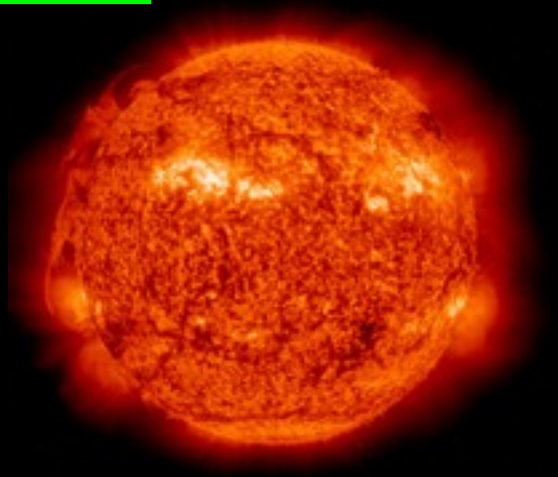
The Sun's Influence on Planetary Atmospheres



Frank Eparvier
eparvier@colorado.edu
University of Colorado,
Laboratory for Atmospheric & Space Physics

Who am I?

Dr. Frank Eparvier

Research Scientist @ LASP

- Training in Aeronomy
  - Aeronomy = study of how energy inputs drive the physics and chemistry a planetary atmosphere
- Experimentalist: I like to measure things
  - "Experiment is the test of all knowledge."
- Currently work with instruments that measure the solar photonic output of aeronomical importance:
  - Co-I on TIMED-SEE
  - Co-I on SDO-EVE
  - PI on GOES-R EXIS
  - Lead on MAVEN-EUVM

Storytelling

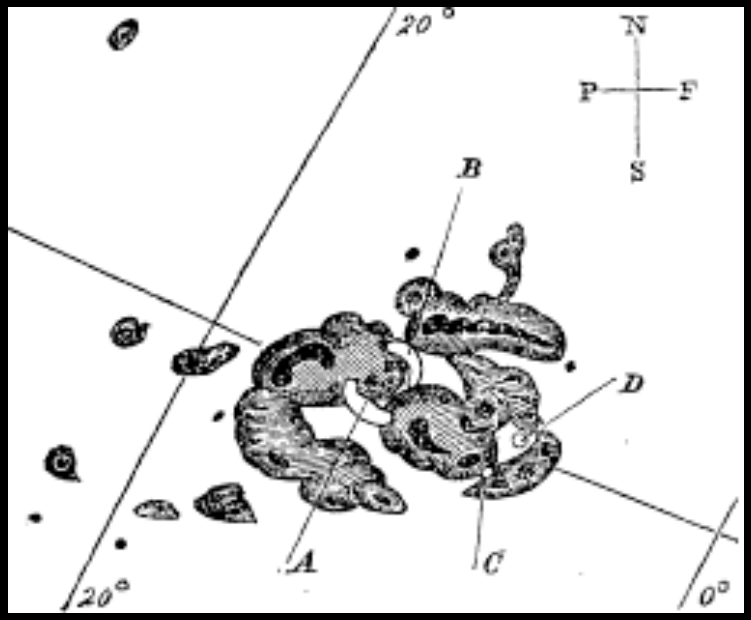
- **Personal Recollection:** My first aurora
- **Historical Event:** The Carrington event
- **Here and Now:** How space weather affects Earth
- **There and Now (and Then):** How space weather affects other Planets (Mars in particular)

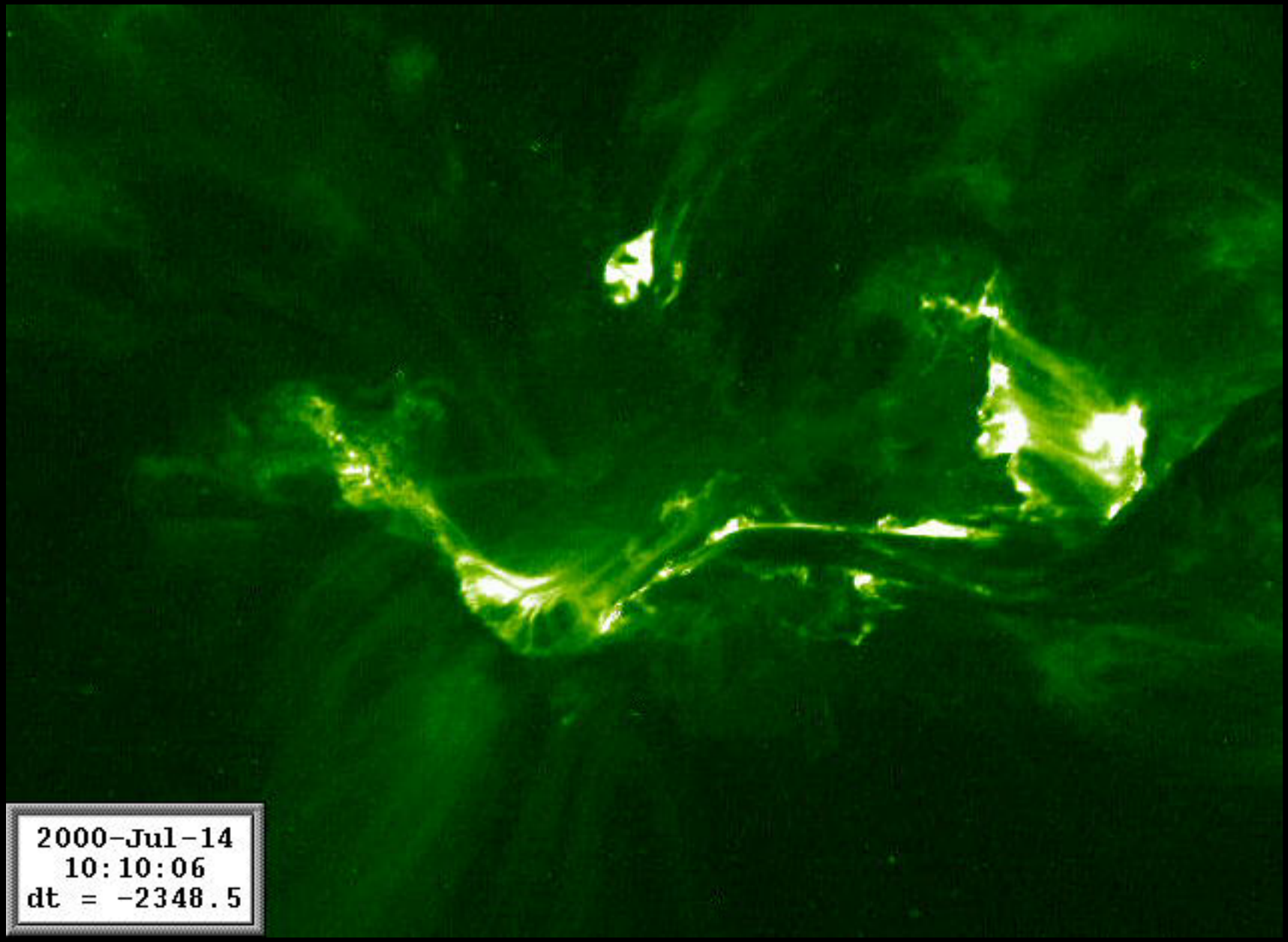
Personal Story

- **Northeast Wisconsin, August 1983**
- **A young scientist "sees the light"**

History: Someone Else's Story

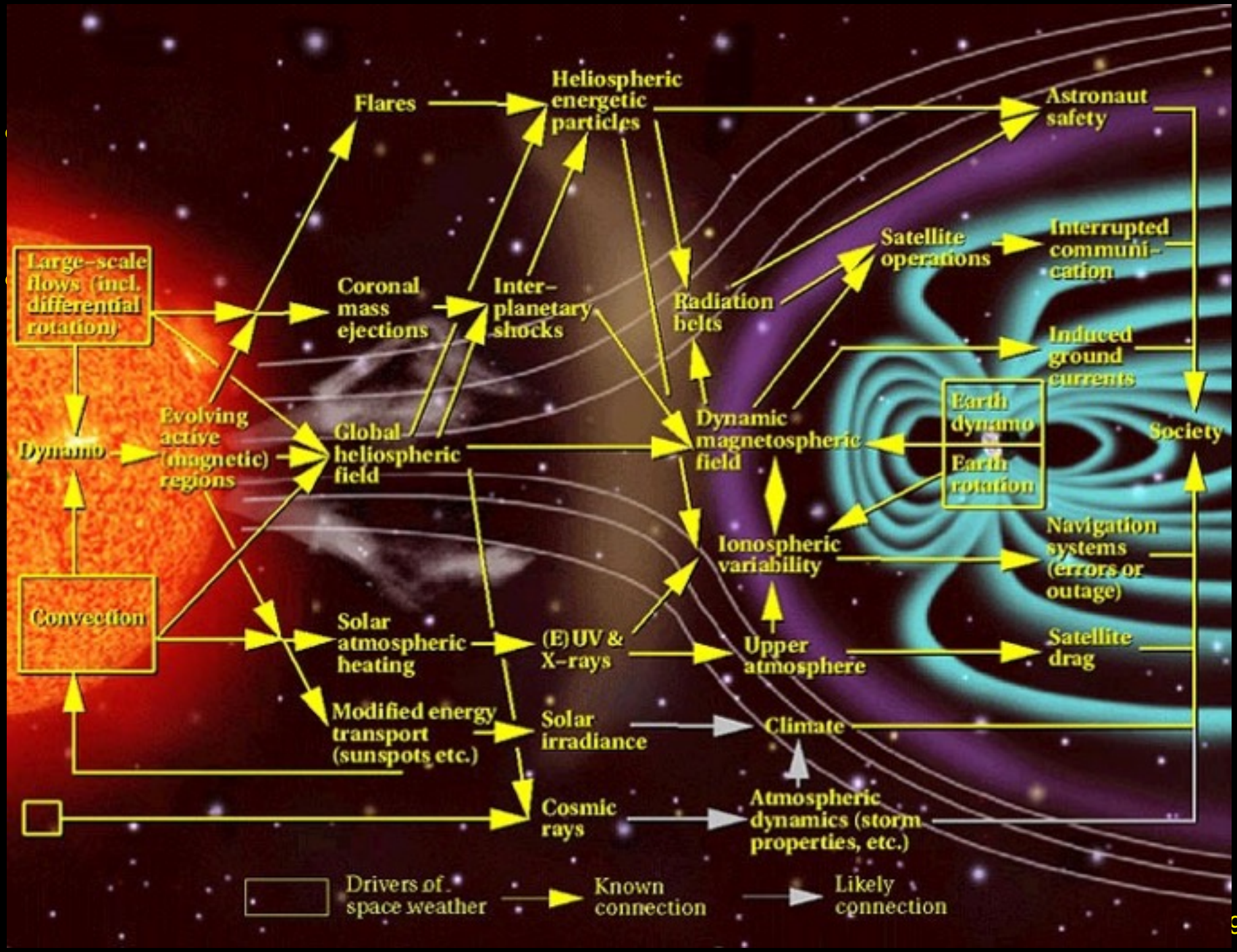
- Thursday, September 1, 1859, 11:18 am
- Richard Carrington, a British astronomer, was observing the Sun
- Saw a "white light flare" that lasted a few minutes




