Polarimeter to UNify the Corona and Heliosphere (PUNCH): Science, Status, and Path to Flight

Craig DeForest[1], Ronnie Killough[1], Sarah Gibson[2], Alan Henry[1],
Traci Case[1], Matthew Beasley[1], Glenn Laurent[1], Robin Colaninno[3], Nick Waltham[4], and
the PUNCH Science Team

[1]Southwest Research Institute, 1050 Walnut Street 300, Boulder, CO 80302
[2]NCAR High Altitude Observatory, 3080 Center Green Drive, Boulder, CO 80301
[3]U.S. Naval Research Laboratory, 4555 Overlook Ave SW, Washington, DC 20375
[4]RAL Space, Harwell Oxford, Didcot, OX11 0QX, UK

2022 IEEE Aerospace Conference (AERO) | 978-1-6654-3760-8/22/$31.00 ©2022 IEEE | DOI: 10.1109/AERO53065.2022.9843340

Abstract— PUNCH is a Small Explorer constellation mission in development for NASA's Heliophysics Division. PUNCH will image the transition zone between the outer reaches of the solar corona and the solar wind in the inner heliosphere, helping to unify the fields of solar physics and solar wind (space) physics. A constellation of four microsatellites (microsats) in Sun-synchronous LEO will produce deep field, continuous, 3D visible-light images of the corona and young solar wind from $6R_s$ to $180R_s$ in polarized visible light. A single Narrow Field Imager (NFI) on one microsat captures the outer corona from 6 R_s to 32 R_s, and three Wide Field Imagers (WFIs) on the remaining microsats capture from $20R_s$ to $180R_s$. The instruments are matched and synchronized to operate as a single "virtual observatory", with a 90-degree field of view centered on the Sun. The instruments use conventional lens optics and deep baffles to image the faint traces of visible sunlight that are Thomson-scattered by free electrons in the tenuous plasma of the outer corona and young solar wind. PUNCH includes polarized optics to produce 3D images using the polarization physics of the scattering. By bringing imaging science outward from the Sun and into the heliosphere, PUNCH fulfills its science objectives to (1) understand how coronal structures become the ambient solar wind, and (2) to understand the dynamic evolution of transient structures (such as CMEs) in the young solar wind. We briefly introduce the PUNCH science, describe fundamental trades that enabled the mission, and report current development status and the steps ahead toward on-orbit science operations.

TABLE OF CONTENTS

1. INTRODUCTION

The Polarimeter to UNify the Corona and Heliosphere (PUNCH) is a transformative mission to reveal the as-yet largely unexplored region from the middle of the solar corona out to 1AU from the Sun: i.e., the "young solar wind". PUNCH will observe the corona and heliosphere as elements of a single, connected system through direct, global, spatially continuous, 3D deep-field imaging of the faint traces of sunlight reflected by free electrons in interplanetary space (Figure 1).

PUNCH's integrative science bridges a major gap that currently separates the fields of solar physics and heliospheric physics. For over 40 years, solar physics has focused on imaging and spectral measurements of the Sun itself, in visible, ultraviolet, and X-rays; and space physics has focused on in-situ measurements of the solar wind and its interaction with Earth's magnetic field. However, the large-scale structure and evolution of the region relating these measurements – the transition from the solar corona to the heliosphere – has remained largely unexplored, limiting understanding of the Sun-Earth system.

Compared to earlier spaceborne coronagraphs, PUNCH will bring high quality imaging outward from the corona to capture large- and cross-scale physics in the young solar wind as it leaves the star. This complements the Parker Solar Probe mission[1], which approaches the same gap by flying an in-situ probe inward through the solar corona itself.

The PUNCH space segment, scheduled to launch no earlier than 2024-Oct, comprises four microsatellite Observatories in Sun-synchronous, dawn/dusk low Earth orbit (LEO). Each Observatory carries one polarizing visible-light imager. The imagers operate synchronously, acquiring one polarized image sequence every four minutes for the life of the two-year nominal mission. One Observatory carries a Narrow Field Imager (NFI): a compact-design coronagraph that points directly at the Sun with an in-line occulter to hide the star itself, that images features at elongation (radial) angles between 1.5° and 8° (6 R_s to 32 R_s) on the celestial sphere, measured from Sun center. The other three Observatories have Wide Field Imagers (WFIs), each of which covers an approximate 40° square of sky, covering

978-1-6654-3760-8/22/$31.00 ©2022 IEEE

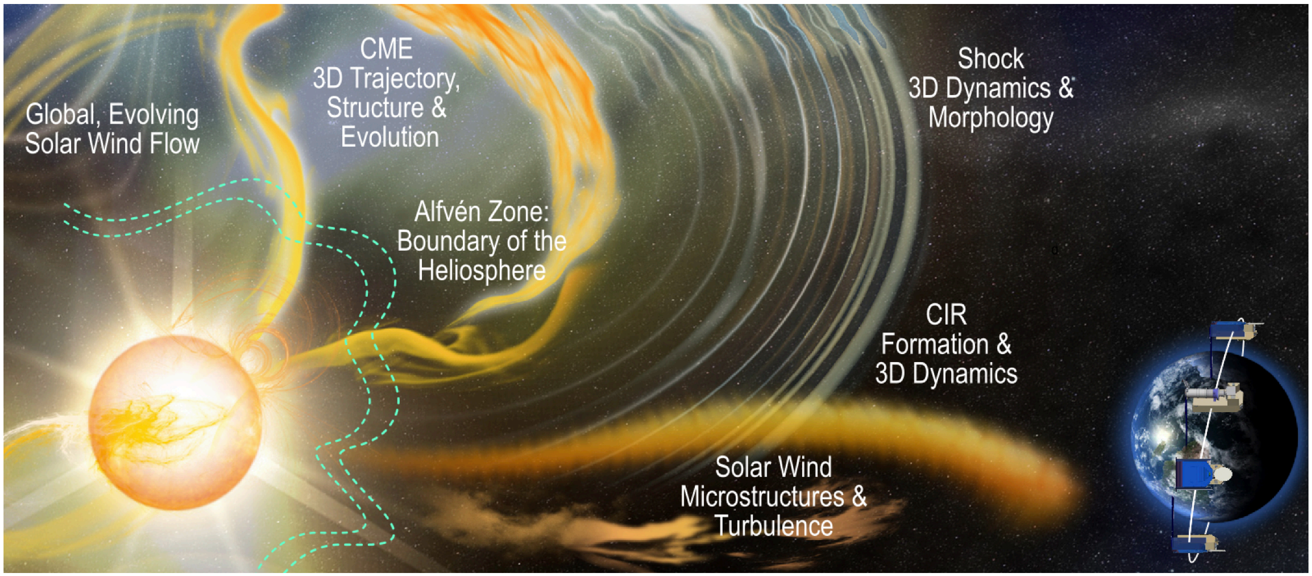

Figure 1: PUNCH observes the Sun from a global constellation of four smallsats, to address two science Objectives that ramify into six major science topics

elongations from 5° to 45° (20 R_s to 180 Rs**)**. The NFI and three WFIs work together to capture all position angles around the Sun over the course of 1/3 of an orbit.

Science data are downlinked approximately daily via the SSC Space-US commercial network of ground stations, and merged on the ground into photometrically precise, background-subtracted science data products that simulate a “virtual coronagraph” with a 90° diameter field of view on the sky.

