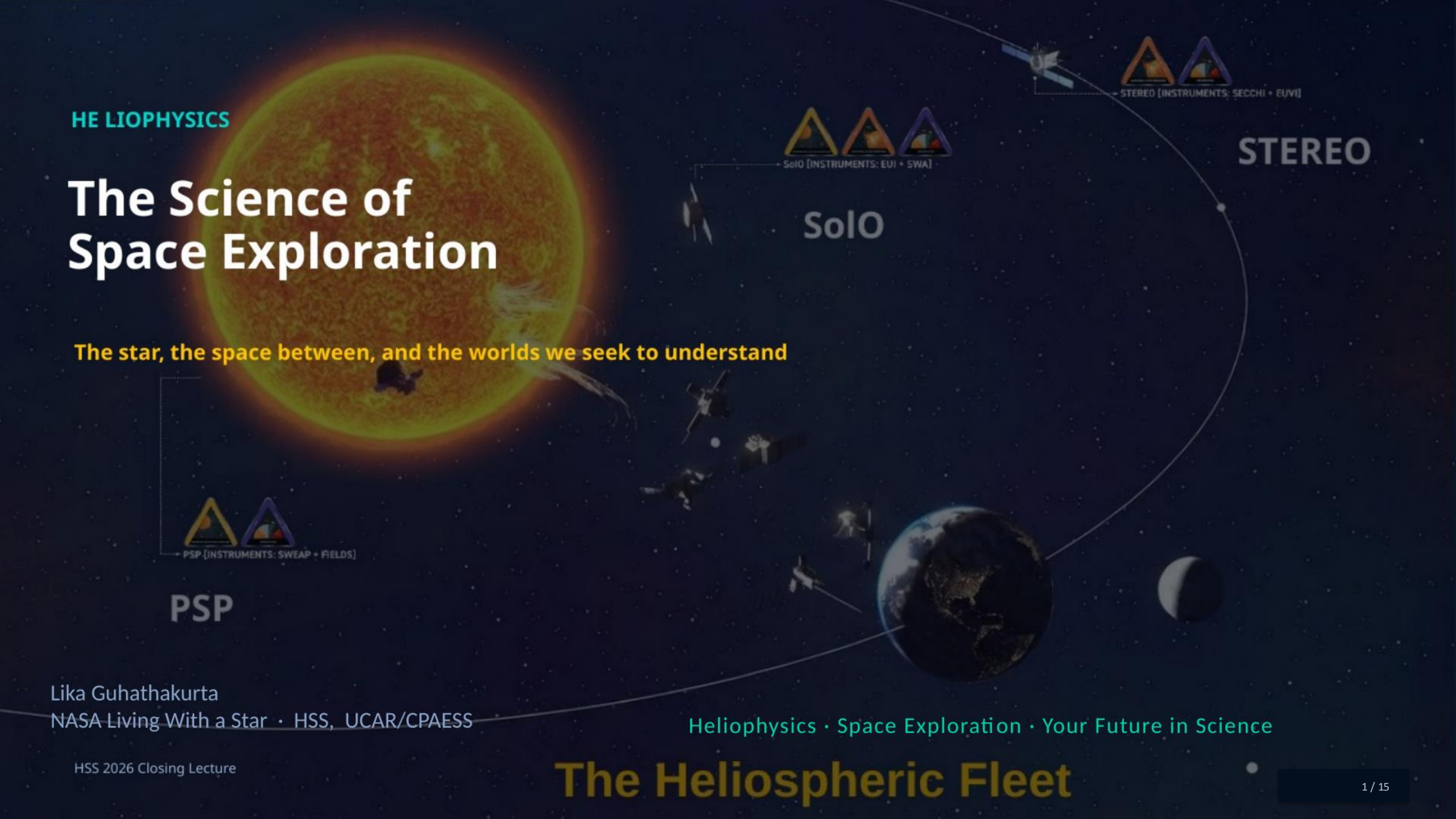
HELIOPHYSICS

The Science of Space Exploration

The star, the space between, and the worlds we seek to understand



Lika Guhathakurta
NASA Living With a Star · HSS, UCAR/CPAESS

Heliophysics · Space Exploration · Your Future in Science

HSS 2026 Closing Lecture

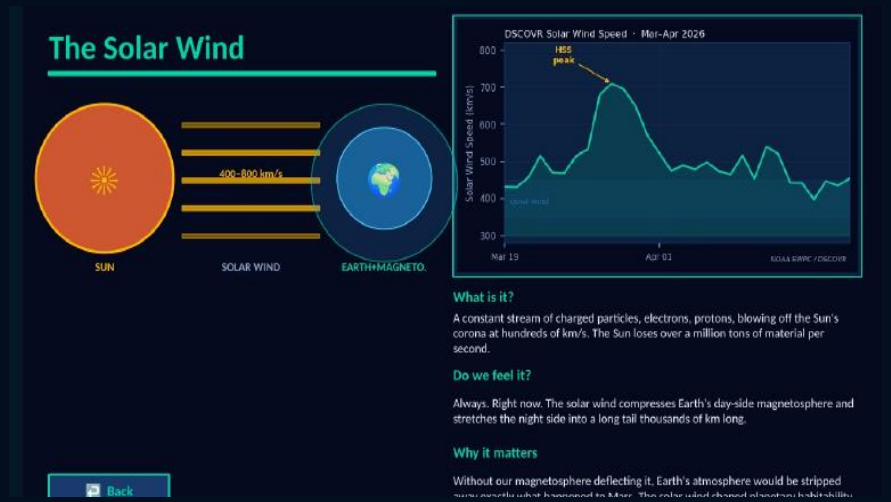
The Heliospheric Fleet

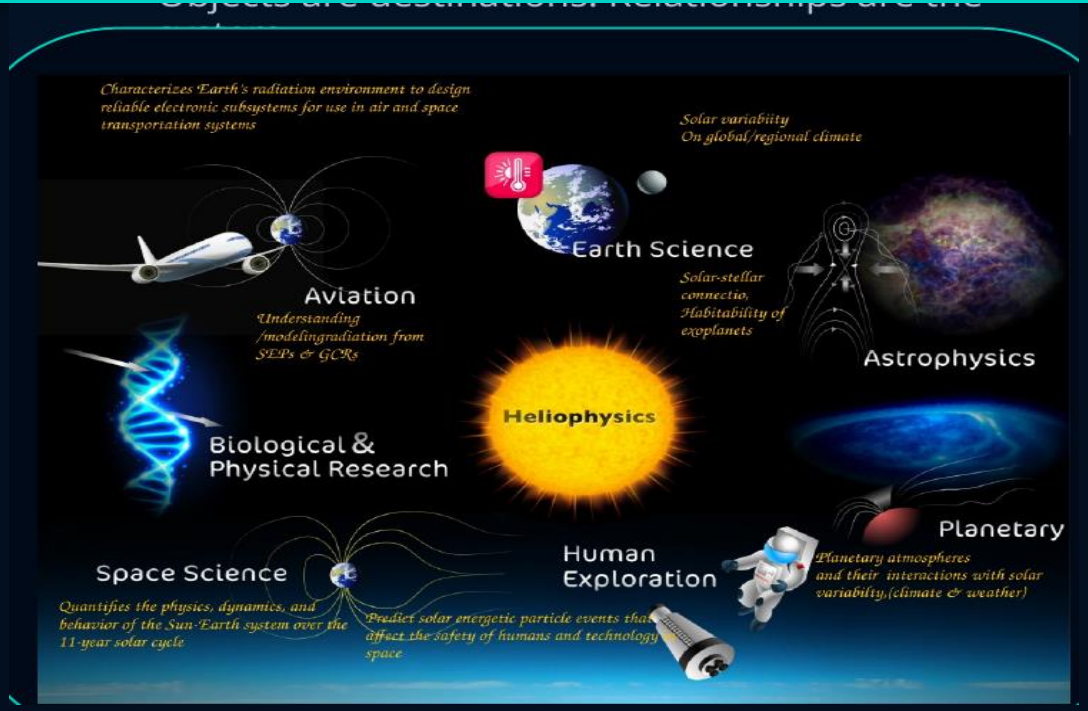
FIRST CORRECTION

Space is not empty

It is the medium through which exploration happens.

Objects are destinations. Relationships are the system





A spacecraft flies through:

plasma
magnetic fields
shocks
turbulence
energetic particles
moving boundaries

A spacecraft flies through relationships, not emptiness.

Question: what state variables must we observe directly before an environment becomes predictable?

What heliophysics is

A hybrid environmental science with its own paradigms — and consequences for exploration.

George Siscoe's discipline-defining frame

- Not simply space physics renamed
- Applied branch: space weather
- Pure branch: universal processes
- Magnetized plasmas + neutrals interacting with bodies and atmospheres

What are heliophysics' Kepler-like laws still waiting to be discovered?

