National Aeronautics and Space Administration

Coronal Microscale Observatory (CMO)

Discussion with HSD Coronal Heating Team
July 14, 2021

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NASA Goddard Space Flight Center

Today

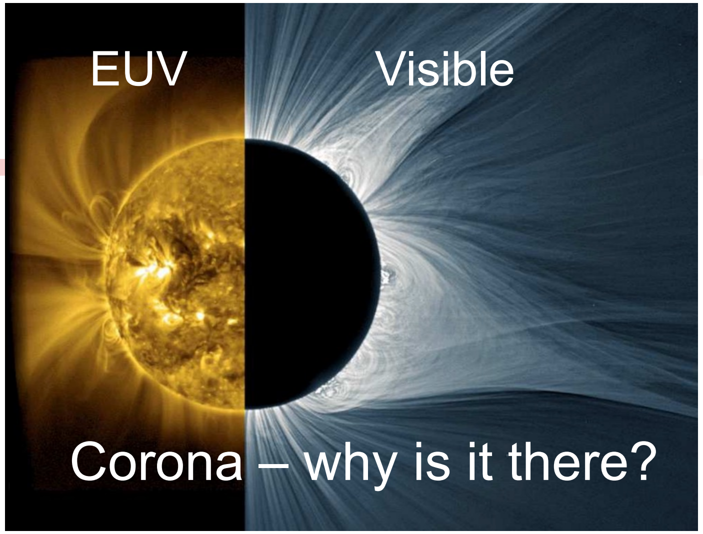
Looking for …

- Input on the science message – e.g., “incomplete”, “inaccurate”, “uninspiring” – and concrete suggestions for improvement
- Figures or simulations/animations that make the case stronger
- Elimination or A vs. B scenarios: measurements that would rule out (or strongly disfavor) some theory or mechanism; measurements that would strongly favor hypothesis A over hypothesis B. (Reviewers love these scenarios. They are hard to construct.)

Presenting …

- Preliminary science traceability
- Mission concept going into next week’s Mission Design Lab study (not going into the weeds)

Science Pitch



- The Sun has a thin outer atmosphere, the corona, that is 100–1000 times hotter than the visible surface of the star. Many other stars have a corona; many do not. Why? Why does it matter?

- The Sun's corona is scientifically important because it provides a window into fundamental physical processes. We can't yet definitively explain why it is there, and science advances by solving mysteries!
- The corona is also important because it is the source of "space weather" that can harm satellites and astronauts and can disrupt communication and navigation systems.
- Today's leading theories of coronal heating share a key ingredient: the interaction of matter with magnetic fields on spatial scales smaller than we have ever resolved. Theories are tested by comparing them with observations, but we don't have the observations we need to carry out definitive tests.
- Perhaps we will never resolve the smallest scales of coronal heating from outside the corona itself, but seeing never-before-detected features will provide breakthroughs in understanding and prediction.

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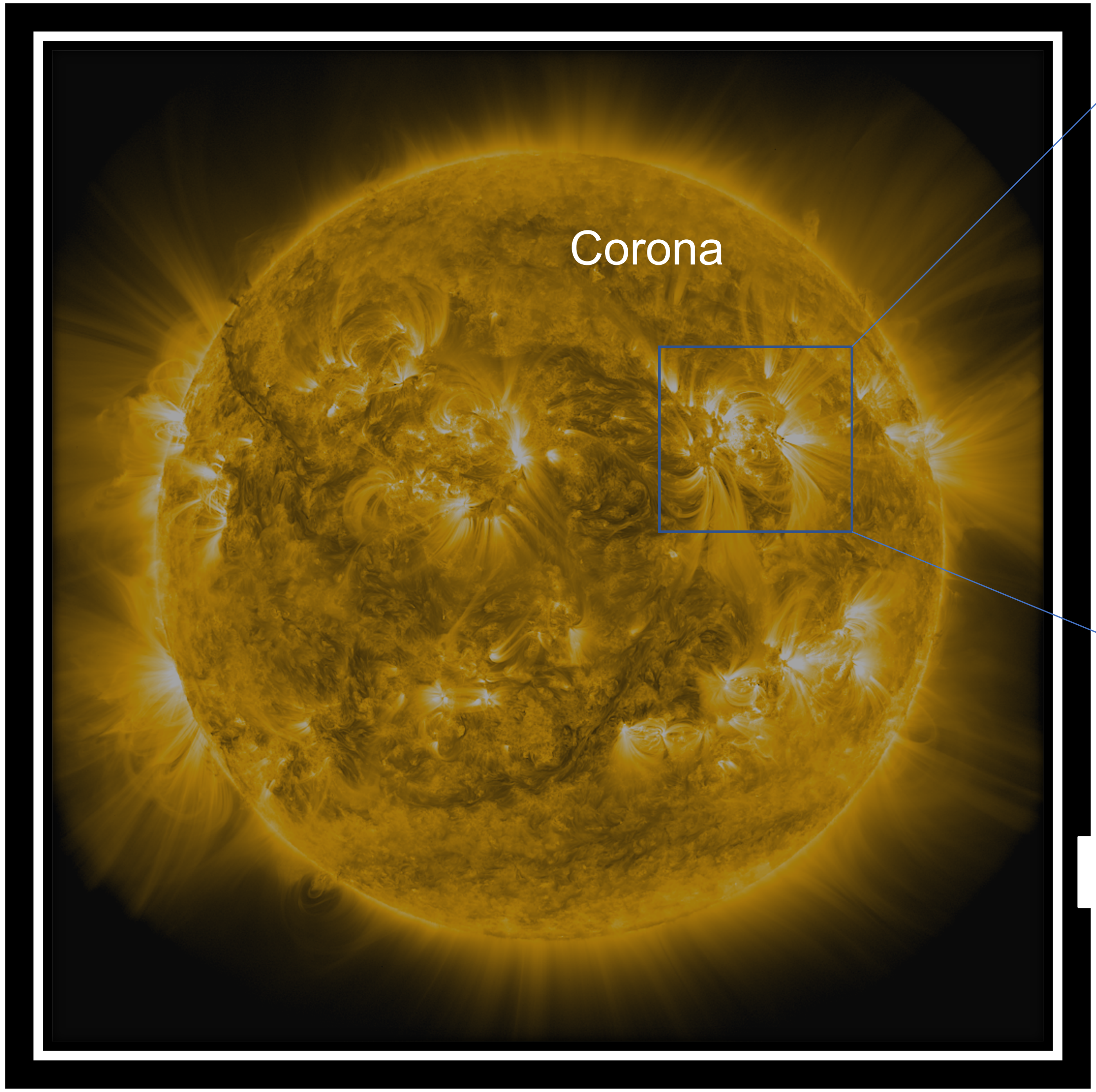
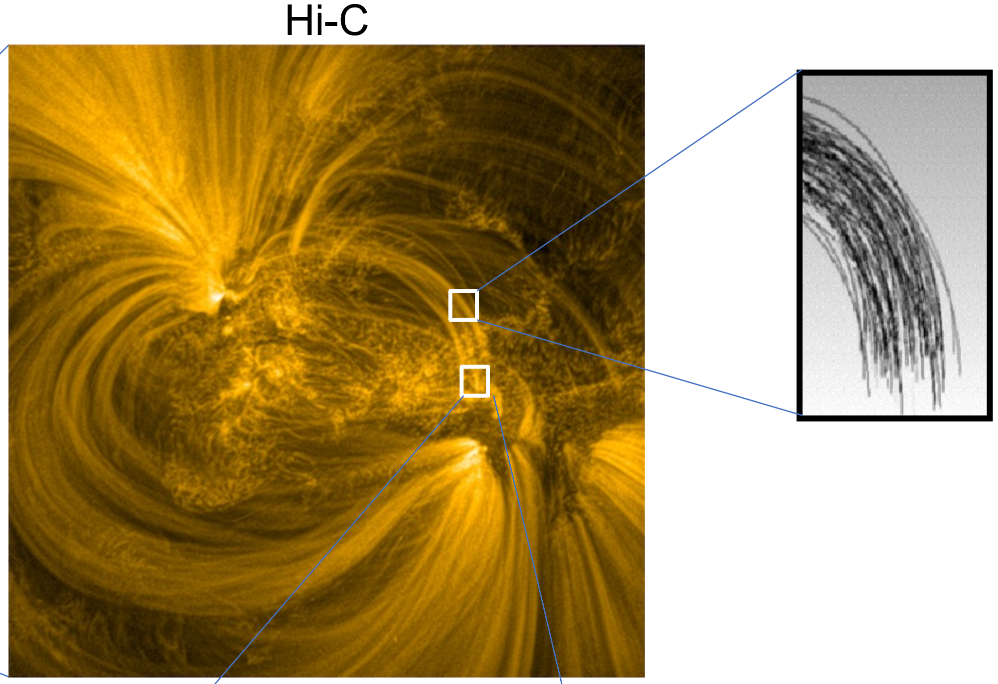
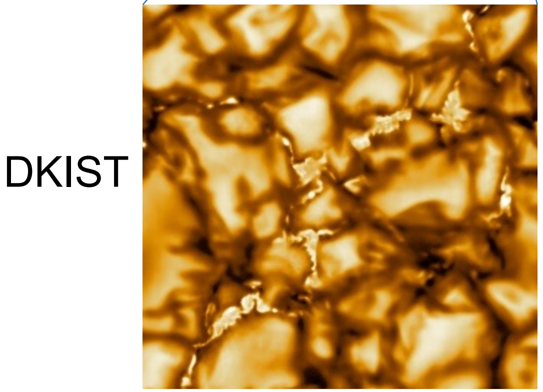
What heats the solar corona to 1000 times the temperature of the photosphere below?



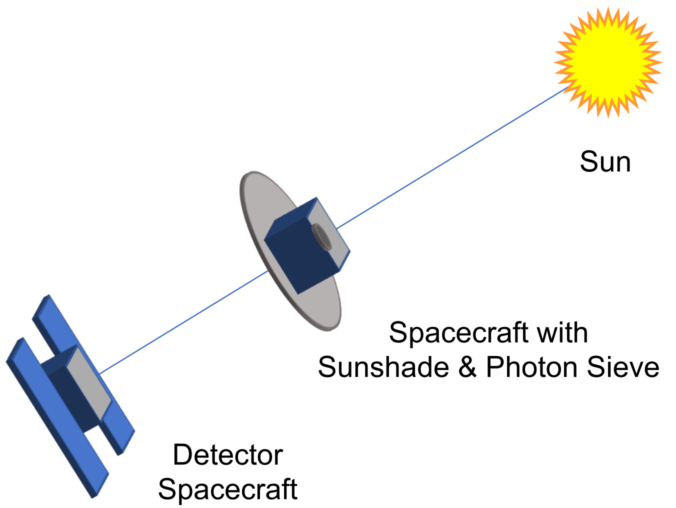




How does this mechanical motion in the photosphere (solar surface) get dissipated as heat in the solar corona?

