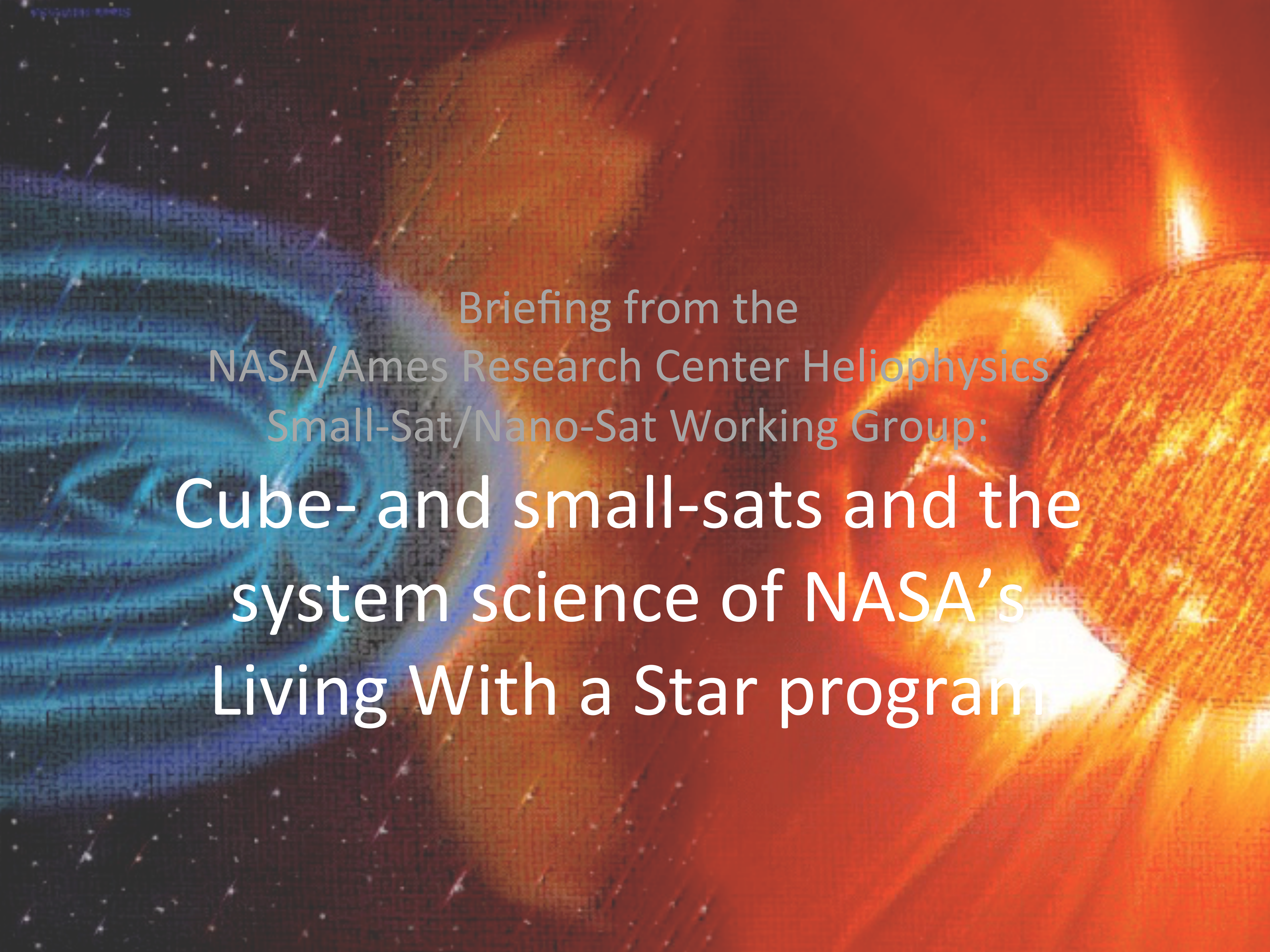

Briefing from the
NASA/Ames Research Center Heliophysics
Small-Sat/Nano-Sat Working Group:

Cube- and small-sats and the system science of NASA’s Living With a Star program

Why now?

- Rapidly developing capabilities of nano and small spacecraft (driven in a large part by the frequent access to space): CubeSats are now capable of sophisticated measurements, with architectures capable of significant data volumes.
- Small spacecraft buses (e.g. those compatible with EELV Secondary Payload Adaptors) are becoming more capable and affordable.
- The extension of the International Space Station (ISS) to 2024 has opened a reliable, cost effective platform for achieving new science (or "taking new measurements.")
- These new, cost effective platforms have the potential to provide new tools to address significant science goals, particularly when such goals are best addressed using distributed measurements.

Charter

- Charge to the the NASA Ames Research Center (ARC) Small-sat/nano- sat working group:
- "develop a strategy to exploit these new capabilities to address "Living with a Star" system science goals."

Key Tasks

Synthesize the existing goals of the LWS program to identify measurement and knowledge gaps that are addressable with nano-spacecraft, small spacecraft, and/or ISS payloads (based on the Decadal Survey, the Living With a Star 10-year plan, relevant parts of the COSPAR/ILWS Roadmap, and other relevant documents).

Sketch example mission scenarios that have the potential to address these gaps.

Identify relevant existing and developing technologies.

Working group members

Neil Murphy (chair)
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Jitendra Joshi
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With additional input from
Mihir Desai
Craig DeForest
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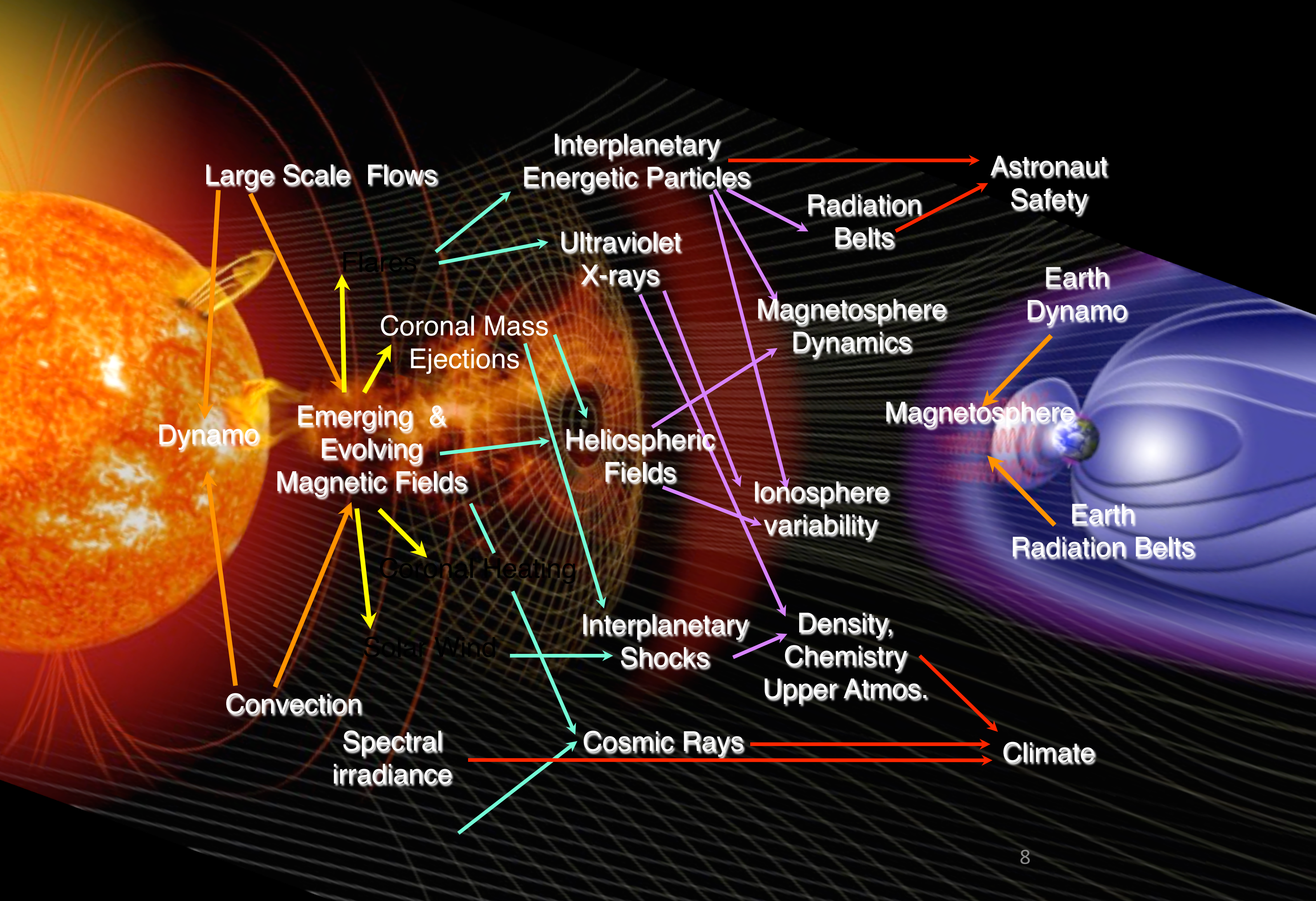
Dan Moses
Jeff Newmark
David Pierce
Robb Pfaff
Nathan Schwadron

How we are complimentary to NRC

- The data compiled by the ARC Working Group and the final report will be provided to the NRC study group that is currently assessing the cubesat capabilities to achieve the broader science goals of the Science Mission Directorate (SMD) at NASA HQ. Communication with the NRC study team is encouraged to ensure no duplicity between the two studies.

Living With a Star - Studying the System

A Complex, Coupled System



Overarching Science Areas from LWS 10-yr plan

- **Physics-based Understanding to Enable Forecasting of Solar Electromagnetic, Energetic Particle, and Plasma Outputs Driving the Solar System Environment and inputs to Earth's atmosphere**

- **Physics-based Geomagnetic Modeling Capability**
  - Enable1-3 day (long lead-time) and 15-30 min (short lead-time) predictions of pending extreme fluctuations in geomagnetic field
- **Physics-based Satellite Drag Modeling Capability**
  - Enable specification of the global neutral density in the thermosphere and its variations over time
- **Physics-based Solar Energetic Particle Modeling Capability**
  - Probabilistic prediction of the intensity of SEP events, and increased time periods for all-clear Forecasting Capability with higher confidence level
- **Physics-based TEC Modeling Capability**
  - Enable specification of the global ion density in the topside ionosphere and plasmasphere and its variations over time under varying geomagnetic conditions
- **Physics-based Scintillation Modeling Capability**
  - Enable prediction of scintillation occurrence utilizing limited sources of available data and ascertain how radio signals are degraded by ionospheric irregularities
- **Physics-based Radiation Environment Modeling Capability**
  - Enable predictive capability for the radiation environment and its effective dose as well as dose rates based on GCR, SEP, cutoff rigidity, atmosphere density, and gamma-ray/X-ray inputs

From the Decadal Survey …

Heliophysics Key Science Goals for the Next Decade

Determine the origins of the Sun's activity and predict the variations in the space environment.

Determine the dynamics and coupling of Earth's magnetosphere, ionosphere, and atmosphere and their response to solar and terrestrial inputs.

Determine the interaction of the Sun with the solar system and the interstellar medium.