2000-Jul-14
10:10:06
dt = -2348.5

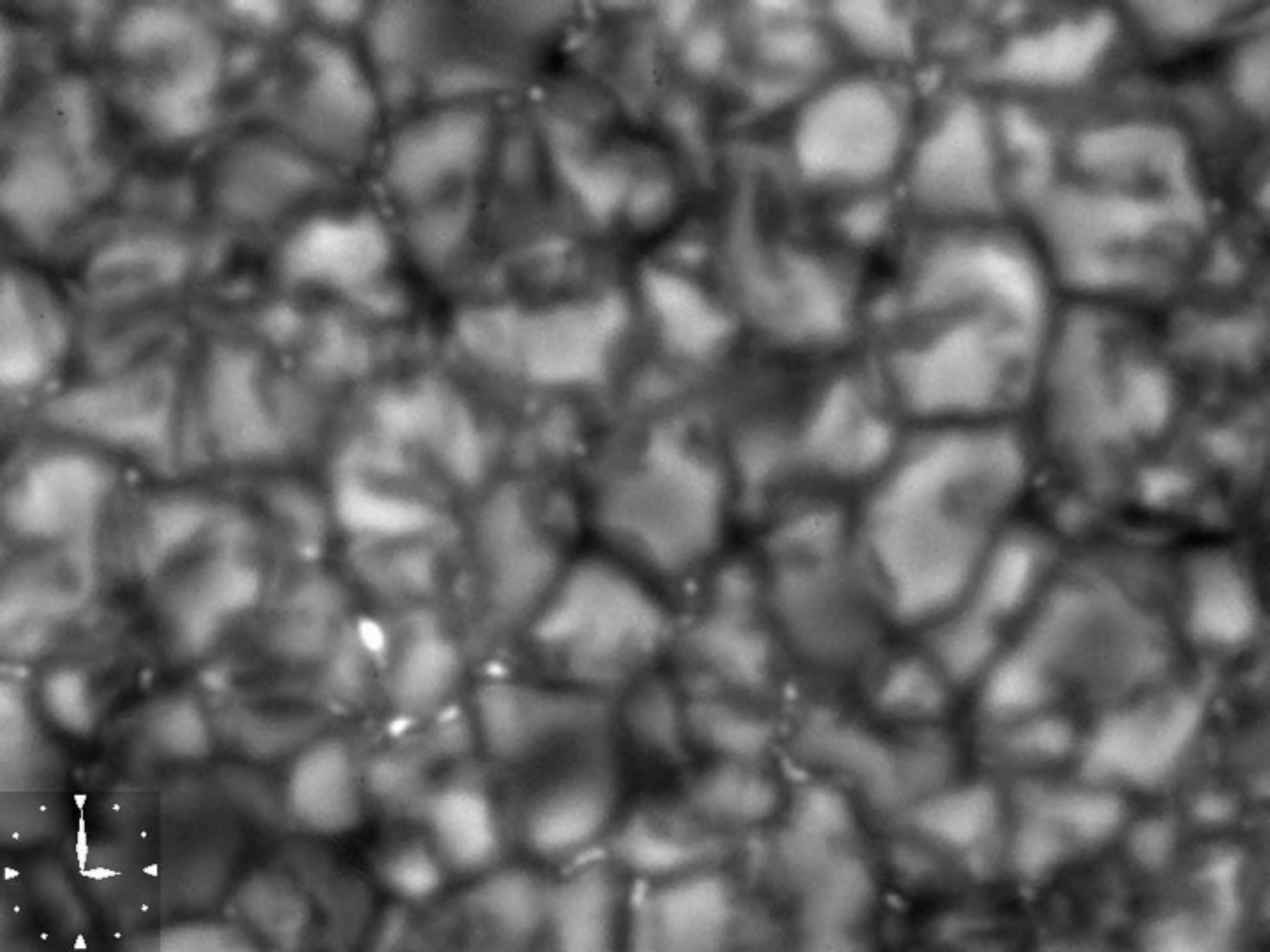
The Next Day

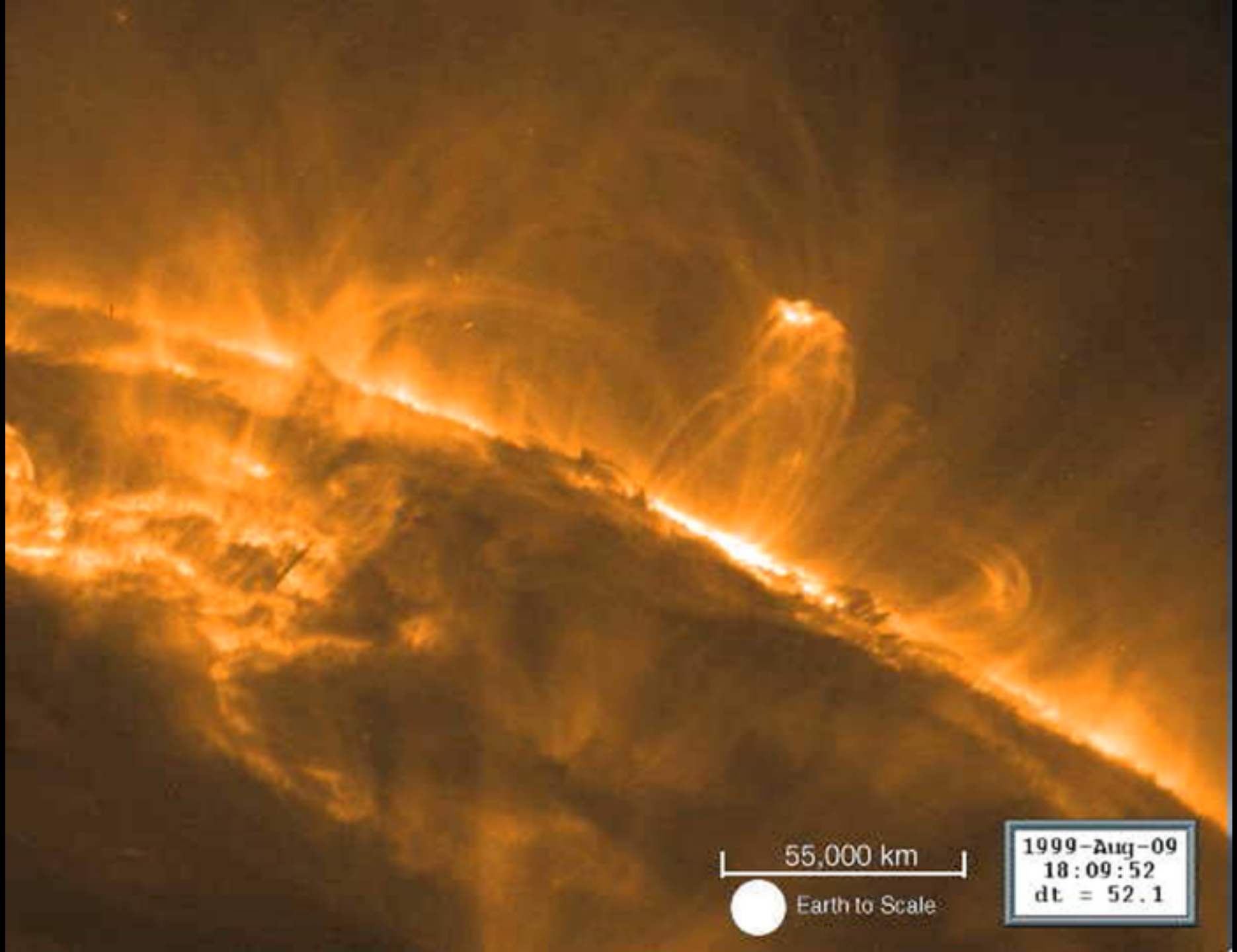
- **All heck broke lose**
- Telegraph operators around Europe & US had problems:
  - Could transmit without turning on their power
  - Sparks flew from equipment
  - Fires broke out and burned down stations
- Aurora were seen far to the south of normal
  - Cuba, Bahamas, Jamaica, Hawaii, Rome, Hong Kong
- Carrington speculated the solar and terrestrial events were connected
  - Many scientists poo-pooed the idea that what happened on the Sun could affect the Earth

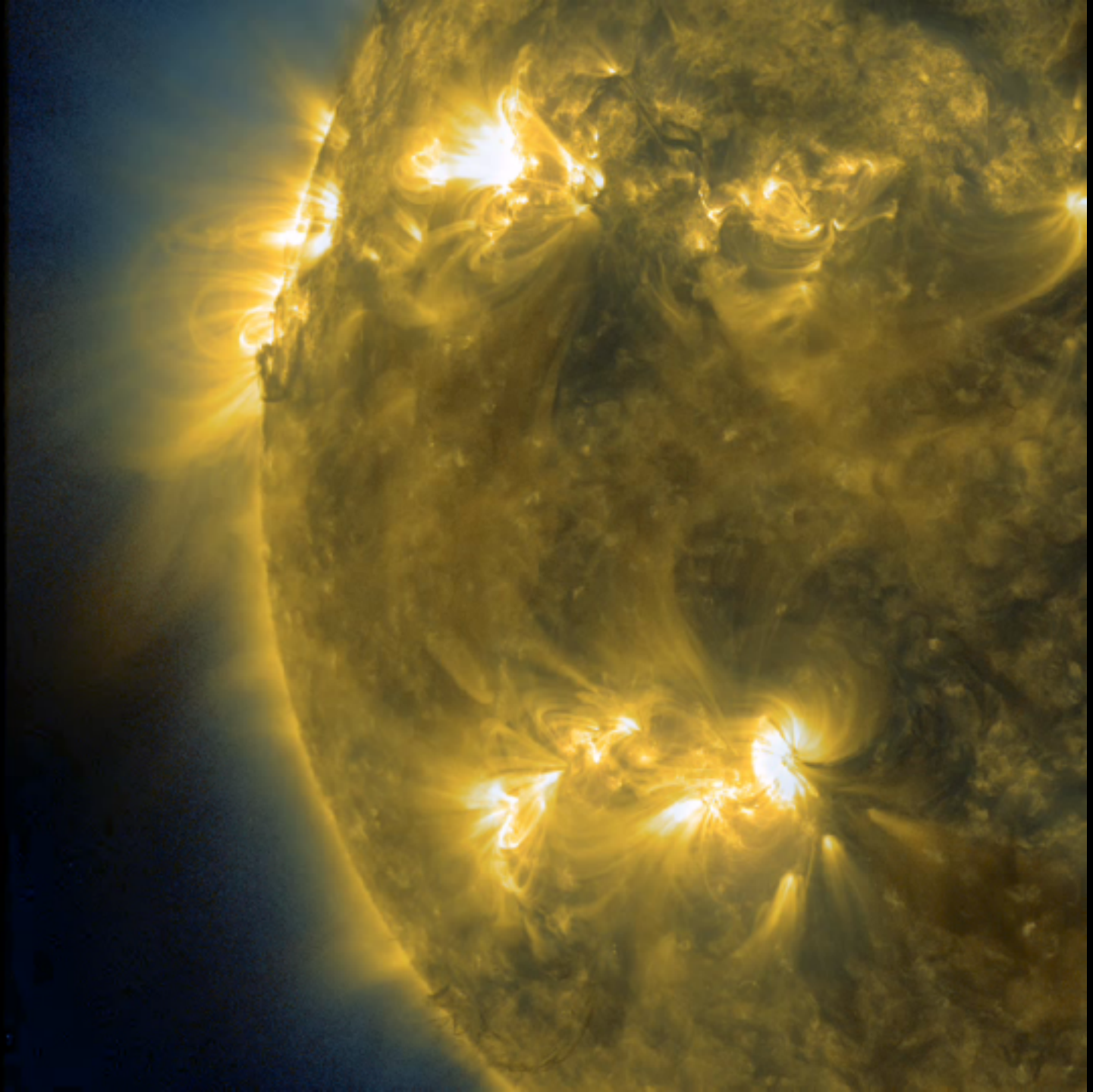

Flares
Heliospheric energetic particles
Astronaut safety
Large-scale flows (incl. differential rotation)
Coronal mass ejections
Inter-planetary shocks
Radiation belts
Satellite operations
Interrupted communi-cation
Induced ground currents
Dynamo
Evolving active (magnetic) regions
Global heliospheric field
Dynamic magnetospheric field
Earth dynamo
Earth rotation
Society
Ionospheric variability
Navigation systems (errors or outage)
Convection
Solar atmospheric heating
(E)UV & X-rays
Upper atmosphere
Satellite drag
Modified energy transport (sunspots etc.)
Solar irradiance
Climate
Cosmic rays
Atmospheric dynamics (storm properties, etc.)
Drivers of space weather
Known connection
Likely connection