Scientific understanding is an enabling technology

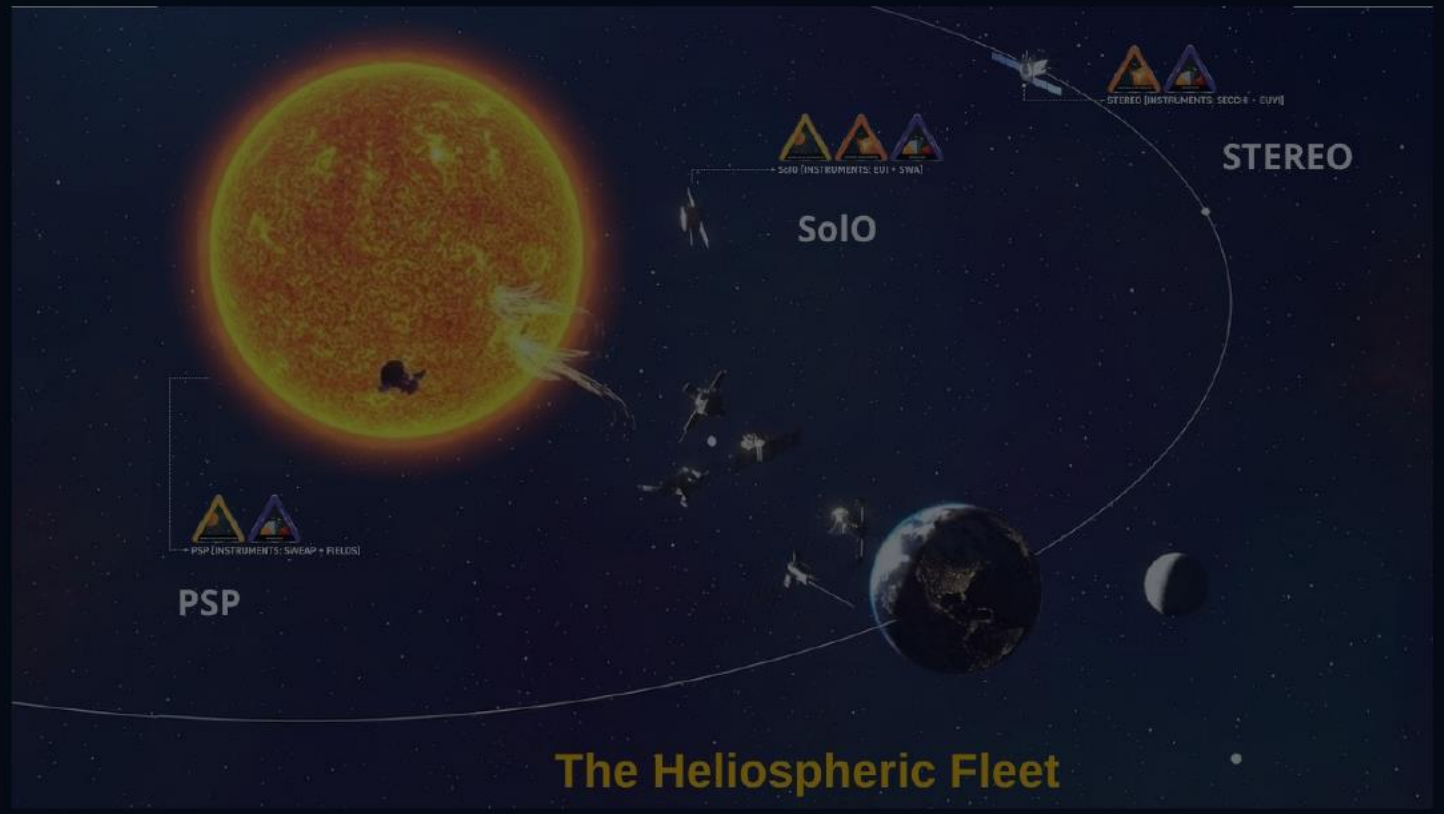
Radiation timing
Storm sheltering
Spacecraft electronics
Orbit drag
Communications
Surface charging
Safe-to-exit decisions

Scientific understanding does not decorate exploration. It changes what becomes possible.

We explore the star and its environment

Parker, Solar Orbiter, SDO: not better pictures, new regimes.

The heliospheric fleet: remote sensing + in situ + context



SDO continuity, magnetic context, multichannel solar evolution

PSP in situ plasma, turbulence, switchbacks near the source

SolO composition, polar views, source-region connectivity

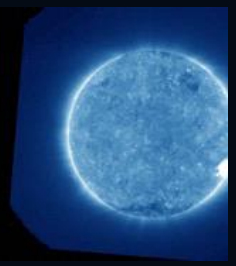
Together they ask where solar-wind organization begins and how energy is converted.

We explore the medium between worlds

From optically thin projection to continuous heliospheric structure.

STEREO: A single line of sight is not 3D

The next frontier in space weather forecasting involves the uninterrupted tracking of storm clouds from the sun to the planets



NASA's STEREO spacecraft and new data processing techniques have succeeded in tracking space weather events from their origin in the Sun's ultra hot corona to impact with the Earth's magnetosphere

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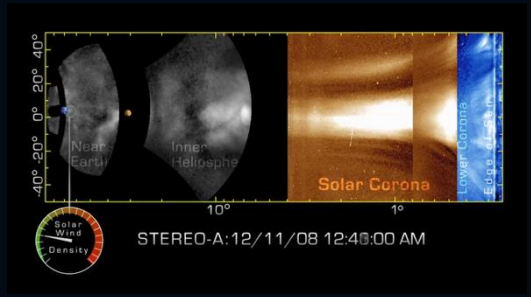
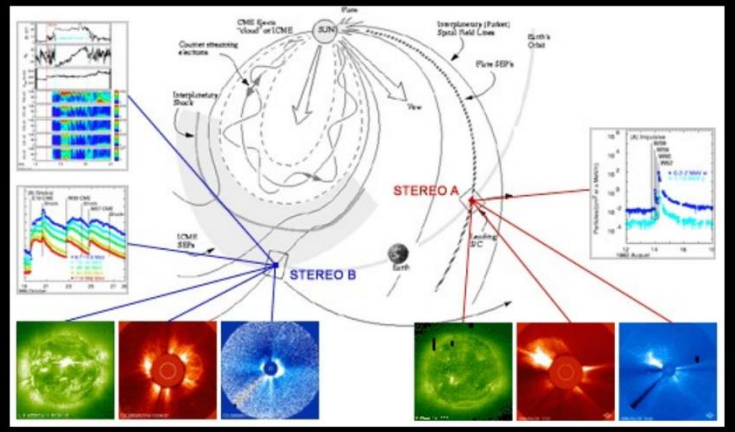


