NOTE: This document was prepared by a team that participated in the 2018 Workshop on Autonomy for Future NASA Science Missions. It is for informational purposes to inform discussions regarding the use of autonomy in notional science missions and does not specify Agency plans or directives.

2018 Workshop on Autonomy for Future NASA Science Missions: Heliophysics Design Reference Mission Reports

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Introduction

Autonomy is changing our world; commercial enterprises and academic institutions are developing and deploying drones, robots, self-driving vehicles and other autonomous capabilities to great effect here on Earth. Autonomous technologies will also play a critical and enabling role in future NASA science missions, and the Agency requires a specific strategy to leverage these advances and infuse them into its missions. To address this need, NASA sponsored the 2018 Workshop on Autonomy for NASA Science Missions, held at Carnegie Mellon University, October 10-11, 2018.

The Workshop goals included:

- Identifying emerging autonomy technologies (10-15 years) that will:
    - Enable or enhance mission capabilities
    - Reduce risk
    - Reduce cost
- Identifying potential collaborations, partnerships, or linkages involving government, industry, and/or academia to enable these technologies

Capturing crosscutting autonomy technology requirements for future NASA missions
Over 90 individuals from industry, academia, and NASA participated in the workshop, which included presentations by keynote speakers, panel discussions, and small group discussions.

To provide structure for workshop discussions and post-workshop analysis, NASA established eight teams to examine the following Design Reference Mission (DRM) areas: Astrophysics, Earth Science, Heliophysics, Mars, Moon, Ocean Worlds, Small Bodies and Venus. Each DRM team was led by a scientist and a technologist, and team members consisted of workshop participants with relevant experience and interest. NASA asked each team to develop one or more mission scenarios that would be enabled by infusion of autonomous technology. The Agency provided guidance to support these team discussions; in particular, NASA urged the DRM teams to "think out of the box" and to consider bold missions that would be enabled by autonomous technology to provide valuable science results. Each DRM team developed mission scenarios that included defined science objectives, capability and technology needs, system requirements, and a concept of operations. Teams also identified gaps where autonomy technologies and other supporting technologies need to be developed and/or infused to enable each mission.

The DRM teams conducted small group discussions at the workshop and then presented a summary of their findings to all workshop attendees. Each DRM team continued to refine its mission scenarios after the workshop, creating both a full report and a summary report to document team findings. DRM teams also reported results at the December 2019 meeting of the American Geophysical Union.

This document contains the full report and summary report generated by the Heliophysics DRM team. Full and summary reports generated by all eight DRM teams, plus a summary of workshop results are available online.

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The Heliophysics Design Reference Mission Report

Part I: Abstract

Heliophysics Overview

The science of Heliophysics is focused on understanding the formation and evolution of the solar wind and solar ejecta, and how those impact objects in the solar system. In the near future, we expect to send astronauts to the Moon and Mars. As humans leave the safety of Earth's protective magnetic bubble, they will be exposed to the harsh environment of space weather. Safeguarding human and robotic exploration and eventual colonization of the solar system is a prime motivator for this DRM, and autonomous technologies would enable mission success.

Design Reference Mission

The Heliophysics Team suggests two Design Reference Mission (DRM) scenarios that autonomy would enable.

- The **Autonomous Space Weather Constellation** scenario would improve space weather predictions. Its aim would be filling the gaps in our observational capabilities in order to facilitate validated, near-real time, data-driven models of the Sun's global corona, heliosphere and associated space weather effects to safeguard human and robotic exploration throughout the solar system.

- **An Interstellar Probe** scenario would travel to the Local Interstellar Medium (LISM) and measure the environment beyond the solar system. The probe would launch around 2030 and travel 20 AU/year for 50 years to reach 1000 AU. The probe would make comprehensive, state-of-the-art, in situ measurements of plasma and energetic-particle composition, magnetic fields, plasma waves, ionic charge states, energetic neutrals, and dust that are required for understanding the nature of the outer heliosphere and exploring our local galactic environment.

Critical Autonomous Technologies

The critical autonomous technologies needed to achieve both of these scenarios are **situation and self-awareness** and **collaboration and interaction**, including:

- Joint knowledge and understanding
- Event and trend identification
- Sensing and perception
- Anomaly detection

- Activity and resource planning and scheduling
- Learning and adapting
- Modeling and simulation

Those technologies will enable the following capabilities:

- Autonomous spacecraft fault detection and correction
- Onboard feature identification and downlink of interesting regions and events only
- Onboard machine learning (inference) of individual active regions to predict solar flares
- Stereographic imaging of coronal mass ejections, and autonomous detection, evaluation, and warning
- Global imagers autonomously identify 'interesting' regions, and direct more detailed telescopes.

