

# *The High Resolution Solar-C International Collaboration: Probing the Coupled Dynamics of the Solar Atmosphere*

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## **1 Introduction**

Many problems in solar physics, such as the heating of the solar chromosphere and corona, the onset of coronal mass ejections, and the origin of the solar wind, remain unresolved. This is because current and planned instruments do not provide comprehensive temperature coverage at the spatial, temporal, and spectral resolution needed to resolve and trace the elementary processes that dominate the energization of the solar atmosphere, such as magnetic reconnection, wave dissipation, and particle acceleration. During the past few years, space-based and ground-based observations and numerical models have provided tantalizing glimpses of the fundamental heating processes, while exposing crucial gaps in our arsenal of observational tools that have hampered progress for decades and that need to be filled to gain a full understanding of how the solar atmosphere is energized.

For the past year solar physicists in Japan, the United States, and Europe, many of whom were involved in the highly successful Solar-A (*Yohkoh*) and Solar-B (*Hinode*) missions, have been studying the possibility of next generation instrumentation that would make major steps forward in all of the necessary observational dimensions. Participation in such a large-scale, international collaboration led by the Japanese would leverage a relatively small investment from NASA to produce an extraordinary scientific return. The Japanese solar physics community is currently considering two mission concepts for Solar-C: an out of the ecliptic mission (plan A) and a high resolution mission (plan B). This white paper gives a brief overview of the science objectives for the high resolution (plan B) Solar-C mission and the instruments required to achieve them.

The unifying goal behind the high resolution Solar-C mission is to understand how the Sun's magnetic field drives mass and energy flows from the thermally dominated lower solar atmosphere into the magnetically dominated corona and solar wind acceleration region. This can only be accomplished with an instrument suite that *simultaneously* observes emission from the photosphere, chromosphere, transition region, and corona at *similar and high spatial, temporal, and spectral resolution*. Solar-C will be the first mission to reveal the spatial and temporal scales on which the energy release processes appear to aggregate according to recent observations and numerical simulations. Unlike previous instrumentation, Solar-C will be able to measure magnetic fields in and above the region where the field is dominated by plasma pressure, providing the first proper boundary conditions for coronal and heliospheric magnetic field extrapolations.

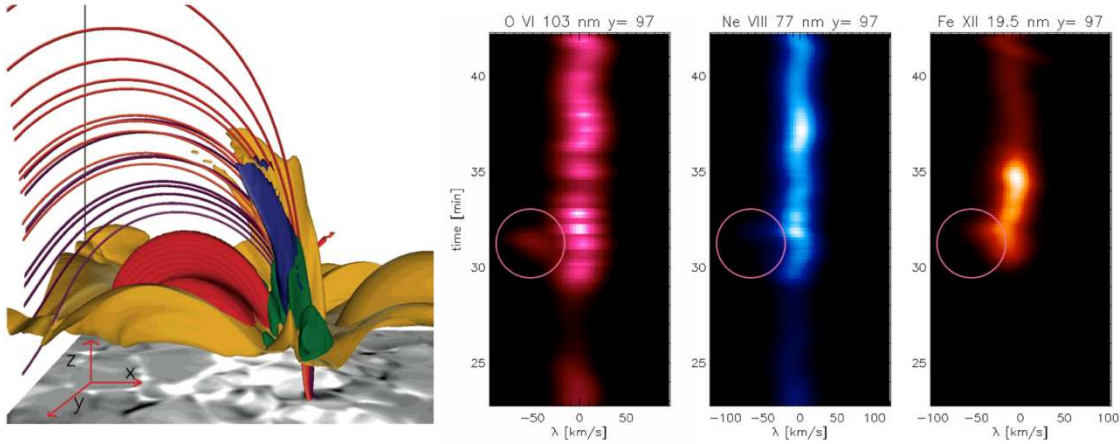


Figure 1: A 3D MHD simulation of a jet produced by emerging magnetic flux. This simulation illustrates the need for simultaneous imaging and spectral data covering the photosphere, chromosphere, transition region, and corona at high temporal, spatial, and spectral resolution. The left panel shows the magnetic field in the low chromosphere (grayscale image), magnetic field lines (red and purple lines), the location of the magnetic heating (green isosurface), the location of a chromospheric jet (blue isosurface), and the transition region and coronal emission (yellow and red surfaces). The right panels show the subtle velocity signature of the jet at three different temperatures as a function of time.

