Exploring the Heliosphere from the Solar Interior to the Solar Wind

FIREFLY

The Case for a Holistic Understanding of the *Global Structure and Dynamics of the Sun and the Heliosphere*

A White Paper to the Decadal Survey for Solar and Space Physics (Heliophysics) 2024-2033

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Synopsis

This white paper presents the current knowledge gaps in understanding how magnetic fields control solar (and by extension, stellar) activity in timescales from minutes to years and discusses a transformative observational approach to fill those gaps. The solar activity drives space weather as the result of dynamic magnetic fields forming in the solar interior and evolving continuously until reaching levels of complexity in the atmosphere that trigger eruptions. However, we do not fully understand how solar and, more generally, stellar magnetic fields are generated and how they evolve through the eruptive states.

The major obstacle is our reliance on observations from a single viewpoint, particularly in the ecliptic plane. This vantage point can only provide limited information for (i) understanding the generation of solar magnetic fields deep in the convection zone; (ii) determining the origin of the solar cycle and predicting its timing and strength; (iii) explaining the causes of solar activity and their triggers; (iv) reliably predicting when and how CMEs will impact Earth and other planets; (v) fathoming the structure and dynamics of the corona as it creates the heliosphere; (vi) understanding the energization and transport of energetic particles; etc.

Firefly will revolutionize solar and heliospheric research by implementing a holistic observational philosophy from the Sun's interior, through the photosphere, to the corona, and into the solar wind. This approach will provide simultaneous observations from multiple vantage points, enabling a continual and global 4π-steradian coverage of the Sun over much of a solar cycle. ***Firefly*** focuses on the global structure and dynamics of the Sun's interior, the generation of solar magnetic fields, the deciphering of the solar cycle, the conditions leading to the explosive activity, and the structure and dynamics of the corona as it drives the heliosphere. ***Firefly*** provides diverse and complementary observations across multiple disciplines, bringing together a diverse group of scientists and engineers to deliver a unified 4π-steradian view of the heliosphere.

NASA selected the ***Firefly*** concept for study through a competitive open solicitation (NNH21ZDA001N-HMCS) for innovative spaceflight mission concepts with compelling science investigations that expand and advance the frontiers of heliophysics (grant #80NSSC22K0115). A full report on the ***Firefly*** mission concept study is ready for delivery to NASA in 2022.

Science Motivation

Magnetism is paramount to most, if not all, solar and stellar physics phenomena and how stars interact with planetary environments. Magnetic fields are generated by dynamo processes in the stellar interior and produce activity that can crucially affect the physical and chemical evolution of planetary atmospheres and, consequently, the habitability of these planets[1,2]. The Sun is the only star readily available for revealing the mechanisms of stellar magnetism thanks to its proximity to Earth. Nonetheless, observing the Sun from only a single viewpoint is a severe obstacle, limiting our ability to ascertain global solar dynamics. For instance, from our vantage point in the ecliptic, we cannot observe the solar poles, which are critical for deciphering the physical processes that power the solar dynamo, the solar cycle, and the consequent solar and heliospheric phenomena[3].

Despite decades of ground- and space-based observations of the Sun, there are major gaps in our understanding of the solar magnetic cycle, of how it generates its cyclic magnetic fields, which in turn create instabilities impacting the entire heliosphere. Examples of these knowledge gaps include (see Fig.1):

