Chapter 21
From *Hinode* to the Next-Generation Solar Observation Missions

Kiyoshi Ichimoto, Hirohisa Hara, Yukio Katsukawa, and Ryoko Ishikawa

Abstract Ten years of *Hinode* operation have indicated the direction of the new challenges in solar physics. The task of the next solar observation missions is to determine the three-dimensional (3D) structure of magnetic fields that connect the photosphere and the corona by resolving the elementary magnetic structures in the solar atmosphere. SOLAR-C is the long-awaited next-generation international solar physics satellite that will observe the magnetic field of the chromosphere and the plasma dynamics from the photosphere to the corona with much higher spatial and temporal resolutions than *Hinode*. To this end, the Japanese solar physics community is promoting a sounding rocket experiment, the Chromospheric Lyman-Alpha SpectroPolarimeter, and a balloon experiment, SUNRISE-3, to pave the way for measuring the chromospheric magnetic fields with spectropolarimetry in the ultraviolet and infrared, respectively. Additionally the algorithm for determining the 3D magnetic field from spectropolarimetric data is investigated using a newly developed multi-wavelength spectropolarimeter at the Hida observatory. Solar telescopes with 4 m aperture are expected to begin operating in Hawaii and the Canary islands in the 2020s and introduce a new approach to uncovering fine-scale structures with the highest-ever spatial resolution. The continuous and high-precision observation by SOLAR-C, which has large spatial and temporal coverage, will contribute indispensable information for understanding the fundamental plasma process occurring in the Sun and in the Universe and for establishing the foundation for the next-generation space weather prediction.

Keywords Solar observation · Space mission · Future plan

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21.1 Introduction

As discussed in this volume, *Hinode* has achieved a significant progress in solar physics. It has been revealed that the solar atmosphere is governed by fundamental plasma processes such as magneto-convection, magnetic reconnection, magnetohydrodynamic waves, turbulence, and energy dissipation. The hot and dynamic solar atmosphere sustains occasional large-scale destabilizations and explosive energy releases, which are generated through a chain of such fundamental processes. Additionally, the high-quality images of *Hinode* have demonstrated that the chromosphere, an interface region between the photosphere and the corona, is extremely dynamic much more than previously thought and of crucial importance for understanding the origin of the active solar atmosphere. How the hot and dynamic solar atmosphere is formed; how flares, prominence explosions, and violent disturbances of solar wind are generated; and how the solar magnetic fields are maintained and modulated are still major questions in solar physics that must be answered. As a star that provides the magnetized plasma models that apply ubiquitously in the Universe, a huge-scale plasma laboratory that can never been realized on the ground, and the boundary condition that governs the space environment of the earth, the Sun is becoming recognized as an important research object in relation to research fields such as astronomy, plasma physics, and heliophysics. In this manuscript, we will discuss the future direction of solar research by focusing on future and ongoing projects undertaken by the Japanese solar physics community.

21.2 The SOLAR-C Project

Hinode has revealed the vigorous chromospheric activity (Okamoto 2016; Katsukawa 2016) and the plasma dynamics in the corona (Hara 2016) from space (see the other articles in this volume for details on the scientific achievements of *Hinode*). Although simultaneous observations from the photosphere to the corona have been achieved by *Hinode*, the physical processes producing these dynamic phenomena are still enigmas due to the lack of key observations that we have identified after *Hinode*. To further understand the physical processes that cause these activities, new observations with largely improved precision and spatial resolution are necessary. They are (1) the magnetic field observation in the chromosphere, which requires a higher precision polarimetry, for understanding the origin of the small-scale dynamics and (2) high-resolution observations of the corona that enable seamless coverage of the entire atmosphere for directly connecting the photospheric magnetic structure to the coronal structures. The SOLAR-C mission has been proposed to realize these key observations.

The following are the SOLAR-C science objectives, which include the major solar physics problems:

I. Investigate the formation mechanisms of the chromosphere, the corona, and the solar wind
II. Understand the physical origin of large-scale solar eruptions to build an algorithm for their prediction
III. Elucidate the origin of the solar activity cycle

Each science objective contains the following science topics: plasma heating and acceleration processes of plasmas (Topic I), destabilization of global magnetic structures and fast magnetic reconnection processes with the small-scale internal structure (Topic II), and regeneration of magnetic fields and magnetic flux transport in the Sun (Topic III). Through the study of these science topics, the scope of the mission includes a viewpoint that contributes to the understanding and prediction of the influence of the solar activity on the Earth and the human society.

