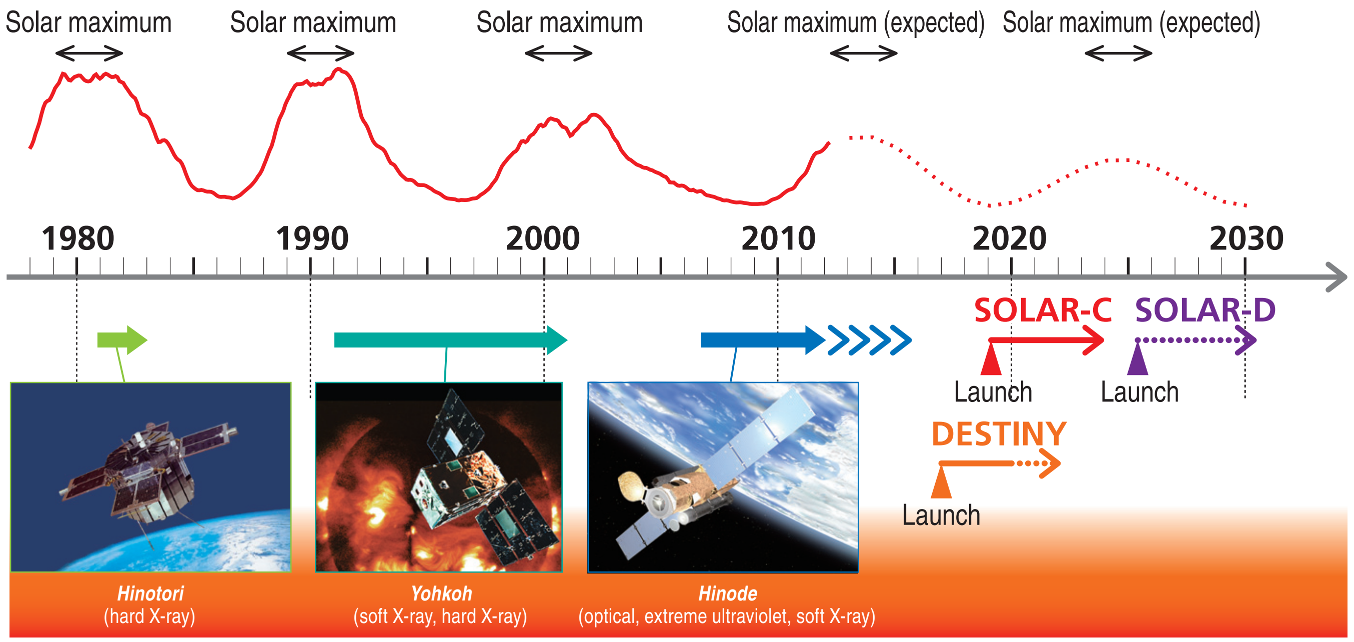
Space Solar Missions by Japan and Future Roadmap

To date Japan has launched the ***Hinotori***, ***Yohkoh***, and ***Hinode*** satellites, achieving highly significant scientific results. **SOLAR-C**, the fourth space solar mission, is under study with a launch target of fiscal year 2018. Currently the sun is showing signs of entering a period of unusual activity not seen in recent years, with the next few cycles presenting an excellent opportunity to understand the links between the sun and the earth's environment. The high-spatial-resolution magnetic field observations by ***Hinode*** at last have allowed us to investigate the long-term magnetic field fluctuations across the entire sun, including quiet regions and polar regions; and we are in the process of learning how reversal of polarity occurs in the polar magnetic field, important for understanding the 11-year solar cycle. From the standpoints of continuity with ***Hinode*** data and conducting comparative studies with previous activity cycles, it will be especially important to capture the transition from the next solar minimum to solar maximum, making it essential to realize the **SOLAR-C** mission in the latter part of this decade. Moreover, for realizing the **SOLAR-D** mission early in the 2020s, the Destiny mission (to be proposed to ISAS Small Scientific Satellite #3) will play an important role in demonstrating the applicability of the large ion engine and the ultra lightweight solar array, etc.



SOLAR-C WG Activities

The **SOLAR-C** Working Group defined two mission plans, Plan A for exploring the polar regions of the sun away from the ecliptic plane, and Plan B for high-resolution spectroscopic observation of the sun seamlessly from the photosphere to the corona. It then formed a sub-working group to study these plans, consisting mainly of the Japanese solar physics community with cooperation from scientists in the United States and Europe. The studies were summarized and made public in an interim report (**http://hinode.nao.ac.jp/SOLAR-C/Documents/Interim_report2011.html**). Together with NASA a Joint Solar-C Science Assessment Committee was formed to choose between the two plans, based on the interim report, from such standpoints as (1) the science merit, (2) the technical readiness of the spacecraft and the strawman science instruments, (3) initial estimates of the total costs to JAXA, (4) the broad participation of overseas space agencies, and (5) whether Japan could enhance its own instrument development capability in this opportunity by providing one major instrument. The decision reached by the committee was that Plan B would be implemented as **SOLAR-C** and Plan A, involving development elements for interplanetary flight, would be implemented as **SOLAR-D**. As an extension of the sub-working group activities, a European group in December 2010 proposed the **SOLAR-C** EUV/FUV high-throughput spectroscopic telescope (**EUVS**) to ESA's Cosmic Vision, giving it the name **LEMUR**. In order to raise the technological readiness level, taking advantage of strategic development funding by the Institute of Space and Astronautical Science (ISAS), studies and development are being carried out toward realization of large-scale telescopes and focal plane instruments, a highly reliable rotational drive mechanism capable of high-frequency operation, a photon-counting X-ray telescope, and satellite systems for achieving image stability.

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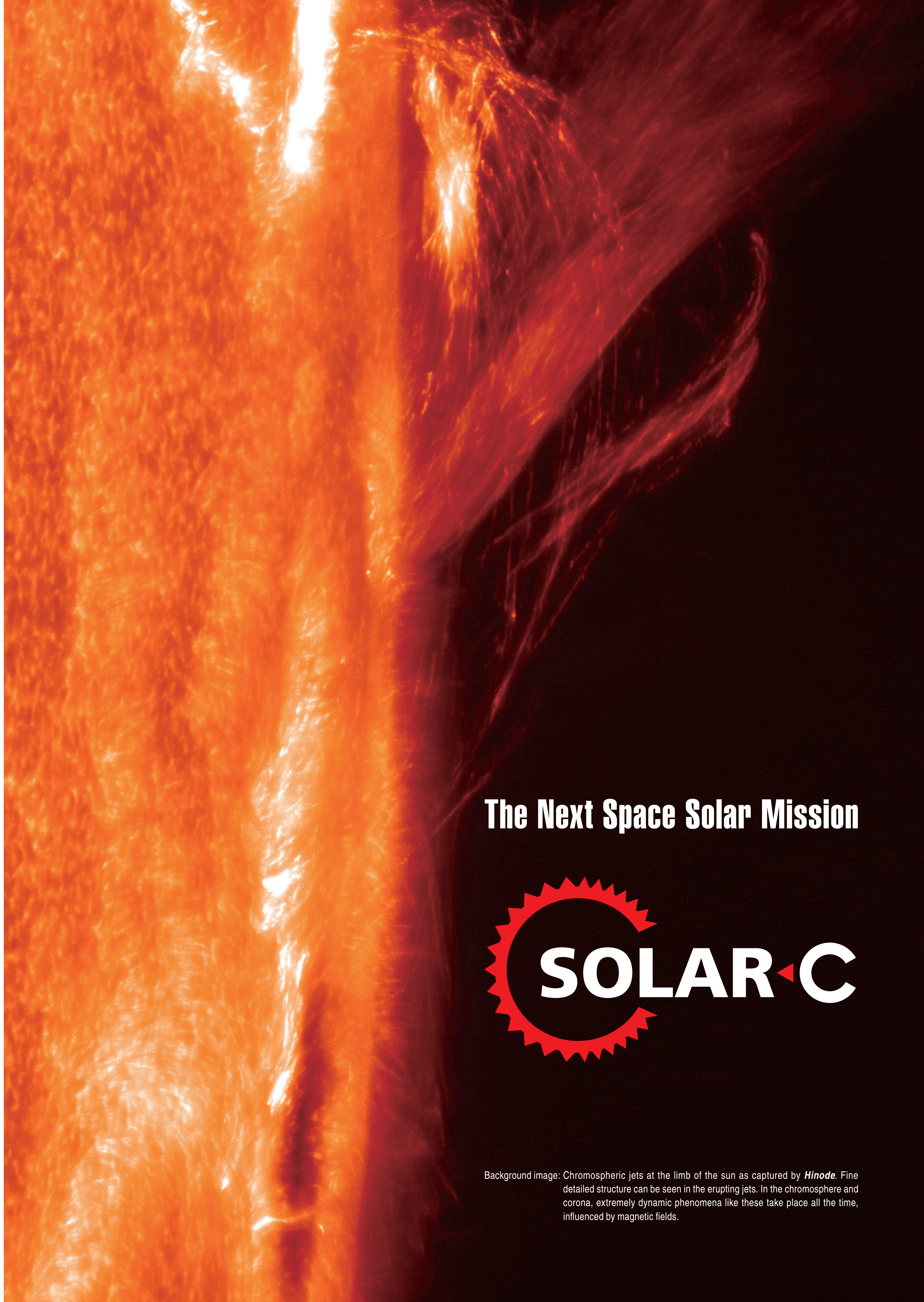


