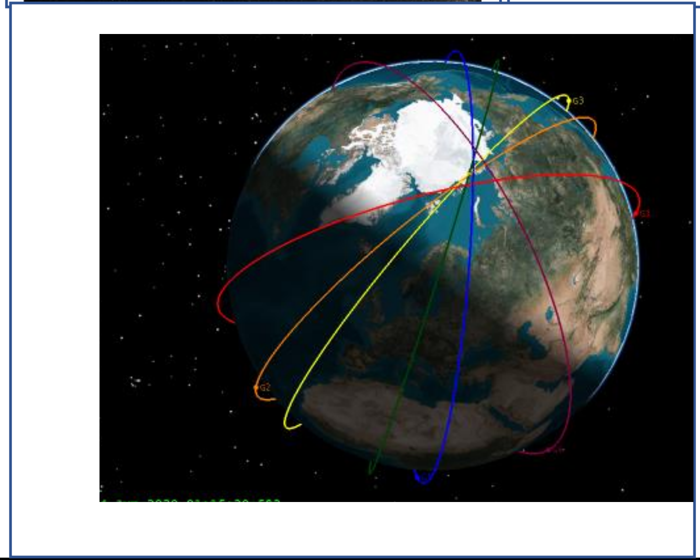
”Regional” phase



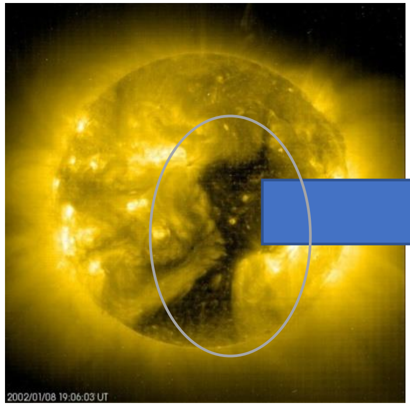


”Global” phase



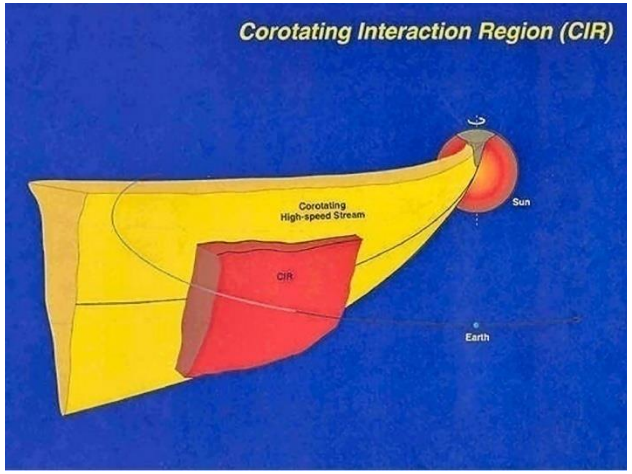


Solar Coronal Holes

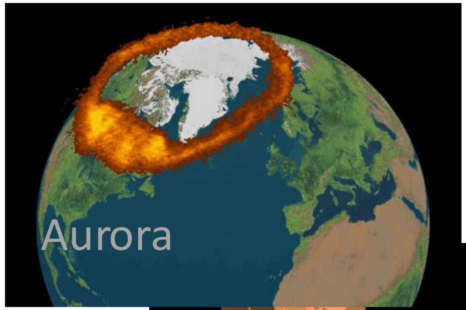


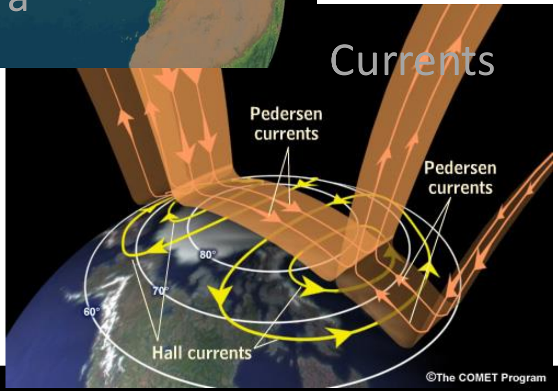
High Speed