Discover and characterize fundamental processes that occur both within the heliosphere and throughout the universe.

Charge to COSPAR/ILWS:

The COSPAR/ILWS RoadMap

- focuses on high-priority challenges in key areas of research
- leading to a better understanding of the space environment and
- a demonstrable improvement in the provision of timely, reliable information
- pertinent to effects on civilian space- and ground-based systems,
- for all stakeholders around the world.

The RoadMap prioritizes those advances that can be made on short, intermediate and decadal time scales, identifying gaps and opportunities from a predominantly, but not exclusively, geocentric perspective.

Definition: "Space weather refers to the variable state of the coupled space environment related to changing conditions on the Sun and in the terrestrial atmosphere."

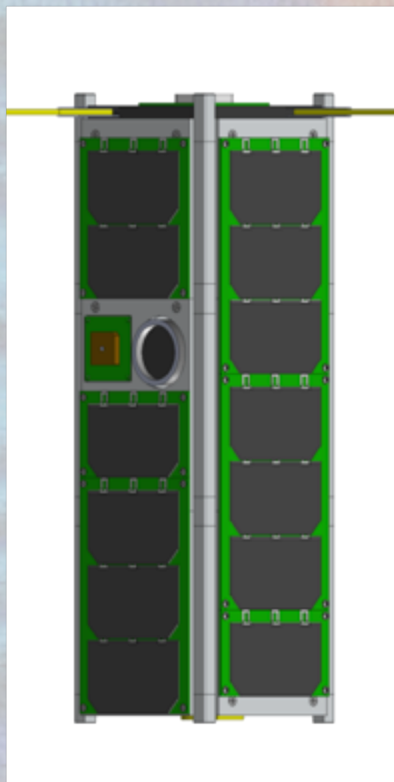
Published in Advances in Space Research 55, 2745 (2015)

Small-nano sat capabilities
New Tools/Emerging capabilities

Rethinking the Satellite

Standard 3-Unit CubeSat

~30 cm



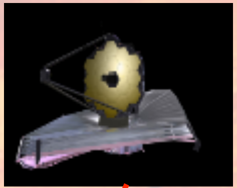
~10 cm

Chipsat

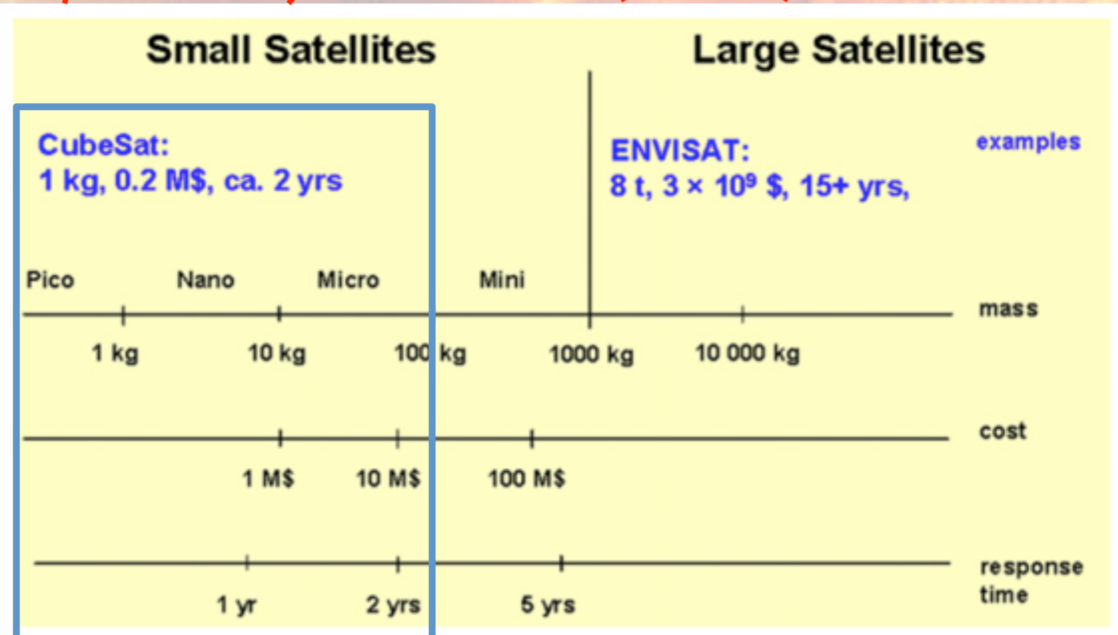
CubeSat

Curiosity

James Webb ST



Images: NASA



Small Satellites Mass-Cost-Time Relation

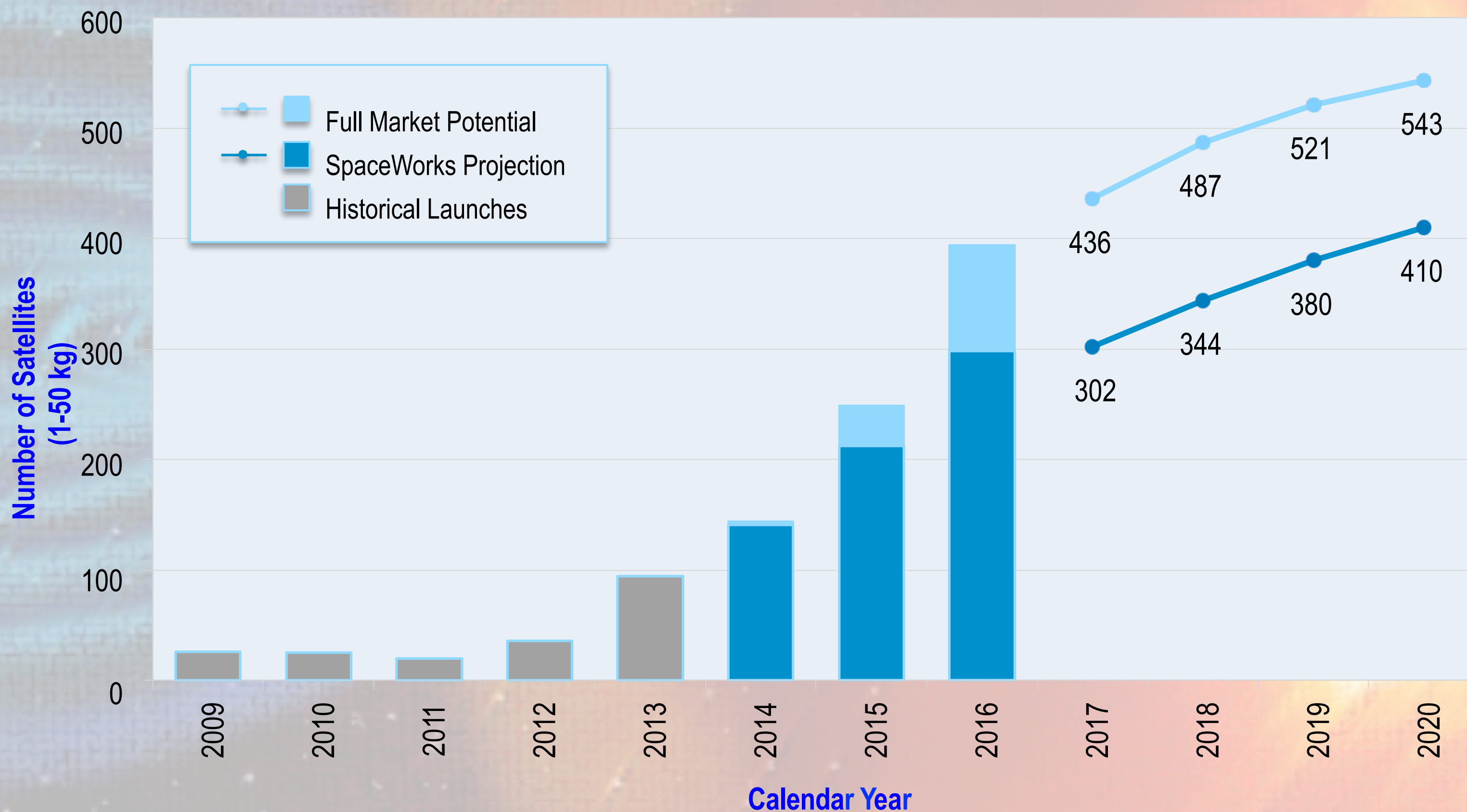
(from: Sandau et al., ISPRS Journal of Photogrammetry and Remote Sensing, 65, 2010)

A Brief History of Small Satellites

1990's	U. Surrey (UK) leads small satellite renaissance with ~100 kg satellite technology demonstrations	UoSAT series
1997	DOD meeting initiates 1 kg satellite concept	
2000	Definition of CubeSat Standard by CalPoly and Stanford University	SNAP-1 and Tsinghua-1
2000's	Development of commercial CubeSat deployers and secondary rideshare launch opportunities	MEPSI , AeroCube series
2007	NSF establishes CubeSat Space Weather and Atmospheric Research program	GeneSat, CANX-2
2010	NASA begins CubeSat Launch Initiative program providing launches for selected projects	RAX, NanoSail, DICE
2013	NanoRacks provides commercial deployment of CubeSats from International Space Station	SkySats, Doves
2015	NRC forms committee to review potential of CubeSats to perform high priority science goals	Flocks, FIREBIRD, Lightsail

Access to Space

Projections based on announced and future plans of developers and programs indicate between 2,000 and 2,750 nano/microsatellites will require a launch from 2014 through 2020



The Full Market Potential dataset is a combination of publically announced launch intentions, market research, and qualitative/quantitative assessments to account for future activities and programs. The SpaceWorks Projection dataset reflects SpaceWorks' expert value judgment on the likely market outcome.