We need new technology that can resolve fundamental scales sizes of energy release in the corona

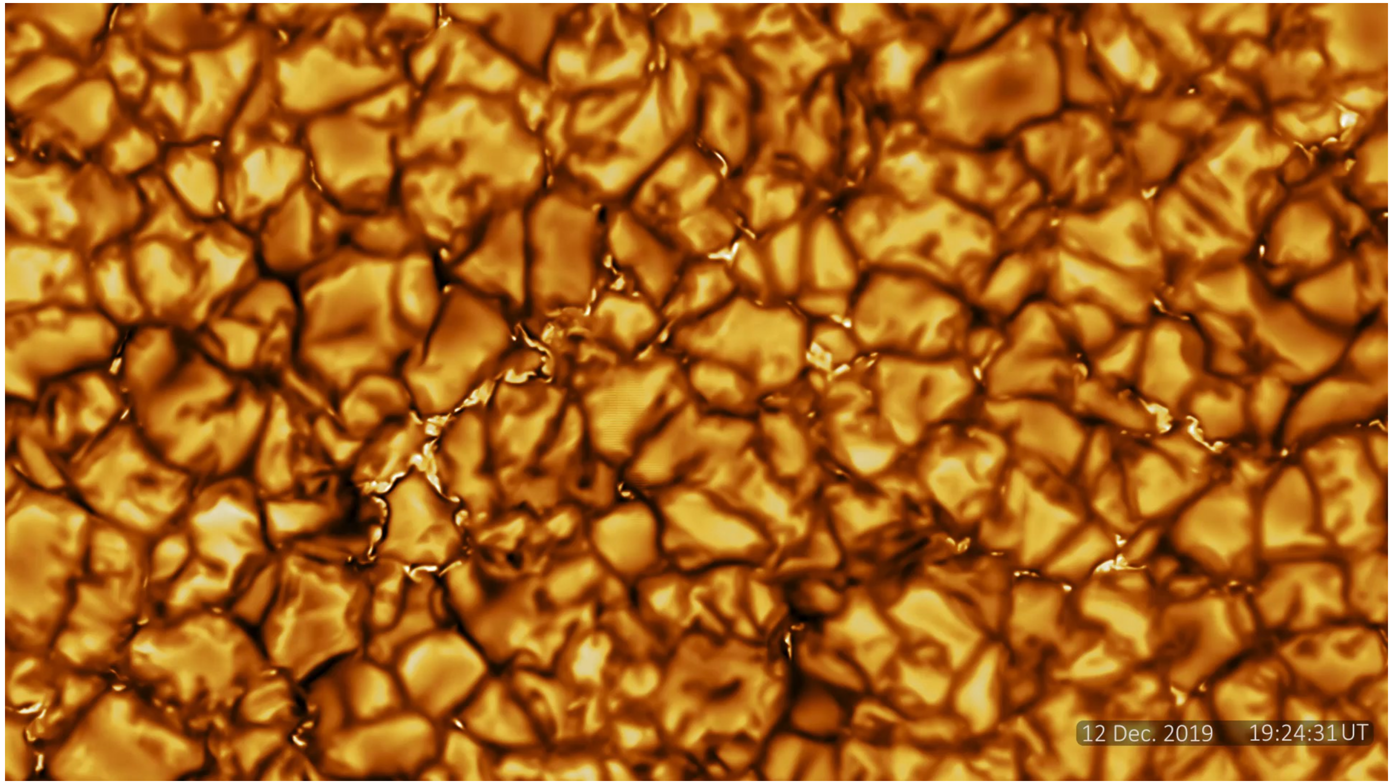
- Nanoflares have never been directly measured; currently we must infer their energy, rate, and size.
- No current technology can access these scales. The closed-field corona (quiet Sun and active regions) is inaccessible to Parker Solar Probe in situ data. SDO/AIA images are 50x too coarse, and Hi-C images are 10x too coarse.
- A breakthrough in understanding the corona and its heating requires direct observation of the individual structures and their evolution.



Are they? Why specifically do we believe that there will be structure below 200 km but above unobservable dissipation scales? CMO will resolve 20 mas (15 km).

Solar imaging in the EUV with a formation flying photon sieve will provide revolutionary observations. It will directly measure – for the first time – the spatial and temporal properties of coronal heating, and determine the sizes, shapes, and evolution of the elementary structures that make up the corona.

Energy originates in photospheric motions



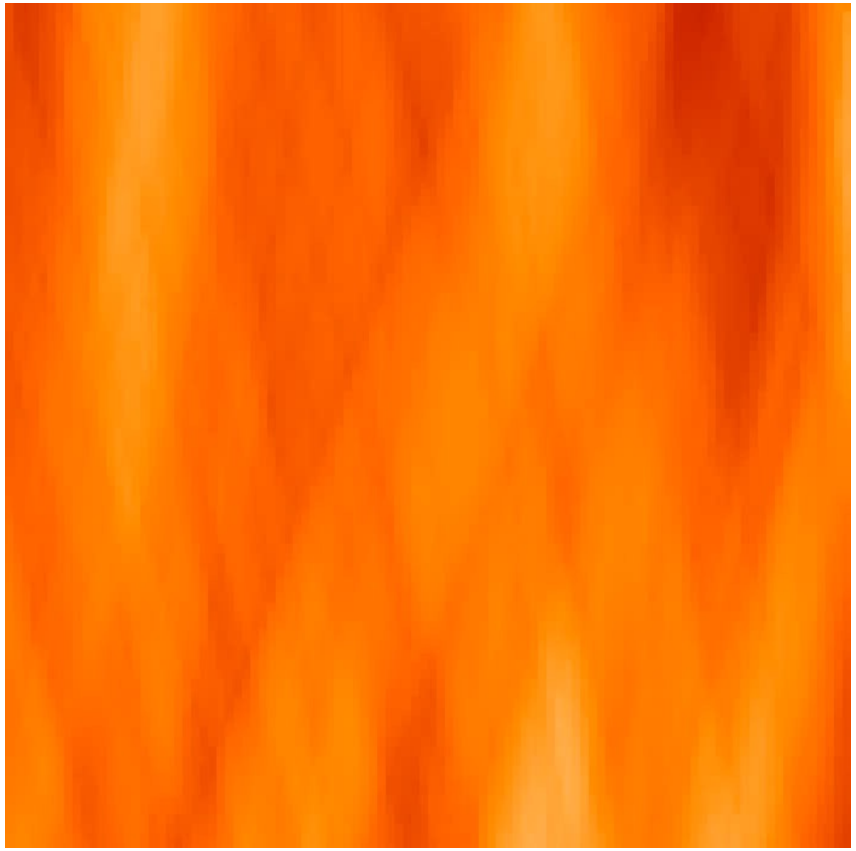
19,000 km (27 arcsec)

Daniel K. Inouye Solar Telescope

What the Coronal Microscale Observatory could see

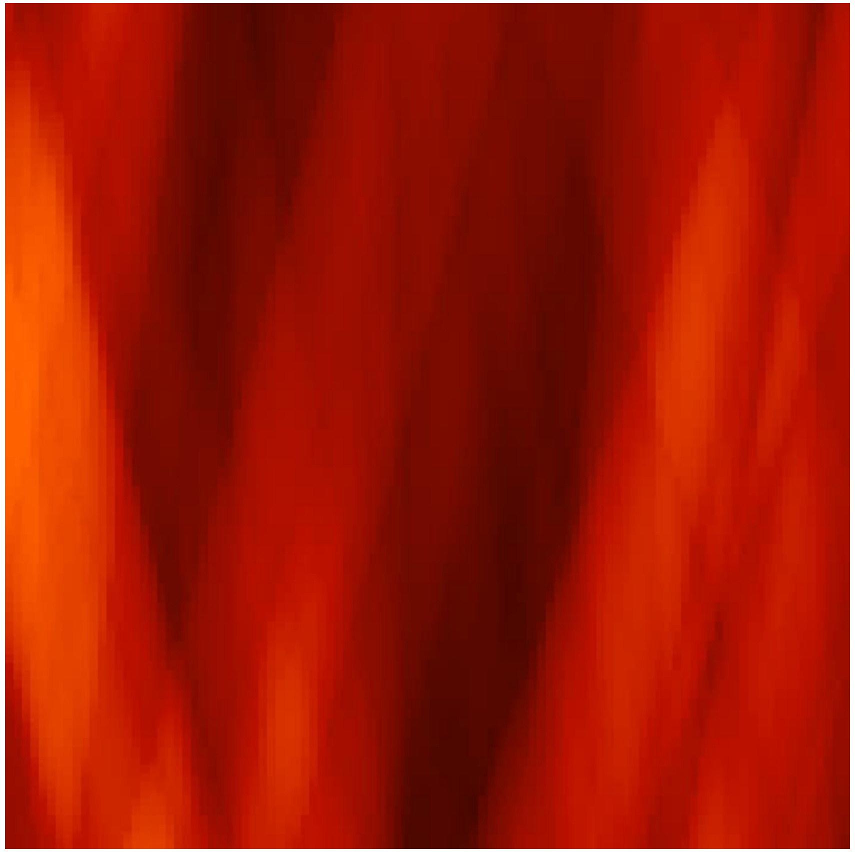
- Looking at nanoflares through the apices of coronal loops
- 1250 magnetic strands of 200 km diameter
- Random nanoflares, power law distribution

