The space environment

MAE 4160, 4161, 5160

V. Hunter Adams, PhD

“The most terrifying fact about the universe is not that it is **hostile** but that it is **indifferent**, but if we can come to terms with this indifference, then our existence as a species can have genuine meaning. *However vast the darkness, we must supply our own light*.”

–Stanley Kubrick

Today’s topics:

- Atmospheric density
- Atomic oxygen
- Ionosphere
- Vacuum
- Magnetic field
- The Sun
- Galactic cosmic rays
- Van Allen Belts
- Microgravity
- Orbital debris

Atmospheric density

This is why we care about atmospheric density

atmospheric density

drag coefficient

surface area

acceleration from drag

$$a_d = \frac{1}{2}\rho V^2 \frac{C_D A}{m}$$

velocity

mass

Atmospheric density

This is why we care about atmospheric density

atmospheric density drag coefficient

Why is this so hard? Recall the ideal gas law, what affects the density of a gas?

acceleration from drag

surface area

velocity

mass

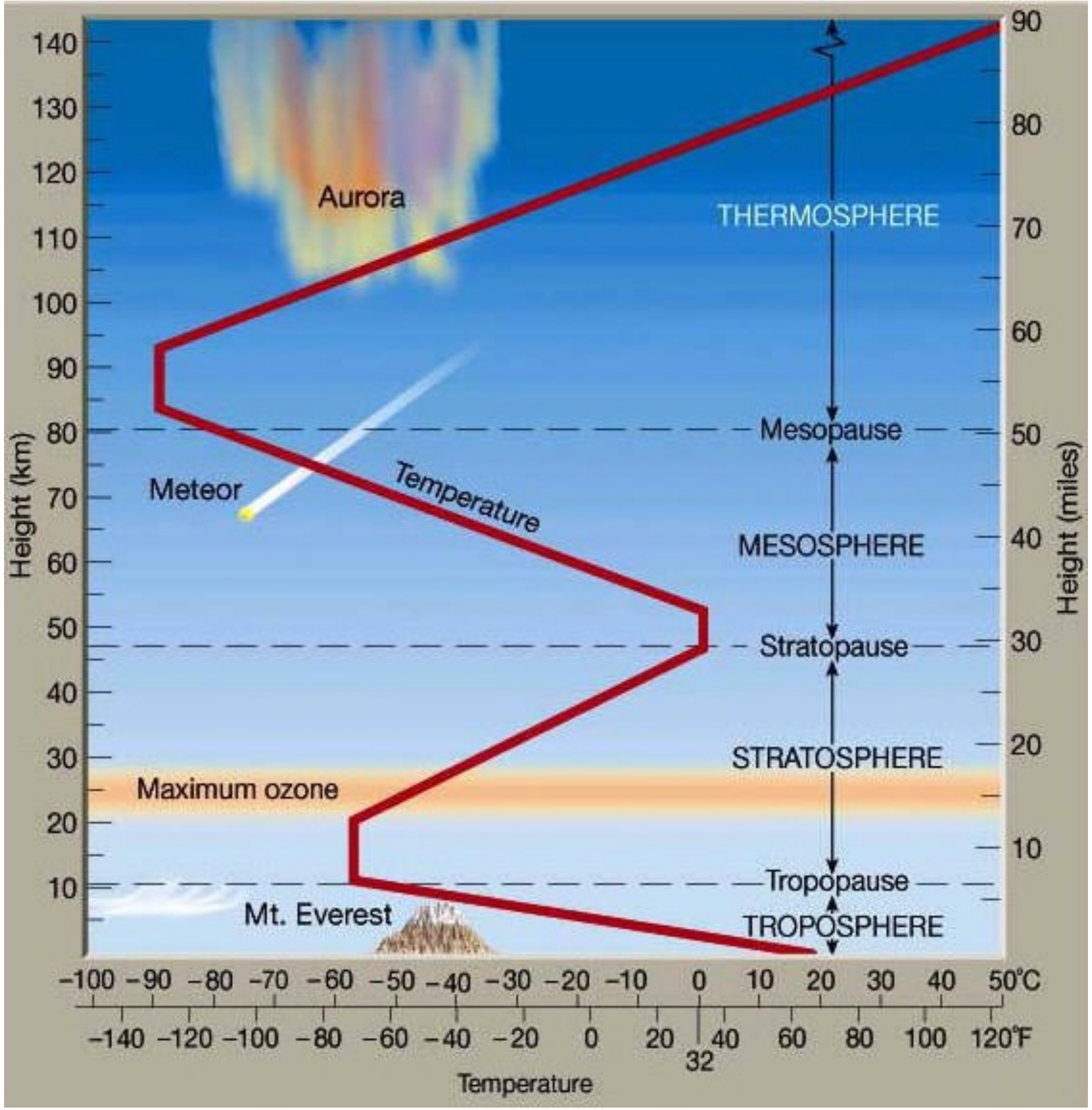
Atmospheric density

. . . is coupled with **temperature**

the ideal gas law

$$pV = NRT \longrightarrow \rho = \frac{pM}{RT}$$

- Temperature does not monotonically decrease with altitude, and provides a metric for dividing atmospheric layers



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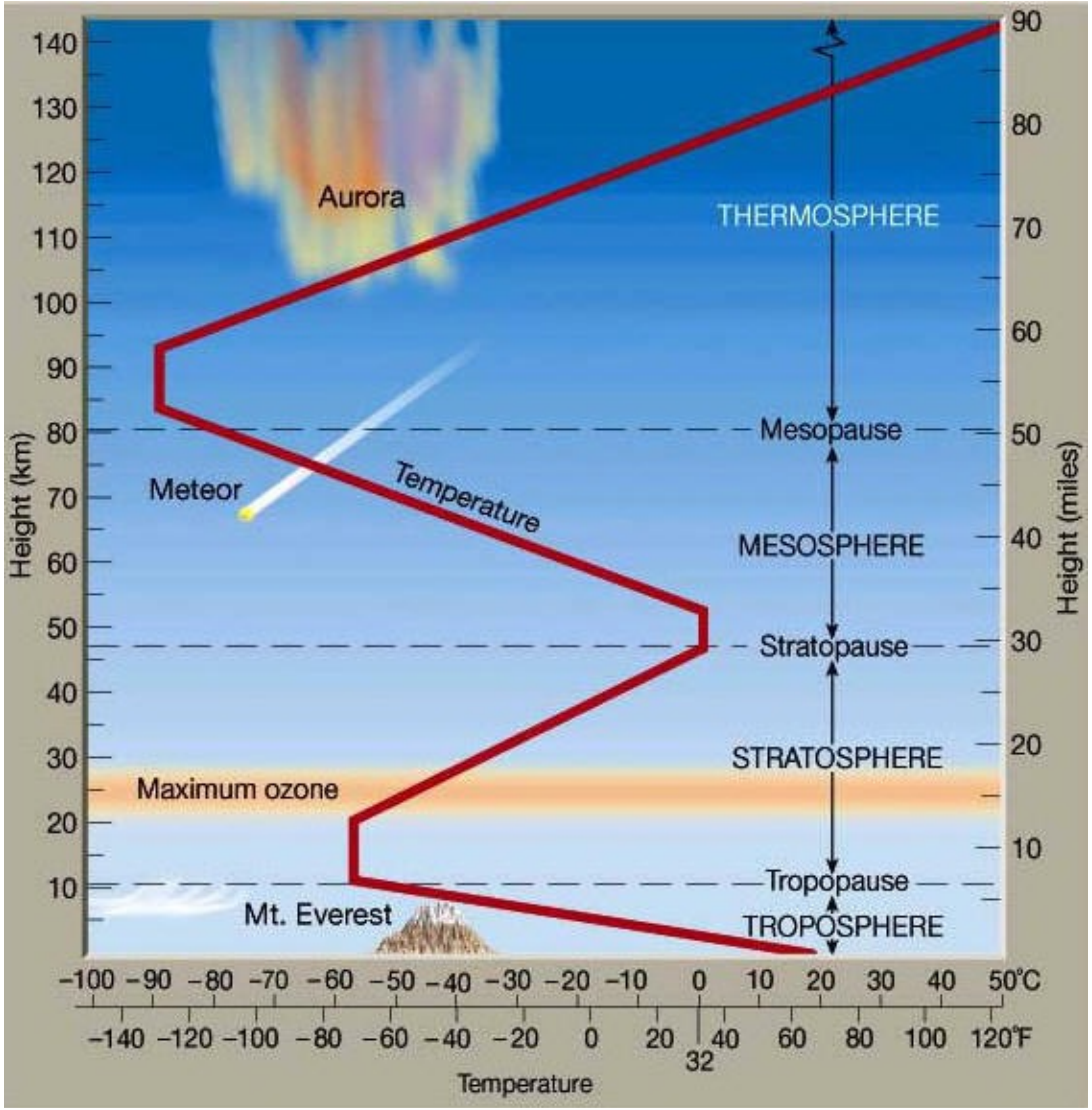

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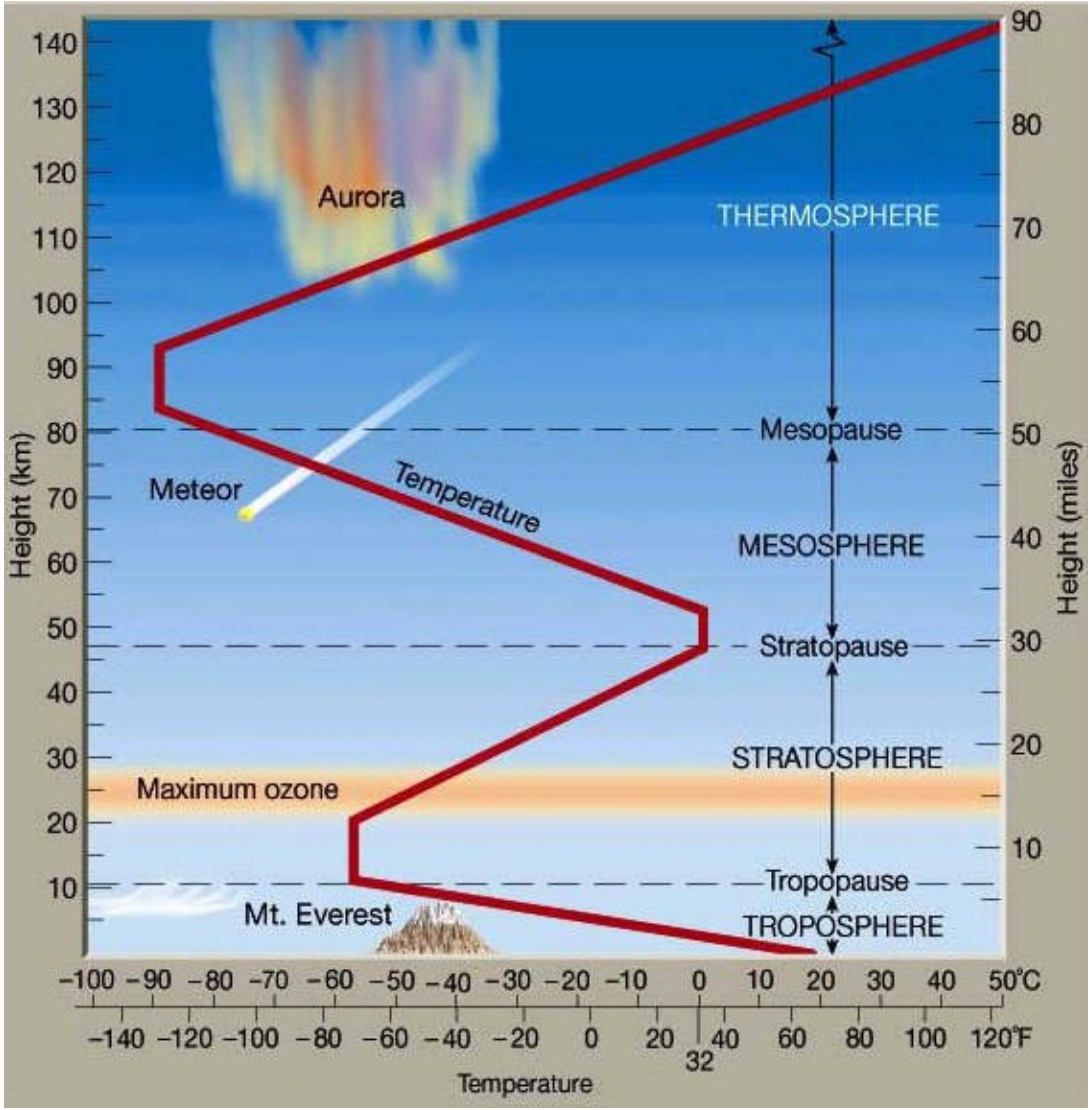
- Temperature/density is driven largely by the Sun, which affects the atmosphere via photoabsorption and photodissociation



Atmospheric density

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Does the high temperature in the thermosphere mean that the atmosphere would "feel" warm?

a

s

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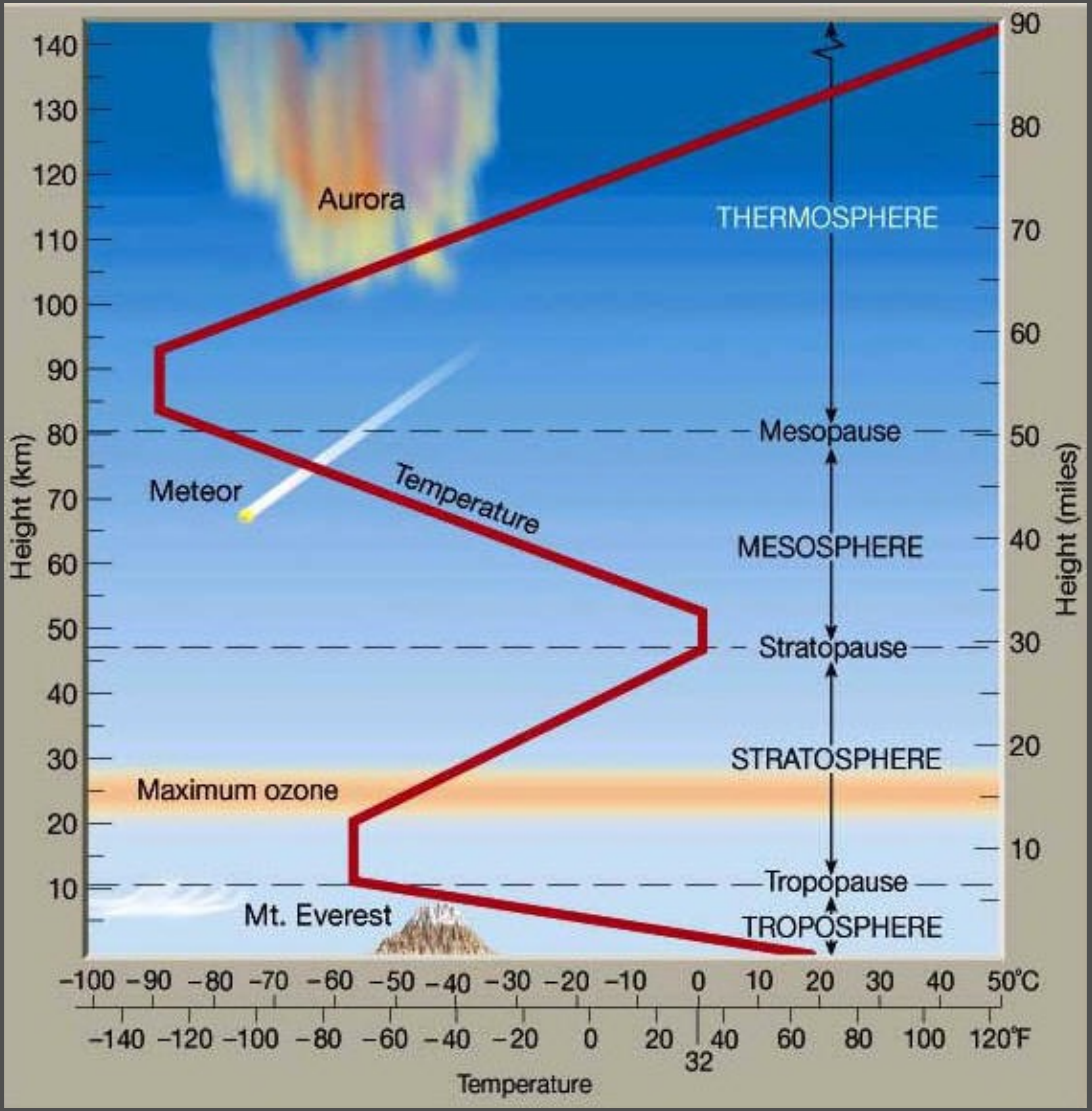