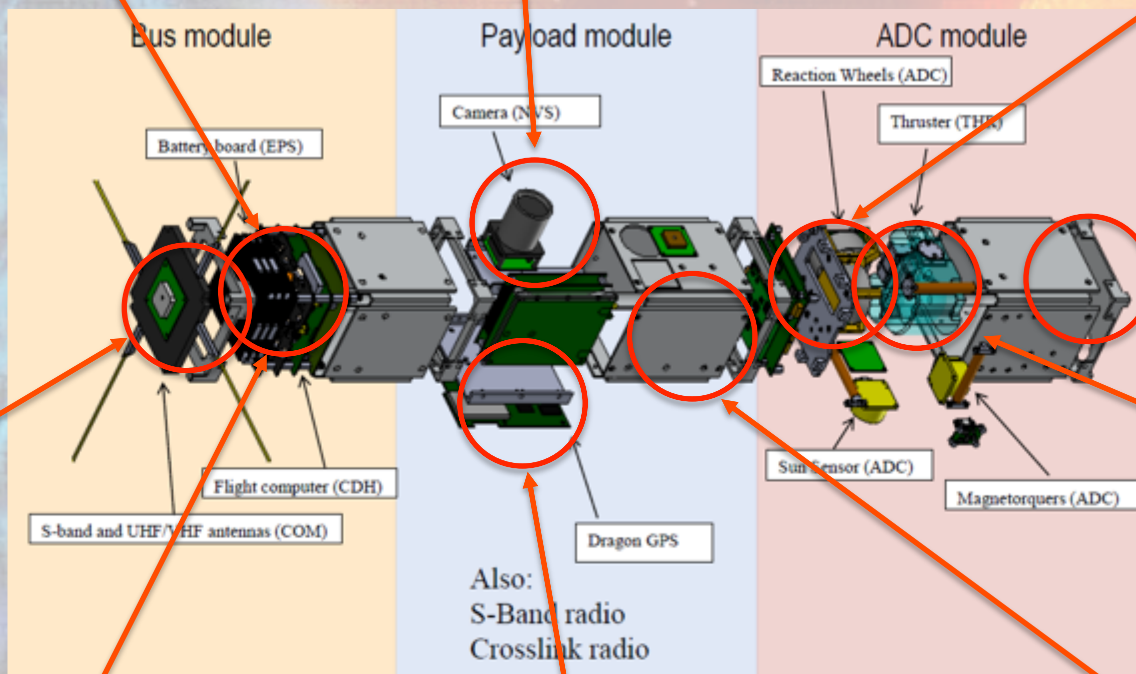
Enabling Technologies for Small Satellites

Radiation tolerant systems

Optical sensors

Miniaturized attitude determination and control

Drag-assisted deorbit devices



Agile high gain communications

Low power propulsion

Autonomous operations

Space navigation systems

Integrated structure and thermal stabilization

Small Satellite Capabilities

Attitude Control

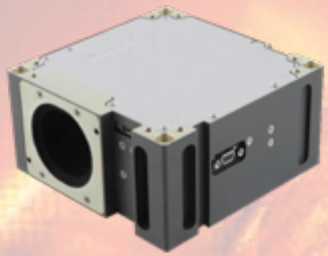
Current	Emerging	Developing
Demonstrated	Within 2 years	Expected in 5 years
0.1 degrees	0.02 degrees (arc-minute)	0.0003 degrees (arc-second)

Propulsion

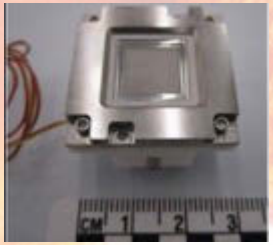
Current	Emerging	Developing
Demonstrated	Within 2 years	Expected in 5 years
N/A	Inert gas, 3D printed 50 m/s	Micro Electrospray 300 m/s

Radiation Tolerance

Current	Emerging	Developing
Demonstrated	Within 2 years	Expected in 5 years
10 krad Si total dose 12 months LEO	Selective hardened 12 months interplanetary	Radiation hardened bus Multi-year interplanetary



Blue Canyon XACT attitude control system



JPL Indium MEP thruster

Astrium LEON microprocessor

Small Satellite Capabilities

Solar Power Generation

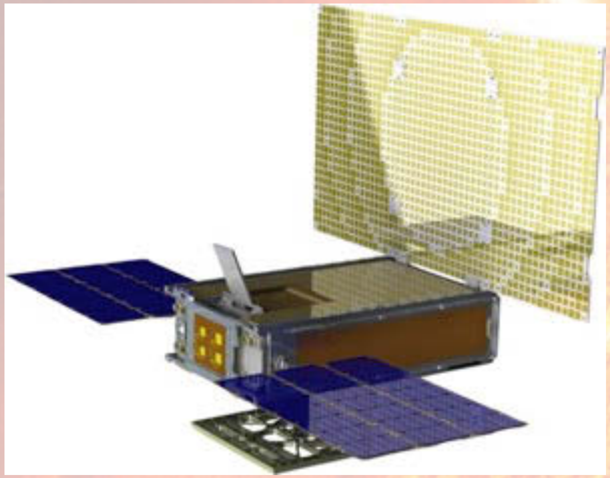
Current	Emerging	Developing
Demonstrated	Within 2 years	Expected in 5 years
Body panels 10 W	Fixed arrays 30 W	Sun tracking 100 W

Communications

Current	Emerging	Developing
Demonstrated	Within 2 years	Expected in 5 years
UHF, S-band LEO 100 kbps	X-band Interplanetary 250 kbps	Software Defined 1 Mbps

Autonomy and Formation Flying

Current	Emerging	Developing
Demonstrated	Within 2 years	Expected in 5 years
Stored commands Single vehicle	Proximity operations Two vehicles	Event driven data collection Multi-vehicle formations



JPL MarCO CubeSat with MMA Hawk solar arrays and high gain antenna/radiator

NASA photo of two CubeSats in proximity

Mission Concepts for:

1) Solar Outputs
2) Ionospheric Inputs
3) Satellite Drag and Thermospheric Density
4) Plasmaspheric Plasma Irregularities, Total Electron Content (TEC), and Scintillation
5) Solar Energetic Particles

1) Mission Concepts for Solar Outputs

Determine the incoming CME field from solar observations

- The intensity of CME-related space weather is a function of the strength and geometry of the magnetic field impacting the terrestrial environment.
- Forecasts of the incoming CME field configuration beyond 0.5-1 hour require that the field be modeled from the eruption site through the heliosphere.
- Determination of the incoming, erupted field is hampered by the fact that we cannot reliably model the coronal magnetic field based on only surface-field measurements of the visible hemisphere of the Sun.

Determine the incoming CME field from solar observations

- The COSPAR/ILWS roadmap① articulates rationales and concepts for instrumentation on designed to enable real-world MHD modeling of CMEs in the heliosphere:
  1. ***Mission Concept 1: Stereoscopic EUV imaging*** of the solar corona from a perspective some 5-15 degrees off the Sun-Earth line to complement Earth-perspective observations. These binocular image pairs constrain the 3D loop trajectories of active regions,② which can then be combined with surface (vector-)magnetograms before and after eruptions to establish the ejected magnetic configuration.
  2. ***Mission Concept 2: Magnetography well off the Sun-Earth line*** (such as from an L5 perspective) to increase the magnetograph coverage of the solar surface sufficiently to improve global coronal field models, through which eruptions can be propagated before they are handed off to heliospheric MHD models.

Heliophysics objectives: 24h ahead of geospace arrival:

- specify the field geometry of the erupted rope and of the surrounding field, and evolve these jointly into the heliosphere towards Earth.

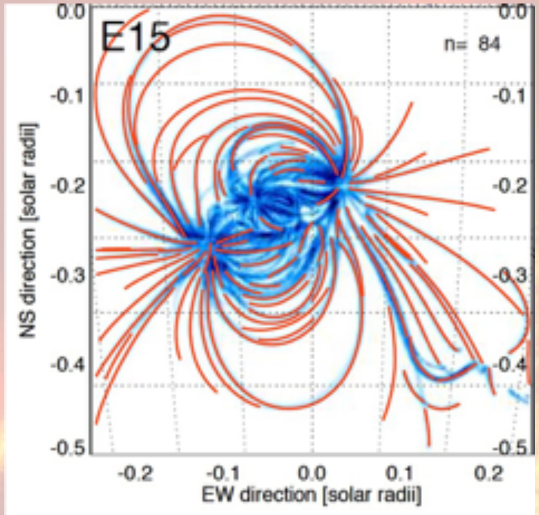
Space Weather user objectives: for long ground-based conductors, in particular electrical power:

- forecast the heliospheric field & plasma that will reach Earth with at least 24-h lead time.

① Understanding space weather to shield society: A global road map for 2015-2025 commissioned by COSPAR and ILWS*, C. Schrijver, K. Kauristie, . Aylward, C. Denardini, S. Gibson, A. Glover, N. Gopalswamy, M. Grande, M. Hapgood, D. Heynderickx, N. Jakowski, V. Kalegaev, G. Lapenta, J. Linker, S. Liu, C. Mandrini, I. Mann, T. Nagatsuma, D. Nandi, T. Obara, T. O'Brien, T. Onsager, H. Opgenoorth, M. Terkildsen, C. Valladares, N. Vilmer, Advances in Space Research 55, 2745 (2015).*

② Blind stereoscopy of the coronal magnetic fiel*d, M. Aschwanden, C.. Schrijver, A. Malanushenko, Solar Physics 290, 2765 (2015).*

Mission Concept 1: Stereoscopic EUV imaging



Example of simulated (negative) coronal image (blue) and 3d loops traced from an image pair at 15 degrees of separation in perspective. Separations from 5-15 degrees minimize loop confusion while maximizing height information. From Aschwanden et al. (2015, SPh 290, 2765).

Science Objective for Mission Concept 1:

Develop magnetic field modeling of solar regions around times of flares and CMEs to enable >12h geomagnetic storm forecasts by:

- ***stereoscopic observations of the configuration of coronal loops over active regions involved in flares and CMEs***. These observations provide the 3D information of the magnetic field that, when combined with magnetic maps, can yield determinations of coronal geometry, energy, helicity, …
- **combining pre- and post-event observations to determine the field configuration that left the Sun in a CME**, which can then be fed into a heliospheric model to understand and forecast what will impact the terrestrial magnetic field driving geomagnetically-induced currents.

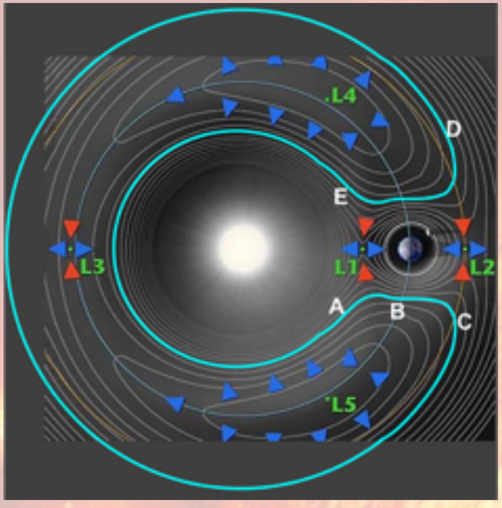
Mission requirements:

- EUV images from two perspectives, prior to and after flares and eruptions, at appr. 1-arcsec resolution, with optimal separation angle of 5-15 degrees between lines of sight, observing out to ~1.5 solar radii from disk center, with at least 1 image pair per 10 min.

Mission Concept 1: Stereoscopic EUV imaging

Mission implementation:

- Primary instrument: Single dual-channel EUV imager of the solar corona on disk and out to ~1.5 R_{Sun}, to be matched by a second imager with identical pass bands and resolution (e.g., existing SDO/AIA 195A and 304A; or a new identical sister S/C near Earth).
- Desired augmentation: compact coronagraph with inner field of view reaching outer edge of coronal EUV imager.
- Potential augmentation: in-situ energetic particle sensors.
- Attitude control: 3-axis stabilized, with image stabilizers.
- Type of instrument(s): remote sensing imagers, possibly in situ
- Telemetry: approximately 1-2 giga-bit/day.



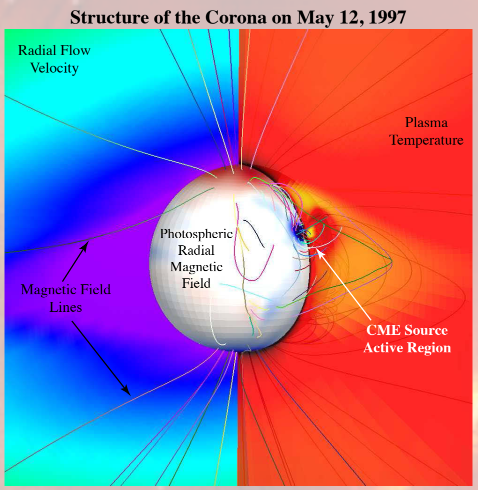
Horseshoe orbit in the co-rotating reference frame of the Sun-Earth line, with the Sun in the center, and the Earth to the right. Prime mission phases (A-C or D-E) can last up to 5 years without propulsion requirements.