Fe XVI (335 A) 3 MK



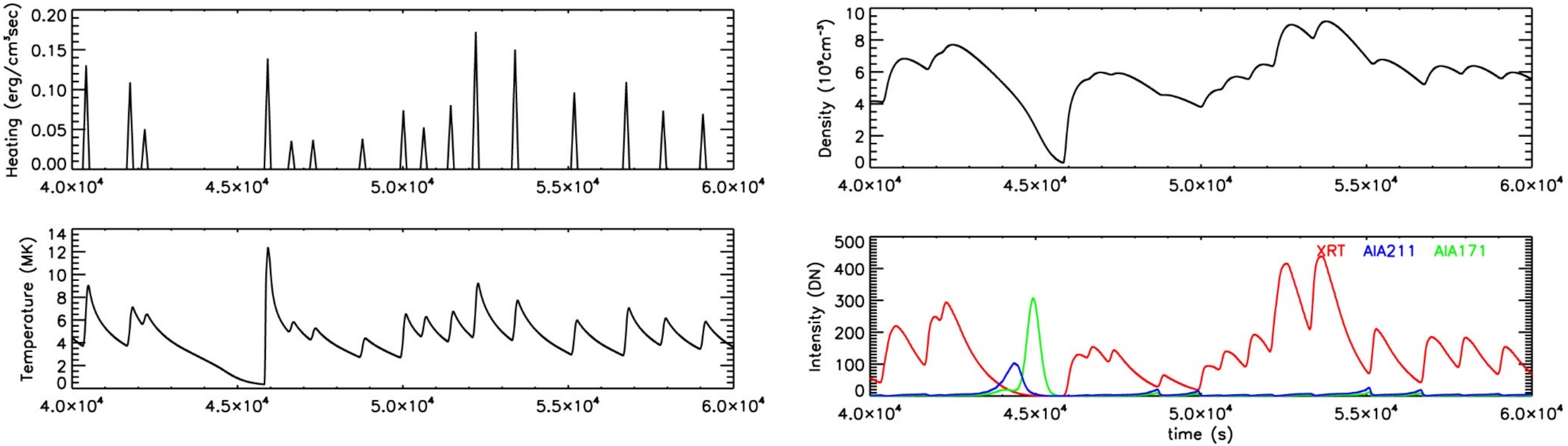
1000 km (1.3 as)

Fe XVIII (94 A) 8 MK



1000 km (1.3 as)

Behind simulated movies are physical quantities



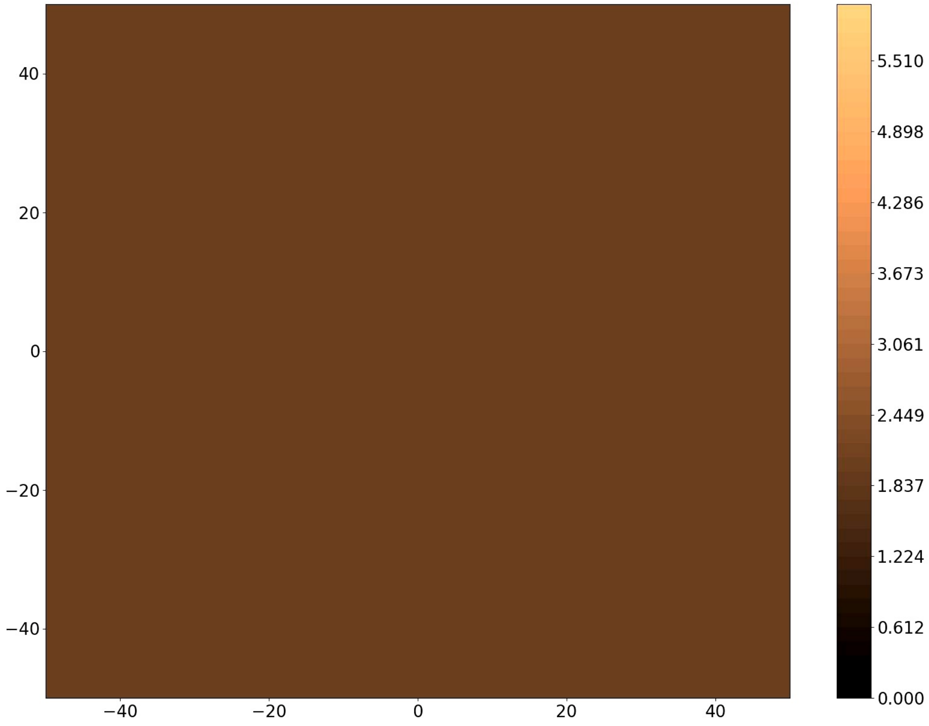
Plasma response to a series of 200-sec nanoflares modeled with the EBTEL code (López-Fuentes & Klimchuk 2016)

We will identify the heating mechanism and its properties by comparing multi-temperature observations of individual energy release regions with reconnection and wave-heating models.

Elimination or A vs. B tests?

How nanoflares manifest at the footpoints of the flux tubes

194 Å (1.5 MK)

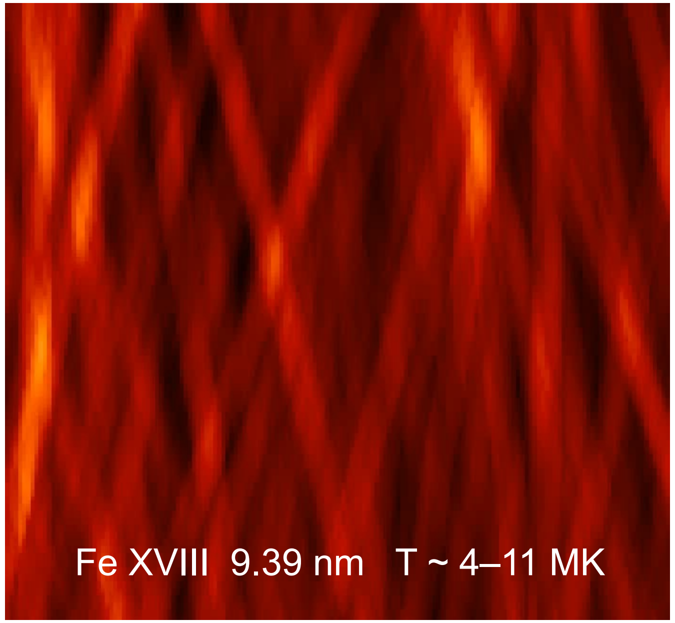


Simulated image of a cross section of a coronal flux tube ensemble as a proxy for transition region footpoint emission. (CMO will observe flux tube cross sections in the transition region.)

Reconnection, waves and shocks

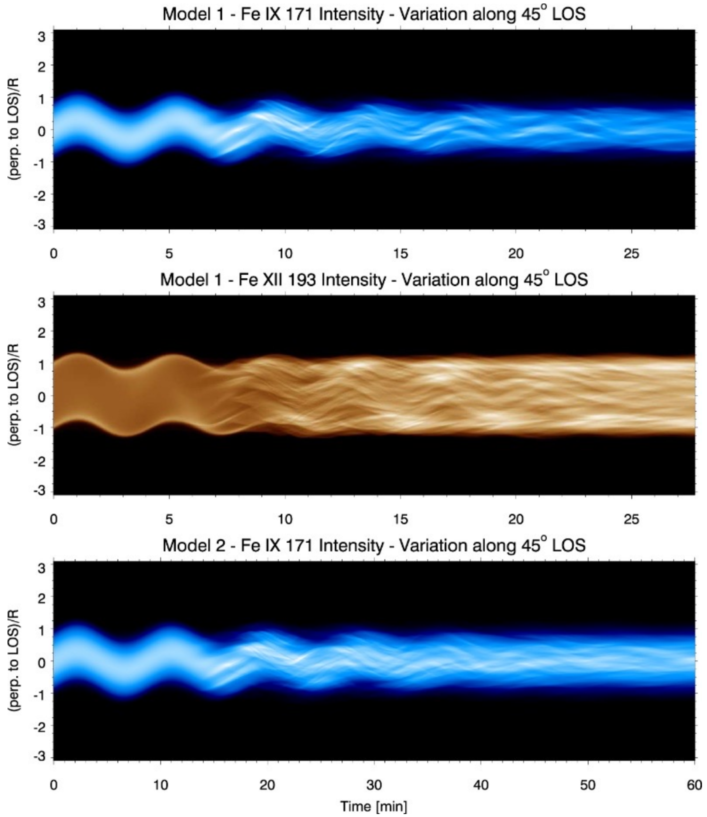
Constraints on dimensionless parameters?
How many theories are there? – i.e., distinct enough to be tested individually or comparatively.

- Reconnection, waves, and shocks have all been proposed to play an important role in coronal heating. Energy dissipation is impulsive and small scale, but microscales interact with larger scales up to the order of the solar radius.



2,000 km
(2.8 arcsec)

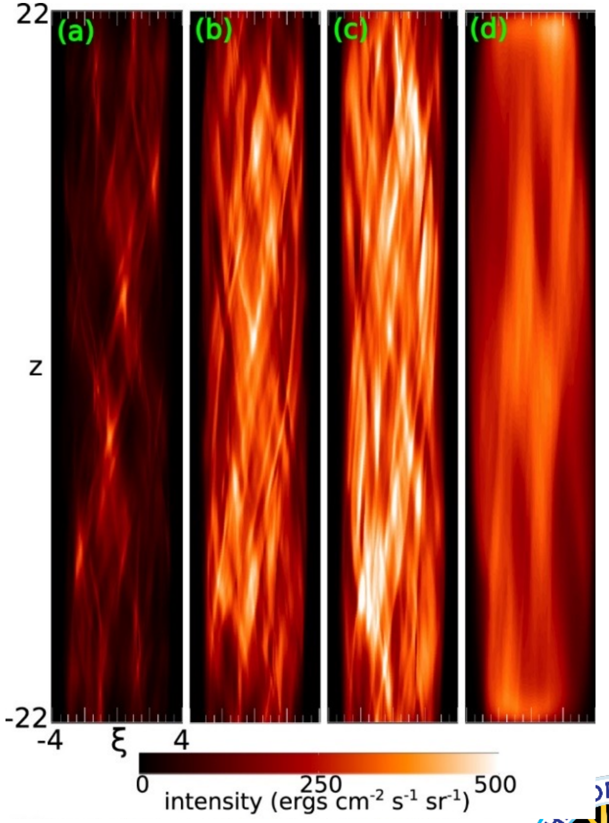
Nanoflare simulation (Klimchuk 2019)



Transverse MHD waves (Antolin et al. 2017)

Reconnection in braided loops
(Pontin et al. 2017)