Supporting technologies that are needed for both of these scenarios are:

- A testbed for simulating the constellation
- Small-spacecraft-based communication and propulsion
- Space qualified high-throughput processors
- Advanced propulsion technology (long-lasting)
- Compact instrumentation
- High-temperature-resistant materials

Findings

The Heliophysics DRM team finds the following activities would enable the mission scenarios described above:

- Developing a space weather buoy demonstration mission to orbit the Moon and serve as a gateway space weather buoy.
- Developing a testbed to assess effectiveness and return-on-investment of various Space Weather Constellation configurations.
- Developing spacecraft hardware and software fault detection and recovery
- Developing compact "smart" instrumentation
- Considering a magnetohydrodynamics modeling component as a key element of the mission
- Developing artificial intelligence/machine-learning techniques to facilitate onboard data processing and local space situational awareness

- Developing advanced observation modes and a smart downlink strategy for key measurements
- Developing autonomous fault detection and mitigation technologies for the spacecraft subsystems
- Requiring a path for flight demonstration for technologies such as computer accelerators as part of the technology readiness level (TRL) maturation

Part II: The Case for Heliophysics

Heliophysics is a discipline that is focused on understanding the formation and evolution of the solar wind and solar ejecta, and how those impact objects in the solar system, including Earth, the energization of particles, etc. Even within Earth's protective magnetic bubble, our technological society experiences impacts due to space weather. In the near future, we expect to send astronauts to the Moon and Mars. As humans leave the safety of Earth's protective magnetic bubble, they will be exposed to even harsher effects of space weather. Safeguarding human and robotic exploration and eventual colonization of the solar system is a prime motivator for this DRM.

Our vision is an interconnected network of satellites throughout the heliosphere, ground networks on other planets (e.g., radiation sensors on Mars), instruments on human spacecraft (both commercial and NASA), all autonomously connected to predictive capabilities. The system has the capability to launch 'spacecraft on demand' (e.g., from interplanetary human-carrying spacecraft) dropped as 'buoys' to monitor space weather. The system will autonomously decide to launch spacecraft, rapidly commission them, pull data from the spacecraft online, and assimilate it into space weather predictive models. Autonomous monitoring of solar active regions, coupled with models of solar eruptive events, will enable predictions that provide enough lead time to prepare for space weather impacts. Machine learning about active regions will enable flare predictions.

Part III: Design Reference Missions

DRM Scenario 1: An Autonomous Space Weather Constellation

Solar activity controls space weather in the near-Earth environment and in interplanetary space over multiple spatial and temporal scales. On timescales of minutes to hours, solar flares and energetic-particle events disturb the ionosphere/thermosphere, increase drag on satellites in low Earth orbit (LEO), disrupt global positioning systems and radio communications, and endanger astronaut safety. In less than one day, coronal mass ejections (CMEs) can impact Earth's magnetosphere, causing geomagnetic storms that can potentially disrupt power distribution over extended geographic areas. Over longer timescales, solar magnetic activity makes an imprint on space climate in terms of the average spectral solar irradiance driving Earth's atmosphere, and in terms of the magnetic terrain that accelerates, funnels, and shapes the solar wind. Even near the solar-cycle minimum, the global magnetic field from the Sun extending into the heliosphere can result in fast solar wind structures that drive geomagnetic storms on Earth.

Improved space-weather predictions are critical to safeguarding the nation's technological assets and the safety of astronauts, whether they are in Earth orbit or en route to/from the Moon or Mars. Such improvement requires the development and validation of physics-based, data-driven numerical simulations. **This document summarizes the science case for an Autonomous Space Weather Constellation to observe the Sun from multiple vantage points and to sample solar-wind conditions from multiple locations. Required autonomy capabilities are driven by the science case.**

The current Heliophysics System Observatory (HSO) has provided unprecedented coverage of the Sun and its impact on Earth, the planets, and other small bodies (e.g., comets) in the solar system. Data from different HSO missions have been combined to help us understand (post facto) how solar activity causes space weather events. Some data exists for the development of statistical models predicting the likelihood of flares and geomagnetic storms. Furthermore, sophisticated physics-based models have been developed to model solar-wind conditions at 1 AU (including disruptions from CMEs). However, the research community and the National Oceanic and Atmospheric Administration (NOAA) are not close to providing the following types of predictions with high accuracy and confidence:

- Predict (not after the fact) whether a sunspot region will spawn CMEs, solar flares and energetic particle events in the next hours to days
- Predict the arrival time and physical properties of abrupt changes in the solar wind (including CMEs)
- Predict the geoeffectiveness (in terms of geomagnetic storm strength, e.g., *Kp* index or *Dst*) of CMEs, whether they are directed toward Earth or slightly away from Earth
- Provide an "all clear" prediction for inclement space-weather activity over the next month