The SOLAR-C spacecraft, shown in Fig. 21.1, consists of three major payloads: the Solar Ultraviolet(UV)-Visible-IR Telescope (SUVIT) for observing the velocity and magnetic fields in the photosphere and chromosphere in addition to the imaging observations; the High-Resolution Coronal Imager (HCI), with a spatial resolution improved by an order of magnitude compared to that of all instruments ever flown; and the Extreme UltraViolet Spectroscopic Telescope (EUVST) for spectroscopy of the chromosphere through the corona, with a similar spatial resolution to that of HCI. The candidate spacecraft orbit is the geosynchronous orbit to avoid the

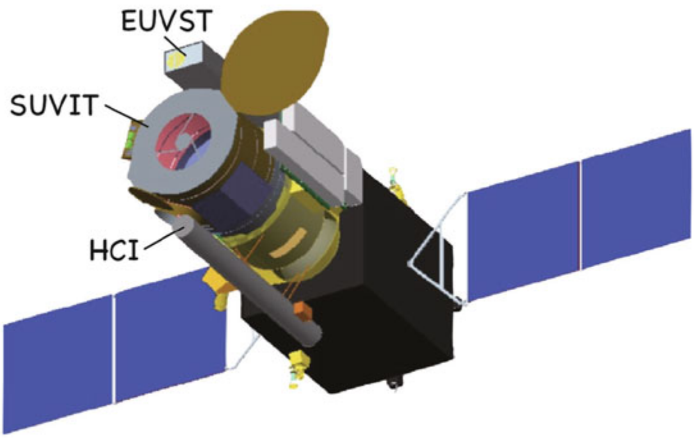

Fig. 21.1 Schematic view of the SOLAR-C spacecraft. The spacecraft is equipped with the 1 m-diameter optical telescope SUVIT at the center, the high-resolution spectrograph EUVST on one side, and the high-resolution imager HCI on the other side

eclipse due to the shadow of the Earth and to minimize the thermal distortion by the infrared (IR) radiation from the Earth. The SOLAR-C magnetic field observations are characterized by a spatial resolution of 0.1 arcsec to resolve the elemental magnetic field structure that we have inferred from the *Hinode* observations and a field of view of a few arcmin to cover entire sunspot regions, coronal loops, and flare structures. This superb targeted performance, which connects small-scale dynamics with the formation of large-scale structures and destabilization, makes SOLAR-C observations exceptionally unique.

SOLAR-C is a proposed Japanese-led mission that assumes international collaboration with the USA and European countries, and the mission proposal has been prepared for a target launch date in the 2020s. The task of aligning the step of the major space agencies for the first SOLAR-C proposal was not easy. A new approach, a working group activity whose committee members are selected by the major space agencies in the world, has started to realize the next-generation solar physics mission.

21.3 Small-Size Space Missions

The *Hinode* observations of the dynamic chromosphere were followed by spectroscopy of the chromospheric lines with the *Interface Region Imaging Spectrograph (IRIS)* which started measurements in 2013. *IRIS* is one of the small exploration (SMEX) NASA programs. Although the *IRIS* spacecraft is much smaller than *Hinode*, it has achieved significant progress in our understanding of chromospheric dynamics owing to its unique capability of performing high-resolution spectroscopic observation of UV emission lines. The success of *IRIS* suggests that new observations following *Hinode* strongly require the development of unique observational technologies. In parallel with a large-scale spacecraft mission like SOLAR-C, which requires a long realization period, it is important to acquire new technologies for the next mission through development of small-size space experiments, such as sounding rockets and balloon experiments.

21.3.1 Sounding Rocket Experiment, CLASP

As discussed in Sect. 21.2, the frontier of solar physics is the direct measurement of the magnetic fields in the upper atmosphere, where the magnetic forces dominate over the gas pressure. In the UV range that has to be observed from space, there are abundant spectral lines that are emitted from plasma of 10^4–10^5 K and allow us to access the chromosphere and the transition region. The magnetic field information in these upper atmospheric layers is embedded in these spectral lines, whose polarization signals have only been explored before in a few pioneering experiments

(Stenflo 1980; Henze and Stenflo 1987). One line of particular interests is the hydrogen Lyman-α line at 121.57 nm, which is the brightest in the vacuum-UV range and is expected to show a measurable scattering polarization sensitive to the Hanle effect (see next paragraph and Trujillo Bueno et al. 2011). To verify the utility of this spectral line, an international team consisting of Japan, the USA, Spain, France, and Norway started a sounding rocket project called the Chromospheric Lyman-Alpha SpectroPolarimeter (CLASP) in 2008 (2 years after the launch of *Hinode*).

One of the physical mechanism that produce the polarization in this spectral line is the Zeeman effect, which has been widely used for many years to characterize the magnetic field mainly in the photosphere. Indeed, *Hinode*/SOT reveals the new features of the photospheric magnetic fields by measuring the Zeeman effect with unprecedentedly high spatial resolution and high-precision spectropolarimetry. However, in many cases, the polarization signals induced by the Zeeman effect in spectral lines that originate from the upper atmospheric layers are too small to be detected because these spectral lines are broad and the magnetic field strength there is low.