The Next Space Solar Mission

SOLAR-C

Background image: Chromospheric jets at the limb of the sun as captured by ***Hinode***. Fine detailed structure can be seen in the erupting jets. In the chromosphere and corona, extremely dynamic phenomena like these take place all the time, influenced by magnetic fields.

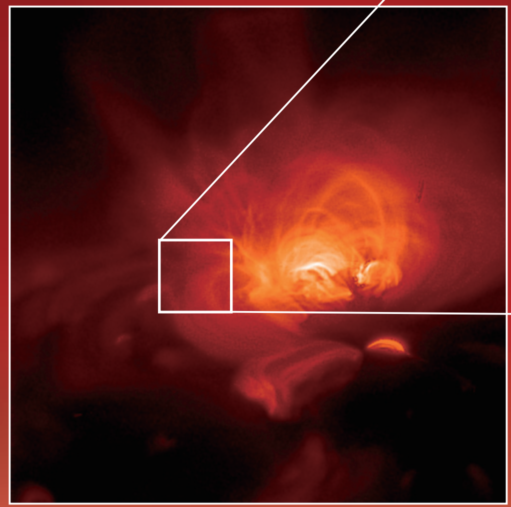
From *Hinode* to SOLAR-C

Revealing the sun's secret in the magnetic activity by magnetic field observations of the chromosphere and high-resolution observations of the corona

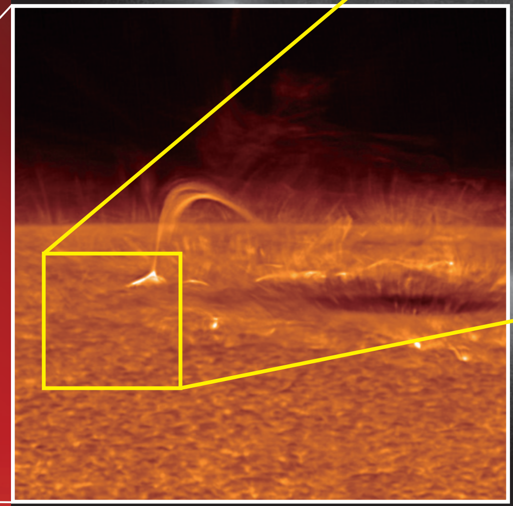
The sun's surface (photosphere) has a temperature of 6,000 K. Above that is the chromosphere at around 10,000 K, and farther out still is the corona at more than a million K; the origin of these atmospheric layers is still not well understood. In the vicinity of sunspots, huge eruptions called flares spontaneously release enormous amounts of energy, with their effects extending to interplanetary space. On a smaller scale, there are processes at work heating the sun's atmosphere everywhere, which are believed to be involved in formation of the chromosphere and corona. The source of this activity is the magnetic field energy created by the solar convection zone, but just how this results in formation of an active magnetic atmosphere is not well understood.

In order to understand the activity observed in the solar atmosphere, it is necessary to view the photosphere, chromosphere, and corona as one system coupled by magnetic fields. To do this it is necessary to resolve the size scale of the fundamental physical processes connecting these atmospheric layers. From results obtained by the ***Hinode*** satellite, the needed resolution is estimated to be 0.1 to 0.5 arcseconds. Since the chromosphere links the photosphere and the corona, it is especially important to study properties and magnetic structure in the chromosphere. And in order to understand in detail the transition between the chromosphere and the corona, high-resolution coronal observations are essential.

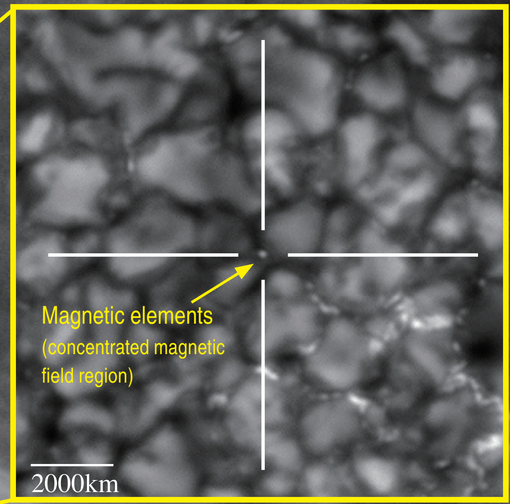
Using high-resolution spectropolarimetry, **SOLAR-C** will measure magnetic fields of both the photosphere and the chromosphere; up to now measuring the chromospheric field has proved extremely difficult and elusive. Moreover, the three-dimensional magnetic field structure of the corona will be sought by indirect means based on these measurements. In addition to chromospheric magnetic field measurements, **SOLAR-C** will observe the corona at resolutions far higher than with ***Hinode***, and will attempt to capture the fine-scale dynamics of the chromosphere and corona by means of spectroscopic observations. By determining the diversity of elementary processes (fine-scale structures) and global structures involved with the magnetic field as well as their changes, while at the same time observing the corona at unprecedentedly high resolution, the mission will clarify the processes that create the high-temperature atmosphere of the sun, and also the atmospheres of stars in general. Overall, the mission will yield a complete picture of the sun's vigorously changing magnetic activity.



Corona (1 million K)



Chromosphere (10,000 K)

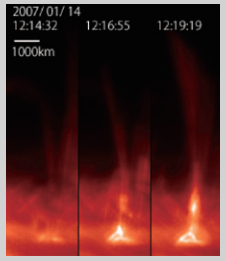


Photosphere (6,000 K)

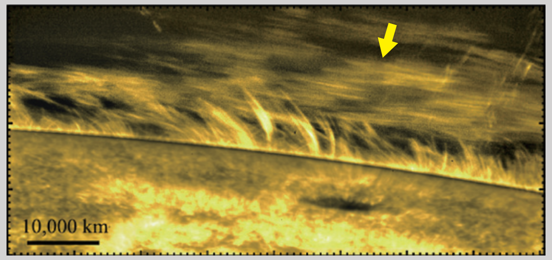
Outstanding science questions of solar physics

- H-ow are the chromosphere and corona heated?
- What drives the solar wind?
- How are the diverse magnetic structures observed in the chromosphere formed?
- How do solar flares and other such eruptive phenomena occur?
- What causes the solar magnetic cycle?