While there are isolated instances of success, none of the aforementioned can be provided with reliability over a broad spectrum of solar conditions. One major reason for the lack of reliable space-weather predictions is the sparse coverage of measurements in interplanetary space at scales of 1 AU. Most HSO missions are in Earth orbit. Missions like the pair of STEREO (Solar TErrestrial RElations Observatory) spacecraft that drift around the backside of the Sun in a 1-AU orbit have demonstrated how multi-vantage point observations in the extreme ultraviolet (EUV) and white light help us pin down the source region properties of the solar wind and CMEs, and better track their propagation from Sun to Earth.

Improvements for space weather predictions are hampered by a lack of multi-vantage point observations of the Sun-Earth system:

- Currently, **only one STEREO spacecraft remains in operation**, giving us only a second vantage point to complement the perspective from the Sun-Earth/L1 line. The Parker Solar Probe does not have a remote sensing EUV imager nor a magnetograph (it does have a white light imager).

- There exists no simultaneous, 360-degree coverage of the Sun's surface magnetic field. Data-constrained and data-driven **magnetohydrodynamics (MHD) models of the Sun's coronal magnetic field and its extension into the heliosphere require full-sphere magnetic maps.** The input data currently used are so-called synoptic (but not synchronic) magnetograms composing of data collected over the Sun's rotation (about 1 rotation per month). Due to the fast emergence of sunspot groups and their more gradual disintegration, the solar magnetic field changes substantially over days and weeks. While sunspot groups appear isolated on the solar surface, they have a global influence on magnetic connectivity in the corona and heliosphere. Reliable observations of the Sun's polar fields will also improve models. At present, there is no consensus on the strength of the Sun's polar fields (uncertainty is a factor of 2 to 3). By missing one active region or by using poorly measured (inaccurate) polar fields in the boundary condition magnetic map, the 3D magnetic topology—and hence the modeled solar wind properties—can be drastically wrong. The wrong ambient magnetic topology and solar-wind structure also leads to errors in models of CME propagation.

- **The properties of CMEs, from their initial formation in the solar corona to their propagation through interplanetary space, are poorly characterized.** For most CMEs, there exists at most a single spacecraft providing in situ measurements of the magnetic field and plasma properties. Isolated measurements at Lagrangian point 1 (L1) along the Sun-Earth are too late and too few for reliable predictions with lead times exceeding one or two hours. Except in numerical models, we generally do not know how CMEs evolve as they propagate to 1 AU. Simultaneous in situ measurements over extended areas covered by a CME are needed to resolve the question of evolution and internal structuring of CMEs. To further constrain the properties of CMEs, EUV and coronagraph imagers from multiple vantage points will be needed. Data from these remote sensing instruments will allow for tomographic reconstruction of the coronal field and CME structure, which will put tighter constraints on CME orientation, speed, and direction of propagation.

- **The Autonomous Space Weather Constellation is a DRM aimed at filling the gap in our observational capabilities in order to facilitate validated, near real-time, data-driven models of the Sun's global corona, heliosphere, and associated space weather effects.** The next section outlines the concept of operations for this DRM, and how this drives the need for specific autonomy capabilities.

The Concept of Operations

To capture a broad range of solar conditions (from solar minimum to maximum, back to minimum), the DRM has a nominal mission length of 10 years.

Consider a constellation of spacecraft **S** = $\{S_0, S_1, \ldots, S_n\}$ offering a simultaneous 4π steradian view of the solar surface. Each spacecraft will have a different orbit. A subset of spacecraft will be placed in STEREO-like 1-AU orbits, such that they drift behind the Sun. Using $n \geq 3$ such satellites, with an angular separation of (360/n) degrees is needed to maintain consistent, continuous coverage over the length of the mission. At least two more spacecraft are needed in orbits out of the ecliptic to simultaneously observe both the north and south poles. All aforementioned spacecraft are equipped with a magnetograph, coronagraph, EUV imager, and in situ instruments. A further set of (#TBD) spacecraft with portions of orbits between 0.5 and 1.0 AU is required to provide only in situ measurements of the solar wind (and CMEs) before their arrival at Earth.