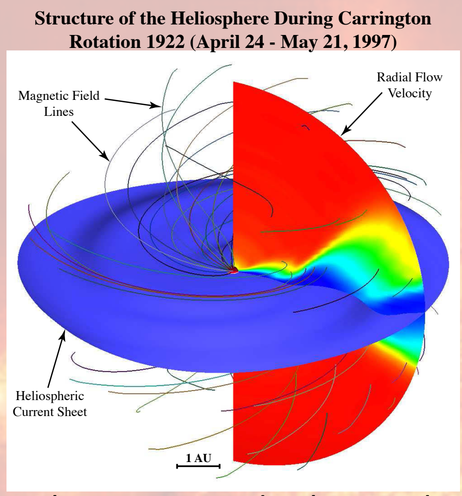
Orbit option:

- Perspective separation of 5-15˚ is optimal to minimize ambiguity when matching pairs of traced coronal loops in stereo image pairs while maximizing height resolution.
- Orbital option: horseshoe orbit. After insertion into an Earth-trailing or Earth-leading orbit (TBD), the S/C slowly drifts around L5 or L4, pulled by quasi-forces in the rotating frame of reference subject to solar and terrestrial gravity. 5-15˚ separation can be maintained for several years.
- After the 5y prime phase, the S/C would slowly drift behind or ahead of the Earth.
- Data rate requires a meter-class antenna on the S/C and 8-15m class antenna(e) on Earth.

Mission Concept 2: Magnetography well off the Sun-Earth line

- The structure and dynamics of the ambient solar corona and solar wind determine the trajectory, speed, and magnetic-field direction of (I)CMEs.
- The surface magnetic field of the Sun is the crucial input to coronal/solar wind MHD models.





Global MHD models can describe the corona and solar wind

<u>Science Objective for Mission Concept 2:</u>

- Improve the accuracy of global coronal field models and of solar-wind MHD models by obtaining magnetograms from perspectives that complement Earth perspective, adding at least one near the east limb of the Sun (as seen from Earth), but ideally multiple perspectives around the Sun.
- Integrate multi-perspective observations into surface flux transport models that provide accurate full-sphere, evolving magnetic maps to coronal and heliospheric MHD models.

<u>Mission requirements:</u>

- Magnetographs from at least two perspectives, at ~1-arcsec resolution, with at least one full-disk magnetogram per 30 min.
- Optimal configuration: observations from around the Sun from at least three perspectives 120˚ apart, or up to five perspectives drifting around the Sun always providing full-Sun coverage.

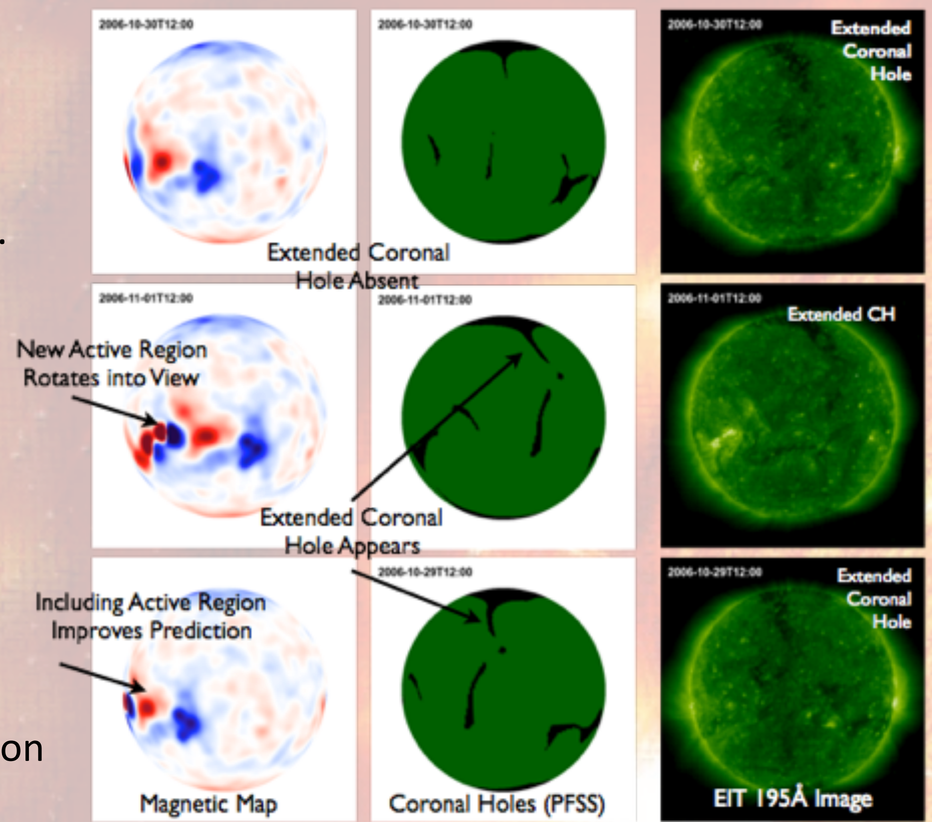
Mission Concept 2: Magnetography well off the Sun-Earth line

Minimum mission implementation:

- Primary instrument: 1 or 2 arcsec-resolution magnetograph (like SDO/HMI, ideally vector, but line-of-sight (LOS) is adequate).
- Location: Earth-Sun L5, at ~60˚ trailing Earth.
- Attitude control: 3-axis stabilized, with image stabilizers.
- Telemetry: approximately 1-2 giga-bit/day.
- Desirable instrumentation: EUV Imager, 195Å or soft X-ray for coronal holes (model validation).

Optimal mission implementation:

- 5 S/C, each with only a 1 or 2 arcsec-resolution LOS magnetograph.
- "Nano-sat" design, fitting within ~12U cube-sat volume.
- Injected into orbits leading and trailing Earth, spaced in time to form a complement that provides continuous full-sphere solar observing.



Using Map from 11/1 Improves the Comparison with 10/29

2) Mission Concepts for Ionospheric Inputs

Geoeffectiveness of solar wind drivers, and their impacts

Fidelity of forecasting geomagnetically-induced currents (GICs) depends on knowledge of the solar wind and on magnetospheric modeling accuracy.

Global MHD and hybrid magnetospheric models are increasingly sophisticated with input from current missions, capturing localized magnetotail injections, partial ring current dynamics, and ionospheric conductivity gradients. But the desired fidelity cannot be achieved for 1-2 hrs warning time (consistent with solar wind monitoring from Sun-Earth L1).

Progress is hampered because the solar wind magnetic field that reconnects at the magnetopause is not necessarily what is measured at L1 due to significant cross-flow structure of the field at $30R_{Earth}$ scales. Multi-point upstream solar wind observations are needed.

Moreover, the solar wind interacts with foreshock ions at 15-30 R_E upstream, creating foreshock transients of 3-5 R_E scale, modifying the energy input into the magnetosphere. Modeling of these upstream kinetic interactions requires observations, which also provide high-fidelity measurements of the solar wind streamlines driving the magnetosphere.

Geoeffectiveness of solar wind drivers, and their impacts

Even with added multi-point in-situ solar-wind measurements, magnetospheric models cannot, presently, be sufficiently validated and improved with in-situ data, because the vast magnetospheric/ionospheric coupled system is woefully under-sampled, and effects are regional in scale (100-1000km for GICs).

Prediction fidelity can be improved by testing coupled magnetospheric-ionospheric models that use data from an array of polar-orbiting satellites that span the local times of major field aligned current sources (within a few hours of noon-midnight), capture their closure in the ionosphere, and have sufficient recurrence over each latitude to capture their evolution.

Geoeffective Solar Wind Drivers and their Ionospheric Effects

To enable high-fidelity modeling of the magnetospheric processing of the solar wind energy both solar wind inputs and resultant currents must be measured with sufficient spatial resolution. *Two observational platforms can realize this goal*:

Mission Concept 1: **A solar wind constellation that observes from ~ 30 R_E upstream** the pristine solar wind and its alteration due to interactions foreshock particles upstream from the magnetopause.

Mission Concept 2: **An ionospheric constellation to drive coupled magnetospheric-ionospheric models** to predict the intensity and location of field aligned currents and the distribution of the ionospheric currents that drive GIC.

Heliophysics objectives: create improved models of the solar-wind-magnetospheric-ionospheric interaction that will encompass foreshock phenomena and ionospheric conductivity.

Space Weather user objective: high fidelity forecast of GIC from pristine solar wind measurements: first from 30 R_E (5-10 min lead time) and eventually from L1 (0.5-1hr lead time) and beyond.

Mission Concept 1: Solar wind constellation

The solar wind streamline connecting to the nose is the one carrying the field responsible for Sun-Earth coupling.

The solar wind flow is structured by foreshock transients in ways that still remain poorly understood and modeled due to lack of multipoint measurements.

Needed: pristine and foreshocked solar wind data.

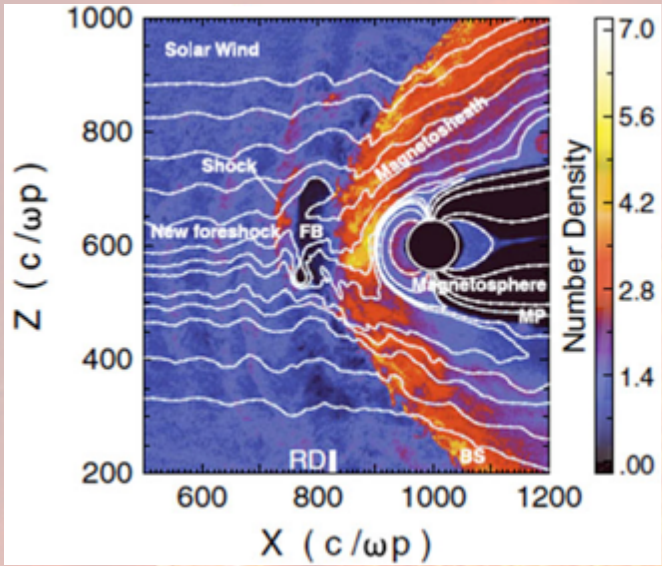
Science Objective for Mission Concept 1:

Understand and model how foreshock interactions modify the geoeffective streamline. Develop the capability to predict the exact solar wind input to the magnetosphere with 1-2hrs or greater advance warning.

Mission requirements:

Solar wind/upstream particles and magnetic field at 3s resolution, from spacecraft in the pristine ($30R_E$) and foreshocked ($13\text{-}20R_E$) solar wind at $5R_E$ cross-flow spatial resolution over a $15x15{R_E}^2$ area.

First perform coordinated observations of foreshock phenomena, then aim at predicting properties of the geoeffective streamline from progressively larger distances.



Global hybrid simulation [Omidi et al, 2010] of Earth's interaction with a seemingly innocuous solar wind rotational discontinuity (RD) shows the formation of a Foreshock Bubble (FB) of low density (hot) plasma and a reformed shock upstream of the FB and the nominal bow shock (BS). The FB changes considerably the density and field that arrive at the nose and the resultant dayside reconnection efficiency.

