Polarimeter to UNify the Corona and Heliosphere

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PUNCH is a NASA Small Explorer mission to better understand how the mass and energy of the Sun's corona become the solar wind that fills the solar system. The flight segment consists of a constellation of four small satellites in Sun-synchronous, low Earth orbit that together will produce deep-field, continuous, 3D images of the solar corona as it makes a transition to the young solar wind from the outermost solar atmosphere to the inner heliosphere.

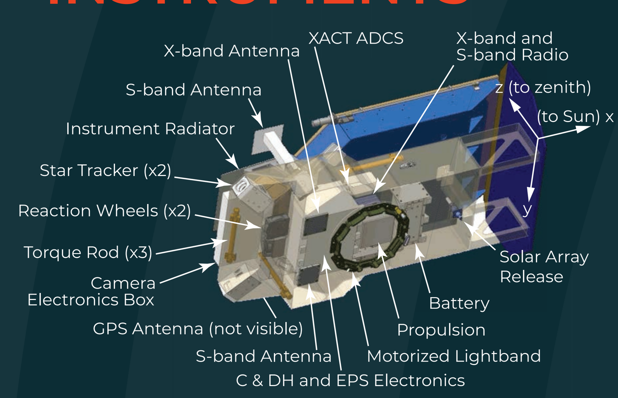
PUNCH's science goal is to comprehend cross-scale physical processes of heliophysics, from micro scale turbulence to the evolution of global scale structures. There are six science objectives that span the quiescent and dynamic young solar wind, which will be achieved by activities of six working groups. PUNCH is sponsoring a series of open workshops with the heliophysics community to develop tools in anticipation of the data and to foster a broad and inclusive community of PUNCH users. Workshops are announced in field newsletters and on the PUNCH mission website.

An undergraduate student collaboration to search for X-ray signatures of coronal heating mechanisms includes development of another instrument, the Student Thermal Energetic Activity Module (STEAM). Moreover, PUNCH engages interested heliophysicists in a mission-embedded outreach program with an Ancient & Modern Sun Watching theme that is collaborating with underserved and underrepresented populations and connecting to the broader public in the US Southwest and beyond. PUNCH is scheduled to launch in April of 2025.

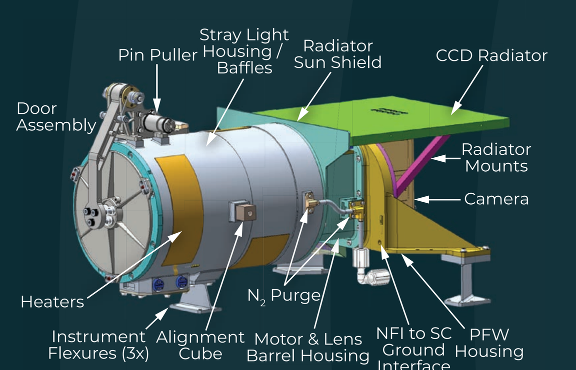
https://punch.space.swri.edu

INSTRUMENTS

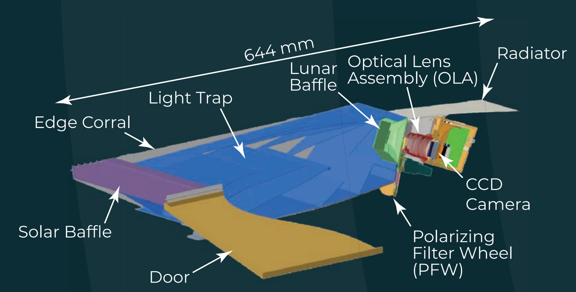
https://punch.space.swri.edu



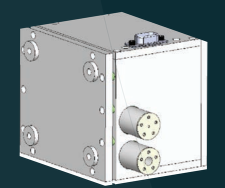
Each of the four **PUNCH spacecraft** is just over a meter long and supports one instrument on the +Z deck (maintained toward the zenith in flight). Each spacecraft supports three-axis pointing (to within a few arc-seconds), dual-band high-speed downlink, orbital-trim propulsion, and sophisticated, autonomous fault recovery. The four spacecraft are launched and deployed in orbit from a single rocket. Their orbital formation is established over the first 90 days of flight.



The **Narrow Field Imager (NFI)** is a compact externally occulted coronagraph with a field of view from 6 to 32 $R_\odot$. The external occulter blocks direct sunlight from entering the main optical aperture, which views the corona and starfield around the Sun using a compound lens system. Polarization is resolved using a polarizing filter wheel (PFW) assembly, and the image is digitized using a CCD camera assembly (CCA) with a 2k x 2k active detector area.