With a full suite of instruments onboard each spacecraft, the rate of data flowing into the onboard computer can easily be on the order of 100s of MB/s. The aim of the tiered storage/downlink concept is to cull the data so the required telemetry is a factor of 1000 lower. This reduction cannot be done using conventional compression alone. Various approaches are required to achieve this data rate reduction. These include:

A. Onboard data processing from observables to higher level, science quality data products (e.g., 24 Stokes polarization images to 6 atmospheric measurements by performing onboard inversions, e.g., use of a field-programmable gate array [FPGA] on Solar Orbiter's Polarimetric Magnetic Imager)
B. Data culling (data cutouts, subsampling, onboard averaging): requires onboard inference to categorize datasets
C. Compressed sensing: i.e. designing detectors so that they capture the signal in terms of specially-chosen basis functions, and downlink those sparse coefficients for reconstruction on Earth
D. Conventional lossy data compression

To enable A, the onboard computer will need the capability to process the raw data into scientifically useful higher-level observables. We assume the calibration/processing pipeline will be finalized during the commissioning phase, and then uplinked to the spacecraft. This approach requires certain flexibility in the flight software/hardware stack. It also requires efficient pipelines enabled by a combination of fast onboard central processing units/graphics processing units (CPUs/GPUs) and machine learning techniques. For instance, it has been shown that neural networks can accelerate some physics-based inversion tasks by two or three orders of magnitude (Cheung 2018; Wright 2018).

To enable B, the onboard computer will run pattern detection/classification algorithms on all data delivered from the instruments and rank the data in terms of the following metrics: (M1) urgency/pertinence for space weather predictions, (M2) relevance to intended scientific goals, and (M3) uniqueness.

- Datasets ranked highest in terms of metric (M1) will receive highest priority for downlink to a data center on Earth for immediate use by space weather stakeholders and for input to MHD models. An example of such a dataset would be EUV imager observations of a coronal mass ejection.
- Datasets ranked high in M2 and M3 will be stored in onboard memory for delayed downlink.
- Datasets ranked low in all three metrics will be discarded (neither saved nor transmitted).

The pattern detection/classification algorithms can be based on supervised or unsupervised learning on datasets taken during the commissioning period. More likely they would have been validated and tested on existing large-scale data sets (e.g., against the petabyte-scale data archive of the Solar Dynamics Observatory). We distinguish training and inference as distinct tasks. The *training* of a classification/regression model is typically computationally expensive, and depending on the problem size, requires dedicated GPU resources drawing hundreds of Watts of power. It would be unrealistic to perform such tasks onboard. However, once the model (e.g., a neural network) has been trained (i.e., network weights and biases have been fixed), the deployment of the network to perform classification/regression—a task called *inference*—requires far less computation. This is the approach of machine-learning applications deployed in embedded devices.

Capabilities C and D are not necessarily autonomous concepts/technologies but still require high-throughput onboard processing. The software stack required to facilitate A-to-D are enabling technologies for this DRM and investments in their development are just as important as for hardware.

Downlink concept: One concept for downlinking data from the constellation is peer-to-peer relay communication. This approach may be necessary to increase effective mission-wide bandwidth, maximize temporal coverage, and minimize latency. For instance, consider a spacecraft at 1 AU behind the Sun. It is not possible to directly downlink data from the satellite to a ground station on Earth. To avoid a latency of several months to send the data, this satellite can send data to a peer in the constellation. The receiving peer, with a direct line-of-sight to the ground station, can then relay the data.

Each message is considered a *Local Space Situational Awareness Memo* (LSAM). A LSAM contains the following contents:

- Sender
- Receiver
- Instrument data from different instruments, with associated priorities M1, M2 and M3
- Metadata attached to the instrument data, including reports of feature detections (e.g., coronal mass ejection found at a certain location on the Sun at a certain time)

Each satellite is an autonomous agent. The message to be sent from one satellite to another (or to the ground station) is written entirely by the sender. The receiver then must prioritize which data sets (its own, or LSAMs it received from peers) to send to the next peer and/or to the ground station. But LSAMs need not be sent purely for the purpose of downlinks. LSAMs can be sent to peers who are not close to ground stations. They can be sent for the purpose of providing global situational awareness for the peers. For example, when the front-side satellite detects an eruption toward solar north, it may notify its peers (some of whom maybe on the Sun's backside), so the peers can decide whether to allocate future telemetry and memory for observations of the northern portion of the Sun. To benefit other NASA activities each peer in the constellation can also serve as a router to facilitate downlink (e.g., to increase telemetry for planetary explorers).

Assumptions

- Sufficiently powerful antennas (radio or optical) to enable peer-to-peer communication
- Radiation hardened CPUs/GPUs/FPGAs/application-specific integrated circuits (ASICs) available for high-throughput (>1 teraflop) data processing and inference

Autonomy is needed for this DRM scenario for the following purposes:

- Maximize scientific/operational value for given telemetry
- Mission resilience: no single satellite agent failure should terminate the mission
- Provide space situational awareness in a local context, and then in a global context
- Provide data needed for a continuously driven model of the Sun and heliosphere to improve space weather predictions
- To collect data from unprecedented vantage points and unexplored regions to help us understand the Sun-to-Earth connection.