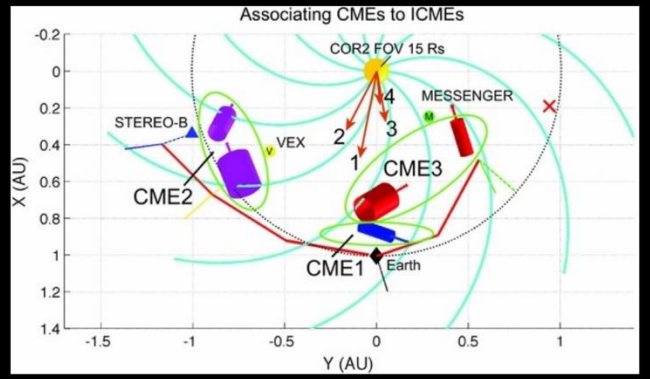
STEREO/SECCHI: tracking CMEs through interplanetary space

While we are imaging the Sun, in-situ detectors on STEREO and ACE measure the solar wind and energetic particle (SEP) signatures of space weather at their locations



Reconstructions of solar-system-wide space weather

Combined with in-situ instruments on planetary missions, (MESSENGER, or ESA's Venus and Mars Express-VEX and MEX), 'reconstructions' of solar system-wide space weather conditions are now possible



Moestl et al., ApJ 2012

STEREO turned projection from an inconvenience into a measurable geometry problem.

PUNCH extends the logic: corona and heliosphere as one observable system.

Interplanetary space weather is exploration of the medium, not just the endpoints.

Where does the uncertainty enter as a CME moves from corona to geospace?

We explore planetary environments

Comparative heliophysics is regime thinking, not copy-paste Earth.

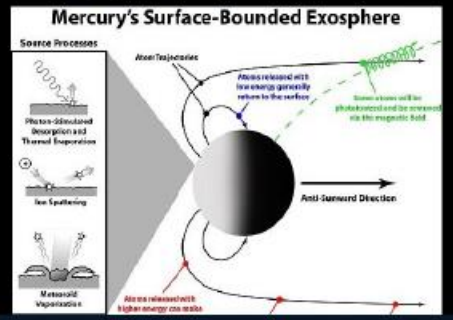
Mercury and Mars: small worlds, exposed boundaries

Space Weather on Mercury

The most ferocious space weather in the solar system is felt on Mercury, the closest planet to the Sun. MESSENGER has observed a highly dynamic magnetosphere with magnetic reconnection events taking place at a rate 10 times greater than what is observed at Earth during its most active intervals.

CME impact on Mercury

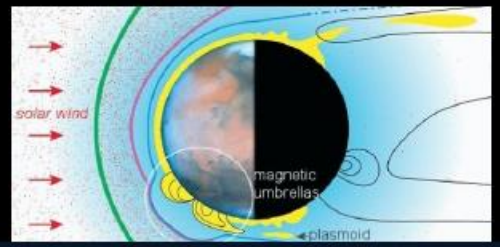
Exactly what we would see is not known. Even garden- variety CMEs may be strong enough to overwhelm Mercury's magnetic field and strip atoms right off the planet's surface. Mercury's comet-like tail of sulfur is likely populated by this process. **If operators know when a CME is coming, special preparations can be made.**



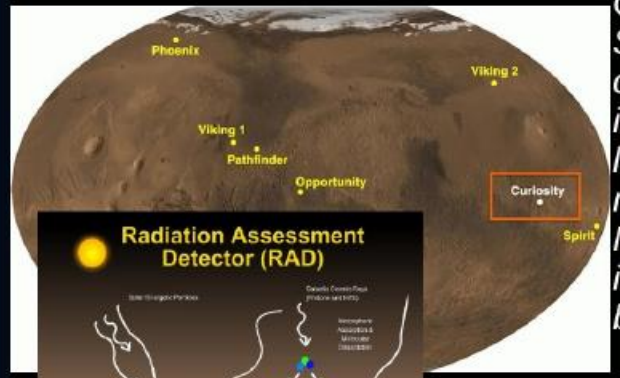
Space Weather on Mars

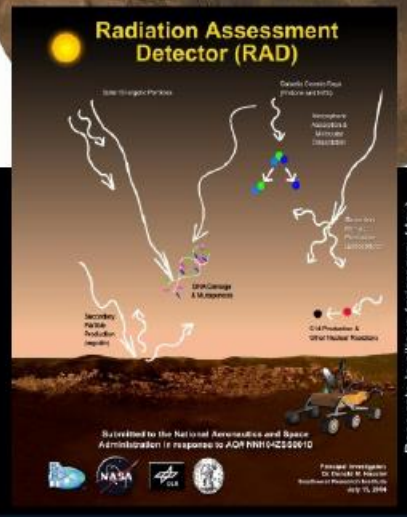
In 1998, MGS discovered that Mars has a very strange magnetic field. Instead of a global bubble, like Earth's, the Martian field is in the form of magnetic umbrellas that sprout out of the ground and reach beyond the top of Mars' atmosphere. These umbrellas number in the dozens and they cover about 40% of the planet's surfce, mainly in the southern hemisphere. When Mars gets hit by a CME, the resulting magnetic storms take place not at the planet's poles but rather in the umbrellas.