PUNCH relies heavily on the current market of small commercial off-the-shelf (COTS) systems, the development of which is driven largely by the CubeSat market, that replace larger, higher-cost custom or semi-custom systems normally used in spacecraft design. This market, together with operational economy of scale, greatly reduces cost, enabling the PUNCH project to build and fly a constellation of four three-axis-pointed, high-capability smallsats within the framework of the NASA Explorers program, for less than the Small Explorer cost cap.

PUNCH ground systems include a sophisticated Science Operations Center (SOC) to remove background that is up to 1,000x brighter than the science signal in the downlinked data, while merging the images into mosaics that are photometrically calibrated to the 0.01% level (relative). Specific photometric and polarimetric techniques developed to enable PUNCH include fully electronic shuttering for exposure stability; nonlinear per-pixel calibration of the flight Charge-Coupled Device (CCD) detectors built by RAL Space; post-facto Point-Spread Function (PSF) equalization across the field of view to regularize image characteristics; optimized resampling to merge data without blurring the starfield; and background removal methods that include smooth background estimation and Fourier motion filtering.

The data will be made available via the Virtual Solar Observatory (VSO), via NASA’s Solar Data Analysis Center (SDAC), and via the PUNCH mission website at https://punch.space.swri.edu. PUNCH has an open data policy and data will be released to the world at the same time as to the science team. The science team meetings are semi-annual and are announced in AGU/SPA, AAS/SPD, and SHINE newsletters, and on the website; they are open to all. PUNCH also supports an Associate Investigator program to recognize early-career scientists who are doing work relevant to PUNCH.

PUNCH is led by Southwest Research Institute (SwRI), with major partners including the Naval Research Lab (NRL) and Rutherford Appleton Labs (RAL) Space. PUNCH is currently in Phase C: final design and fabrication.

2 SCIENCE OBJECTIVES

The scientific goal of PUNCH is to determine the cross-scale processes that unify the solar corona and heliosphere. This goal drives two science objectives: (1) to understand how coronal structures become the *ambient solar wind*; and (2) to understand the dynamic evolution of *transient structures* in the young solar wind. Each of these objectives further ramifies into three scientific questions that, together, address the objective. The PUNCH science team is organized into working groups, each of which addresses one major question.

2.1 THE AMBIENT SOLAR WIND

PUNCH will reveal the global, evolving solar wind, its microstructure, and its boundaries as they vary day to day and with the solar cycle. Even in its ambient (typical, “steady”) state, the solar wind is highly variable in time and space. Microstructures, waves, and turbulence form a fluctuating background that is sensitive to local physical characteristics yet also preserves information about the Sun. To improve understanding of this ambient sate, PUNCH focuses on three specific questions:

Question 1A: How does the young solar wind flow and evolve on global scales?

The solar wind originates in the corona and fills the heliosphere. Although basic models of the solar wind have existed for decades[2], detailed models are an area of active

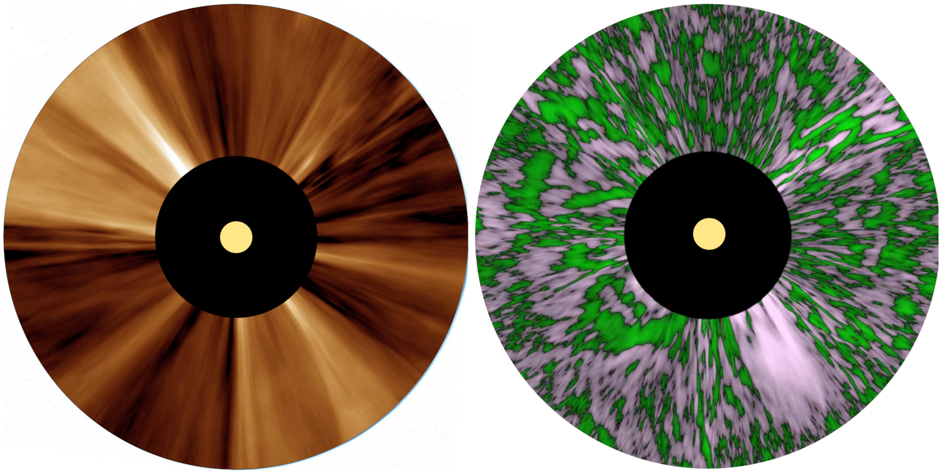

Figure 2: Deep-field views of the outer solar corona, from STEREO/COR2, reveal fine structure both in space and time[4]. These images show the inner half of the NFI field of view. LEFT: fine structures, laterally confined by the magnetic field, dominate the outer corona. RIGHT: Removing a running average reveals a "riotous torrent" of ejecta at all times and locations. PUNCH uses these ejecta to trace solar wind flow.

research[3] and solar wind acceleration continues surprisingly far from the Sun[4]. Simply measuring the global flow and its variations across solar distance and lateral position is critical to advancing understanding of the outer corona and how it becomes the solar wind. Existing speed profiles are in-situ orbital "scans" from Ulysses[5] or Parker Solar Probe[1]; these do not provide large scale context or sufficient time resolution as the flow evolves hourly and daily. PUNCH uses density inhomogeneities, observed in the outer corona and inner heliosphere (Figure 2) as tracers of the solar wind flow to reveal its evolution with a time cadence of 6 hours.

Question 1B: Where and how do microstructures and turbulence form in the solar wind?

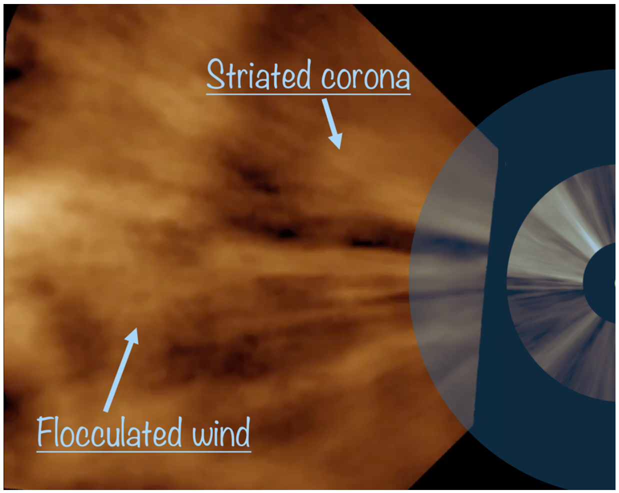

Figure 3: The character of coronal structure shifts at elongations of about 10° (40 solar radii) from the Sun, possibly pointing to hydrodynamic turbulence. By imaging this region with 10x-30x better sensitivity and resolution, PUNCH reveals the balance between enroute turbulence and solar ejecta in the gusty solar wind.

The solar wind near Earth is gusty and variable. Mesoscale structures in particular are almost certainly caused by a mix of solar and turbulent effects[7][8]. There is strong evidence both for at least some solar wind features originating in the corona and also for turbulent processing of the plasma en route through the solar system [9][10]. STEREO imaged an important transition, from striated flow confined by the magnetic field to mixed flow thought to be driven by hydrodynamic turbulence; but it could not resolve the mechanism[11]. PUNCH will use higher resolution and sensitivity to identify the nature of this transition.

Question 1C: What are the evolving physical properties of the Alfvén zone?

The "Alfvén point" or, more recently, "Alfvén surface" or "Alfvén zone", is the location where the gradually accelerating solar wind speed exceeds the gradually decreasing speed of Alfvén waves or, more importantly, fast-mode magnetohydrodynamic (MHD) waves aligned along the magnetic field. At that location, parcels of solar wind plasma and magnetic field become causally disconnected from the Sun in ideal MHD[12], and are properly considered "solar wind" rather than part of the "outer solar corona". The Alfvén surface is at least 15 solar radii from the Sun[13] based on imaging measurements, and is being actively studied through theory and direct sampling with Parker Solar Probe[14][15]. The outer corona's density, and hence Alfvén speed, is sufficiently variable that the boundary is more properly considered a "zone" than a "surface"; and its unique large-scale physics has yet to be measured and explored[13]. By mapping the location, scale, and falloff of inbound features in the outer reaches of the corona, PUNCH will map this important, but currently poorly observed, boundary between two major parts of the heliosphere.

