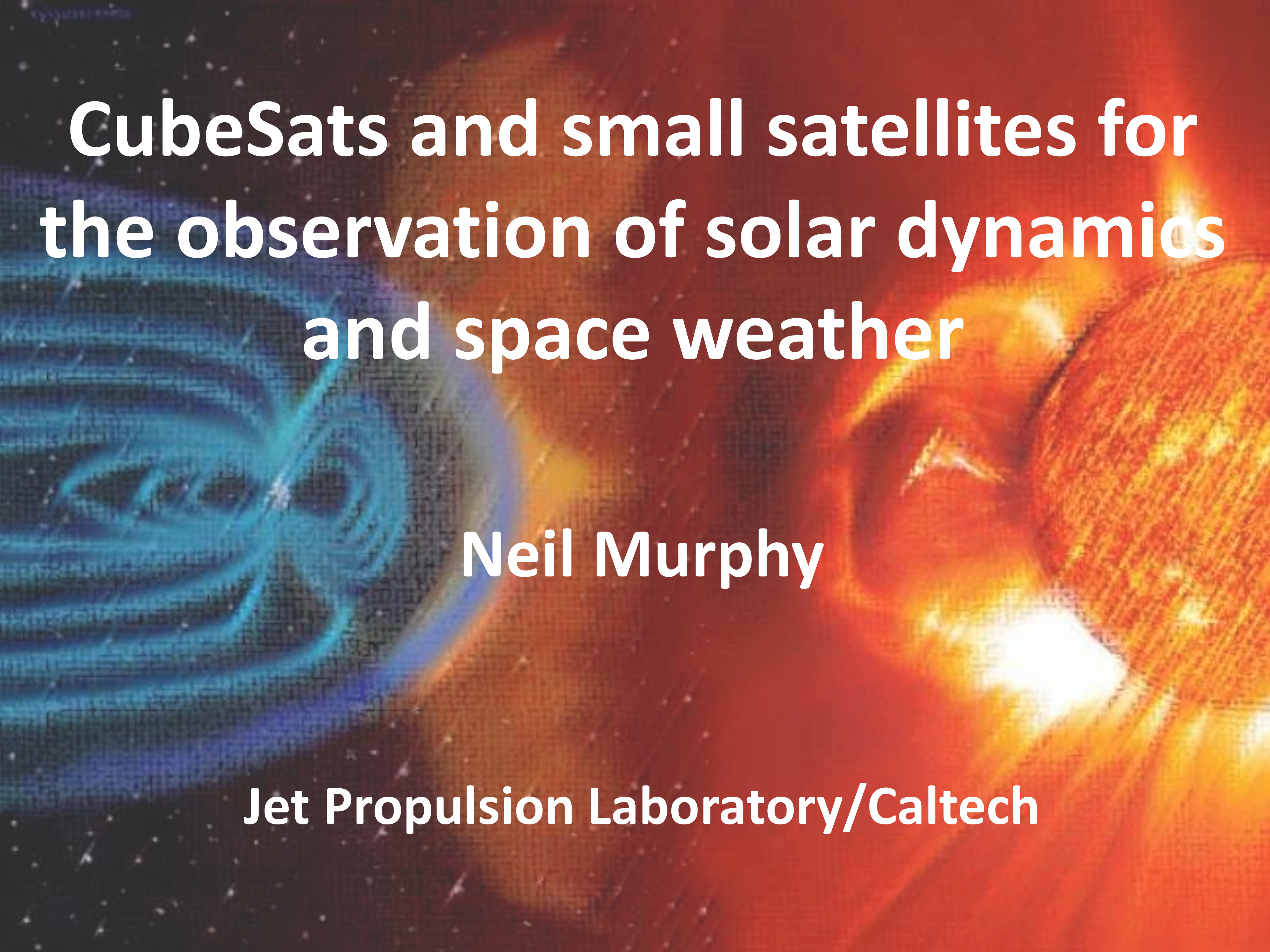


CubeSats and small satellites for the observation of solar dynamics and space weather

Neil Murphy

Jet Propulsion Laboratory/Caltech

A starting point…

Keck Institute for Space Studies (KISS) held two ‘small-spacecraft’ workshops in 2012:

“to explore how <u>small satellite systems</u> can uniquely enable new discoveries in space science. The disciplines studied span astrophysics, heliophysics, and planetary science”

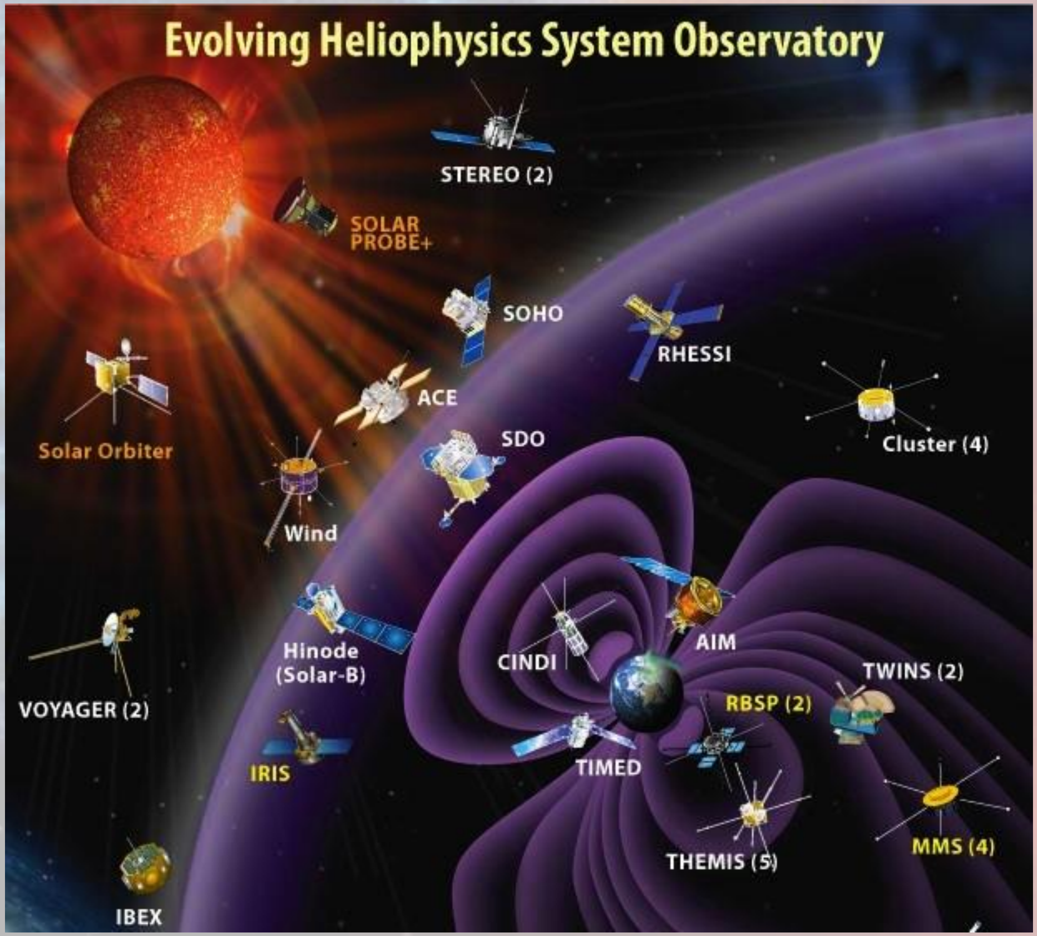
What is a CubeSat?

A nano-spacecraft, based on a standard size (multiple of ‘1U‘ = 10 x 10 x 10 cm) and launch interface

Currently u p to 6U systems have plentiful launch opportunities

Understanding the impacts of solar variability

Studying and ultimately forecasting space weather requires distributed measurements over a wide range of scales (space and time), both within the magnetosphere, and from beyond earth orbit



- To improve our understanding of the processes involved
- To collect data from multiple vantage points to assimilate into models
- To provide local situational awareness for key assets (e.g. Moon, Mars)

Diverse observation targets

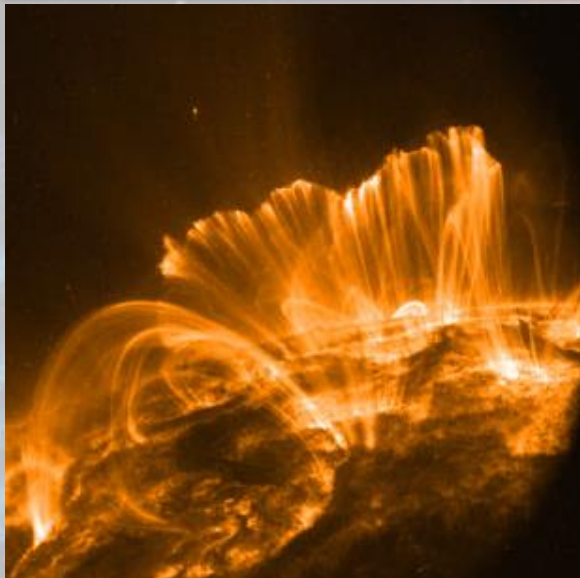


Figure 1.2: Transition Region And Coronal Explorer (TRACE) image of the solar corona illustrate the dynamic Sun.