Atmospheric density

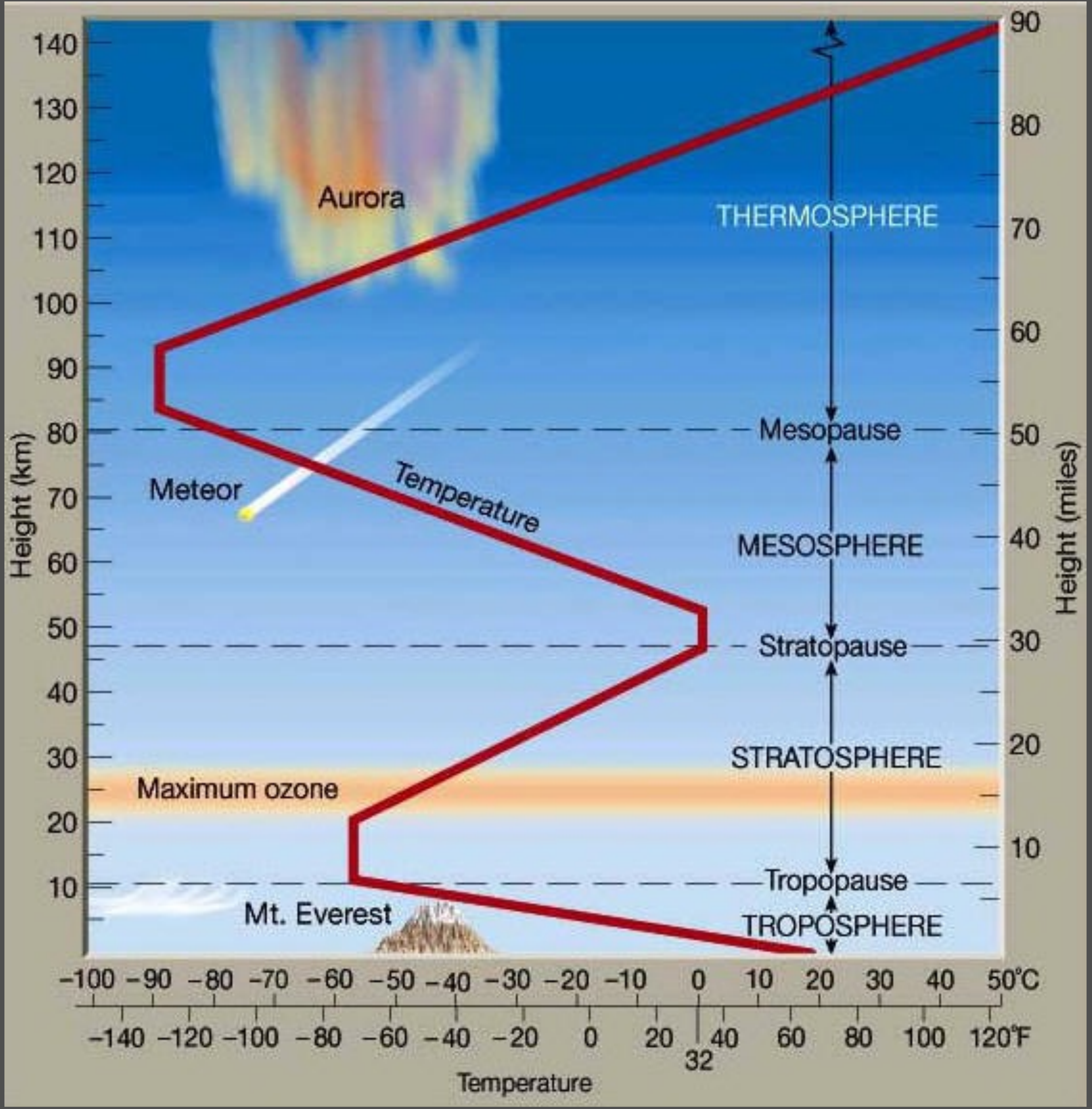
. . . is coupled with **temperature**

Photodissociation/ photoabsorption rates depend on the irradiance of the Sun, which varies.

It can vary with flares (hours), solar rotation (27 days), active region evolution (3-6 months), and solar cycle (10-12 years).

More on this later.

by the Sun, which affects the atmosphere via photoabsorption and photodissociation



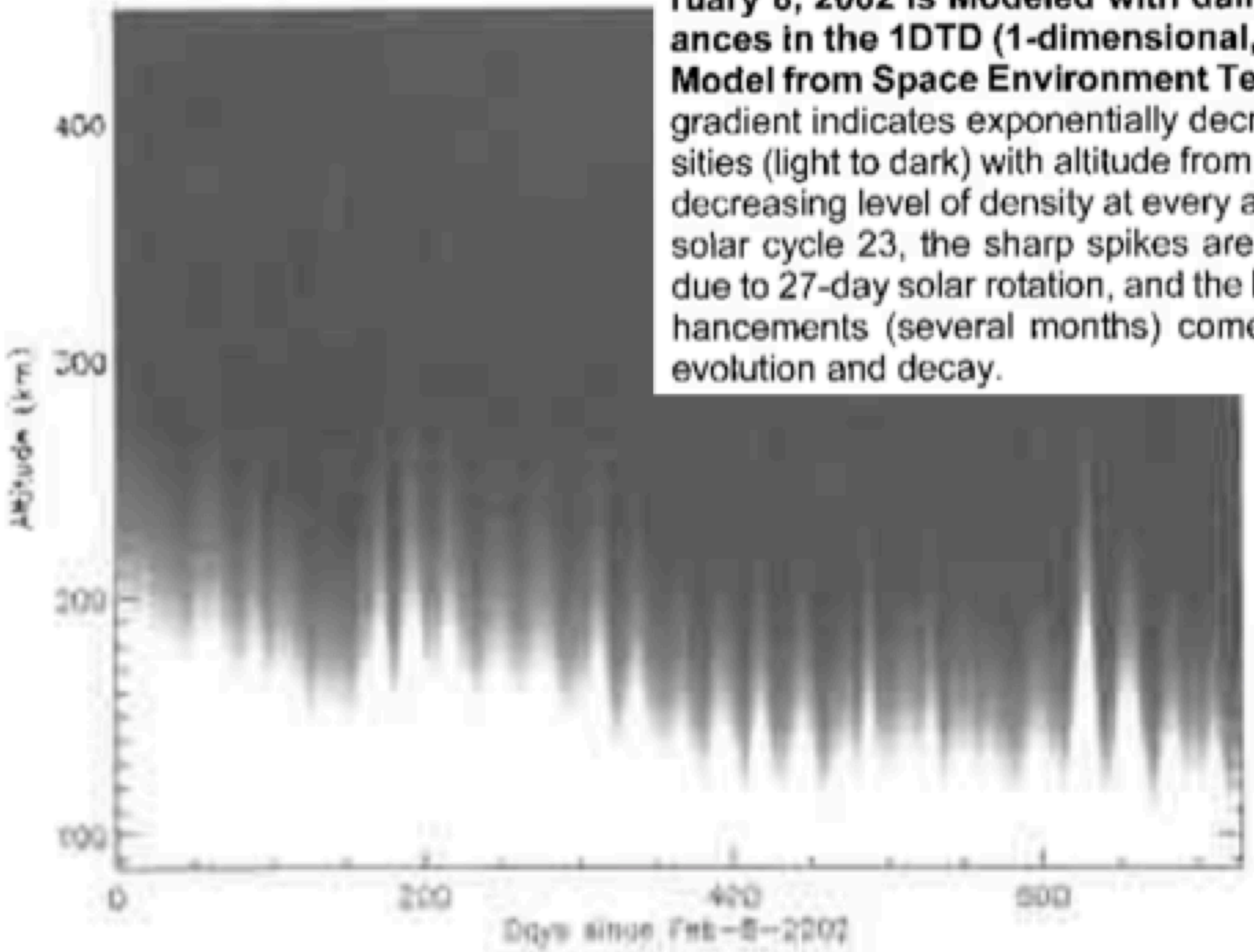


Fig. 7-2. Thermosphere Density for Two Years Starting February 8, 2002 is Modeled with daily SOLAR2000 EUV Irradiances in the 1DTD (1-dimensional, time dependent) Physics Model from Space Environment Technologies. The grayscale gradient indicates exponentially decreasing sub-solar daily densities (light to dark) with altitude from 100 to 450 km. The secular decreasing level of density at every altitude is from the decline of solar cycle 23, the sharp spikes are the density enhancements due to 27-day solar rotation, and the broader periodic density enhancements (several months) comes from solar active region evolution and decay.

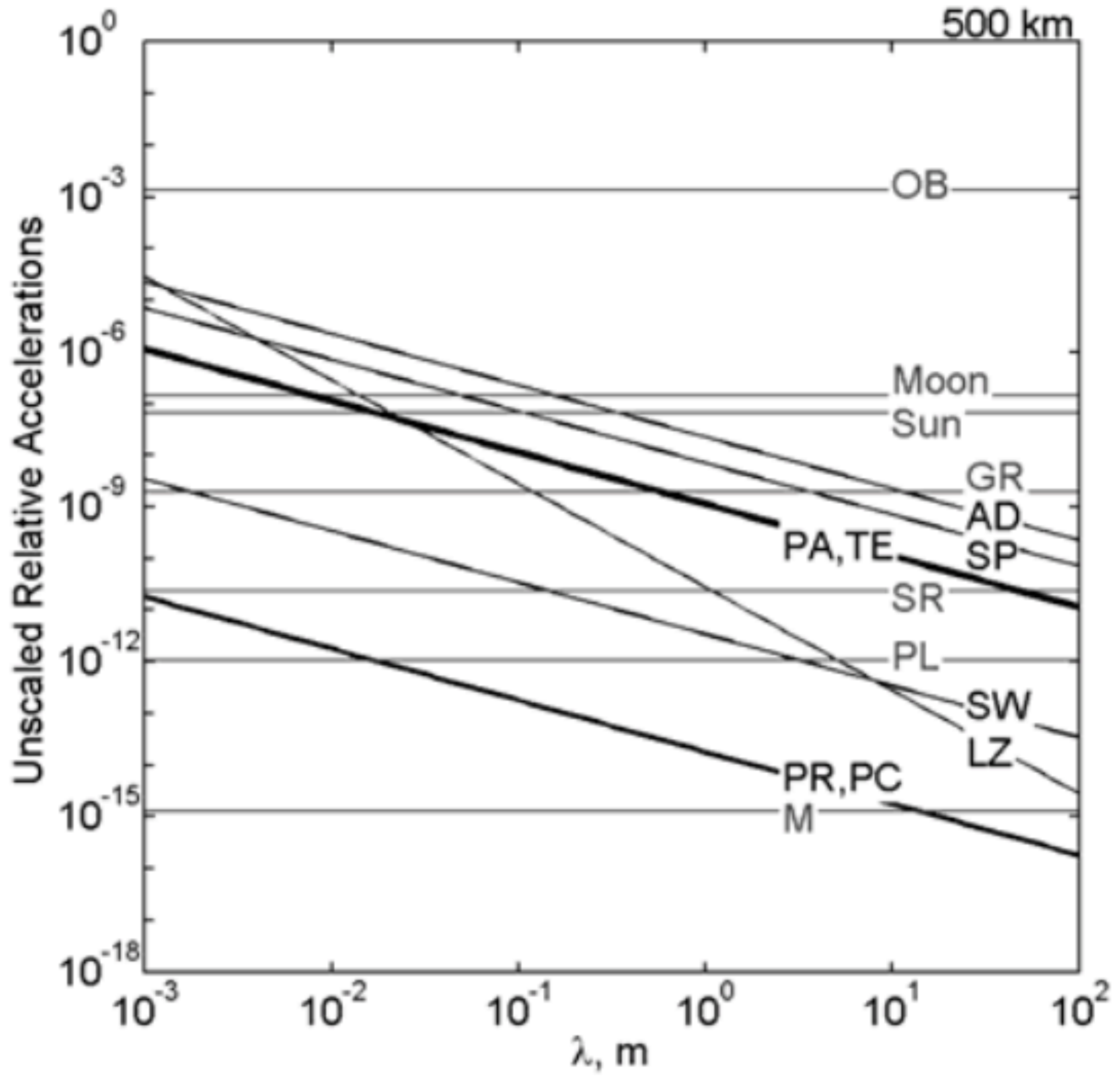


Figure 2.7. Unscaled accelerations at 500 km altitude as a function of characteristic length, normalized to Earth's two-body gravity.

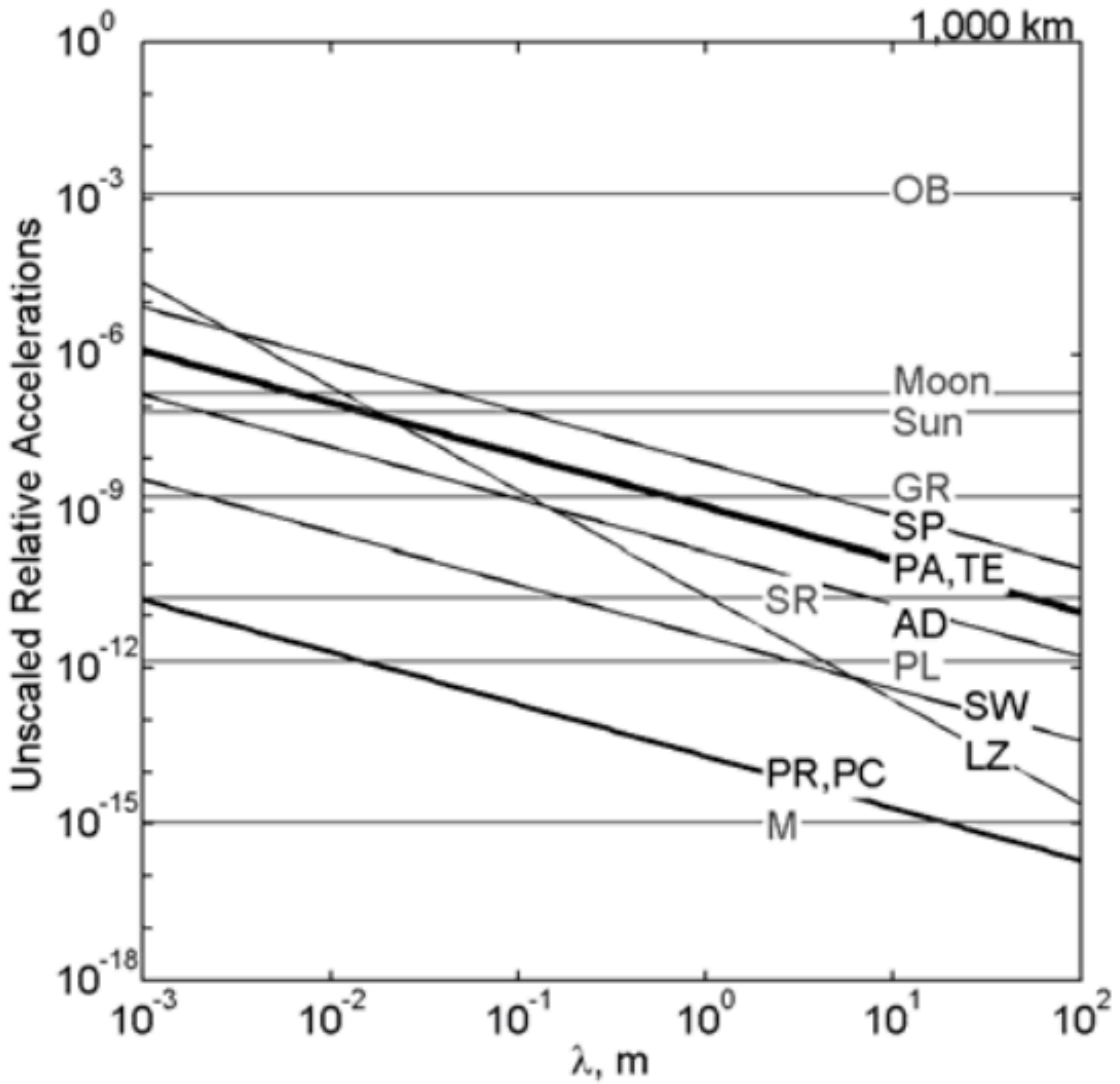


Figure 2.8. Unscaled accelerations at 1,000 km altitude as a function of characteristic length, normalized to Earth's two-body gravity.