Solar Wind Streams

Interplanetary Medium



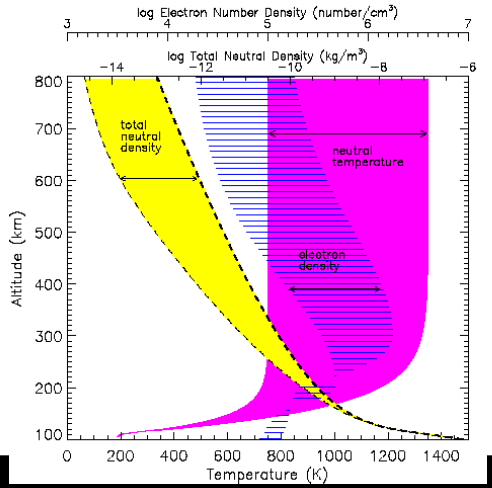
Geomagnetic Storm





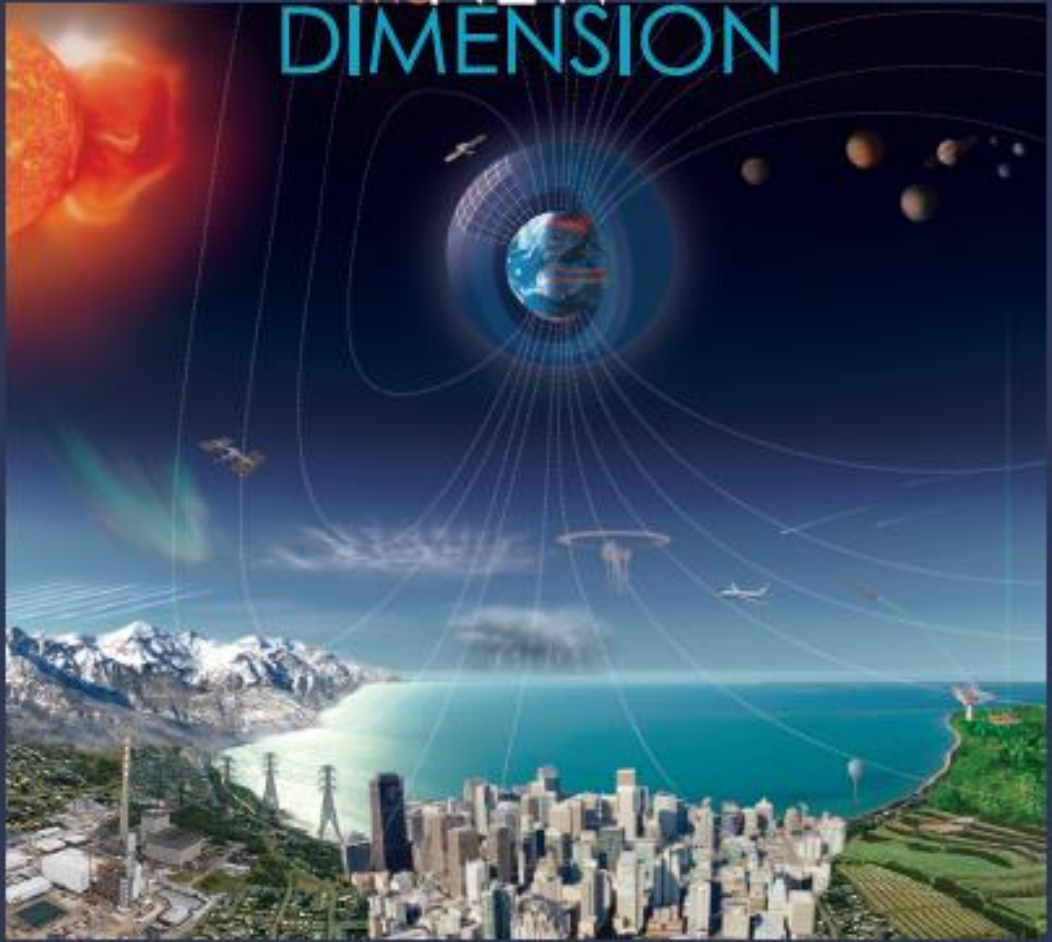
Global Thermosphere
Heating

Thermosphere Breathing



CEDAR

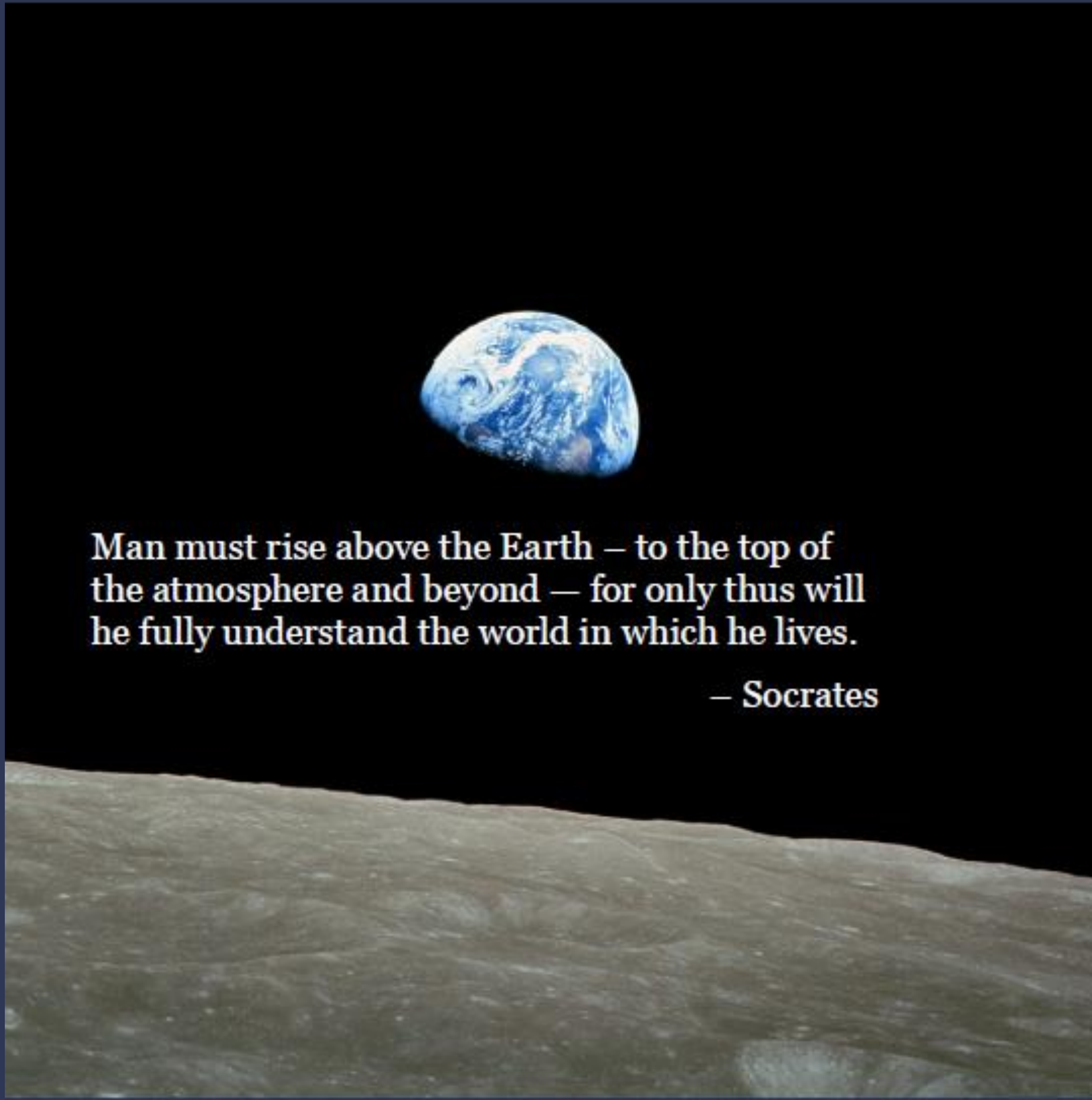
The NEW DIMENSION