Mission Concept 1: Solar wind constellation

Mission implementation:

Sixteen spacecraft 4 on highly eccentric orbits. Spacecraft cover 4 GSE latitude ranges and are “locked” into fixed Sun-Earth longitudes using electric propulsion or solar sails.

Initial mission phase (top figure) is concerned with studies of geoeffective streamline and the modifications of its properties by upstream phenomena. 8 spacecraft measure foreshock bubbles and other transients in the foreshock region while the other 8 measure the relatively pristine solar wind.

The final mission phase (bottom figure) determines the properties of solar wind streamlines that hit the Earth. Thus even when foreshock bubbles or other foreshock phenomena reach as far as $30R_E$ they are well captured. The dataset enables development of high-fidelity forecast models of the solar wind parcels that affect Earth’s space environment.

Spacecraft characteristics:

6U spin-stabilized s/c with particle (solar wind and foreshock ions) and magnetic field instruments. 2.5kb/s data rate

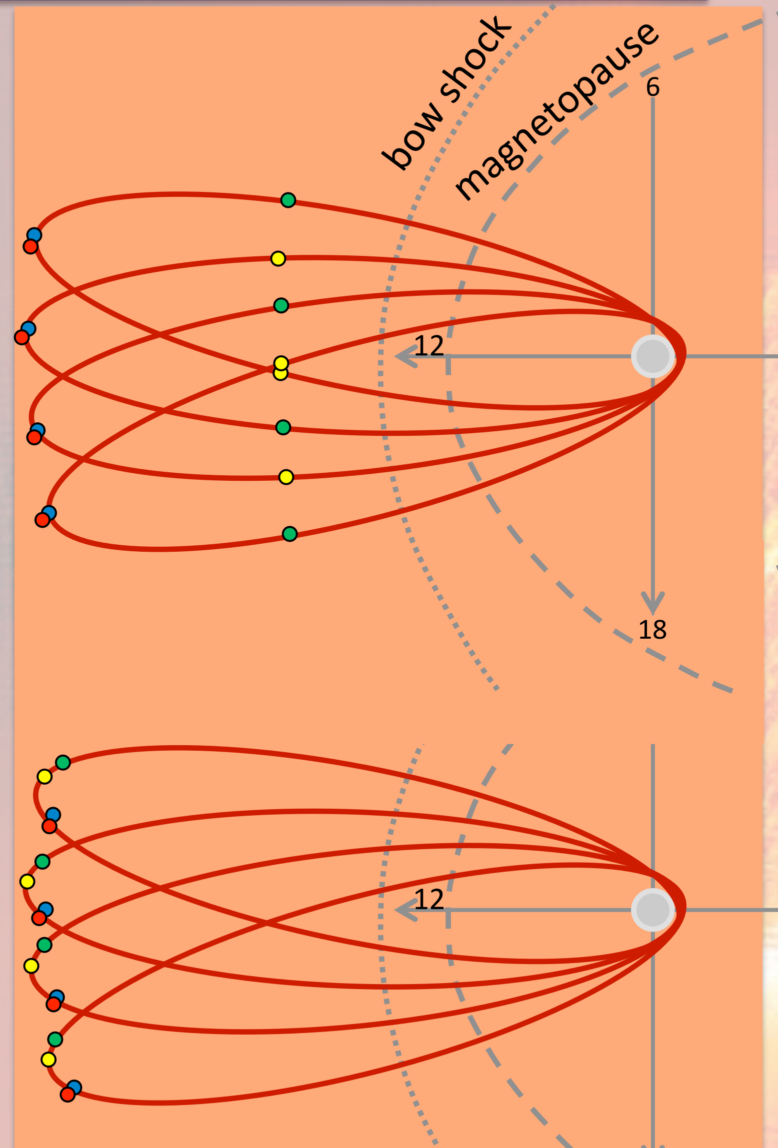


***Figure (right)**: Solar wind constellation representative orbits (red ellipses) and spacecraft (small round filled circles). Colors represent different latitudes relative to equator. Top represents a target configuration during the initial mission phase; bottom is target configuration during the final mission phase.*

Mission Concept 2: Ionospheric constellation

The horizontal ionospheric currents that cause GIC are driven by magnetospheric field aligned currents (FACs).

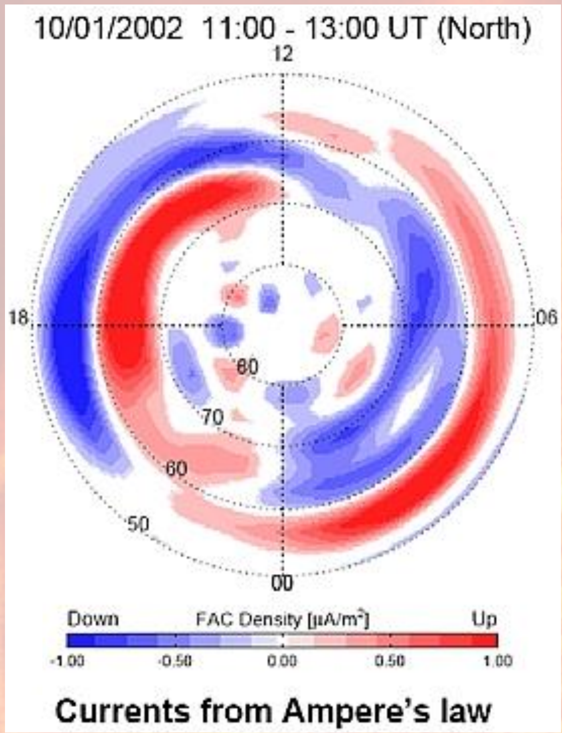
Solar wind driven magnetospheric models of ionospheric FAC generation cannot, presently, be sufficiently validated and improved with in-situ data because the magnetospheric-Ionospheric system is woefully under-sampled.

GICs are regional in scale (100-1000km) owing to local ground conductivities and to localized FACs from the magnetosphere.

Needed: synoptic maps of ionospheric field aligned currents, horizontal currents, and conductivities. The conductivities require measurements of local electron precipitation spectra. Global imaging needed to complement in-situ measurements.

Science objective for Mission Concept 2:
Improve global magnetospheric-ionospheric coupled models of GIC drivers, by providing the horizontal and field-aligned currents, J, and conductivities, Σ, needed to compare with model outputs.

Mission requirements: Magnetometer and conductivity in-situ measurements from low altitude satellites, plus FUV imaging.



AMPERE reconstruction of ionospheric field aligned curent from Iridium (77 satellite) constellation. Due to fitting and averaging the currents are about 10 times smaller than typical and far less structured than inferred by individual spacecraft. Tighter spacing is needed to infer currents.

Mission Concept 2: Ionospheric constellation

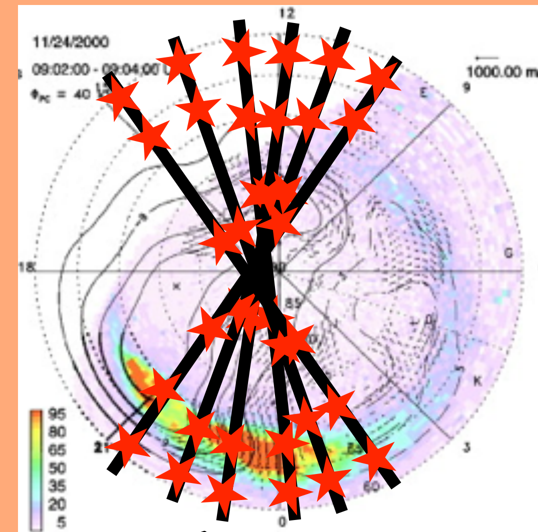
Mission implementation:
60 LEO (600km) S/C on 6 polar orbits (10 S/C per orbit) to provide 10-min. resolution of the global current system. Nominal orbits at 1MLT separation centered at 00-12MLT (around the most intense dayside and nightside FACs).

A reconfigurable constellation (e.g., to a denser configuration) can trade <100% duty cycle for increased time resolution of J, Σ measurements. It also allows for orbit plane shifts from 1MLT separations to smaller or larger ones.

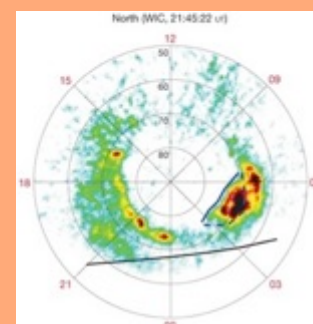
FUV imaging of both auroral ovals from two satellites on two highly eccentric polar orbits (one north, one south).

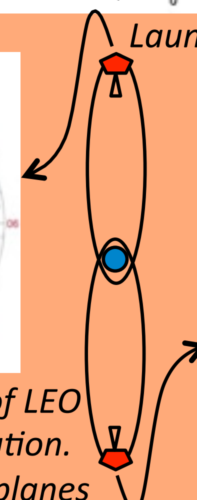
Spacecraft characteristics:
- LEO constellation: Spin-stabilized 6U S/C with particle (10eV – 30keV electrons) and magnetometer instruments. Data rate 4 kb/s.

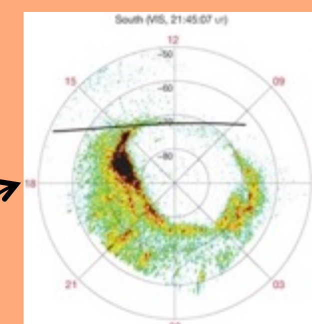
- High-altitude imagers: 6U 3-axis stable platform imaging auroral ovals at 10km resolution. Additionally, a solar wind and magnetometer package to provide solar wind information from high latitudes. Data rate 4 kb/s.



Laundal & Ostgaard, 2009





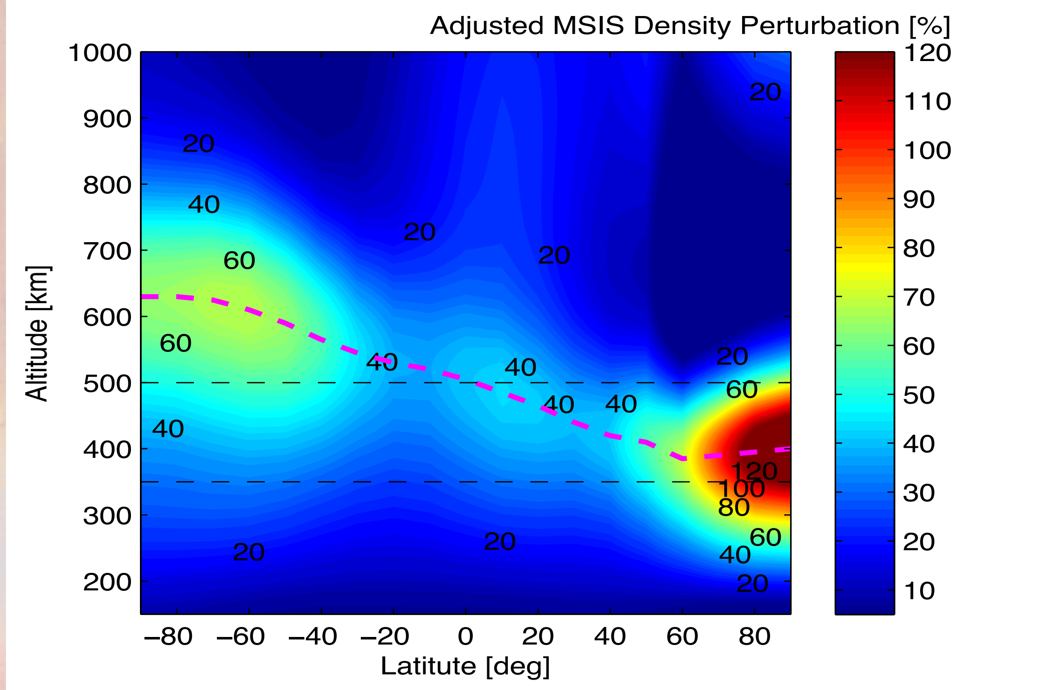


Orbit configuration of LEO ionospheric constellation. Arranged on 6 orbit planes round 0-12MLT it establishes intensity, location, and localization of strongest field aligned currents during storms. It is superimposed on a Super-DARN ionospheric convection map. High-altitude imagers provide global conductivity information.