1. **Structure of the Solar Interior (Fig. 1a).** At least three major gaps exist in observations of the solar subsurface flows that are critical to understanding the solar dynamo:
   - **a.** A "polar gap" exists above ~60° in latitude, in which the magnetic field and the plasma flows as a function of depth remain inaccessible from an ecliptic vantage point.
   - **b.** The structure of meridional circulation in latitude, longitude, depth, and time (e.g., single vs. multiple cells), remains unknown because we cannot resolve the critical high-latitude regions from the ecliptic plane.
   - **c.** The variable longitudinal structure and the dynamics of zonal flows, including their variations over the cycle, cannot be fully observed from a single viewpoint, not even from brief high latitude glimpses.
2. **Solar Cycle Predictions (Fig. 1b).** A major goal of long-term space weather forecasting is to accurately predict the timing and magnitude of oncoming activity cycles. The unreliable solar cycle predictions are primarily due to the lack of understanding of the innerworkings of the drivers. Relying on single vantage point observations, particularly from the ecliptic, will not solve this problem. We need to acquire the measurements of surface and subsurface flows necessary to develop data-assimilative, non-axisymmetric, global dynamo models.
3. **Coverage and Continuity Magnetic Fields (Fig. 1c).** Magnetic field measurements from a single viewpoint are reliable only up to ~60° from the disk center, which is only 25% of the total solar surface area (Fig. 1c). To understand the physical processes leading to the formation of complex sunspot active regions and filaments prone to eruption, continuity of observations is essential to following the evolution of magnetic structures and the buildup of energy in the solar corona. This is not possible from single viewpoint observations, leading to many critical events that cannot be analyzed thoroughly. Fig. 1c provides a telltale example of these events as flux emergence started just outside the 60° boundary where magnetic field measurements are reliable, resulting in an X-class flare a day later. The lack of coverage and continuity also precludes understanding the long-range interactions leading to sympathetic eruptions.
4. **Space Weather Predictions (Fig. 1c,d).** Relying on single viewpoint measurements to predict the solar eruptive activity and the arrival of CMEs to Earth is greatly hindered by the lack of continuous following of the evolution of magnetic structures. The continuous and near-simultaneous observations from multiple vantage points will substantially expand our knowledge of the solar environment and thus greatly advance our capabilities to predict solar magnetic activity and space weather.

5. **Coronal and Heliospheric Modeling (Fig. 1e,f).** Because of this severe limitation, the global "synoptic" maps of the magnetic field (Fig. 1d) used as the boundary condition for the coronal and heliospheric models are stitched together from daily observations of a limited portion of the Sun. These global maps, each constructed over a solar rotation, has significant errors, particularly during solar maximum. By definition, the synoptic maps cannot include the evolution of active regions that have rotated to the far side of the Sun, newly emerged far-side active regions, or complete and accurate polar field measurements. The critical polar regions must be extrapolated from noisy high-latitude data leading to systematic errors that propagate to the coronal and solar wind models. These major issues are currently treated by remedies whose reliability is often in question[4–6].
6. **Structure and evolution of the Heliosphere.** The solar polar magnetic fields play a critical role in shaping the large-scale structure of the corona and heliosphere. The solar wind state also varies with latitude and longitude in response to changes in the global solar conditions. However, the exact links to the global magnetic field are not understood. It is critical to understand how the global solar magnetic field structures the heliosphere and how it interfaces with the interstellar medium. Until we can fully measure the solar magnetic field over at least a solar cycle, we will not be able to link solar variability to observed changes in the heliosphere.