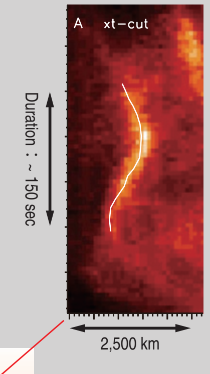
New findings and New Questions by *Hinode*



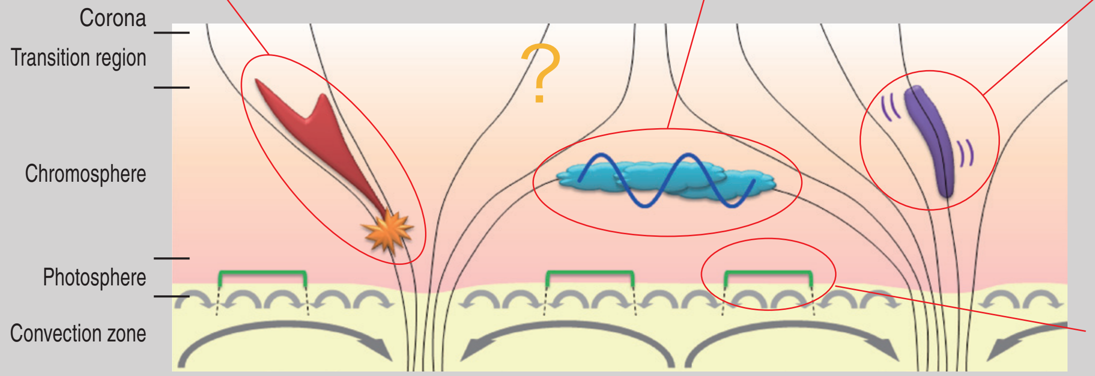
(A) Chromospheric jet

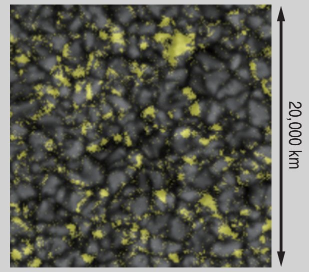


(B) Waves propagating in a prominence (yellow arrow)



(C) Swaying spicule





(D) Transient horizontal magnetic fields in the photosphere (shown in yellow)

Above the sun's "surface" (photosphere) are layers of hotter plasma called the chromosphere, transition region and the corona. While the photosphere is ~ 6000 K temperature, the chromosphere and the corona are ~ 10,000 K and over 1 million K, respectively. The heating mechanism of these high temperature layers is one of the outstanding questions of solar physics. While the chromosphere is cooler than the corona, its higher density means the amount of heating needed to maintain the chromosphere is 10 to 100 times larger than that of the corona. Observations by the ***Hinode*** satellite discovered a variety of dynamic events in the chromosphere such as various types of jets and wave phenomena (Figures A to C), indicating that these events may be responsible for heating the chromosphere and corona. In addition, ***Hinode*** observations of the photosphere show numerous transient horizontal magnetic field structures which may drive the dynamics of the chromosphere (Figure D). Magnetic fields dominate the dynamics in the chromosphere, transition region and the corona, and likely play a central role in the heating mechanisms. For understanding the heating mechanisms it is essential to carry out high accuracy and high spatial-resolution observations of magnetic fields from the photosphere to the corona, including the chromosphere.

Science Objectives of SOLAR-C

Is the solar corona heated by nanoflares, having only one billionth the energy of giant flares? Or are magnetohydrodynamic (MHD) waves responsible both for heating the corona and at the same time causing the solar wind to accelerate to supersonic speeds? High-resolution observations of magnetic fields by ***Hinode*** revealed the presence of many kinds of magnetic structures in the photosphere, differing greatly in size and in the scale of their changes over time. But the structure of the magnetic field higher up in the solar atmosphere, in the chromosphere and corona, is still not well understood. Is the coronal magnetic field made up of a multitude of magnetic sub-structures, complexly intertwined reflecting photospheric dynamics and readily conducive to the generation of nanoflares? Or does the nature of the magnetic structures facilitate the transporting of energy to the corona by MHD waves?

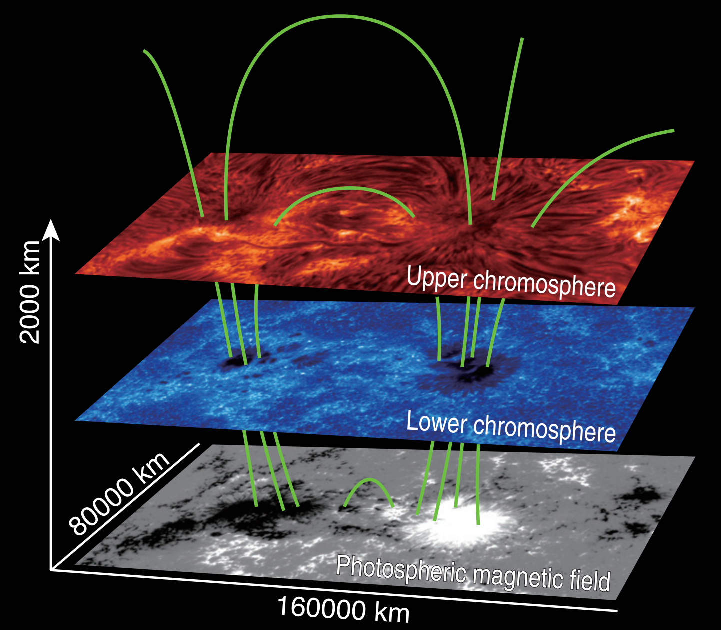
The **SOLAR-C** satellite, equipped with the Solar UV-Visible-IR Telescope (**SUVIT**), the EUV/FUV High Throughput Spectroscopic Telescope (**EUVS/LEMUR**), and the X-ray Imaging Telescope (**XIT**) all working together to make closely coordinated observations, is designed to answer such questions. Various phenomena spanning from the solar photosphere to the heliosphere are believed to be the result of magnetic reconnection and wave phenomena, which in turn give rise to physical phenomena on a smaller scale such as shock waves and turbulence. Observing magnetic reconnection and wave phenomena at the sun will require both (1) high resolution for capturing fine-scale structures and (2) high sensitivity for tracking rapid changes. For this, telescopes larger than those on Hinode are needed.

The high resolution of the three telescopes on **SOLAR-C** will enable observations of the magnetic coupling from the photosphere, to the chromosphere and the corona. Observations with **SUVIT** of photospheric and chromospheric magnetic fields will then make it possible to infer the three-dimensional magnetic structure extending from the photosphere through to the corona. This in turn will help identify the kinds of magnetic structures that lend themselves to magnetic reconnection, and clarify how waves are propagated, reflected, and dissipated. Phenomena indicative of or byproducts of magnetic reconnection, such as inflow and outflow, turbulence, shock waves and other wave motions, will be captured by **SUVIT** and by spectroscopic observations using **EUVS/LEMUR**, while **XIT** will observe the rapid changes in temperature distribution of plasma heated by shock waves.

A few science questions to be tackled by **SOLAR-C** are described here. The success criterion is whether **SOLAR-C** observations give significant advancement of our understanding to the major questions in solar physics.