A cubesat in 400 km orbit has a lifetime of 1-9 months, a cubesat in 600 km orbit has a lifetime >25 years

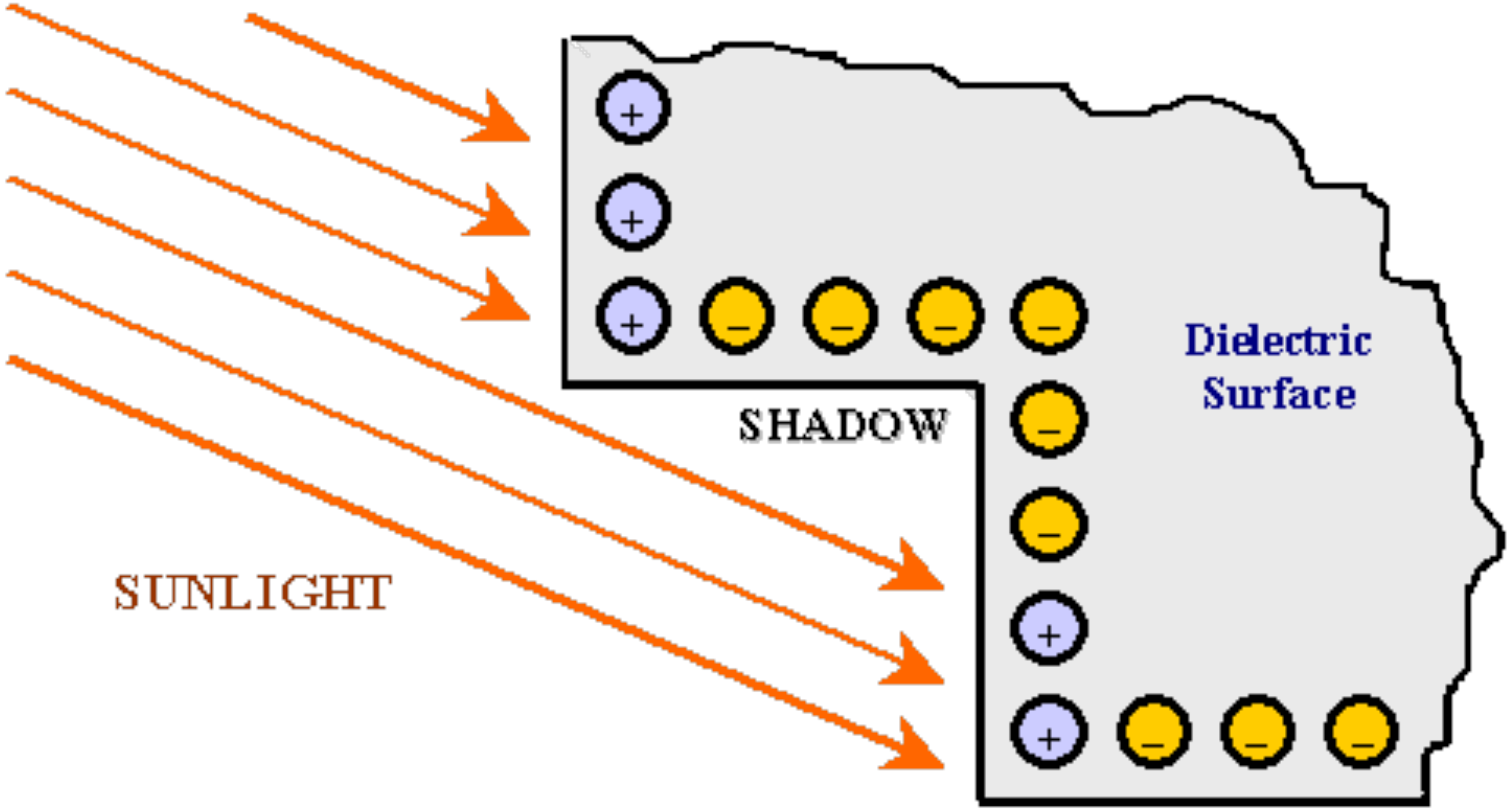
Solar activity also dissociates oxygen (O_2) to create atomic oxygen (O)

Atomic oxygen

- Above 110 km, the atmospheric constituents distribute themselves based on how affected they are by gravity
- Far UV dissociation of oxygen creates atomic oxygen, which is lighter than nitrogen and oxygen, making it the dominant element above 200 km
- Atomic oxygen reacts with organic films, composite, and metallized surfaces.
- More solar activity means more atomic oxygen. Sometimes missions are phased with the Sun so that they take place during a solar activity minimum.
- Spacecraft protect against atomic oxygen with coatings that are "immune," including silicon dioxide or aluminum.

Ionosphere

- The ionosphere is formed by solar photons stripping electrons from neutral particles, creating a plasma.
- As such, there is a diurnal cycle to the ionosphere. At night, electrons reattach to ions and the thermosphere collapses.
- Charged particles *differentially charge the spacecraft*. This can lead to electrostatic discharge.
- The potential of the spacecraft can be different enough from that of the environment to disrupt instrumentation.
- Nearby materials should have similar dielectric constants or involve conductivity to make charge uniform.

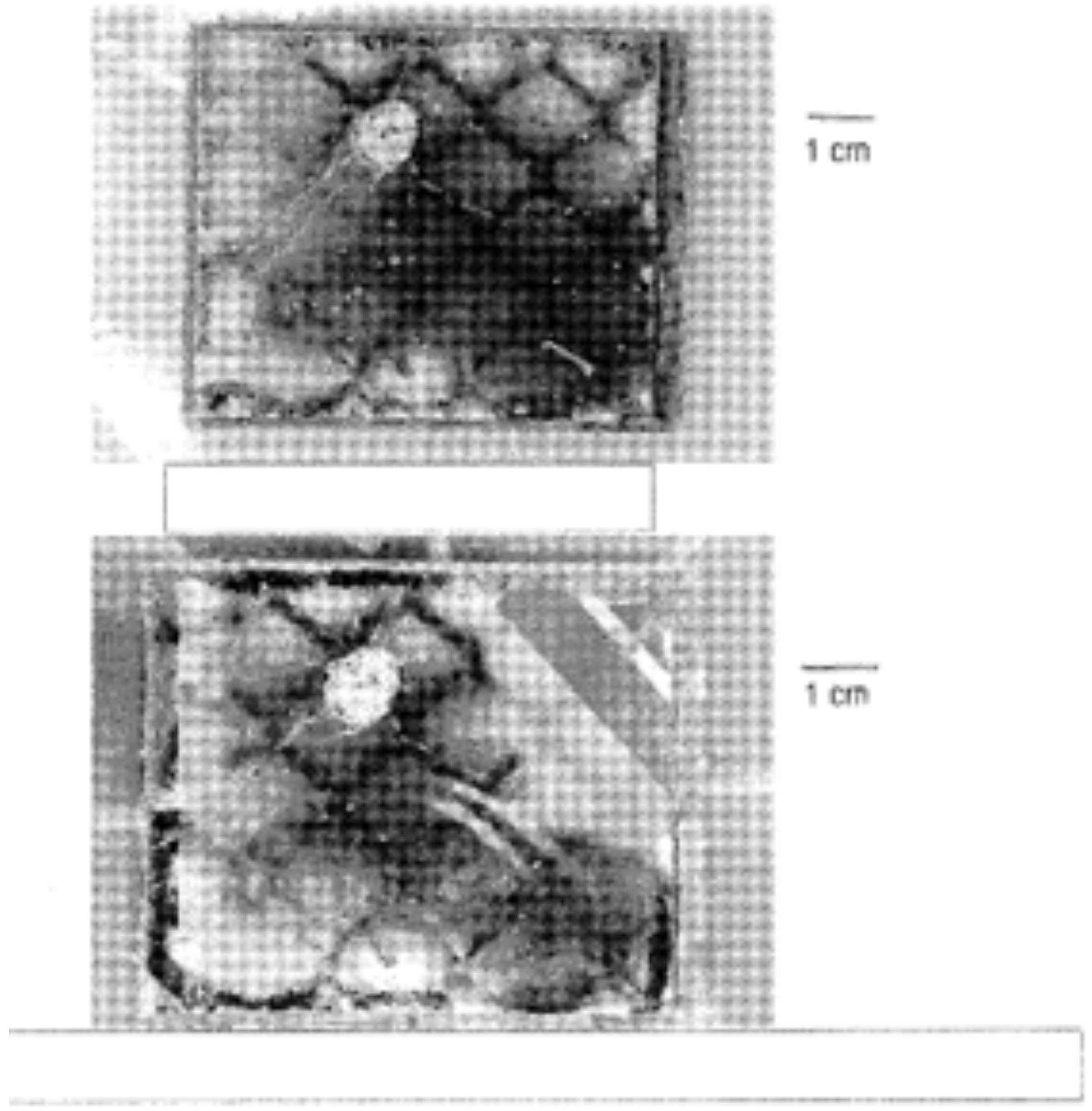


West Ford Needles

- At particular frequencies, radio waves will reflect off the ionosphere, enabling over-the-horizon radio transmissions.
- Performance is variable and unreliable, relying on things such as time of day, season, weather, and sun cycle.
- In an attempt to create a reliable ionosphere, 480,000,000 copper dipole antennas 1.78 cm long were placed in 3500 km orbit.
- Most deorbited after 3 years, but there are still clumps up there. 40, as of May 2019.
- Led to the creation of the 1967 Outer Space Treaty

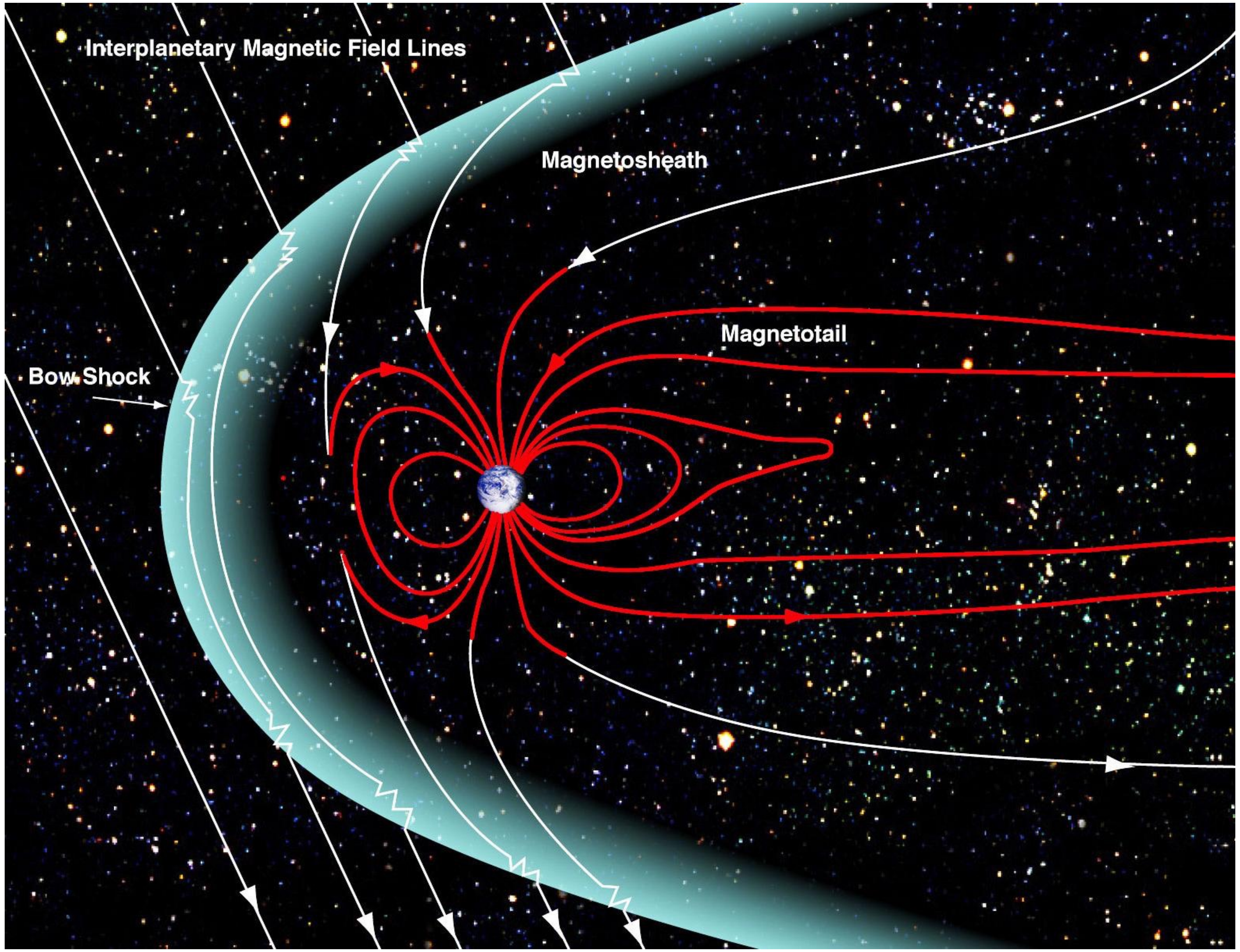
Vacuum

- The lack of atmospheric pressure decreases sublimation/evaporation points of materials.
- Outgassing is the process by which gas that was trapped in some material (adhesive, insulator, thermal coatings, electrical shields) is released.
- Outgassed materials tend to condense onto cooler surfaces (optical elements, radiators, solar cells)
- UV light interacts with this condensed material to form dark stains, inhibiting performance of instruments and solar cells
- See outgassing.nasa.gov for a list of the outgassing properties of various common materials.
- Sealed components (e.g. caps) can pop in the absence of atmospheric pressure.
- Pressure difference from here to space is the same as here to 33 ft. underwater. 3000 ft. for Venus.



Magnetic field

- Created by dynamo feedback effect. A rotating, conducting, convecting planetary core can maintain a magnetic field over astronomical timescales
- Approximately dipolar, but with many higher-order perturbations.
- Lookup tables are used (IGRF, WMM)
- Creates the *magnetosphere*, a region around the Earth in which ions are controlled by the magnetic field
- Solar wind interacts with the magnetic field, creating a long *magnetotail*. Kinetic energy of incident particles is transferred into magnetic field energy, which is occasionally released in geomagnetic storms
- Storms deposit energetic ions in the region just inside GEO orbit, which can differentially charge spacecraft.



Magnetic field models

- The IGRF is a series of mathematical models for the Earth's main field and its annular rate of change (**secular variation**)
- In source-free regions at the Earth's surface and above, the main field, with sources internal to the Earth, is the negative gradient of a scalar potential V which can be represented by a truncated series expansion. In practice, this becomes a position-based lookup table.
- **Implications for spacecraft design:**
    - Onboard model for magnetometer-based attitude estimation
    - Magnetic moment of the spacecraft must be minimal (except when desired, like when using torque coils)
    - Time-varying aspects are more important for higher-altitude spacecraft

Magnetic field models

- The ... ular var...
- In s... is the neg... actice, this...
- **Imp...**

... coils)

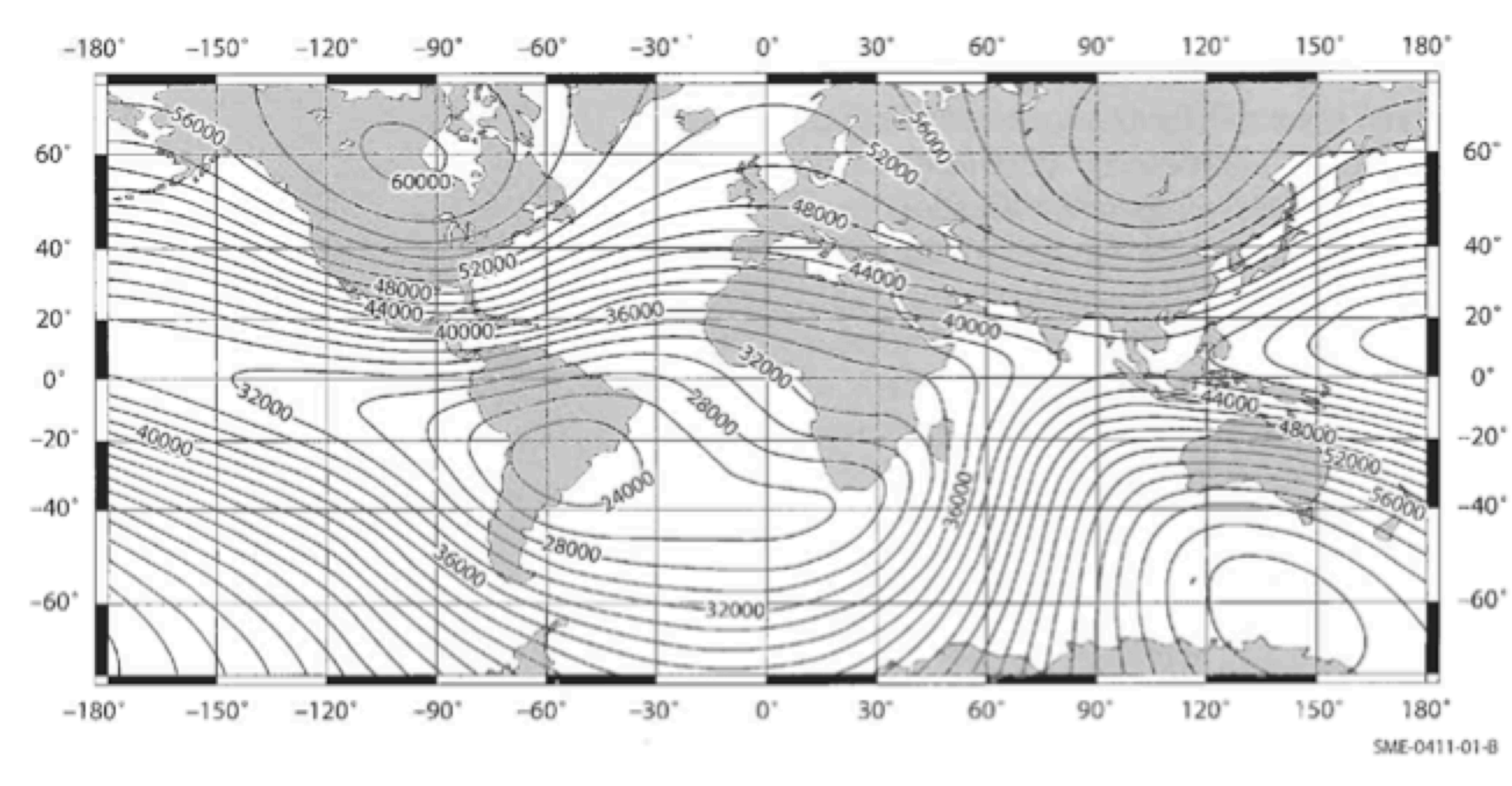


Fig. 7-4. The WMM2000 Earth Main Field Model is Shown with 2000 nT Contour Intervals.