2.2 TRANSIENT STRUCTURES IN THE SOLAR WIND

PUNCH will track and measure major transient structures in the solar wind. These large-scale and energetic structures are critical to understanding space weather and the largest disturbances in the solar system space environment. Important classes of transients are coronal mass ejections (CMEs), co-rotating interaction regions (CIRs), and plasma shocks. PUNCH has the unique ability to track these features in 3D and across the entire inner solar system.

Question 2A: How do coronal mass ejections (CMEs) propagate and evolve in the solar wind in three dimensions?

CMEs are well known to be the source of the strongest space weather events at Earth. Observations at the Sun and in-situ generally support a predominant model of CMEs as erupting flux ropes that arise from destabilized magnetic systems on the Sun[16][17][18]. However, tracking CME structures across the solar system – either from one vantage or multiple vantages – currently relies on extrapolation via shape and propagation models that are at best weakly supported by image data[19]. Further, CMEs may be deflected[20] or interact with other CMEs as they propagate[21] as well as evolving in shape[22]. PUNCH will track CMEs in 3D using the polarization properties of Thomson scattering[23], dissolving these barriers to understanding the largest transients in the solar wind.

Beyond overall propagation, CMEs have rich interior structure, which has been imaged by STEREO/HI in two dimensions and which is difficult to interpret with current imagers (Figure 4). By distinguishing these structures in 3D, PUNCH will enable separation of interior structures as they propagate, revealing the chirality (direction of twist) and evolution of CMEs and how the physics of their complex interior affects geoeffectiveness.

Question 2B: How do quasi-stationary corotating interaction regions (CIRs) form and evolve?

CIRs are regions where fast solar wind overtakes slow solar wind due to the Sun's rotation[24] (Figure 5). CIRs are associated with density increases and shocks, and are more common sources of geomagnetic storms than are CMEs. Because most studies of CIRs have historically relied on interplanetary radio scintillation[25] or in-situ data[26], the formation, cross-scale structure, and evolution of CIRs were largely inaccessible until STEREO visible-light imaging became available[27]. PUNCH will, for the first time, image CIR formation, evolution, and front morphology routinely and in 3D, exploring these important, enigmatic structures.

Question 2C: How do shocks form and interact with the solar wind across spatial scales?

Shocks are important to space physics, but interplanetary shocks are not well understood. The one-dimensional physics of simple shock fronts is well established[28], but shock fronts are rarely one-dimensional and simple. CME shocks may be imaged in white light[29]. They are frequently observed at the flank, rather than the front of the CME; and inhomogeneities in the solar wind often cause shocks to evolve in large-scale shape and/or develop crinkles as they interact with the surrounding medium[30]**.** PUNCH brings high resolution, high sensitivity, and 3D context to shock front imaging, allowing new understanding of shock morphology and its relationship to solar energetic particles, shock propagation and dissipation, and – ultimately – space weather.

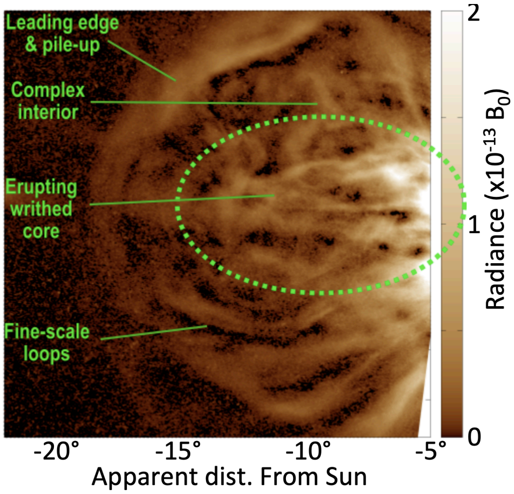

Figure 4: CMEs, such as this event imaged by STEREO/HI1 and enhanced by unsharp-masking, have rich interior structure including a writhed flux-rope core, pile-up on the leading edge, and complex interior structure including fine-scale loops; by imaging these structures in 3D, PUNCH will enable identifying the chirality and tracking the evolution of this interior structure

3. INSTRUMENTATION

The PUNCH primary instruments are white-light imagers. The four-satellite mission is specifically designed to act as a single "virtual instrument": a coronagraph with an extraordinarily wide field of view. The constellation, as a whole, images the corona and heliosphere at all solar position angles (around the Sun), from 1.5° to 45° from the Sun itself – a 90° wide, circular field of view with a 3° diameter cutout around the Sun. Over that range of angles, the overall brightness varies by over four orders of magnitude (Figure 6), necessitating at least two different instrument types. A *Narrow Field Imager* (NFI) covers the coronal portion of the field of view, from 1.5° to 8° from the Sun. Three complementary *Wide Field Imagers* (WFIs) image from 5° to 45° from the Sun. The imagers are specifically designed to work together, with significant field-of-view (FOV) overlap and matched instrument characteristics including their exposure sequence, wavelength range, and resolution. The WFI field of view is sufficiently wide that, from LEO, each WFI can only view the sky in the hemisphere closest to the zenith. Therefore, PUNCH uses three WFIs, mounted on separate spacecraft, to

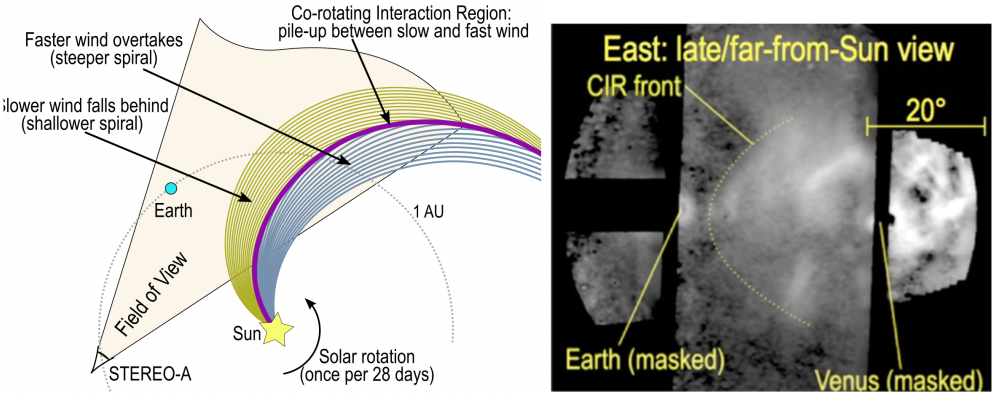

Figure 5: CIRs are density enhancements and/or shocks where fast solar wind overtakes slow solar wind in the "Parker spiral" from the Sun's rotation (left). PUNCH will image in detail these enigmatic structures and their formation, first glimpsed by STEREO-A (right).

spread around the Earth and achieve its full FOV. For consistency of design each primary instrument is carried by a separate smallsat. The instruments are operated simultaneously via synchronized onboard clocks, to allow their image data to be merged seamlessly.