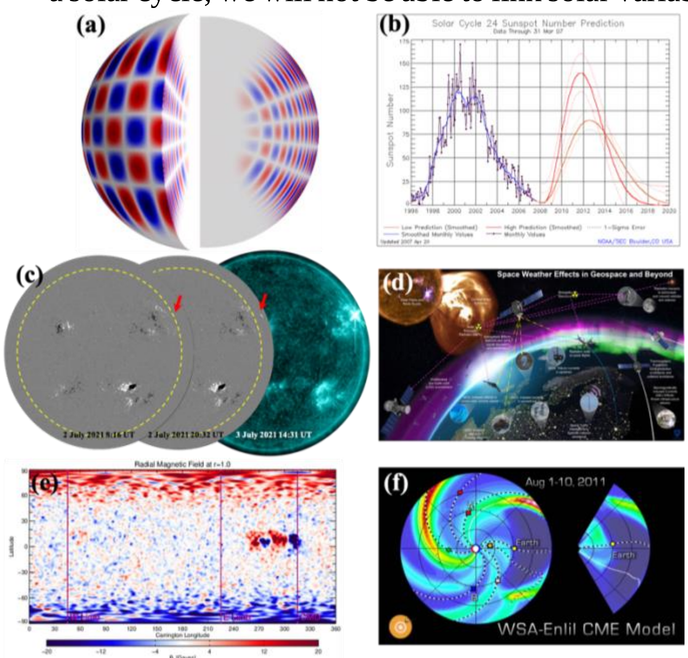


Fig. 1: *Example of the major knowledge gaps in our understanding of the Sun and the Heliosphere. (a) SOHO/MDI helioseismic measurement of a solar global oscillation mode; global modes are insensitive to conditions at high latitudes. (b) Unreliable forecast of the solar cycle (i.e., timing of the start and maximum, amplitude, etc.). (c) A newly emerging active region (AR) near the limb produced an X1.5-class flare that could not be forecast due to a lack of magnetic field data for the AR. (d) Unreliable forecasting of solar drivers of space weather, i.e., flares and CMEs. (e) Example of a magnetic field "synoptic map" built over a whole solar rotation (Carrington rotation 2217 and 2218). (f) Coronal and heliospheric models use the synoptic maps as the boundary condition. Most measurements are not up-to-date, and the polar regions are extrapolated and distorted due to low S/N above 60° latitude and lack of visibility.*

We need a new approach to observing the Sun and its environment to fill these knowledge gaps. ***Firefly*** will provide the necessary observations to achieve that but also make significant strides in understanding cross-disciplinary phenomena ranging from the solar interior to the Heliosphere.

Firefly**'s Science Objectives.** ***Firefly*** is a spacecraft constellation designed under a holistic observational philosophy from multiple spacecraft at multiple vantage points, optimized for continuous global coverage over much of a solar cycle. It will provide simultaneous observations (remote sensing and *in situ*) extending from the Sun's interior to the photosphere, through the corona, and into the solar wind. The ***Firefly's*** overarching goal is *to understand the global structure and dynamics of the Sun's interior, the generation of solar magnetic fields, the origin of the solar cycle, the causes of solar magnetic activity, and the structure and dynamics of the corona as it creates the heliosphere*. ***Firefly*** includes two spacecraft off the Sun-Earth line in the ecliptic plane and two orbiting out of the ecliptic as high as ~70º solar latitude. The ecliptic spacecraft will orbit the Sun at fixed angular distances of ±90 to ±120º from the Earth.

SO-1: Understand how surface and subsurface flows and toroidal magnetic field instabilities produce the cyclic dynamo, the root cause of solar activity: The solar dynamo remains one of the most enigmatic aspects of the Sun. Despite decades of research[7], we have an incomplete picture of the global-scale motions that drive it, both in the interior and at the surface. Model approaches cannot predict critical details of the solar cycle, such as the timing of the sunspot maximum, the north-south asymmetry in activity, and longitudinal flux emergence sites. A significant goal of long-term space climate forecasting is to accurately and precisely predict the timing and magnitude of oncoming activity cycles. But these goals will remain unmet until we develop data-assimilative, non-axisymmetric, global dynamo models, along with the necessary measurements of surface and subsurface flows to feed such models.

Major gaps exist in our observations of the solar surface and subsurface flows that are critical to understanding the solar dynamo. Time variations in speed and profile of the Sun's global meridional circulation play a crucial role in determining the solar cycle properties (e.g., amplitude, phase, duration, etc.). Perhaps the most significant gap is that neither the meridional circulation nor the differential rotation has been measured in the solar polar regions. Local helioseismology measurements from the ecliptic do not help: the high LOS angles to the solar poles still impose low S/N conditions on the measurements. Although, helioseismic measurements from a single platform orbiting over the solar poles can reveal flows within the near-surface layers, measuring deeper flows over the solar cycle will require coordinated Doppler measurements from multiple polar viewpoints over a significant fraction of a solar cycle.

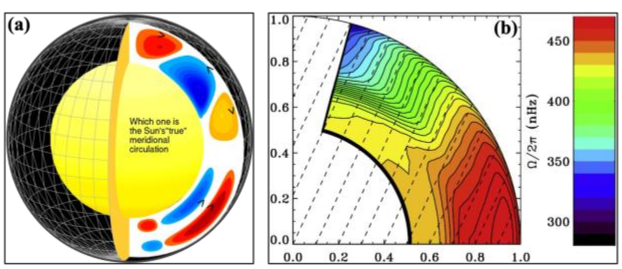


Fig. 2: *(**a**) The structure and solar cycle evolution of the meridional circulation in latitude and in-depth is debated vigorously: multiple cells vs. a single cell; counter cells at high latitude; a shallow return flow vs. a return flow at the base of the convection zone. Source: NCAR/HAO. (**b**) Contour map of the rotation rate in and below the convection zone. The dashed lines are at a 25° angle to the rotation axis*[8,9].