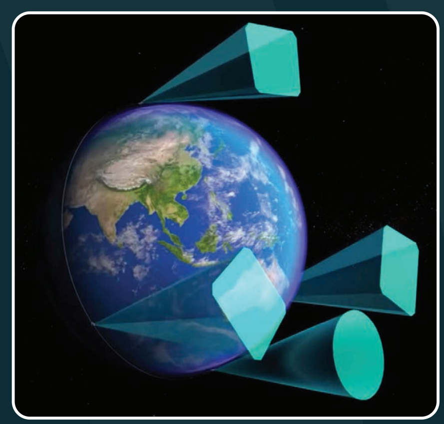
The **Wide Field Imager (WFI)** is a wide-field heliospheric imager (HI) design based on STEREO/HI. It images from 18 to 180 $R_\odot$. HI designs are analogous to coronagraphs, but in linear instead of circular geometry. WFI attenuates direct sunlight by over 16 orders of magnitude. The wide-field achromatic optics are based on the Nagler eyepiece in reverse geometry. Polarization and detection use the same PFW and CCA designs as NFI. PUNCH includes three copies of WFI to achieve the required observing cadence.



The STudent Energetic Activity Monitor (STEAM) will advance understanding of solar flares and help identify why the solar corona is far hotter than the solar surface by measuring enhancement of key elements and temperature in solar flares and solar active regions. It will do this by measuring the Sun's X-ray spectrum in quiet conditions, with visible active regions, and during solar flares. The single STEAM instrument is mounted on the NFI Observatory.

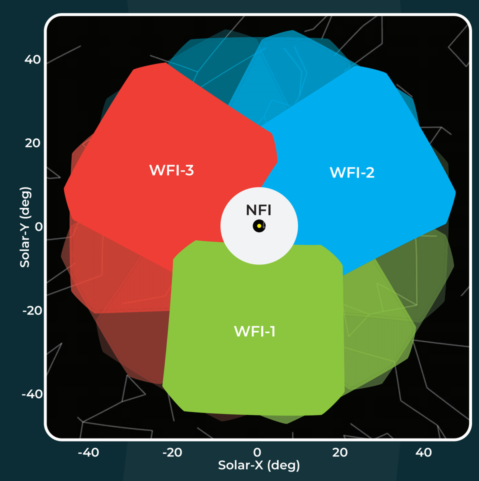
THE MISSION

The four spacecraft are synchronized in flight. Each spacecraft orients +X at the Sun and holds inertial pointing for 30° of orbital motion (8 minutes elapsed time). At the end of the hold, it rotates 30° about the X axis, to maintain the Earth below the instrument reference plane. **Every eight minutes, each PUNCH spacecraft acquires seven images: one unpolarized image and six polarized images in dual three-image sets. All four spacecraft are synchronized in-flight and the data are merged on the ground to produce the 3D imagery.**



The four PUNCH imaging instruments work together to form a trefoil field-of-view (FOV) on the Celestial sphere. Each individual FOV overlaps significantly with the other three, to ensure cross calibration and seamless merging of the data. The full field of view is 90° across, aligned around the Sun (small yellow dot at center).

FOV and spatial coverage of each instrument (30 degree rotations fill in the coverage)



ANALYSIS TOOLS

As we move closer to launch, we are developing and testing methods to characterize multi-scale structures in the young solar wind. To that end, we are exploiting a variety of techniques including:

- Flow mapping (Figure 1)
- Polarization diagnostics (see bottom left of this poster)
- MHD-constrained tomographic inversions
- Forward modeling of global structures and turbulent flows (Figure 2)

Flow Mapping Challenge

A numerical model of a dynamic solar corona that can be used as a benchmark for testing a variety of data analysis methods designed to measure radial velocity and acceleration in the corona.