## 2 Science Goals

### 2.1 How does the magnetic field structure the solar atmosphere?

Low in the solar atmosphere gas pressure dominates the magnetic field. In the corona the situation is reversed, and plasma is generally frozen to the magnetic field. The  $\beta = 1$  transition typically occurs in the chromosphere. Most previous instrumentation has focused on measuring magnetic fields in the photosphere, i.e., below the  $\beta = 1$  surface, where the magnetic field properties can be determined relatively easily. This has led to enormous advances in our understanding of the photospheric fields, with *Hinode* providing unparalleled views of the fine-scale structure of flux tubes on spatial scales of 100 km ( $0.2''$ ) and the processes leading to their formation, as well discovering ubiquitous weak fields on granular scales ( $< 1''$ ), with potentially profound consequences for the energetics of the entire solar atmosphere (Lites, 2006).

To understand how the magnetic field drives coronal topology and large-scale field reorganizations in flares and CMEs and to establish the connectivity to the heliosphere, photospheric field measurements are used as a boundary condition for magnetic field extrapolations. But the photospheric field is not force-free, so the extrapolations fail to reproduce the observed topology of solar active regions (De Rosa et al., 2009). The forcing of the field in the chromosphere implies that much of the magnetic energy release occurs well above the photosphere, so tracing the release of free energy of the magnetic field and its effects on the momentum and energy balance of the chromosphere and corona using only photospheric fields is almost impossible.

Solar-C will tackle this problem by measuring the magnetic fields in the chromosphere, both around and above the plasma  $\beta = 1$  surface (using, for example, the He I line at

1083 nm and the Ca II infrared triplet lines around 855 nm), with enough sensitivity and spatial resolution to provide meaningful boundary conditions for extrapolation methods. These measurements will reveal where and how magnetic free energy is released in the solar atmosphere. By simultaneously measuring photospheric and chromospheric fields, Solar-C will be able to measure the vertical gradients in the magnetic field, which will provide information on the Poynting flux into the solar atmosphere. This will yield important information on where and how the field is forced, and what role the magnetic fields play in heating and accelerating plasma in the corona and the solar wind.

Recent advances in numerically modeling the solar atmosphere, the impact of the Zeeman and Hanle effects on spectropolarimetric measurements, and the inversion of chromospheric lines to establish magnetic field properties are opening a new window into the magnetized chromosphere. This makes Solar-C particularly timely. Forward modeling with advanced numerical codes indicates that useful chromospheric measurements require a spatial resolution of  $0.5''$  or better and a signal-to-noise of order  $10^3$ . For the optimal spectral lines, a meter-class optical telescope would be able to provide such measurements at a cadence of 20 s at one spectral position, which is adequate to capture the dynamics of the chromospheric fields, as evidenced by the chromospheric dynamics observed with *Hinode* (which occur on timescales of order 30 s).

## 2.2 What energizes and maintains the plasma in the complex magnetic environment of the solar atmosphere? — Measuring the signatures of magnetic reconnection, wave dissipation, and particle acceleration

Theoretical work tells us that the smallest spatial scales over which important physical processes such as magnetic reconnection, wave dissipation, and particle acceleration occur may be only meters in size — far smaller than will be resolvable with solar telescopes for the foreseeable future. Solar observations, however, suggest that these physical processes are coherent over much larger spatial scales. Chromospheric jets observed with *Hinode* and ground-based telescopes, for example, have spatial scales of about  $0.1\text{--}0.3''$  (about 70–200 km at the Sun). Similarly, observations of transition region and coronal structures taken with  $1''$ -resolution instruments indicate that about 10% of the observed area is filled with emitting plasma, again suggesting spatial scales that can be observed with next generation solar instrumentation.

Even at the spatial and temporal resolution of *Hinode* there are clues to how the flow of mass and energy through the solar chromosphere can drive coronal activity. De Pontieu et al. (2009), for example, have found evidence of chromospheric jets (type-II spicules) that are heated to high temperatures and appear to supply mass to the corona. It is difficult to follow this chromospheric material into the corona, however, because of the mismatch between the optical, EUV, and X-ray instruments on *Hinode*. Observational challenges such as this drive the design of the spectroscopic and imaging instruments for Solar-C. The optical telescope will obtain intensity measurements of full spectral line profiles of chromospheric lines within 10 s to fully capture the dynamics of the chromospheric plasma. The spectrometer will combine UV observations of the chromosphere and transition region with EUV observations of the corona in a single instrument with very high spatial ( $0.2''$ ), spectral ( $\sim 30,000$ ), and temporal (1–10 s) resolution. This will be complemented by comparable spatial and temporal

resolution observations from narrow EUV passbands using normal incidence, multi-layer telescopes.