STRATEGIC VISION

for the National Science Foundation Program on

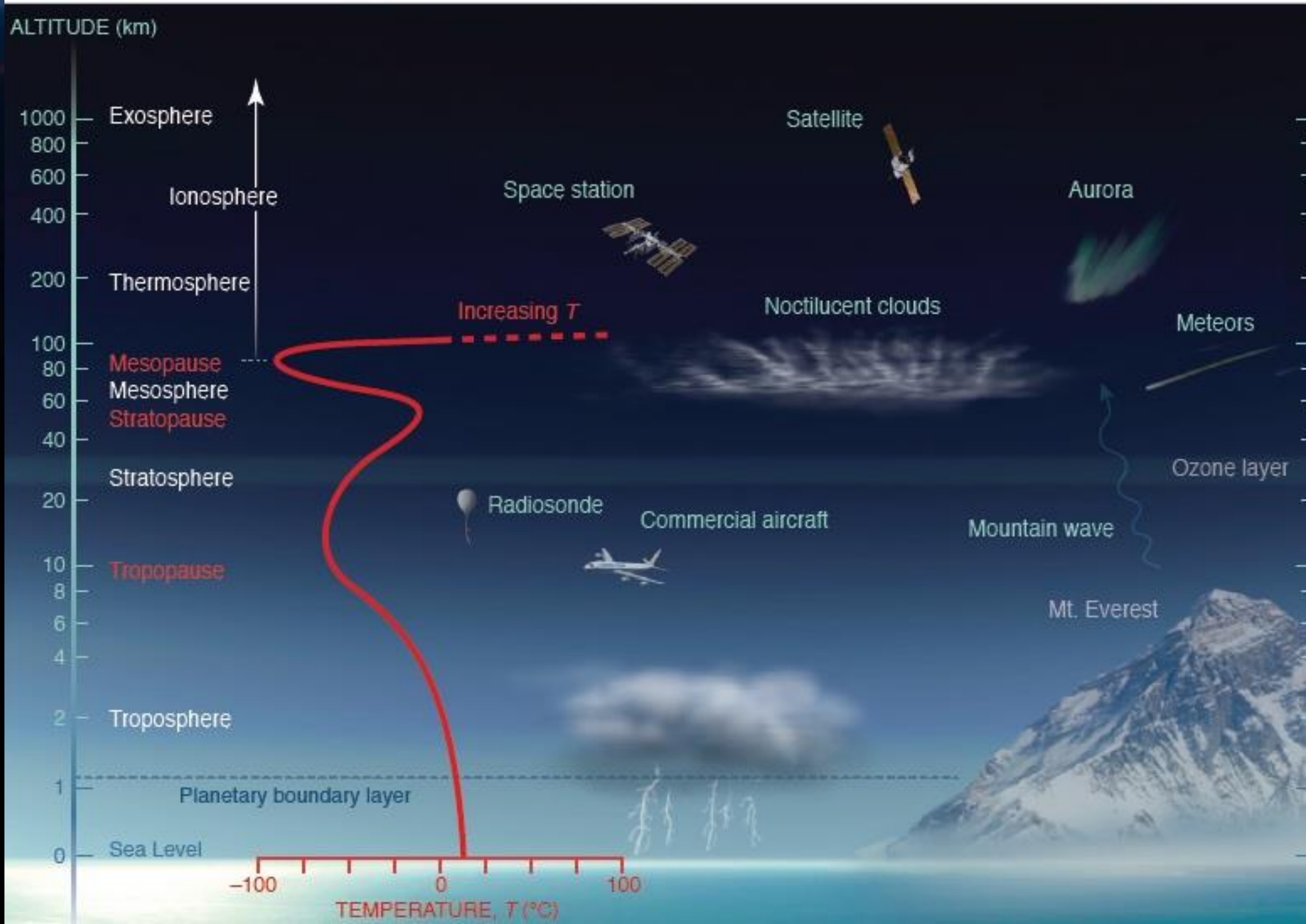
COUPLING, ENERGETICS AND DYNAMICS OF ATMOSPHERIC REGIONS



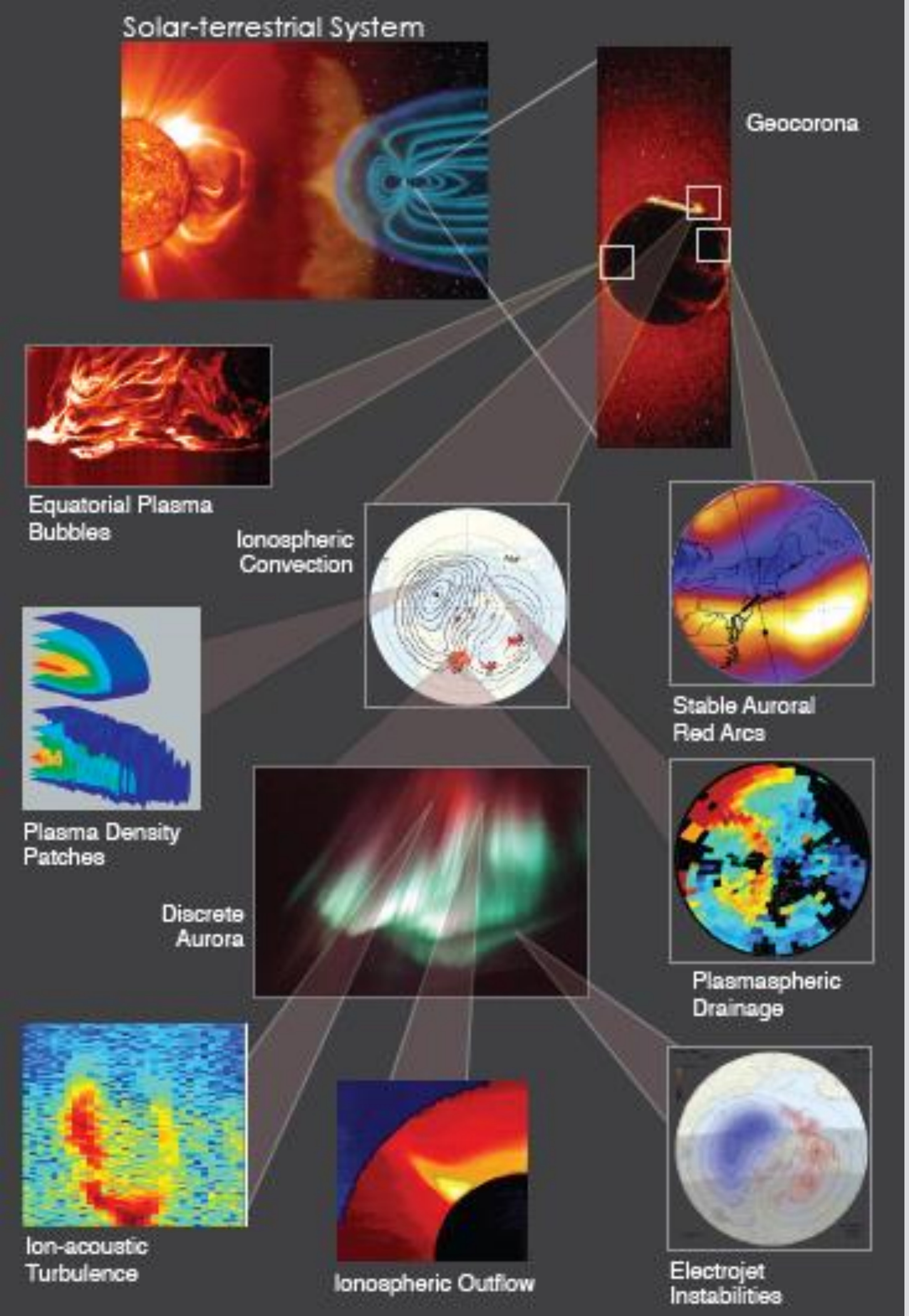
Sunset over western South America. International Space Station Imagery, NASA.