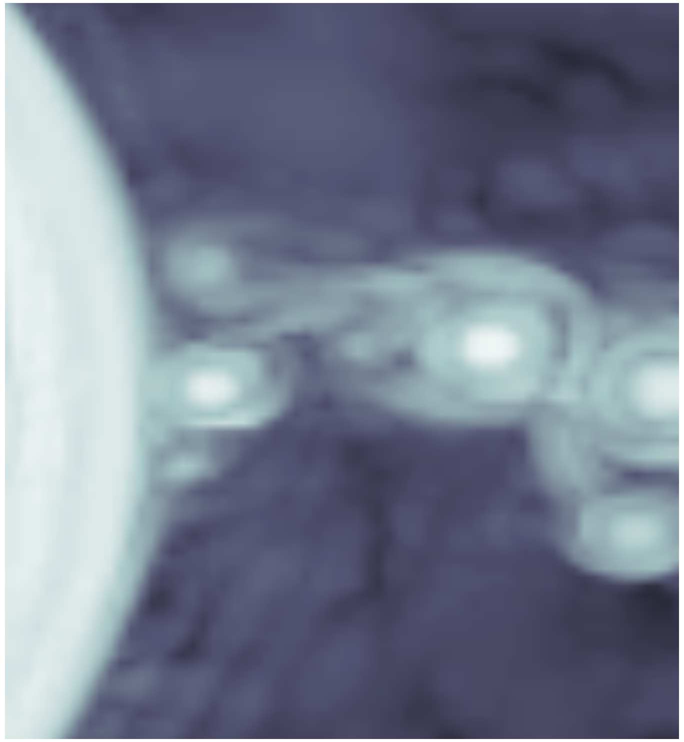
Fe XII, t = 44,61,78,309 s



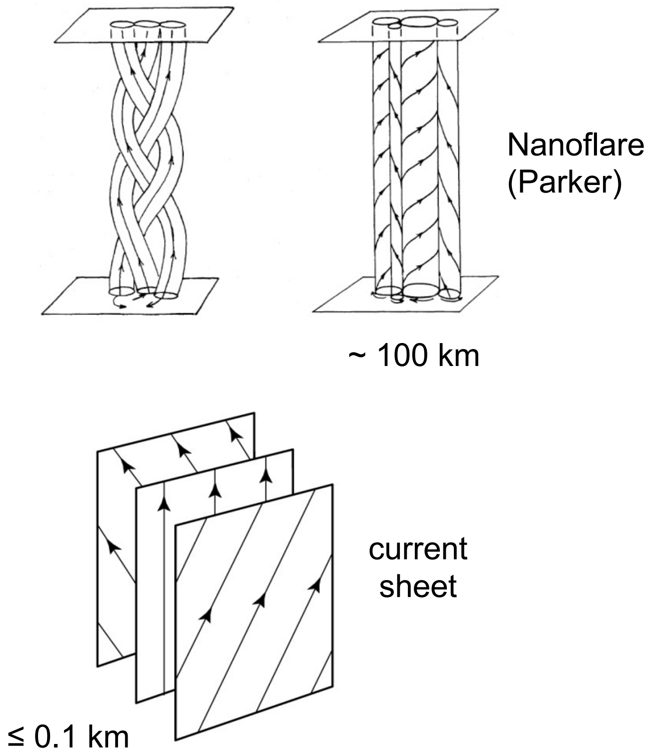
Other examples, better examples?

What is the Fundamental Nature of Magnetic Reconnection?

Plasmoids



Turbulence

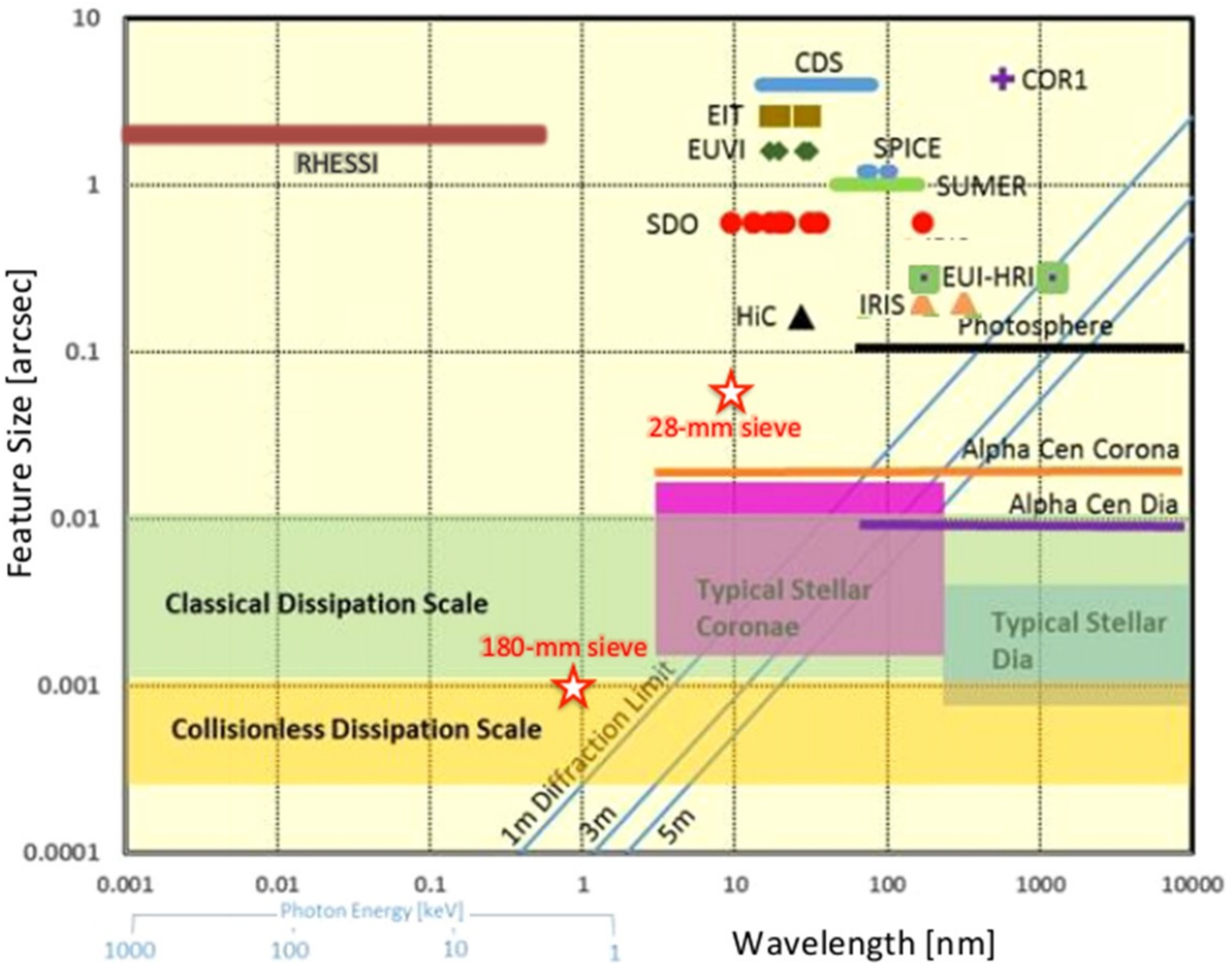


Do these illustrations translate into feasible tests with remote sensing (15 km resolution)?

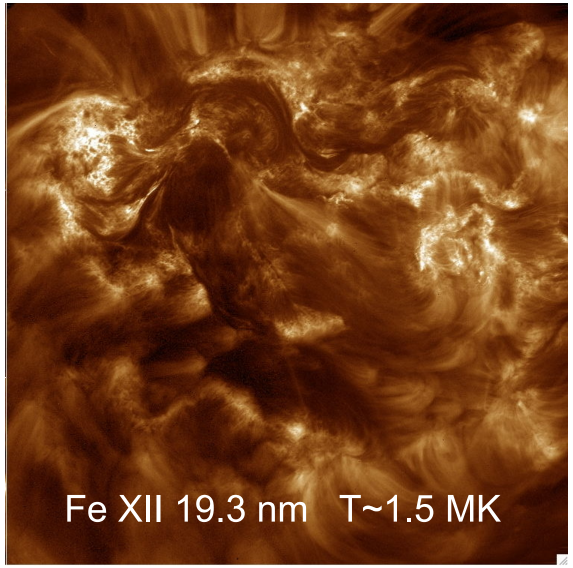
Big Picture:
Where distributed diffractive telescopes can take us

Where we have been

Where physics drives us

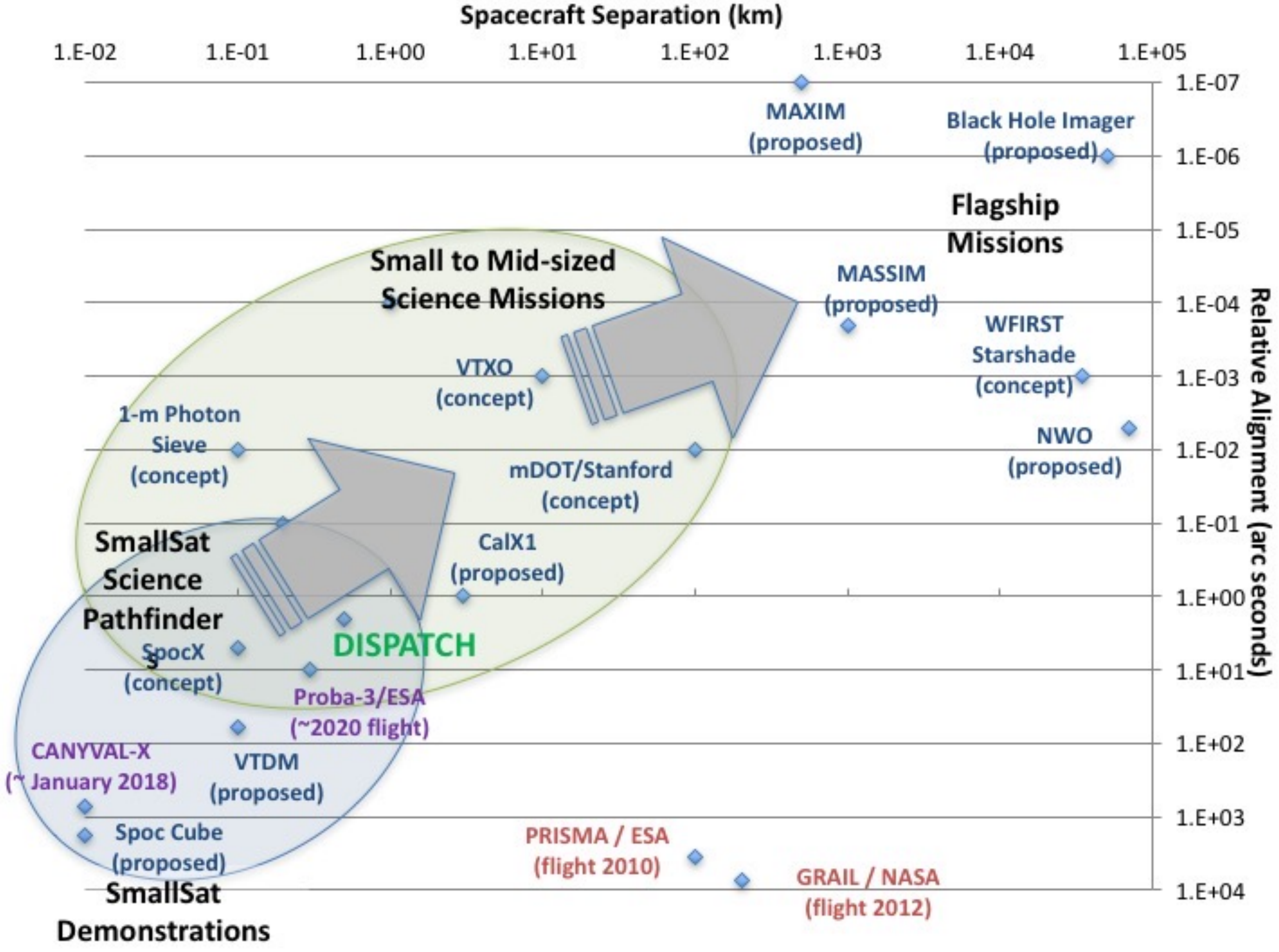


240 Mm
(5.5 arcmin)



Hi-C sounding rocket
~0.2 arcsec (150 km) resolution

Bigger Picture: Precision Formation Flying (PFF) Roadmap



Heliophysics
- X-ray, EUV, and UV imaging
- Solar coronagraph

Astrophysics
- Milli-arcsecond and Micro-arcsecond X-ray imaging
- In-space X-Ray telescope calibration
- Starshade/Exoplanet detection

