Pre-Study Report

4π Heliospheric Observing System (4π-HeliOS)

Solicitation: NNH21ZDA001N-HMCS

Science goals and objectives

Magnetism lies at the center of solar and stellar physics. Magnetic fields are generated by dynamo processes in the interior and trigger activity that can affect crucially the composition and the physical and chemical evolution of planetary atmospheres and consequently the habitability of these planets. We possess an incomplete understanding of how solar and more generally stellar magnetic fields are generated and how they evolve. The Sun is the ideal target to understand stellar magnetism thanks to its proximity and the extensive observations gathered over the last few decades. Nonetheless, there are severe obstacles caused by the single viewpoint observations limiting the instantaneous coverage of the solar magnetic surface including access to the solar poles that are critical for deciphering the solar dynamo and the consequent evolution of solar magnetic fields. The best way forward is to achieve full coverage of the Sun from different viewpoints. The *4π-HeliOS* mission concept provides the observations, both remote sensing and *in situ*, needed to fill this critical knowledge gap in heliophysics (Fig. 1).

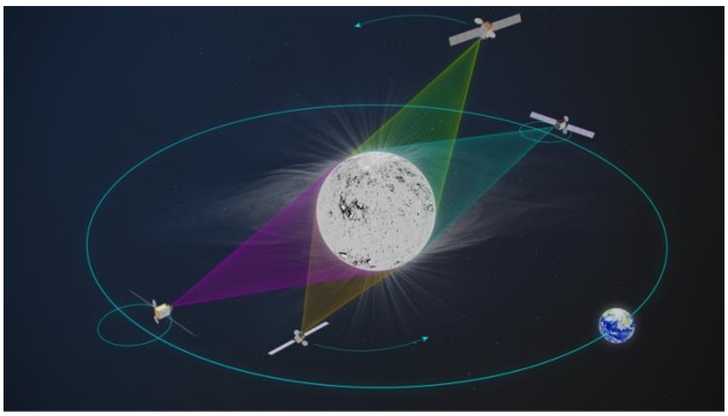

Fig. 1: *An artist's concept of the 4π-HeliOS mission providing full coverage of the Sun and inner heliosphere.*

4π coverage enables the determination of the structure of the global field, the local and global magnetic connectivity, and modeling of the magnetic structure in the upper solar atmosphere and heliosphere using near-simultaneous measurements. The overarching goal of the *4π-HeliOS* mission is to understand the global structure and dynamics of the Sun's convective zone, photosphere, corona and heliosphere, including the generation of solar magnetic fields, the origin of the solar cycle, and the causes of solar activity. To address this goal, the proposed concept focuses on four fundamental science questions:

- What are the characteristics of the flows and magnetic fields at and below the photosphere, particularly in the unexplored polar regions, and how do they drive the global dynamo to create sunspot activity over the solar cycle?
- How does the magnetic energy flow through the different layers of the solar atmosphere and accumulate into the corona?
- How non-potential fields are created in the corona, how they store energy and evolve towards eruption and what is the role of the large-scale magnetic field?
- How do conditions in the solar wind vary with latitude and longitude in response to changing global solar conditions?

Relevance to and impact of the proposed work for the Solar Terrestrial Probes program

The mission's science objectives directly relate to the STP Program's focus on the fundamental physical processes that determine the mass, momentum, and energy flow in the solar and space environments. *4π-HeliOS* targets the magnetic field – the most important physical quantity in all

Heliophysics. Our mission concept comprises a comprehensive, focused, set of science objectives and tailored instrumentation to finally understand how the magnetic field controls the Heliosphere (and consequently, astrospheres). Among other things, the *4π-HeliOS* measurements will reveal how and why active regions form, how the magnetic energy flows from the photosphere, through the chromosphere and then out into the corona, how it accumulates there and eventually how it erupts into the solar wind.

These potential achievements correspond to major knowledge gaps in Heliophysics (and Astrophysics). While closing these gaps, *4π-HeliOS* will open new research pathways, such as subsurface mapping of solar activity, studies of the feedback between surface transport and the solar dynamo; of the long-range interactions among active regions; of the 3d topology of both large and small-scale magnetic fields in the corona; of the interplay between the emerging CMEs and jet with their ambient fields, among others.

Planned research methods

To accomplish the mission science goals, various tools, ranging from data analysis to numerical modeling and theory, will be used. These tools depend on the data to be analyzed and modeled.