https://tinyurl.com/bp9npr9d

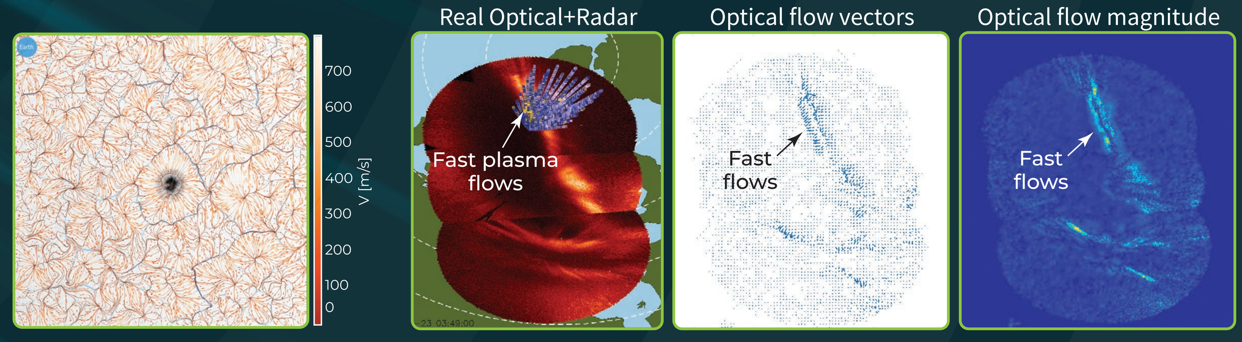


Fig. 1 (a) Map of horizontal flows around a sunspot, produced by the Balltracking algorithm applied to SDO/HMI data. Large-scale supergranular and moat flows are revealed (image credit: Raphael Attie). **(b) Auroral flows determined from optical data.** Radar observations (left) validate optical results, showing fast flows related to the auroral arc (image credit: Bea Gallardo-Lacourt).

CME Tracking Challenge

tinyurl.com/2s4cynpk

The Gamera simulation (left) can be used as a benchmark for testing a variety of CME diagnostics.

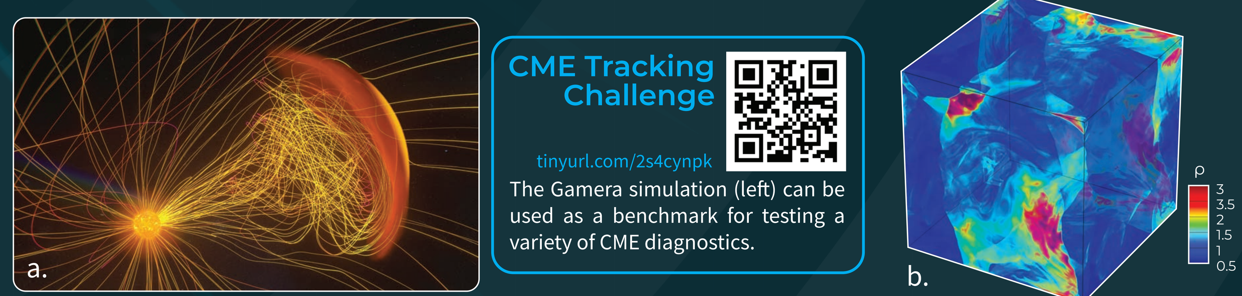


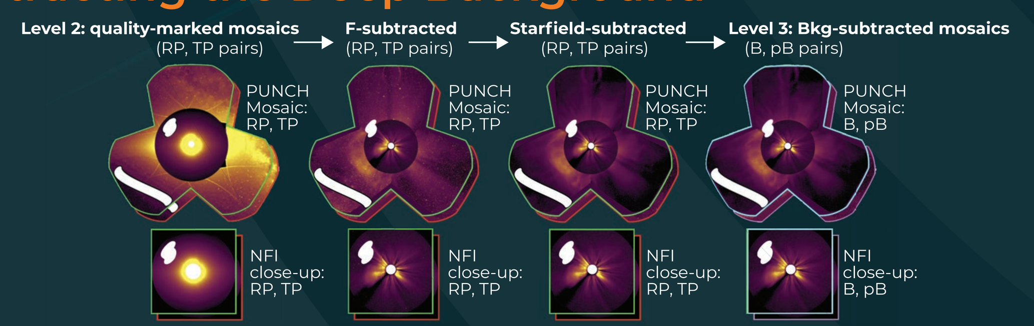
Fig. 2. Forward modeling of realistic global and small-scale density and flow structures allows us to test flow tracking, polarization, and tomographic techniques. (a) Magnetic field lines from GAMERA global MHD simulation of a CME moving through the heliosphere (image credit: Elena Provornikova). (b) 3D density field of a homogeneous isotropic turbulence simulation (image credit: Yan Yang).