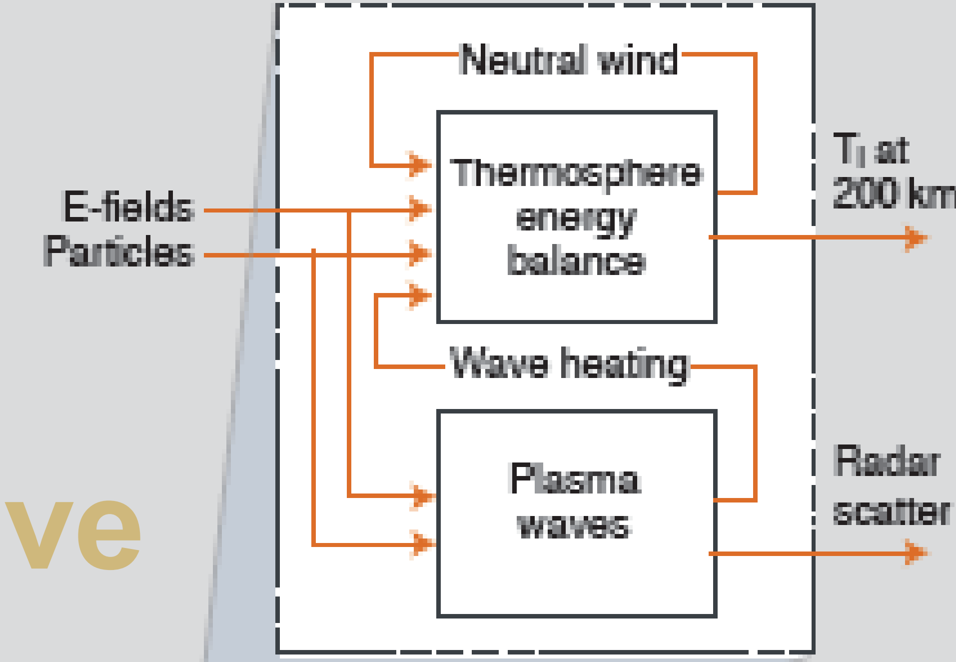
2 The Space-Atmosphere Interaction Region

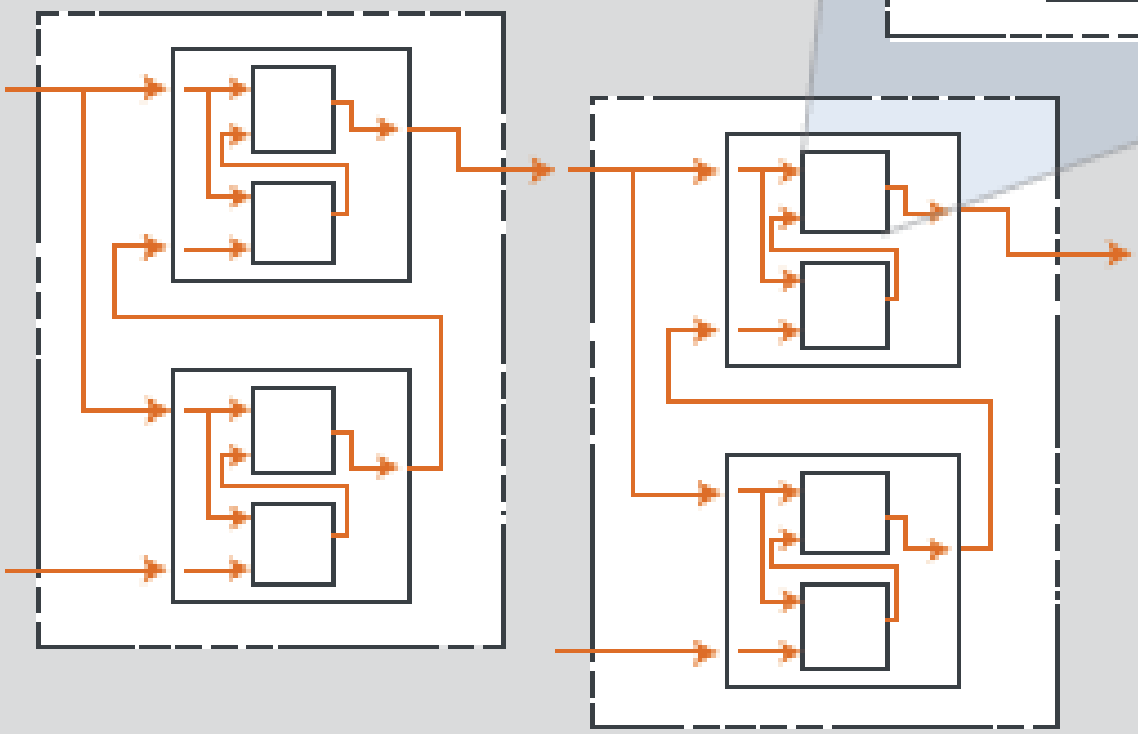
To understand the processes that govern the coupling, energetics, and dynamics of the upper atmosphere, it is useful to envision this as an *interaction region*, coupling the lower atmosphere with space and the universe beyond.