One important focus of MAVEN is to determine how CMEs and solar energetic particles alter the upper atmosphere and escape rates. Space weather alerts would certainly advance the goals of missions like this.

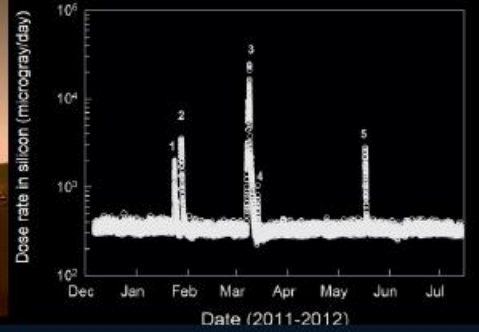


Mars: atmosphere, radiation, surface chemistry





Combinations of SDO, SOHO, STEREO and ACE contextual space weather information with MAVEN local orbital and MSL RAD measurements on the Martian surface are tieing into surface chemistry and biological implications



Images from JPL and SWRI-RAD websites

Mercury and Mars

Same solar wind. Different gravity, fields, surfaces, and atmospheres. The response changes with regime.

Mars as ground truth

MAVEN, MSL/RAD, and contextual solar observations connect atmosphere loss, radiation, and surface chemistry.

For students

Do not ask whether a planet has space weather. Ask what kind of star-planet coupling it permits.

Mercury tests extreme reconnection. Mars tests atmospheric escape. Jupiter tests rotation-dominated magnetospheres.

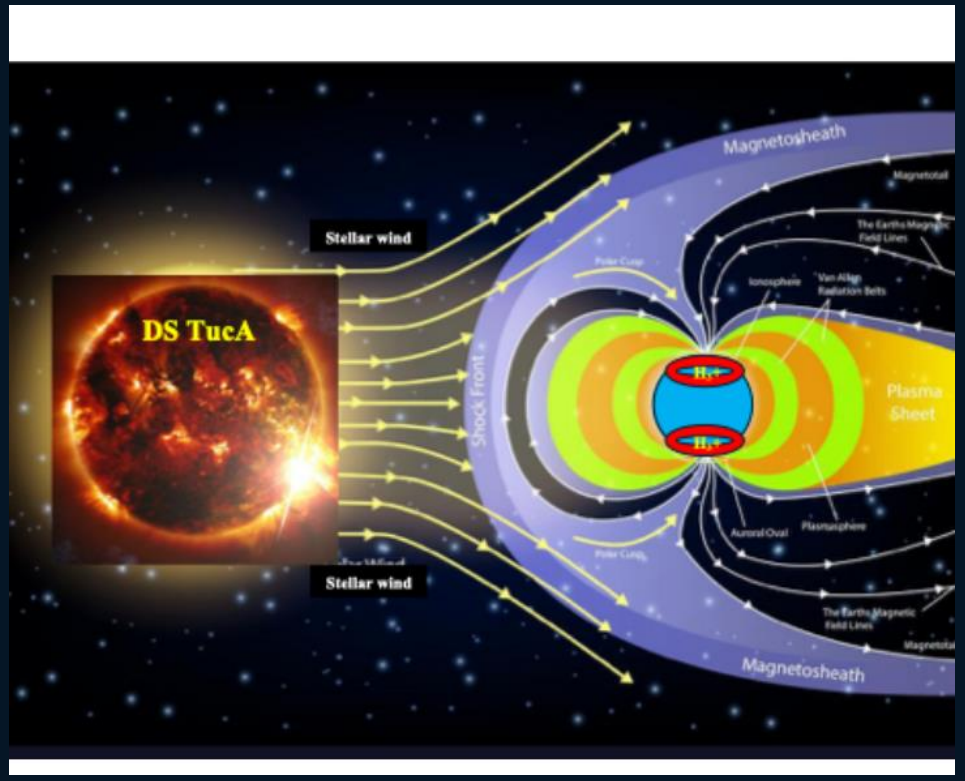
Habitability is a heliophysical question

Goldilocks is not just distance.
It is a star–planet relationship.

STAR ACTIVITY → SPACE WEATHER → ATMOSPHERE SURVIVAL

Can the atmosphere survive the star?

Example: DS TucAb — auroral emission as a possible tracer of star–planet coupling



Stellar wind compresses and powers a planetary magnetosphere/atmosphere system

The environment decides the risk

From astronaut safety to power grids, heliophysics becomes operational knowledge.

Human exploration

Radiation sources: GCRs are persistent; SEPs are sudden, intense, and operationally dangerous.
Operational need: early warning before radiation rises, and safe-to-exit prediction after sheltering.

When can an astronaut come out of shelter?

Infrastructure on Earth

- grid currents
- satellite drag
- GNSS/timing
- aviation
- radiation exposure
- rail / pipelines

DAGGER example: localized geomagnetic perturbation forecasts.
Not just whether a storm arrives, but where, how strongly, and with what uncertainty.

Every additional hour is a decision window.

For an astronaut: safe sheltering. For a grid operator: localized impact.

The physics is connected. The decisions are different.