Similarly, polar magnetic field measurements are severely degraded due to projection, inclination, and solar atmospheric effects. [[10]] show surprising hints of strong-field regions near the poles where current models predict only weak network fields. Are these strong field regions the signatures of complex polar vortex flows like those seen on Jupiter and Saturn? Ecliptic-plane observations alone cannot answer this critical question. If the solar polar flows turn out to be as complex as those seen on Jupiter and Saturn, it would have a revolutionary impact on solar dynamo models since these models depend critically on the structure and magnitude of polar flows[3].

The ***Firefly*** mission concept includes a solar polar orbiting component to regularly capture the helioseismology observations (~3 month-long pass/pole/year) required to fill the "polar gap." Together with magnetic field measurements and imaging of the solar atmosphere, these observations, with ecliptic plane measurements, will reveal the time-varying structure and dynamics of flows and magnetic fields at the polar regions of the Sun *and* throughout the convection zone. The ***Firefly*** mission will provide over 80% coverage of the Sun and over a significant part of the solar cycle, which will advance significantly our understanding of the solar (and stellar) dynamo and paving the way toward reliable predictions of the solar cycle.

SO-2: Understand solar magnetic eruptions and the role of large-scale magnetic field connections in triggering eruptions: Solar magnetic eruptions are the most powerful explosions in the solar system, releasing 25,000 times more energy in several hours than consumed on Earth over an entire year. Solar magnetic eruptions result in flares[ref], coronal mass ejections (CMEs[11]), and energetic particles[ref], which drive space weather impacts to Earth- and space-based technology. CMEs are one of the most impactful drivers of geomagnetic storms, which can result in multiple space weather hazards: i) threat to satellite systems and astronaut health; ii) stress or even damage critical infrastructure of the power grid; iii) adversely affect satellite communications and precision navigation and timing; and iv) increase satellite drag and orbital uncertainty. The 2015-2025 COSPAR/ILWS space weather roadmap[12] and NASA Space Weather Gap Analysis Report highlight the need for advanced systems to forecast solar activity and mitigate its effects on the Earth environment and elsewhere in the heliosphere.

Previous studies[13] identified the critical role the solar magnetic field plays in releasing magnetic energy that drives flares and CMEs. Modeling and understanding CMEs is severely hindered by single viewpoint observations. CME 3D reconstruction and essential parameters' evaluation have been attempted using 2D plane-of-sky projected observations[11,14–16], but such methods suffer from LOS integration effects, causing loss of information and ambiguity[17,18].

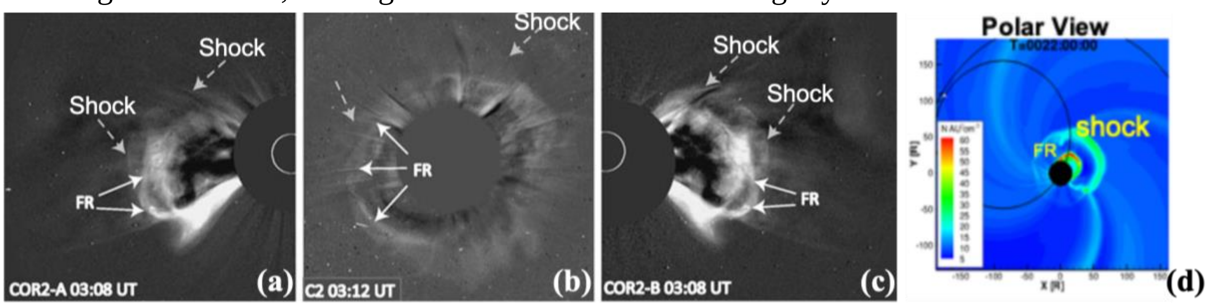


Fig. 3. *(**a-c**) CME imaged by three coronagraphs in quadrature[19]. The shock sheath and the magnetic flux rope driver can be discerned, but the true extent of the shock and accurate CME directions can only be obtained from a polar perspective, as shown in (**d;** courtesy N. Lugaz).*