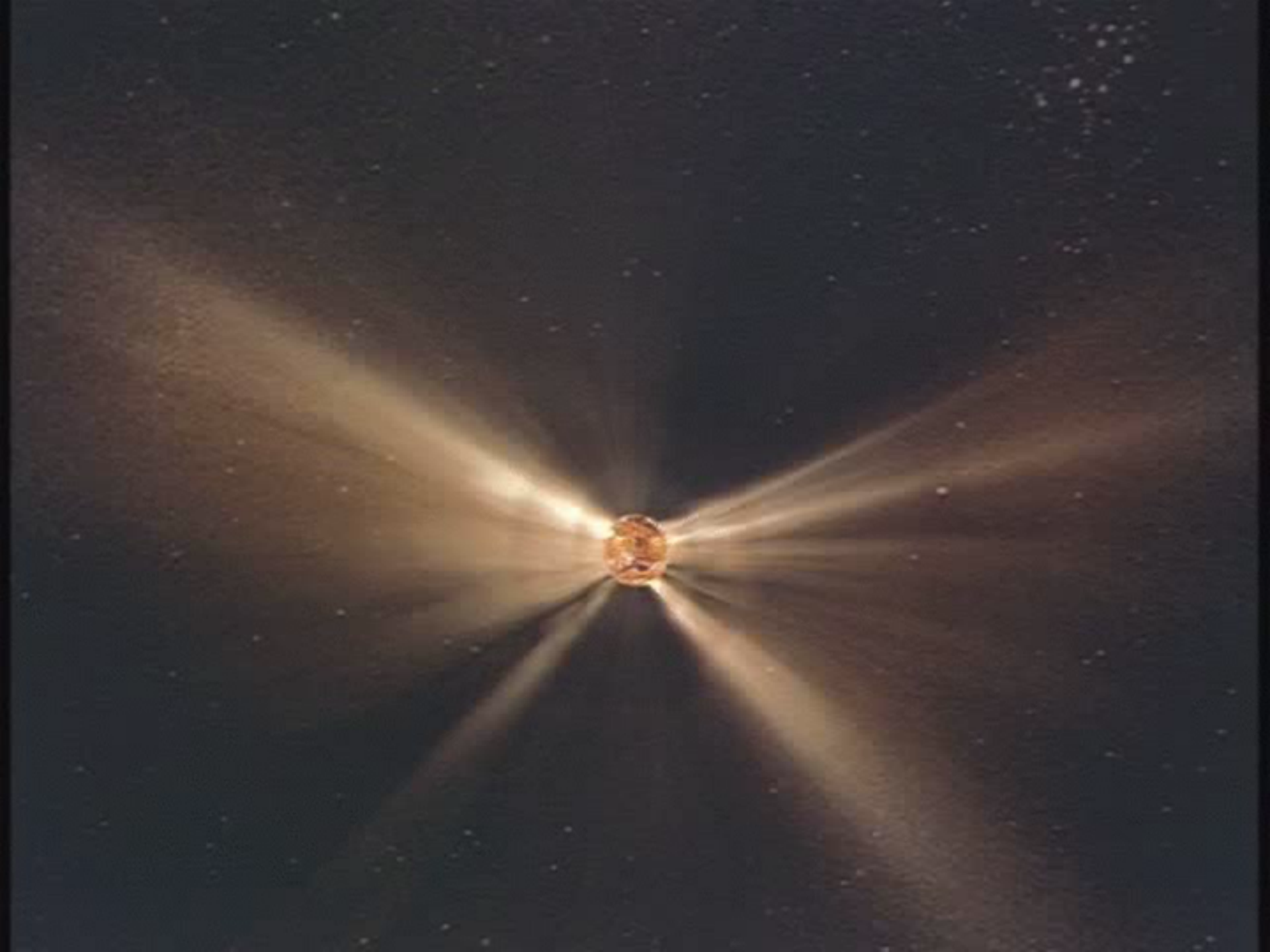
The Story Starts at the Sun

- Gives off energy of many forms
  - Light
    - of all wavelengths
  - Solar Wind
    - Charged particles
    - Magnetic fields
- The Sun is constantly changing
  - On all time scales from seconds to centuries
  - On all size scales from millimeters to megameters