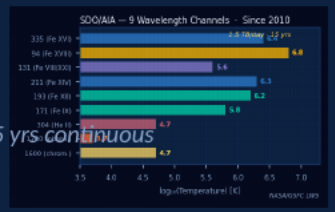
No Single Spacecraft Can Answer the Question.

The Sun-Earth system requires simultaneous, multi-point, multi-scale observation — from inside the corona to the ionosphere.

SDO

NASA LWS · 2010–

Geosync · 1.5 TB/day · 300M+ images · 15 yrs continuous



Continuous EUV/UV/HMI watch of the Sun. AI model (Surya) trained on 9 years of SDO data released Aug 2025. Senior Review FY27 budget: watch this space.

Parker Solar Probe

NASA · 2018–

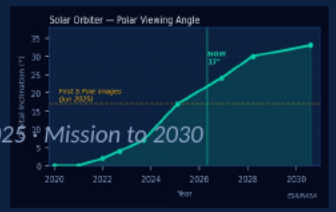
Orbit 27 · 3.8M mi · 430K mph · Funded 2030

Inside the corona where no spacecraft has gone before. Sampling solar wind at its source. Extended mission under NASA review.

Solar Orbiter

ESA/NASA · 2020–

17° inclination · South pole images Jun 2025 · Mission to 2030

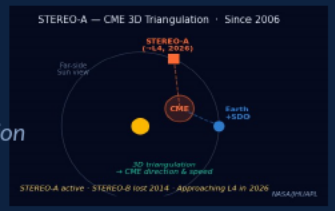


First close-up polar views. Linking solar wind streams to surface source regions. Working with PSP for coordinated inner-heliosphere science.

STEREO-A

NASA · 2006–

En route to L4 · 2026 · 3D CME triangulation

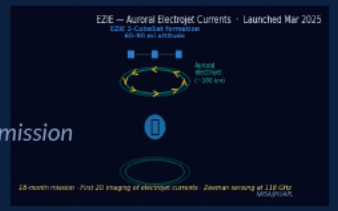


Gives us stereoscopic CME tracking and far-side solar imaging. STEREO-B lost 2014. STEREO-A en route to L4, a strategic vantage point for space weather.

EZIE

NASA · Launched Mar 2025

3 CubeSats · 260–370 mi LEO · 18-month mission

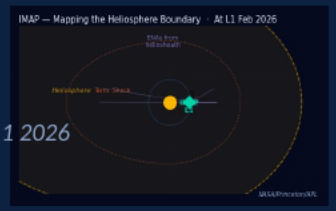


First 2D imaging of auroral electrojet currents, the coupling layer between magnetosphere and ionosphere. Zeeman sensing at 118 GHz. Key gap in Sun-Earth chain.

IMAP

NASA · Launched Sep 2025

At L1 since Jan 2026 · Science started Feb 1 2026



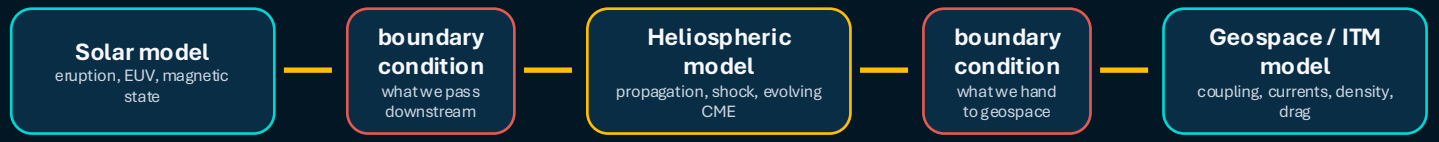
Maps the heliosphere boundary using energetic neutral atoms. Real-time solar wind & SEP data. 30-min advance warning capability for hazardous space weather.

● Active	PUNCH	4 spacecraft · LEO · Imaging CMEs globally · Mar 2025 →
◆ In Dev.	GDC	6-sat constellation · Ionosphere-thermosphere · Launch ~2030s
◐ On Hold	HERMES	Gateway paused Mar 2 · Deployment TBD

THE BOUNDARY CONDITION CAN HIDE THE PROBLEM

Coupling models is not the same as coupling physics

A relay race is not yet a system model.



The L1 handoff is a scientific boundary, not merely a file format.

CISM lesson

Connecting successful domain models can expose assumptions instead of removing them.

Hidden physics

Kinetic processes, reconnection, turbulence, and unresolved structure can disappear inside a boundary.

CCMC lesson

Benchmarks, event suites, metrics, and trusted validation are part of the science.