3) Mission Concepts for Satellite Drag and Thermospheric Density Variability

Thermospheric Variabliity

- The mass density of the thermosphere varies dramatically in response to changes in solar EUV and magnetospheric energy inputs.
- At typical LEO satellite altitudes, high latitude densities are in error by 80% relative to standard empirical models.
- At the altitude of the ISS, the errors are even larger.



Empirical model errors during quiet solstice conditions. Models do not treat Helium concentration accurately. [Thayer et al.]

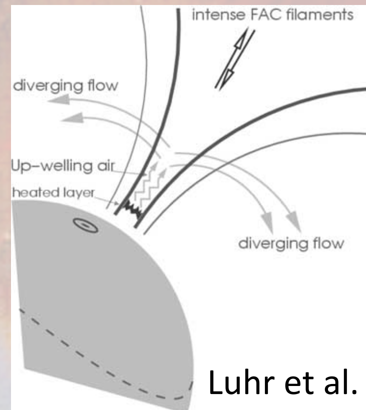
Satellite drag: F = ∫ ½ ρ v^2 along the track

ρ is mass density -- depends on concentration of all species

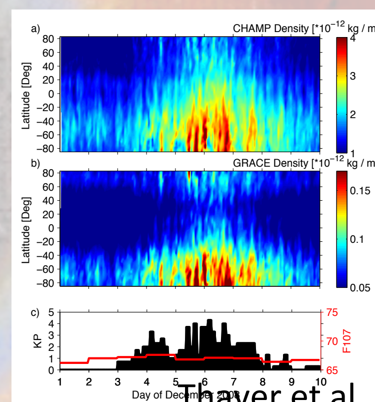
v is spacecraft velocity in rest frame of neutrals – includes neutral wind effects, which can be up to 20%

Knowledge Gaps

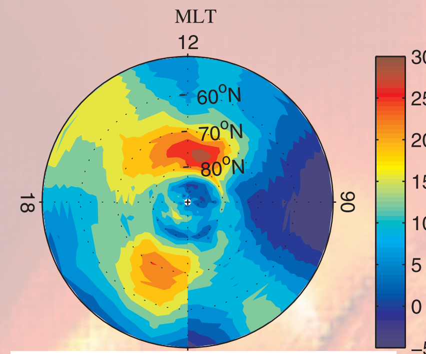
- Evolving local magnetospheric energy input (charged particle vs. Joule heating; location, scale size, temporal persistence)
- Global response of thermosphere-ionosphere system to these inputs (mechanisms, role of temperature enhancement vs. vertical wind vs. horizontal transport)
- Variability of detailed EUV spectrum and EUV radiance – presumed covered by GOES but may need “gap filler” missions



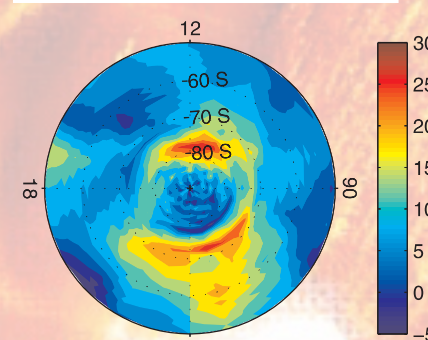
Luhr et al.



Thayer et al.

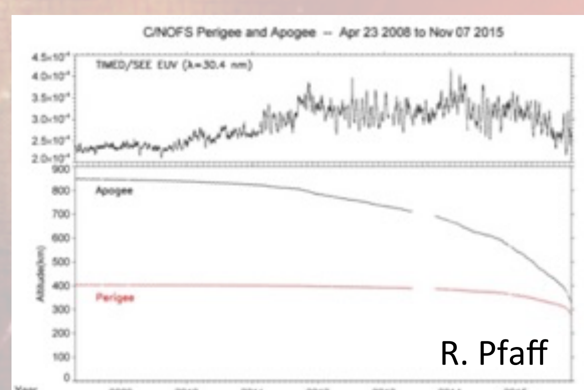


Northern Hemisphere

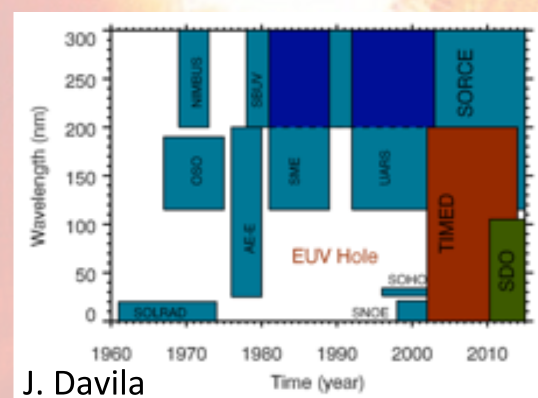


Southern Hemisphere

Liu et al.



R. Pfaff



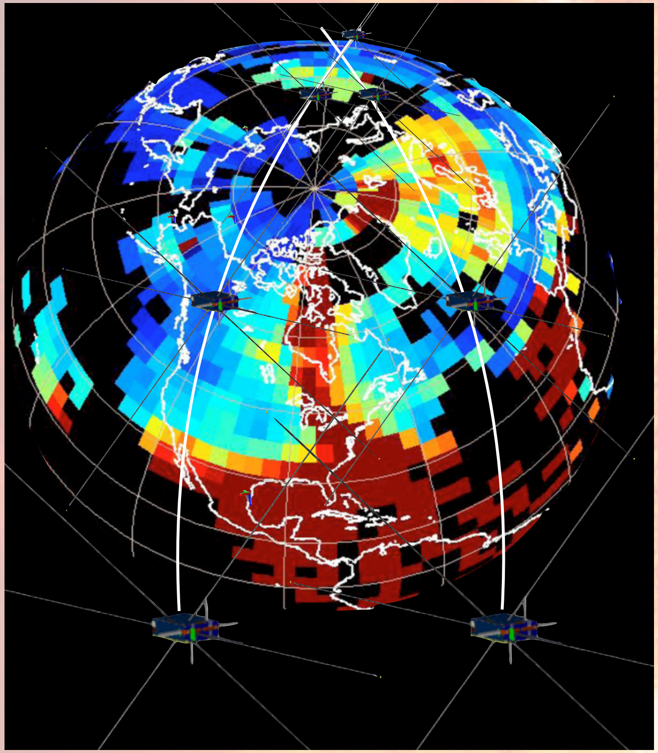
J. Davila

Small-sat Concept to Address the Gaps

- Fleet of 12U–27U 3-axis stabilized small-sats to measure thermospheric mass density, temperature, and composition, over the globe. Accompanied by measurements of magnetospheric energy inputs (20 – 20 keV electrons and Poynting flux) and F-region winds which modify the drag predictions and drive horizontal transport.

- Can be an ad-hoc constellation, launched as secondary rides become available – minimum useful set would be 3-6 in a single orbital plane to assess spatial and temporal scales of inputs and responses, and also a spread of several (4-6) spacecraft at different local times to measure the global response. Significant coverage at high latitude required.

- Sweet spot for initial studies would be 500-600 km altitude circular orbits – highly complementary to larger scale planned missions, which carry much more comprehensive instrumentation and propulsion to measure the heart of the ion-neutral coupling region.

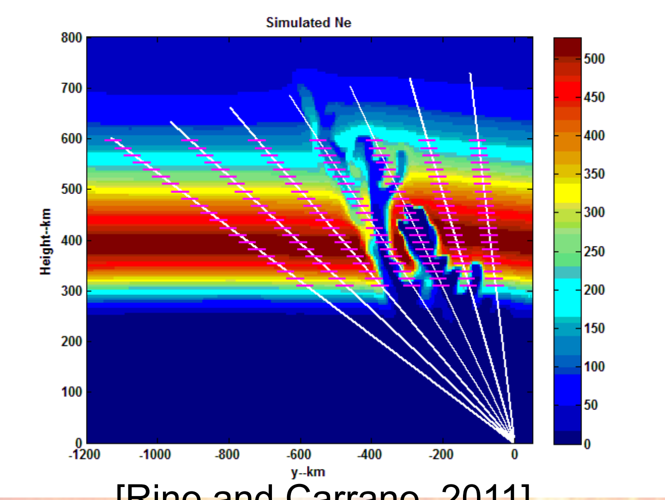


4) Mission Concepts for Ionospheric and Plasmaspheric Plasma Irregularities, Total Electron Content (TEC), and Scintillation

Ionospheric Plasma Disturbances

- Ionospheric irregularities, caused by plasma instabilities and plasma turbulence, can create significant RF scintillation.

Plasma instabilities are widespread and occur at low, middle, and high latitude in the E and F regions of the ionosphere. In the auroral zone, scintillations are strongest during geomagnetically active periods, but occur at all times in auroral bands. At low latitudes scintillations are associated with equatorial spread F events triggered by such large-scale instabilities as Rayleigh-Taylor, which occur in both active and quiet periods.



[Rino and Carrano, 2011]

- Spatial gradients and temporal variability of the plasma density can cause strong fluctuations in signal amplitude and phase, hence hindering precise and safety–critical operations such as positioning and navigation.

Knowledge/Measurement Gaps

- Forecasting plasma instabilities is challenging, both because the most important drivers are difficult to measure and/or predict, and because the ionospheric response to the drivers is often complicated and not obviously deterministic.
- The physical mechanisms responsible for producing ionospheric irregularities are elusive: the most important sources of free energy, and the causal chains that both generate and suppress irregularities leading to scintillations, are unclear.
- The plasma irregularities drift, limiting the duration ground-based investigations and making it unlikely that a single LEO satellite can revisit an individual patch/bubble event on successive orbits.