FROM OBSERVATIONS TO SCIENCE

Filling the Gaps

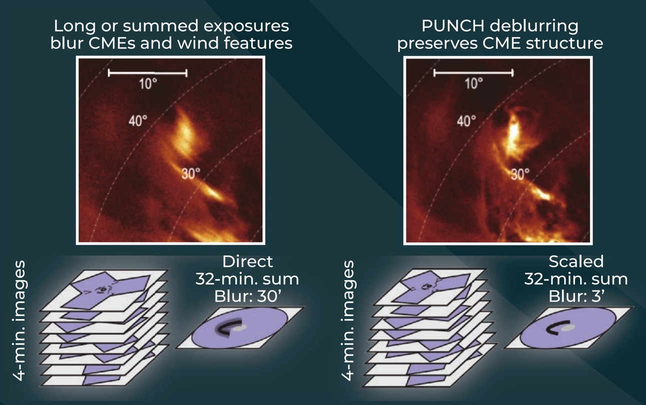
PUNCH stitches images from multiple cameras together in order to fill the gaps between existing coronal and heliospheric imagers. All four PUNCH cameras have overlapping fields of view, ensuring that no gaps remain in the final combined images. The result is a seamless image of the Young Solar Wind.

Subtracting the Deep Background



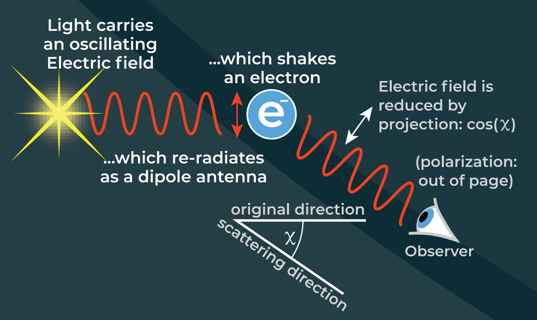
Signal is as little as 0.1% of star field. After images are photometrically calibrated and aligned, the NFI and three WFI images are merged into mosaics of positive-definite radial (RP) and tangential (TP) polarizer brightnesses. Background F corona (dust) and starfield are removed, resulting in background-subtracted Brightness (B) and polarized Brightness (pB) mosaics of scattered sunlight from the electrons in the corona ("Thomson-scattered" light from the "K-corona"). Separation of background is precise to <3% of K corona despite the varying starfield and the much brighter dust in the inner solar system (the "F corona").

Deblurring the Images

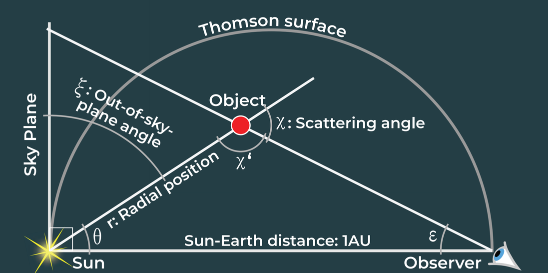


All previous heliospheric imagers have been subject to motion blur. Typical CMEs and solar wind features move about a degree every hour. Since the features are faint on the sky, long exposures are required to produce clean images. This leads to motion blur (left). PUNCH overcomes this problem by collecting a full polarized image set every four minutes. The PUNCH ground system averages the exposures together in a moving coordinate system (right), matched to the overall flow rate. This minimizes motion blur and improves image sharpness.

Extracting 3D from Polarization



The corona is visible because electrons scatter sunlight. When light passes over a free electron in space, the electric field moves he electron back and forth. The moving charge then rebroadcasts light, emitting dipole radiation that is coherent with the incoming light. The emitted light is linearly polarized; the degree of polarization depends on the scattering angle ("χ" in the figure).



When PUNCH observes light from a feature in the corona or solar wind, it can measure its polarization. It also measures the angle between the object and the Sun ("ε" in the figure). Polarimetry from PUNCH measures the angle χ directly. Analysis software automatically solves the triangle in the diagram, determining the location of each visible feature in three dimensions.

SCIENCE OBJECTIVES

The PUNCH science goal is to determine the cross-scale physical processes that unify the solar corona with the rest of the solar system environment (the heliosphere). The goal divides into two major science objectives, subdivided into 3 topics each:

1. Understand how coronal structures become the ambient solar wind

a. Global evolving solar wind

How does the solar wind flow?

Wind speed can be traced using small features in the corona and heliosphere.

On global scales, the ambient solar wind is roughly bimodal, with fast and slow streams. This simple description is complicated by shears and complex structure that may dominate the behavior of the solar wind.

b. Solar wind microstructure and turbulence

Where does the corona end and the solar wind begin?

Slow solar wind near Earth is dominated by fluctuations of unknown origin.