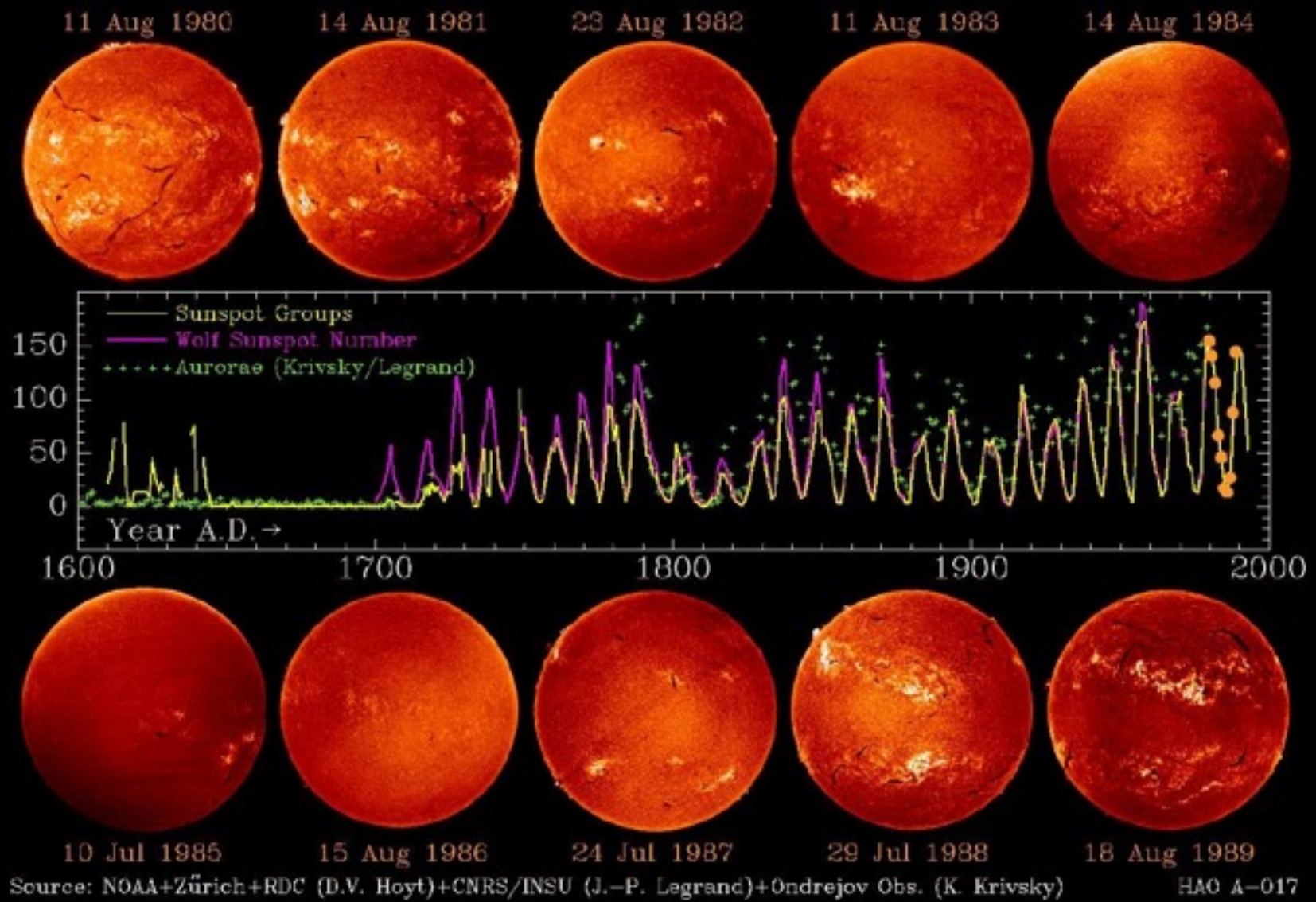

55,000 km
Earth to Scale
1999-Aug-09
18:09:52
dt = 52.1





Solar Cycles

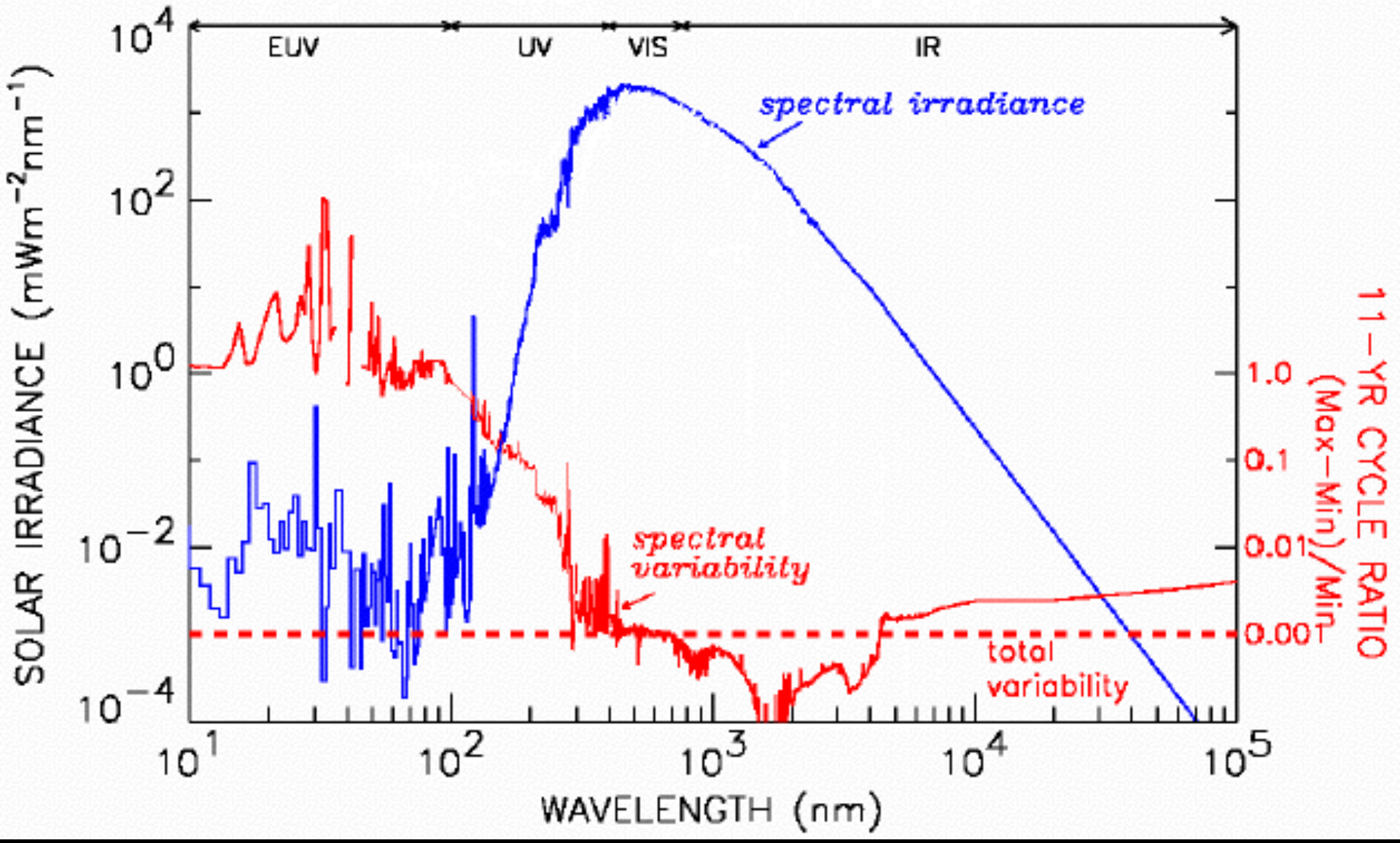
- The Sun goes through activity cycles



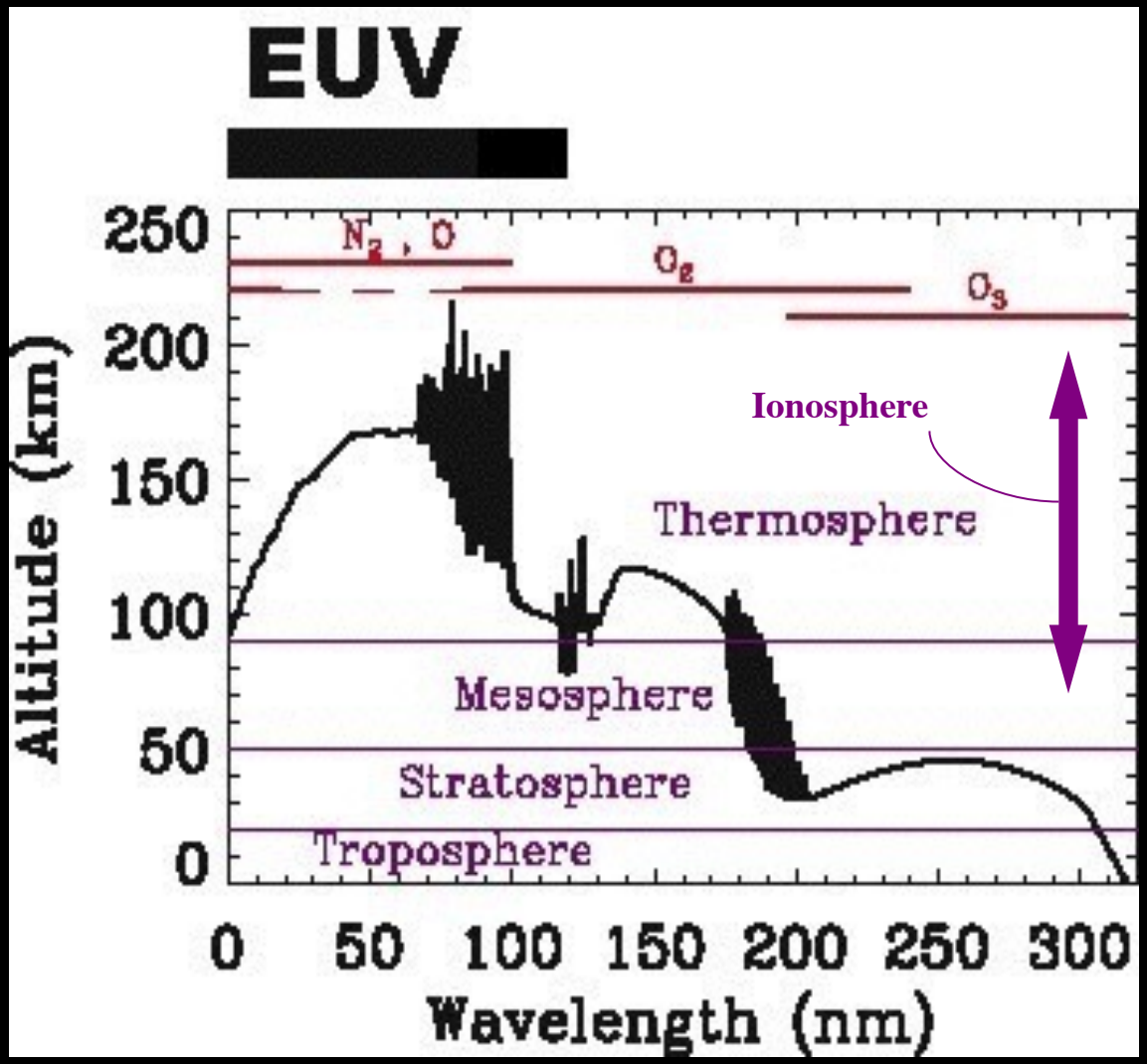
Photon Effects

- Increased light from Sun (especially UV and X-Rays) means:
  - Heating of the upper atmosphere
    - Temperatures at 200 km can range from 500 to 1500 K
    - Results in expansion of atmosphere
    - Density at a particular altitude can change by an order of magnitude
  - Ionization of the upper atmosphere
    - The ionosphere exists because of solar EUV
    - Large day/night changes and solar activity changes
  - Dissociation of molecules
    - Changes the chemistry and constituents of atmosphere

Irradiance Spectrum and Variability

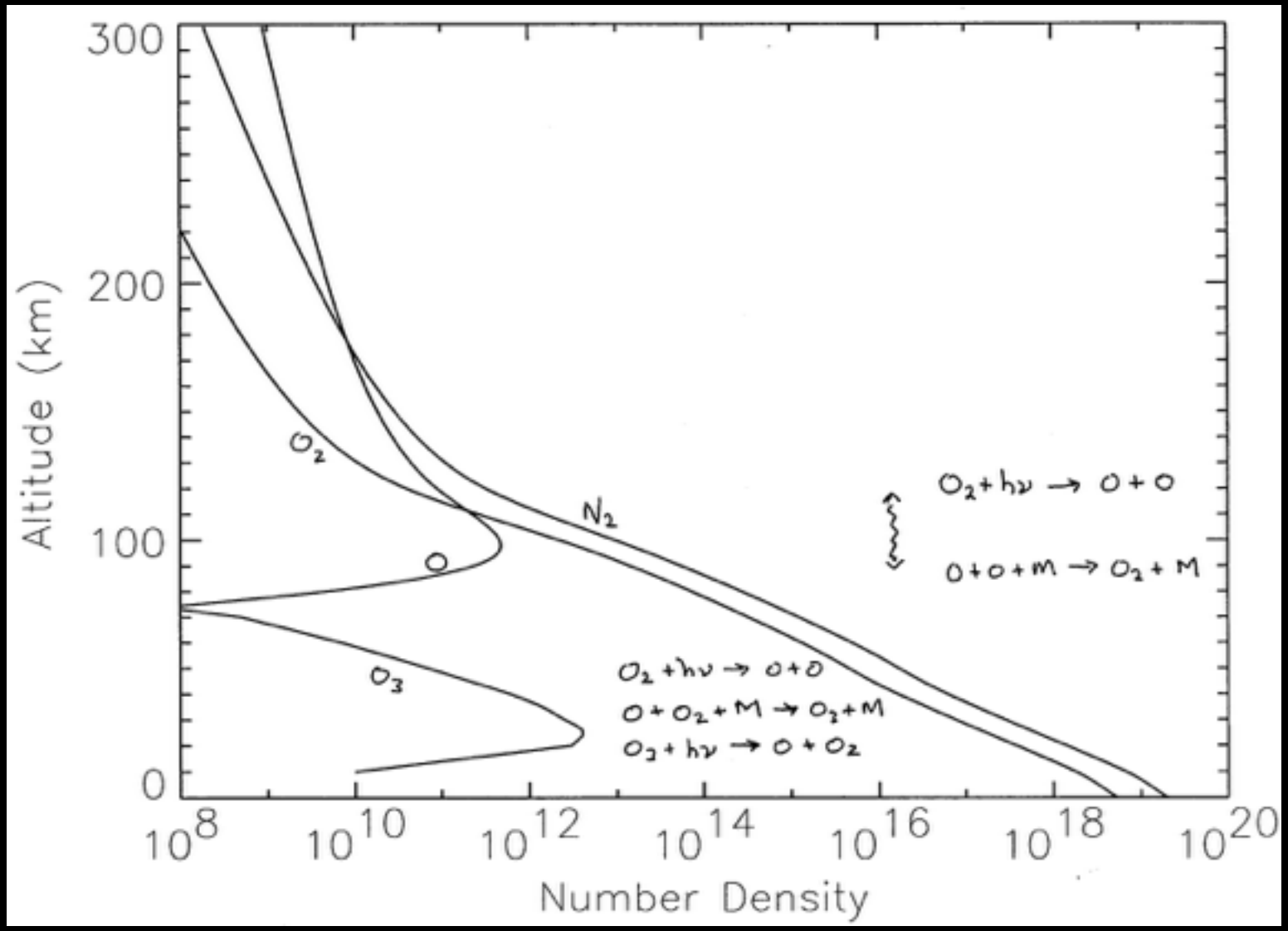


How Does all this Affect the Earth?



- Sunlight in the ultraviolet and X-rays is absorbed in the Earth's upper atmosphere
  - Heating to make the thermosphere
  - Ionizing to make the ionosphere
- Changes in the amount of UV from the Sun cause changes in the upper atmosphere