Sun: electromagnetic radiation

Energy from the Sun is transferred to the Earth via **electromagnetic radiation** (photons), **charged particles** (ions/electrons), and **magnetic, electric, and gravitational fields.**

We describe electromagnetic radiation by its frequency/wavelength, energy, and momentum:

$$f = \frac{c}{\lambda}$$

$$E = hf = \frac{hc}{\lambda}$$

$$p = \frac{E}{c} = \frac{h}{\lambda} \longrightarrow$$

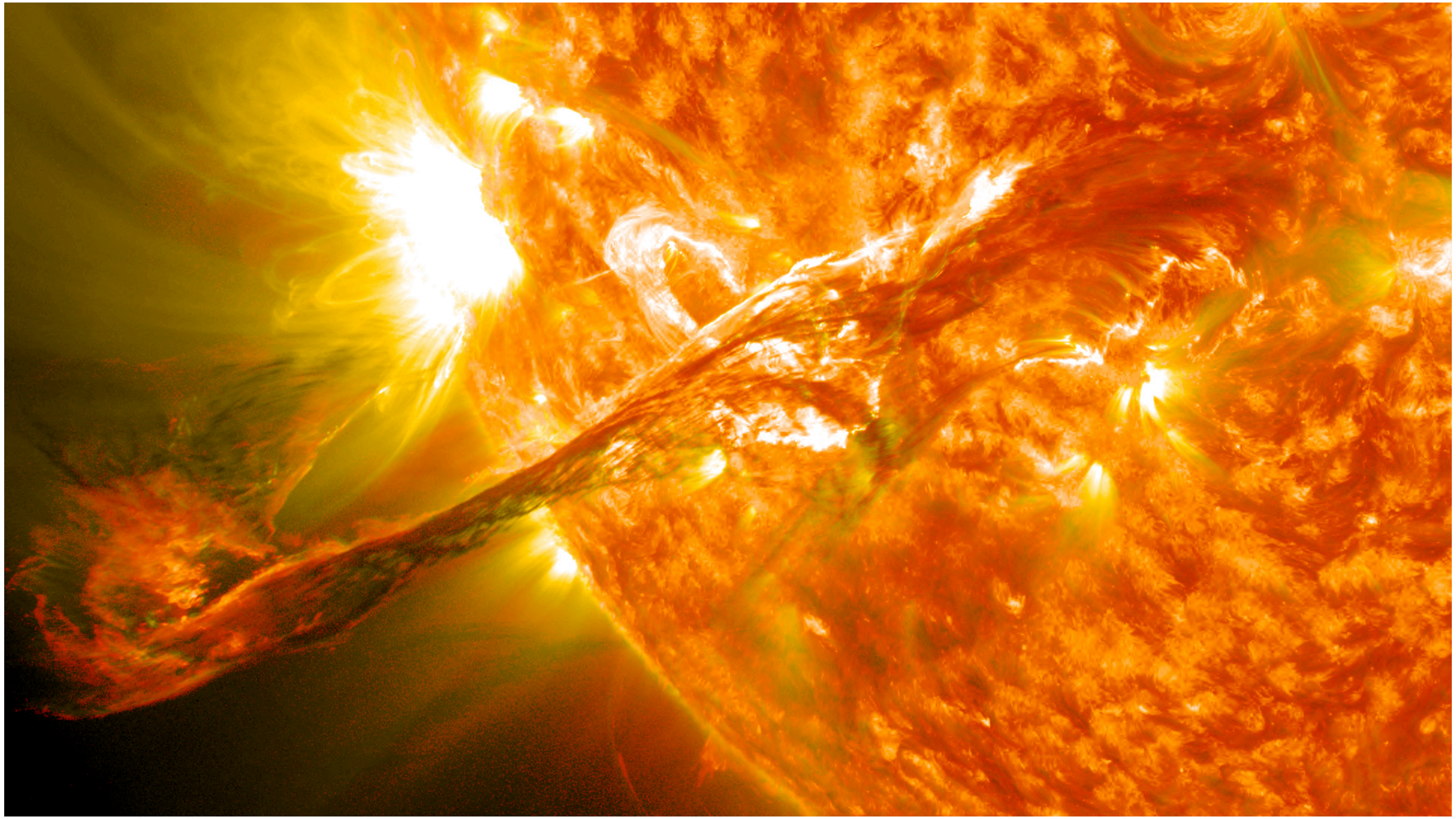
Photons have momentum! This is why solar sails work.

Events on the Sun can change the rate of energy transfer from Sun to Earth.

- Solar flares
- Coronal mass ejections
- Solar cycles

Solar flares

Huge bursts of electromagnetic radiation in all wavelengths, but mostly X-ray and ultraviolet. (The Sun gets really bright for a short time)



Captured by Solar Dynamics Observatory. Lighten-blended version of the 304 and 171 angstrom wavelengths.

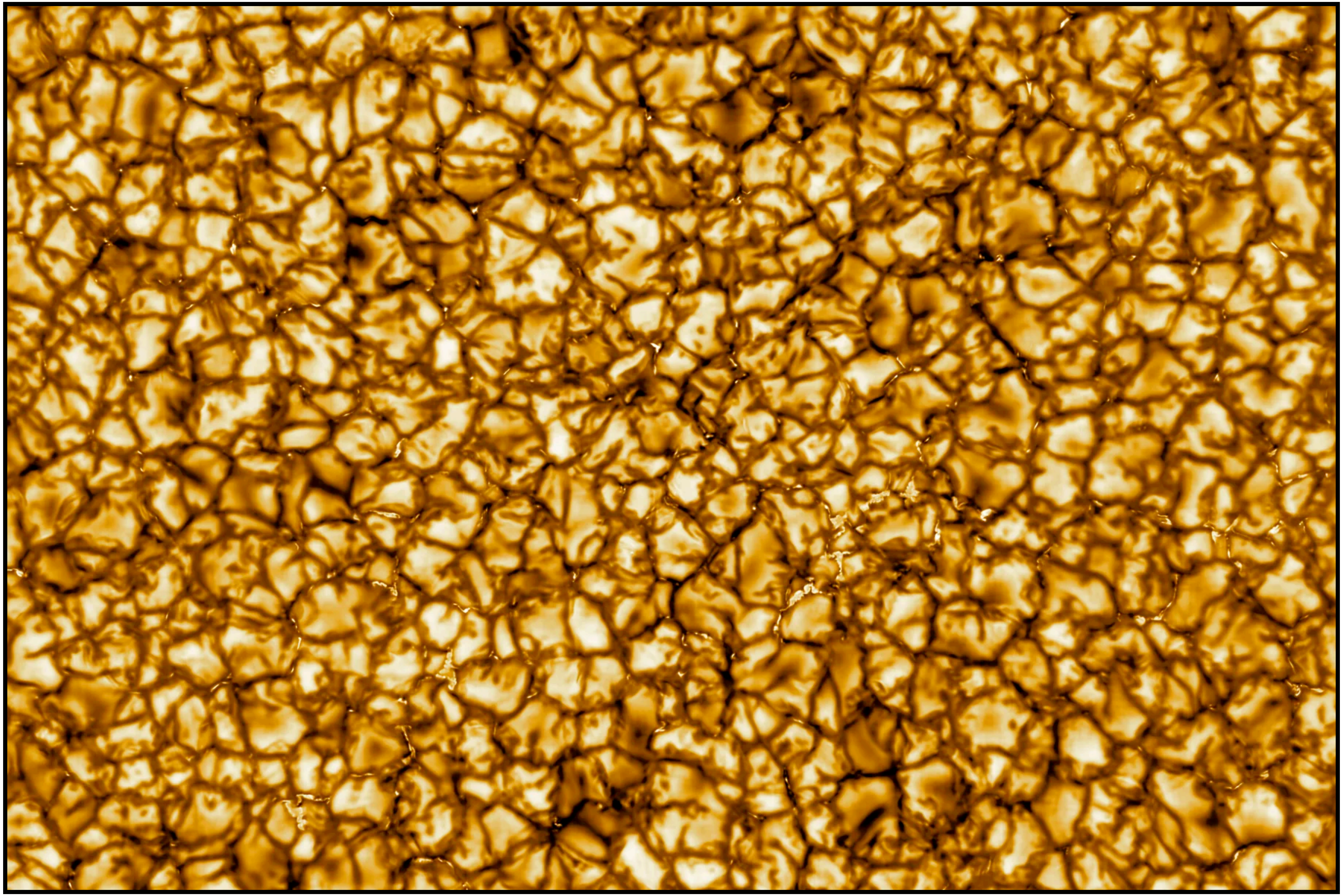
Often facilitated by magnetic reconnection.

Often occurs in conjunction with a coronal mass ejection.

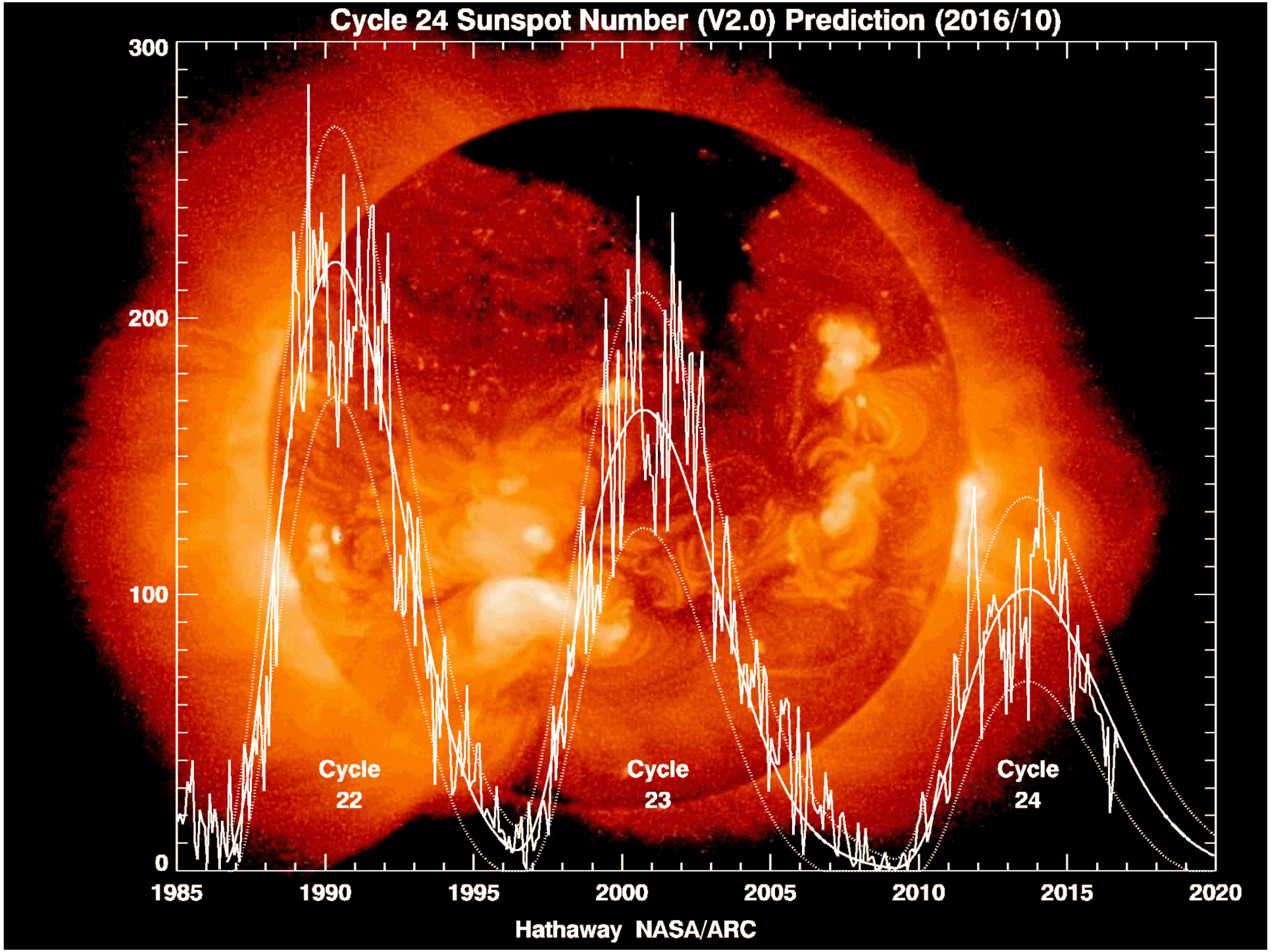
~10^{20} Joules of energy (about the same as world energy consumption in 2010)

Coronal mass ejections

Made of particles (ions and electrons) ejected at very high speed (solar wind). These particles take ~3 days to reach Earth.




12 Dec. 2019 19:24:31 UT

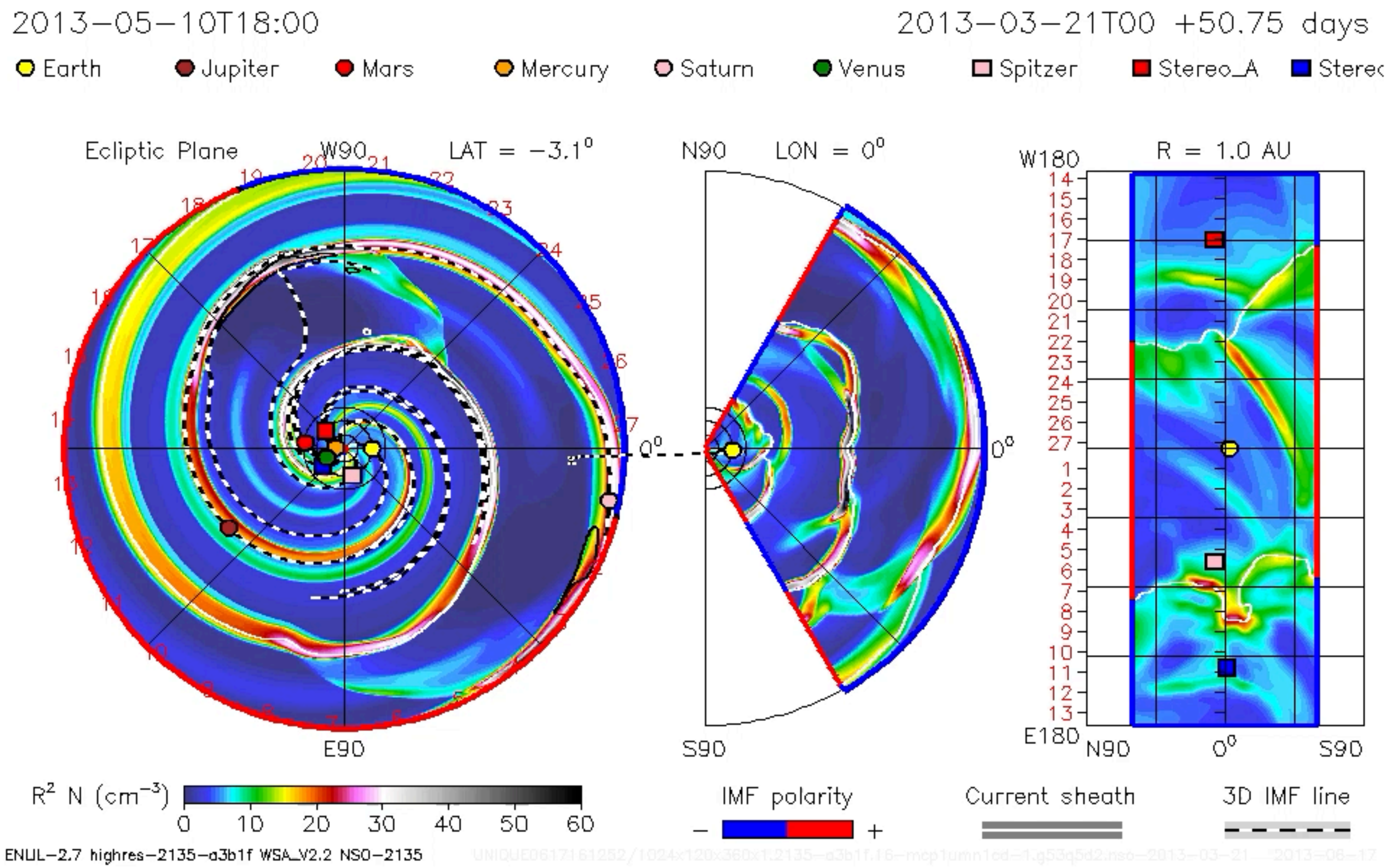


- Periodic, ~11-year change in the Sun's activity
- Levels of solar radiation and rates of coronal mass ejections/solar flares increase and decrease in ~11-year cycles
- Sometimes, spacecraft will phase their launch with the solar cycle. But, a solar cycle minimum is a galactic cosmic ray maximum.