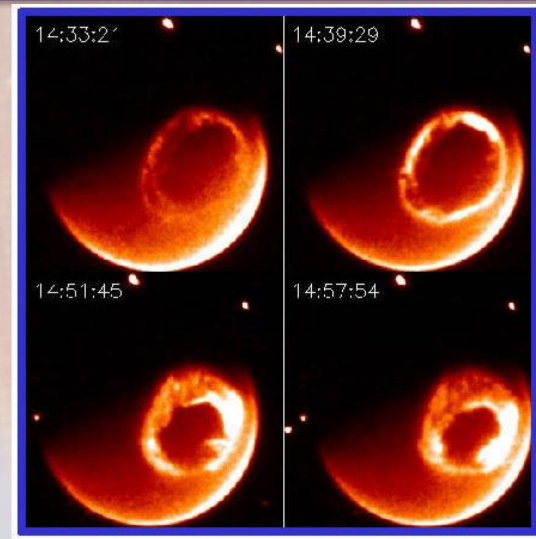
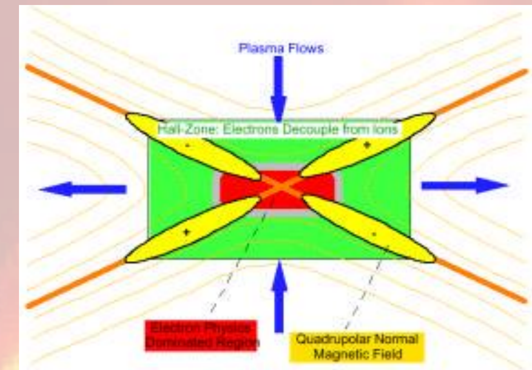
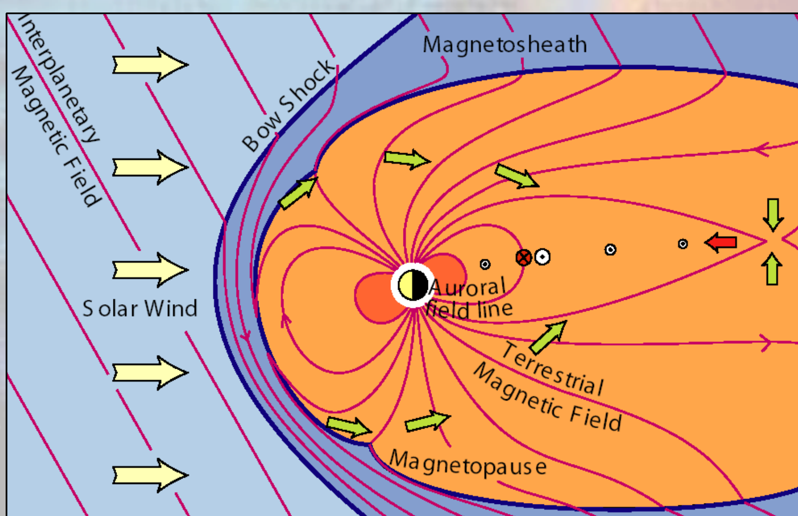


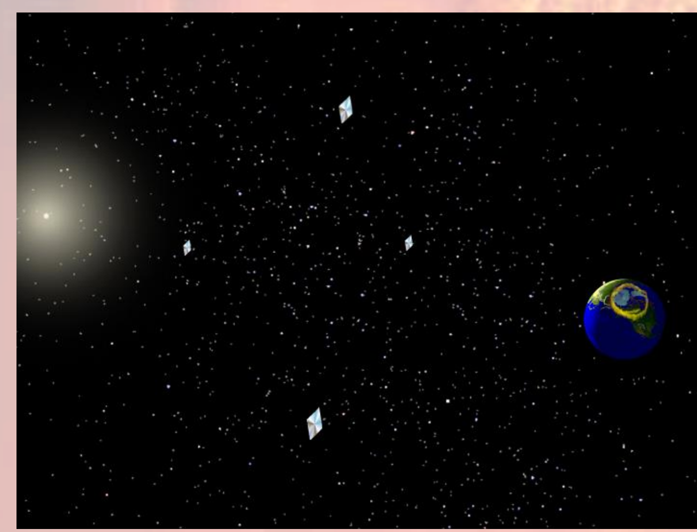
Figure 1.3: Imager for Magnetopause-to-Aurora: Global Exploration (IMAGE) images of the Earth's auroral oval during a powerful geomagnetic storm.



Small scale processes



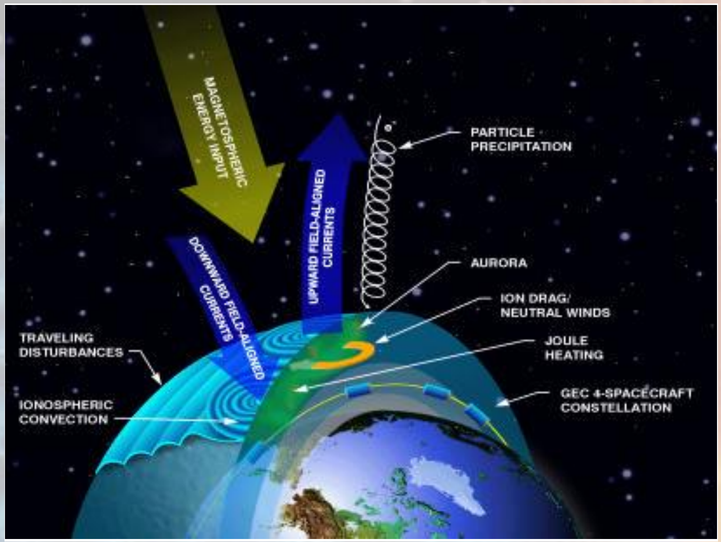
magnetospheres



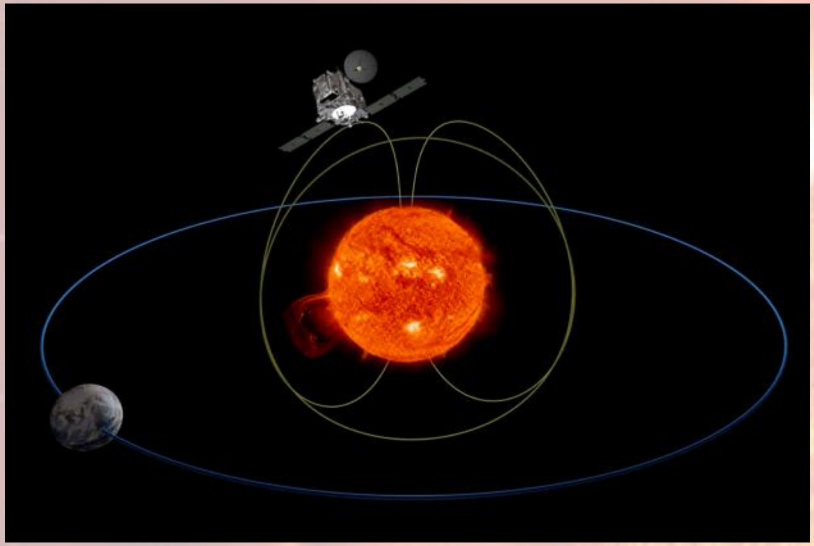
Solar wind

Existing mission concepts – in-situ and remote sensing

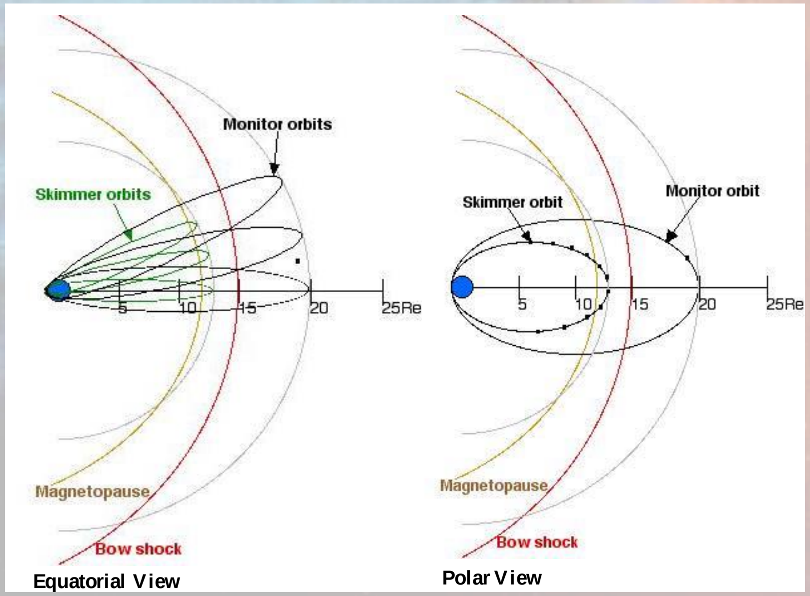
Geospace Electrodynamics Connections



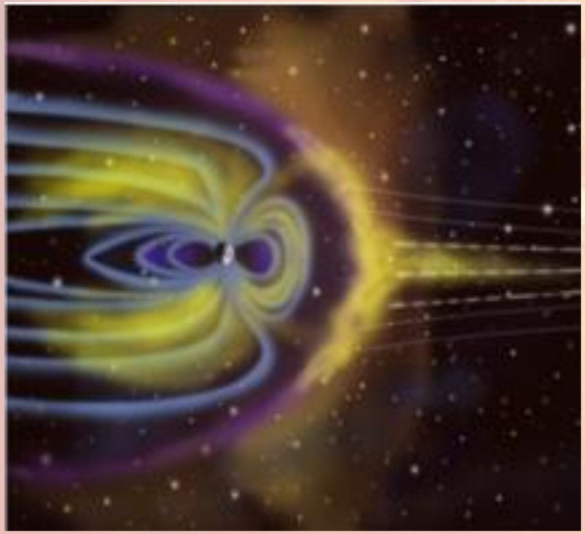
Solar Polar Imager



Dayside Boundary Constellation



MagCon



Space Weather with CubeSats

- Many of the required instruments can be accommodated on CubeSats
- They naturally support constellation architectures
  - Via individual launches and dedicated constellation missions
- Can produce an architecture that is evolvable
  - Capabilities can be expanded or upgraded regularly
  - Constellation lifetime is much longer that the lifetime of an individual element
  - The system is more reliable than its individual components

Space Weather with CubeSats

- Why use CubeSats?
  - Constraints on mass and volume may not be optimum, but this is significantly outweighed by rapid access to space (more than 100 launches per year, some with C3>0)
- Development times are short (as little as 18 months),
- Supports maturation of instrument and s/c technology
- Supports the development of instrument scientists and engineers

INSPIRE

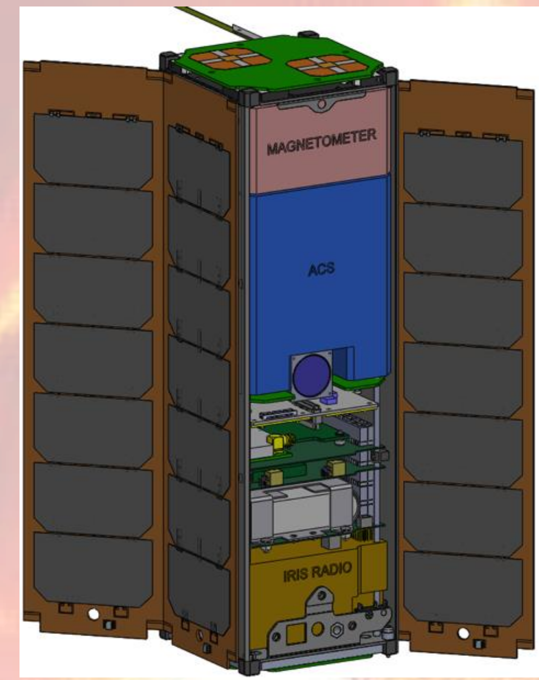
PI: Andrew Klesh (JPL)

(Interplanetary NanoSpacecraft Pathfinder In a Relevant Environment)