Earth's Atmosphere Composition & Density



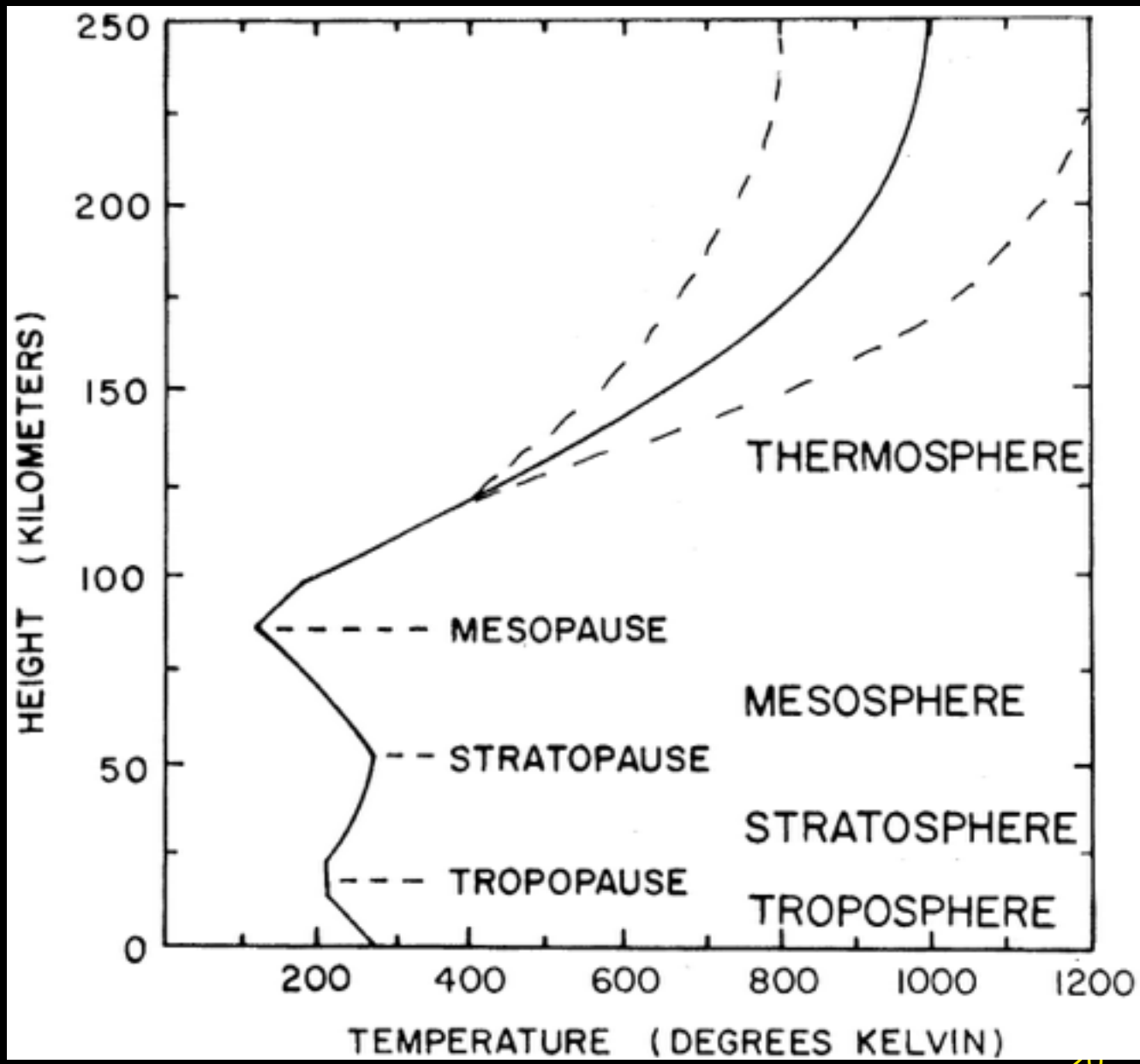
Typical Atmospheric Temperature Profile

EUV, FUV, Soft X-rays absorption
and ionization heating

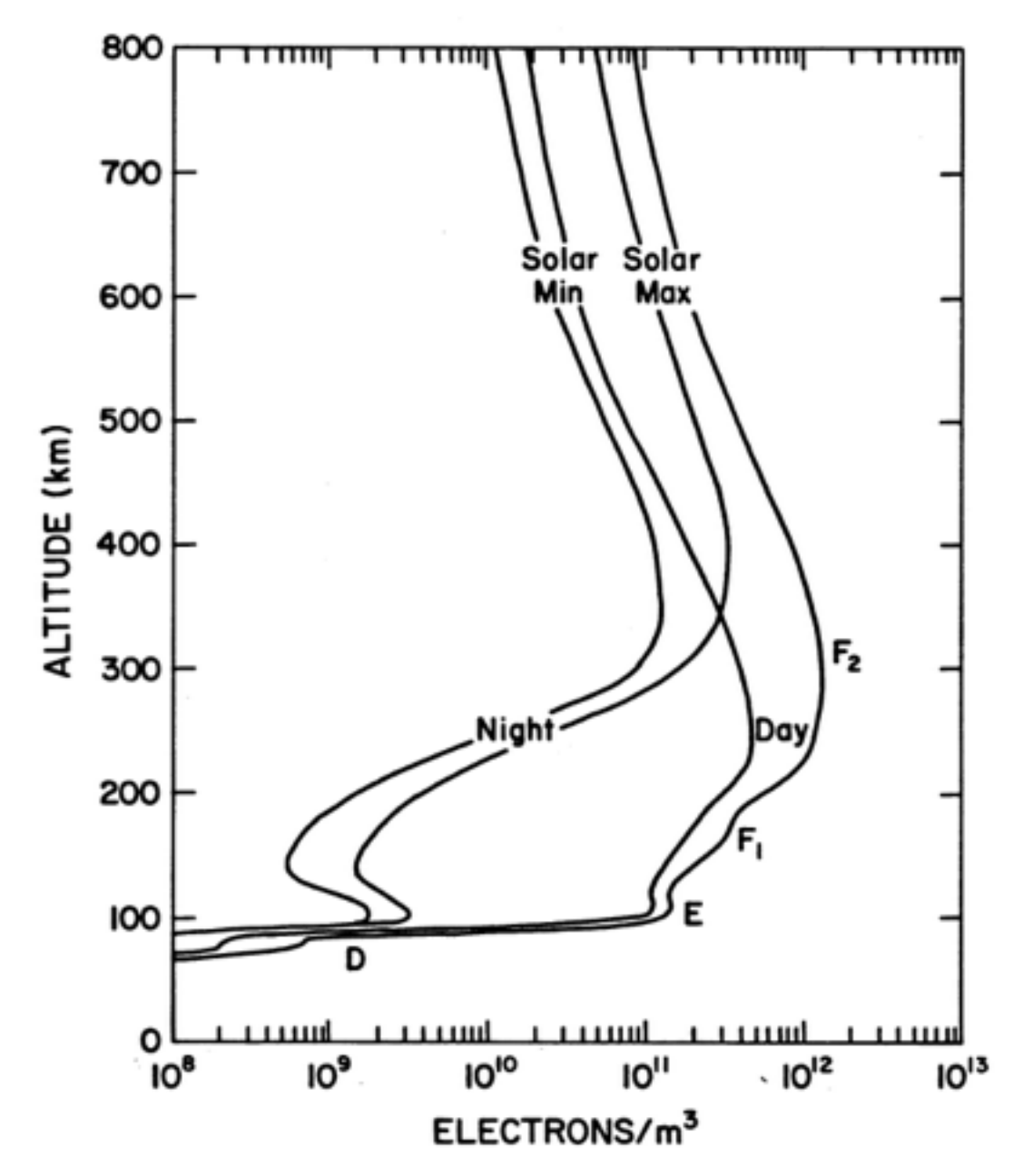
Primarily IR radiating to space cooling,
Some FUV absorption heating

MUV Sunlight absorption by O_3 heating

Visible, NIR, NUV absoprtion of sunlight
by air and surface, surface heats from below

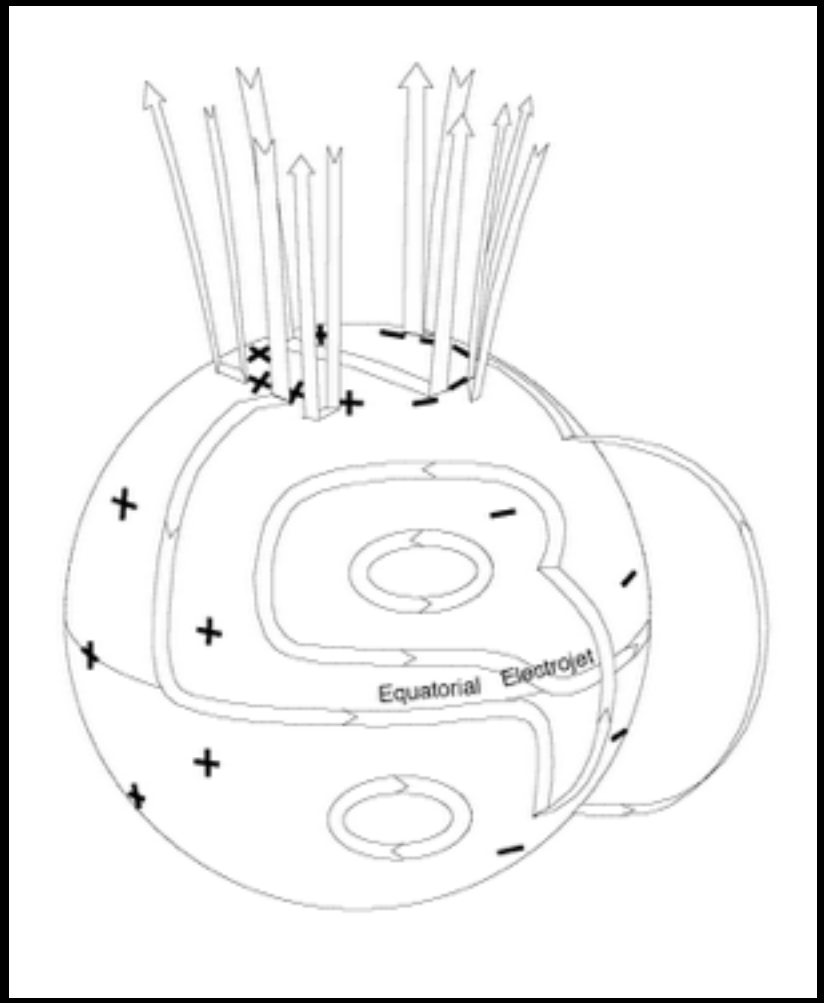


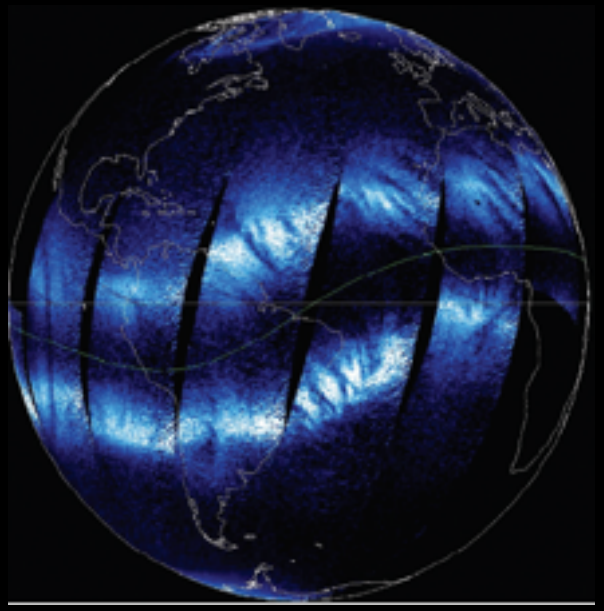
Ionosphere Reaction to Solar Variability