Science question 1: Determining three-dimensional magnetic structures in the solar atmosphere

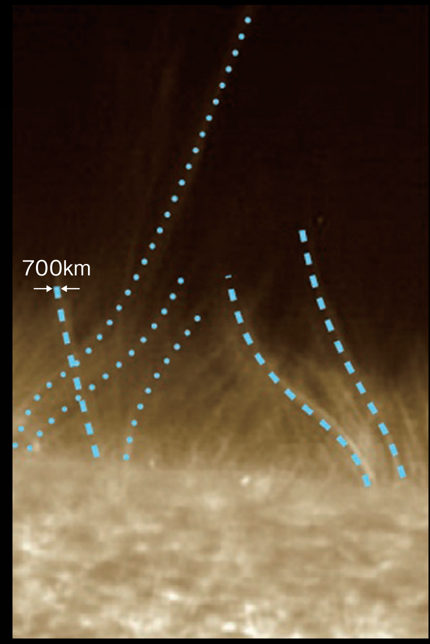
As indicated above, determining the three-dimensional structure of the solar magnetic field from the photosphere to the corona will be necessary for clarifying the many different phenomena associated with those magnetic fields; and this itself is an extremely important science challenge for **SOLAR-C**. **SUVIT** will resolve the magnetic elements in the photosphere (believed to be around 100 km), and for the first time ever will directly observe the chromospheric magnetic field from space. By observing the magnetic fields in the magnetically-dominated upper chromosphere (plasma β<1), it will also be possible to infer the coronal magnetic field, using the chromospheric observations as a boundary condition. Using the three-dimensional magnetic field structure information, it will be possible to advance our understanding of the role of magnetic reconnection and magnetohydrodynamic (MHD) waves in phenomena such as heating of the chromosphere and corona, acceleration of the solar wind, and the triggering mechanism of solar flares. ***Hinode*** found that magnetic fields on a small scale of a few hundred km or less appear all over the sun's surface with surface convective motions, and their total magnetic flux is greater than that of sunspots. A challenge for **SOLAR-C** is to find out how the occurrence of these ubiquitous small-scale and transitory magnetic fields affects the formation and evolution of the overall three-dimensional photospheric-chromospheric-coronal magnetic fields.



The three-dimensional structure of the solar magnetic field. The green lines are magnetic field lines extrapolated from the photospheric magnetic field. In the upper chromosphere, fine dark filamentary structures can be seen following the magnetic field lines.

Science question 2: Can we understand the chromosphere, corona, and solar wind by MHD waves?

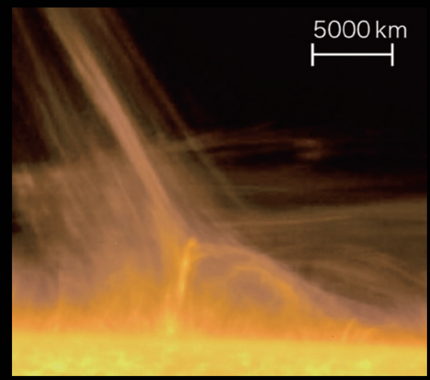
From ***Hinode*** results, we know that MHD waves are constantly being generated through the shuffling and twisting of magnetic flux tubes by convective motions in the photosphere. A theory attracting attention today is that this wave motion, as it propagates outward while being reflected and refracted in the chromosphere and chromosphere-corona transition zone, causes the heating of the corona and acceleration of the solar wind. Needle-like spicules (figure on the right) extending from the chromosphere to the corona are thought to supply mass to the corona, while wave motion is believed to play an important role in the creation of dynamic phenomena such as these spicules. It has further been suggested that dynamic phenomena in the chromosphere observed by ***Hinode*** (cover photo) may be responsible for generating strong waves that propagate into the corona. One of the important science objectives of **SOLAR-C** will be to clarify the nature of these waves from the photosphere and chromosphere, and determine whether they are responsible for coronal heating and solar wind acceleration. **SUVIT** and **EUVS/LEMUR** on **SOLAR-C** will for the first time identify waves from observations of small fluctuations in chromospheric magnetic fields. By observing the photosphere and chromosphere, as well as the MHD waves of the corona, it should be possible to estimate the wave energy flux at each layer and gain an understanding of the amount energy in, and the mechanism of energy dissipation in, the chromosphere and corona.

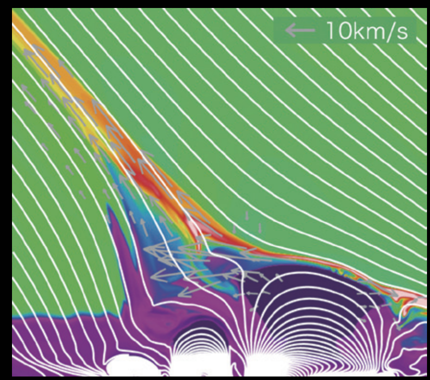


Right figure: Spicules extending from the chromosphere to the corona at the limb of the sun (as observed from ***Hinode***)

Science question 3: Understanding magnetic reconnection on the sun and its role to chromospheric and coronal heating

In the sun, phenomena such as solar flares, jets (cover photo) in the chromosphere and corona, and other eruptive activities occur over broad spatial and temporal scales. The results of observations from ***Yohkoh*** and ***Hinode*** show that these phenomena are strongly connected to magnetic reconnection. Magnetic reconnection is a phenomenon in which nearly-antiparallel magnetic field lines interact and reconfigure, quickly releasing magnetic energy, and accelerating and heating plasma. Jets caused by magnetic reconnection might supply mass from the lower to the upper solar atmosphere. Moreover, the sudden deformation of magnetic structures in the magnetic reconnection process generates MHD waves, and it is possible that these waves heat the corona. Another plausible theory is that numerous tiny flares are what heat the solar corona. An understanding of magnetic reconnection itself, including the role of shock waves involved with magnetic reconnection, is essential to clarifying these phenomena. There is however a lack of observational data regarding the temperatures, velocities, and magnetic fields in the areas around the occurrence of magnetic reconnection. Up to now it has been difficult to obtain such data since the plasma immediately after acceleration and heating by magnetic reconnection is fainter than the background plasma, and because the properties of the region around the reconnection undergo rapid changes. High-resolution spectroscopic imaging observations over a broad wavelength range by **EUVS/LEMUR** and **XIT** on board **SOLAR-C** will make it possible for the first time to make seamless observations across the solar atmosphere, at various temperatures, of reconnection-induced plasma flows, MHD waves, and shock waves. It also may even be possible to directly observe changes accompanying reconnection in upper-chromospheric (plasma β<1) magnetic structures.





Top: Chromospheric jets at the limb of the sun (as observed from ***Hinode***).
Bottom: Jets occurring due to magnetic reconnection (MHD simulation).

SOLAR-C's Three Large Telescopes: From imaging to spectroscopic observation

On solar-observing satellite missions up to now, imaging observations were highly beneficial for quickly obtaining a wide range of information. There are limits, however, to the physical information that can be gained from imaging observations alone. In order to probe into the physical processes responsible for various solar phenomena, it is important to obtain highly precise spectroscopic measurements of the light emitted by the solar atmosphere. Such observations will allow us to obtain basic physical information, such as temperature, velocity, and magnetic energy, of plasma composing the solar atmosphere.

SOLAR-C is equipped with three telescopes, each sensitive to a different wavelength regime, for seamlessly observing the entire range of temperatures in the solar atmosphere, from the photosphere to the corona.