Do they form mainly from turbulence in the solar wind or is the slow solar wind intrinsically intermittent from its origins?

c. Alfvén Zone: Boundary of the Heliosphere

A natural dynamical boundary where the solar wind disconnects from the solar corona

Location where speed of the solar wind exceeds that of the fast MHD waves.

It is complex and changes with solar magnetic evolution – the "riotous torrent" seen by STEREO indicates there is likely a fractal "Zone" rather than a surface.

It has never been observed; models are largely unconstrained.

2. Understand the evolution of transient structures in the young solar wind

a. CME 3D Trajectory, Structure, and Evolution

Tracking CMEs' Evolving Structure in 3D

CME magnetic structures are known to change in the solar wind due to distortion, deflection, rotation, CME-CME interactions, and magnetic reconnection/erosion.

Current white-light imagers can track only the largest components of CME structure beyond 20 Rsun.

We thus know almost nothing about how the sub-structures of CMEs interact with each other or with the solar wind.

b. CIR formation and 3D dynamics

PUNCH moves beyond a planar perspective on corotating interaction regions (CIRs)

Understanding CIR formation and wind/streamer interaction is critical to predicting spiral angle and impact time with the earth.

Shock onset in CIRs is not well understood.

CIRs are believed to launch strong waves near their source region as pileup begins, but measurements are sparse.

c. Shock 3D dynamics & morphology

PUNCH provides a cross-scale picture of shock dynamics

Simulations suggest that CMEs are strongly affected by turbulent instabilities across their shocks.

Corrugations of shock fronts may be responsible for the acceleration of solar energetic particles (SEPs) and type II radio bursts.

The current generation of coronagraphs and heliospheric imagers are not designed to capture shock evolution, interactions and possible instabilities, due to sensitivity and motion blur effects, but PUNCH will observe global shock structure and resolve shock-turbulence interactions.

Outreach

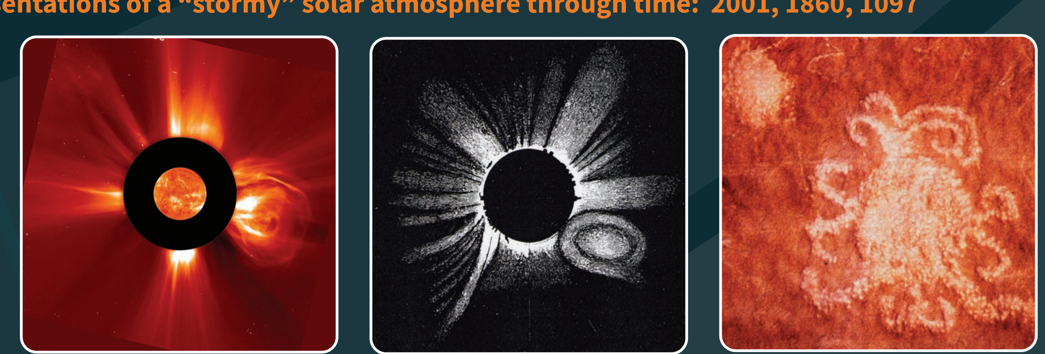
The Outreach Program for the NASA PUNCH mission collaborates with heliophysicists plus Native American, Hispanic, Girl Scout, and Blind & Low Vision partners to create activities, planetarium films, and multi-sensory, multicultural Sun-watching events enriching for all.

Our Ancient & Modern Sun Watching theme makes heliophysics personally & culturally relevant.

Novel outreach products using our theme (above), embodied learning, social & emotional learning, and arts integration ready for use with eclipse events:

Tactile representations of the Sun, New Kinesthetic Astronomy activities, Girl Scout patch, planetarium short and long films, digital interactives, and planning guides for STEAM (Science, Technology, Engineering, Art, and Mathmatics) events.

Representations of a "stormy" solar atmosphere through time: 2001, 1860, 1097



The **2001** NASA SOHO spacecraft image [left] shows a large coronal mass ejection (CME). PUNCH will be uniquely capable of tracking such storms continuously throughout the inner heliosphere between the Sun's corona and Earth orbit.

A hand-drawing [center] made during the **1860** total solar eclipse is commonly cited as the first recording of an active (or "stormy") solar corona in an enduring medium. Note the similarity to the left SOHO image .

PUNCH Outreach is working to include the possibility that a unique Ancestral Puebloan petroglyph in Chaco Canyon [right] represents an active solar corona visible during the **1097** total solar eclipse.