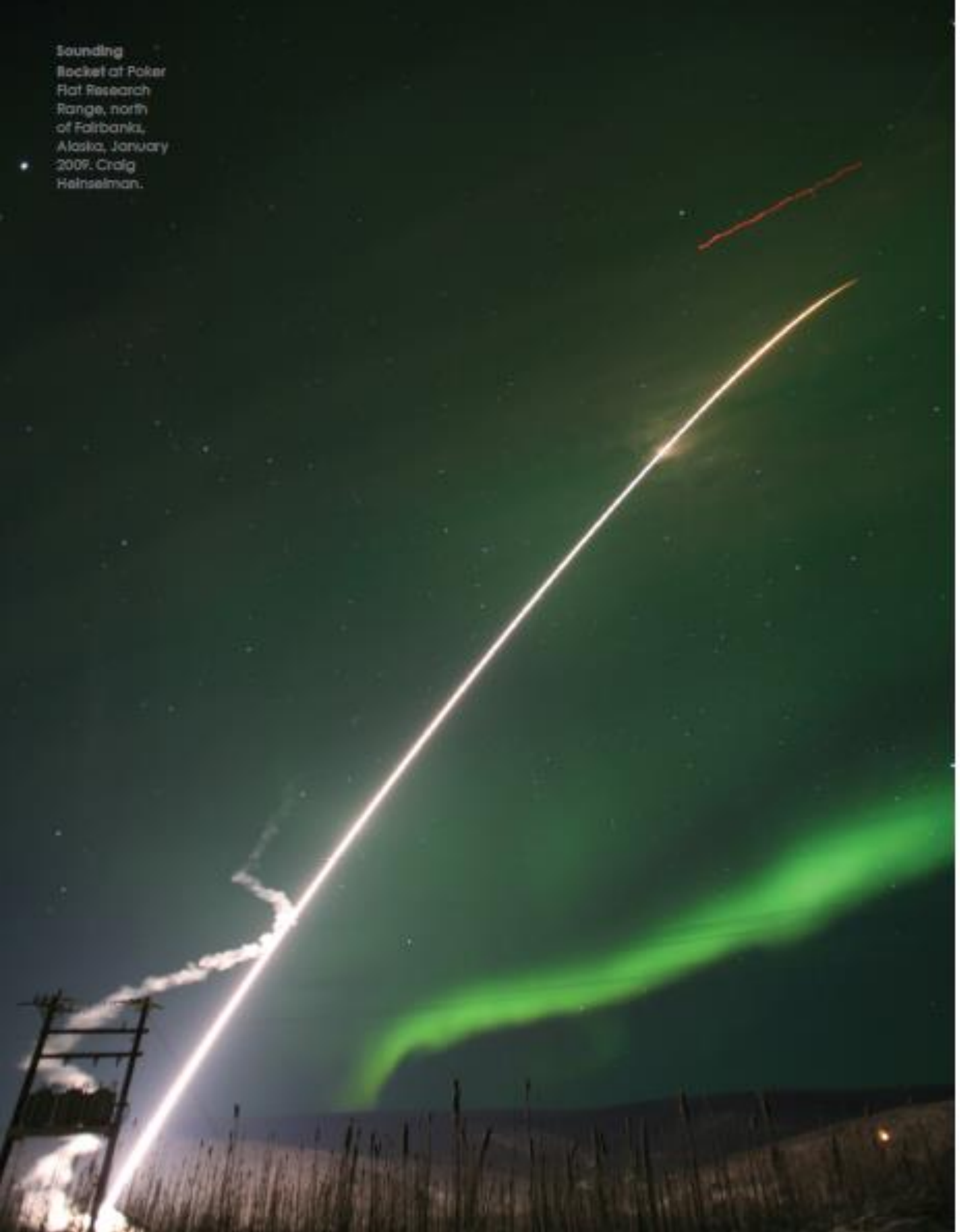


Systems Perspective





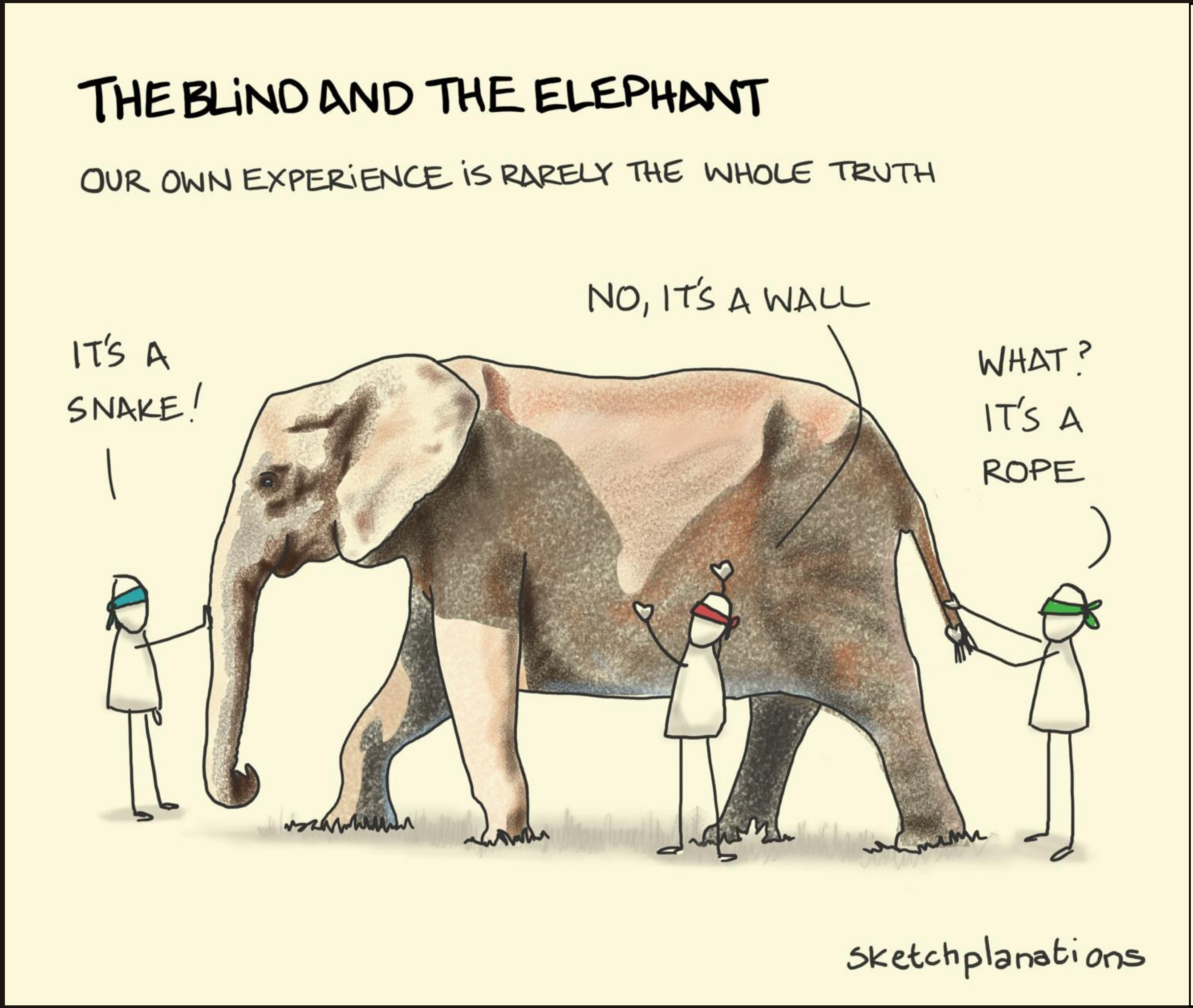


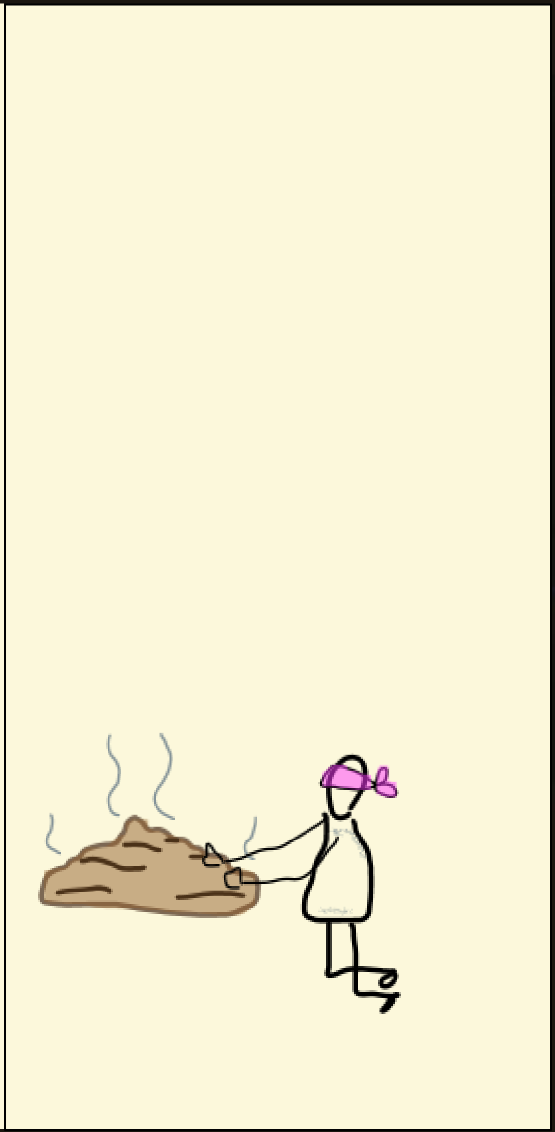


4 The Way Forward

The 21st century approach to understanding the Sun-Earth system is to explore new avenues of progress, building on past decades of accomplishments.