It is widely believed that magnetic reconnection plays a central role in many solar phenomena, such as flares and coronal jets. The physics of magnetic reconnection, however, is still poorly understood. For example, it is clear that magnetic reconnection on the Sun occurs much faster than the time scales predicted by the classic Sweet-Parker model, but what drives this fast reconnection? Recent theoretical work has suggested that it is the formation of magnetic islands in the current sheet that leads to fast reconnection (e.g., Bhattacharjee et al. 2009; Edmondson et al. 2010). To reconcile the observations with theory and numerical models, the physical conditions in and around the current sheet must be explored in detail. Of particular importance are the inflow and outflow velocities. Since the density in this region is close to that of the ambient corona and the volume is small, such measurements are very challenging. This motivates the selection of multiple wavelength ranges so that the brightest emission lines at critical temperatures can be observed spectroscopically.

The process of energy release in magnetic reconnection is also not well understood. Acceleration of particles to high energies is the dominant energy transport mechanism during the earliest phase of a flare. The mechanism responsible for this acceleration, however, has not been identified. One theory is that electrons gain energy from interacting with magnetic islands in the current sheet (Drake et al., 2006). Direct detection of energetic non-thermal electrons requires high energy spectroscopic observations (above 10 keV). The impact of these electrons on the chromosphere, however, can be directly measured by high resolution UV/EUV spectroscopy. The new, high-cadence observations from Solar-C will provide insights into the total energy carried by non-thermal particles. The magnetic tension in newly reconnected magnetic flux tubes is another source of energy. The gas dynamic shocks that form as these field lines slingshot away from the reconnection region can heat and compress plasma (Longcope et al., 2009). To understand this energy release process, the dynamics of post-reconnection flare loops must be observed (e.g., Savage et al., 2010). These observations will be possible only with the broad temperature coverage, high spatial resolution, and high cadence of Solar-C.

Solar-C will be able to establish the role of waves in providing the corona with energy and also exploit coronal seismology as a diagnostic of heating processes in the atmosphere. For example, we know that transverse magnetic waves carry enormous amounts of energy upward through the chromosphere (De Pontieu et al., 2007; Cirtain et al., 2007), but Solar-C's high resolution at a wide range of temperatures is required to trace the propagation, mode-coupling, reflection, and dissipation of these waves as they cross the  $\beta = 1$  surface into the transition region and corona while resolving their short periods (as low as 60 s) and the displacement of the field lines ( $< 1''$ ).

### **2.3 What drives large-scale restructuring and energy release in the outer solar atmosphere? — Predicting the onset of space weather**

The primary science goals of the high resolution Solar-C mission, understanding the magnetic field throughout the solar atmosphere and the release of energy through magnetic reconnection, wave dissipation, and particle acceleration, lay the foundation for studying a wide range of complex solar phenomena. Of particular interest are phenomena that influence

the near-Earth environment, such as coronal mass ejections (CMEs), flares, and the solar wind. A critical goal for solar physics research is to improve our ability to predict space weather events. Predicting the occurrence of CMEs and flares requires understanding the storage and release of magnetic energy in the solar atmosphere. It is clear that these occur on very different time scales. Magnetic energy is built up slowly, through shearing motions along the neutral line. The release of energy, in contrast, occurs rapidly, but what actually triggers an eruption has not been firmly established.

One class of theories about CME initiation is tied to magnetic topology. In the “breakout model,” for example, the overlying, coronal unshredded field is removed through reconnection at a magnetic null, allowing the stressed field along the neutral to erupt (Antiochos, 1998). In contrast, in the “tether-cutting” (e.g., Moore et al., 2001) and “flux rope” models (e.g., Forbes & Isenberg, 1991), the eruption is triggered by reconnection low in the solar atmosphere. In all cases the key to progress is relating signatures of energy release in different atmospheric regions to the magnetic structure of the solar atmosphere. Solar-C is flexibly designed to accomplish this task due to its ability to observe energy release and follow its transport through all regions of the atmosphere.

