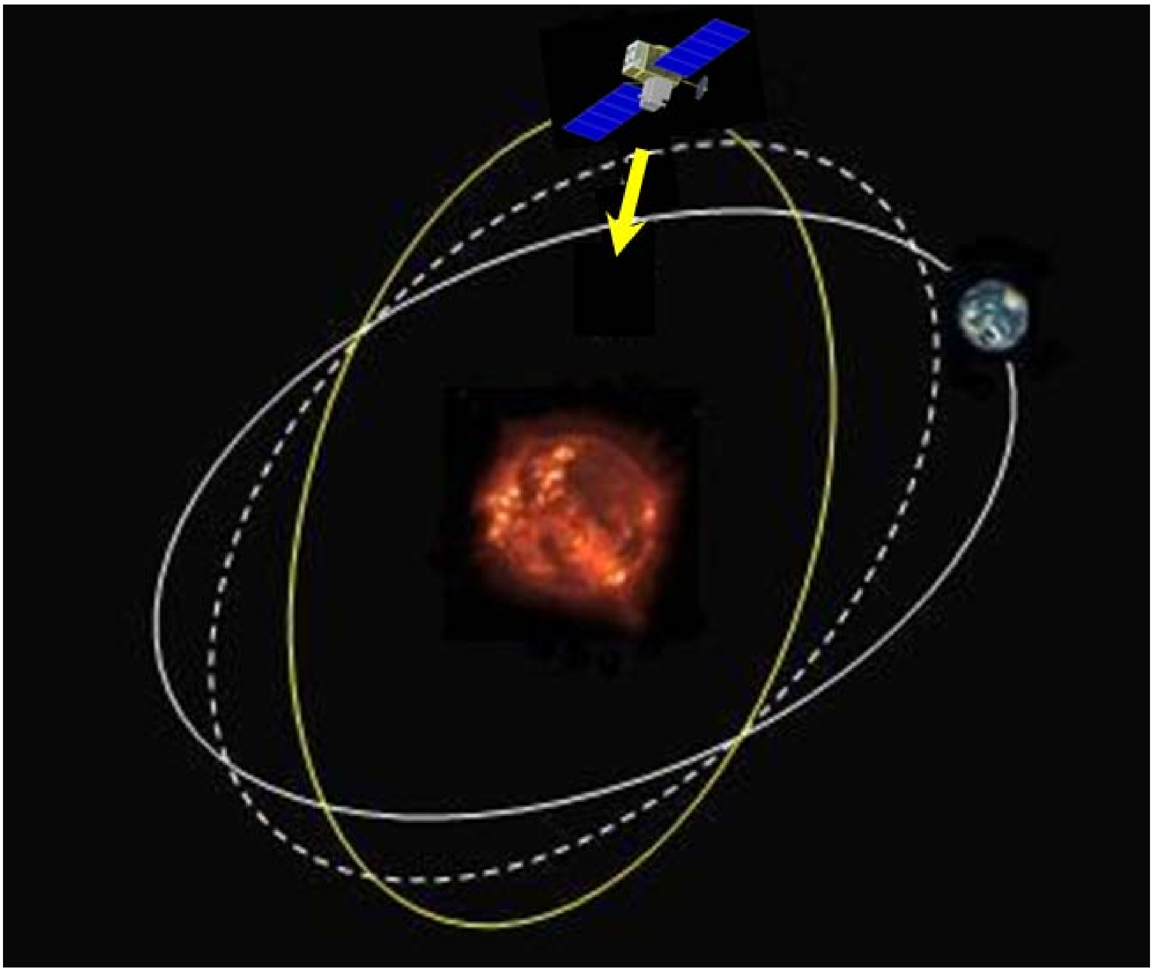
SOLAR-C Interim Report:

SOLAR-C Plan-A
A Direct Approach to the Origin of the Solar Activity Cycle



ISAS/JAXA SOLAR-C Working Group

Contents

Executive Summary

Scientific Background

Understanding the origins of solar magnetic activity has been at the forefront of solar and stellar physics since the discovery of the 11-year sunspot cycle nearly two centuries ago. Unraveling this mystery has broad implications not only for promoting a deeper knowledge of the Sun itself but also for understanding the Sun's influences on the heliosphere, the geospace environment, and potentially the Earth's climate system. Such influences regulate space weather, with increasing economic impacts on our technological society as our reliance on telecommunications systems, power grids, and airline travel continues to grow. As a readily observable example of an astrophysical magneto-hydrodynamic (MHD) dynamo, the Sun also provides unique insights into the generation of magnetic fields by turbulent plasma flows throughout the universe, from planetary and stellar interiors to stellar and galactic accretion disks to interstellar clouds.