1. Encourage and undertake a Systems Perspective of Geospace
2. Explore Exchange Processes at Boundaries and Transitions in Geospace
3. Explore Processes Related to Geospace Evolution
4. Develop Observational and Instrumentation Strategies
5. Fuse the knowledge Base across Disciplines
6. Manage, Mine, and Manipulate Geoscience/Geospace Data and Models

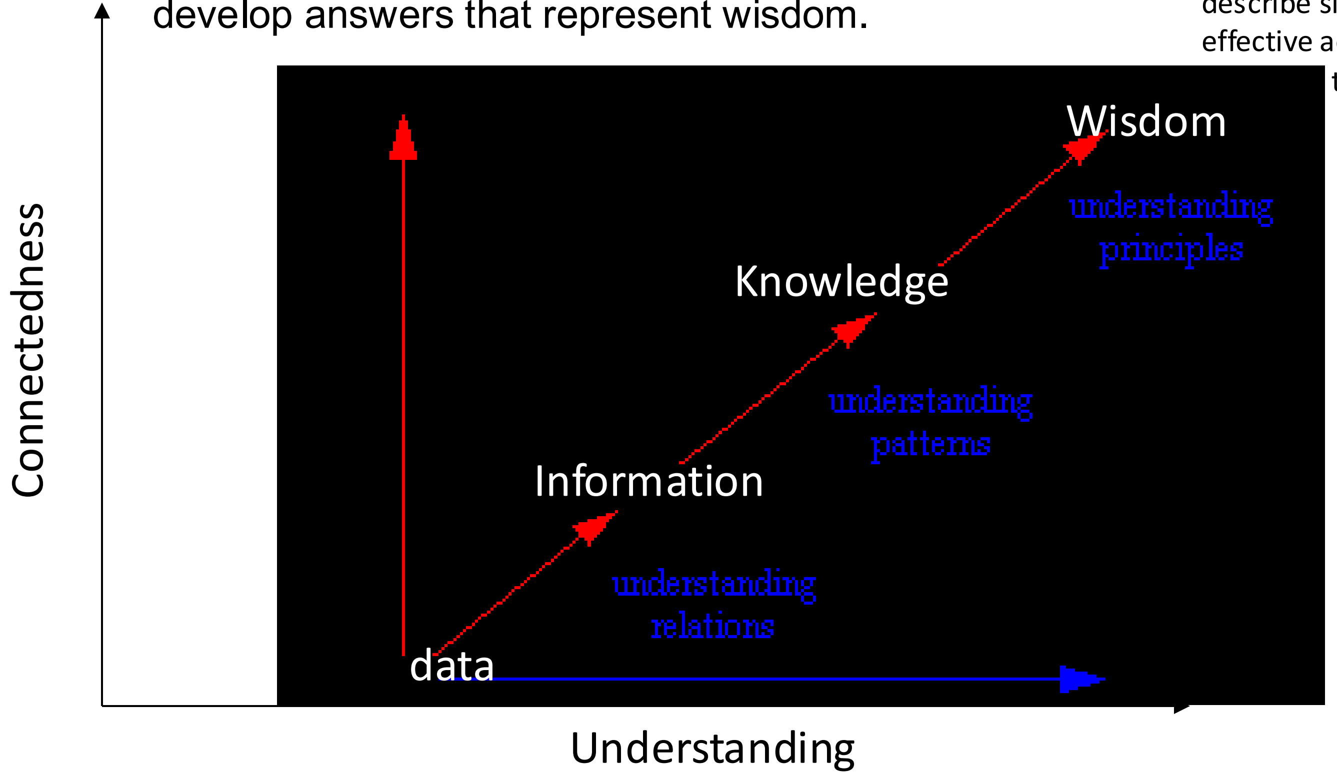




"It ain't what you don't know that gets you into trouble. It's what you know for sure that just ain't so." — Mark Twain

- To improve the character of the questions we ask it is important to transcend the levels in the above diagram. If we ask questions that allow data to be an answer that is what we will get. If we ask questions regarding relations, i.e. cause and effect, then we will find, or make up, causes as answers to the questions we pose. When we finally reach the level of asking questions that cause us to seek out and understand the patterns responsible for the situations we consider we finally arrive at answers that represent knowledge. Finally when we ask questions which cause us to seek the underlying fundamental principles that are responsible for the patterns represented in the knowledge we are finally in a position to develop answers that represent wisdom.

The following diagram provides a perspective on the relation of data, inf
describe situations and seek understanding further up this path we deve
effective actions. Actions which are more likely to produce the desired r
to be solved.



The CEDAR mission is to understand the fundamental properties of the space-atmosphere interaction region (SAIR); identify the interconnected processes that define the SAIR's global behavior, evolution, and influence on the Sun-Earth system; and to explore the SAIR's predictability.

Perspective

Coupling, Energetics and Dynamics of Atmospheric Regions

The Cedar Post

Winter 2010 Issue 58

The 1990 CEDAR Workshop attracted 267 participants from more than 50 institutions in the United States, Canada, France, West Germany, Sweden, Finland, United Kingdom, Norway, Peru, and Puerto Rico. On the afternoon of June 14, the CEDAR "crew" gathered in the NCAR courtyard for a group photograph of all attendees (top) and for a special photograph of the student attendees (bottom).