The first interplanetary CubeSat

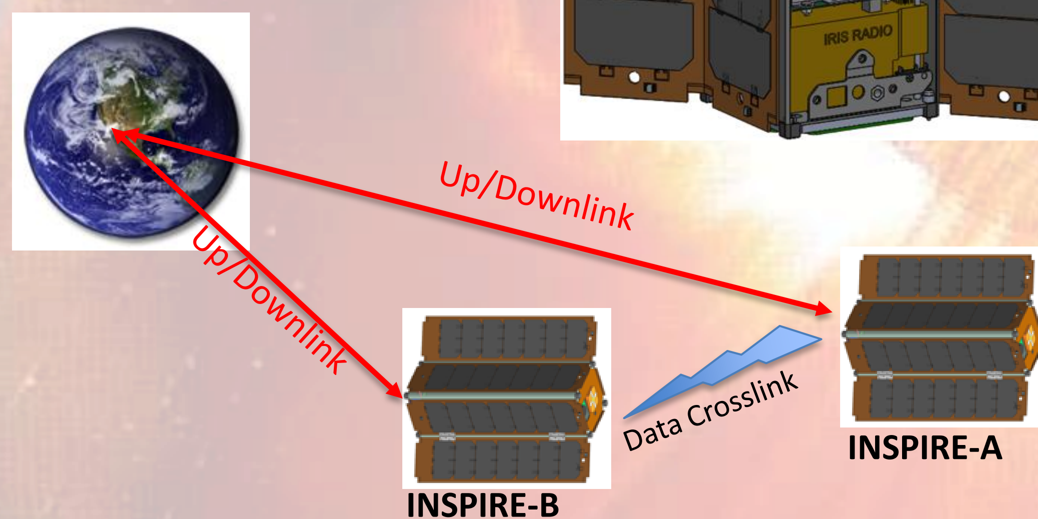
Mission Objectives

- Demonstrate and characterize key nano-spacecraft technologies: telecom, NAV, C&DH, and s/c- s/c relay communications
- Demonstrate science utility with compact science payload (Magnetometer, Camera)



Mission Concept

- Launch two 3U CubeSats as a secondary payload on an Atlas V out of Earth orbit
- JPL-built spacecraft, in partnership with University of Michigan, University of Texas Austin, and CalPoly/Tyvak. Ground stations at U. Michigan and Goldstone.



INSPIRE Design Overview

Overview:
Volume: 3U (10x10x30cm)
Mass: 3.8 kg
Power Generation: 20 W
Data Rate: 62-64,000 bps

Software:
Developed in-house

I&T:
JPL In-house S/C I&T, CalPoly P-Pod/Launch Integration

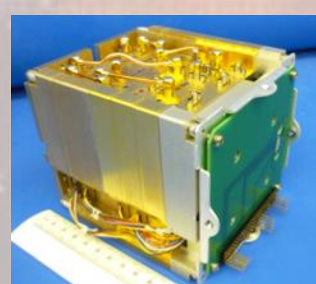
Operations:
DSN, DSS-13 (JPL), & Peach Mountain (U. Michigan)

S/C components will provide ***the basis for future high-capability, lower-cost-risk missions*** beyond Earth

INSPIRE will be the ***world's first deep-space CubeSats***

Cold-Gas ACS (U. Texas)

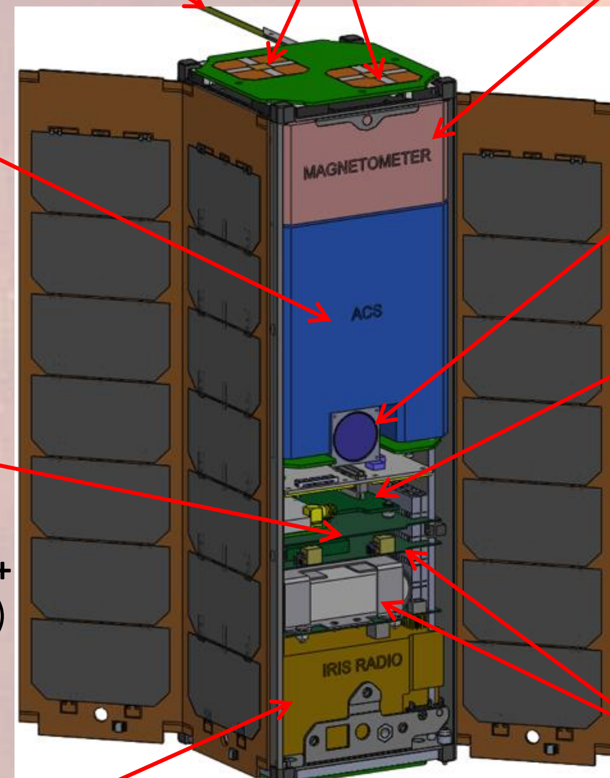
C&DH + Watchdog Board + Lithium UHF (U. Michigan)



Nav/Comm X-Band Radio (JPL)

UHF Antenna

X-Band Patch Antennas (JPL) [two sets]

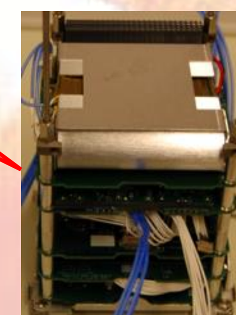


Solar Panels + Structure (Pumpkin)

Helium Magnetometer (JPL/UCLA)

Star Tracker (Blue Canyon)

Processing Board (CalPoly)



Electrical Power System + Battery Board (U. Michigan)