Solar UV-Visible-IR Telescope (SUVIT)
for measuring magnetic fields in the chromosphere and photosphere

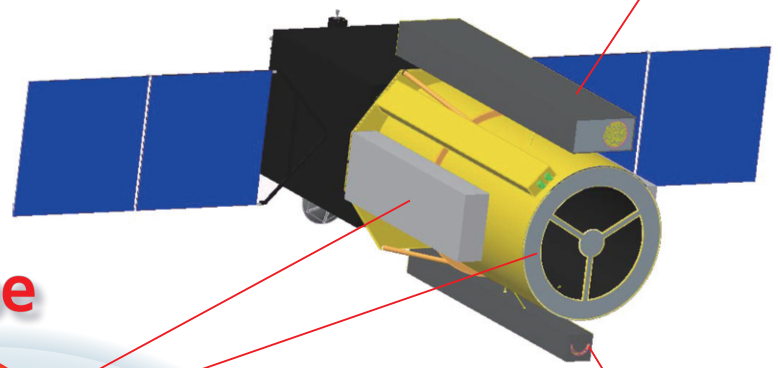
EUV/FUV High Throughput Spectroscopic Telescope (EUVS/LEMUR)
for high-resolution spectroscopic observations of the chromosphere and corona

X-ray Imaging Telescope (XIT)
for spectroscopic imaging observations of high-temperature plasma in the corona and solar flares

Spacecraft system supporting the observation instruments

The spacecraft system must be able to accomplish the following:

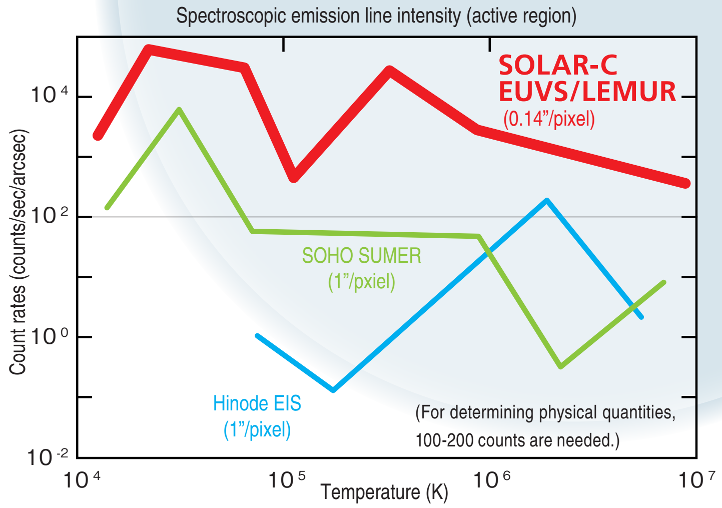
- Flexibility similar to that of ground-based telescopes to rapidly modify observation targets and programs in response to changes in solar activity.
- Continuous observations 24 hours a day, with no satellite-night interruptions.
- Ability to accurately align images taken with different instruments.
- Obtain and transmit 20 times more data than *Hinode*.



EUVS/LEMUR

EUV/FUV High Throughput Spectroscopic Telescope

Spatial resolution	0.28″
Temporal resolution	<10 seconds (0.28″ sampling)
	<1 second (1″ sampling)
Field of view	280″ x 300″
Velocity resolution	2 km/s or less
Observed wavelengths	17-21 nm, 46 - 128 nm



By performing spectral analysis of emission lines, the **EUVS/LEMUR** telescope will measure the velocity, temperature, and density of solar plasmas. It will need more than 5 times the spatial resolution and 10 times the throughput* of the currently operational ultraviolet spectrometers. It must be able to observe over a wide wavelength range (17 to 128nm) in the ultraviolet, seamlessly across the sharp-temperature-change transition region from the chromosphere (around 10,000 degrees) to the corona (5 million degrees). It will have high throughput performance, enabling spectroscopic observations with short exposure times of around 1 second, so that it can reliably capture the rapid temporal fluctuations of magnetic structures and waves resulting from magnetic reconnection, jets, and photospheric motions.

Up to now the spatial resolution of coronal observations has been only a fraction of that of complementary photospheric observations. **SOLAR-C** will to the extent possible employ the similar spatial resolution from the photosphere to the corona, enabling it to obtain decisive information as to where and how heating takes place in the magnetic field structures observed by **SUVIT**.

*When using observation modes optimized for spatial and temporal resolutions, respectively.

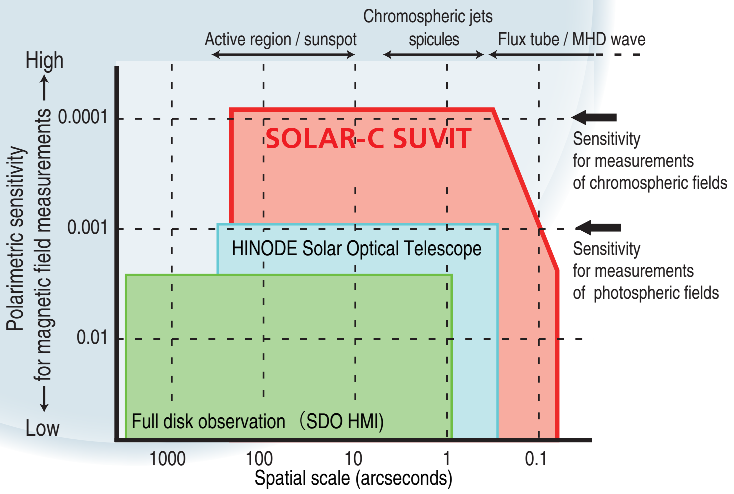
SUVIT

Solar UV-Visible-IR Telescope

SUVIT will take the first ever space-based measurements of chromospheric magnetic fields; up to now chromospheric magnetic field measurements have proved extremely difficult. ***Hinode*** was able to achieve the major accomplishment of mapping photospheric magnetic fields with high accuracy, by using the Zeeman effect. **SUVIT** in addition to the Zeeman effect will use the Hanle effect to measure magnetic fields in the chromosphere, which are weaker than those of the photosphere. The polarization of the chromosphere due to the Hanle effect is very weak, being only about one-tenth the intensity of the photospheric polarization. Since the strength of the polarization signal from a point-like magnetic flux-tube element varies in proportion to the square of the observing-telescope's aperture diameter, a telescope with an aperture of roughly 1.5m, three times that of ***Hinode***, is necessary. Such a large telescope can achieve high resolution of 0.1 to 0.2 arcseconds, by which high-precision magnetic field measurements of the photosphere and chromosphere can be carried out.

Obtaining accurate magnetic field measurements of the chromosphere will make it possible to calculate magnetic fields of the corona, and from this together with the photospheric data we can then expect to derive the three-dimensional solar magnetic field structure from the photosphere to the corona. This should in turn bring us closer to an understanding of magnetic reconnection and wave phenomena that are keys to heating and dynamics of the chromosphere and corona. To achieve these goals, not only high spatial resolution but also seamless observations over a wide field of view and long time span are essential. These requirements can be met only by observations from space.

Spatial resolution	0.1″ - 0.2″
Temporal resolution	0.1 - 1s (imaging)
	1 - 20s (spectropolarimetry)
Field of view	180″ x 180″
Observed wavelengths	280 - 1100 nm



XIT

X-ray Imaging Telescope

	XIT-PC	XIT-NI
Spatial resolution	1″ - 2″	0.2″ - 0.3″
Temporal resolution	10s	<10s
Field of view	80″ x 400″	400″ x 400″
Observed wavelengths	0.5 - 5 keV	9 - 21 nm

Photon Counting Imaging Spectroscopy Soft X-ray Telescope (XIT-PC):

Combining grazing incidence optics with a photon-counting CMOS detector, the telescope will perform the world's first X-ray imaging spectroscopic observations of the solar corona and flares. Boasting the highest spatial resolution to date of a grazing incidence optical system, it will be able to obtain an overview of coronal structures and features across various temperatures. With the ability to obtain an X-ray spectrum for each pixel, it will be able to observe the behavior of plasmas after heating but before reaching thermal equilibrium, leading to breakthroughs in research on coronal heating, flares, and shock waves accompanying magnetic reconnection.