To address these issues, observation of the Sun simultaneously from strategically chosen multiple viewpoints is essential. 4π-steradian coverage enables monitoring of the birth-to-death evolution of solar ARs, which is critical since many large eruptions occur shortly after new flux emerges[20]. A polar vantage is particularly powerful for resolving longitudinal structure and avoiding center-to-limb projection effects that severely impact the quality of photospheric boundary conditions for high-latitude structures such as coronal holes that drive high-speed streams (HSS) in the solar wind. The interaction of CMEs with solar wind HSS structures significantly influences the arrival time at Earth of weaker CMEs and changes the ensuing geomagnetic storm characteristics. HSS and the associated Corotating Interaction Regions (CIRs) can also drive geomagnetic storms, sometimes more powerful than CMEs. [21] found that 13% of major geomagnetic storms are caused by CIRs. Without an accurate measurement of polar fields, we cannot properly model global coronal magnetic fields. Hence, all solar wind models that would enlighten us on CME-solar wind interactions may well include critical inaccuracies.

With the unique combination of observations within and out of the ecliptic plane, ***Firefly*** will provide critical observations for understanding better the physics of solar magnetic eruptions while also informing the global coronal and heliospheric models.

SO-3: Determine how conditions in the solar wind vary with latitude and longitude in response to changing global solar conditions and throughout the solar cycle: So far, only

Ulysses explored the solar wind out of the ecliptic plane. Soon, Solar Orbiter will fly up to ~30° latitude, with glimpses of the solar polar regions. *Ulysses* revealed how high-speed streams fill the heliospheric space above the poles at the solar minimum and how this state is disrupted at the maximum. The data also show how MHD turbulence and wave-particle interactions in collisionless plasma regimes differ significantly from those in the ecliptic[22,23]. However, *Ulysses* only provided three polar passes and also lacked remote-sensing observations. The low-density polar regions are better for exploring such connections because the field lines do not experience as much stochastic mixing from, say, corotating stream interactions or Coulomb collisions. The ***Firefly*** mission has transformative potential to improve our knowledge of how the solar magnetic field connects different coronal regions to the high-latitude, often high-speed, wind that can influence speeds and structures in the ecliptic.

Global MHD solar wind models depend on photospheric magnetic-field maps as a lower boundary condition. The ability to augment existing magnetograms—obtained from the Sun-Earth line vantage points—with data from other viewpoints will significantly improve the accuracy of these simulations and forecasts (see, e.g., [3,24]). The lack of reliable polar magnetic-field data at the solar surface is also one of the reasons that the so-called "open-flux problem" (i.e., the discrepancy between the modeled and measured flux at 1 AU) remains unsolved ([25,26]; Linker+2022). Thus, the continuous full-surface coverage of ***Firefly*** provides ground-truth data that will improve our knowledge of Sun-to-heliosphere connections.

Measuring the longitudinal evolution of the solar wind is crucial to understanding its evolution in its acceleration zone and beyond the breakdown of the corotation. Ulysses data also indicated that the momentum flux modulates over the solar cycle, which might affect the whole structure of the heliosphere. However, these data are very sparse and from a single point. Models suggest that the heliospheric structure evolves over the solar cycle, but we do not have the data to quantify that.

SO-4: Understanding for the first time the 360º view of global sources and transport of energetic particles through the inner heliosphere: High-energy charged particles are the riskiest space weather manifestations for human life in deep space. In the modern space exploration era, no astronauts have been situated beyond LEO during the few extreme SEP events. But this will certainly not be the case in the future. We currently lack predictive capabilities for whether and when SEPs will occur in connection to any given solar magnetic eruption. Although the acceleration and transport of energetic particles in the heliosphere have been studied extensively[27–32], there are still many open questions. Using only data acquired in the ecliptic and within 1 AU has proven insufficient to answer these questions.

In addition, we know very little about the SEP environment out of the ecliptic plane. CIR electrons have been observed during the *Ulysses* three polar passes at very high latitudes. The sporadic measurements did not fully illustrate the physical processes at the origins of these particles and how they are transported from (or to) the solar polar regions. Additionally, CIRs with well-developed shocks are rare near Earth since the shocks tend to form between 2 and 3 AU. During the cruise phase (5-6 years), the *Firefly*-polar spacecraft will fly multiple times through the region between 2 AU and 5 AU. It will provide sufficient data to shed light on the physical processes at the origin of the CIR particle acceleration.