AI-era warning

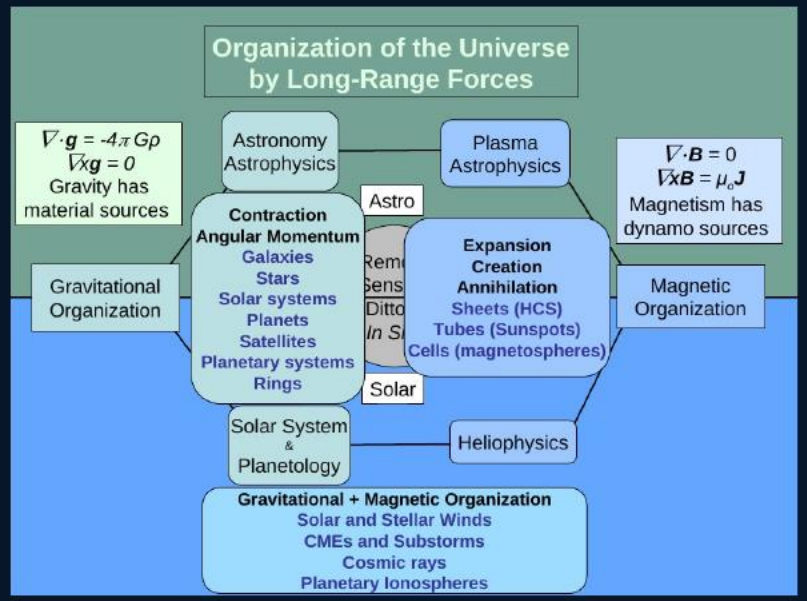
More models will not automatically create more understanding. Trust will come from validation, not beautiful demos.

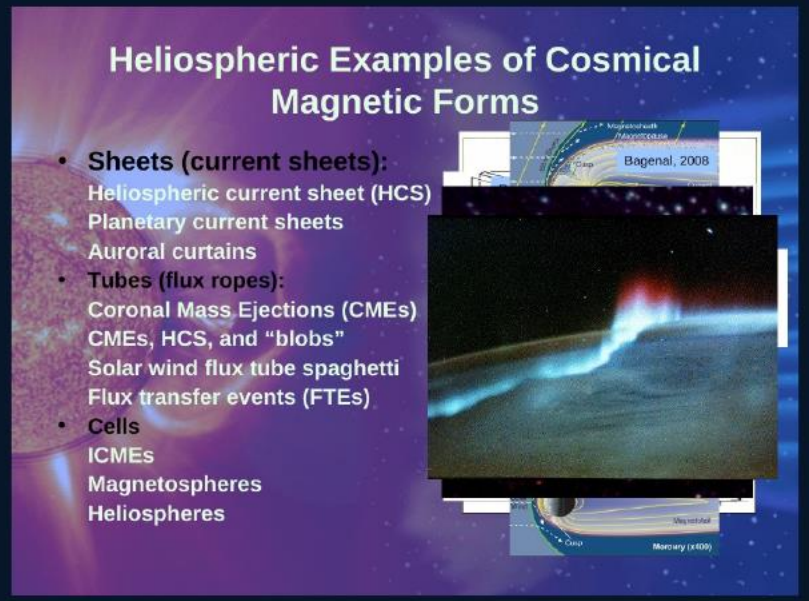
Boundary question

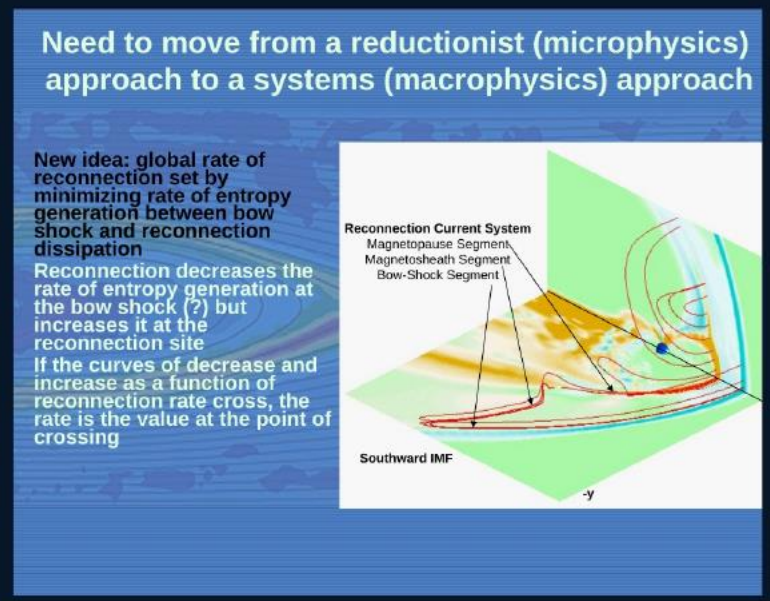
Where does your model stop because the physics is difficult, not because nature stops there?

SAME LAWS, DIFFERENT REGIMES

Universal processes: the deep reason heliophysics travels







Magnetic organization

Fields form sheets, tubes, cells, flux ropes, current sheets, magnetospheres, and heliospheres.

Explosive energy conversion

CMEs and substorms are not identical, but they let us test universal questions about storage and release.

Systems over reductionism

The reconnection rate is not only microphysics; the global system helps set the problem.

Why this belongs in a space-exploration talk

Exploration moves us into new parameter regimes. Universal processes tell us what travels from the corona to planets, labs, and stars.

Student question

What is universal across solar corona, planetary magnetospheres, laboratory plasmas, and stellar environments?

Universality does not mean sameness. It means asking what survives when the regime changes.

AI becomes science only when it earns physical trust

The mathematics is necessary. It is not the transformation.

Representation

Surya
foundation model from the SDO record

Application

HelioLab, DAGGER, FOXES, Karman
real problems, rapid prototypes

Validation

baselines, uncertainty, OOD tests
community benchmarks

Judgment

physical interpretation
human skepticism

AI is very good at looking intelligent. Science requires being correct.