Autonomy Capabilities needed for an Autonomous Space Weather Constellation

- Onboard decision making to effectively utilize resources (power, observing capabilities, onboard storage, telemetry). Autonomy will help maximize scientific/operational value for given telemetry. Observed regions deemed most important for accomplishing scientific and operational space weather objectives will be prioritized for transmission to mission ground stations. This capability will provide the data needed for a continuously driven model of the Sun and heliosphere to improve space weather predictions.

- **Onboard machine-learning (inference) for local space situation awareness and to provide space weather alerts.** Each probe in the constellation must be capable of preparing its own space weather report and broadcasting the report to the constellation. This capability should improve global space weather awareness by the constellation.
- **Provide multi-vantage point data needed for a continuously driven model of the Sun and heliosphere.** Autonomy is needed to collect data from unprecedented vantage points and unexplored regions to help us understand the Sun-to-Earth connection. The integrated space weather model should autonomously decide which data sources will be used in updating the estimated state of the Sun and heliosphere, be able to evaluate the accuracy of its own predictions, and adaptively improve. To speed up the model's improvement, there should be a mechanism by which human feedback can be accepted (i.e., an active learning feedback loop).
- **Global imagers autonomously identify 'interesting' regions, and direct more detailed telescopes.** To autonomously direct other resources, mission elements must possess space situational awareness in a global and local context.

Using NASA's Autonomous Systems Capability Leadership Team (AS-CLT) Taxonomy document as a reference, the autonomous technologies needed for these capabilities are:

- *Joint knowledge and understanding:* Collection, assembly, sharing, and interpretation of information and intent among elements to solve problems and plan actions/responses.
- *State estimation and monitoring:* Estimation of internal and external states from raw or processed inputs generated by multiple sensors/instruments, ascertainment, and continual comparison to expected states.
- *Event and trend identification:* Analyses of data (about environment or system) to identify events and trends that may affect future state, operations, or decision-making.
- *Sensing and perception:* Collection and processing of information internal and external to the system from sensors and instruments.
- *Anomaly detection:* Determination that the environment or system does not exhibit expected characteristics.
- *Activity and resource planning and scheduling:* Selection and ordering of activities to be performed while managing system resources to achieve mission goals.
- *Learning and adapting:* Adapting to changing environments and conditions without explicit re-programming using knowledge collected from the past, or from other systems' experiences.
- *Modeling and simulation:* Representation of an autonomous system and/or its operation for use in system design, evaluation, or operational assessment.

Other supporting, non-autonomous technologies that are needed include small-spacecraft-based communication and propulsion, space-qualified high-throughput processors and a testbed for simulating the constellation. Even though the testbed itself is not considered autonomous technology, it drives development of the aforementioned autonomous capabilities. It is also needed to refine satellite/instrument requirements. The testbed needs the following components:

- Physics-based MHD solver(s) driven by remote-sensing and in situ observations
- Modules for synthesizing observables measured by instruments in the constellation, including instrument characteristics (e.g., telescope point spread function, particle hits on detectors, noise etc.)
- Modules for simulating onboard processing, including inference
- Module for the creation, sending, and receiving of LSAMs
- Module for autonomous decision-making by members of the constellation

DRM Scenario 2: An Interstellar Probe

From just after the beginning of the Space Age and the establishment of NASA, a mission to the Local Interstellar Medium (LISM) has been under discussion. The remarkable science opportunities that arise from such an "Interstellar Probe" traveling beyond the Sun's sphere of influence have fueled the community for almost six decades, resulting in multiple international study efforts including the Interstellar Probe (Holzer et al., 1990), the Innovative Interstellar Explorer (IIE) (Fiehler et al., 2006), NASA-funded Sun-Earth-connection Roadmap study for an Interstellar Probe mission in 1999-2000 (Liewer et al., 2000; McNutt et al., 2011; Mewaldt et al., 2001), the European-led Interstellar Heliopause (IHP) mission (Wimmer-Schweingruber et al., 2009), the Keck Institute for Space Studies Workshop series conducted in 2014 and 2015 on the topic *"Science and Enabling Technologies for the Exploration of the Interstellar Medium"* (Stone et al., 2015; Arora et al., 2015), and the "Interstellar Express: A New Chinese Space Mission to Explore the Outer Heliosphere" (Wang, 2018; Zong, 2018). Most recently, NASA funded a study of the "Pragmatic Interstellar Probe" (McNutt et al., 2019; Brandt et al., 2019; http://interstellarprobe.jhuapl.edu) which would use available/near-term technology launch vehicles and kick stages to reach asymptotic speeds at least three times that of Voyager 1, which is currently the fastest spacecraft escaping the Sun's gravity well.