The solar wind is another important component of space weather. Coronal holes are the source of the fast solar wind ( $700\text{--}800\text{ km s}^{-1}$  at the earth’s orbit). The origin of the slow solar wind ( $300\text{--}400\text{ km s}^{-1}$ ) is unknown. Recently instruments on *Hinode* have detected persistent high speed outflows from large areas at the periphery of many active regions (e.g., Doschek et al., 2007; Harra et al., 2008; Del Zanna, 2008). These outflows are characterized by bulk shifts in the line profile of up to  $50\text{ km s}^{-1}$  and enhancements in the blue wing of up to  $200\text{ km s}^{-1}$  (Bryans et al., 2010; McIntosh & De Pontieu, 2009), and may lie on open field lines and contribute to the solar wind. Schrijver & De Rosa (2003), for example, have used magnetic field extrapolations to show that connections of active region fields to the heliosphere are common and suggest that up to 50% of the heliospheric field may originate in and around solar active regions.

Despite the extensive work on the outflows that has been done with *Hinode* a number of important questions remain. Perhaps the most important question that Solar-C can address is how these high speed outflows are heated and accelerated. Temporally resolved observations suggest that the outflows are composed of episodic events that originate low in the solar atmosphere. Because of the high velocities involved, however, the evolution of these events in space and time is difficult to follow. Solar-C will provide the observations necessary to understand how these high speed outflows are formed.

### 3 Mission Concept

To reach the science objectives outlined above, three state-of-the-art instruments have been designed in considerable detail: A Solar Ultra-violet Visible and IR Telescope (SUVIT), a UV/EUV High-Throughput Spectroscopic Telescope (here called EUVST), and an X-ray Imaging Telescope (here called XIT). These instruments have been well-studied by the Solar-C International Science Working Group and detailed descriptions are available in the Japanese Draft Interim Report; all instruments are at TRL 6. The planned orbit is geosynchronous to accommodate a high data rate.

Solar-C is envisioned as an International Partnership Mission led by JAXA with substantial contributions from NASA, ESA, the UK, and several other European countries. It is designed to be a Small Strategic Mission from NASA's standpoint; the maximum cost to NASA for such a mission is \$250M. This investment will ensure full participation in a large international mission, whose total cost may be of order \$750M.

The high resolution Solar-C mission will make fundamental advances in many Research Focus areas listed in the 2009 Heliophysics Roadmap. It was specifically listed as a partnership mission to discover precursors to solar disturbances in the chromosphere and corona and is also key to the outstanding questions of heating and acceleration of the solar wind (Roadmap, P. 50). It is well-timed to provide crucial coordinated observations with Solar Probe Plus, Solar Orbiter, and the Roadmap mission STP #6, Solar Energetic Particle Acceleration and Transport.

**SUVIT** The primary science requirement of SUVIT is to determine the physical processes responsible for the dynamics of the photosphere/chromosphere and to measure chromospheric magnetic fields. This is done by making intensity and spectro-polarimetric measurements of photospheric and chromospheric spectral lines. From these measurements, physical parameters like temperatures, velocities, and magnetic fields (Zeeman and Hanle effects) will be determined. SUVIT is a meter-class telescope currently under study at 1.5 m.

With this diameter, the polarimetric sensitivity is designed to be  $10^{-4}$  for  $0.2''$  pixels and 20 s exposure times. In contrast *Hinode*/SOT and ground-based solar telescopes do not have sensitivities better than  $\sim 10^{-3}$ . In addition, compared to ground-based telescopes (e.g., ATST), Solar C will have stable, seeing-free imaging quality, which is crucial for high S/N polarimetry, so that the resulting long time series will uniquely allow us to track the evolution of the boundary condition for the coronal and heliospheric magnetic field. The spatial and temporal samplings are dictated by *Hinode* observations of chromospheric dynamics which shows intensity changes on timescales of order 20–30 s. The strawman design parameters are:

Telescope	Aplanatic Gregorian 2 mirror telescope
Primary mirror	1.5 m
Spectral lines (intensities)	Mg II k 2796 Å, Ca II 8542 Å, H I $\alpha$ 6563 Å He I 10830 Å, He I D3 5875 Å,
Spectral lines (polarimetry)	(chromosphere) He I 10830 Å, He I D3 5875 Å, Ca II 8542 & 8498 Å (photosphere) Fe I 8538 Å, Si I 10827 Å
Spectral resolution	100,000 (can observe a $3 \text{ km s}^{-1}$ Doppler shift)
Spatial resolution	$0.1''$ at 2796 Å (intensity measurements), $0.2''$ pixels (polarization measurements), with S/N $10^4$
Temporal resolution	0.1 s (imager, broadband filters), 1 s (imager, narrowband), 10–20 s (spectropolarimeter)
Field-of-View	$200'' \times 200''$
Focal Plane	Spectrograph Package and Imager Package

**EUVST** The primary science requirement of EUVST is to observe the flow and dissipation of energy from the top layers of the chromosphere into the transition region and corona, and to observe multi-million degree flare plasma. EUVST can observe all temperatures

from about 20,000 K to about 20 MK with high spatial, spectral, and temporal resolution. EUVST has higher spatial, spectral, and temporal resolution than *Hinode*/EIS as well as *SOHO*/SUMER. Its wavelength coverage in an amalgamation of EIS and SUMER wavebands. The strawman design parameters are:

Telescope	Single parabolic mirror on-axis system feeding an off-axis spectrometer
Grating	4000 lines/mm, elliptical substrate, VLS
Primary Mirror	40 cm
Spatial resolution	0.2'' pixels
Spectral ranges	130–250 Å, 510–630 Å, 690–810 Å, 940–1060 Å
Spectral resolution	40,000 near 1000 Å, 20,000 between 130 and 630 Å
Slit/slot sizes	slits: 0.16'', 0.32'', 0.96''; slots: 10'', 40'', 200''
Temporal resolution	1–10 s
Field-of-view	400'' × 400''
Detectors	5Kx2K CCD/APS

**XIT** The primary science requirement of XIT is to investigate the physics of magnetic energy storage and release in coronal plasma by observing how the corona reacts to activity that occurred in the transition region, chromosphere, and photosphere. Two X-ray telescopes are under consideration by the International Working Group: (1) a grazing-incidence telescope with photon counting detectors such that imaging spectroscopy can be achieved, and (2) an ultra-high spatial resolution normal incidence X/EUV telescope. In this document we discuss only the normal incidence telescope because it has a higher TRL level. The strawman design parameters are:

Telescope	Ritchey-Chretien form of Cassegrain
Primary Mirror	32 cm
Spatial resolution	0.1'' pixels
Wavebands	Wavebands at 94, 131, 171, 195, 211, 304, 335 Å, and in the UV are being considered
Temporal resolution	10 s
Field-of-view	400'' × 400''

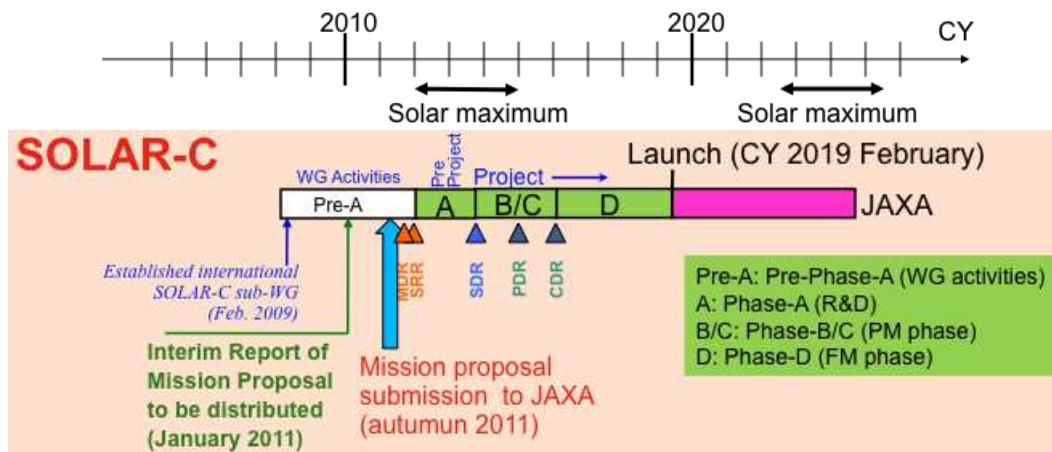


Figure 2: A preliminary schedule for the Solar-C mission.

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