The experiment: distinguish physical learning from statistical imitation.

Question for students: how do we use AI to discover heliophysics, not merely demonstrate machine learning?

NOT SLOGANS, RESEARCH PROGRAMS

Questions worth inheriting

Do not inherit our answers passively. Inherit the assumptions inside them.

Predictability

What is predictable, at what scale, with what lead time?

flares · CME arrival · Bz · geomagnetic response

Boundary physics

Which boundary condition hides the physics?

coronal field → heliosphere → magnetosphere → ITM

Scale coupling

How does kinetic physics organize global behavior?

current sheets · reconnection · turbulence · particles

Trustworthy AI

What experiment distinguishes physical learning from statistical imitation?

Surya · DAGGER · FOXES · Karman · OOD events

Carry these forward, or replace them with better ones.

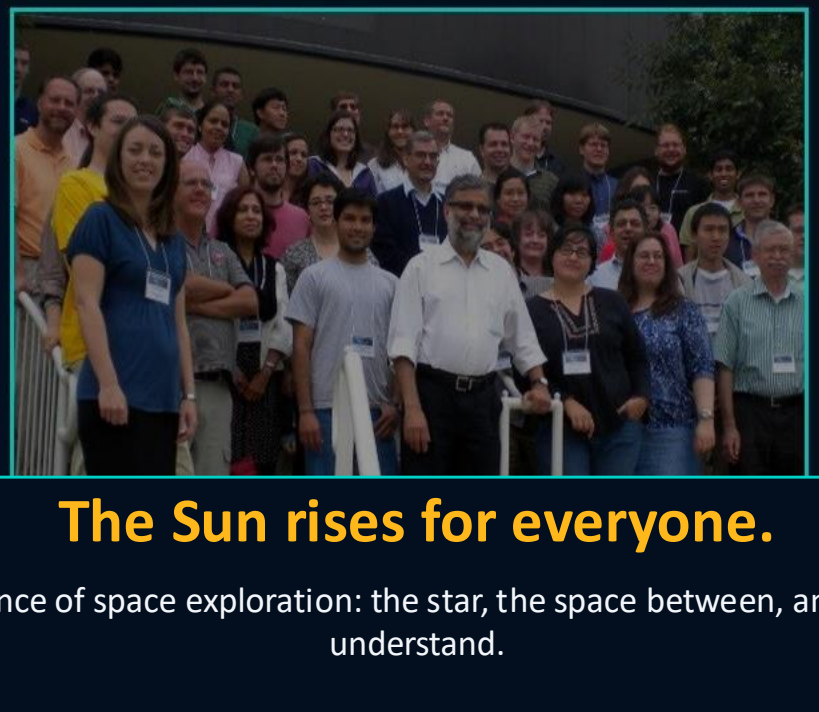
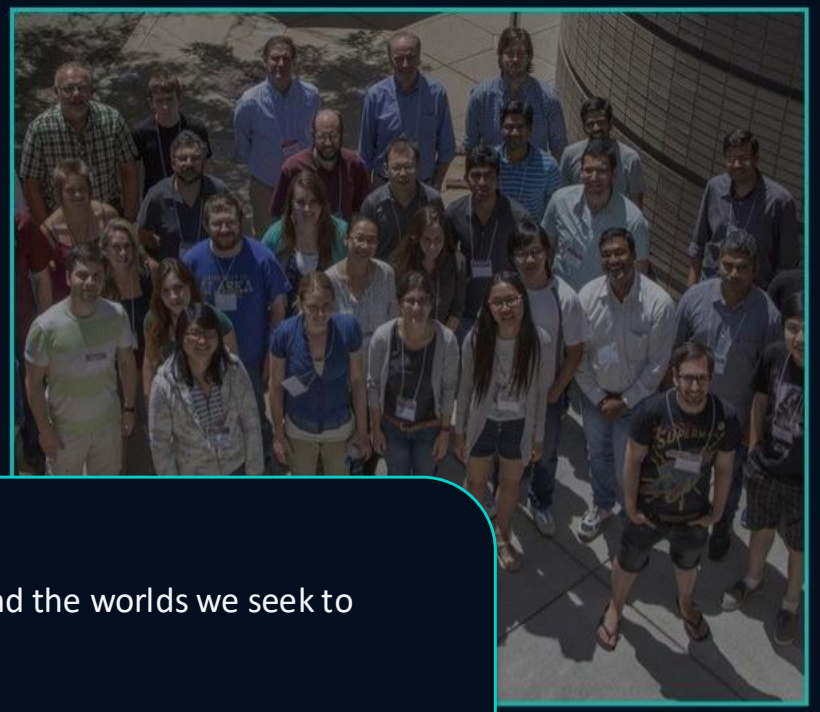
HSS became a global community

HSS by the numbers

2007	Summer School launched
613	students educated to date
28 / 141	2025 cohort / applications
41 hrs	2025 instructional content
18 + 4	lectures + lab activities

Education scales through people, not buildings.

Two decades of HSS seeded a distributed scientific network fluent across heliophysical boundaries.

The Sun rises for everyone.

Heliophysics is the science of space exploration: the star, the space between, and the worlds we seek to understand.

Programs may pause. The questions do not. Choose the questions.