Three generations of Helium magnetometers

Cassini 1996 –

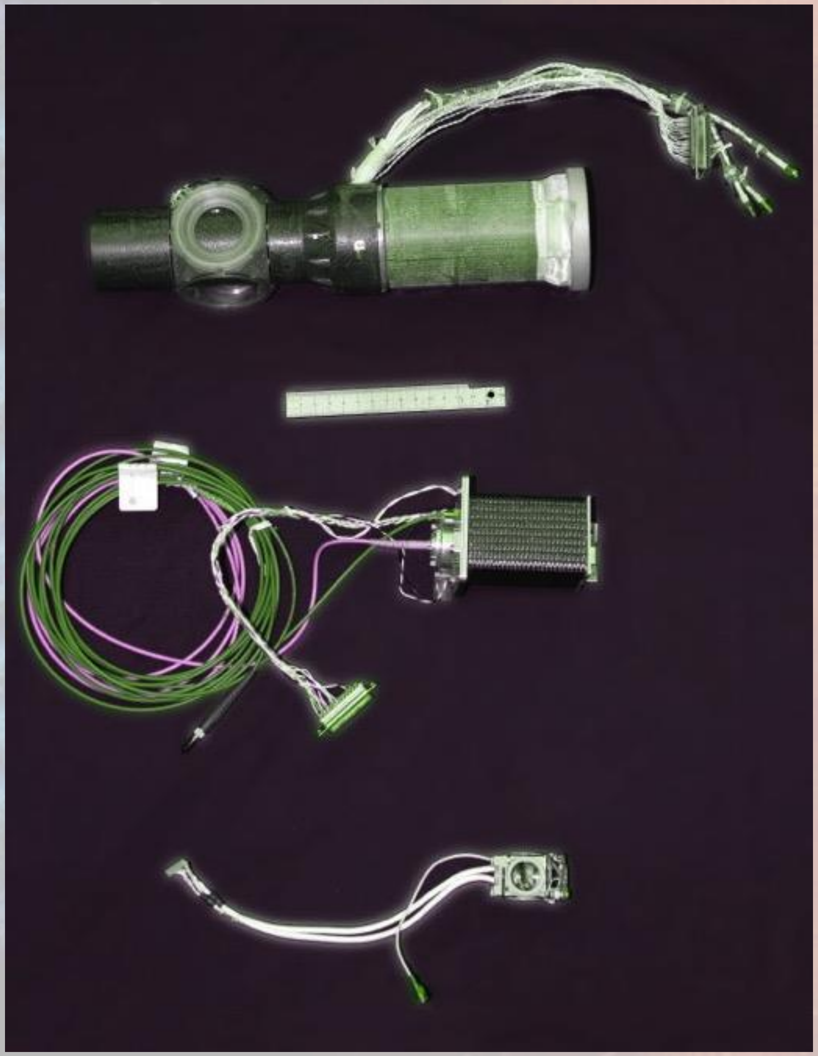
sensor mass ≈ 800g

Three generations of Helium magnetometers

Cassini 1996 –
sensor mass ≈ 800g

Dynamo 2011 –
sensor mass ≈ 230g

Three generations of Helium magnetometers



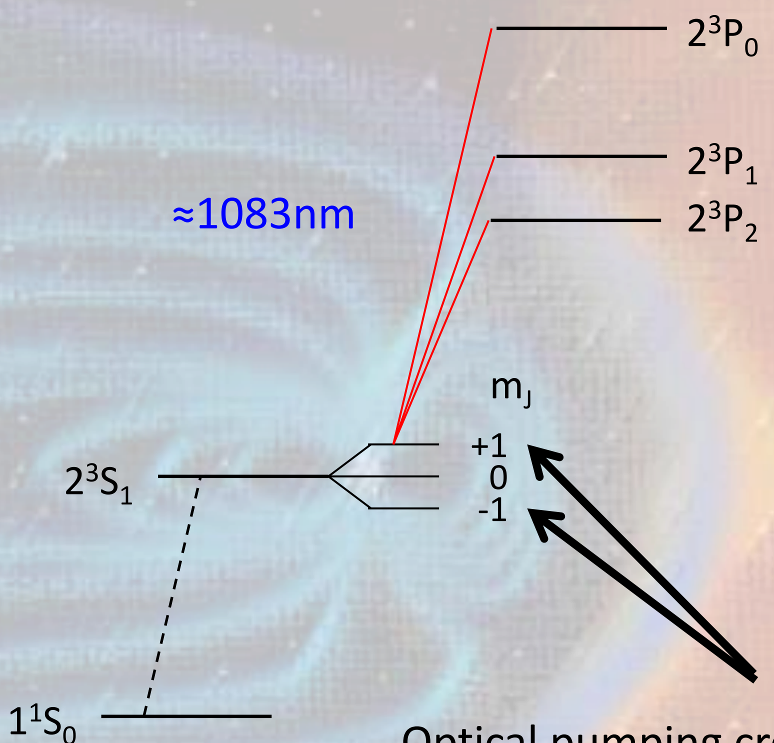
Cassini 1996 –
sensor mass ≈ 800g

Dynamo 2011 –
sensor mass ≈ 230g

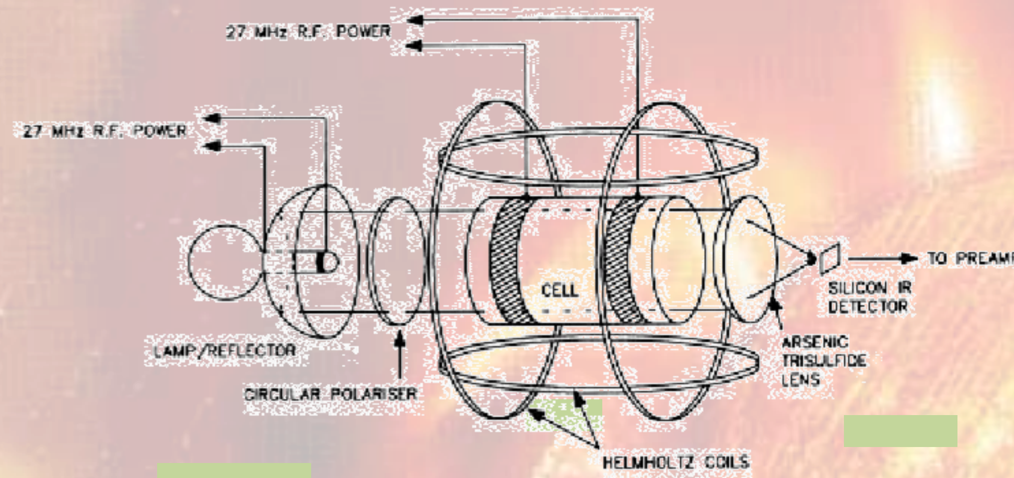
INSPIRE 2014 –
sensor mass ≈ 95g

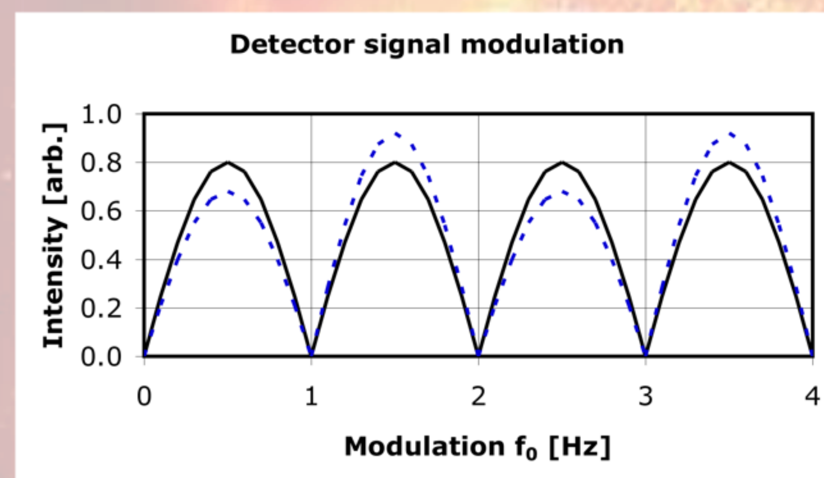
Optically Pumped Helium Magnetometer

He atom energy levels



Optical pumping creates an imbalance in these two metastable energy levels, which depends on the field direction



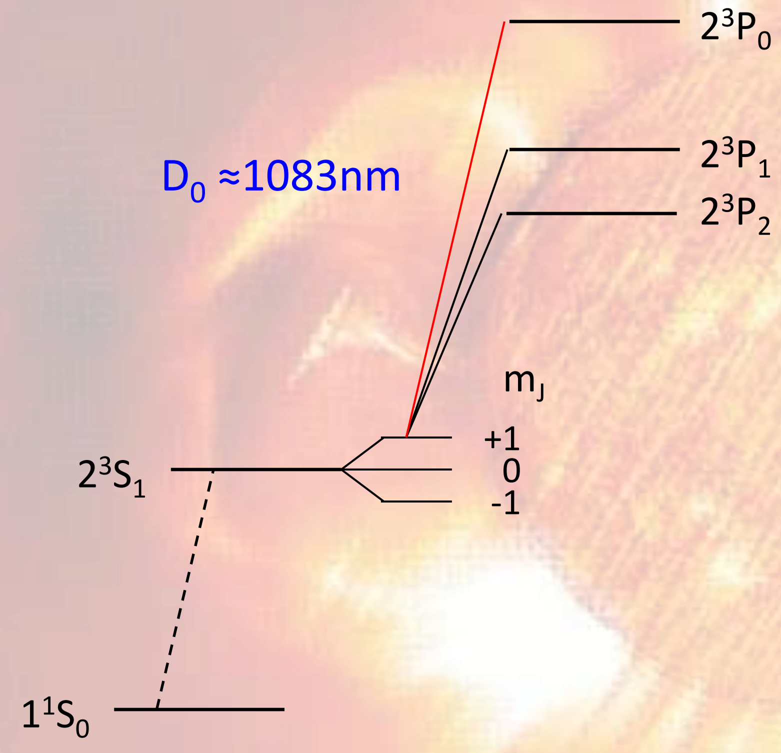


Optically Pumped Helium Magnetometer

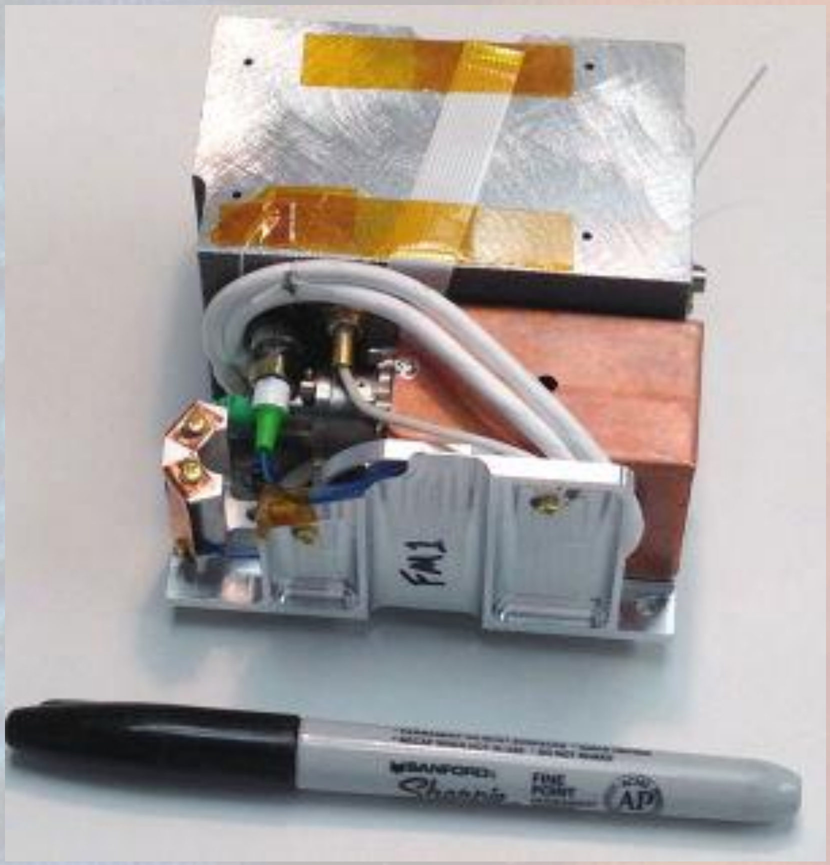
The laser pumps just the D_0 line (the traditional lamp pumps all three)

Because of this, laser optical pumping is much more efficient, leading to higher sensitivity or smaller sensor

Laser diode is housed with the instrument electronics, coupled to the sensor via an optical fiber



The INSPIRE vector helium magnetometer (VHM)



Main goal for the VHM development was technology maturation

1/2U volume
Weighs 436g (sensor 95g),
Power consumption ≈> 3W
(depends on TEC)

Led to the development of instruments for the CuSP and Europa missions

Other missions

Science with CubeSats:

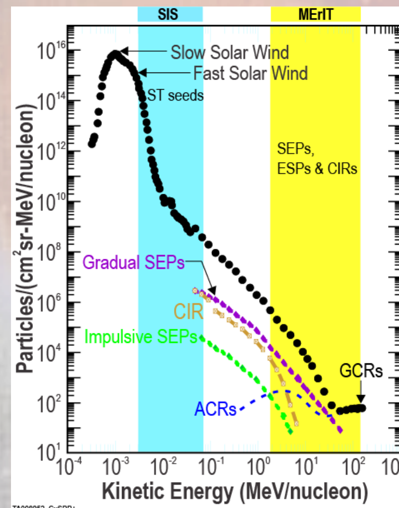
CuSP – currently funded

L5 – more aggressive concept

CubeSat mission to study Solar Particles: CuSP PI: Mihir Desai

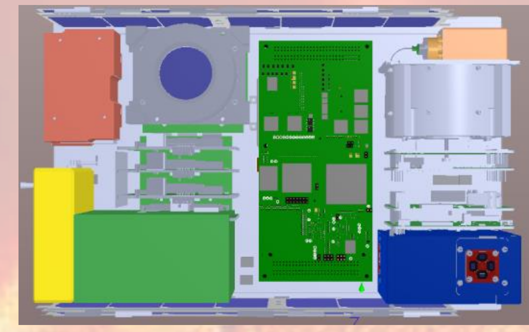
Mission Goals

- Study the sources and acceleration mechanisms of solar and interplanetary (IP) particles near-Earth orbit
- Support space weather research
- Increase TRL of SIS

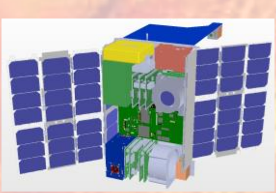


CubeSat

Instruments and systems layout



CuSP in its flying configuration

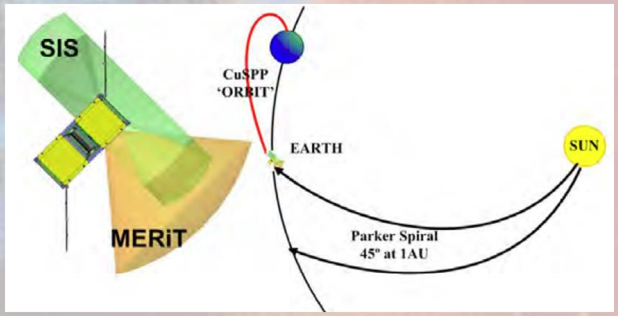


Mission Description

6U CubeSat Payload:

- Suprathermal Ion Spectrograph (SIS) - SwRI
- Miniaturized Electron Proton Telescope (MERiT) - GSFC
- Vector Helium Magnetometer (VHM) - JPL

3-axis Stabilized CubeSat Bus: SwRI avionics with BCT ADCS and thruster; Deployable Solar Arrays, Batteries: Clyde Space; Deep Space XPDR and Antennas: JPL; Ground Station: DSN



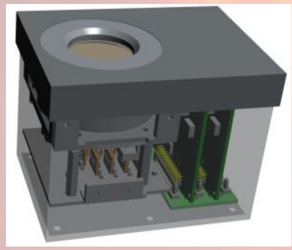
Co-Is: F. Allegrini (D-PI), E. R. Christian, S. Kanekal, J.M. Jahn , S. Livi, N. Murphy, K. Ogasawara

Collaborator: D. J. McComas

PM: M. Epperly & J. Ford / SE: D. George

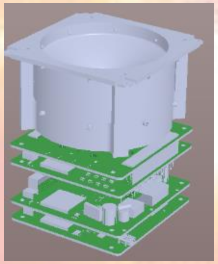
Payload

MERiT



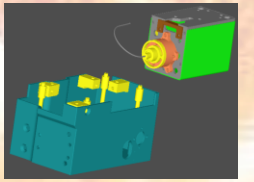
Measures ~100 keV–3 MeV electrons, ~2–40 MeV/n protons and He, and ~5–150 MeV/n C-Fe at 60 s resolution

SIS



Measures spectral and angular distributions of ~3–70 keV/q ST ions at ~60 s resolution.