Past 30 years – Moving ahead by Looking

1990 CEDAR MEETING AGENDA

TUESDAY
June 12, 1990-NIST/NCAR

8:30-8:45	Welcome at NIST Killeen/Gardner, NCAR/HAO, Bierly/NSF
8:45-10:00	Introductions CEDAR post docs CEDAR prize lecturer Students
10:00-10:15	BREAK
10:15-10:45	CEDAR Prize Lecture
10:45-11:00	CEDAR Post-Doc report Julie Moses
11:00-12:30	NASA Future Programs: Ionosphere-Thermosphere-Mesosphere and Magnetospheric Physics Killeen, Szuszczewicz and community discussion
12:30-2:00	LUNCH (adjourn to NCAR)
2:00-5:30	Workshops at NCAR
5:30-6:30	Reception at NCAR

WEDNESDAY
June 13, 1990-NIST/NCAR

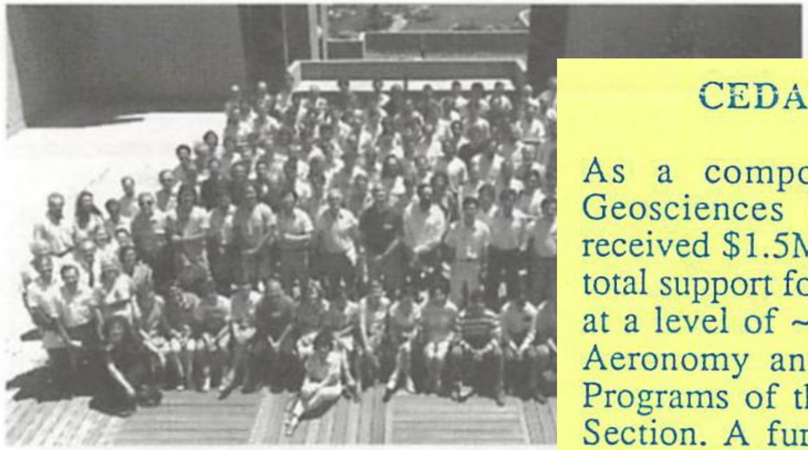
8:30-9:30	Tutorial 1 - Peter Stubbe Review of Ionospheric Modification
9:30-10:30	Instrument updates and short talks
10:30-10:45	BREAK
10:45-12:30	Instrument updates and short talks
12:30-2:00	LUNCH (adjourn to NCAR)
2:00-5:30	Workshops at NCAR
about 6:30	Bar-B-Q at NCAR on *tree plaza*

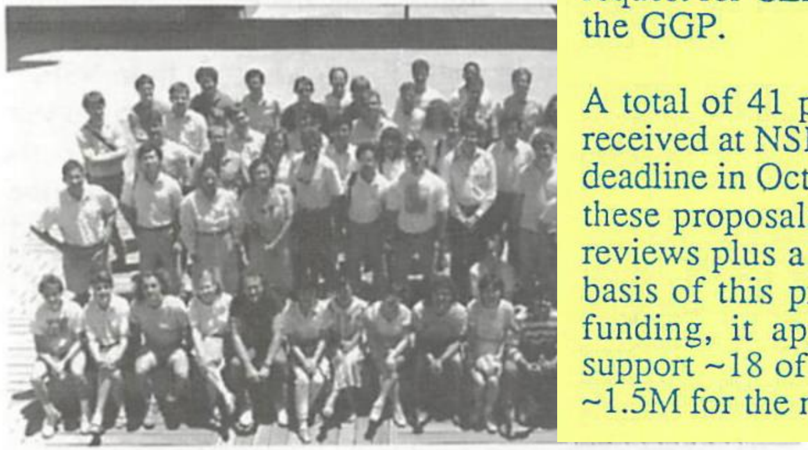
THURSDAY
June 14, 1990-NIST

8:30-9:30	Tutorial 2 - Larry Lyons Ionosphere/Magnetosphere Coupling and Auroral Acceleration Processes
9:30-10:30	Poster previews (2 min or 2 figures)
10:30-10:45	BREAK
10:45-12:30	Poster session at NIST
12:30	Adjourn for the day

FRIDAY
June 15, 1990-NIST/NCAR

8:30-9:30	Tutorial 3 - Tom Slanger Aeronomical Laboratory Work
9:30-10:30	Instrument updates and short talks
10:30-10:45	BREAK





The 1990 CEDAR Workshop attracted 267 participants from more than 50 institutions in the United States, Canada, France, West Germany, Sweden, Finland, United Kingdom, Norway, Peru, and Puerto Rico. On the afternoon of June 14, the CEDAR "crew" gathered in the NCAR courtyard for a group photograph of all attendees (top) and for a special photograph of the student attendees (bottom).