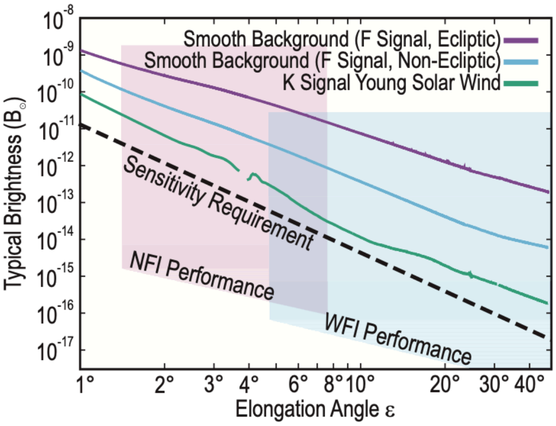

Figure 6: The F corona (and zodiacal light) brightness varies by four orders of magnitude across the PUNCH field of view, as measured by STEREO; this drives two instrument types to cover the complete field of view.

In addition to the primary instrumentation, PUNCH carries a student-contributed full-Sun X-ray spectrometer, the *Student Energetic Activity Monitor* (STEAM), which carries out supporting science and rides on the NFI spacecraft on a do-no-harm basis.

To simplify subsystem-level design and save cost, NFI and WFI development was closely coordinated, several common elements are identical between the instruments, and each instrument is controlled directly by the spacecraft. Common subsystems include the CCD camera and electronics; a motorized polarizing filter wheel; instrument door actuators; heaters and thermistors; and the spacecraft control interface. The instruments and spacecraft are specifically designed to be interchangeable, with the only control difference being in easily-updated software tables that specify the instrument control signals and sensor ranges.

3.1. COMMON ELEMENTS

The important common elements are a CCD camera, supplied by RAL Space, and a polarizing filter wheel, supplied by NRL.

3.1.1 CCD Camera

PUNCH uses a CCD detector for its linearity and uniform characteristics. The CCD is a 2kx4k, back-illuminated, back-thinned 15µm pixel device made by Teledyne E2V, and broadband coated to achieve ~90% quantum efficiency over its passband. It is operated in frame-transfer mode to minimize exposure time jitter: exposure times are stable to better than 10^{-4} (relative). Transfer time from the 2kx2k active area to the 2kx2k storage area is 125ms; readout time is 3 sec.

The CCD response to fluence is linear to better than 0.5% across the full well; additional nonlinear (quartic-polynomial) calibration is used to produce a signal that is linear to 2×10^{-4} (relative). On-orbit the nonlinear flat field is maintained by exposure scans with stimulation LEDs that are pulse-width modulated using an ultrastable, switchable current supply. This strategy provides rigorous maintenance on-orbit of the photometric calibration, provided only that the detector is reciprocal (yields values dependent on total fluence and independent of temporal pattern within an exposure).

The CCD values are read out and digitized to 16 bits per pixel via dual-channel readout and control electronics made by RAL Space. These are controlled directly from the spacecraft via SpaceWire. The gains are tuned to ¾ full well dynamic range, resulting in 2-3 e^- per DN. Total read noise is 12-15 e^- per pixel; at the nominal -50°C CCD temperature leakage current and time-dependent dark noise are negligible.

3.1.2 Polarizing Filter Wheel (PFW)

NFI and each WFI use a 5-position PFW in the optical train. The filter wheel holds three polarizers at 60° relative angles, plus a blank-off and a clear position. Each wheel is driven by a stepper motor controlled by the spacecraft. The polarizers are nanowire type, chosen for their very broad wavelength range, insensitivity to incidence angle, and radiation tolerance. The PFWs are made by NRL.

3.2 NARROW FIELD IMAGER (NFI)

The NFI instrument is an externally occulted compact-coronagraph design, built by NRL (Figure 7). NFI has approximately the same 6-32 R_s field of view as SOHO/LASCO-C3[31]. Based on a lesson learned from development of the STEREO/COR2 instrument, NFI uses only a single optimized multi-disk external occulter instead of a traditional multi-stage coronagraph design[32].

Light enters through an A0 aperture that is toothed to prevent circularly-symmetric diffraction; passes the occulter; and enters an A1 aperture where it is imaged, by a dioptric lens barrel assembly, through a PFW onto a CCD. A low-scatter "heat rejection mirror" images the solar disk into the empty space opposite the occulter-support pylon, dumping sunlight away into space. The interior of the "vestibule" (the space between A0 and A1) is baffled with matte black ring baffles to prevent internal glint.

Because of its extensive heritage including LASCO, STEREO/COR, and CCOR, NFI uses a protoflight development program.

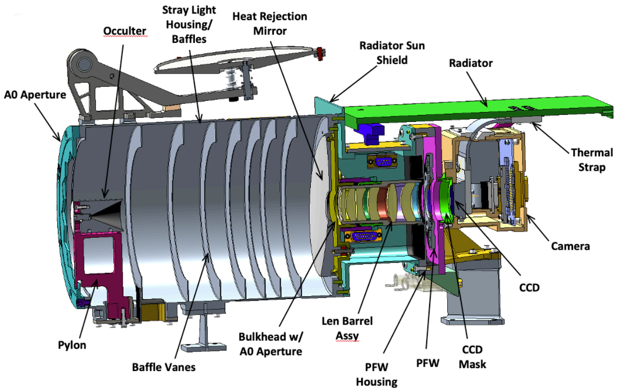

Figure 7: The PUNCH Narrow-Field Imager (NFI) has a single optimized external occulter and views from 1.5°-8° from the Sun at all position angles.

3.3. WIDE FIELD IMAGER (WFI)

The WFI instrument is a now-conventional heliospheric imager design, built by SwRI (Figure 8). Its field of view is a 40° square, truncated by a 50° circle (rounded corners).

Light enters over the solar baffle at the front of the instrument, through a small two-bounce lunar baffle, passes through a PFW, and is focused by a dioptric optical lens assembly onto the CCD. The solar baffle casts a shadow that extends the length of the instrument. A set of deep "light trap" baffles capture any glint or moonlight incident on the instrument. The lunar baffle reduces the overall field of regard to minimize lunar interference with observations.

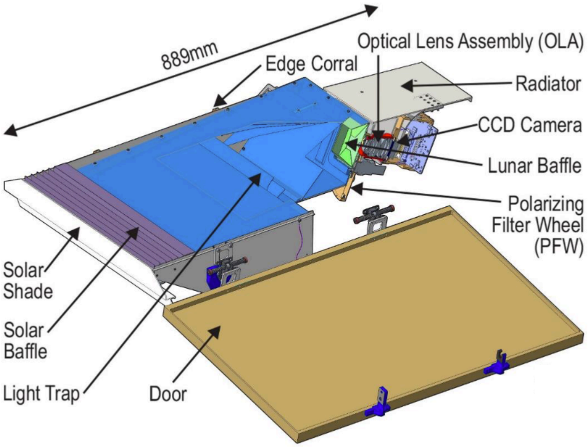

Figure 8: The PUNCH Wide-Field Imager (WFI) uses a single louvered "solar baffle", a deep light trap, and a smaller "lunar baffle". It views a truncated 40° square FOV, between 5°-45° from the Sun.

WFI is proceeding through a conventional engineering-model (EM) to flight-model (FM) development program. The EM is complete and has undergone environmental testing at SwRI and stray light testing at NRL's Solar Coronagraph Optical Test Chamber (SCOTCH) facility (Figure 9), and attenuates incident sunlight by more than 16 orders of magnitude at the center of the field of view.