VHM

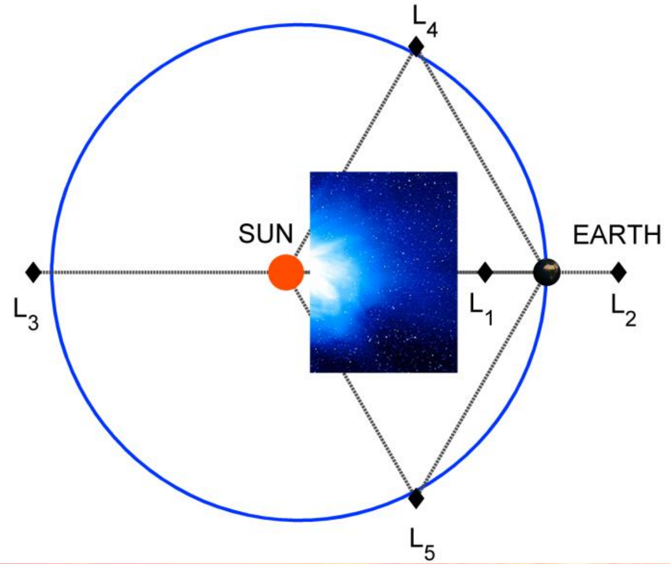


Measures magnetic field vectors to <25 pT/√Hz at 12 s resolution

L5 mission using a fractionated architecture

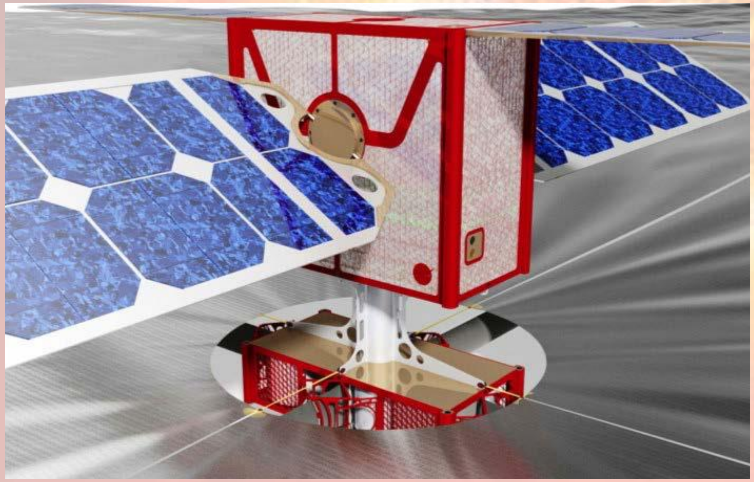
A five s/c swarm of 6U cubesats (**Liewer et al, 2013**)

- Common Subsystems - Solar Sail (8m in 2U), Avionics, ADCS, Power, Communication (2U)

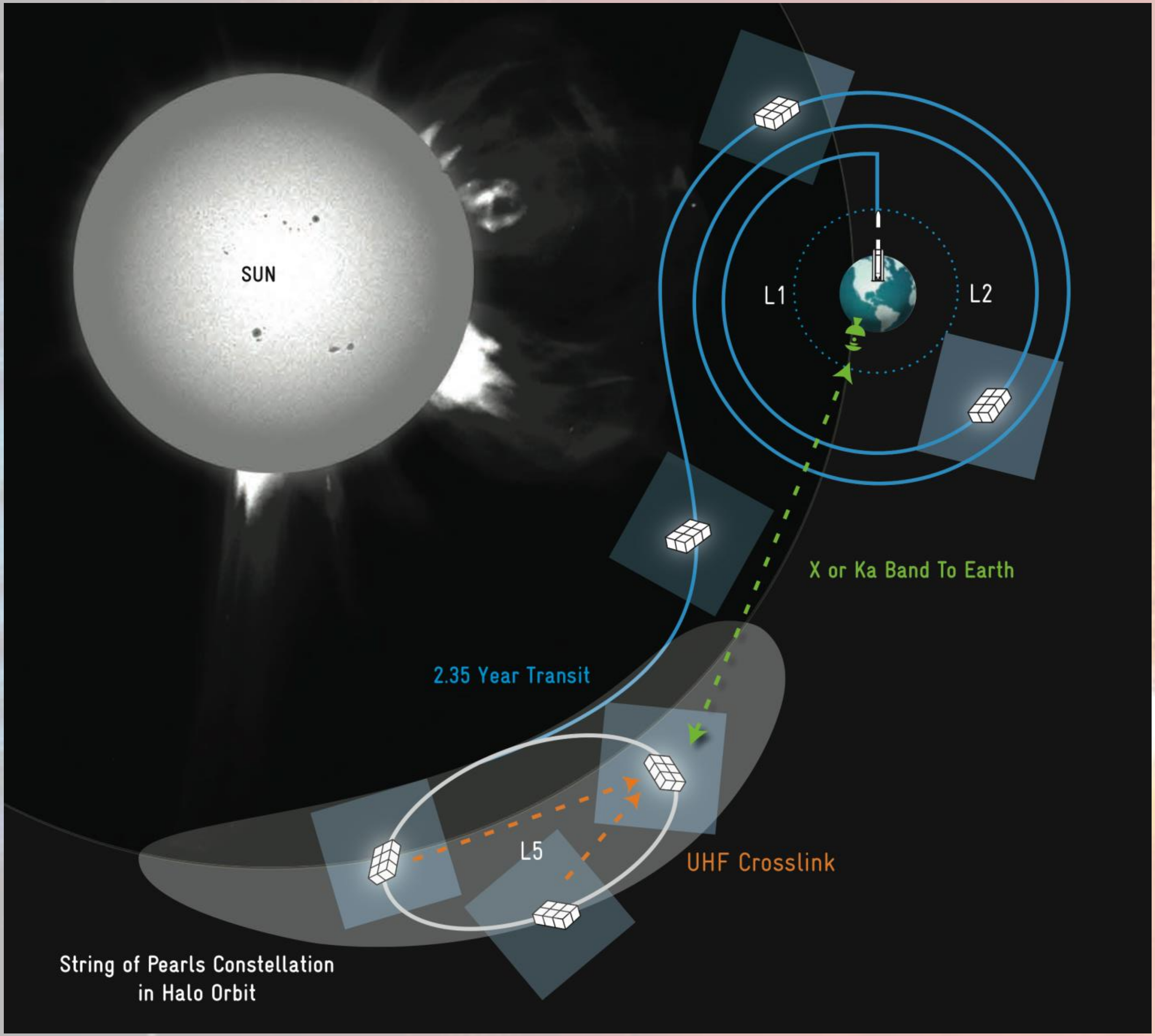


The unique payloads of the five sailcraft, each require the remaining 2U.

- Spacecraft 1: **Relay spacecraft** (3-axis stabilized).
- Spacecraft 2: **Heliospheric Imager** (3-axis stabilized).
- Spacecraft 3: A **magnetograph** (3-axis stabilized).
- Spacecraft 4: A solar **wind plasma instrument** and **magnetometer** (spin stabilized).
- Spacecraft 5: An **energetic particles** instrument and **magnetometer** (spin stabilized).