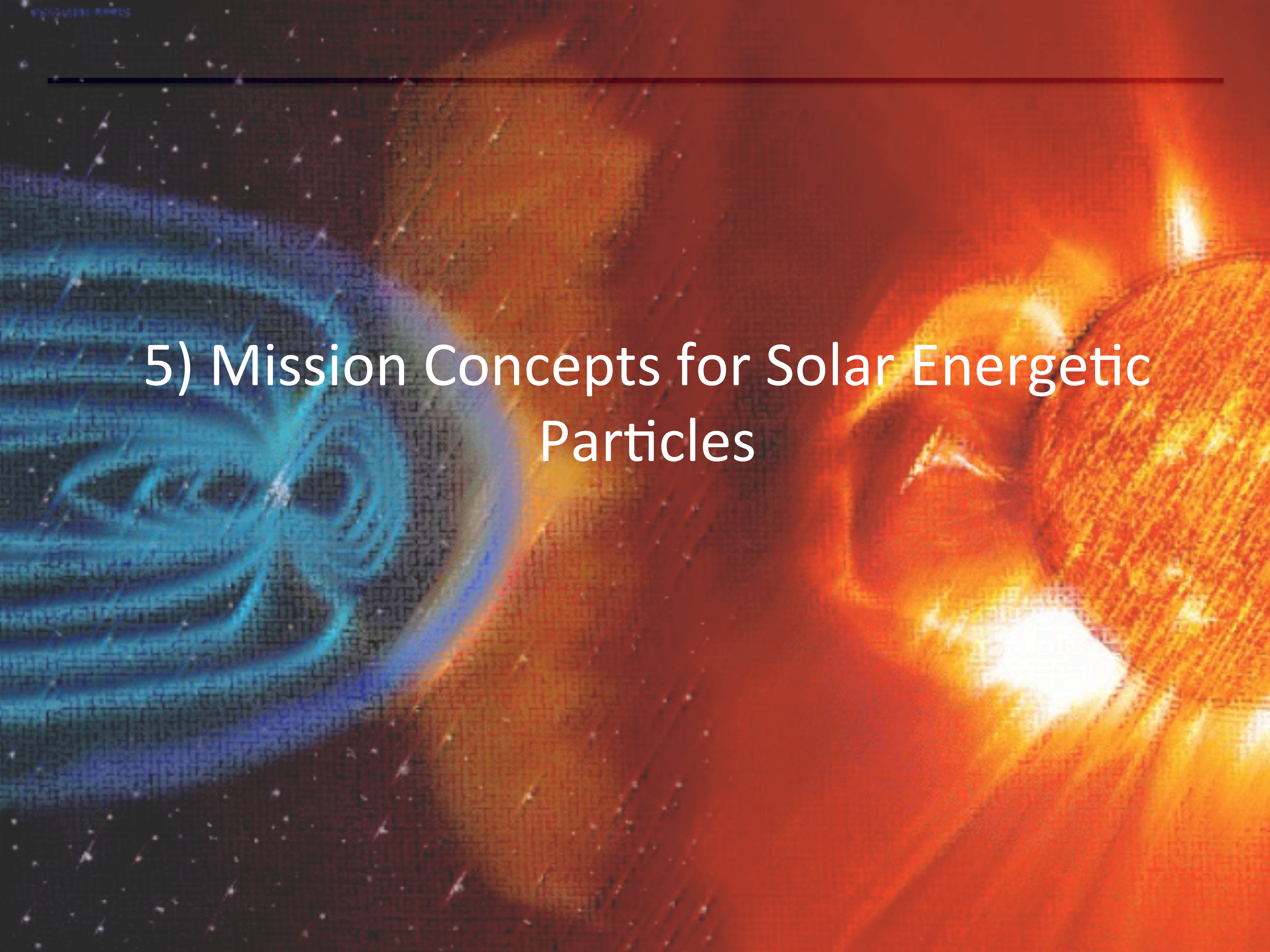
Small Sat Concepts to Address the Gap

- US Nat'l SWx Action Plan: the ionospheric disturbance benchmarks and associated confidence levels will define at least the following:
  - Ionospheric radio absorption and duration as a function of frequency;
  - Total electron content (TEC; slant, vertical, and rate of change);
  - Ionospheric refractive index; and
  - Peak ionospheric densities and the height of the peak.

- ***Mission Concept 1:*** **Active direct measurement (VHF-UHF Radio) of TEC** directly from a constellation of transmitting/receiving 6U CubeSats. LEO observations will measure bottom-side TEC; higher orbits will measure top-side TEC and enable plasmaspheric investigations.

- ***Mission Concept 2:*** **Passive indirect measurements (UV) of TEC** —via 135.6 nm, 91.1 nm, 83.4 nm from a spinning, scanning platform of a single or multiple 6U CubeSats to map plasma density, as well as investigation of compositional change associated with storms.

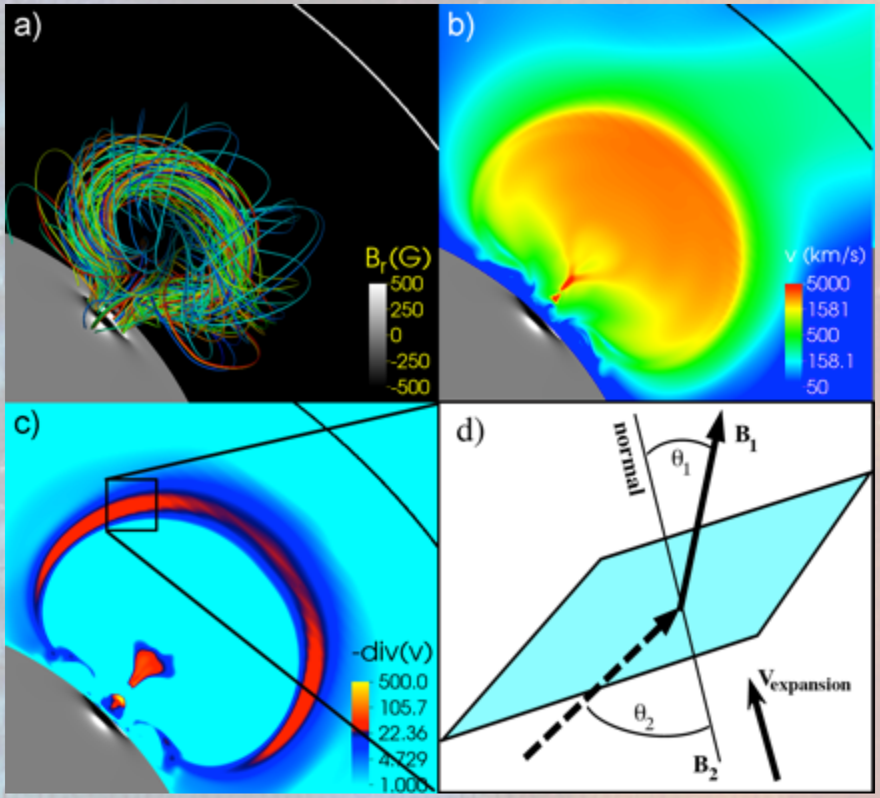
5) Mission Concepts for Solar Energetic Particles



Driving Science Questions

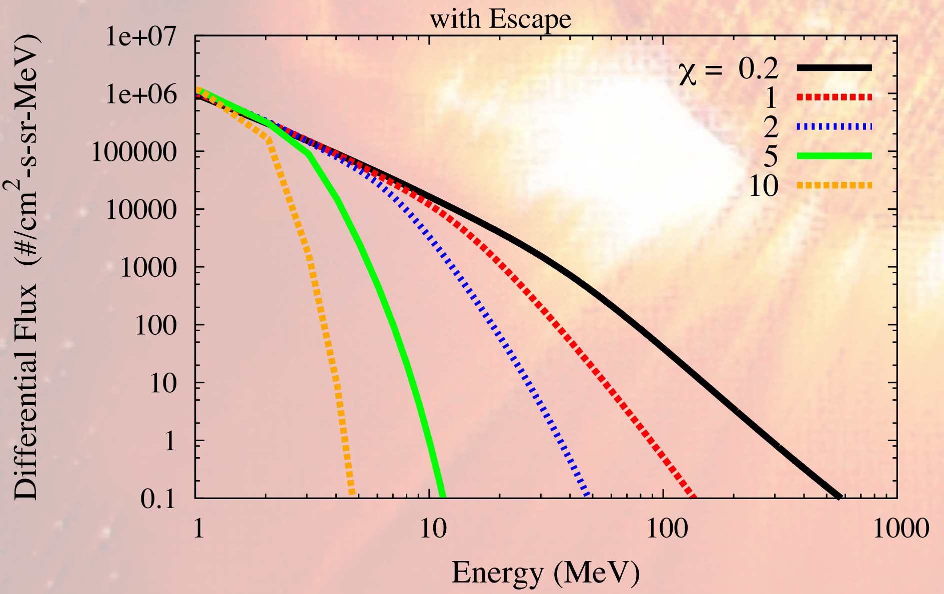
- What are the sources of solar energetic particle (SEP) acceleration?
- What determines the longitudinal & latitudinal distributions of SEPs?
- How do radiation hazards evolve?
- What are the secondary components of radiation?