Why do we care about these solar processes?

- Solar radiation can cause geomagnetic storms, which can increase drag on spacecraft, increase spacecraft charging, and induce radiation poisoning in astronauts
- Generally, these particles are not high enough energy to cause immediate and catastrophic destruction of electronics, but they do degrade solar cells, increase background noise in electro-optical sensors, and make astronauts sick.

Solar wind simulation (MSISE) for Cassini



A brief aside about human radiation exposure

Acute Dose Effects on Humans

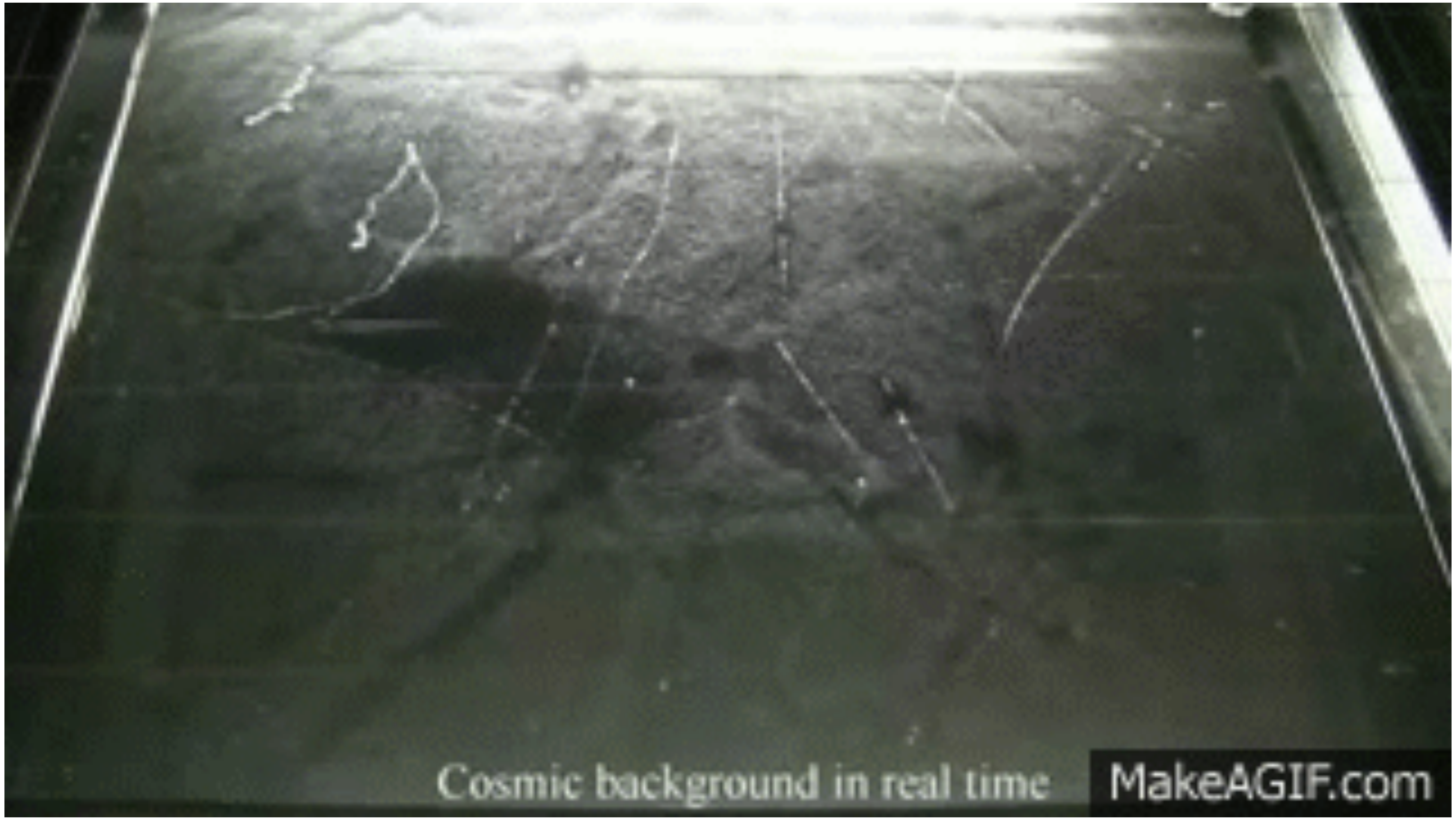
Dose (Rads)	Probable Effect
0–50	No obvious effects, blood changes
80–120	10% chance of vomiting/nausea for 1 day
130–170	25% chance of nausea, other symptoms
180–220	50% chance of nausea, other symptoms
270–330	20% deaths in 2–6 weeks, or 3 mo. recovery
400–500	50% deaths in 1 mo., or 6 mo. recovery
550–750	Nausea within 4 hours, few survivors
1000	Nausea in 1–2 hours, no survivors
5000	Immediate incapacitation, death within 1 week

A brief aside about human radiation exposure

The Demon Core

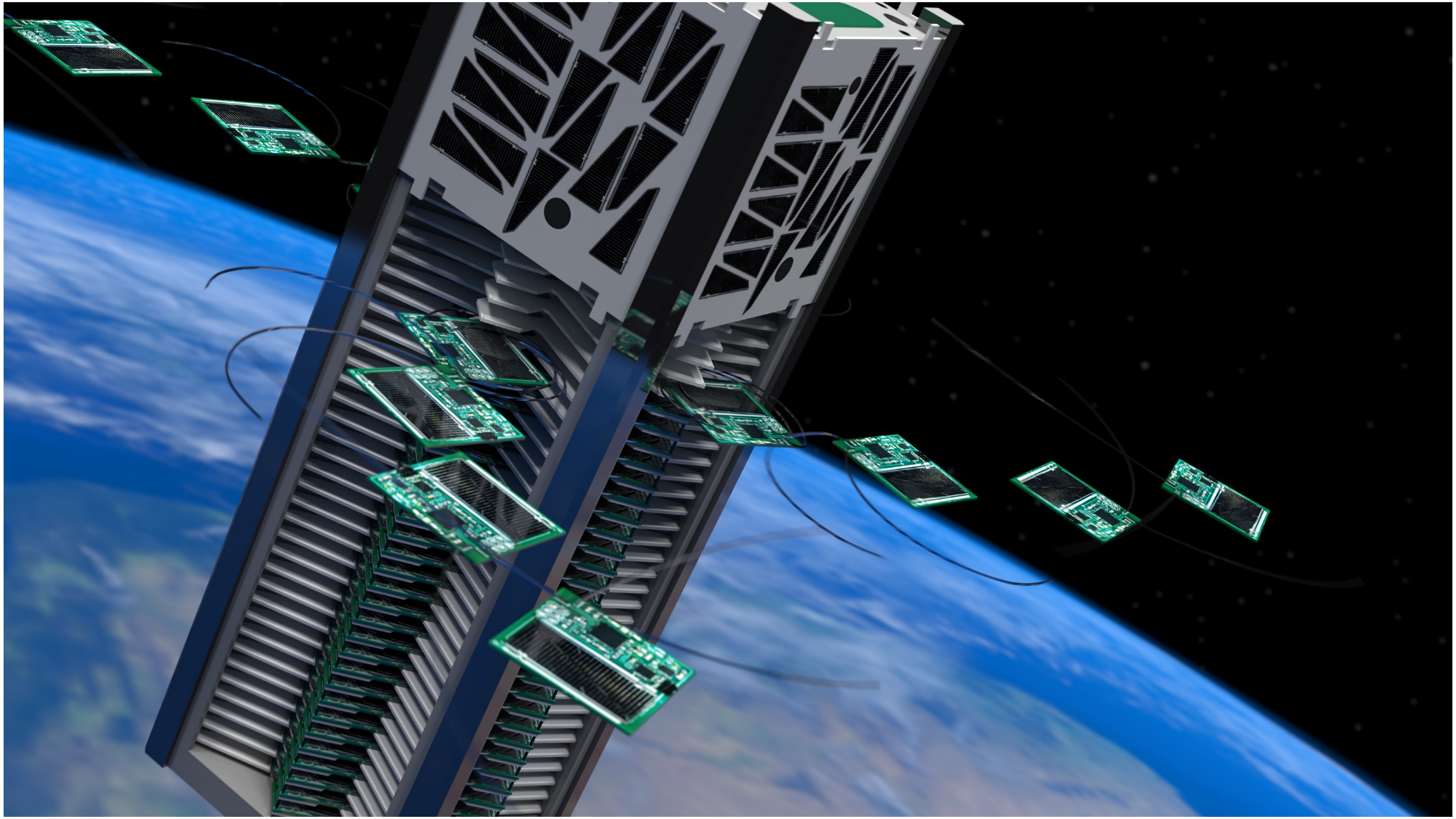
- Among the best human radiation exposure datasets
- Leo Slontin: >1000 rad
- “Tickling the dragon’s tail.”

Galactic Cosmic Rays

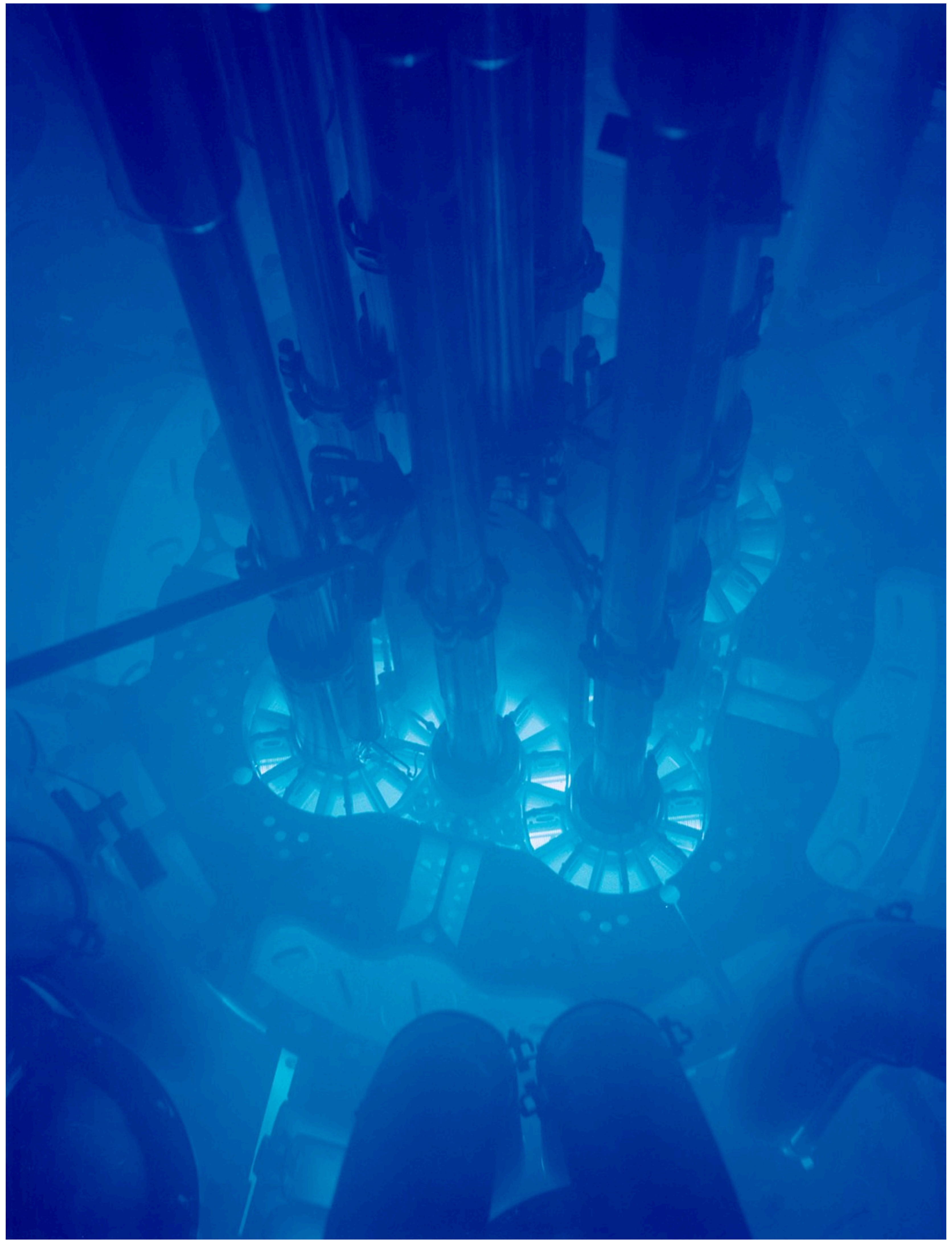


- Radiation which originates *outside* the solar system (black holes, supernovae, etc.)
- Very high energy (GeV - PeV). These are protons or heavier ions traveling at relativistic speeds
- If they strike a sensitive piece of electronic equipment (a transistor, for example), they can destroy it (“Single Event Burnout”). In less severe cases, they may simply cause a latchup or a bit flip
- To mitigate risk, many spacecraft use radiation-hardened electronics

Galactic Cosmic Rays: a cautionary tale

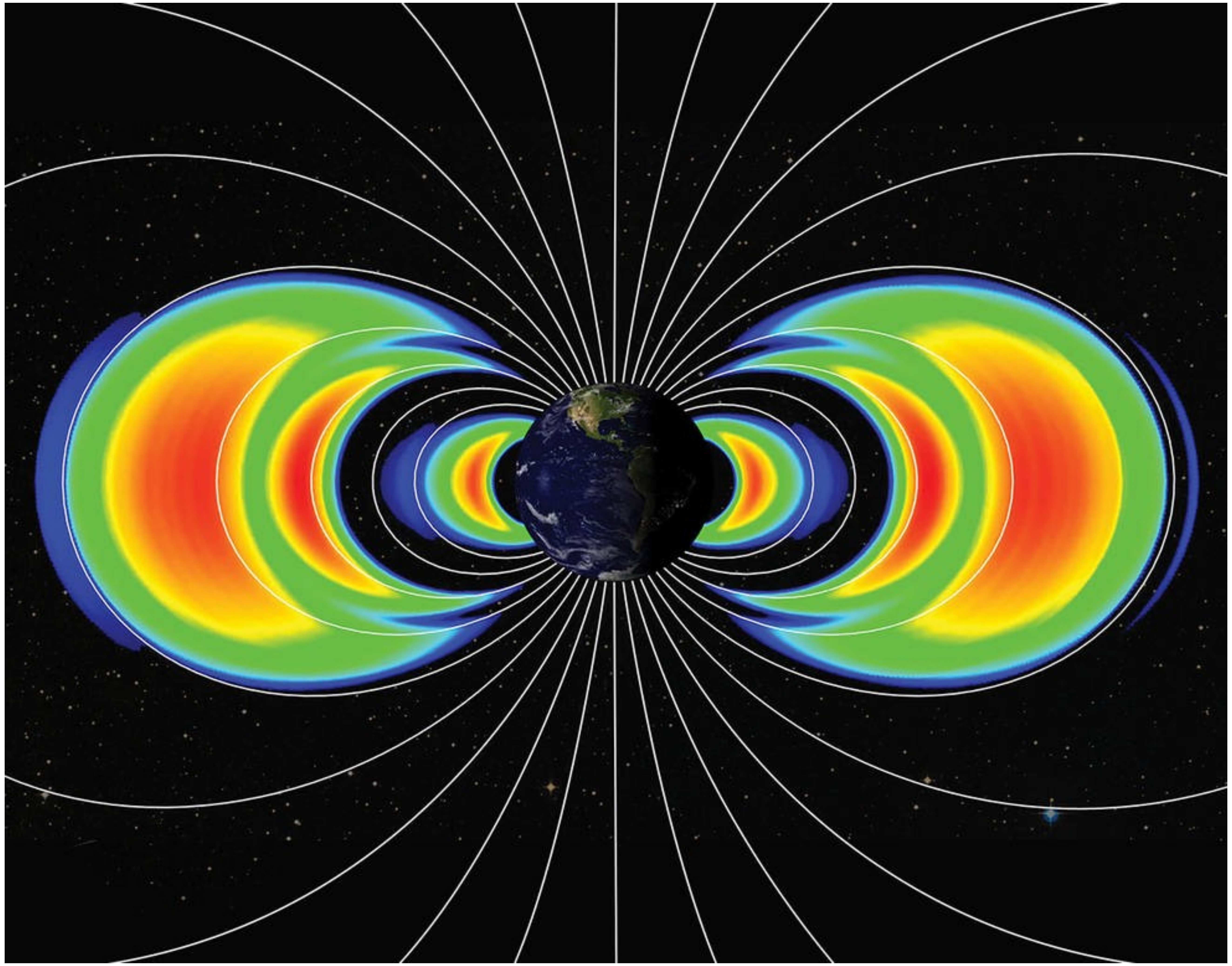


Cosmic ray visual phenomena



- Many astronauts experience spontaneous flashes of light outside the magnetosphere of the Earth.
- It is believed that these flashes are due to cosmic rays interacting with the optical pathway (Cherenkov radiation in the eye, direct interaction with the optic nerve, or direct interaction with the visual centers in the brain).