The global magnetic polarity of the Sun reverses during each 11-year sunspot cycle so that the overall period of the solar magnetic activity cycle is 22 years. It is a formidable challenge to understand how such remarkable regularity arises from the highly turbulent conditions of the solar convection zone and how magnetic flux emerges from the solar interior to energize the solar atmosphere and power solar variability. Large-scale flows (differential rotation and meridional circulations) established by turbulent convection, plasma instabilities, and nonlinear feedbacks all play an important role, spanning many orders of magnitude in spatial and temporal scales.

Modern solar observations coupled with sophisticated theoretical and numerical models have yielded important insights into many aspects of solar magnetism but the basic physical mechanisms responsible for generating these fields are still not understood. To make great scientific progress in our understanding the Sun and the fundamental problems of cosmic magnetism, there is no doubt that we need to continue both theoretical and observational efforts. On the observational side, measuring solar internal flows is of the greatest importance. For this task helioseismology has proven to be a powerful tool.

Helioseismic measurements are based on surface wavefield data, normally and preferably temporal series of photospheric Dopplergrams, which are then analyzed to probe the solar interior structure and flows. With the so-called global methods, the wavefield data are used to measure (mainly acoustic) eigenfrequencies of the Sun. The eigenfrequencies are then analyzed, often by way of inverse methods, to probe the solar interior for thermal and dynamical structure of high degrees of symmetry, such as the spherically symmetric distribution of sound speed, or differential rotation as the axisymmetric component of flows. With new local methods, wavefield data are used to measure local resonant properties or wave propagation time for a given pair of points, by cross-correlating local wavefields. These travel-time data are then analyzed to probe the interior for local and/or asymmetric structures, such as meridional flow, convection and flows around active regions.

Differential rotation and meridional flows have already been measured by such helioseismology techniques, up to about 60° latitude with a typical uncertainty of the order of a m/s. It is essential to extend this measurement to the polar region, partly because without such measurement we will never be confident of our understanding of dynamics of the Sun as a whole, and partly because the polar region is where the magnetic flux reverses and the meridional flow, which plays an important role in carrying the magnetic flux, should turn in towards the solar interior, and where polarity reversals take place in the surface layers.

Another related mystery is the total solar irradiance variation over the solar cycle. The total irradiance of the other solar-like stars that exhibits activity at a level that is similar to the Sun, on average varies around 0.3 per cent over their activity cycles. On the other hand, the solar irradiance varies only by 0.1 per cent. There is a well-founded suspicion that the solar irradiance depends on latitude, thereby creating a great interest in measuring the solar irradiance from high heliographic latitudes.

Science Objectives

SOLAR-C Plan A, from its highly inclined orbit around the Sun, aims to combine helioseismic and magnetic observations, solar irradiance measurements at various latitudes, and finally EUV and X-ray observations of the solar polar regions, to advance our understanding of solar variability.

The highest science objective of SOLAR-C Plan A is measuring subsurface flow at high-latitude regions, by local helioseismology techniques, based on Dopplergrams acquired by an HMI-MDI type instrument. From this measurement we will derive differential rotation, meridional circulations and convective flows in the upper convection zone. These flow-field measurements will then be cross-correlated with surface magnetic field measurement, to reveal how magnetic flux is transported to the polar region, and how the polarity reversals take place as interplay between plasma flows and magnetic fields. The predominantly vertical kG-field patches that *Hinode* has found in the polar regions are large enough to be observed. A serious attempt will also be made for stereohelioseismology, for investigating deeper layers, including the best ever shot of the solar tachocline region.