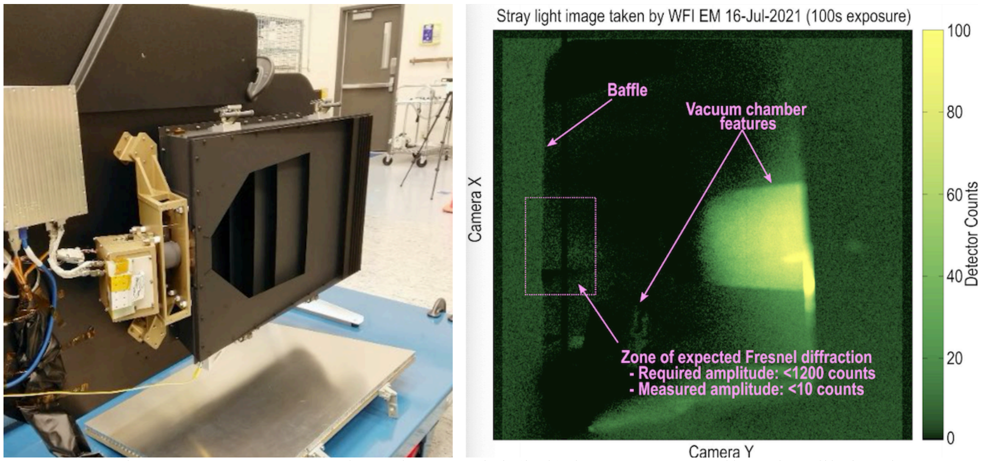

Figure 9: The PUNCH WFI engineering model (left) incorporates all major flight elements, and has undergone stray light testing in the SCOTCH vacuum stray light chamber at NRL. Solar attenuation is over 16 orders of magnitude at the center of the field of view.

3.4 STUDENT ENERGETIC ACTIVITY MONITOR (STEAM)

The STEAM instrument is a dual-channel, solid-state X-ray spectrometer built by the students of the Colorado Space Grant Consortium (Figure 10). Using two Amptek X123 detectors, STEAM measures spectra of the full-sun X-ray flux from 1 to 125 keV. STEAM science includes probing the nature of coronal heating and large solar flares, using both abundance (via line ratios) and the shape of the X-ray continuum during large and small flare events.

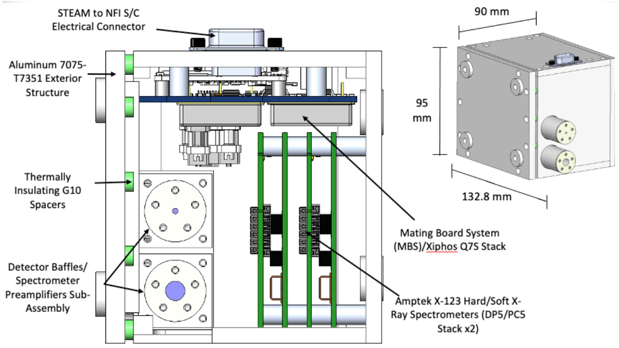

Figure 10: STEAM is a student-built X-ray spectrometer built around two Amptek X123 solid-state detectors.

4. MISSION DESIGN

The PUNCH mission is designed around the required high data volume and wide field of view. Wide field of view drives an obstruction-free location; data volume drives proximity to Earth. PUNCH solves that dilemma by expanding the "virtual instrument" to be the size of Earth, by merging data from four separate cameras mounted on four separate spacecraft: one NFI and three WFIs (Figure 11ab). This design is cost-enabled by the current market in COTS subsystems for smallsats and heritage small-constellation integration processes developed at SwRI during development of the Cyclone Global Navigation Satellite System (CYGNSS) mission0.

The four PUNCH Observatories will launch on a single launch vehicle (Figure 11c), to a Sun-synchronous 6am/6pm (terminator) orbit at 620km altitude. The four spacecraft are spring-deployed at approximately 1m/s from the launch vehicle, at specific angles relative to the launch vehicle velocity vector. This places the four spacecraft in different orbits with very slightly different periods; during a 90-day commissioning phase, the three WFI Observatories drift to 120° separation in mean anomaly (orbital phase); the position of the NFI Observatory relative to the WFI Observatories is not constrained. Using an orbital

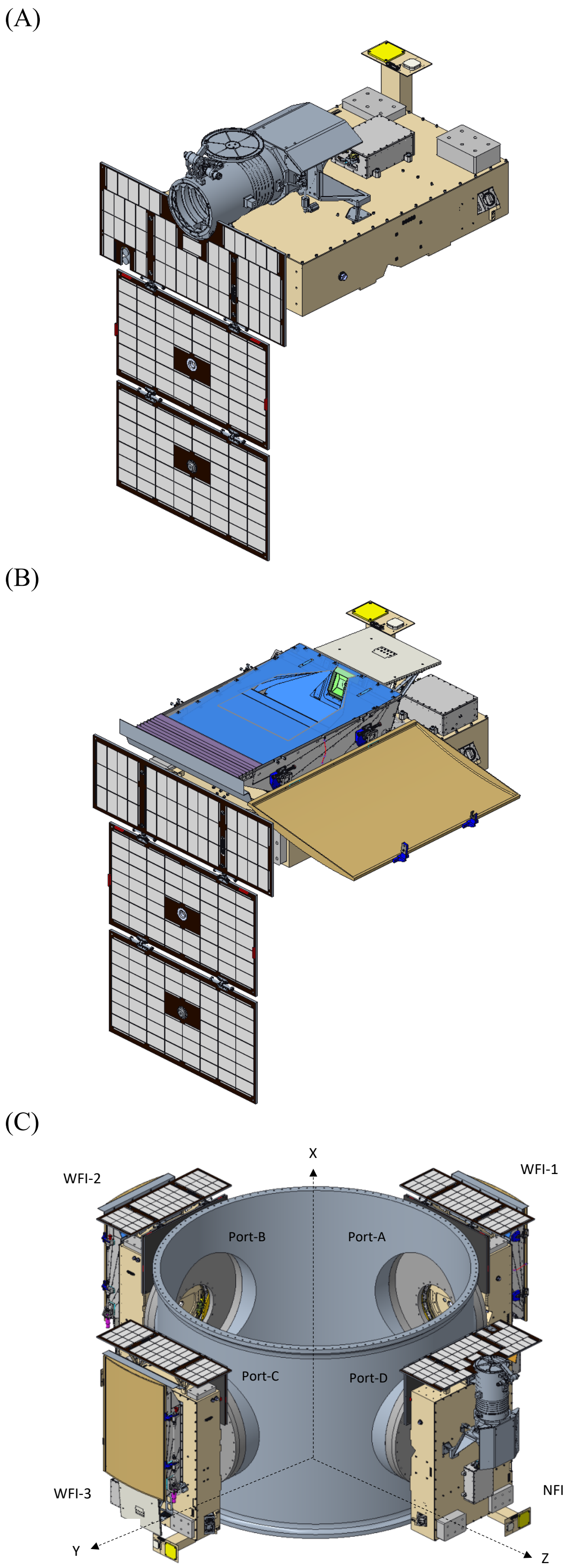

Figure 11: The PUNCH instruments are mounted, one per instrument, on interchangeable spacecraft. (A) NFI; (B) WFI; (C) launch configuration on a 4-port ESPA Grande type launch ring. The spacecraft are mounted with Motorized Light Band spring separation systems.

trim propulsion system, the Observatories halt their relative drift and maintain relative positions during the rest of the mission. Once operations begin, the Observatories execute a roll-and-hold program: the Observatories maintain their +X axis pointing toward the Sun, and rotate their +Z axis to point approximately at the zenith. At the start of each hold the zenith is 15° toward the +Y direction from the +Z axis. The Observatory holds position relative to the fixed stars for approximately 8 minutes (30° of orbital motion), at which time the zenith is 15° to the -Y direction from the +Z axis. Then the Observatory rotates to the new position. During the hold interval, the Observatory executes two separate polarization exposure sequences and collects one clear exposure of its target. (Figure 12).