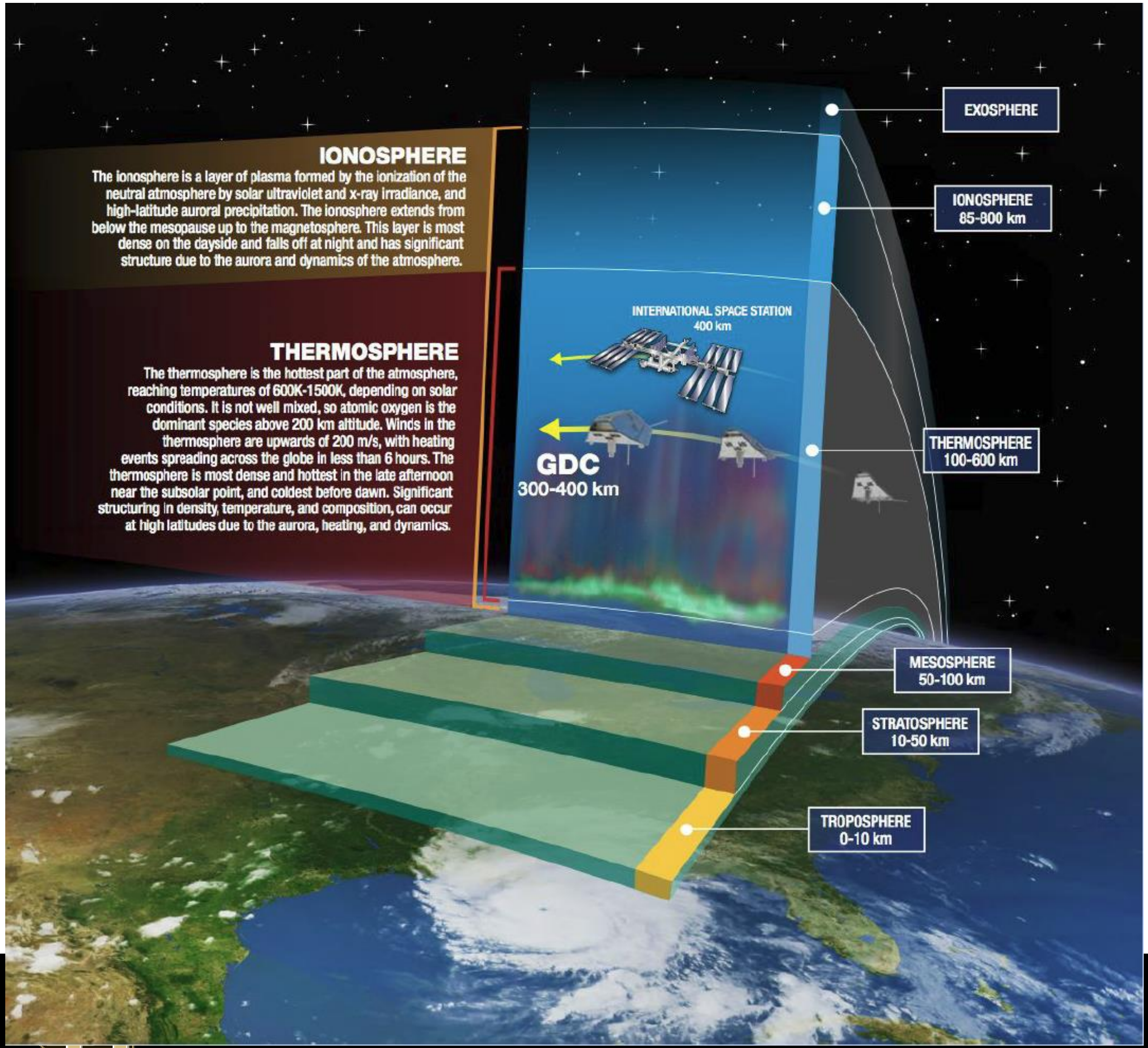
CEDAR budget for FY 1990

As a component part of NSF's Global Geosciences Program (GGP), CEDAR has received $1.5M in new funds for FY 1990. The total support for CEDAR within the GGP is now at a level of ~ $2.6M and is split between the Aeronomy and Upper Atmosphere Facilities Programs of the Upper Atmospheric Research Section. A further $1.2M is in the President's request for CEDAR in FY 1991 - again as part of the GGP.

A total of 41 proposals requesting ~ $4M were received at NSF in response to the latest proposal deadline in October 1989. The review process for these proposals included the traditional mail-in reviews plus a subsequent panel review. On the basis of this process and the available level of funding, it appears that NSF will be able to support ~18 of these proposals at a total level of ~1.5M for the next fiscal year.

Next 30 years – Winds of Change

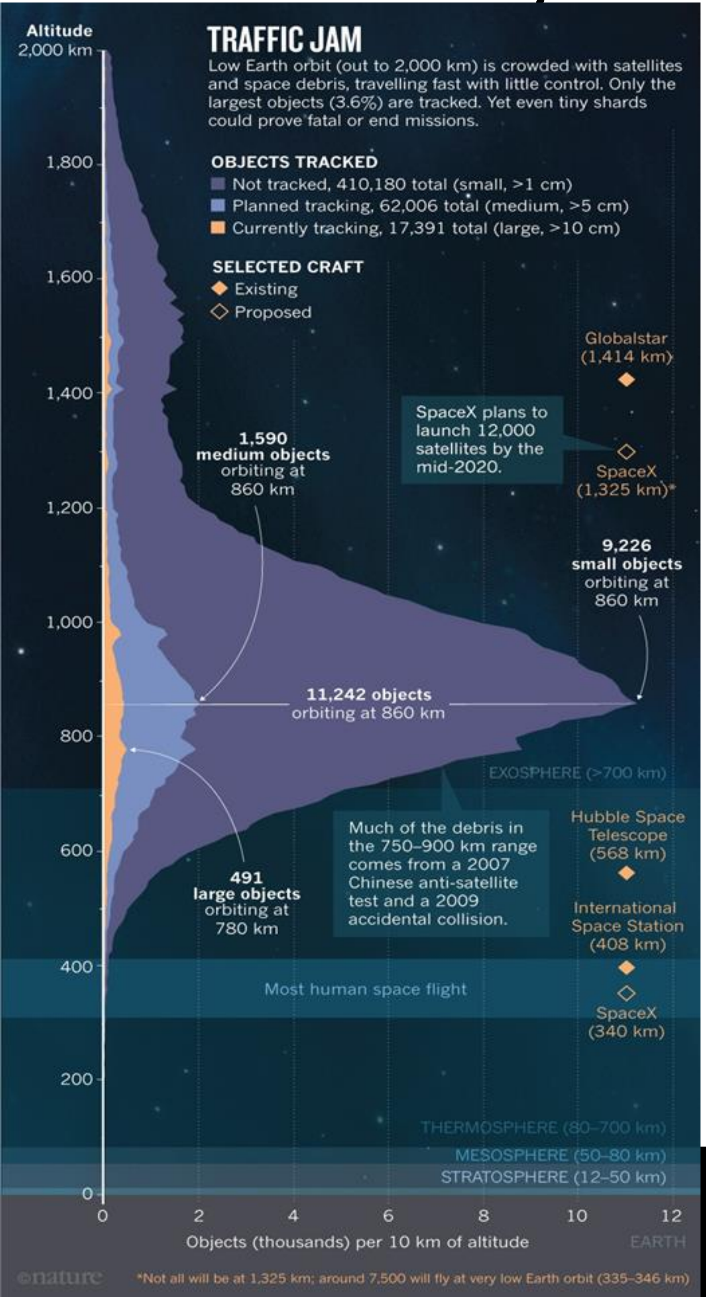
Literally, Figuratively, and Aspirationally



Literally:

- Close the thermosphere gap - Thermosphere neutral gas wind field requires observation but poses a significant challenge as the 4-D field, not just local motion, is required.
- Explore “integrative aeronomy” as a system that exhibits complexity – characterized by having multiple drivers, by featuring adaptive feedback and memory, by its nonlinear response and instabilities, and by exhibiting sensitivity to initial conditions.
- Apply CEDAR’s modeling, observational techniques, and insight beyond the Earth system and contribute to (exo) planetary coupling energetics and dynamics [redacted]

Next 30 years – Winds of Change



Figuratively:

ITM is rapidly becoming a crowded orbital domain involving a public-private enterprise with growing commercial use and mega-constellation concepts to provide such societal services as global internet connectivity and 5G wireless networks for Internet of Things devices.

- How can CEDAR science benefit from such a concentration of operating spacecraft?
- How can CEDAR science help inform society’s future use of space in LEO?
- More generally, how can CEDAR science make NSF a major player in space research?

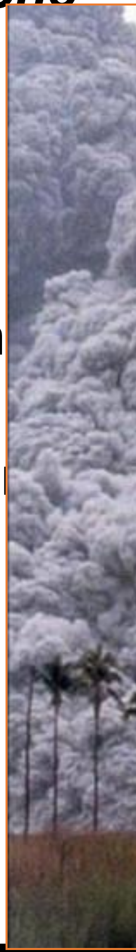
Next 30 years – Winds of Change

Aspirationally: ***The most fruitful areas for growth of the sciences are those between established fields. Science has been increasingly the task of specialists, in fields which show a tendency to grow progressively narrower. Important work is delayed by the unavailability in one field of results that may have already become classical in the next field. It is these boundary regions of science that offer the richest opportunities to the qualified investigator.***

– Norbert Wiener

This can be applied more broadly to current and future times where inclusivity and equity of diverse thought, experiences, and backgrounds yield unbounded and undiscovered opportun for personal and scientific enrichment and advancement.

I believe CEDAR has the opportunity to bridge across scientific and societal boundaries to en the field and the individual’s experience, growth, and impact through inclusivity and equity.



Community

Equity

Diversity

Altruism

R