Ultra High Spatial Resolution Normal Incidence EUV Telescope (XIT-NI):

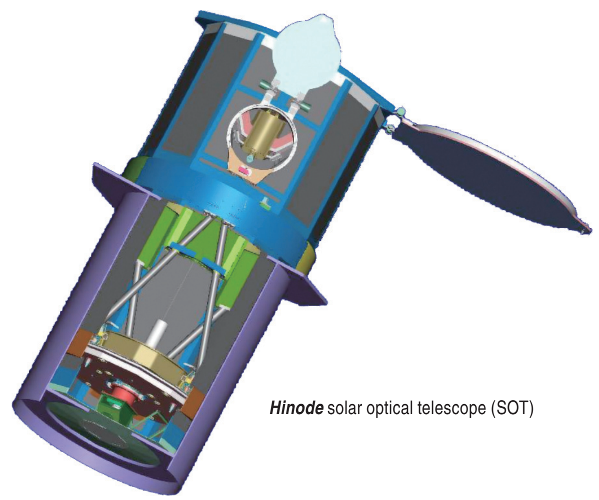
This multilayer X-ray telescope will perform large-field-of-view, high-time-resolution direct imaging of the corona at an unprecedentedly high spatial resolution of 0.2 to 0.3 arcseconds. It will provide high-quality image information to complement the detailed spectroscopic information from **EUVS/LEMUR**. In addition, in combination with the photospheric and chromospheric magnetic field observations from **SUVIT**, it will shed light on the mechanisms of coronal heating and solar wind acceleration.

Advances in Technologies for High-Resolution Space Observations in SOLAR-C

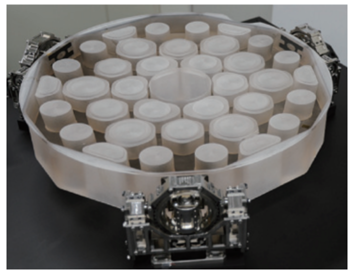
The space telescope technologies developed for the ***Hinode*** satellite, launched in 2006, are to be further advanced with **SOLAR-C**, notably in the area of high-resolution satellite-based observations as well as in leading-edge technologies of the spacecraft system for high-resolution observations.

Space telescope achieving diffraction-limited resolution

The **SUVIT** telescope to be carried by **SOLAR-C** will be designed with an aperture nearly 3 times larger than that of the solar optical telescope (SOT) on ***Hinode*** while being only about twice as long. This compact design requires tight positional tolerance on its optical components. The techniques resulting from development of the optical telescope on ***Hinode***, including high-precision telescope structural and thermal design, assembly and alignment, and optical interferometry techniques, will be applied and advanced further. The main structure of the ***Hinode*** solar optical telescope used ultra-low-thermal-expansion carbon fiber reinforced plastic (CFRP), with a thermal expansion ratio of 0.1ppm or less, to achieve diffraction-limited performance for a 50cm aperture with no adjustment mechanism in orbit. The heritage of the precision telescope structure developed in ***Hinode*** will be applied to a 1.5m-class aperture telescope for **SOLAR-C**. Development is also being carried out in Japan of a high-precision, long-life movement mechanism for space use, which is necessary for the focal plane instrument.

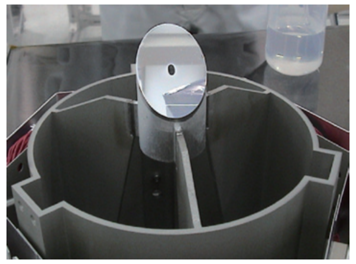


Hinode solar optical telescope (SOT)

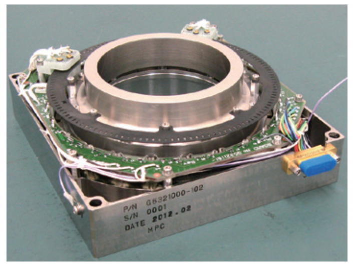


The 50cm-aperture lightweight ULE-glass primary mirror and 3-point static support mechanism used in the ***Hinode*** solar optical telescope. **SOLAR-C** will have a nearly 90% light-weighted mirror with a stress-free support mechanism.

Wavefront error distribution of the ***Hinode*** solar optical telescope. Wavefront error of 18nm (RMS) was achieved. High-precision interferometry with an error of 5nm (RMS) enabled to eliminate alignment errors of optical components so that the telescope delivered the diffraction-limited performance at visible wavelengths.



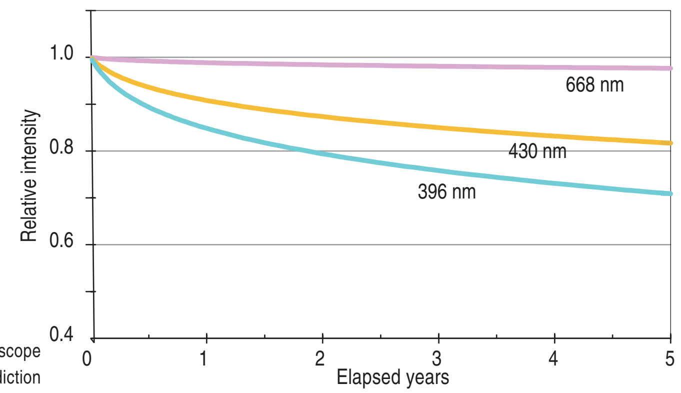
Heat dump mirror at the primary focus of the ***Hinode*** optical telescope. By applying a silver reflective coating to an aluminum mirror, a solar light absorption ratio of around 5% was achieved. By means of coating durability tests and contamination control of the mirror surface, the heat dump mirror maintains a temperature of 50°C or below even when subjected to a light concentration 1500 times that of the sun.



A rotational drive mechanism is being developed in Japan, which is a key technology for development of the focal plane instrument. The prototype is a thin large-aperture-bearing drive mechanism, and can be used as a continuously-rotating waveplate needed for a high-precision polarimetry.

Contamination control for the space optics and its mathematical modeling

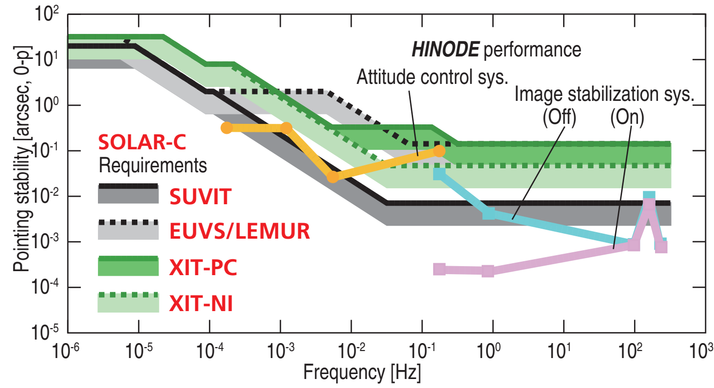
The lifetime of a space solar telescope is largely influenced by degradation in reflectivity due to contamination on the mirror surface and its blackening by ultraviolet radiation, as well as resulting mirror thermal deformation. For the ***Hinode*** optical telescope, the materials used in the telescope structure and adhesives were selected based on outgas measurements, and were subjected to baking based on a mathematical model for contamination prediction, under the careful contamination control. Since the **SUVIT** telescope aboard **SOLAR-C** will observe in the ultraviolet range, it will require even more stringent contamination control than did in ***Hinode***.