Fractionated L5 mission

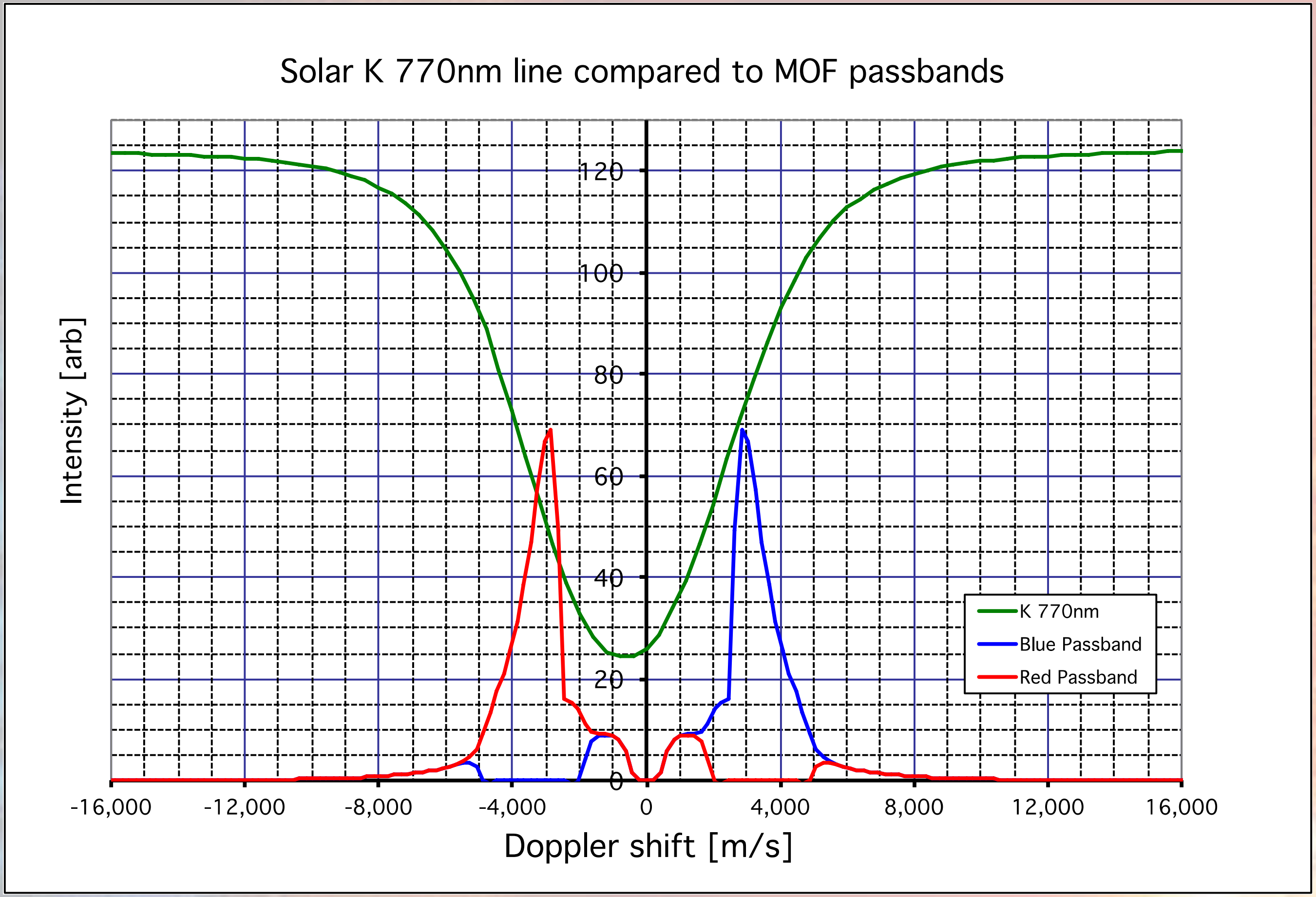


Solar imaging

Remote sensing from earth orbit and beyond

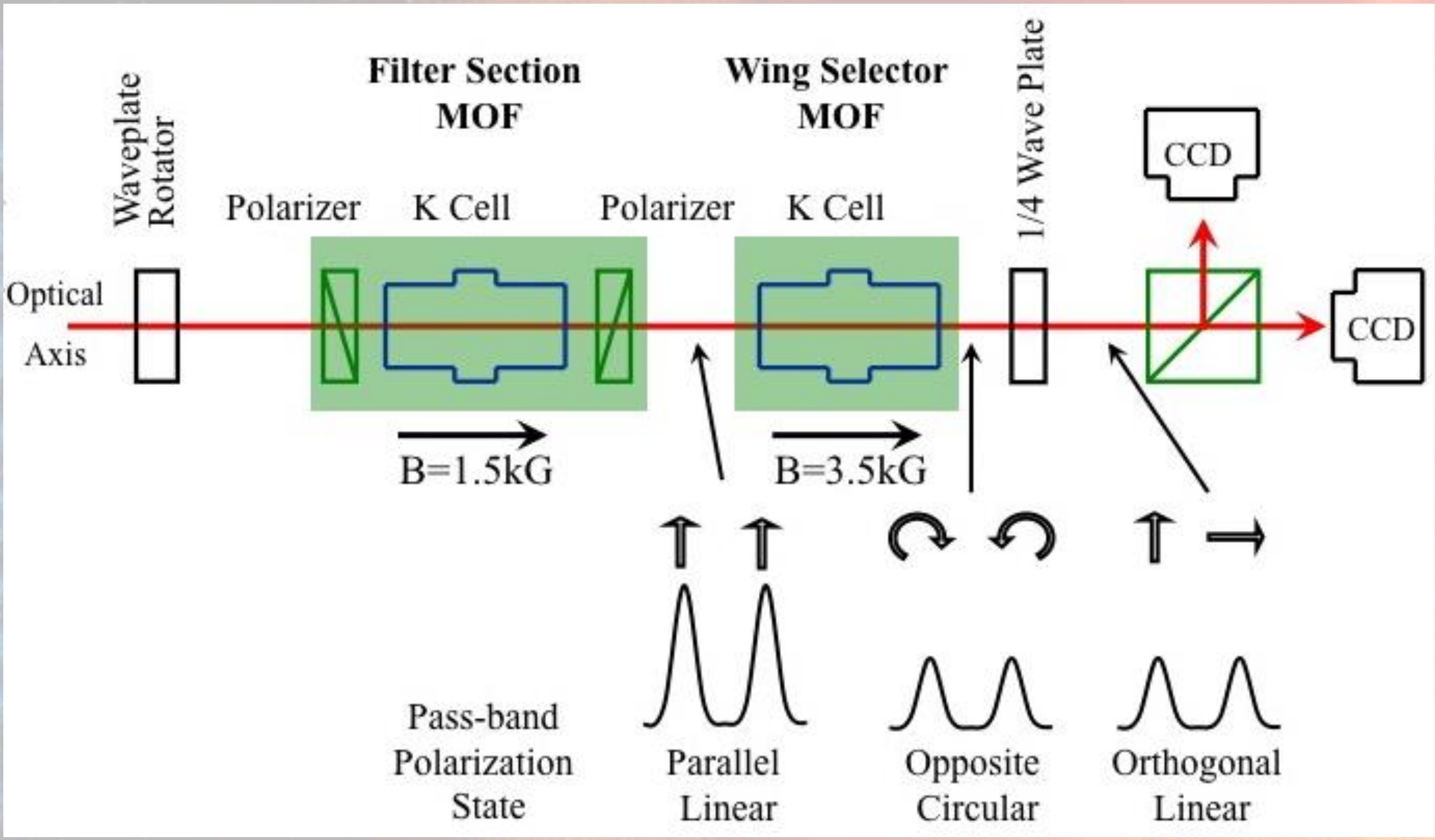
- Several research groups are developing CubeSat scale solar imagers
  - EUV
  - Coronagraph/heliospheric imagers
  - Doppler/magnetographs (images of velocity and magnetic fields)

Key measurements: velocity and magnetic fields

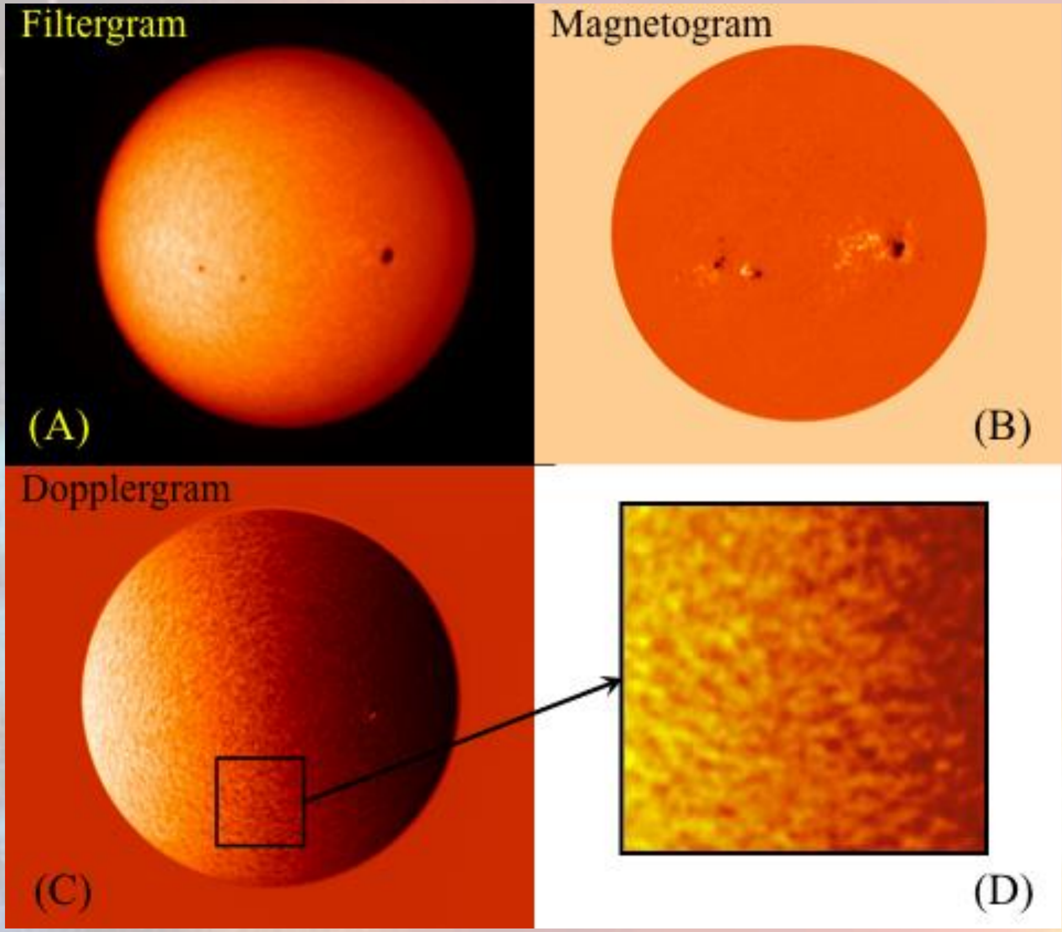


Red and blue Doppler Imager pass-bands, compared to the K 770 nm solar absorption line. Intensity ratios are proportional to Doppler shift, circular polarization is proportional to the line-of-sight magnetic field

Magneto-optical filter (MOF)