Solar irradiance measurements at various latitudes will, for the first time, enable us to measure the anisotropy of the total solar irradiance. The unexplained low photometric variability of the sun may be explained by higher variability at higher latitudes, likely caused by faculae. If it is not the case, then we must conclude that the Sun is a rather atypical star, which will lead to more fundamental questions in astrophysics.

The solar polar region also hosts various activity phenomena, and EUV and X-ray observations will be important in studying them, in particular atmospheric plasma flows in solar-wind source regions. Other scientific topics that SOLAR-C Plan A may address, exploiting its unique vantage point, include evolution of heliospheric structures (by a heliospheric imager) and cosmic-ray transport in the inner heliosphere (by a particle counter) when the optional payload is adopted..

Scientific Strategy

The outstanding issues confronting our current understanding of the solar dynamo may be summarized through several key scientific questions:

Q1) How is the global, cyclic, solar magnetic field generated?
Q2) What is the nature of flows in the polar regions of the Sun and how do they interact with magnetism?

Q3) How does the radiative energy output of the Sun depend on latitude?
Q4) How does magnetic activity shape the structure and evolution of the polar solar corona and how does it affect the Earth?

Progress on these scientific questions requires detailed observations of the solar polar regions, where data is currently scarce and where much of the subtle interplay between plasma flows and magnetic fields that gives rise to cyclic polarity reversals is thought to occur. The out-of-ecliptic observations of the Sun, for the first time, will provide an opportunity for detailed investigations of the magnetic structure and dynamics of the polar regions. High-latitude photospheric observations will also provide an unprecedented vantage point for helioseismic imaging that can be used to probe flows and fields in the deep convection zone and tachocline where solar activity is ultimately thought to originate.

In addition to measurements at the photospheric level, the structures of the outer solar atmosphere in polar regions and the heliospheric structures merit observations from outside the ecliptic. The poles of sun undergo dramatic change during the 11-year solar cycle, driven by the dynamo action in the solar convection zone. The polar vantage point gives unique opportunities for understanding the origin of the fast solar wind spectroscopically and for stereo viewing of surface vector magnetic fields, coronal structures, and Earth-directed CMEs in coordination with observatories near the Earth. The unique inclination for the SOLAR-C Plan-A observatory will also permit unprecedented measurements of the total solar irradiance. This may help resolve the discrepancy of the cycle variation of the solar irradiance of ~0.1% while solar analogs vary, on average, by 0.3%.

With this in mind, we propose the following prime measurement targets for the SOLAR-C Plan-A mission:

T1) Photospheric magnetic flux distribution and evolution in the polar regions
T2) Dynamical coupling between magnetic fields and flows
T3) High-precision measurement of total solar irradiance
T4) Structure and dynamics of the high-latitude solar corona and solar wind

The methodology, significance and expected scientific impact of each of these observational targets are discussed in Section 2.1.

Measurement Requirements

The following observables are required to address the SOLAR-C Plan-A top science objectives: (A) full-Sun photospheric line-of-sight Dopplergrams for measuring the subsurface flows by helioseismology, and (B) full-Sun photospheric magnetograms for tracking the evolution of magnetic fields on the surface.

These measurements must come from an orbit inclined to the solar ecliptic, with maximum orbit inclination ≥40°. The orbit must allow observations from >30°inclination for periods of >40 days for each polar passage. To maximize the telemetry available, the orbit shall be circular with a 1-year period, to synchronize the orbital motion of the spacecraft with that of the Earth.

The orbit gives a unique vantage point for the other science objectives. The following observables shall be taken to address them: (C) total solar irradiance, (D) full-Sun chromospheric images, (E) full-Sun transition region (TR) images, (F) full-Sun coronal images to monitor the dynamic activity and the evolution of high-latitude structures, and (G) emission-line imaging spectra in chromospheric, TR, and coronal lines for investigating the source region of fast solar wind and dynamics of the outer solar atmosphere, (H) visible-light images monitoring interplanetary space between the Sun and Earth, and (I) in-situ measurements including magnetic field, solar wind protons and electrons (TBD). Currently, (H) and (I) are treated as options in this Interim Report.