Science Goal 1: Understand our heliosphere as a habitable astrosphere. Investigate the plasma physical processes and global nature of the outer heliosphere boundary and beyond to the pristine LISM through comprehensive particle and fields measurements, and remote energetic neutral atom (ENA) and ultraviolet (UV) observations.

Science Goal 2: Understand the evolutionary history of the solar system. Explore dwarf planets and Kuiper Belt Objects (KBOs) through flybys observing atmospheric and surface properties. Determine the large-scale distribution of the circum-solar debris disk by detecting the infrared (IR) emissions from dust in the 0.5-10 µm range on an outward trajectory, while measuring in situ dust densities.

Science Goal 3: Open the observational window to early galaxy and stellar formation. Measure the integrated diffuse Extragalactic Background Light (EBL) from redshifted stars and galaxies dating back to ~200 million years after the Big Bang by detecting the near-infrared emissions beyond the Zodiacal cloud.

The Interstellar Probe DRM scenario is a proposed mission to travel to the LISM and measure the environment beyond the solar system The probe would launch around 2030 and travel 20 AU/year for 50 years to reach 1000 AU. The Interstellar Probe would make comprehensive, state-of-the-art, in situ measurements of plasma and energetic-particle composition, magnetic fields, plasma waves, ionic charge states, energetic neutrals, and dust that are required for understanding the nature of the outer heliosphere and exploring our local galactic environment.

A mission beyond the Sun's sphere of influence as outlined above represents humanity's first deliberate step in to the galaxy. Beyond its transformational promise, an Interstellar Probe would be a stunning revolution in space missions demanding it to be a multi-generational facility.

The Concept of Operations

As the Interstellar Probe transits outside our solar system, the spacecraft must rely on "smart" autonomy systems on multiple spacecraft subsystems (e.g., anomaly recovery) because telecommunication capabilities will be severed degraded. In addition, the payloads must have autonomy capabilities to take advantage of unexpected observations once the spacecraft is in a new, unexplored region while utilizing a limited data downlink for science measurements.

Autonomy Capabilities needed for an Interstellar Probe

- Autonomous spacecraft fault detection and correction. Autonomy is needed for spacecraft hardware and software fault detection and recovery. As the Interstellar Probe transits to the outer heliosphere and even beyond the solar system, the real-time commanding of both the spacecraft and payloads will be severely limited and not feasible due to the increased time required to transmit commands over increasingly long distances. Hence, it is essential that the spacecraft should have autonomous fault detection and correction capability because it will be on its own once it travels beyond the real-time commanding region.
- Smart-instrument data taking. The science telemetry will be severely limited, hence a uniform data-collection strategy (i.e., constant rate) may not be the best observation plan, especially when the spacecraft transits some unforeseen interesting regions (e.g., heliopause). Hence the instrument must be "smart" enough to switch to a higher data rate once it detects an interesting region.
- Onboard feature identification and prioritization. Similar to the Space Weather Constellation DRM, the Interstellar Probe mission will also require some type of onboard feature identification capability in conjunction with the smart-instrument data taking.

The combination of the two advancements in autonomous technology will mitigate risk and enable the mission.

The autonomous technologies needed for this capability include:
- Spacecraft hardware fault detection and recovery
- Spacecraft software fault detection and recovery
- Smart instrument data taking system
- Onboard feature identification and prioritized downlink
- Autonomous spacecraft fault detection
- Autonomous instrument mode switching

The following additional technologies (not related to autonomy) are also needed to support this mission scenario:
- Advanced propulsion
- Advanced communication
- Heat shield
- Lightweight material
- Compact instrumentation

The Relevant Research and Development Projects for these DRMs

- NASA Frontier Development Lab projects that apply AI techniques for accelerated processing of existing Heliophysics data (e.g., SDO images)
- Raising TRLs of low-power compute accelerators (e.g. GPUs, neuromorphic chips, FPGAs)
- R&D project to develop a testbed to quantify the performance of different constellation configurations (i.e., number of probes, how many remote sensing instruments, which orbits)
- Raising TRLs of optical satellite communications to increase telemetry

The Potential Challenges, Risks, or Questions for these DRMs

- Keeping costs down
- Reduces ground operations costs and improves resiliency
- Question about whether small spacecraft can carry the payloads (100-200 kg class satellite can carry one, perhaps two remote sensing instruments—more if in situ).
- Reduce risk to astronauts, particularly for spacewalks and Mars surface exploration