Key measurements: velocity and magnetic fields

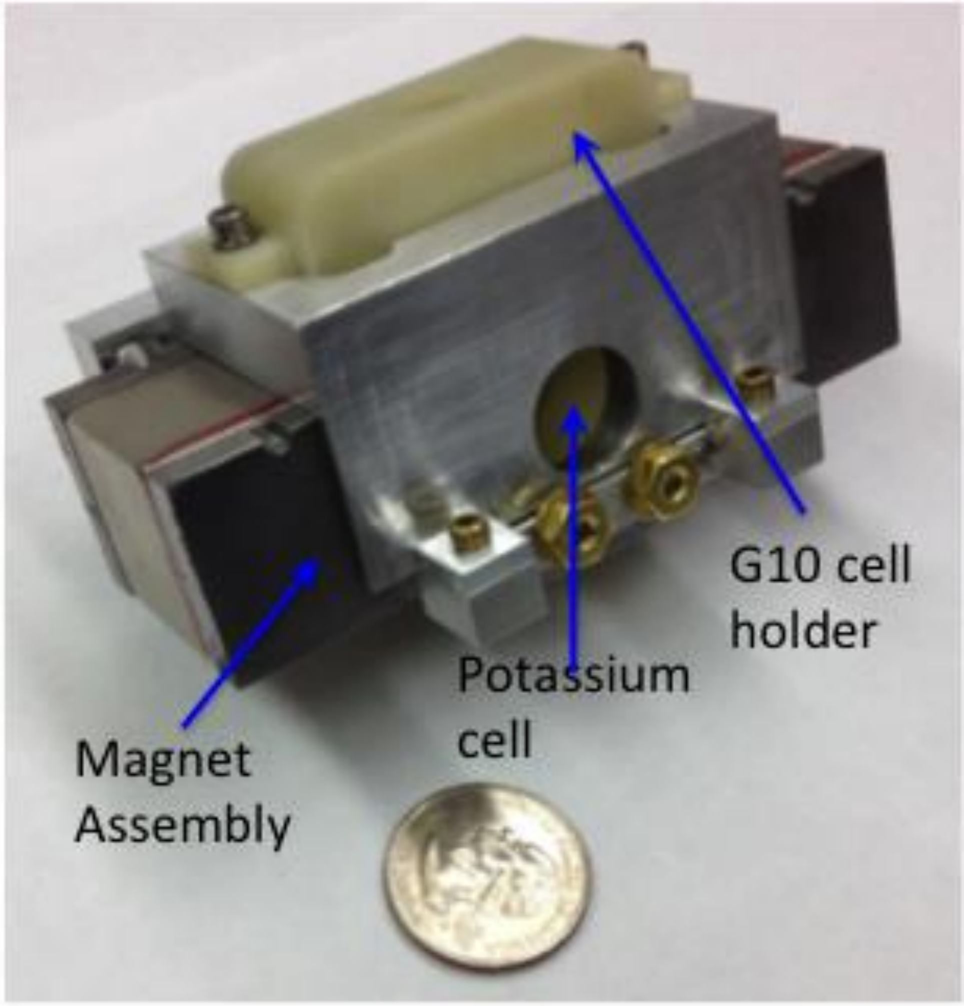


Panel A) shows an image of the sun, through a single MOF passband, B) shows an image of the net circular polarization, ie a magnetogram, C) shows a normalized difference image between the two passbands, which is proportional to Doppler shift - a Dopplergram.

Magneto-optical filter (MOF)

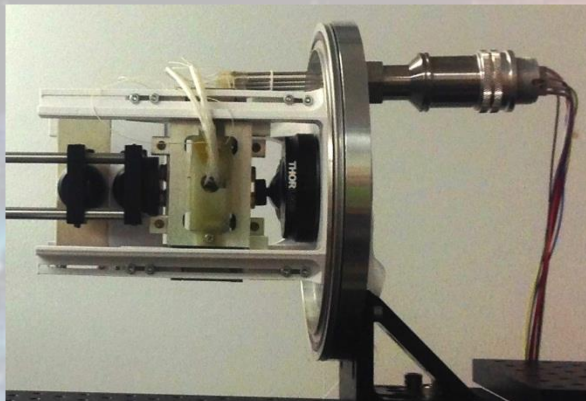
Mass:
Filter section 500g,
Wing selector 1040g
Power: max 3.0W

Flight version of MOF is much less massive and consumes les power than the ground based instrument



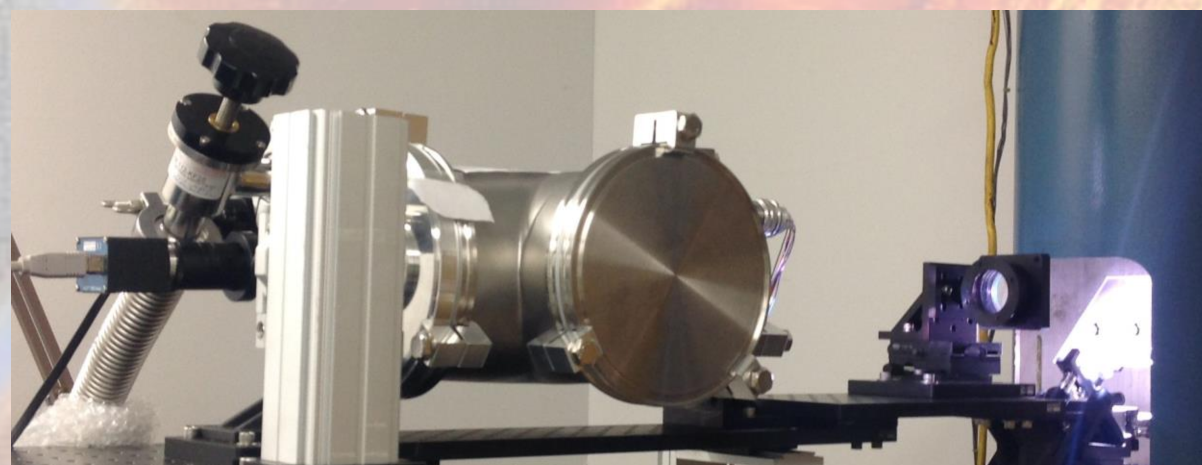
A compact MOF

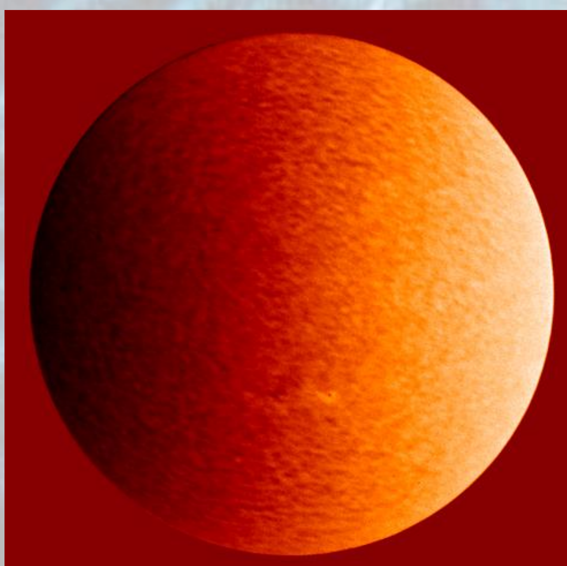
MOF testing – ‘Technology Readiness’



(Left) MOF and optics during integration to the vacuum chamber.

(below) Test chamber in operation



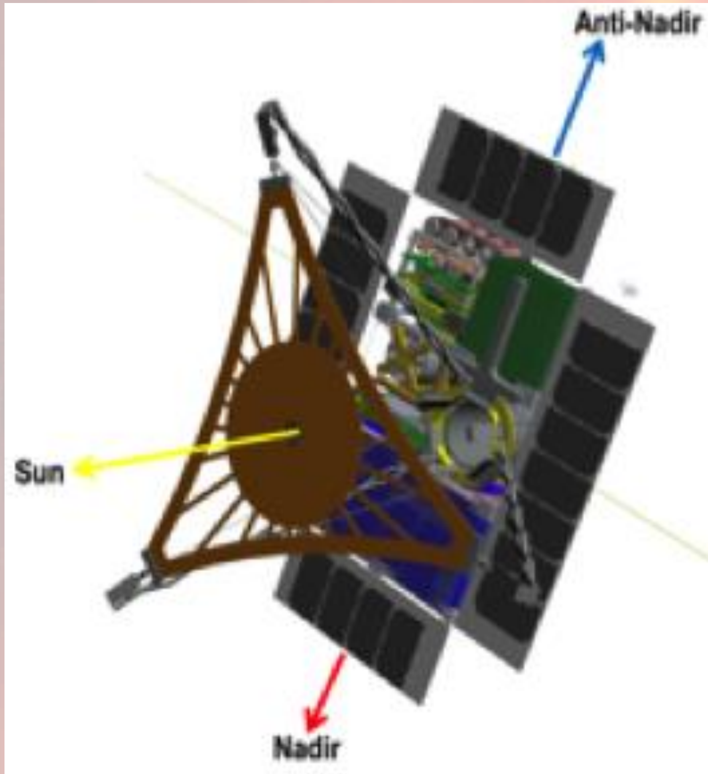


Test Dopplergram

Used for verifying thermal models and power consumption in vacuum, testing performance. Limited vibration testing already completed

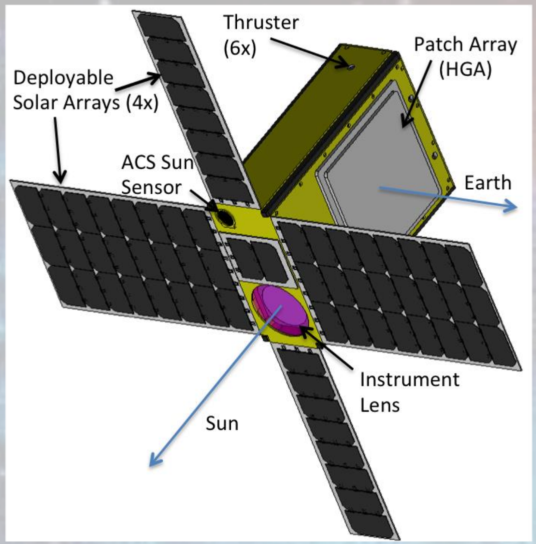
Solar Atmospheric Seismology (SAS) concept

- 6U system in a dawn-dusk low-earth obit
- Dopplergraph with 20 cm photon sieve aperture (Falconsat-7 – 2016 launch)
- s/c pointing control 0.1°, stability 10 arcsec/min (reaction wheels)
- Payload stabilization <1 arcsec/min
- 200m/s delta-V
- 3 mbps downlink (store and dump)
- 32 Gbytes data storage