Sources of Low Coronal Particle Acceleration



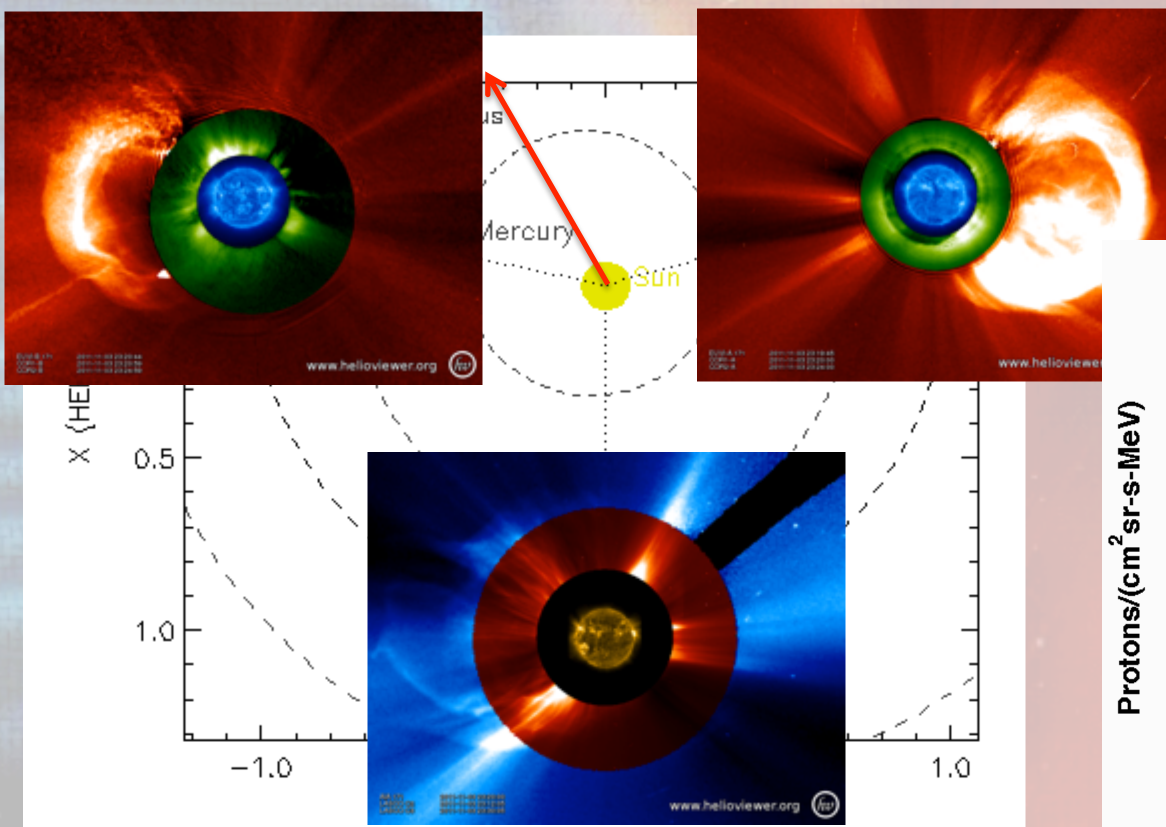
Schwadron et al., ApJ, 2015

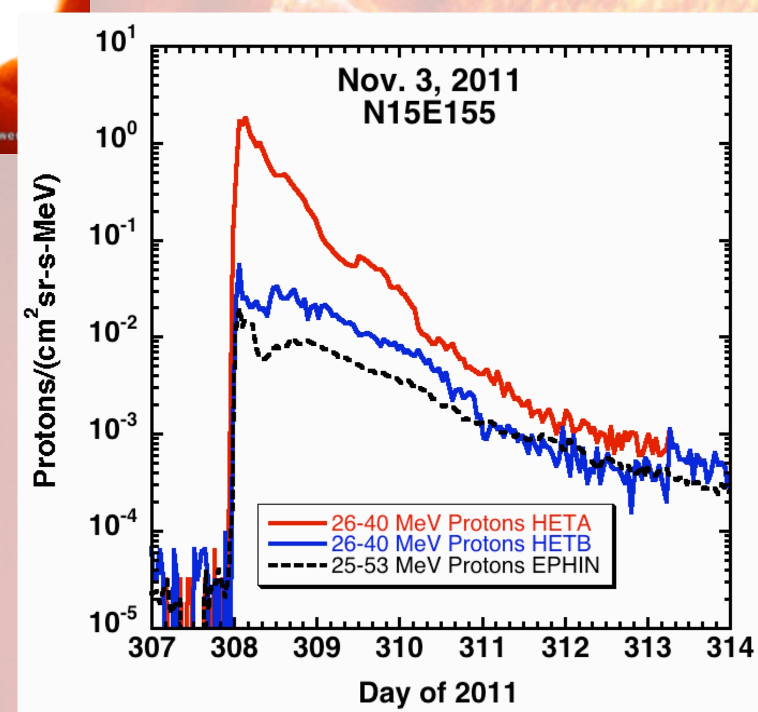
- Flanks of CMEs show significant acceleration
  - Strong Compression
  - Quasi-perpendicular shock/ compression
  - Longer connection time
- Broken power-law due to footpoint motion across the face



Longitudinal Distribution

- High-energy protons are seen 360° around the Sun within 30 minutes – how does that happen?
- ^{3}He broadly distributed (>100°) with and without CMEs
- Presence of CMEs narrows longitude distributions



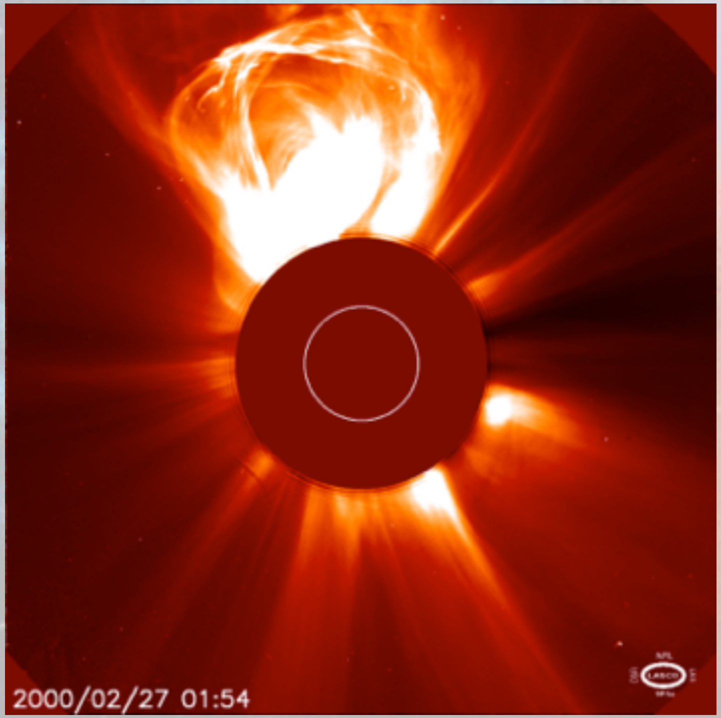


Low-frequency Imaging Array in Space

Question: Where in the inner heliosphere does particle acceleration occur and why?

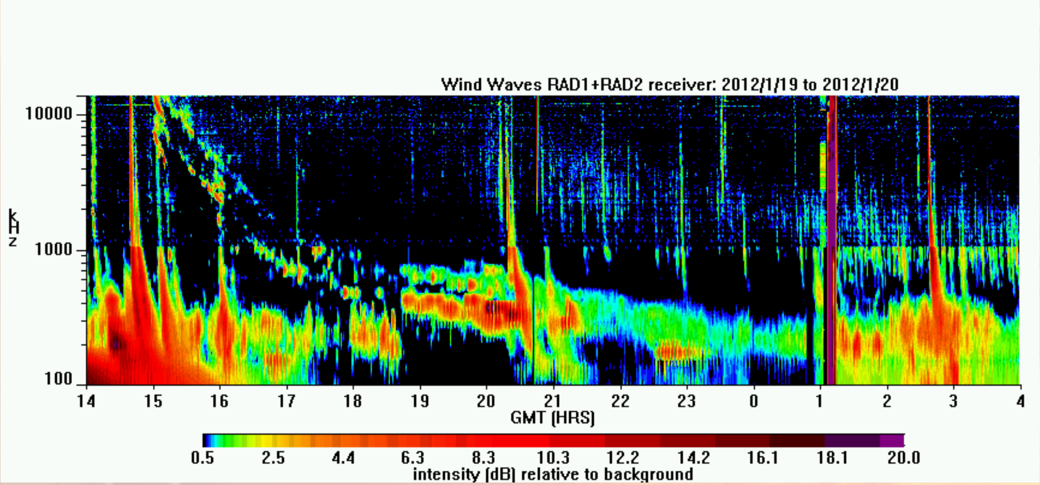
- Approach: Image coherent radio emission produced by energetic electrons at shocks.
- Background: This emission is detected all the time from space (need to be above ionosphere) but we cannot image, just measure total power. NOAA uses this routinely to tell if there is a strong shock, but we do not know where on the shock acceleration occurs, or where the shock is headed.

A coronagraph can image CME and shock, but not energetic particles



Emission frequency $f \propto \sqrt{n} \sim 1/r$

In this example CME emits all the way out to 1 AU a day later

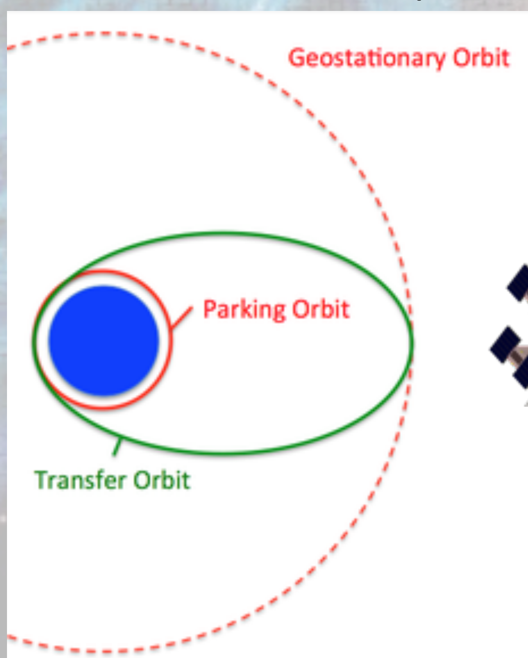


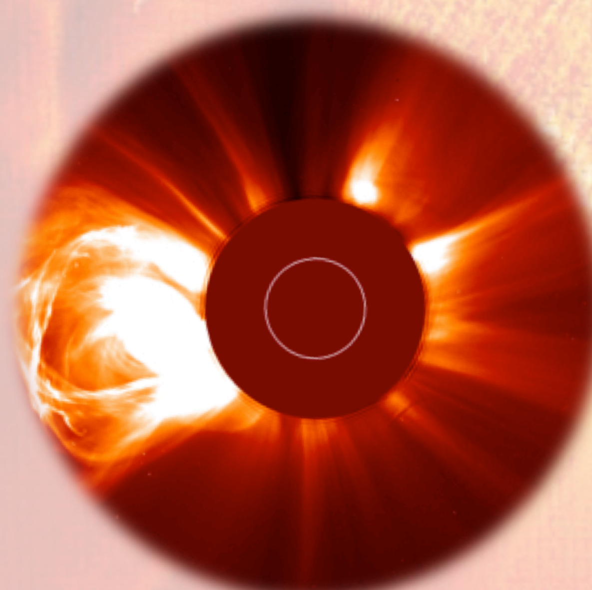
We know this emission exists, it is strong and easy to detect, we just need a way to image it.

Low-frequency Imaging Array in Space

Mission Concept:

- Sun-pointed 6U spacecraft with basic antennas and receivers, GPS for timing and formation knowledge (not active)
- Performance driver: Image quality grows as the number of independent combinations of antennas.
- Sensitivity, pointing, power are easy to achieve at low frequencies.
- Deploy spacecraft into a loose 10-100 km constellation, observe up to 50 events per year
    - 6 spacecraft = 15 independent baselines per frequency + Hundreds of frequencies + Relative motion in orbits = High-quality radio images
- Pathfinder for more capable missions (Heliophysics, Astrophysics, Terrestrial)





Summary: conclusions from the set of mission concepts

Critical LWS Needs

a) additional remote-sensing perspectives, and
b) multi-point (and often multi-orbit) in-situ measurements.

Spacecraft sizes

from 6U CubeSats to 12U small-sat and larger for solar, magnetospheric, and ionospheric/thermospheric/mesospheric remote sensing

6U CubeSats for in-situ measurements

Spacecraft number

swarms or constellations with at least 6 S/C, up to 60 S/C, but some of these may be launched sequentially

Spacecraft capabilities

Data rates from 1 kb/s ->

Orbits from LEO to interplanetary

Some concepts need S/C propulsion for prime-phase orbital adjustment.

Conclusions for LWS System Science

1) LWS system science has a critical need to use cubesat / smallsat technologies and launch opportunities to enable essential multi-point (and often multi-orbit) in-situ and remote-sensing measurements in key regions in the Sun-Earth domain.

2) Many LWS mission concepts enabled by cubesat / smallsat opportunities require either swarms or constellations of at least 6 S/C up to 60 S/C small-sats (up to ~1/2 as large as a typical SMEX), all (considerably) larger than 1U–3U cubesats. Consequently, many of these missions are not "small" in their class, although they benefit from technologies emerging from the cubesat realm, and their capability for a given cost is substantial

3) Because true cubesats are of limited value to LWS system studies when flown as single S/C, these LWS concept missions can be viable only if new cost structures and risk concepts are implemented that use functionality of the whole constellation in addressing LWS goals as a metric of success, but not the functionality/risk of each of the component S/C.