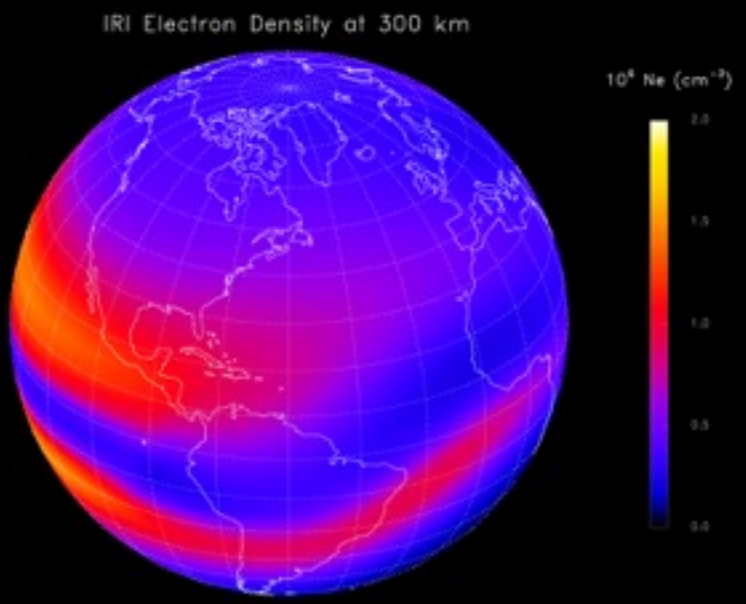


Ionosphere in Itself is Complex System

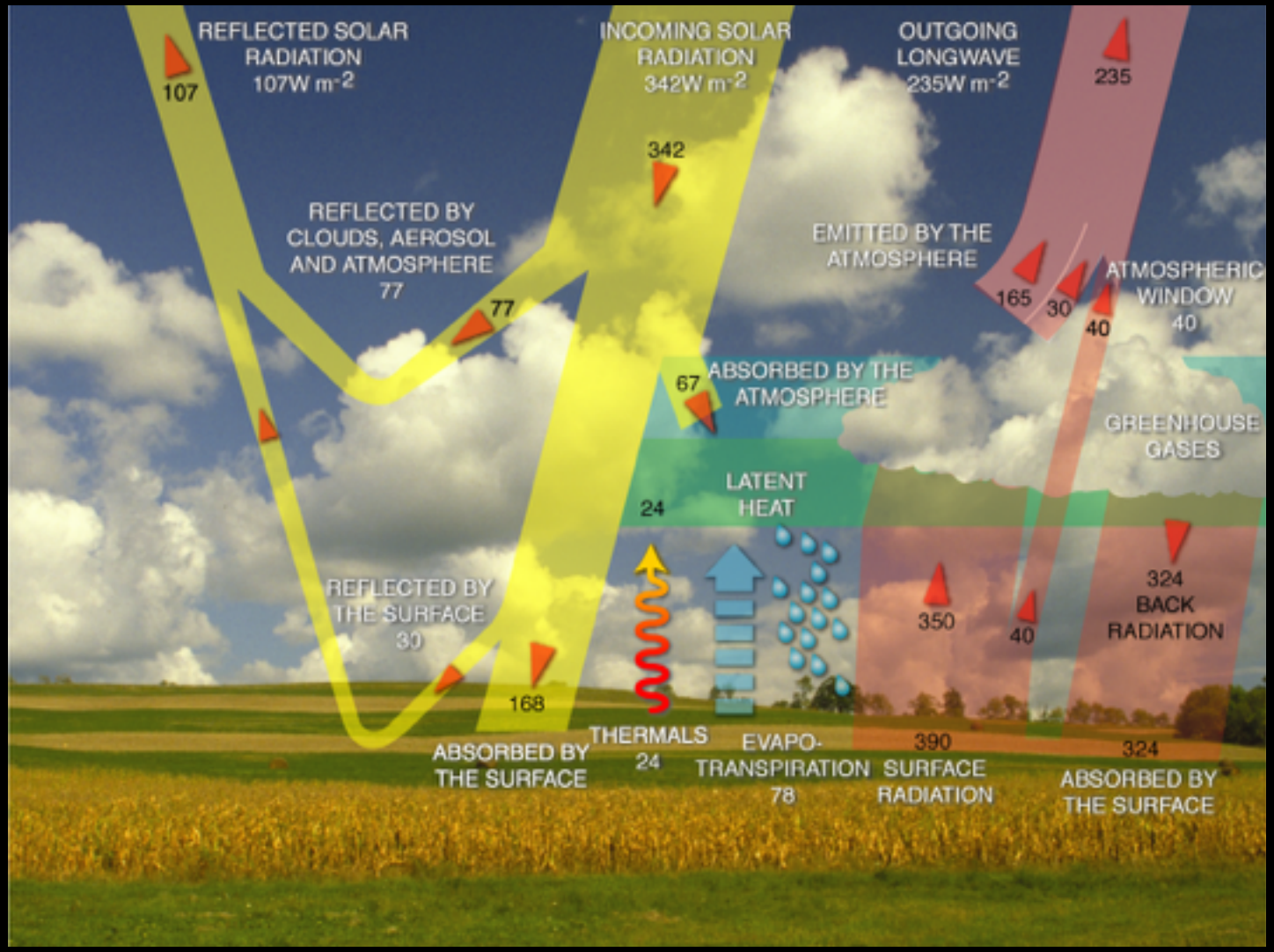
Ionospheric Electrodynamics







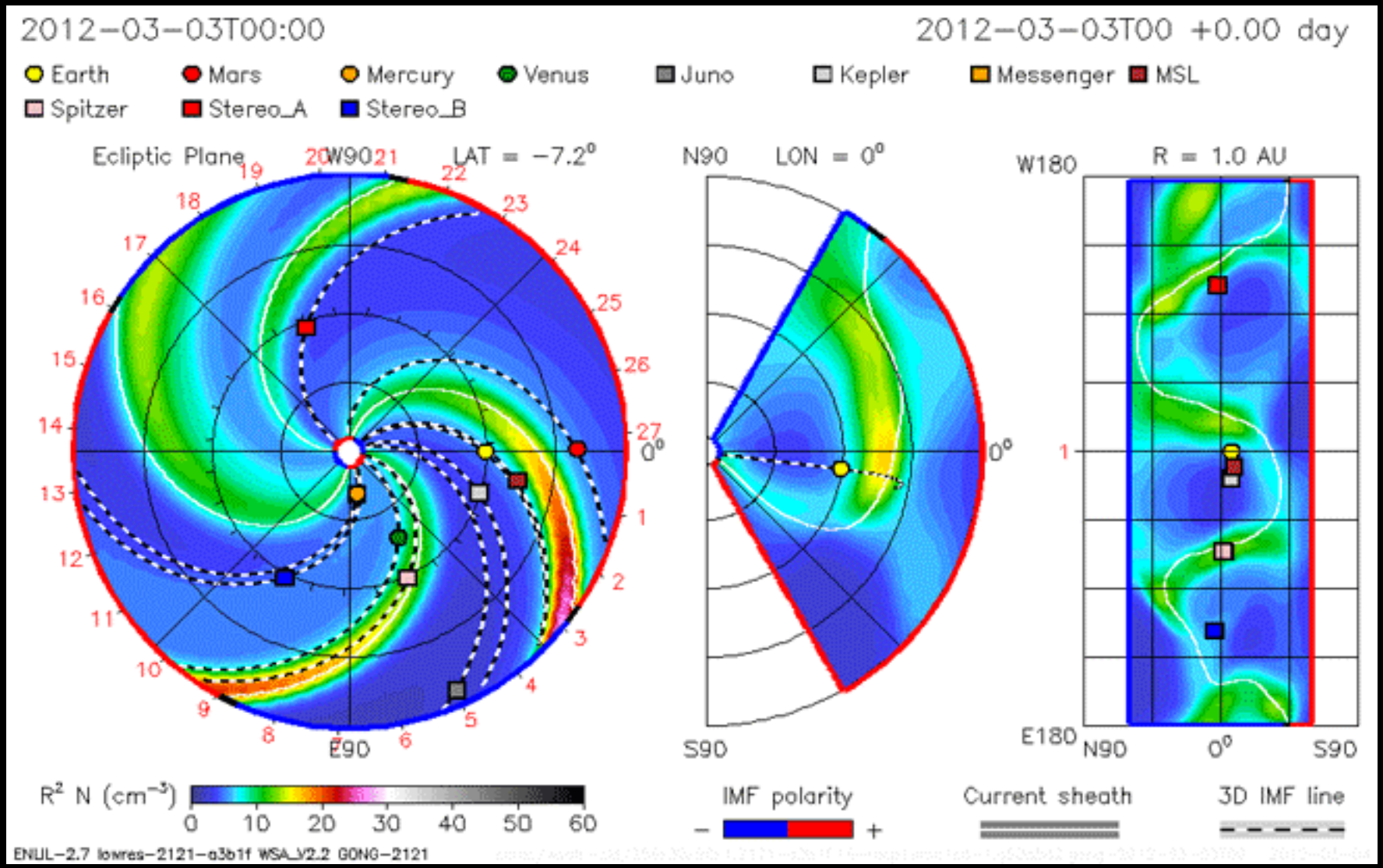
The Earth's Radiative Energy Balance



Particles and Fields Effects

- The Solar Wind, IMF, and CMEs all have impacts at Earth:
  - Magnetic fields from Sun interact with Earth's magnetic field and depending on orientation and strength can shake, rattle, and compress it.
  - Energetic particles can either penetrate the Earth's magnetic shield, or be diverted by it and get trapped in the radiation belts or magnetotail
    - Trapped particles can follow field lines down to impact the upper atmosphere at high latitudes and ionize it and make the aurora.
    - If the magnetic field is disrupted, particle effects can extend down to mid-latitudes.

Spirals for SW and CMEs

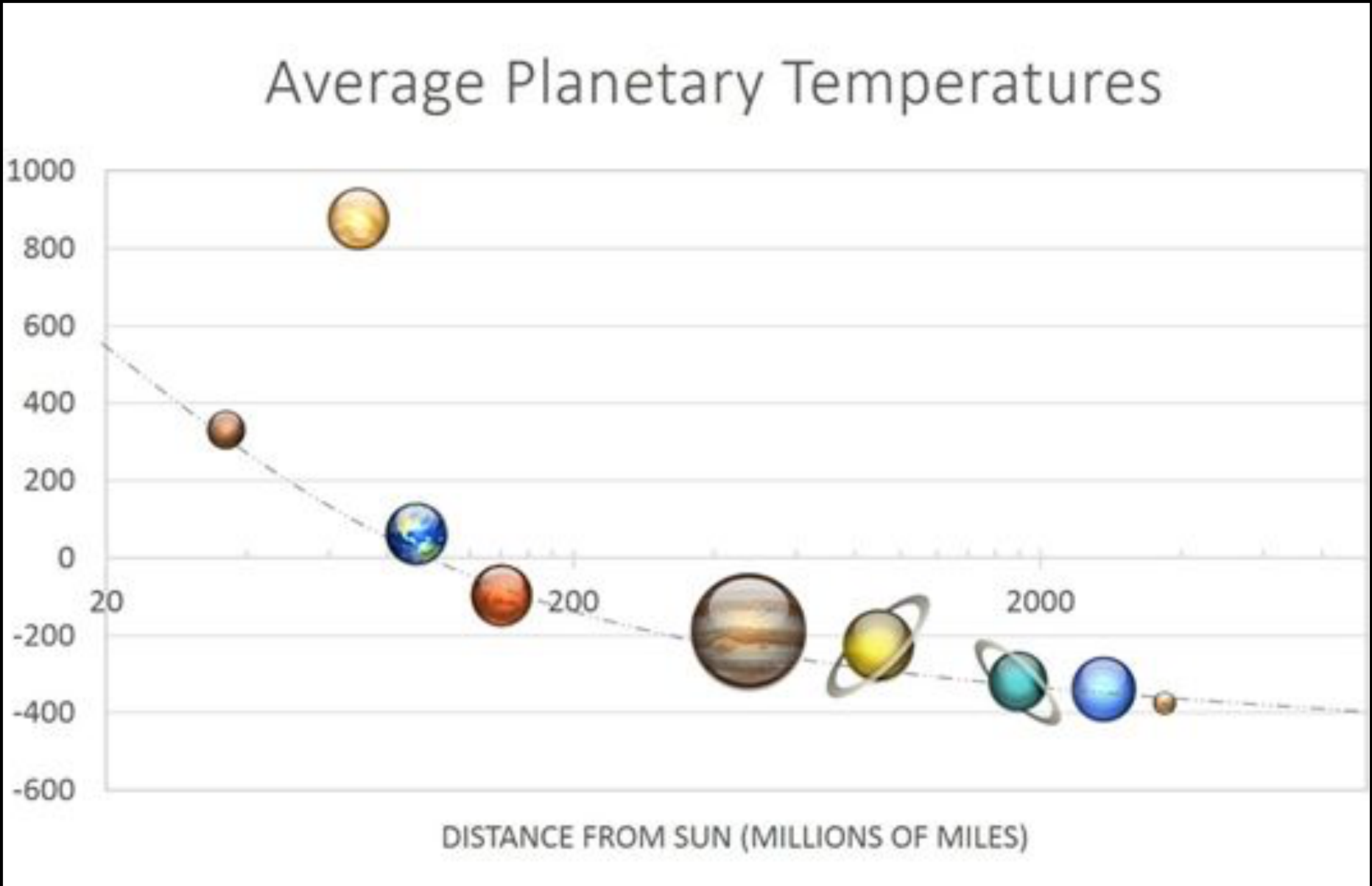


CME Impacting Earth

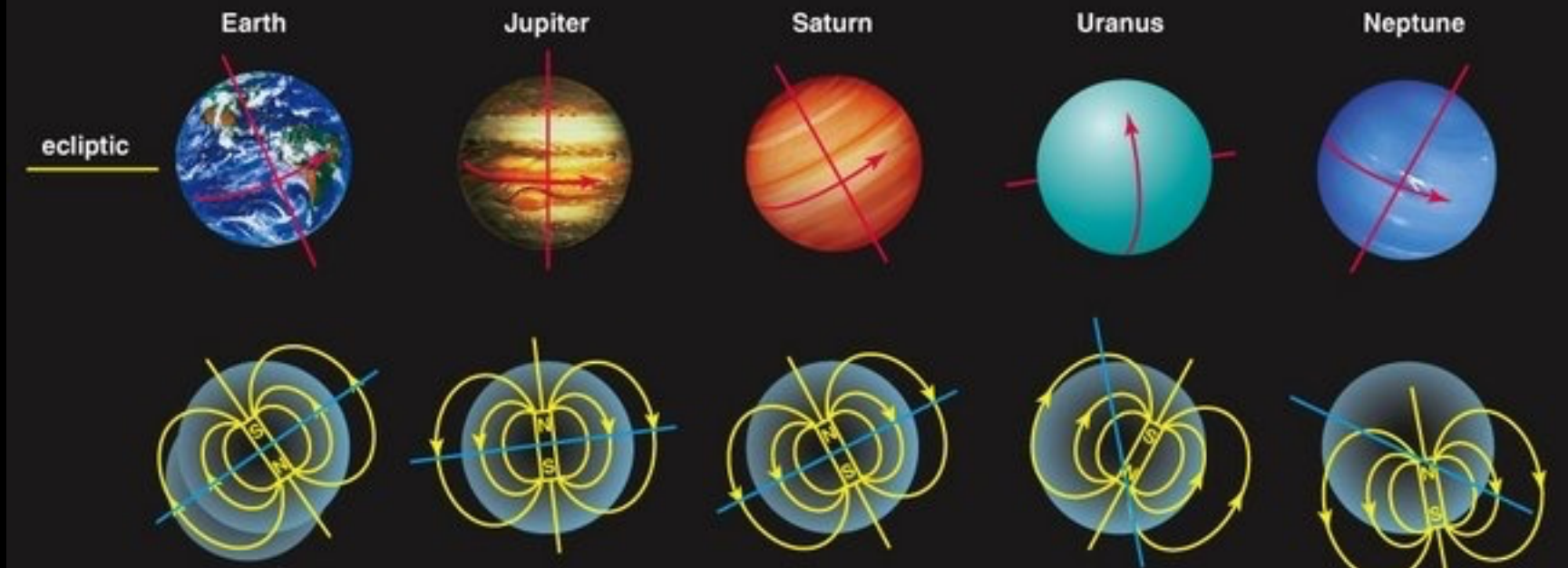
What About Other Planets?