Van Allen Belts



- Two toroidal regions with particularly high concentrations of high energy electrons and ions.
- Inner belt at 1000-6000 km, outer belt at 13,000-60,000 km
- Most LEO satellites exist below the lower ring, but GEO satellites are on the edge of the outer ring and must deal with higher radiation doses.

Radiation shielding

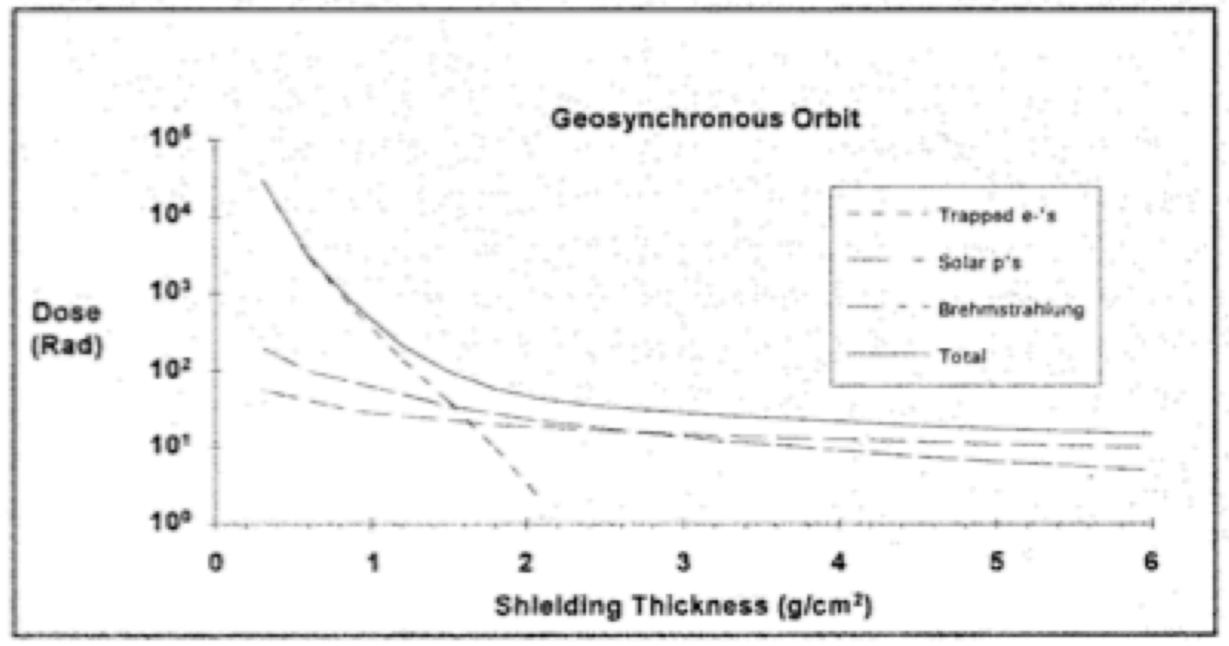
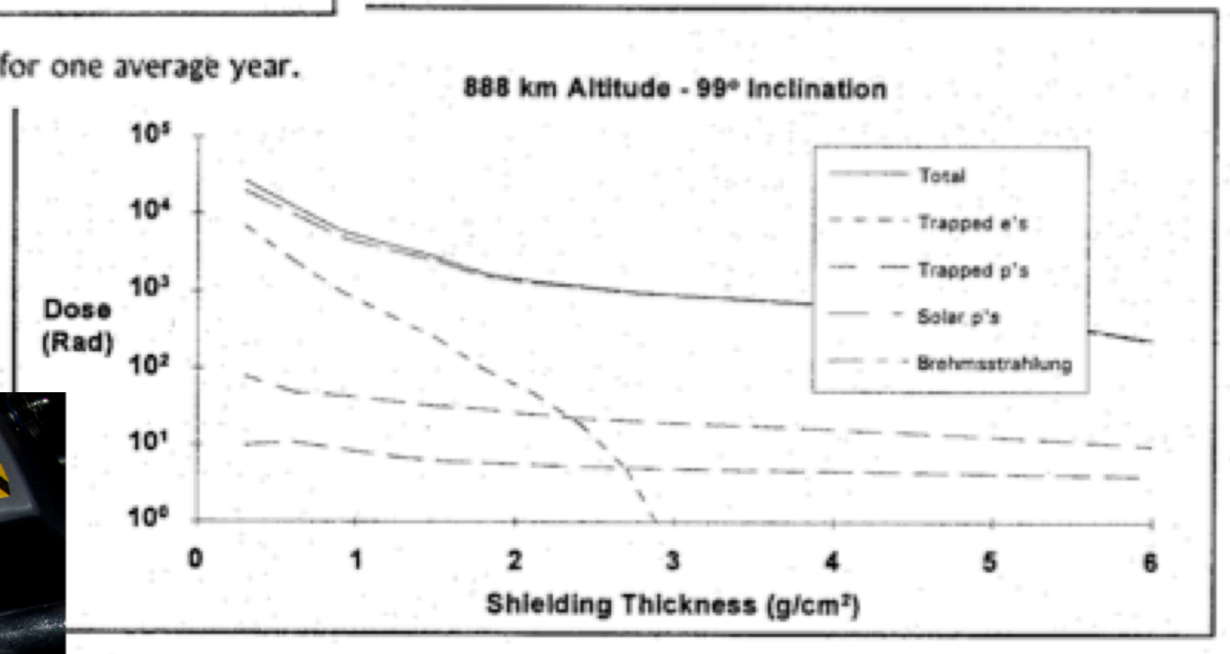


Fig. 5.10 Geosynchronous orbit dose versus depth curve for one average year.

Al 2.7 g/cc
H_2O 1 g/cc



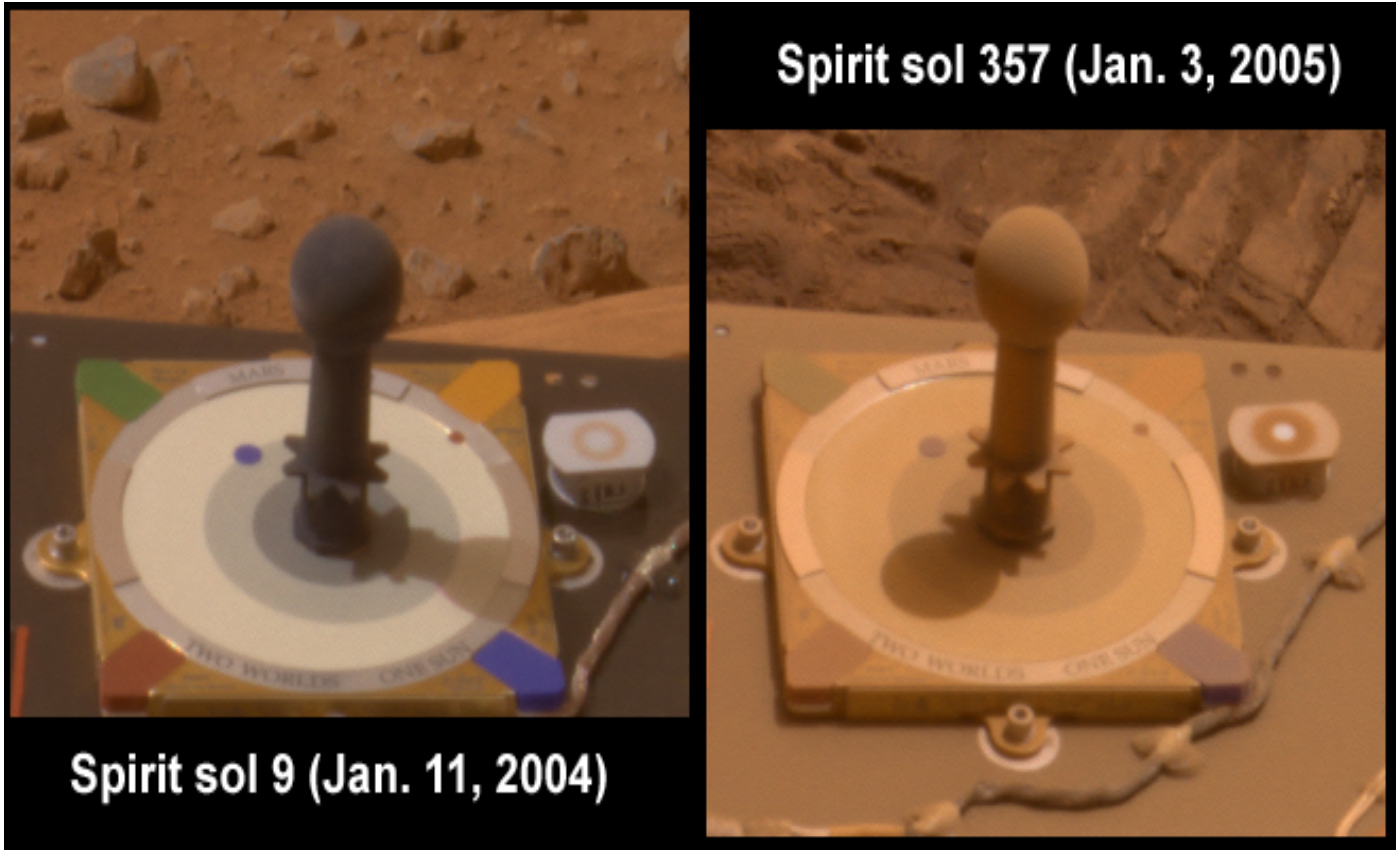
g. 5.11 Sun-synchronous orbit dose versus depth curve for one average year.

- To protect against radiation, spacecraft (and people) often employ **shielding**
- A thick layer of aluminum or water is used to reduce total dosage
- The thickness of the layer can be computed as a function of the total dose in rad.

Microgravity

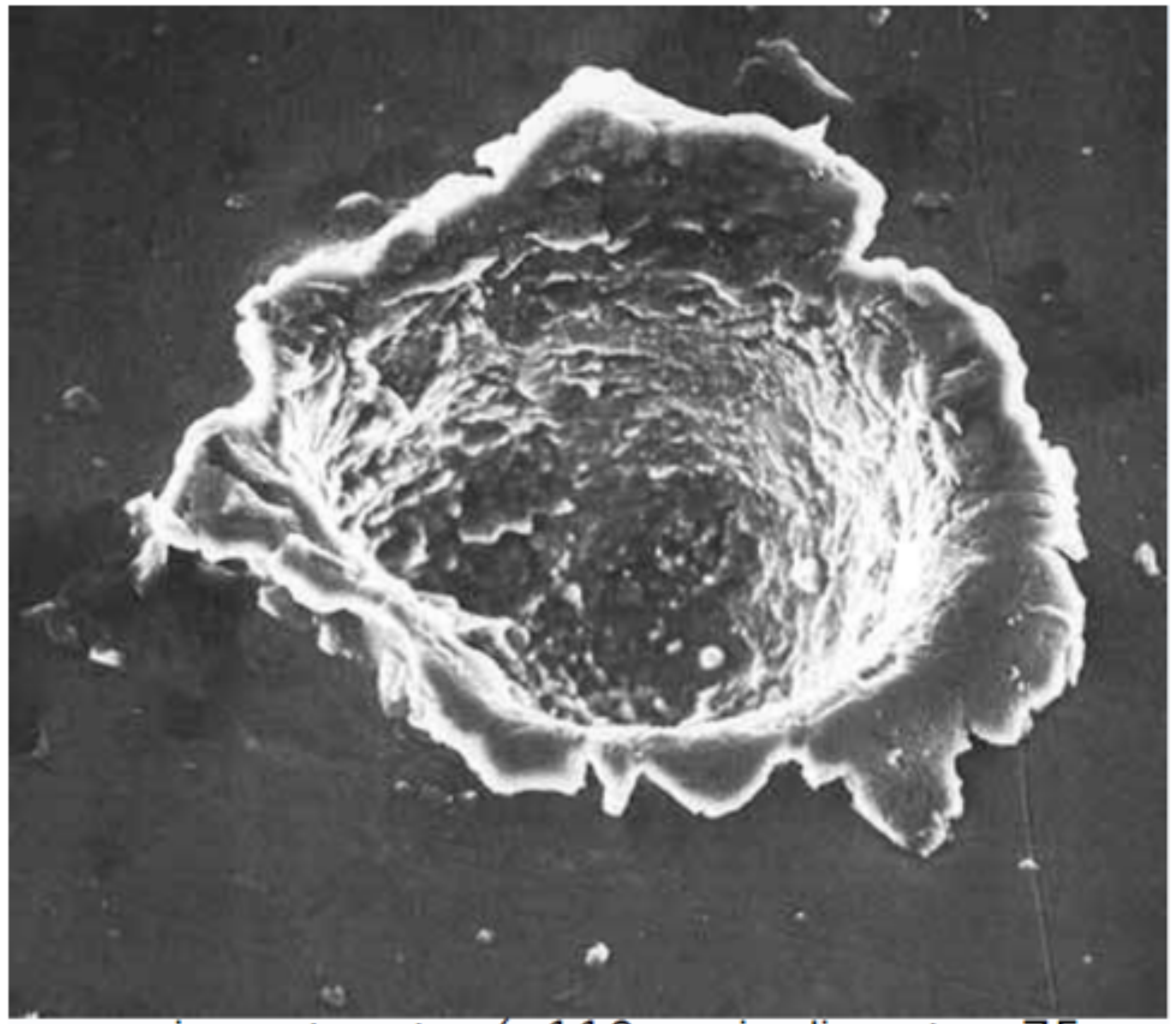
- Bubbles don’t rise, objects don’t fall, particles don’t settle in solution, and there is no convection
- The human body realizes that it no longer needs a strong skeletal system, and begins to remove bone mass
- Also creates the opportunity for container less processing and large crystal formation

Dust

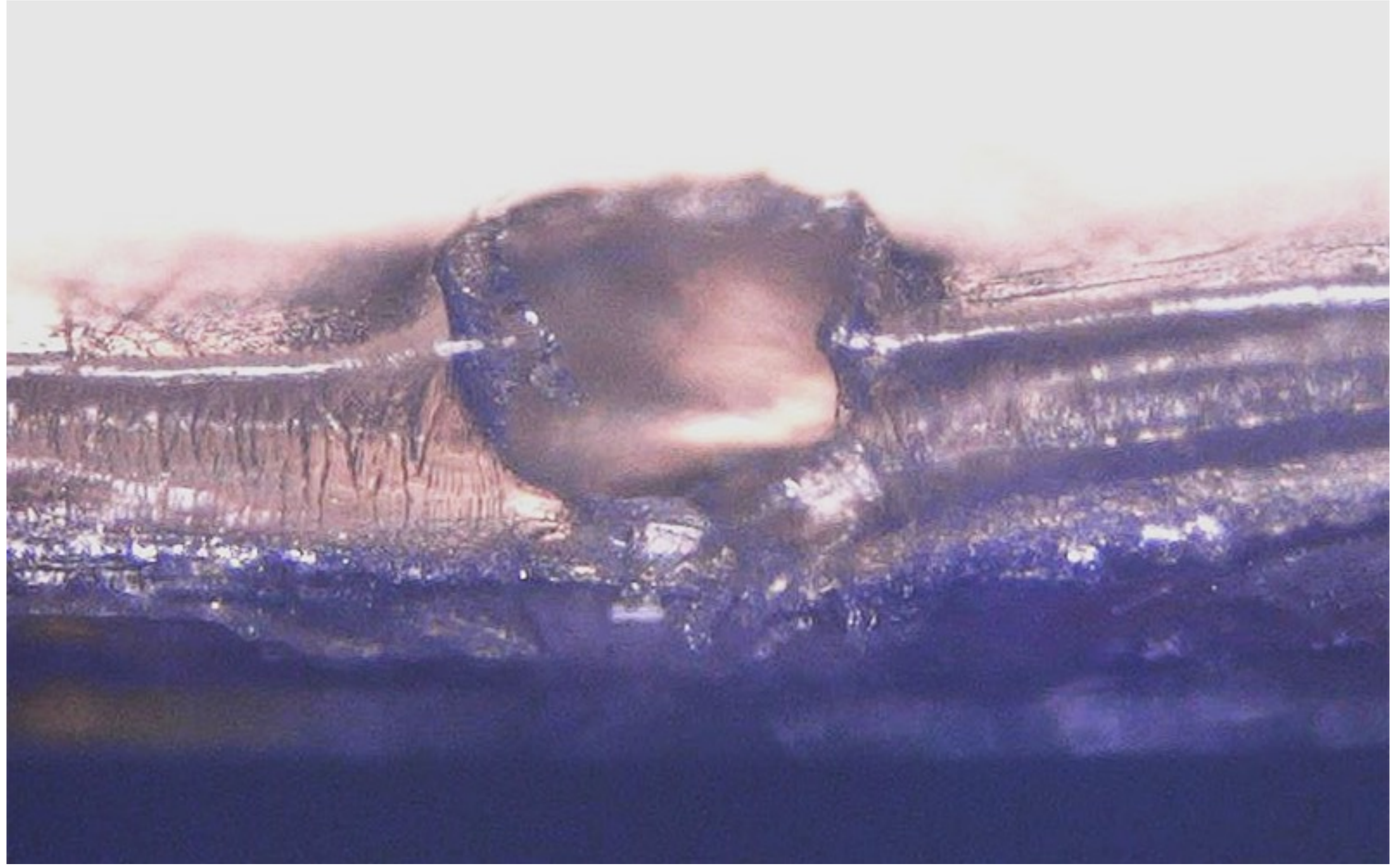

Spirit sol 9 (Jan. 11, 2004)
Spirit sol 357 (Jan. 3, 2005)
MARS
TWO WORLDS
ONE SUN