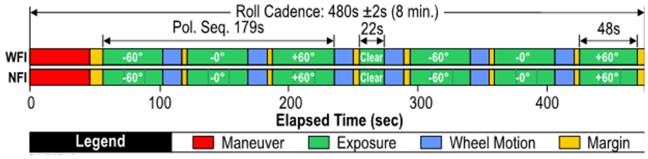

Figure 12: PUNCH repeating exposure sequence includes two full polarization sequences plus one clear, every 8 minutes. The instrument actively collects photons over 60% of the time during science operations. All four Observatories are synchronized and act as a single "virtual coronagraph".

All four Observatories are synchronized to roughly ±1 sec, so that the exposures may be treated as synchronous. Their instantaneous fields of view (IFOVs) form a trefoil on the celestial sphere, and each IFOV intersects the other three (Figure 13). The result is that, out to roughly 80 R_s, the whole constellation collects one full exposure sequence every four minutes. At higher solar elongation angles out to 180 R_s (45°) from the Sun, PUNCH collects one full exposure sequence three times per orbit (approximately a 35 min cadence).

Roughly once per month, each Observatory executes an internal exposure sequence using the stim lamps, to maintain nonlinear calibration of the cameras. As needed to maintain

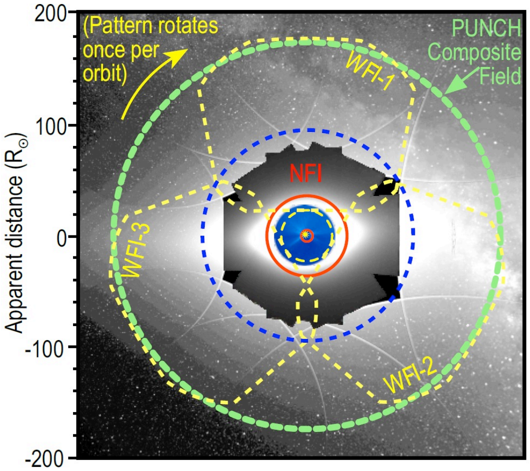

Figure 13: the PUNCH instantaneous fields of view (IFOVs) form a trefoil on the Celestial Sphere (NFI: red; WFI: yellow). Inside 80 Rs (blue circle) each point on the sky is imaged every four minutes; outside, coverage cadence is 3x per orbit (green circle).

120° separation, each WFI Observatory executes an orbital trim maneuver during one 8-minute hold sequence, approximately every 90 days. Ground passes do not interrupt the repetitive operations sequence. There are no other variations in the repeating operational sequence, aside from anomaly resolution if necessary.

4.1. SPACECRAFT DESIGN

The PUNCH spacecraft (Figure 14) are specifically designed for high performance and mission flexibility, in full "sciencecraft" mode: the primary avionics also handle instrument operation and management. Major systems are:

Structure: the overall spacecraft structure is machined from aluminum. The primary structure is a monolithic base box in the form of a flat rectangular slab. Secondary structures include standoffs for antennas and solar arrays, a closeout panel, and instrument supports. One entire deck (the +Z deck) is reserved for an instrument.

Avionics: The avionics are designed around a SwRI-built Centaur single-board computer (SBC) with additional interface cards for digital subsystem command, actuator control, analog-to-digital sensor interfaces, power handling, and solar array power conditioning.

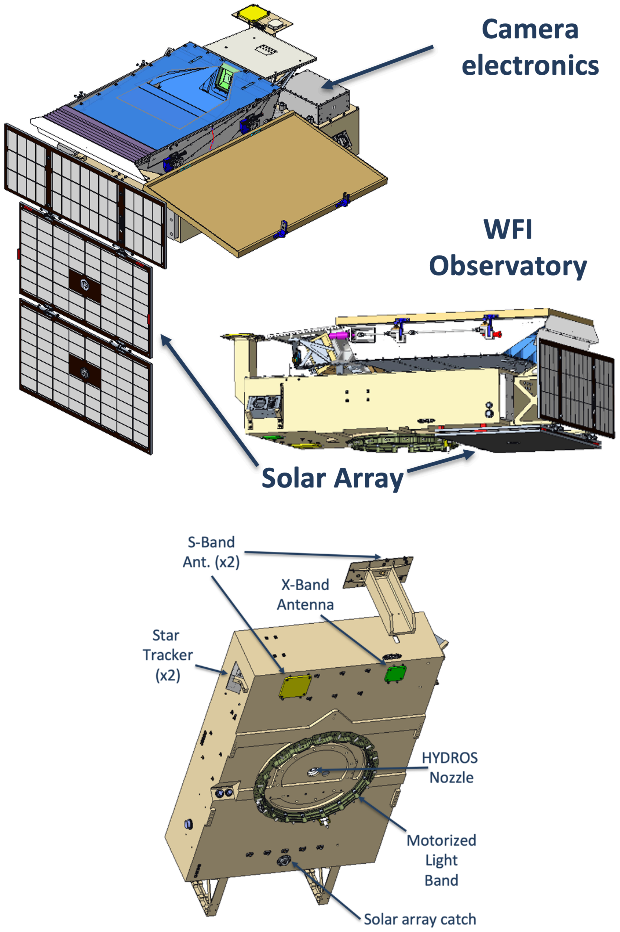

Figure 14: External views of the WFI Observatory and PUNCH spacecraft show major features: solar panel standoffs and geometry; ground antennas; and star trackers. TOP: one instrument is mounted on the +Z deck of the spacecraft. MIDDLE: in launch configuration, solar arrays are stowed against the -Z face of the spacecraft. BOTTOM: The propulsion nozzle and separation system are aligned with the spacecraft center of gravity.

Command & Data Handling (C&DH): The Centaur SBC, together with the SwRI-developed flight software, handles uplink commands, including controlling and monitoring all subsystems scheduling absolute- and relative-time sequence command sets, and collects housekeeping and science data and stores them for downlink during ground passes. The general-purpose CPU is augmented by dual FPGAs that handle major functional blocks such as data compression and packetization.

Power: Direct power is supplied by a stowable, one-time deploy solar array from Sierra Nevada Corporation. Power is regulated by a SwRI Peak Power tracker, distributed by a 28V service bus with switchable and non-switchable outputs, and down-converted by a multi-voltage power supply, all of which are built into the SwRI avionics package. Energy storage is in a COTS battery from ABSL.

The solar arrays are mounted on standoffs on the +X face of the spacecraft, and are stowed in a folded configuration for launch. The spacecraft is power-positive in Sun-pointed safe mode, even with the solar arrays stowed.

Communications: the command link is via an S-band full-duplex radio transceiver from Tethers Unlimited (TUI), via low-gain patch antennas mounted on the -Z and +Z faces of the spacecraft. The +Z antenna is on a small standoff tower to separate it from the instrument. The S-band rate is up to 5 Mbps downlink (256kbps nominal), 64kbps uplink.

The nominal science downlink channel is via an X-band transmitter, also from TUI, via a single low-gain patch antenna mounted on the -Z face of the spacecraft. The X-band rate is 25 Mbps. The S-band link can be used as a backup science link in case of X-band failure.

Attitude Determination and Control (ADCS): The ADCS is an XACT system built by Blue Canyon Technologies (BCT). The XACT control module is augmented with a second star tracker, three external magnetic torque rods, four reaction wheels, and a GPS receiver. Time signals and orbital elements can also be jammed via ground command in case of GPS failure.