- Space Weather Impacts will vary by:
  - Distance from Sun (photon and particle fluxes "spread out" with distance).
  - Intrinsic Magnetic Field (Jupiter has largest, Venus has only an induce one, Uranus has a complex quadrupole)
  - Atmosphere Size and Composition
    - Outer gas giants have huge atmospheres, Mercury almost none,…
    - Jupiter' is mostly hydrogen, Venus' and Mars' are mostly carbon dioxide
  - Conditions at planets have evolved over history of the solar system.

Distance from Sun Matters



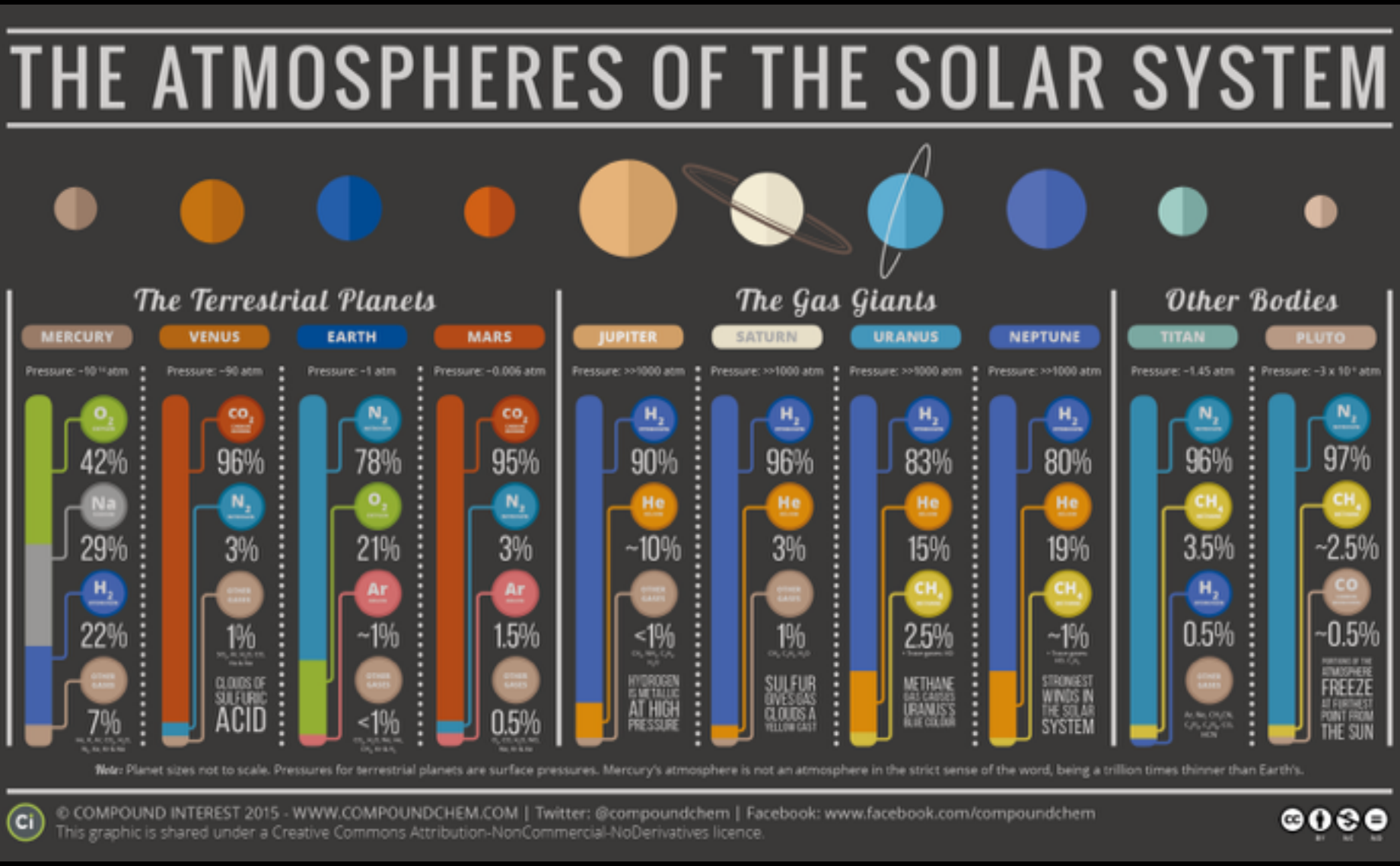
Magnetic Fields of Other Planets



	Earth	Jupiter	Saturn	Uranus	Neptune
Tilt of rotation axis	23°	3°	27°	98°	30°
Tilt of magnetic axis	12°	−10°	−0°	−59°	−47°
Offset of magnetic axis	8%	10%	5%	31%	55%
Field at equator	31,000 nT	428,000 nT	22,000 nT	23,000 nT	13,000 nT
Magnetosphere	10 R_{Earth}	65 $R_{Jupiter}$	20 R_{Saturn}	18 R_{Uranus}	25 $R_{Neptune}$

Aurora on the Outer Planets

Composition Changes Response



MAVEN

Mars Atmosphere and Volatile Evolution Mission

CU/LASP • GSFC • UCB/SSL • LM • JPL

“Exploring Mars’ Climate History”

Mars Now

Mass: 0.11 M_{Earth}

Radius: 0.53 R_{Earth}

Rotational Period: 24.6 hours

Obliquity: 25.2˚ → Seasons!

Distance from Sun: 1.38 – 1.67 AU (mean 1.52 AU) → Eccentric!

Orbital Period: 686 days

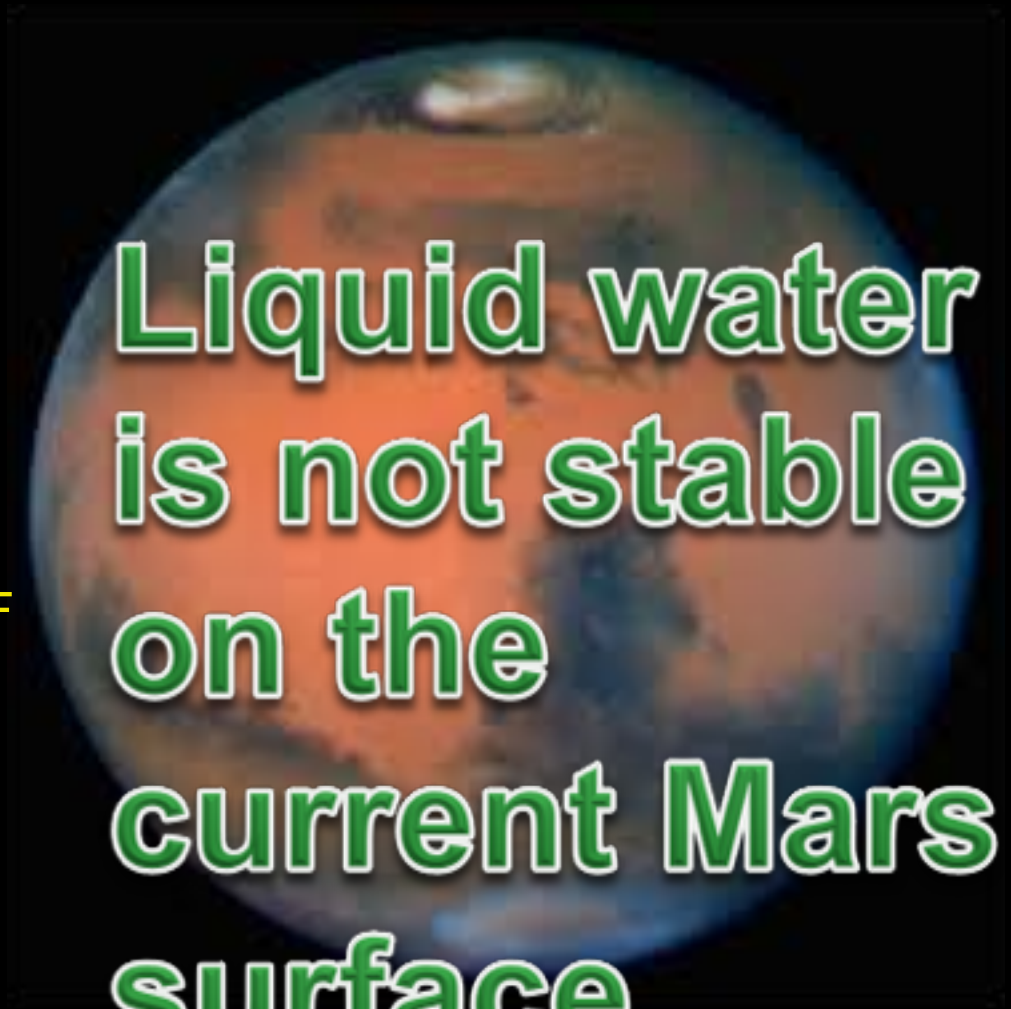
Surface Pressure: 6-10 mbar (seasonal)

Surface Temperature: -195˚F to 70˚F (mean: -80˚F)

Ice Caps: Seasonal CO_2 over H_2O

Atmospheric Composition:

- CO_2 95.3%
- N_2 2.7%
- Ar 1.6%



Mars 2 – 3.5 Billion Years Ago (we think)