Photospheric magnetograms and Dopplergrams are made from multiple images. Not all the images can be transferred to the ground due to the expected telemetry rate, so onboard data processing and compression are mandatory to reduce the total data volume transferred, as was done on SOHO/MDI. The field of view for imaging observations needs to cover the full Sun with sufficient spatial sampling for each observable. The science requirements for image size, cadence and duration for the helioseismic observables are discussed in detail in Section 2.1. Table 3 shows estimates of the required data rates. A total average data rate of ~100 kbps is required.

SOLAR-C Plan-A Payload

The SOLAR-C Plan-A has been planned by attaching weight to science topics that are studied by remote-sensing instruments. The best condition for remote-sensing observations from the out-of-ecliptic orbit is selected under the restriction of current or near-future technology.

The science payload to satisfy the primary measurement requirements consists of:

- A visible light imager that can measure the full-Sun photospheric magnetic fields and line-of-sight Doppler velocity, similar to MDI on SOHO or a simplified version of HMI on SDO.
- A total irradiance monitor that measures the irradiance of the Sun. Multiple cavity monitors are needed for self calibration.
- A light-weight EUV imager that monitors the transition-region and coronal activity in the polar region.
- An EUV scanning spectrometer that measures the flow structures in the polar region.

The following instruments provide additional measurements of T4 and are listed as optional:

- A heliospheric imager that observes the space between the Sun and Earth
- In-situ instruments such as instruments measuring the solar wind and cosmic-ray particle sampler (TBD)

Trajectory and Orbit

The major mission requirement of SOLAR-C Plan A is to observe the Sun from high latitude, with target specified as 40°. In order to achieve this target, the SOLAR-C Plan-A Working Group has studied a number of possible mission designs using various trajectory manipulation techniques. The items considered are the tilt of the solar equatorial plane to the ecliptic, launcher capacity, planetary gravity assists, and the use of a highly efficient propulsion system. The launcher assumed is the Japanese H-IIA launch vehicle equipped with a solid motor upper stage. There are two possible options: one is to use solar electric propulsion assisted by an Earth swing-by (SEP option), and the other is to use both Jupiter and Earth swing-bys (Jupiter option). The latter is a purely ballistic trajectory. The final orbit is nearly the same, a circular orbit with 1 AU distance from the Sun and 1 year orbital period, with a different time to reach the maximum inclination (5 years for SEP option and 7 years for Jupiter option). If there is a strong requirement that the spacecraft has to be in the final orbit before the solar maximum around 2024 (assuming launch in 2019), the SEP option is the only currently available way to satisfy the time constraint. The orbit profile in the cruise phase is quite different between SEP and Jupiter options. In the first three years, no observations are expected for the SEP option and there may be a short observing period of about a month at each hemisphere in the following years until the spacecraft enters into the final orbit. On the other hand, observations are possible at any time outside the swing-by operation for Jupiter option, but high telemetry is limited to positions near the Earth until reaching the final orbit.

Spacecraft

The SEP option requires a heavy propulsion system. The assumed μ20 ion engine system is an upgraded version of μ10 that was used in JAXA HAYABUSA sample return mission. The new engine itself has undergone endurance testing in the lab but no flight heritage yet. The μ20 ion engine system consumes 6 kW power, and a lightweight solar array paddle with large area is necessary. The total wet weight of the spacecraft in the SEP option is ~1,200 kg with payload mass of 130 kg. The total wet weight of spacecraft in the Jupiter option is ~750 kg with payload mass of 130 kg.

Launch vehicle

A single spacecraft launch with the JAXA H-II A rocket 202A is assumed. Some orbit cruise methodologies require a kick motor and it becomes one of new development items in the Japanese space agency after the interplanetary missions launched by M-III or M-V solid boosters. The use of a kick motor is assumed for both SEP and Jupiter options. There is a solution in a SEP option by an orbit cruise via Venus swing-by without having a kick motor by reducing the launch opportunity.

The spacecraft attitude is three-axis stabilized to meet the requirements of the imaging instruments. Angular momentum management occurs daily to weekly, using chemical thrusters. 300 kbps X-band downlink telemetry rate and 8 hr downlink time per day are assumed for an average data rate of 100 kbps, at a spacecraft distance at 0.56 AU from the Earth. Downlink stations are needed in the northern and southern hemispheres on Earth. 1 Mbps Ka-band telemetry rate at the same distance is under consideration to enable a greater telemetry volume.