Debris

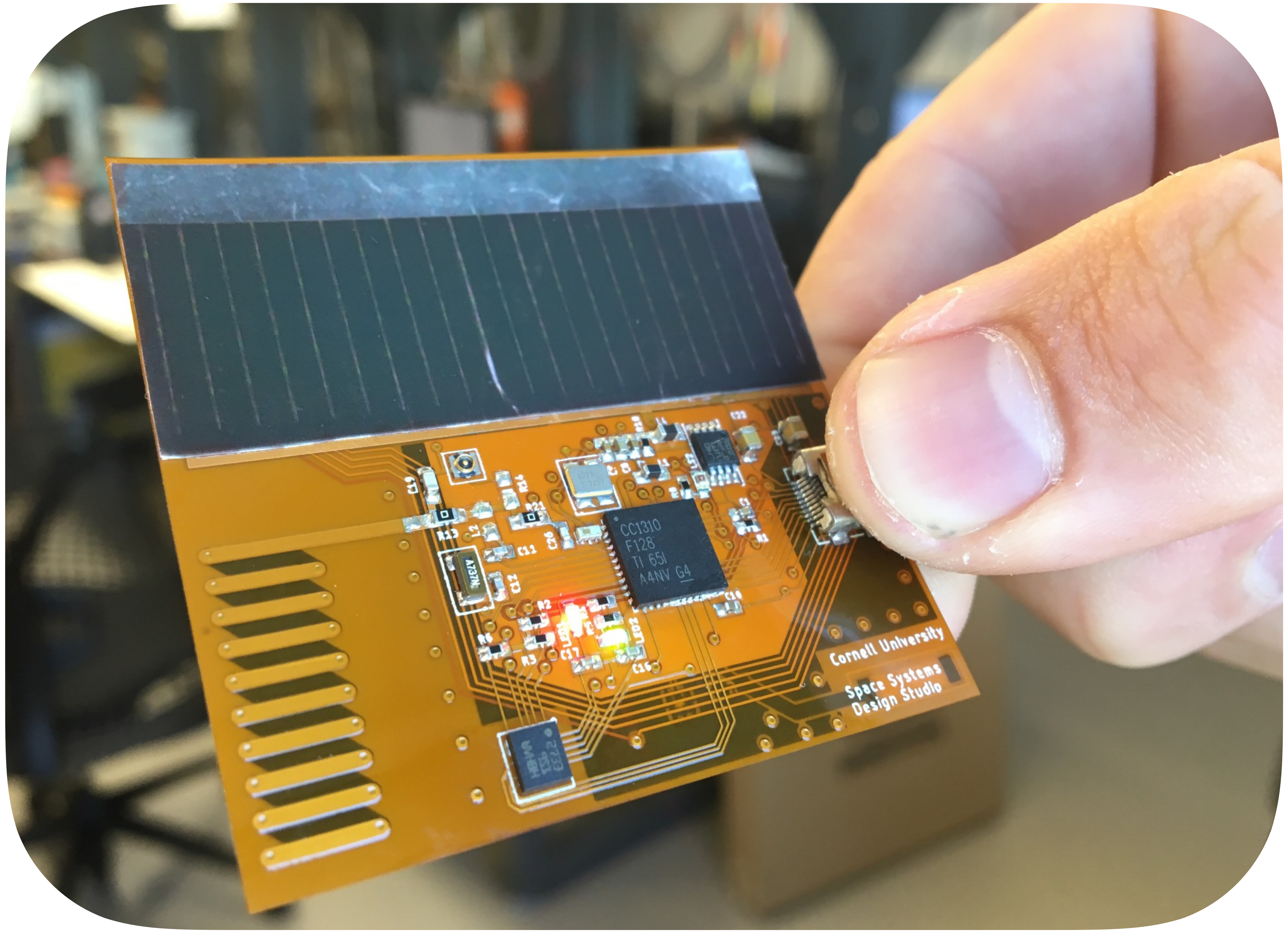
- Any non-operational object in orbit. May include fairings, interstage adapters, Ed White's glove from Gemini 4, pieces of dead satellites, micrometeroids, asteroid particles, etc.
- Can cause immediate and catastrophic damage of all or part of a spacecraft. All objects above 10 cm are visible from Earth and are currently being monitored and catalogued.



impact crater (~110 μm in diameter, 75 μm deep) in pure aluminum foil.



Physical Space-to-Earth Data Transfer with Chip-Satellites



V. Hunter Adams

Mason Peck

November 29, 2018

Spacecraft have two jobs:

1. Gather data
2. Transmit data

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1. Gather data
2. Transmit data

These two tasks occur at massively different rates.

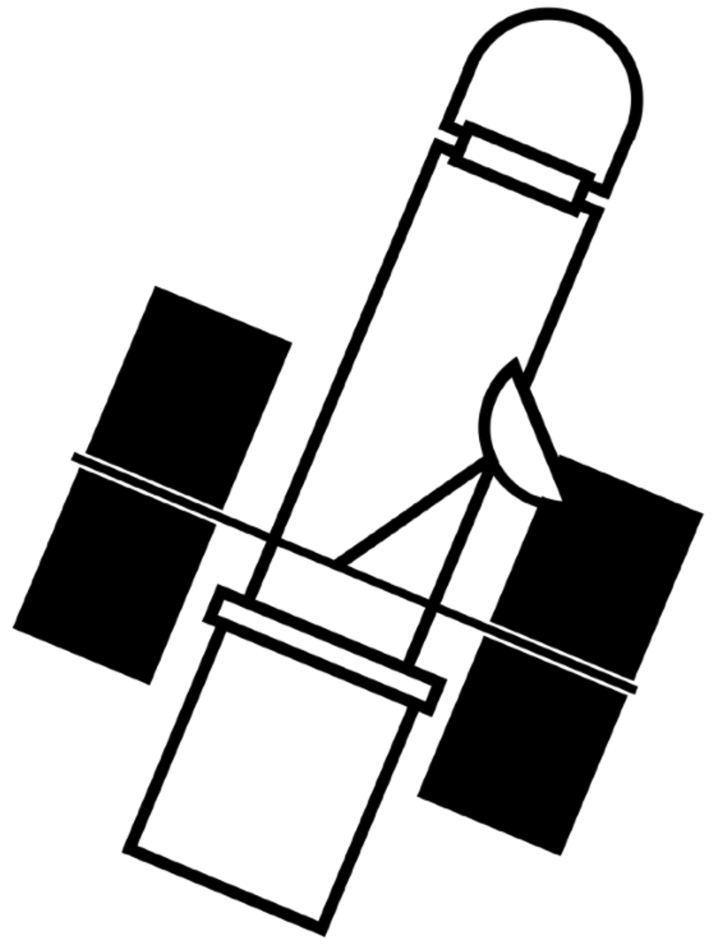
storage rate

one micro SD card

250 MB/sec

transmission rate

Hubble Space Telescope



0.029 MB/sec

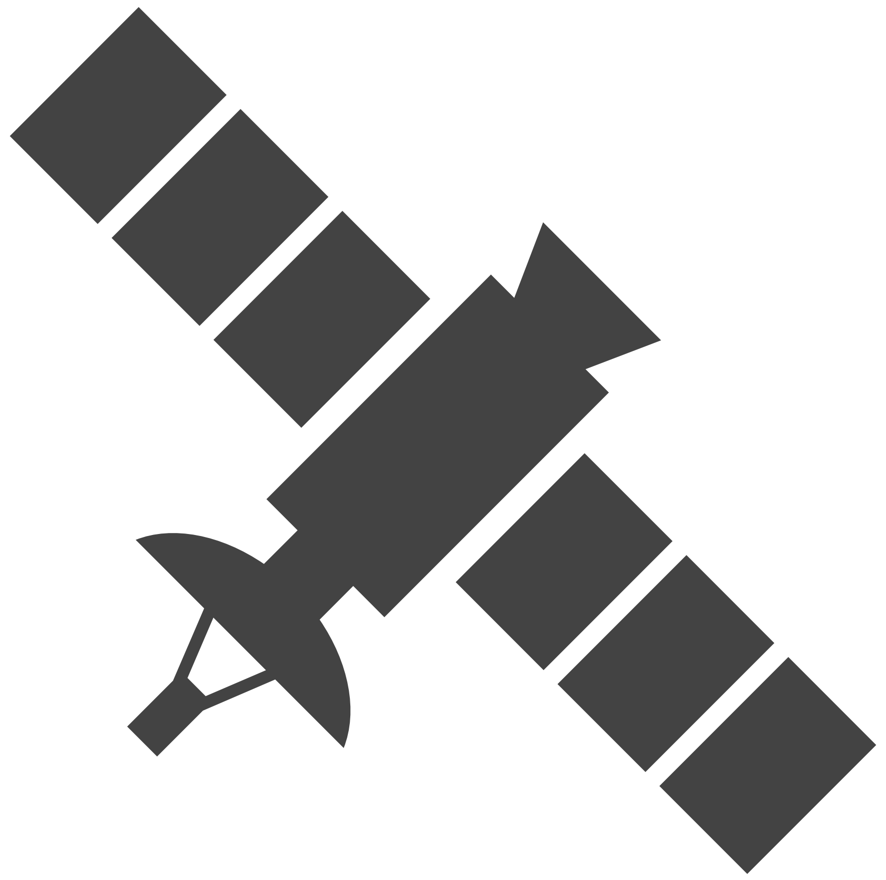
storage rate

one micro SD card

250 MB/sec

transmission rate

Landsat 8



48 MB/sec

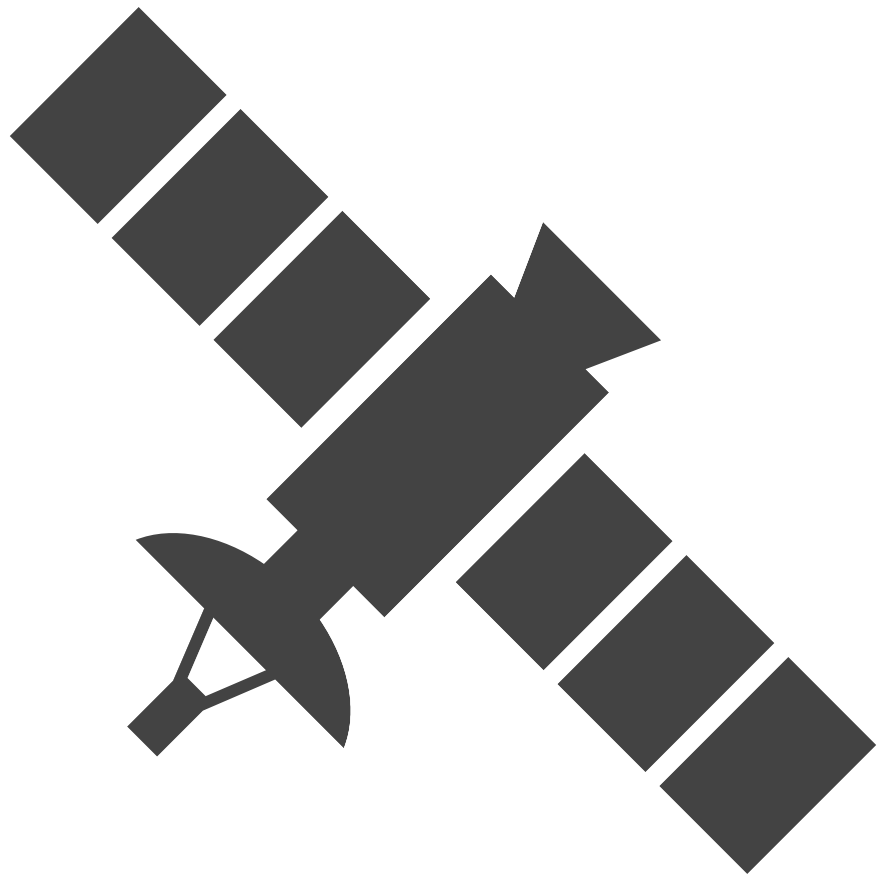
storage rate

one micro SD card

250 MB/sec

transmission rate

Landsat 8



48 MB/sec

There is a calculable upper limit for transmission rate (the Shannon Limit) which always bottlenecks data transfer through a communications channel.

Bandwidth for physical transfer of data vastly exceeds bandwidth for remote transfer of data.

internet

167 Tb/sec

container ship

201,000 Tb/sec

internet

167 Tb/sec

container ship

201,000 Tb/sec

A single container ship full of micro SD cards has 1200 times the bandwidth of the entire internet over a one-day voyage.

“SneakerNet”

For very large amounts of data:

FedEx

is faster than

Internet

For very large amounts of data:

FedEx

is faster than

Internet

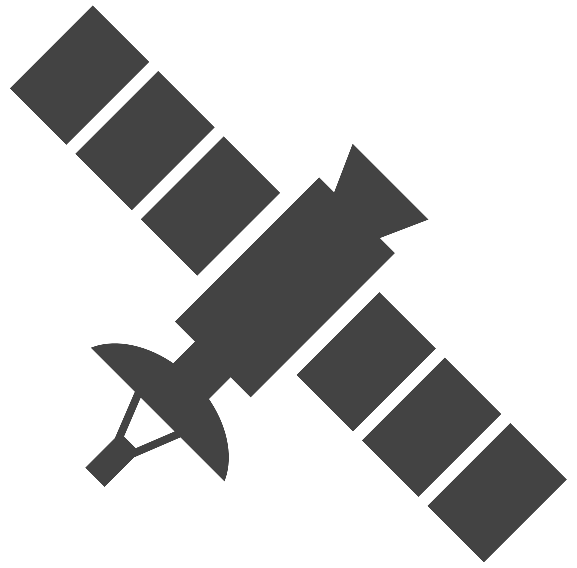
When Google wants to move large amounts of data from one facility to another, they use the mail.

FedEx

is faster than

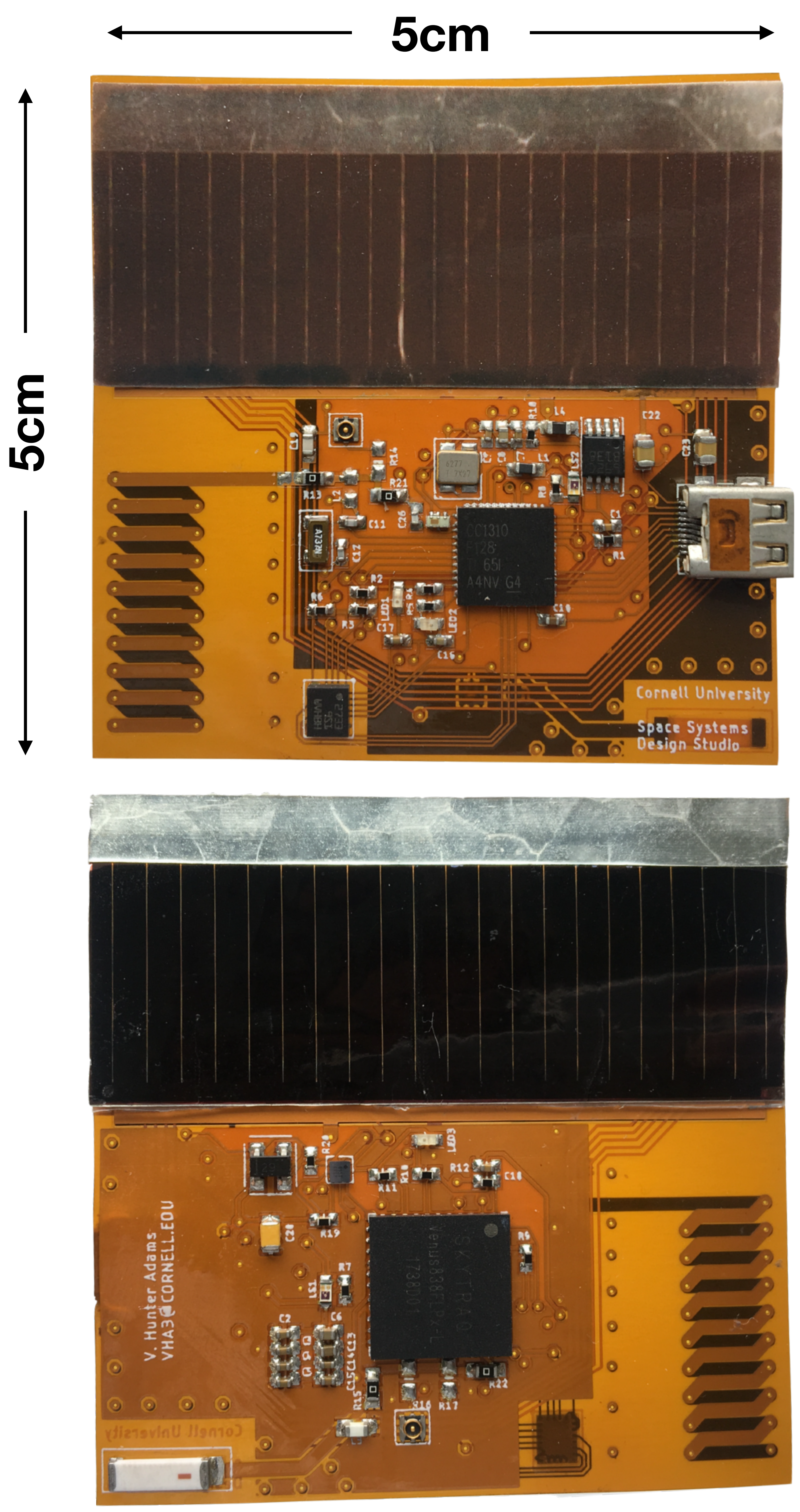
Internet

is *much* faster than



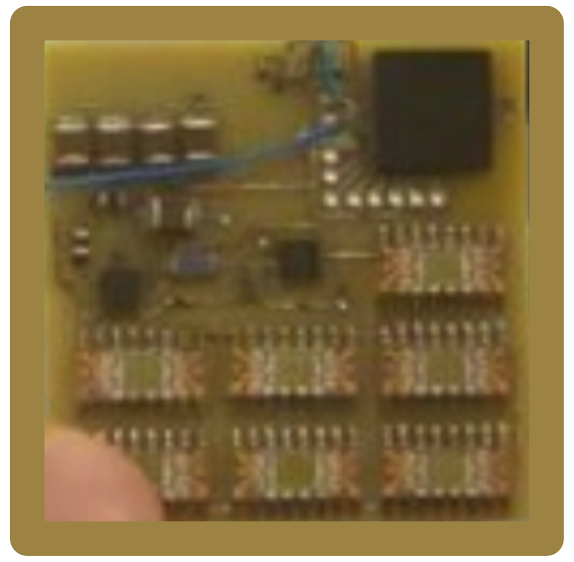
Radio Communication

We propose to increase the data throughput from space to Earth by many orders of magnitude by transmitting data physically rather than remotely.