- Path for maturing the technologies for flight
- Flagship mission that will require agency resources and commitment
- Require multi-year commitment
- Path for TRL maturation

Part IV: Findings

The Heliophysics DRM team finds the following activities would enable the mission scenarios in this DRM:

- Developing a space weather buoy demonstration mission to orbit the Moon and serve as a gateway space weather buoy
- Developing a testbed to assess effectiveness and return-on-investment of various Space Weather Constellation configurations
- Considering a magnetohydrodynamics modeling component as a key element of the mission
- Developing spacecraft hardware and software fault detection and recovery
- Developing compact "smart" instrumentation
- Developing artificial intelligence/machine-learning techniques to facilitate onboard data processing and local space situational awareness
- Developing advanced observation modes and a smart downlink strategy for key measurements
- Developing autonomous fault detection and mitigation technologies for the spacecraft subsystems
- Requiring a path for flight demonstration for technologies such as computer accelerators as part of the technology readiness level (TRL) maturation

Part V: Heliophysics DRM Team

The Heliophysics Design Reference Mission team is comprised of:

- **Larry Kepko**, NASA GSFC
- **George Ho**, Johns Hopkins University APL
- **Mark Cheung**, Lockheed Martin Solar & Astrophysics Laboratory

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Heliophysics Design Reference Mission Report Summary

The current NASA Heliophysics System Observatory (HSO) has provided unprecedented coverage of the Sun and its impact on Earth, the planets, and other small bodies (e.g., comets) in the solar system. However, improved space weather predictions are critical to safeguard the nation's technological assets and ensure the safety of astronauts—whether they are in Earth orbit or en-route to/from the Moon or Mars—and is a prime motivator for this DRM. Improved space weather prediction requires missions that enable scientists to accomplish the following with high accuracy and confidence:

- Predict (not after the fact) whether a sunspot region will spawn coronal mass ejections (CMEs), solar flares, and energetic particle events in the next hours to days
- Predict the arrival time and physical properties of abrupt changes in the solar wind (including CMEs)
- Predict the geoeffectiveness (capability of causing geomagnetic disturbances) of CMEs, whether they are directed toward Earth or slightly away from Earth
- Provide an "all clear" prediction for inclement space weather activity over the next month

Furthermore, from just after the beginning of the Space Age and the establishment of NASA, a mission to the Local Interstellar Medium (LISM) has been under discussion. The remarkable science opportunities that arise from such an "Interstellar Probe" traveling beyond the Sun's sphere of influence have fueled the community for almost six decades, resulting in multiple international study efforts. Most recently, NASA funded a study of the "Pragmatic Interstellar Probe,"[1] which would use available/near-term technology launch vehicles and kick stages to reach asymptotic speeds at least three times that of Voyager 1, which is currently the fastest spacecraft escaping the Sun's gravity well.

Historically, the science related to such a mission has been anchored in heliophysics, but in recent studies and workshops three compelling science goals have emerged that span heliophysics, planetary sciences, and astrophysics:

- Understand our heliosphere as a habitable astrosphere
- Understand the evolutionary history of the solar system
- Open the observational window to early galaxy and stellar formation

Autonomy technology would enable mission success; moreover, autonomous spacecraft and payload operation is the *only* way to execute these missions given the distance involved. The Heliophysics DRM team suggests two autonomous DRM scenarios.

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[1] McNutt, et al. *Interstellar Probe: Humanity's Journey to Interstellar Space*. [http://interstellarprobe.jhuapl.edu] 2019.

DRM Scenario: An Autonomous Space Weather Constellation

This Autonomous Space Weather Constellation consists of a constellation of spacecraft in different orbits around the Sun offering a simultaneous 4π steradian view of the solar surface. Its aim is filling the gaps in our observational capabilities to facilitate validated, near real-time, data-driven models of the Sun's global corona, heliosphere, and associated space weather effects.

Autonomy will enable space weather nowcasting and forecasting from a global-to-regional level that cannot be done today and will safeguard human exploration to the Moon and Mars.

This DRM scenario requires a level of autonomy that is not currently available. Advancements in autonomy technology are required for this mission scenario to perform the following:

Onboard Decision Making to Effectively Utilize Resources (Power, Observing Capabilities, Onboard Storage, Telemetry): Autonomy will help maximize scientific/operational value for given telemetry. Observed regions deemed most important for accomplishing scientific and operational space weather objectives will be prioritized for transmission to mission ground stations. This practice will provide the data needed for a continuously driven model of the Sun and heliosphere to improve space weather predictions.