Early Warm Wet Mars Theory

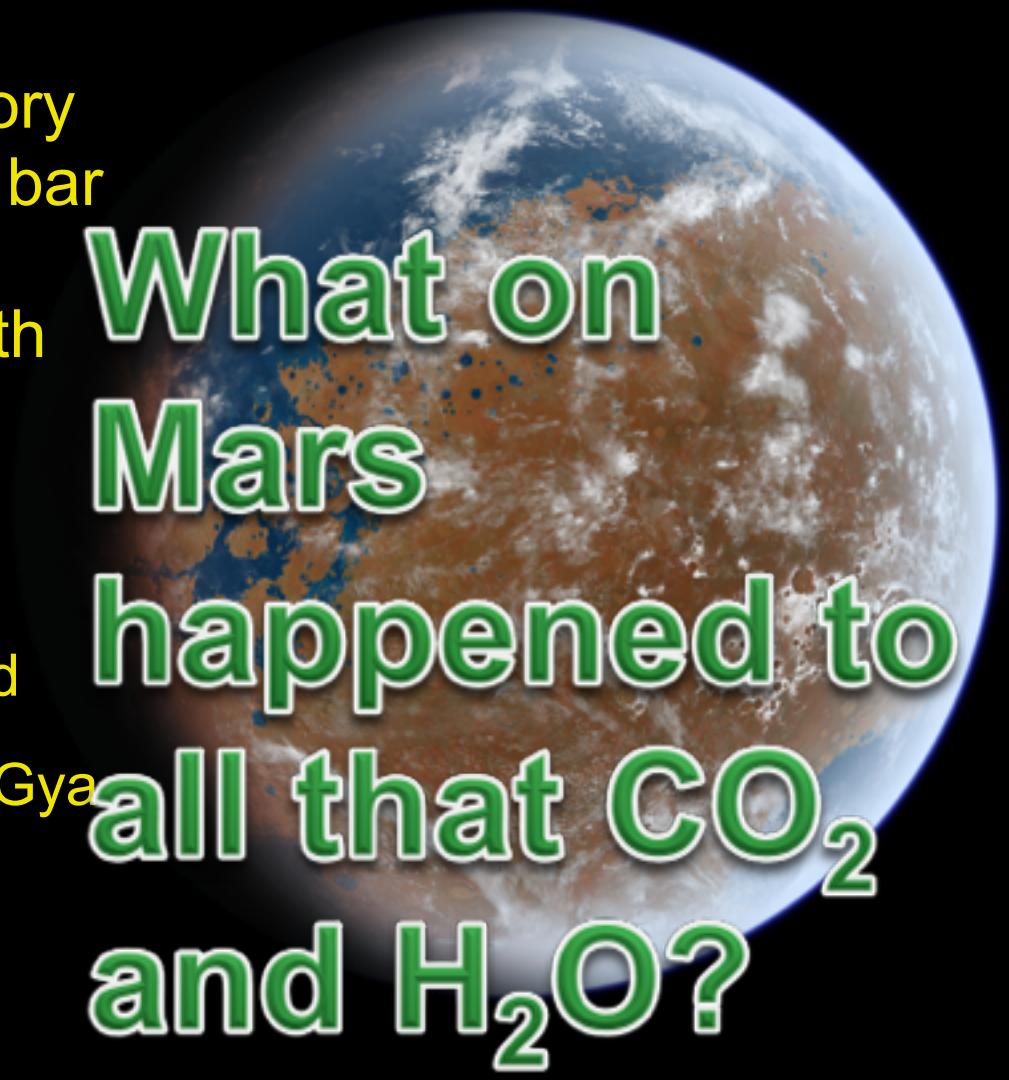
More Atmosphere: 10 – 30 bar (CO_2)

More Water: ~1000 m (Earth has 3000 m worth)

Warmer temperatures (greenhouse)

Liquid Water:

- Oldest flow channels formed 3.5-3.9 Gya
- Other flow features 2.2-3.3 Gya
- Evidence of northern ocean shoreline



What causes atmospheric escape?

Transport into Other Reservoirs ("Hiding")

- Sequestering in rocks, dissolving in oceans, storage in ice caps, life, …

Jeans (Thermal) Escape

- Atoms at top of atmosphere hot enough to reach escape velocity

Hydrodynamic Escape

- Heavier atoms pulled along by flow of escaping lighter ones

Photo-Chemical (Non-Thermal Heating) Escape:

- Charge exchange, Dissociative recombination, Impact dissociation, Photo-dissociation, Ion-neutral reactions, Knock-on (heavy – light collisions)

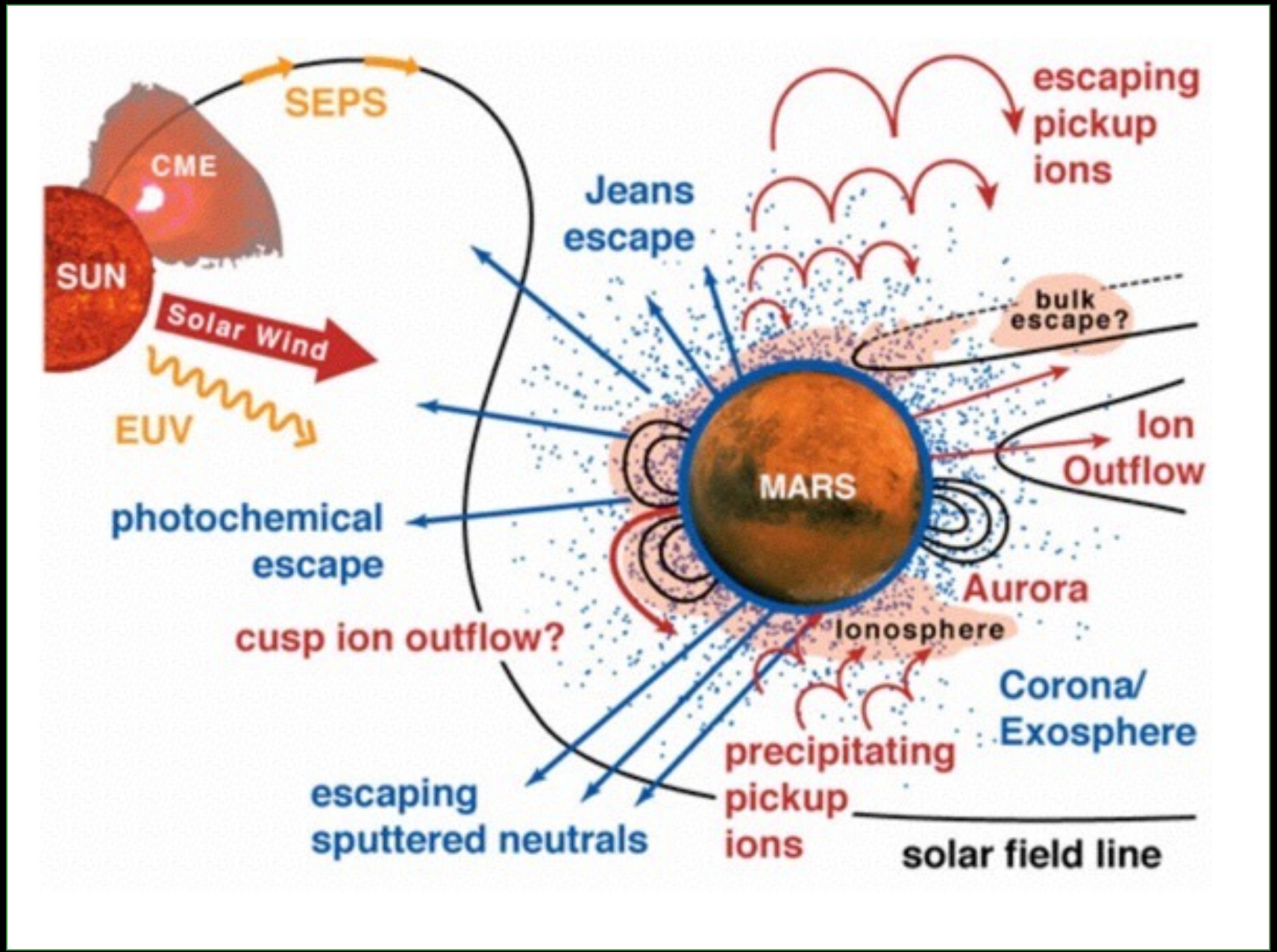
Sputtering/Impact Escape

- Impacts by small or large objects "blowing" off atmosphere

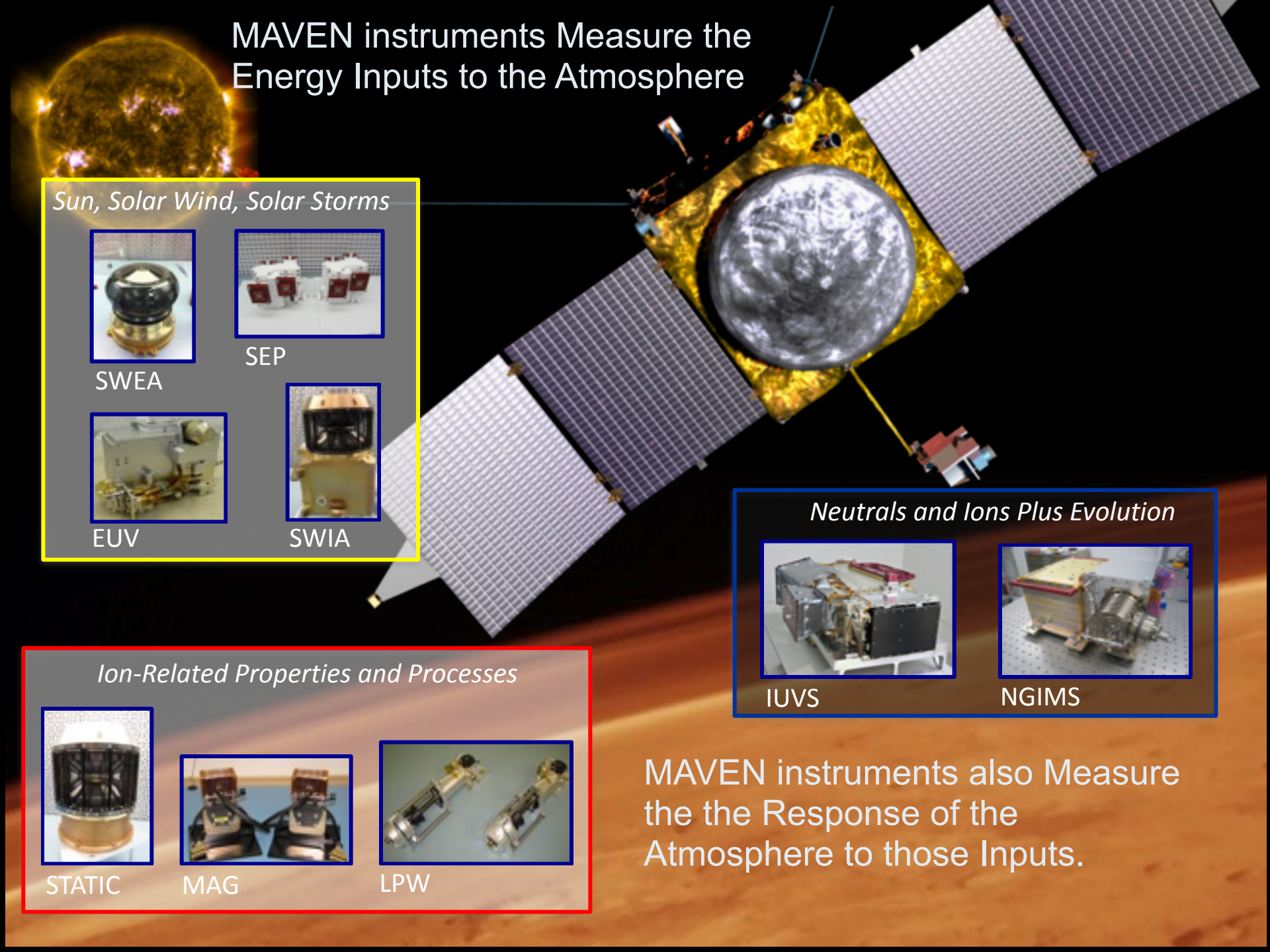
Solar Wind Pickup

- SW carries ions and electrons away with it

Atmospheric Escape Driven by Space Weather



MAVEN instruments Measure the Energy Inputs to the Atmosphere



MAVEN instruments also Measure the the Response of the Atmosphere to those Inputs.

Summary

- The Sun is a primary source of energy for the planets (photons, particles, fields)
  - Space Weather!
- How a planet reacts depends on its particulars
  - atmosphere, magnetic field, distance, etc…
- How a planet reacts depends on its particulars
  - atmosphere, magnetic field, distance, etc…
  - The physics is the same, just what processes are important change