The acceleration and transport of energetic particles out of the ecliptic are also poorly understood. Ulysses collected the only measurements above the solar polar regions during its three polar flybys (1994-95; 2000-01, and 2007). The data obtained led to several open questions. For instance, it is unclear how CIR energetic electrons are transported to the solar polar regions and how the accelerations and transport of particles from flares and CMEs vary with latitude.

Firefly **Mission Concept.** In support of the SSP 2024-2033 Decadal Survey, NASA selected the ***Firefly*** mission concept for a design study because of its compelling and cross-disciplinary science that will expand and advance the frontiers of heliophysics. The study was performed at APL's concurrent engineering laboratory. It focused on the trades and critical factors to achieve a concept representing a mission point design at Concept Maturity Level (CML) 4, understand trades and development to be conducted in subsequent mission phases, and identify mission-level risks and mitigations. A full mission concept study report on ***Firefly*** will be delivered to NASA.

Mission Overview. ***Firefly*** is a constellation of four spacecraft to provide remote sensing and *in situ* observations of phenomena covering diverse temporal scales (i.e., minutes, hours, days, …, to a solar cycle) and spatial domains (i.e., the solar interior, the solar atmosphere, and the solar wind). ***Firefly*** comprises two spacecraft pairs; one pair will orbit the Sun at fixed angular distances of ±90 to ±120º from the Earth, while the other pair orbits out of the ecliptic at ~70º solar latitude.

Science Payload[*]. The ***Firefly*** payload comprises a suite of remote sensing and *in situ* instruments to address the above science challenges. The payload is based on high-heritage representative sensors from previous missions, e.g., STEREO, SDO, SOHO, PSP, Solar Orbiter, Wind, and ACE.

Options	Number of								
	SC	DVM	EUVI/ SSI	WLC	WL HI	FGM	FC	SWC	EPS
1	3	3	2	3	—	3	3	—	3
2	4	4	2	4	—	4	4	—	3
3	3	3	3	3	—	3	3	—	3
4	4	4	3	4	—	4	4	—	3
5	3	3	3	3	1	3	3	1	3
6 (Baseline)	4	4	3	4	1	4	4	1	3
7	4	4	4	4	1	4	4	1	3
8	4	4	4	4	1	4	4	1	4
9	4	4	4	4	2	4	4	4	4

The full ***Firefly*** study report outlines the payload's detailed specification, its traceability to the science objectives outlined in the science traceability matrix, and its distribution among the spacecraft constellation. The current best estimate of the average payload mass and power are 70.5 kg and 76.8 W per spacecraft. A set of nine options are presented in the full report (see Table) and provide flexibility in the mission implementation.

Firefly **Phase A-F Options – FY22$M**				
Option	Phase		Res.*	LV
	A-D	E-F		
1	1,133.3	250.8	626.3	246.9
2	1,336.2	250.8	727.8	313.8
3	1,182.2	250.8	650.8	246.9
4	1,385.2	250.8	752.3	313.8
5	1,283.3	250.8	701.3	246.9
6 (Baseline)	1,486.3	250.8	802.8	313.8
7	1,510.7	250.8	815.0	313.8
8	1,522.3	250.8	820.8	313.8
9	1,606.2	250.8	862.8	313.8

Mission Class & Estimated Cost. The cost estimate uses a combination of high-level parametric and analog techniques and incorporates a wide range of uncertainty in the estimating processes. Furthermore, all estimates and assumptions followed the "Ground Rules for Mission Concept Studies in Support of the Heliophysics Decadal Survey" document dated January 2022.

All cost estimates assume two separate launches for the polar (Falcon Heavy expendable) and ecliptic (Falcon Heavy) spacecraft pairs. For the ecliptic spacecraft, rideshare is a viable option to be considered in the future that can lower the mission cost and schedule.