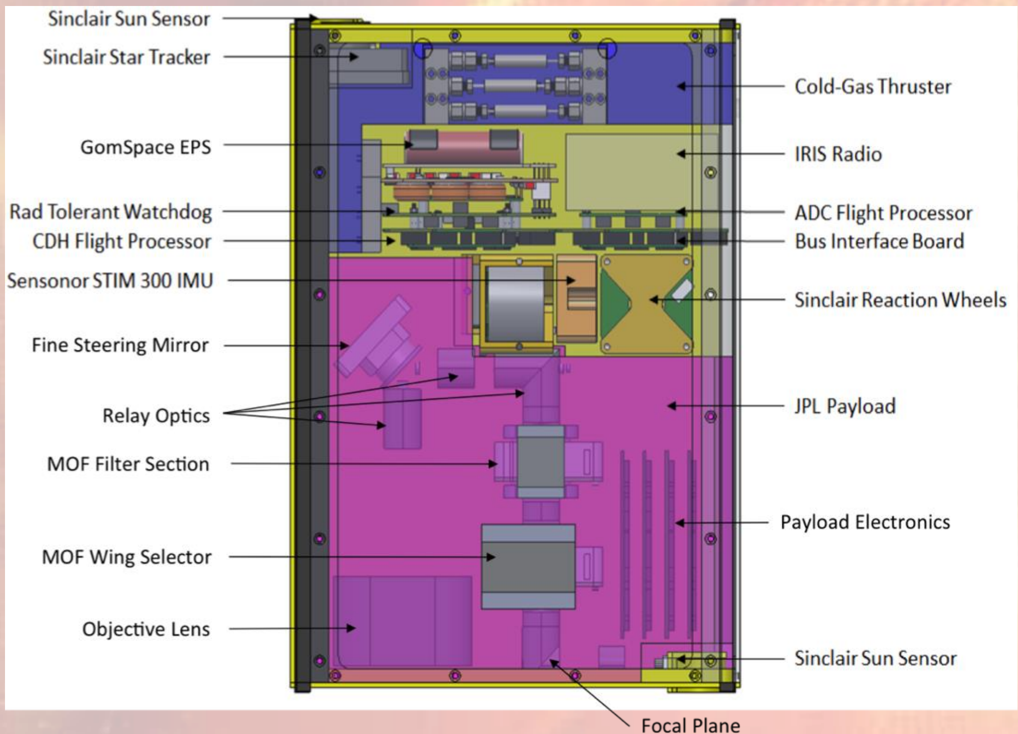


Solar Activity Investigation (SAI) concept

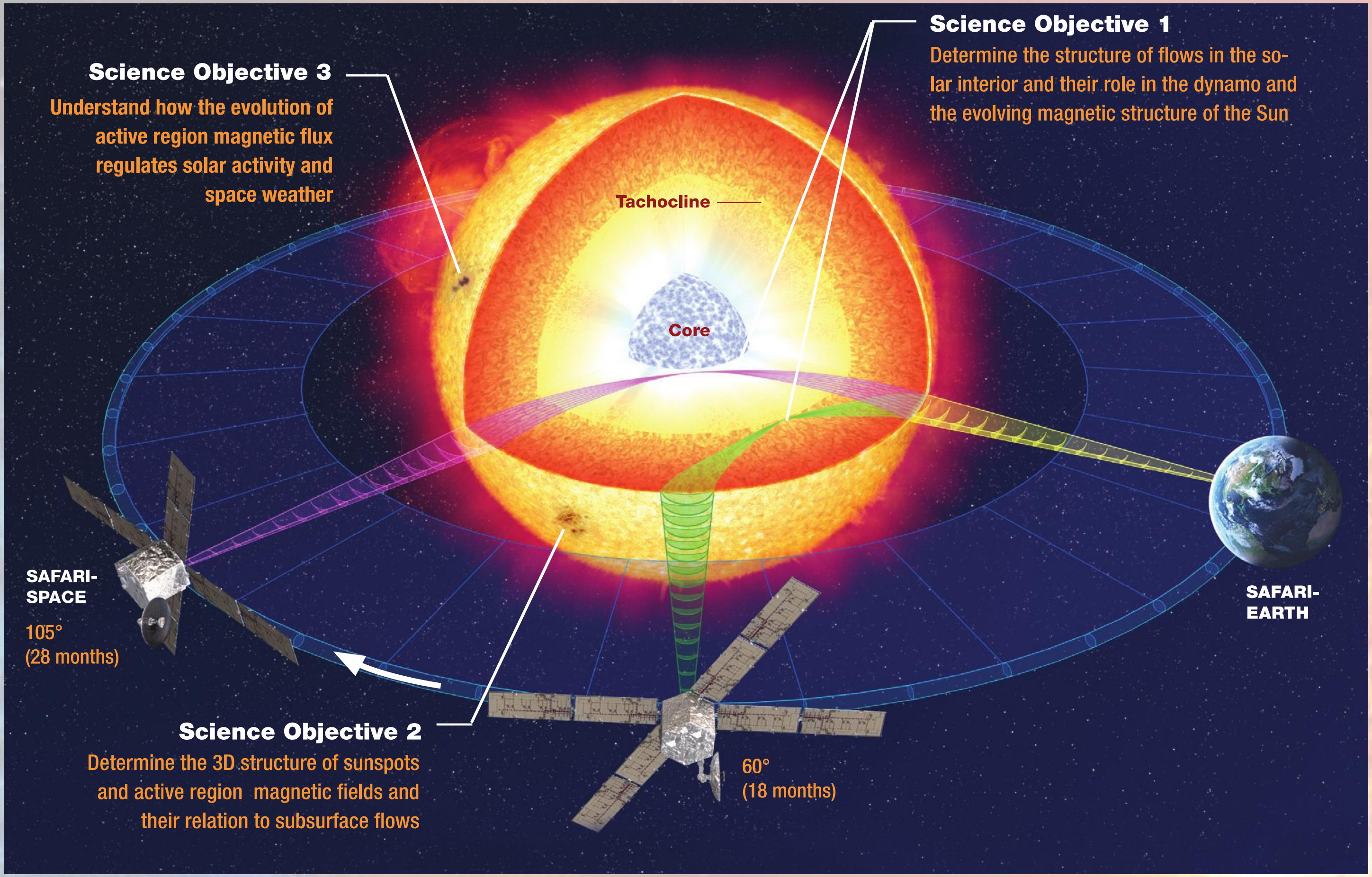
Stereoscopic helioseismology & magnetography; extended view of photospheric magnetic field; vector flows and fields in the photosphere



Subsystem	CBE (kg)	Cont	Total (kg)
Structures	1.68	30.0%	2.18
Power	1.22	7.6%	1.31
C&DH	0.26	26.3%	0.33
ACS	0.79	3.1%	0.81
Telecom	1.02	14.9%	1.18
Payload	2.69	30.0%	3.50
Propulsion	1.30	10.0%	1.43
Cabling	0.30	30.0%	0.39
Total	**9.26**	20%	**11.13**
Allocated			13.67
Margin			**19%**



SAFARI mission concept (PI – M. Velli)



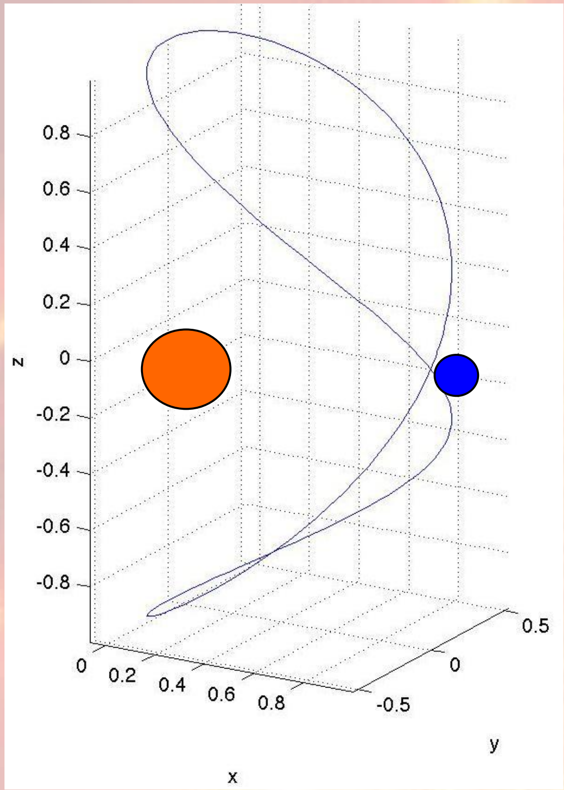
An overview of SAFARI – by by making helioseismic and magnetic measurements from two vantage points – one on the earth, we can probe the deep interior of the sun, measure transverse flows in the photopshere, and make stereoscopic magnetic field measurements

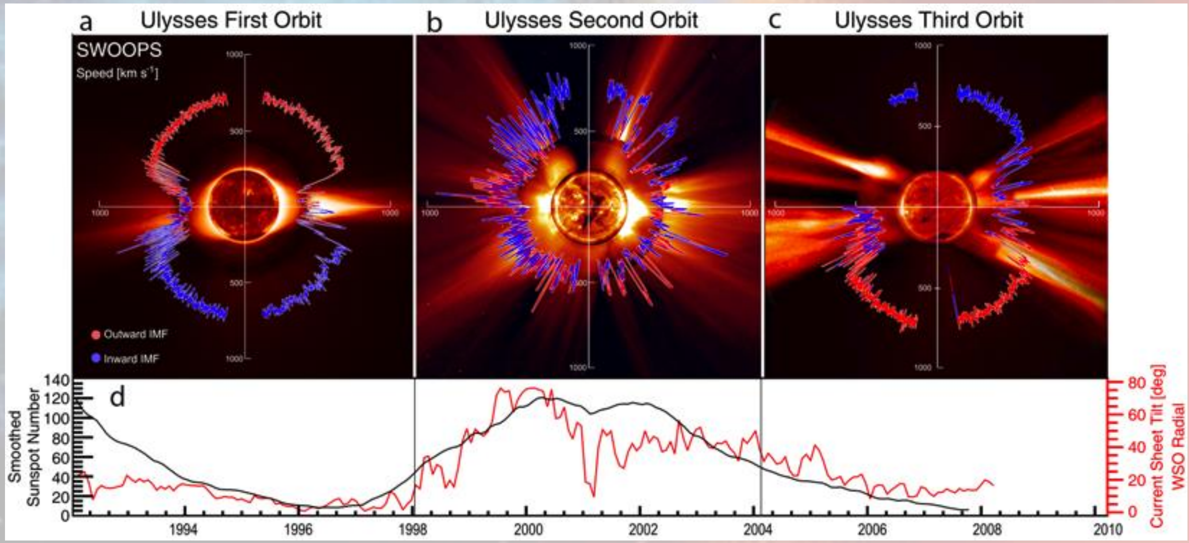
Solar Polar Constellation Concept

"Vertical Orbits"* for Out-of-Ecliptic Solar missions– improves on Solar Polar Imager (SPI)

- Multiple CubeSats, Each would carry 1 or 2 Instruments. – in-situ and remote sensing CubeSats
- High inclination ~75° orbits
- ≈3 years to operational orbit

Would use Vertical Orbit Family (Out-of-Ecliptic) around Earth L1 - orbits exist at all inclinations





*Moulton, F. R., "Periodic Orbits", 1920.

Conclusions

- CubeSats and Small-sats have developed into a new tool for the study of solar physics and space weather
- Many traditional instruments can be accommodated on these small platforms, as we have shown for the magnetometer and Doppler/magnetograph
- Mission concept studies have shown the capability of such missions, and the spacecraft resources required
- In addition to enabling low-cost missions to address targeted science questions, such missions can form the building blocks for interplanetary heliophysics constellations