- **Helioseismology:** *4π-HeliOS* will provide unprecedented coverage of the solar surface that benefits both local and global helioseismology. The expansive coverage will enable deeper probing of the solar interior with 'local' helioseismology, possibly down to the tachocline; significantly improve the quality of the measurements; resolve different modes and reduce aliasing; and constrain models of magnetic flux emergence.
- **Magnetic fields:** *4π-HeliOS* will provide full coverage of the Sun, allowing simultaneous measurement of the magnetic field over the whole solar sphere. Direct benefits are alleviating the above limitations and enabling data-driving of global models. Advanced machine learning-based inversion techniques will be used onboard and/or on the ground to infer the magnetic field from polarimetric imaging.
- **Corona/heliosphere global models:** coronal and heliopsheric models are based on magnetic field measurements in the photosphere. They all these models use synoptic magnetic field data collected over a whole solar rotation. These limitations will be eliminated using near-simultaneous measurements. Another benefit is the possibility of data assimilation, which will significantly improve understanding the inner workings of solar magnetic fields.
- **Coronal and heliospheric imaging:** knowledge of the location, extent, and evolution of coronal structures is essential for understanding their evolution and interaction with their surroundings. *4π-HeliOS* will greatly constrain the evolution of the multi-scale coronal and solar wind structures. EUV and while-light imaging from *4π-HeliOS* will also greatly benefit other science topics such as comets, asteroids, dust, etc.
- **Solar wind and energetic particles:** having multiple probes at different locations throughout the inner heliosphere will allow the study of global phenomena such the spread of energetic particles. This will lead to a much-improved understanding of the physics of the heating and acceleration of all regimes of the solar wind (i.e., slow, fast, and transient).

Notional mission concept

The primary mission requirement for *4π-HeliOS* is to achieve complete coverage of the solar sphere for >80% of the mission lifetime.

- **Mission point design:** The strawman *4π-HeliOS* consists of two pairs of spacecraft carrying remote-sensing and *in situ* payloads. The first pair (*4π-out*) uses Jupiter gravity assists to reach a highly inclined near 1 AU (TBS) orbit (>65° (TBS) relative to the ecliptic). *4π-out* spacecraft use ion engines to circularize their orbits and increase their relative phasing by 180°. The other pair (*4π-in*), is launched into elliptical Trojan orbits around the Sun-Earth L4 and L5 Lagrange points, via lunar and terrestrial gravity assists (TBS). The '*4π-in*' spacecraft oscillates between 40° and 90° relative to the Sun-Earth line during the year, while the *4π-out* spacecraft orbital plane(s, TBS) rotates with respect with to the Earth-Sun line and L4/L5 points over the course of a year. The combined observations of the four spacecraft provide continuous global coverage of the photospheric magnetic field, the solar corona, and local heliospheric conditions, while enabling both global and local helioseismology measurements throughout the solar convection zone.

- **Planned technology gap analysis:** Although high-TRL designs exist for our strawman payload, we anticipate the need for novel, miniaturized versions for many of the instruments. Based on the previous mission designs, that mass (primarily) and power (secondarily) may be highly constrained, particularly for the *4π-out* pair. A compact vector magnetograph is being developed as part of the SOLARIS effort. A compact EUV imager has been proposed for development and a compact coronagraph is under integration to be flown on NOAA's SWFO-L1 and GOES-U observatories. Therefore, we do not anticipate any new enabling technologies for the remote sensing payload.

  On the in-situ side, we baseline a body-mounted MAG to avoid the complexity and cost implication of a boom. Since we do not know of a space-qualified body-mounted magnetometer that meets our strawman specifications, MAG will require some development and TRL promotion investment.

  PSP provides a great heritage for autonomous operations, as it operates completely autonomously during its 11-day solar encounters (i.e., below 0.25 AU from the Sun) and up to 50 days. 4π-HeliOS will benefit greatly from technology developments from current and missions in-development, namely PSP, DART, and DragonFly.

  High-efficiency ion engines will be considered in the trade study to help shorten the cruise phase and circularize the orbits for the *4π-out* pair more rapidly. Another benefit of using ion engines is that they help reduce the mass of the spacecraft. We will also consider the power needed to run the ion engines.

  High-efficiency solar panels will be needed, particularly for the *4π-out* pair, to provide the needed power for operations further away from the Sun. We do not expect developing such systems to be a major problem, but we will consider it during the study.

  Optical communications could be an enabling technology for our mission concept. The helioseismology and magnetic field objectives require high-cadence imaging. Ka-band may be sufficient but require a large gimballed antenna and DSN availability. Both are cost drivers, as is the cost of ground system operations. During the design, we will trade the development cost of deep-space laser communications versus the more conventional radio architectures.

- **Operations concept:** The current concept of operations assumes separate launches for the two pairs. The 4π-in pair embark on science operations during their cruise phase towards the Lagrangian points. The 4π-out pair collects data at intermittent windows during its travel to Jupiter and after the JGA as resources allow. Attention will be given to instances of planetary transits in front of the solar disk, particularly of Earth, for studies to inform stellar-exoplanet research. In-situ operations are well understood from past planetary missions to Jupiter and Saturn.

- **Cost estimate**

  4π-in = $200M ; *4π-out:* $500M ; Payload: $210M ; Operations/Science = $100M
  Total = ~$1.0B – $1.1B