Planetary:
- Chemical composition of Exo-planets
- Near Earth Objects

Science Objectives & Expected Significance/Impact

Objectives

1. Directly measure – for the first time – the spatial and temporal properties of coronal heating.
   - Determine the magnitudes, durations, and frequencies of nanoflares.
   - Distinguish drifting heating (waves) from spreading heating (reconnection).
   - Determine the basic nature of reconnection in different magnetic environments (plasmoids vs. turbulence).

A vs. B simulations of observables?

2. Directly measure – for the first time – the sizes, shapes, and evolution of the elementary structures that make up the corona.
   - Understand how these structures interact to produce nanoflares and how the structures are in turn modified and rearranged by the nanoflare reconnection.
   - Understand the clustering of nanoflares (nanoflare storms) that produce bright coronal loops.
3. Directly observe – for the first time – the substructures that make up flares.
   - Determine the prevalence and size distribution of reconnection plasmoids.
   - Determine similarities and differences among events spanning many orders of magnitude (full, micro, nano flares).

Significance/Impact

- We have reached a limit in our ability to use existing observations to definitively test the leading theories of coronal heating. By comparing multi-temperature, ultra-high-resolution observations with reconnection and wave-heating models, we will finally answer this fundamental question.

Science Traceability Matrix (STM)

Science Goal	Science Objectives	Measurement Req	Instrument Req	Mission Req.
What are the fundamental scales of energy release in the solar corona?	Directly measure – for the first time – the spatial and temporal properties of coronal heating: Determine the magnitudes, durations, and frequencies of nanoflares (reconnection). Distinguish drifting heating (waves) from spreading heating (reconnection). Determine the basic nature of reconnection in different magnetic environments (plasmoids vs. turbulence).	Measure the amount plasma at very how (>5MK) and hot (1-5MK). Measure the spatial distribution and temporal distribution of temperature increases and density structures as a function of many heating and cooling cycles at a given location. Measured this at flux tube apices (coronal temperatures 1-10 MK), and at the flux tube footpoints (transition region, ~0.2-1MK).	- Time cadence of 5 s - Duration of 5 hours uninterrupted - Range of at least six wavelengths/temperatures from (~200,000 K-10 MK) -FOV of at least 5000 km (7 arcsec) -Resolution of 40 km (0.06 arcsec)	2 S/C holding separation of 100–300m Sit and stare at an AR or QS location for 5-hr Requires photon sieve with a focal length of 50 M (implies formation flying)
	Directly measure – for the first time – the sizes, shapes, and evolution of the elementary structures that make up the corona: Understand how these structures interact to produce nanoflares and how the structures are in turn modified and rearranged by the nanoflare reconnection. Measure the conditions that result in clustering of nanoflares (nanoflare storms) that produce bright coronal loops.	Measure density and temperature structures and compare to inferred 200 km elementary structures scale. Measure the relationship of structures in temperatures and density with groups of heating events (increases in temperature), and avalanches of heating events over several heating and cooling cycles. Measured this at flux tube apexes (coronal temperatures 1-10 MK), and at the flux tube footpoints (transition region, ~0.2-1MK).	- Time cadence of 5 s - Duration of 5 hours uninterrupted - Range of at least six wavelengths/temperatures from (~200,000 K-10 MK) -FOV of at least 5000 km (7 arcsec) -Resolution of 60 km (0.06 arcsec)	
	Directly observe – for the first time – the substructures that make up flares: Determine the prevalence and size distribution of reconnection plasmoids. Determine similarities and differences among events spanning many orders of magnitude (full, micro, nano flares).	Measure the spatial distribution and temporal distribution of temperature and density structures during individual flare events spanning several orders of magntitude. Measured this at flux tube apexes (coronal temperatures 1-11 MK), and at the flux tube footpoints (transition region, ~0.2-1 MK).	- Time cadence of 0.1 s - Range of at least six wavelengths/temperatures from (~200,000 K-10 MK) -FOV of at least 5000 km (7 arcsec) -Resolution of 60 km (0.06 arcsec)	Onboard autonomy with image summing to achieve SNR for smaller flares while maintaining high cadence without saturation for large flares Mission duration of 3 year to measure at least one QS region and at least three unique ARs.

Science Traceability Matrix (STM) beyond threshold

Science Goal	Science Objectives	Measurement Req	Instrument Req	Mission Req.
How is the solar wind formed?	Determine from where on the Sun is the solar wind released.	Measure plasma flow via brightness enhancements (density structures) and their optical motion. Measure the nonradial connectivity continuously from the low corona through the transition to the upper corona where radial flows/structure dominate.	-White light density images of solar corona 1.05 Rsun to 5 Rsun, at all latitudes. -Continuous duration of 16 hours -Time cadence 10s -Spatial resolution – 5.5”	1.05 Rsun requires long baseline between occulter and imager; 2 s/c information flying. Radial FOV extent of 5 Rsun and duration of 16 hours requires space based measurements.
	Determine how much solar wind is released through magnetic reconnection.	Image the time-dependent increases of T and N when hotter, denser plasma from closed-fields is released onto cooler, more tenuous open field lines. Measure the density and temperature structures as they advect outward.	-4-color coronagraph images of solar corona 1.05 Rsun to 5 Rsun, at all latitudes. -Continuous duration of 16 hours -Time cadence 10s -Spatial resolution – 5.5”	4-color camera (BITSE)
	Determine the solar wind acceleration as a function of distance from Sun and solar latitude.	Global measurement of N V and T as a function of latitude and distance from Sun. Determine global distribution of acceleration energy and thermal energy.	-4-color coronagraph images of solar corona 1.05 Rsun to 5 Rsun, at all latitudes. -Continuous duration of 16 hours -Time cadence 10s -Spatial resolution – 5.5”	4-color camera (BITSE) Several year mission duration to capture different global solar magnetic configurations.

Relevance to NASA Priorities (English)

- Fundamental physics throughout the universe: magnetic reconnection, waves, and turbulence; onset of reconnection; energy storage and release
- How the Sun forms the heliosphere and closed-field plasma becomes solar wind
- How the Sun's energy creates space weather and affects the Earth's climate
- How the Sun's corona compares to the coronae of other stars
- How flares, energetic particles, mass ejections, and longer timescale x-ray and UV variability from Sun-like stars can affect surrounding habitable worlds

Relevance to NASA Priorities (NASAese)

NASA Strategic Plan 2018

- Objective 1.1: Understand the Sun, Earth, Solar System, and Universe.

Heliophysics Science and Technology Roadmap for 2014-2033

- Strategic Objective: Understand the Sun and its interactions with the Earth and the solar system, including space weather.
- Science Goal F: Explore the physical processes in the space environment from the Sun to the Earth and throughout the solar system.
  - Research Focus Area F1: Understand magnetic reconnection.
  - Research Focus Area F5: Understand the role of turbulence and waves in the transport of mass, momentum, and energy.
- Science Goal H: Advance our understanding of the connections that link the Sun, the Earth, planetary space environments, and the outer reaches of our solar system
  - Research Focus Area H1: Understand the origin and dynamic evolution of solar plasmas and magnetic fields throughout the heliosphere.

2013-2022 Decadal Survey in Solar and Space Physics

- Challenge SHP-2: Determine how the Sun's magnetism creates its hot, dynamic atmosphere.

Study Team

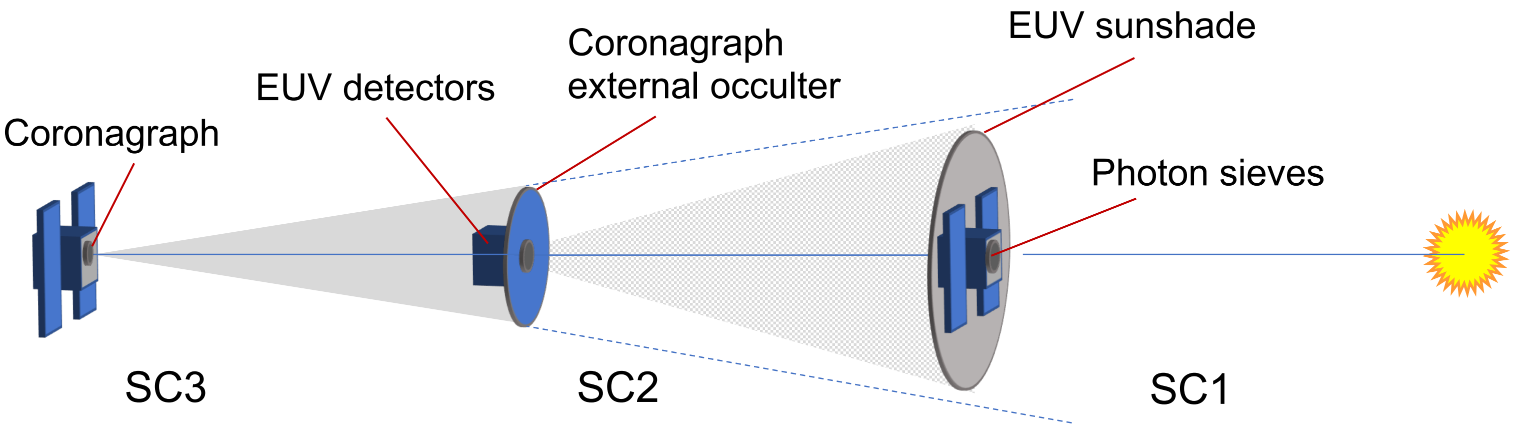
- Science
  - Jim Klimchuk (671) Lead
  - Adrian Daw (671)
  - Doug Rabin (670)
  - Nicki Viall (671)
  - Andrew Inglis (671)
  - Graham Kerr (670)
- Photon Sieve Optics
  - Kevin Denis (553) Lead
  - Adrian Daw (671)
  - Doug Rabin (670)
- Detectors
  - Adrian Daw (671) Lead
  - Andrew Inglis (671)
- Precision Formation Flying Instruments
  - Anne-Marie Novo-Gradac (670) Lead
  - Irving Linares (564)
  - Guan Yang (554)
- Guidance, Navigation, & Control
  - Phil Calhoun (591) Lead
- Sunshade Development
  - Anne-Marie Novo-Gradac (670) Lead
  - Ariel Pond (549)
- Coronagraph
  - Qian Gong (550) optics
  - Doug Rabin (670) requirements
- Thermal Engineering
  - Christine Cottingham (545) Lead
- Mechanical Engineering
  - Paul Mirel (670) Lead
  - Kevin Albin (671)
- Potential Science Partners
  - VISORS participants
    - U. Illinois, LASP, Stanford, Georgia Tech
  - CfA (Golub et al., RAM heritage)
  - U. St. Andrews (De Moortel)