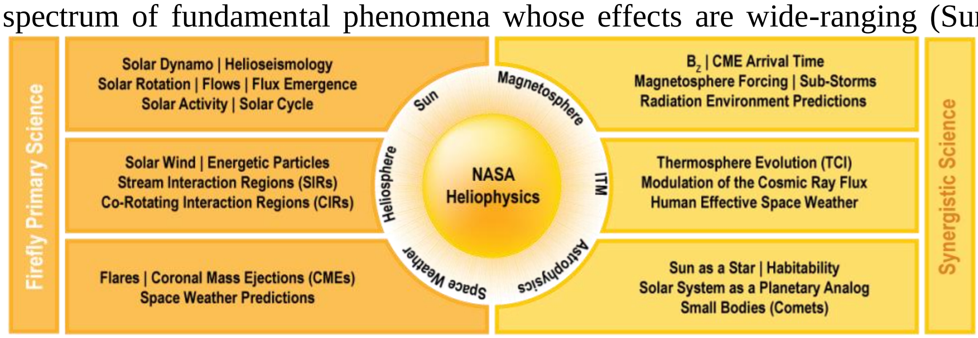
The mission architecture lends itself to a parallel development approach for the ecliptic and polar pairs of spacecraft. This might also be a viable option of multi-agency contributions for the mission development that would benefit the schedule, sharing the total cost, but mainly to bring the heliophysics community together around a transformative mission such as *Firefly.* Reserves are 50% for Phase B-D, 25% for Phase E-F, and exclude launch services costs.

[*] SC: spacecraft; DVM: Doppler vector magnetograph, EUVI: EUV imager; WLC: white-light coronagraph; WL HI: white-light heliospheric imager; FGM: flux gate magnetometer; FC: Faraday cup; SWC: solar wind composition; and EPS: energetic particle suite.

Mission Schedule. The high-level mission schedule for ***Firefly*** is based on Parker Solar Probe and STEREO, two missions already in operation. All spacecraft components are TRL 6 or higher, and all instruments within the payload are based upon previously flown instruments. The development phase critical path includes the spacecraft design and fabrication, followed by integration of the propulsion system and remaining spacecraft integration and testing activities. The schedule also contains a total of eight months of funded schedule reserves. The best estimate for Phase A is ~12 months, followed by 96 months for Phase B-D. The relatively lengthy Phase A-D assumes the design, development, integration, and testing of the four spacecraft in a single institution. Splitting the development of the ecliptic and polar spacecraft between institutions or agencies would reduce the schedule and lower the cost. Phase E extends to a solar cycle (i.e., 10 years), including a ~5 years operations phase for the ecliptic SC while cruising to their final locations and a ~6-year period for circularizing the orbits of the polar SC orbits during which the instruments would collect science data but not continuously. The two launches are scheduled early to mid-2030s to support the simultaneous science phase for all four spacecraft.

Technology Development Needs. Most components of the spacecraft included in the design are at TRL 6 or higher and are based on previously flown instruments. However, there are development avenues worth pursuing to improve on existing technologies. These include the comms and propulsion systems. For instance, ***Firefly*** would benefit greatly from communication systems with high performance, which allow more science data return and smoother operations. The mission would also benefit from technology development of the propulsion system, which would shorten the time for circularizing the orbits of the polar spacecraft. This would also provide full coverage over a longer period of time. The complete ***Firefly*** study reports and several white papers (citations) document the needs.

Expanding the Frontiers of Heliophysics in the Next Decade and beyond. The national and international Heliophysics community has demonstrated considerable interest in the ***Firefly*** *mission*. The Sun is the only star in the Universe that we can observe as a whole, which we have not done so far. This hinders our understanding of key phenomena pertaining to fundamental research but also to how a star shapes its environment, particularly in the habitability zone such as our own Earth. There is a multitude of critical and cross-disciplinary phenomena, covering a wide range of spatial and temporal scales and research domains (see Figure below), that cannot be understood using the single viewpoint observations. Hence, the need and appeal of a cross-disciplinary mission such as ***Firefly*** is greater than ever. ***Firefly*** addresses the long-term science strategy and core STP goal to understand the fundamental physical processes of complex space environments throughout our solar system. To do this we employ a "Cross-disciplinary science strategy that incorporates aspects of heliophysics-planetary and heliophysics-astrophysics goals" (Decadal Midterm Assessment; see finding 6.10). ***Firefly*** will expand the frontiers of the entire Heliophysics field in unprecedented manners by addressing key knowledge gaps of a broad spectrum of fundamental phenomena whose effects are wide-ranging (Sun, heliosphere, space weather, magnetosphere, ITM) and transcend heliophysics to planetary and stellar physics (see Figure below).



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