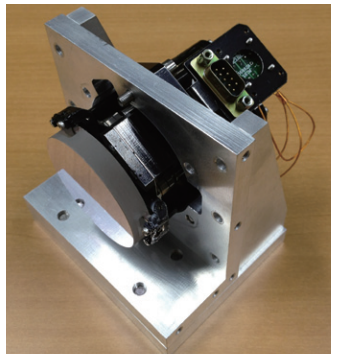
Simulated sensitivity deterioration of ***Hinode*** solar optical telescope based on a mathematical model for contamination prediction

High pointing stability essential to high-resolution observations

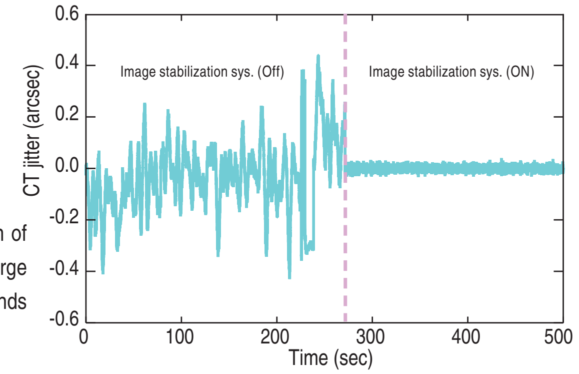
To achieve high-resolution imaging observations and high-precision polarimetry with ***Hinode***, a satellite attitude control system with high pointing stability was developed, as well as an image stabilization system using a tip-tilt mirror to eliminate jitter that could not be suppressed by the attitude control system alone. In addition, a technique was introduced for controlling micro-vibrations in the high-frequency range. To maintain co-alignment among different telescopes, an optical bench with a low thermal expansion was developed for mounting the components. As a result, the highest pointing stability in Japanese space missions was achieved over a wide frequency range. In order to achieve the high resolution and polarimetry precision desired for **SOLAR-C**, its pointing stability will have to be two to three times better than that of ***Hinode***. For further reducing high-frequency micro-vibrations, techniques are being introduced to reduce the transmission of vibrations as well as to broaden the bandwidth of the image stabilization system.



The pointing stability achieved with ***Hinode*** and that required in **SOLAR-C**. **SOLAR-C** will need to have pointing stability two to three times better than ***Hinode***. The keys are improving performance of the satellite attitude control system in the mid-frequency range, and also reducing micro-vibrations in the high-frequency range.



Tip-tilt mirror employed in the image stabilization system of the ***Hinode*** solar optical telescope. It tracks features on the sun's surface by driving three piezoelectric actuators of the tip-tilt mirror.

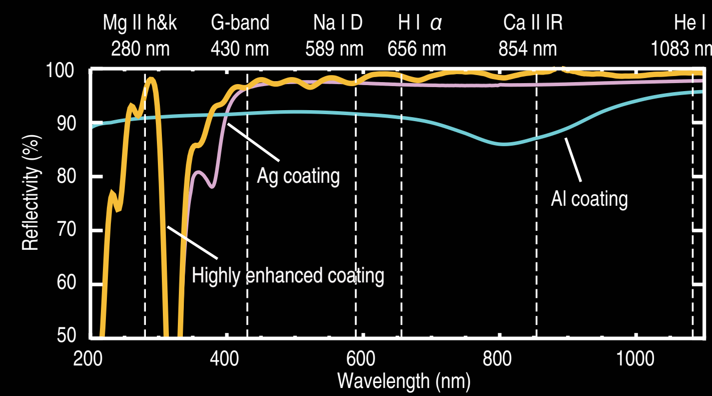


On-orbit performance of the image stabilization system of the ***Hinode*** solar optical telescope. Pointing jitters as large as 0.2 arcseconds are reduced to as low as 0.03 arcseconds (3σ) by operating the image stabilization system.

Leading-edge technologies to be newly developed

Grazing incidence X-ray mirror using nanotechnology

The aimed-for resolution of the X-ray telescope for **SOLAR-C** is 1 arcsecond or better at X-ray wavelengths of 0.5 - 10keV. This will necessitate development of a grazing incidence X-ray mirror with high surface accuracy. It is becoming feasible to manufacture a high-precision grazing incidence X-ray mirror in Japan by applying nanotechnology measurement techniques. The X-ray focal plane is scanned with a nanometer-precision knife edge or cube, and the light diffracted from it is measured. In this way, a point spread function can be measured precisely. The results are used to estimate the surface figuring error, which is fed back into processing of the mirror surface to achieve an X-ray mirror of the required precision.



Mirror coating with highly enhanced reflectivity

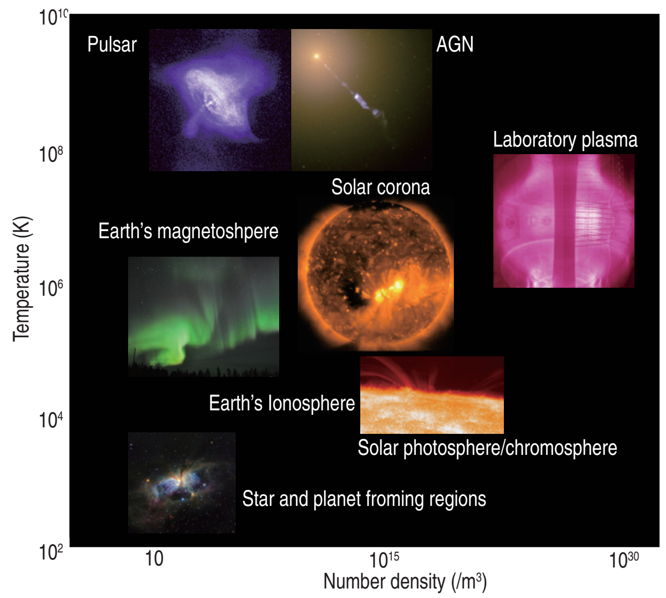
For achieving high optical performance in a solar telescope, the mirror coating must have a low solar light absorption to ward off heat from unwanted sunlight and to prevent thermal deformation, along with a high throughput enabling high-sensitivity polarimetry. Since the ***Hinode*** optical telescope carried out observations only in the visible wavelength range, a silver coating was used, which required fewer development steps. For **SUVIT**, a highly enhanced coating is being developed beyond the ***Hinode*** heritage, aiming at achieving a reflectivity of greater than 90% across a wide wavelength range from ultraviolet to near infrared, and a solar light absorption of 3% or less.

The Breadth of SOLAR-C Science

The sun as a plasma laboratory

The biggest scientific result from the ***Yohkoh*** mission was demonstrating that solar flares occur because of magnetic reconnection. Now that it has been established that magnetic reconnection is an essential process in magnetic plasma dissipation and energy conversion, it has today become an indispensable concept for understanding a wide range of phenomena in astronomy, geophysics, and plasma physics. The transient horizontal magnetic fields observed for the first time by ***Hinode*** indicate that the local dynamo processes driven by convective motions generate more magnetic energy flux than that appearing in sunspots alone. For astrophysics, this represents an important discovery of elementary processes concerning magnetic field creation. In addition Alfvén waves, whose existence had been postulated earlier, were observed for the first time. Alfvén waves are efficient carriers of energy in space, and their possible relation to the solar wind acceleration mechanism is being studied. In such ways the sun plays the role of a laboratory for investigating the behavior of space plasmas.

SOLAR-C, by making accurate measurements of physical quantities of solar plasmas from the photosphere to the corona, such as magnetic fields, velocity, and temperature, will address unresolved issues in solar physics. From comparative studies with plasmas of other astronomical objects, in the geomagnetosphere, and in laboratories on earth, we will find universal properties of plasmas and magnetic fields that exist throughout space.