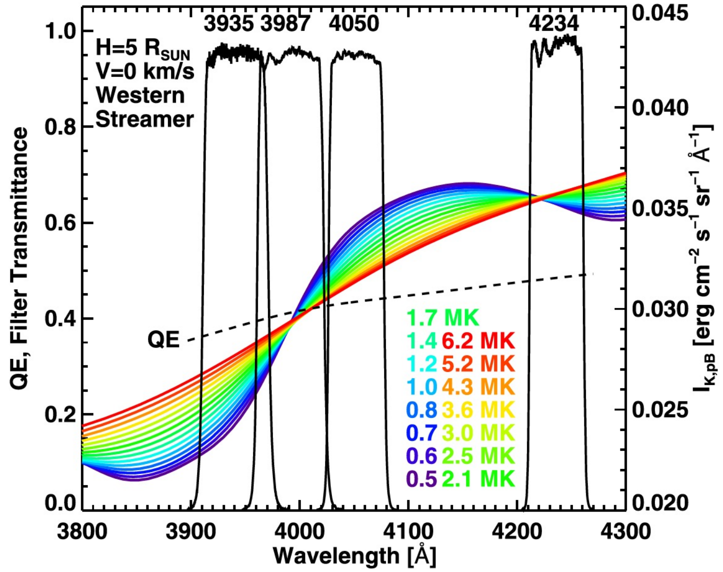
Mission Overview

Different choice of spectral lines? Remember that diffraction limit $\propto \lambda/D$ (D=170 mm for all sieves)

- Large 3-spacecraft mission at Sun-Earth L-1
  - Flying in precise formation
- 6 Photon sieve EUV imagers
- Externally occulted 4-band coronagraph

Ion	Wavelength (Å)	Temperature (MK)	Diffraction Limit (mas)	Narrowest Zone (µm)
Fe XIX	108.4	8 – 10	16	5.5
Fe XVIII	93.93	4 – 11	14	4.7
Fe XV	284.2	1.6 – 4	42	14
Fe IX	171.1	0.4 – 1.4	25	8.6
Ne VII	465.2	0.3 – 0.8	69	23
He II	303.8	0.05 – 2	45	15





Gopalswamy+ 2021

What are the observables?

- Photon sieve telescopes
  - — Sieve images all wavelengths, but only one (centered on a spectral line line) is in focus at a given separation.
  - — Multilayer coating limits bandpass (1-5 nm FWHM depending on line)
  - — FOV is about 40 x 40 as^2 0.25-s cadence
  - — 4Kx4K CMOS, photon-counting if possible
- Coronagraph
  - — Baseline: FOV 1-3 Rs, 5.6 as resolution (2 pixels)
    - Based on PROBA-3 coronagraph, 2Kx2K CMOS
  - — Better: FOV 1-5 Rs, 4.6 as resolution
  - — 10-s cadence
  - — 4-filter BITSE scheme for temperature and flow speed measurements

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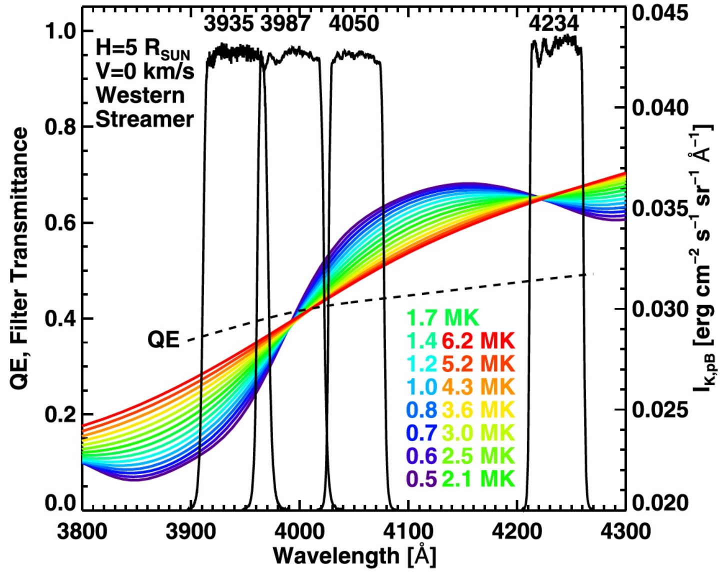
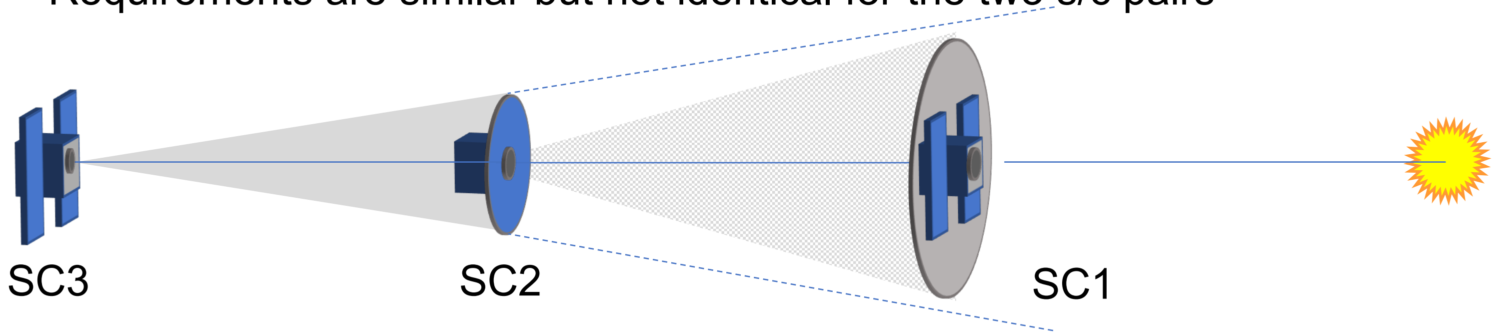


Gopalswamy+ 2021

Formation Overview

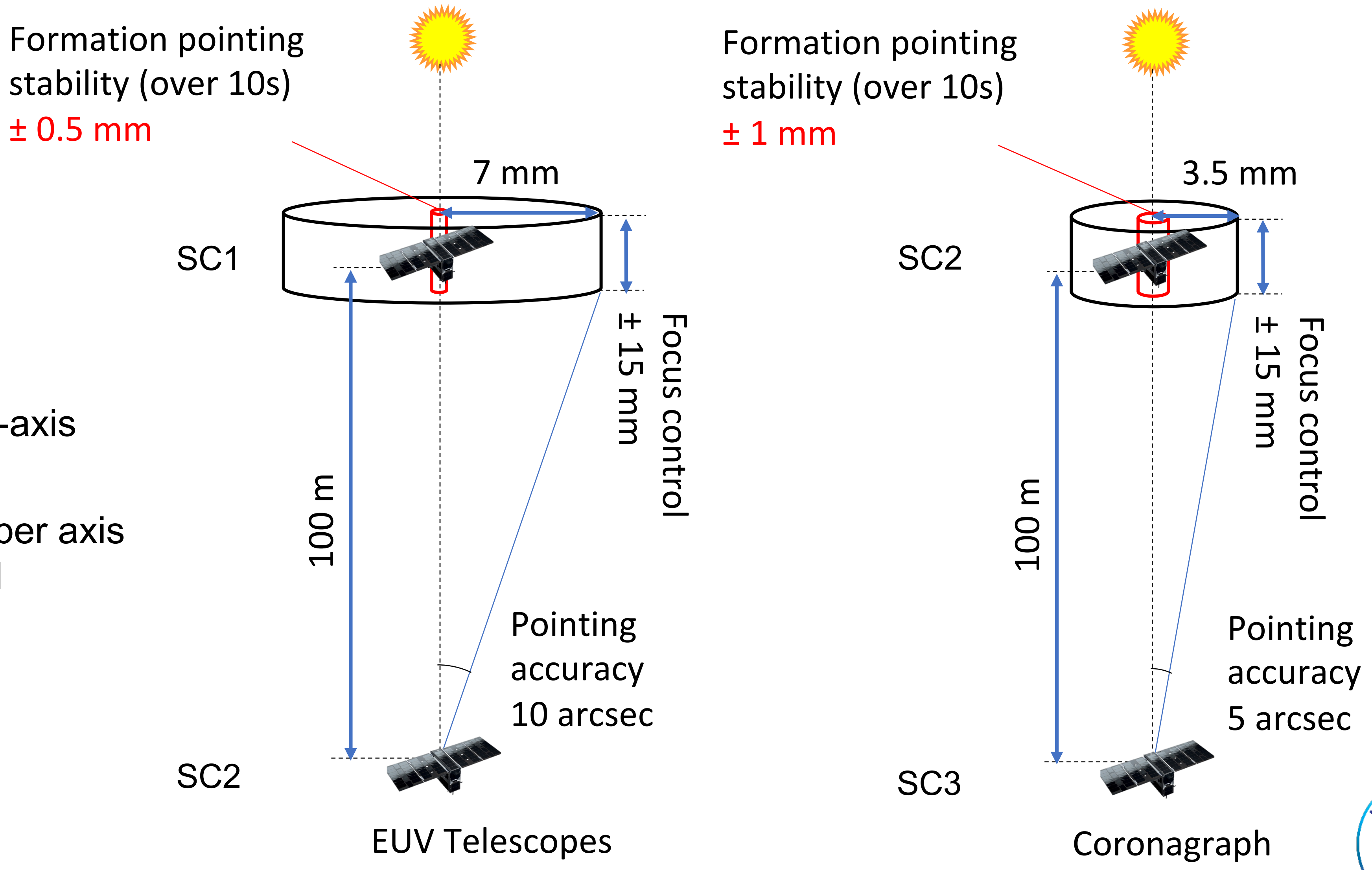
- **Three formation-flying spacecraft**
  - SC1 and SC2 form a distributed EUV telescope: fixed separation ~100 m
  - SC2 and SC3 form an externally occulted coronagraph: fixed separation ~100 m
- **SC1**
  - 6 photon sieves ("lenses"), each 170-mm diameter in hexagonal array
  - 2-m diameter deployable occulter on the OSC
- **SC2**
  - 6 detectors for EUV telescopes, each 2Kx2K CMOS
  - 1-m diameter fixed occulter for coronagraph
- **SC3**
  - Coronagraph optics (120 mm diameter entrance aperture) and detector (2Kx2K CMOS)
- **Formation flying requirements**
  - Longitudinal (on line between s/c): Stay within depth of focus
  - Transverse: Limit image smear
  - Requirements are similar but not identical for the two s/c pairs