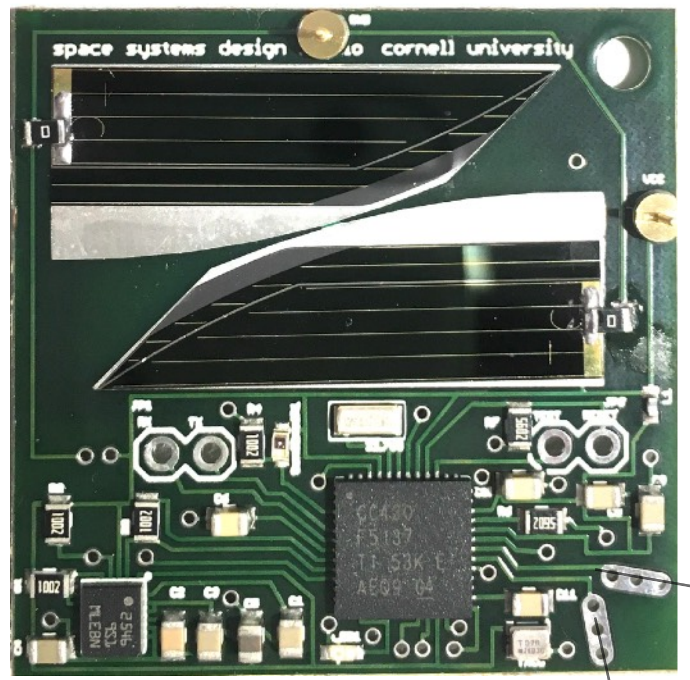


Monarch

- 2.5 grams, 5x5 cm
- chip-to-chip communication from up to 1 km line of sight
- chip-to-receiver communication from >1000 km
- GPS acquisition in 30 seconds
- powering by sun and/or inductive coils
- communication among hundreds of chips on a single ISM-band frequency
- can be made to be waterproof
- extremely shock-proof (>27,000 g's)
- can generate their own magnetic field
- stable flight in 0 g's
- flexible (to an extent)
- capable of accommodating any sensor that meets size and power requirements
- capable of accommodating external memory storage
- operating temperatures from -40 to +85 C



International Space Station Demo



KickSat 2

Alpha

2010

2016

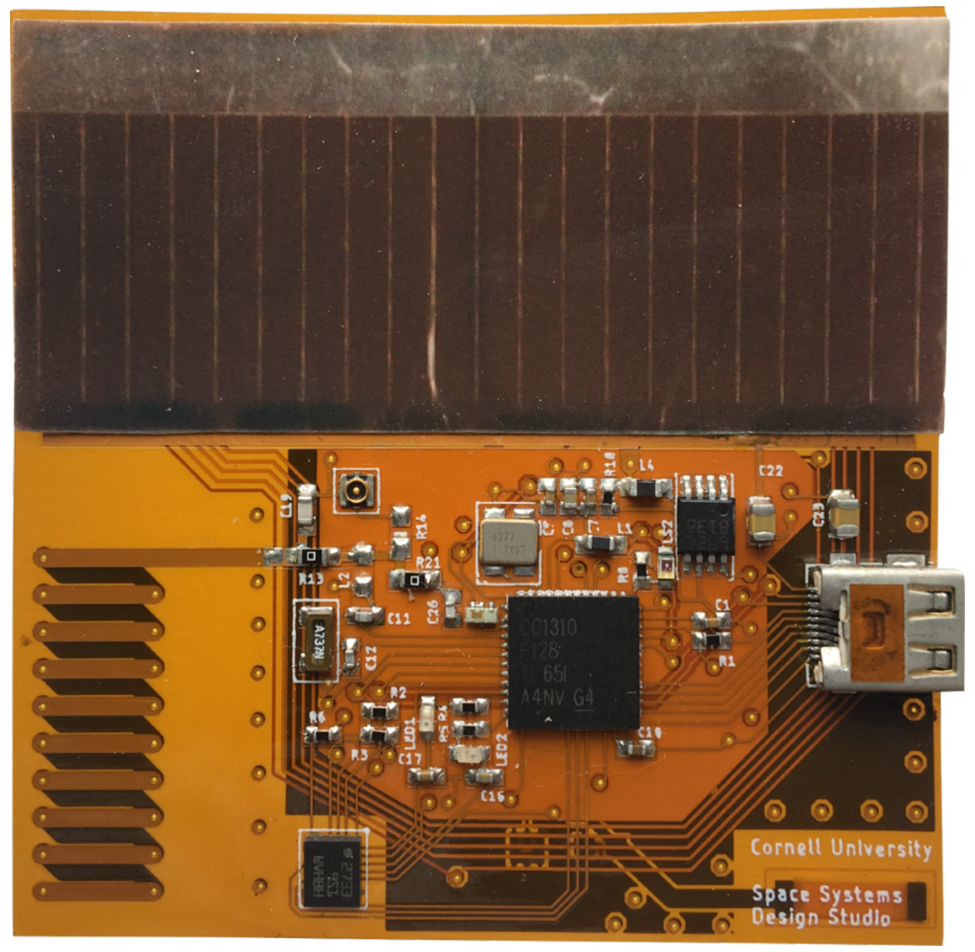
2013

2018

KickSat 1,2

Venta 1

Proposals out



Concept of operations:

1. Carry 1000 Monarchs (2.5 kg) to orbit in a cubesat
2. Deploy all Monarchs as free-flying spacecraft
3. Each Monarch stores sensor data to onboard external memory chips
4. Atmospheric drag causes each Monarch to de-orbit and re-enter the atmosphere
5. Monarchs and external memory chips are recovered from the surface of the Earth

Concept of operations:

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   We've done this before with 128 chip-satellites.

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Concept of operations:

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   Not technically challenging.

4. Atmospheric drag causes each Monarch to de-orbit and re-enter the atmosphere
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   Consequence of size and shape of the Monarchs

5. Monarchs and external memory chips are recovered from the surface of the Earth

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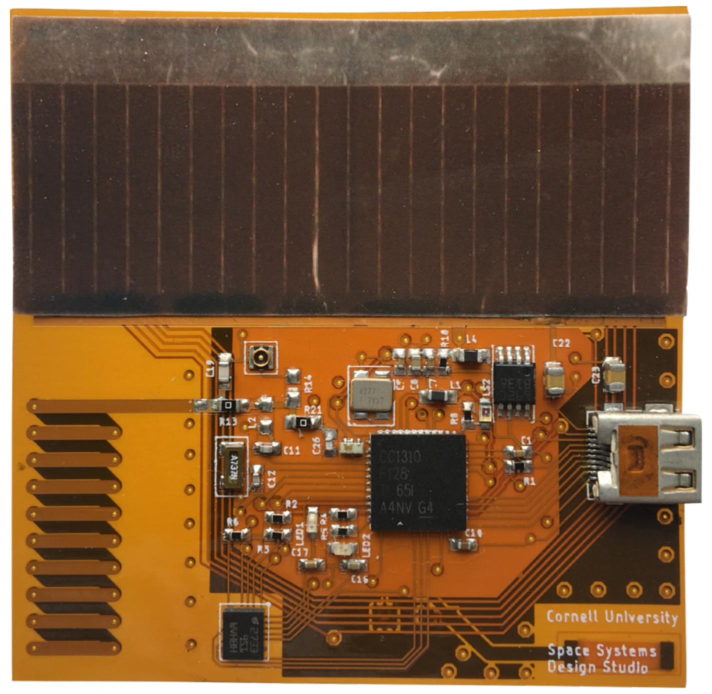
Achievable in one of two ways:

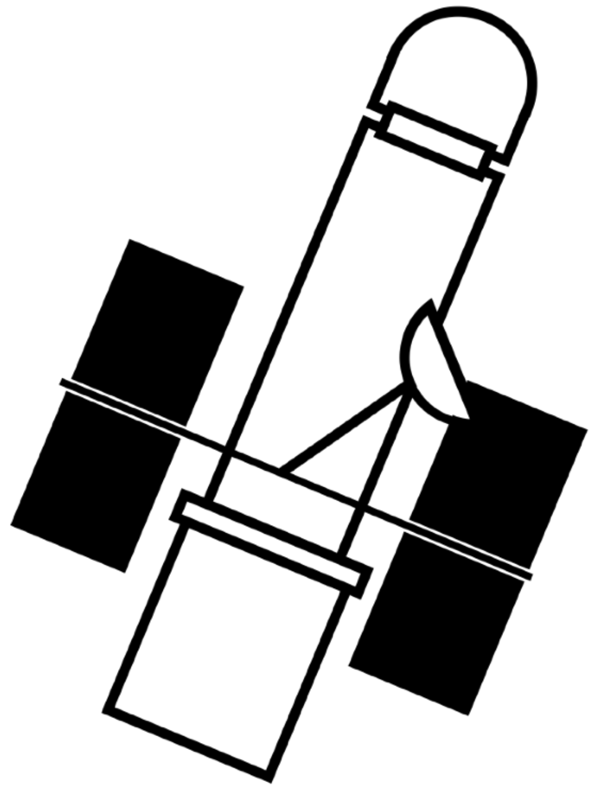
- **Beacon:** each Monarch transmits its GPS coordinates, which are received by handheld receivers or cubesats of the sort that we have prototyped
- **Statistical**: restrict recovery to a designated area and deploy enough Monarchs to provide a statistical guarantee that a desired number land in the designated area

Equivalent data production:



one Monarch recovered after one week

2.5g, $50

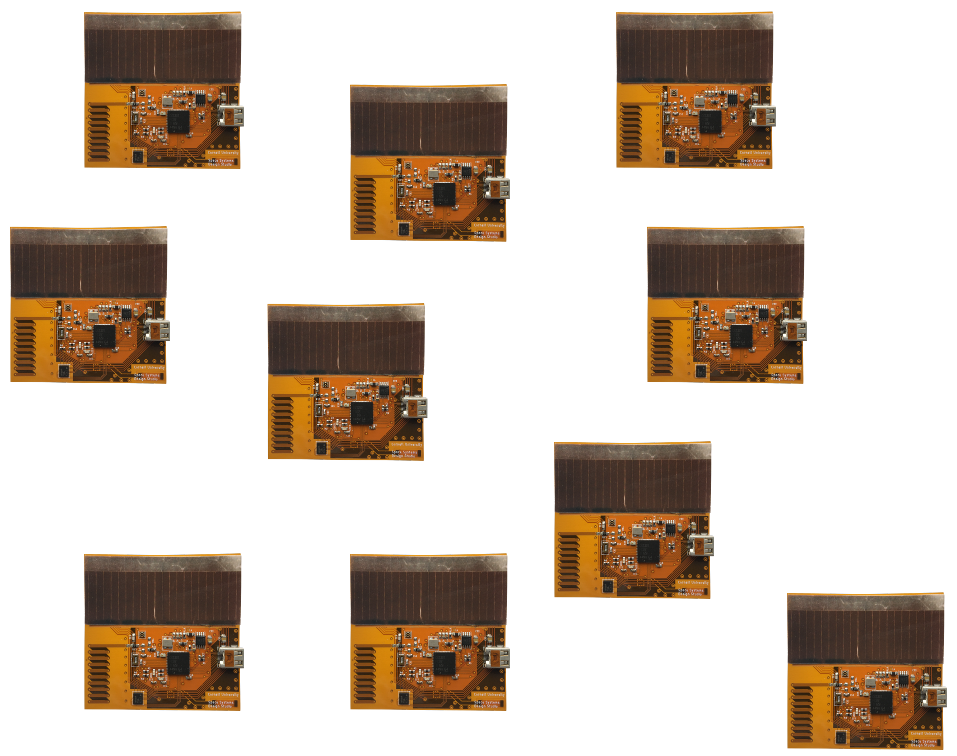


Hubble Space Telescope for 165 years

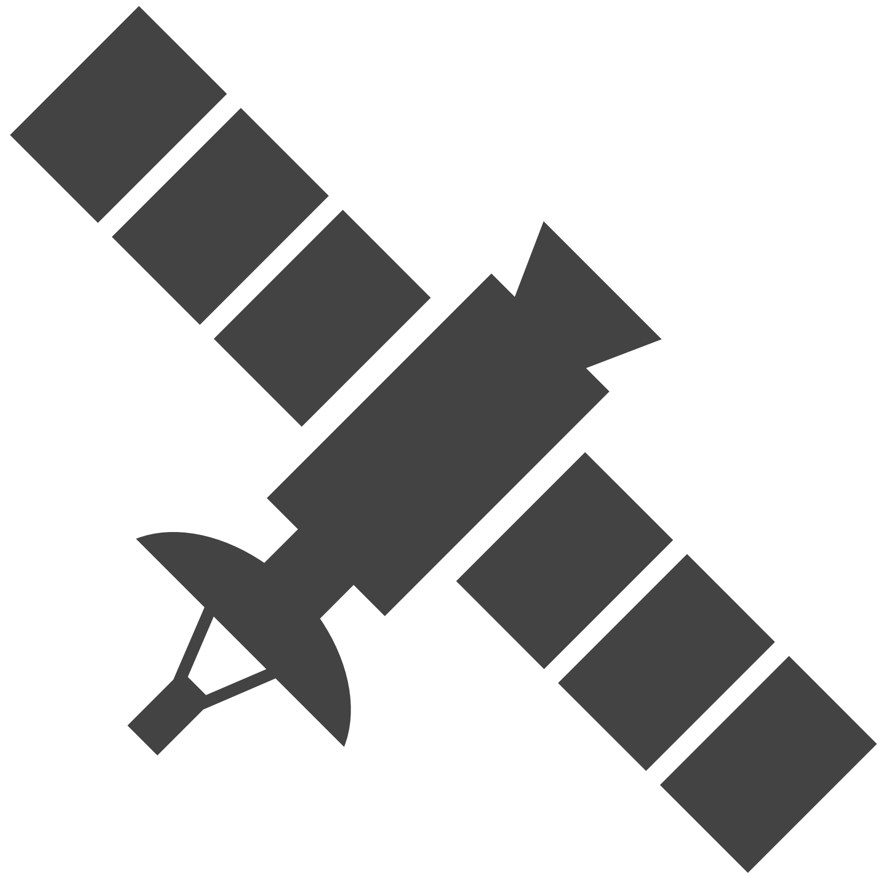
11,110,000g, $2,500,000,000

One Monarch recovered after one week delivers the same amount of data that the Hubble Space Telescope delivers in 165 years, assuming 24/7 downlink.

Equivalent data production:



100 Monarchs recovered after one week
250g, $5000



Landsat 8 for 10 years
2,683,000g, $855,000,000

100 Monarchs recovered after one week deliver the same amount of data that Landsat 8 delivers in 10 years, assuming 24/7 downlink.