In nominal operations, ADCS is keyed to celestial position and solar tracking is maintained using an on-board solar ephemeris. The C&DH system issues celestial-frame pointing commands to the ADCS but is not part of the attitude control loop. Nominal pointing stability is 28.8 arcsec (3σ) over 75 seconds, to hold position for each exposure. The dual star trackers are aimed roughly 90° apart to ensure high precision pointing around all three axes. The reaction wheels are sized to enable a 30° roll (and restabilization) in under 60 seconds, supporting the observing sequence in Figure 12.

On initial deployment, the ADCS begins in a "lost in space" mode and measures and nulls rotational rates using the torque wheels until the rotational rate is low enough to be absorbed by the reaction wheels; then coarse sun sensors are engaged to point the solar arrays in the direction of the Sun. Monte Carlo simulation with higher-than-expected rotational rates yield stable Sun pointing in under 2400 seconds based on extensive simulation (<7200 seconds required).

Propulsion: Each Observatory uses a Hydros-C H_2/O_2 pulsed-combustion propulsion system for orbital trim from TUI. The Hydros-C carries propellant as H_2O, which is electrolyzed as needed using on-board power, and ignited in a small combustion chamber to yield a controlled impulse of up to 1.75 Nsec per thrust event, at I_{sp}=290 sec. The Hydros-C system was selected for its cost, safe propellant storage, flexibility, and compact and modular form factor.

4.2. DATA PRODUCTS AND DATA ANALYSIS

PUNCH images are processed on the ground into usable data products. This is important because the PUNCH images contain other light sources up to 1000x brighter than the solar wind being imaged (Figure 6). Foreground and background sources of light include instrument stray light; transient terrestrial effects, including high altitude aurora[33]; the solar F corona; and the starfield. Removing these layers drives several key steps in the data reduction pipeline including rigorous nonlinear flat field correction, PSF correction, and optimized resampling. Furthermore, PUNCH data are polarized to enable 3D analysis of observed features[23]. Maintaining the polarimetric signal during background subtraction is itself nontrivial. Forcing individual scientists to reduce PUNCH data from scratch would limit productivity, while distributing only processed data would prevent further innovation. PUNCH therefore distributes data products both in the "TRACE mode"[34] as raw data accompanied by the software to reduce it, and in the "ACE mode"[35] as processed, calibrated and background-subtracted data ready for use by interested scientists. All data products are released to the world at the same time as to the science team.

5. STATUS AND PATH TO FLIGHT

PUNCH was proposed to the HPSMEX-2016 Announcement of Opportunity, and selected in the summer of 2019 for acompetitive Phase A (concept study). PUNCH was downselected for Phase B, with a primary NASA launch, in July 2019 and Phase B (preliminary design) began in October 2019. The mission successfully passed preliminary design review (PDR) in May 2021, and confirmation review (KDP-C) in July 2021, authorizing a transition into a combined Phase C/D (final design, fabrication, assembly, integration & test, and launch). The project is currently working toward critical design review (CDR) in early 2022. The current Launch Readiness Date is October 2024, on a ride share launch with NASA's SPHEREx mission.

6. SUMMARY

PUNCH is a NASA constellation mission consisting of four micro-satellites that will carry out breakthrough science within the scope of a Small Explorer program; PUNCH is enabled by the current market of smallsat component systems, which permits construction, deployment, and operation of four satellites within the scope of a Small Explorer budget and schedule. The science covers unification of major subfields of solar and heliospheric physics, through direct imaging. The mission is working toward a scheduled launch date in late 2024, on a ride-share launch with NASA's SPHEREx mission.

The PUNCH investigation is structured specifically to be inclusive and to reach out to the entire interested community, including the heliophysics community. Science team meetings are open to the public and the team welcomes science involvement from the heliophysics community and the public. For more information, visit the PUNCH mission website at https://punch.space.swri.edu.

ACKNOWLEDGEMENTS

PUNCH is a NASA Small Explorer mission, funded via NASA Contract No. 80GSFC18C0014.

REFERENCES

[1] Fox, N.J., Velli, M.C., Bale, S.D., et al. 2016: "The Solar Probe Plus Mission: Humanity's First Visit to Our Star", *Sp. Sci. Rev.* 204, 7.

[2] Parker, E.N., "Dynamics of the Interplanetary Gas and Magnetic Fields", *Astrophys. J.* 128, 664.

[3] Cranmer, S. R. and Winebarger, A. R., "The Properties of the Solar Corona and Its Connection to the Solar Wind", *Annual Review of Astronomy and Astrophysics*, vol. 57, pp. 157–187, 2019.

[4] DeForest, C. E., Howard, R. A., Velli, M., Viall, N., and Vourlidas, A., "The Highly Structured Outer Solar Corona", *Astrophys. J.* 862, p. 18, 2018.

[5] McComas, D. J., "Solar wind observations over Ulysses' first full polar orbit", *J Geophys. Res.* 105, no. A5, . p. 10419, 2000.

[6] Viall, N. M., DeForest, C. E., and Kepko, L., "Mesoscale Structure in the Solar Wind", *Frontiers in Astronomy and Space Sciences*, vol. 8, 2021.

[7] Sheeley, N. R., "Measurements of Flow Speeds in the Corona Between 2 and 30 R_⨀", *Astrophys. J.* vol. 484, no. 1, pp. 472–478, 1997.

[8] Viall, N. M. and Vourlidas, A., "Periodic Density Structures and the Origin of the Slow Solar Wind", *Astrophys. J.* vol. 807, no. 2, 2015.

[9] Elliott, H. A., Henney, C. J., McComas, D. J., Smith, C. W., and Vasquez, B. J., "Temporal and radial variation of the solar wind temperature-speed relationship", *J. Geophys. Res. (Sp. Phys.)*, vol. 117, no. A9, 2012.

[10] DeForest, C. E., Matthaeus, W. H., Howard, T. A., and Rice, D. R., "Turbulence in the Solar Wind Measured with Comet Tail Test Particles", *Astrophys. J.*, vol. 812, no. 2, 2015.

[11] DeForest, C. E., Matthaeus, W. H., Viall, N. M., and Cranmer, S. R., "Fading Coronal Structure and the Onset of Turbulence in the Young Solar Wind", *Astrophys. J.* vol. 828, no. 2, 2016.

[12] Hundhausen, A. J., Coronal Expansion and Solar Wind. 1972.

[13] DeForest, C. E., Howard, T. A., and McComas, D. J., "Inbound Waves in the Solar Corona: A Direct Indicator of Alfvén Surface Location", *Astrophys. J.*, vol. 787, no. 2, 2014.

[14] Cranmer, S. R., DeForest, C. E., and Gibson, S. E., “Inward-propagating Plasma Parcels in the Solar Corona: Models with Aerodynamic Drag, Ablation, and Snowplow Accretion”, <i>The Astrophysical Journal</i>, vol. 913, no. 1, 2021.

[15] Telloni, D., “Exploring the Solar Wind from Its Source on the Corona into the Inner Heliosphere during the First Solar Orbiter-Parker Solar Probe Quadrature”, *Astrophys. J.* vol. 920, no. 1, 2021.

[16] Gosling, J. T., “The solar flare myth”, *J. Geophys. Res.,*vol. 98, no. A11, pp. 18937–18950, 1993.

[17] Gibson, S., “Coronal Cavities: Observations and Implications for the Magnetic Environment of Prominences”, in *Solar Prominences*, 2015, vol. 415, p. 323.