Formation Flying Overview

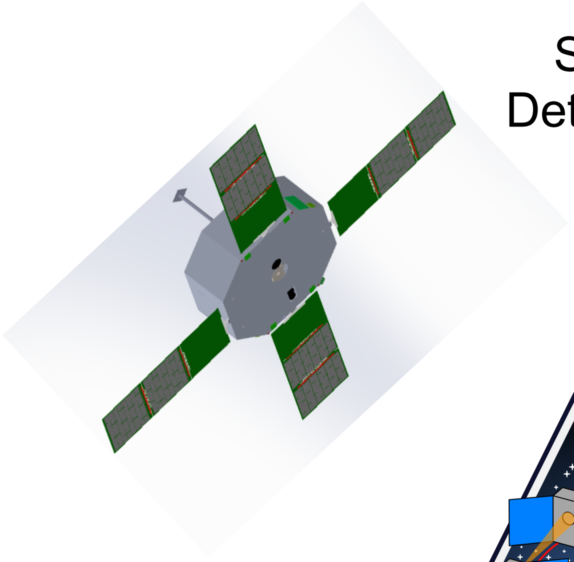
Attitude Control Requirements

- Each spacecraft 3-axis stabilized
- 7 as (3σ) stability per axis over 100 s interval

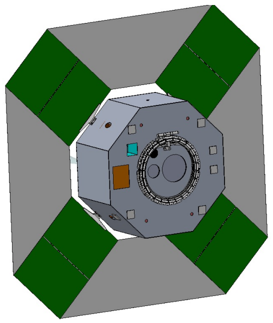


Concept Quasi-Heritage

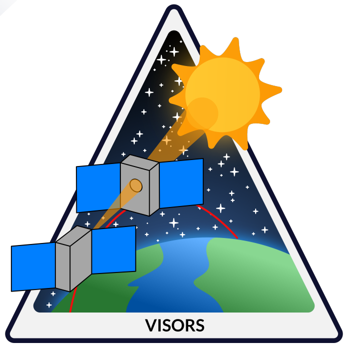
- ONSET Proposal (2016)
  - Visible-light coronagraph and off-limb EUV imager
  - Boom architecture
- SHARPI (2018)
  - Internal mission concept at GSFC
  - PFF architecture
  - MPL study completed at Wallops
- EUNIS (2019)
  - Used sieve for EUV instrument calibration
  - Similar calibration planned for MUSE
- VISORS (Current)
  - NSF funded PFF mission
  - Two 6U CubeSats, one 80-mm photon sieve for He II 30.4 nm
  - Completed PDR Nov 2020, LRD Early 2024
- BITSE
  - Balloon-borne, four-color diagnostic coronagraph (launched 2019)
- Proba-3
  - Massive spacecraft, limited science, long delayed (maybe 2024)
  - Useful development (orbit, metrology, coronagraph)

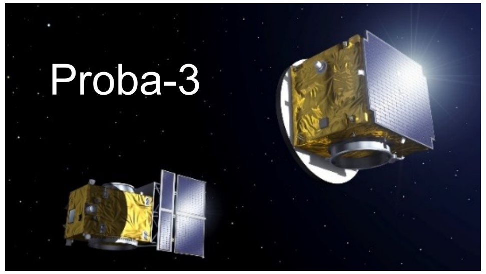


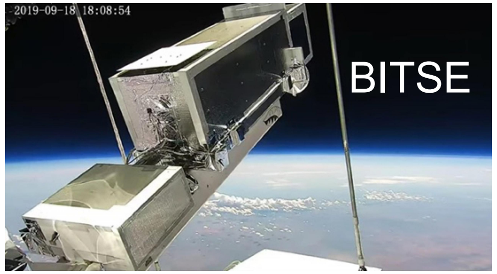
SHARPI Detector S/C



SHARPI Optics S/C

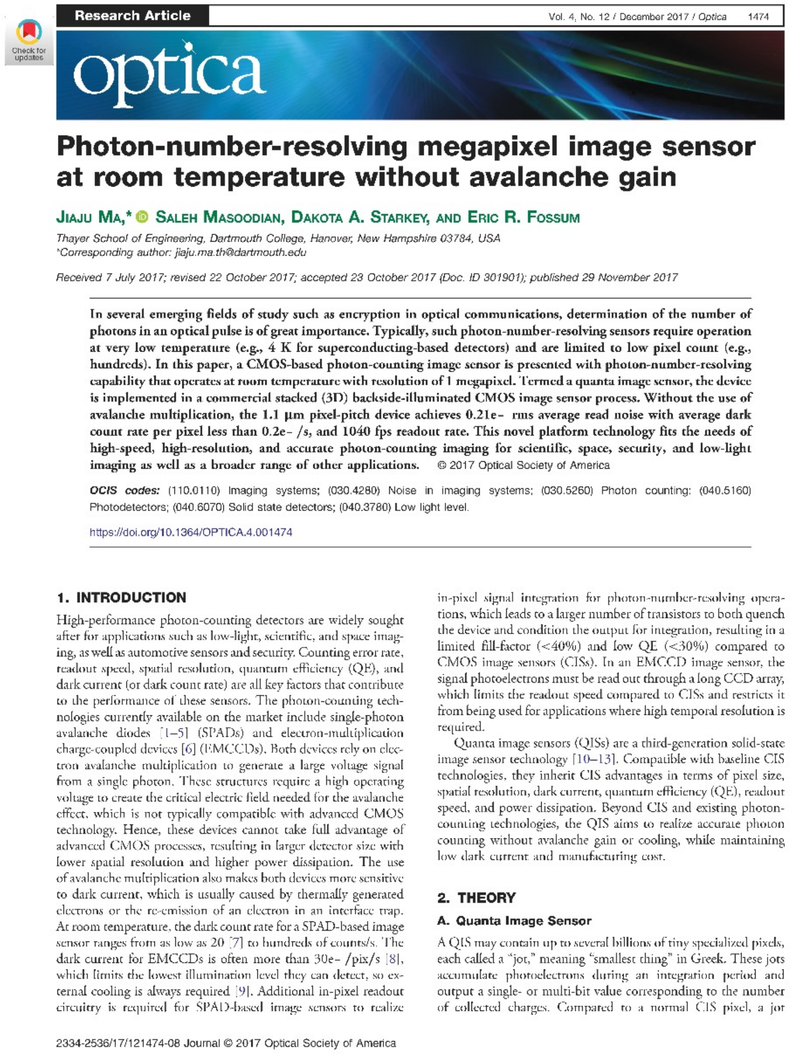






Backup

Photon counting CMOS sensors have arrived


Research Article Vol. 4, No. 12 / December 2017 / Optica 1474

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Photon-number-resolving megapixel image sensor at room temperature without avalanche gain

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In several emerging fields of study such as encryption in optical communications, determination of the number of photons in an optical pulse is of great importance. Typically, such photon-number-resolving sensors require operation at very low temperature (e.g., 4 K for superconducting-based detectors) and are limited to low pixel count (e.g., hundreds). In this paper, a CMOS-based photon-counting image sensor is presented with photon-number-resolving capability that operates at room temperature with resolution of 1 megapixel. Termed a quanta image sensor, the device is implemented in a commercial stacked (3D) backside-illuminated CMOS image sensor process. Without the use of avalanche multiplication, the 1.1 μm pixel-pitch device achieves 0.21e− rms average read noise with average dark count rate per pixel less than 0.2e− /s, and 1040 fps readout rate. This novel platform technology fits the needs of high-speed, high-resolution, and accurate photon-counting imaging for scientific, space, security, and low-light imaging as well as a broader range of other applications. © 2017 Optical Society of America

OCIS codes: (110.0110) Imaging systems; (030.4280) Noise in imaging systems; (030.5260) Photon counting; (040.5160) Photodetectors; (040.6070) Solid state detectors; (040.3780) Low light level.

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1. INTRODUCTION

High-performance photon-counting detectors are widely sought after for applications such as low-light, scientific, and space imaging, as well as automotive sensors and security. Counting error rate, readout speed, spatial resolution, quantum efficiency (QE), and dark current (or dark count rate) are all key factors that contribute to the performance of these sensors. The photon-counting technologies currently available on the market include single-photon avalanche diodes [1–5] (SPADs) and electron-multiplication charge-coupled devices [6] (EMCCDs). Both devices rely on electron avalanche multiplication to generate a large voltage signal from a single photon. These structures require a high operating voltage to create the critical electric field needed for the avalanche effect, which is not typically compatible with advanced CMOS technology. Hence, these devices cannot take full advantage of advanced CMOS processes, resulting in larger detector size with lower spatial resolution and higher power dissipation. The use of avalanche multiplication also makes both devices more sensitive to dark current, which is usually caused by thermally generated electrons or the re-emission of an electron in an interface trap. At room temperature, the dark count rate for a SPAD-based image sensor ranges from as low as 20 [7] to hundreds of counts/s. The dark current for EMCCDs is often more than 30e− /pix/s [8], which limits the lowest illumination level they can detect, so external cooling is always required [9]. Additional in-pixel readout circuitry is required for SPAD-based image sensors to realize in-pixel signal integration for photon-number-resolving operations, which leads to a larger number of transistors to both quench the device and condition the output for integration, resulting in a limited fill-factor (<40%) and low QE (<30%) compared to CMOS image sensors (CISs). In an EMCCD image sensor, the signal photoelectrons must be read out through a long CCD array, which limits the readout speed compared to CISs and restricts it from being used for applications where high temporal resolution is required.