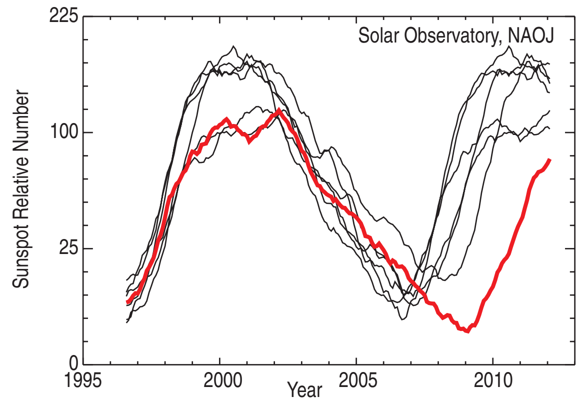
Solar-terrestrial environment and space weather forecasting

Devising algorithms for space weather forecasting

Space weather forecasting attempts to predict in advance short-term changes in the space environment, such as solar flares and associated Coronal Mass Ejections, with accompanying energetic particles contributing to auroras and geomagnetic storms. Predicting space weather requires both an understanding of the physical processes and the devising of forecasting algorithms based on computer simulations using data observed on the sun's surface as input. One role of **SOLAR-C** will be to contribute to the development of flare forecasting algorithms. Because of the extreme difficulty of directly observing magnetic fields in the corona where flares occur, simulations have been carried out using surface (photospheric) magnetic field observation data as boundary conditions. **SOLAR-C** will observe magnetic fields of the chromosphere, near the corona. The accuracy of simulations based on the resulting data will be improved greatly. This should make it possible to achieve space weather forecasting extending to the occurrence of flares themselves, which up to now has been elusive.

SOLAR-C to clarify abnormalities in solar activity

The sun goes through repeated activity cycles of 11 years, but several times in the past it has entered quiet periods during which sunspots vanished for years or even decades. Such cessations in solar activity may affect the earth's weather, as seen in quiet periods since 1600 known as the Maunder Minimum and the Dalton Minimum, when the earth did in fact cool off. During the period from around 2007 to 2009, solar activity declined and the solar cycle was 12.6 years, which was longer than usual cycle. The last time the solar cycle became longer was around 1800 right before the Dalton Minimum, more than two centuries ago. The number of sunspots is an important index for tracking solar activity; but for understanding the mechanism by which that activity declines it is necessary to obtain an overall grasp of the changes in magnetic fields across the entire sun, including sunspots, polar regions, and quiet regions. By observing changes in the fine surface magnetic fields that may cause global changes in the sun's overall magnetic atmosphere, **SOLAR-C** will monitor whether any long-term decline in solar activity occurs and help determine how abnormalities in solar activity patterns affect the earth's climate.



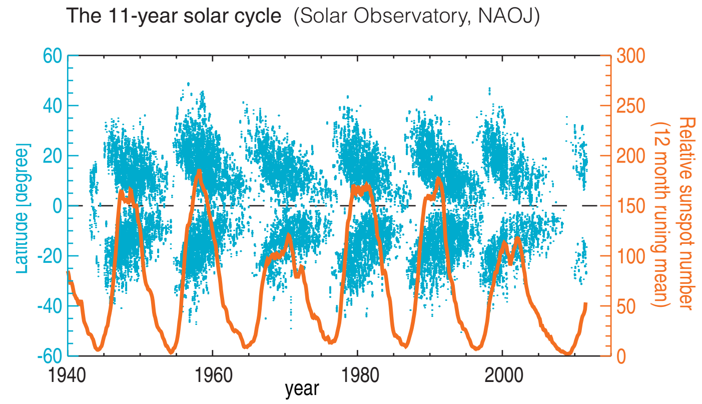
Changes in sunspot numbers in the most recent cycle (red line) and in the past six cycles (black lines). The current cycle of 12.6 years is longer than the usual 11-year cycle; moreover, the next solar maximum period, which should arrive in the latter half of 2013, is expected to be weak.

From SOLAR-C to SOLAR-D

Exploring the hitherto-unexplored sun's polar regions

Explaining solar dynamo processes

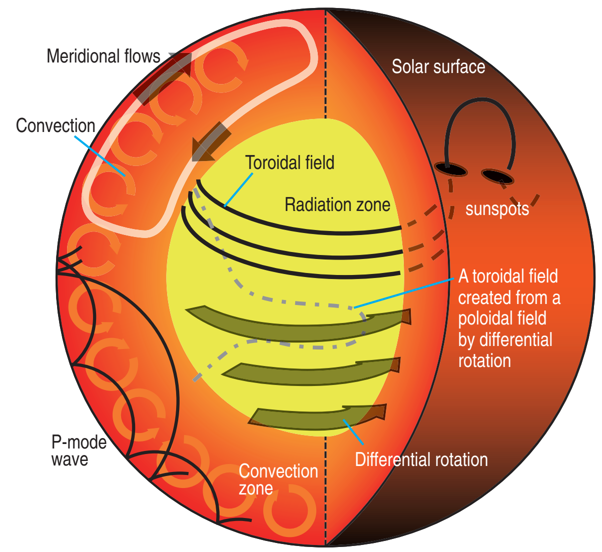
For **SOLAR-C** the most important target is gaining an overall picture of the various magnetic activities seen in the solar atmosphere. **SOLAR-D** will take up the challenge of understanding the "dynamo processes" by which the magnetic atmosphere is formed. A notable example of a global dynamo process is the 11-year solar cycle. The greatest mystery of solar physics is why the number of sunspots, activity, and polarity of the sun go through 11-year fluctuations. Following up on ***Hinode***, **SOLAR-C** will be able to obtain information about surface magnetic fields and surface velocity fields in the sun's polar regions. **SOLAR-D** will add knowledge about rotation and flows in the solar interior, where dynamo processes take place.



Why explore the sun's polar regions?

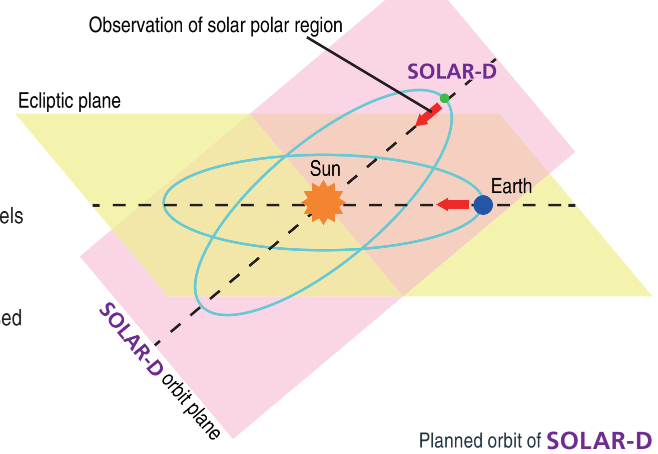
The key to understanding global dynamo processes is the dynamic coupling between magnetic fields and overall flows in the solar interior, such as differential rotation and meridional circulation. In particular, since it is believed that the magnetic fields in the polar regions are the seeds of the next solar cycle, knowing the relation between changes in high-latitude magnetic fields and flows inside the sun is essential to learning the mechanism giving birth to the magnetic fields of the next cycle. Since the interior of the sun cannot be viewed directly, the only means of diagnosing what is going on inside the sun is solar seismology, known as helioseismology, using Doppler observations of oscillations on the solar surface. In the ecliptic plane observations carried out up to now, however, the solar polar regions could not be observed clearly, making it impossible to learn about the flow inside the sun at its poles. To solve this problem **SOLAR-D** will observe the solar surface magnetic fields and Doppler velocity fields from places outside the ecliptic plane (maximum orbit inclination of ≤40°). By simultaneously observing changes in and movements of the overall flows and magnetic fields across the entire sun including polar regions, the mission will attempt to find out the origin of the solar magnetic activity cycle.

Illustration of solar interior



Proposed payload:

- **Visible light imager for observing full-sun magnetic fields and Doppler velocity**
  Using helioseismology, will infer flows inside the sun, and will measure photospheric magnetic fields.
- **Total irradiance monitor**
  Will measure the latitudinal dependence of the solar irradiance, and try to determine why its variation is only around a third that of other solar-type stars having similar levels of magnetic activity.
- **X-ray/EUV imaging and spectroscopic telescopes**
  Will try to determine the three-dimensional structure of the polar solar wind, etc., based on differences in appearance from different orbit inclinations.
- **Optional equipment (interplanetary imager, in-situ instruments, etc.)**



Planned orbit of **SOLAR-D**