Onboard Machine Learning (Inference) for Local Space Situation Awareness and to Provide Space Weather Alerts: Each probe in the constellation must be capable of preparing its own space weather report and broadcasting the report to the constellation. This practice should improve the constellation's global space weather awareness.

Provide Multi-vantage-Point Data Needed for a Continuously Driven Model of the Sun and Heliosphere: Autonomy will enable data collection from unprecedented vantage points and unexplored regions to help us understand the Sun-to-Earth connection. The integrated space weather model should autonomously decide which data sources will be used in updating the estimated state of the Sun and heliosphere, be able to evaluate the accuracy of its own predictions, and adaptively improve. To speed up the model's improvement, there should be a mechanism by which human feedback can be accepted (i.e., an active learning feedback loop).

Global Imagers Autonomously Identify 'Interesting' Regions, and Direct More Detailed Telescopes: To autonomously direct other resources, mission elements must possess space situational awareness in a global and local context.

To enable autonomy in this DRM scenario, advancements in the following supporting technology areas are required:

- Small-spacecraft-based communication and propulsion.
- Space-qualified high-throughput processors.

- A testbed for simulating the constellation. Even though the testbed itself is not considered autonomy technology, it drives development of the aforementioned autonomous capabilities. A testbed is also needed to refine satellite/instrument requirements.

DRM Scenario: An Interstellar Probe

The interstellar probe will travel to the LISM and measure the environment beyond the solar system. The probe will travel at 20 AU/year for 50 years to reach 1000 AU. The probe will make comprehensive, state-of-the-art, in situ measurements of plasma and energetic particle composition, magnetic fields, plasma waves, ionic charge states, energetic neutrals, and dust that are required for understanding the nature of the outer heliosphere and exploring our local galactic environment. The interstellar probe will answer key questions about the evolutionary history of the solar system and provide key measurements pertaining to early galaxy and stellar formation.

As the interstellar probe transits outside our solar system, the spacecraft must rely on a "smart" autonomy system consisting of multiple spacecraft subsystems (e.g., to accomplish anomaly recovery) because telecommunication capabilities will be severely degraded. In addition, the payloads must have autonomous capabilities to take advantage of unexpected observations once the spacecraft is in a new, unexplored region while utilizing a limited data downlink for science measurements.

This DRM scenario requires a level of autonomy that is not currently available. In addition to the autonomy technology advancements required by the previously described DRM scenario (Space Weather Constellation), additional advancements in autonomy technology are required for this Interstellar Probe mission scenario to perform the following:

Autonomous Spacecraft Fault Detection and Correction: Autonomy is needed for spacecraft hardware and software fault detection and recovery. As the Interstellar Probe transits to the outer heliosphere and even beyond the solar system, the real-time commanding of both the spacecraft and payloads will be severely limited and not feasible due to the increased time required to transmit commands over increasingly long distances. Hence, it is essential that the spacecraft possess autonomous fault detection and correction capability because it will be on its own once it travels beyond the real-time commanding region.

Smart-instrument Data Collection: The science telemetry will be severely limited, hence a uniform data-collection strategy (i.e., constant rate) may not be the best observation plan, especially when the spacecraft transits some unforeseen interesting regions (e.g., heliopause). Therefore, the instrument must be "smart" enough to switch to a higher data rate once it detects an interesting region.

Onboard Feature Identification and Prioritization: Similar to the Space Weather Constellation DRM scenario, the Interstellar Probe mission will also require some type of onboard feature identification capability in conjunction with the smart-instrument data collection. Combination of the two advancements in autonomous technology will mitigate risk and enable the mission.

To enable autonomy in this Interstellar Probe scenario, advancements in the following supporting technology areas are required in addition to those listed for the Space Weather Constellation scenario:

- Advanced propulsion technology (long-lasting)
- Advanced communication technology to support long-distance communications
- Lightweight materials
- Compact instrumentation

Findings

The Heliophysics DRM team finds that the following actions and activities would facilitate implementation of the DRM scenarios described above:

1. Develop a space weather buoy demonstration mission to orbit the Moon and serve as a gateway space weather buoy
2. Develop a testbed to assess effectiveness and return on investment of various Space Weather Constellation configurations
3. Consider a *magnetohydrodynamics* modeling component as a key element of the mission
4. Develop spacecraft hardware and software fault detection and recovery
5. Develop compact “smart” instrumentation
6. Develop artificial intelligence/machine-learning techniques to facilitate onboard data processing and local space-situational awareness
7. Develop advanced observation modes and a smart downlink strategy for key measurements
8. Develop autonomous fault detection and mitigation technologies for the spacecraft subsystems
9. Require a path for flight demonstration for technologies such as computer accelerators as part of the technology readiness level (TRL) maturation