Quanta image sensors (QISs) are a third-generation solid-state image sensor technology [10–13]. Compatible with baseline CIS technologies, they inherit CIS advantages in terms of pixel size, spatial resolution, dark current, quantum efficiency (QE), readout speed, and power dissipation. Beyond CIS and existing photon-counting technologies, the QIS aims to realize accurate photon counting without avalanche gain or cooling, while maintaining low dark current and manufacturing cost.

2. THEORY

A. Quanta Image Sensor

A QIS may contain up to several billions of tiny specialized pixels, each called a "jot," meaning "smallest thing" in Greek. These jots accumulate photoelectrons during an integration period and output a single- or multi-bit value corresponding to the number of collected charges. Compared to a normal CIS pixel, a jot

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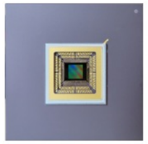
PRELIMINARY

Product Brief: GJ01611

gigajot® WHERE EVERY PHOTON COUNTS

16MP Quanta Image Sensor

Reliable Photon Counting at Room Temperature and Full Speed



The GJ01611 Quanta Image Sensor (QIS) is a stacked BSI CMOS image sensor with 16.7 megapixel (4096 x 4096) resolution. The 1.1 µm x 1.1 µm pixels are designed with Gigajot's proprietary low-noise cluster-parallel readout structures to achieve reliable photon-counting sensitivity at room temperature, with industry-leading 0.19e- rms read noise, while operating at 16 MP resolution and 30 fps frame rate. The sensor has programmable ADC resolution ranging from 10/12/14 bits and it supports 40 fps at 4K resolution and 60 fps at Full-HD resolution. The photon counting GJ01611 Camera Development Kit is available now to evaluate the sensor, or incorporate directly into systems.

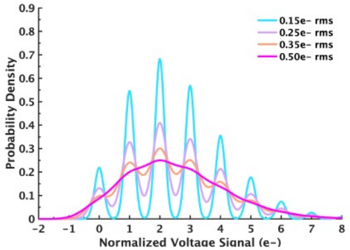
Key Features

- 1.1 µm pixel size
- Photon-counting sensitivity
- Market leading low read noise
- Market leading low dark current
- 30fps frame rate
- Low power
- Patented pixel design and sensor architecture
- Advanced stacked CMOS BSI process

Applications

- Scientific
- Industrial
- Medical
- Space
- Defense
- Other high performance

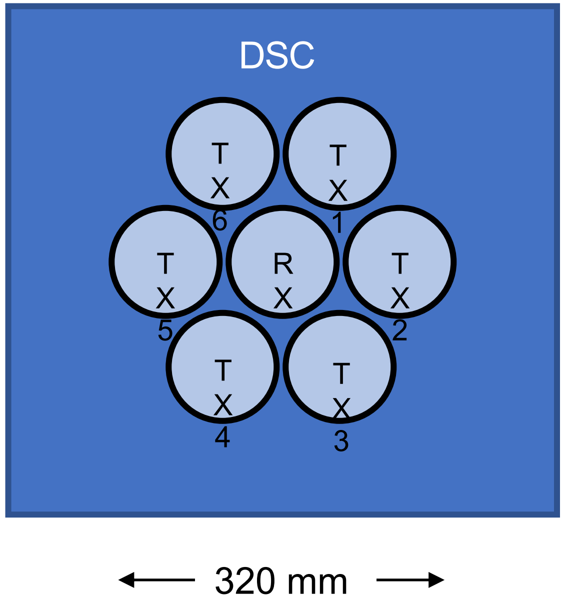
Photon Counting Capability



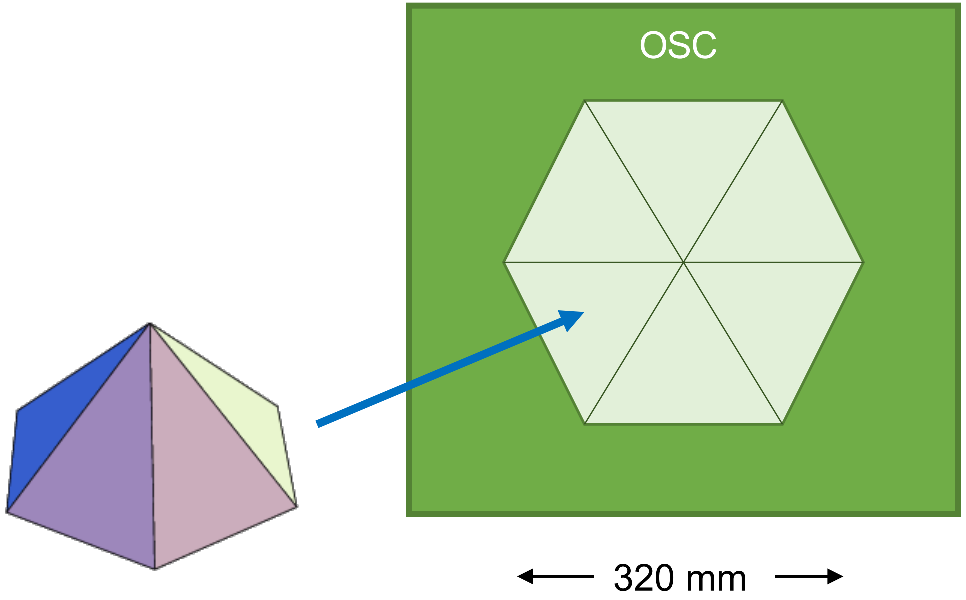
Read Noise	Is Photon Counting Possible?
0.5 e-	✗
0.3 e-	✔
<0.2 e-	✔ (<1% error rate)

Relative Position Sensor

- The laser transmitters and receiver are all on the SC2 and SC3.
- Six transmitter telescopes surround a single receiver telescope.
- Transmitters are time multiplexed to prevent confusion of data.

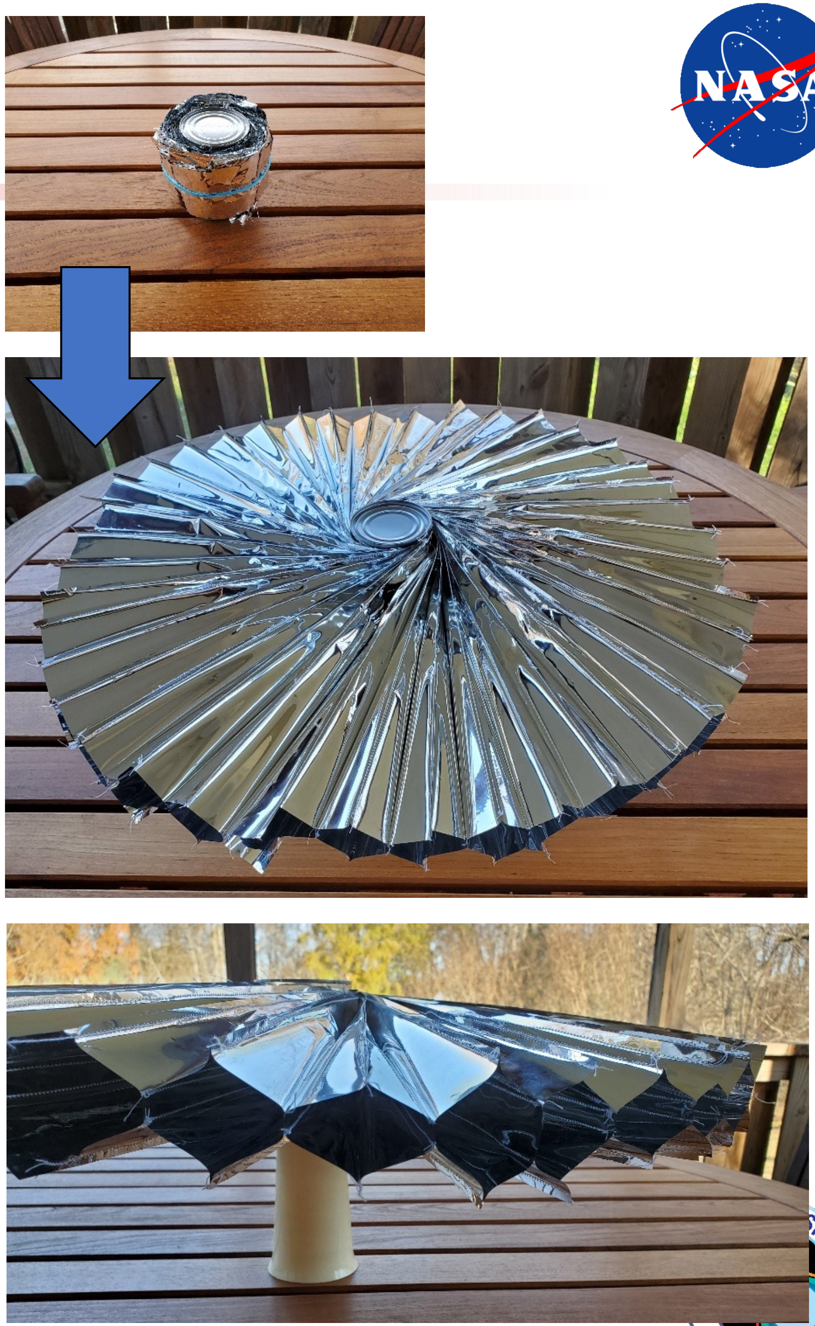


- A hexagonal pyramidal target is on the OSC.
- Elevation angle of faces is 45°.
- Retroreflective material is applied to the pyramid provides return of light along line of sight.



Deployable Sunshade

- GSFC design based on paper party decorations.
  - — Constructed using thermal blanket fabrication methods and materials.
- Shade winds up into compact spiral package.
- Deploys into large disk
  - Robust and self supporting due to honeycomb structure.
  - Opaque due to double layer
- First prototype constructed of polyester film (mylar):
  - — Deployed: 60 cm diameter,
  - — Stowed: 13cm diameter
  - — 154g mass, not including central hub
  - — Central hub provides mount for photon sieve optic
- Thermal test of 1m shade planned for Summer 2021



Deployable Sunshade

“Anne-Marie holding artichoke”
artist unknown, mixed media
2020

NASA