[18] DeForest, C. E., Howard, T. A., and McComas, D. J., “Tracking Coronal Features from the Low Corona to Earth: A Quantitative Analysis of the 2008 December 12 Coronal Mass Ejection”, *Astrophys. J.,* vol. 769, no. 1, 2013.

[19] Howard, T. A., DeForest, C. E., and Reinard, A. A., “White-light Observations of Solar Wind Transients and Comparison with Auxiliary Data Sets”, *Astrophys. J.*, vol. 754, no. 2, 2012.

[20]]Isavnin, A., Vourlidas, A., and Kilpua, E. K. J., “Three-Dimensional Evolution of Flux-Rope CMEs and Its Relation to the Local Orientation of the Heliospheric Current Sheet”, *Sol. Phys.* vol. 289, no. 6, pp. 2141–2156, 2014.

[21] Gopalswamy, N., Yashiro, S., Kaiser, M. L., Howard, R. A., and Bougeret, J.-L., “Radio Signatures of Coronal Mass Ejection Interaction: Coronal Mass Ejection Cannibalism?”, *Astrophys. J.*, vol. 548, no. 1, pp. L91–L94, 2001.

[22] Tappin, S. J. and Howard, T. A., “Interplanetary Coronal Mass Ejections Observed in the Heliosphere: 2. Model and Data Comparison”, *Sp. Sci. Rev.*, vol. 147, no. 1–2, pp. 55–87, 2009.

[23] DeForest, C. E., de Koning, C. A., and Elliott, H. A., “3D Polarized Imaging of Coronal Mass Ejections: Chirality of a CME”, *Astrophys. J.*, vol. 850, no. 2, 2017.

[24] Pizzo, V., “A three-dimensional model of corotating streams in the solar wind 1. Theoretical foundations”, *J. Geopys. Res.* vol. 83, no. A12, pp. 5563–5572, 1978.

[25] Tappin, S. J., Hewish, A., and Gapper, G. R., “Tracking a high-latitude corotating stream for more than half a solar rotation”, *Planetary & Sp. Sci.*, vol. 32, no. 10, pp. 1273–1281, 1984.

[26] Möbius, E., Morris, D., Popecki, M. A., Klecker, B., Kistler, L. M., and Galvin, A. B., “Charge states of energetic (~0.5 MeV/n) ions in corotating interaction regions at 1 AU and implications on source populations”, *Geophys. Res. Lett.*, vol. 29, no. 2, 2002.

[27] Wood, B. E., Howard, R. A., Thernisien, A., and Socker, D. G., “The Three-Dimensional Morphology of a Corotating Interaction Region in the Inner Heliosphere”, *Astrophys. J.,* vol. 708, no. 2, pp. L89–L94, 2010.

[28] Hundhausen, A. J., “Some macroscopic properties of shock waves in the heliosphere”, *AGU Geophys. Monograph Series*, vol. 34, pp. 37–58, 1985.

[29] Vourlidas, A., Wu, S. T., Wang, A. H., Subramanian, P., and Howard, R. A., “Direct Detection of a CME-Associated Shock in Large Angle and Spectrometric Coronagraph Experiment White-Light Images”, *Astrophys. J.*, vol. 598, no. 2, pp. 1392–1402, 2003.

[30] Vourlidas, A. and Ontiveros, V., “A Review of Coronagraphic Observations of Shocks Driven by Coronal Mass Ejections”, in *Shock Waves in Space and Astrophysical. Environments: 18th annual Int’l Astrophysics Conf.*, 2009, vol. 1183, pp. 139–146.

[31] Brueckner, G. E., “The Large Angle Spectroscopic Coronagraph (LASCO)”, *Solar Physics*, vol. 162, no. 1–2, pp. 357–402, 1995.

[32] Gong, Q. and Socker, D., “Theoretical study of the occulted solar coronagraph”, in *Opt. Systems Degradation, Contam., and Stray Light: Effects, Meas., and Control*, 2004, vol. 5526, pp. 208–219.

[33] Mizuno, D. R., “Very high altitude aurora observations with the Solar Mass Ejection Imager”, *J. Geophys. Res (Space Phys),* vol. 110, no. A7, 2005.

[34] Handy, B. N., “The Transition Region and Coronal Explorer”, *Sol. Phys.* vol. 187, no. 2, p. 229, 1999.

[35] McComas, D. J., “Solar Wind Electron Proton Alpha Monitor (SWEPAM) for the Advanced Composition Explorer”, *Sp. Sci. Rev.,* vol. 86, pp. 563–612, 1998.

[36] Ruf, C., “The NASA EV-2 Cyclone Global Navigation Satellite System (CYGNSS) mission”, in *Proc. 2013 IEEE Aerosp. Conf*, 2013.

BIOGRAPHY

Dr. Craig DeForest is Chair of the Solar Physics Division of the American Astronomical Society, Principal Investigator of the PUNCH mission, and a Program Director at Southwest Research Institute (SwRI). He has been studying solar and heliospheric physics for over 30 years, and received his Ph.D. from Stanford University in 1995. His research has focused on probing the solar corona through novel imaging techniques. DeForest is well known for his work on image and signal processing in the context of solar and heliospheric physics; for broad and extensive scientific outreach; and for his experimental and data-processing innovations. He holds multiple U.S. patents covering novel instruments and data analysis methods.

Ronnie Killough is a Program Director in the Space Science and Engineering Division at Southwest Research Institute (SwRI). In his thirty years at SwRI, Ronnie has managed multiple NASA, defense and commercial projects, and has developed and managed software for cruise missile simulators, space shuttle control center systems, and unmanned spacecraft; and has has served on multiple Independent Review Teams (IRTs) and Standing Review Boards (SRBs) for NASA. Ronnie previously served as mission software lead and deputy systems engineer for the Cyclone Global Navigation Satellite System (CYGNSS) mission, and was also one of two flight directors during the CYGNSS Launch and Early Operations phase in 2016. He is Project Manager for the PUNCH mission. Ronnie is a certified Project Management Professional (PMP).

Dr. Sarah Gibson, PUNCH Project Scientist, is a Senior Scientist at the High Altitude Observatory (HAO) of the National Center for Atmospheric Research. She received her B.Sc. in Physics from Stanford in 1989, and Ph.D. in Astrophysics from the University of Colorado in 1995. Her research centers on solar drivers of the terrestrial environment, from short-term space weather such as coronal mass ejections (CMEs), to long-term solar-cycle variation. She led the international Whole Sun Month, Whole Heliosphere Interval, and Whole Heliosphere and Planetary Interactions campaigns to characterize the 3D, interconnected solar-heliospheric-planetary system via coordinated observing and modeling. Dr. Gibson has been a Scientific Editor for Astrophysical Journal and has served on many national and international committees. Her extensive education and public outreach activities include preparing and presenting oral and written testimony to the Committee on Science, Space and Technology (U. S. House of Representatives; 2018).

Alan Henry is the Assistant Director of Spacecraft Development in the Space Sciences and Engineering Division at SwRI. Alan has over 30 years of experience in space hardware design, development, operations and management, and is the Project Systems Engineer for PUNCH. Prior to PUNCH, he served as Systems Engineer or Deputy Project Manager on numerous avionics and power supply systems at SwRI; was the I&T manager of the four Magnetospheric MultiScale (MMS) mission instrument suites, and I&T Manager of the CYGNSS constellation of 8 microsatellites. Prior to joining SwRI, Alan was Sr. Principle Engineer at Orbital Sciences supporting systems engineering efforts on the DAWN mission. Alan received his B.S. in Aerospace Engineering from the University of Texas in 1990.