The Hanle effect is expected to be an alternative diagnostic tool because it results in polarization signals that are not canceled out by Doppler broadening, and it is generally sensitive to weaker magnetic fields than the Zeeman effect. The Hanle effect is the physical mechanism with which the magnetic field modifies the polarization state that is induced by absorbing and scattering the anisotropic radiation. One application of the Hanle effect as a diagnostic tool of the chromospheric magnetic field is the spectropolarimetry of the He I triplet at 1083.0 nm with the ground-based telescopes. This spectral line is easily modeled, and the user-friendly inversion code HAZEL (HAnle and ZEeman Light) (Asensio Ramos et al. 2008), which assumes a constant-property slab located at a given height, is available to interpret the spectropolarimetric data. Thus, this spectral line is one of the candidate to be observed by SOLAR-C/SUVIT. However, the formation of this spectral line in the quiet region (especially in the internetwork region) is difficult, and there are limited quiet Sun observations in the He I triplet.

The Hanle effect in UV spectral lines could enable magnetic field measurements in the quiet Sun region, and it is anticipated to realize UV spectropolarimetry. However, precise spectropolarimetry in the UV range has never been successful, and the CLASP team must initiate the development of optical elements necessary for the UV spectropolarimetry. In addition, the core team members from Japan who led the design and integration of the instrument were Ph.D. students and young scientists who had never experienced the instrumentation. They were supervised by the senior scientists who developed the *Hinode* satellite, and started from the evaluation of the polarization elements at a synchrotron facility (Watanabe et al. 2011; Ishikawa et al. 2013, 2014, 2015; Narukage et al. 2015, 2017). Seven years later, the development of a flight model with diameter 27 cm and length 2.5 m was completed by the international collaboration (right panel of Fig. 21.2) (Giono et al. 2016a,b). CLASP was launched on September 3, 2015, from the White Sands Missile Range in the

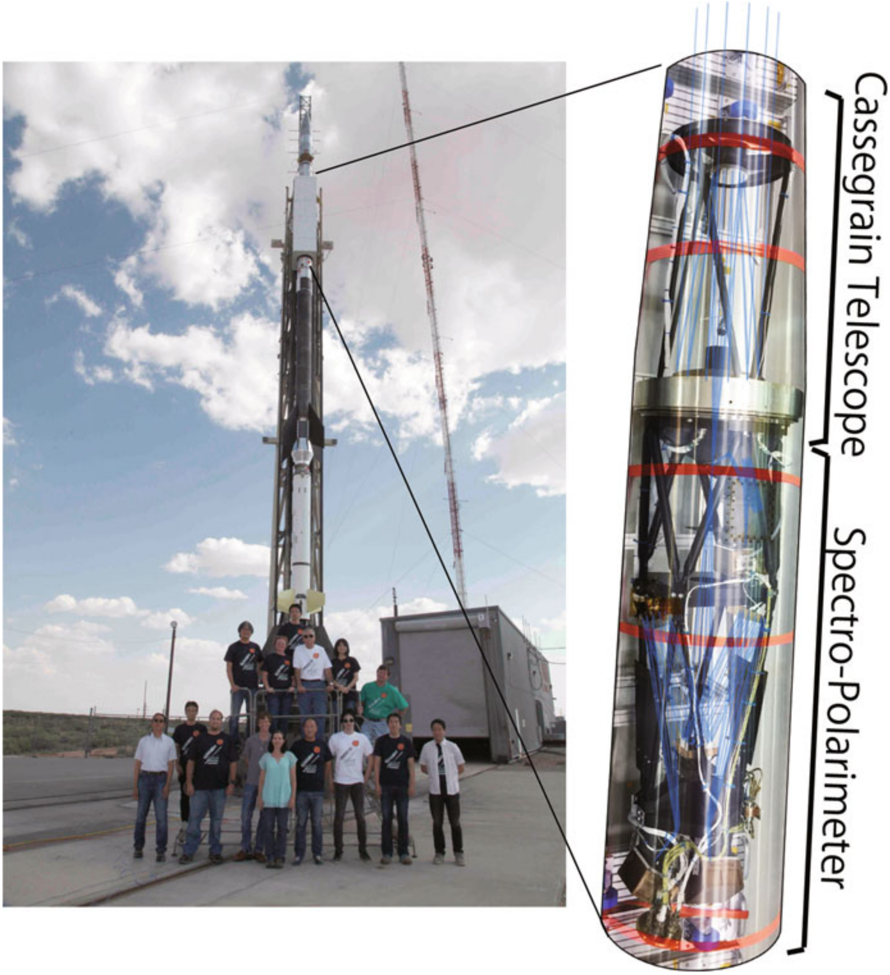

Fig. 21.2 Left: team photo in front of CLASP. Right: flight model of CLASP instrument developed at NAOJ (National Astronomical Observatory of Japan) (Courtesy of the CLASP team)

USA and achieved high-precision (<0.1%) UV spectropolarimetry for the first time (Giono et al. 2017; Kano et al. 2017). After the launch, the payload was recovered without any damage.

CLASP observations confirmed for the first time the presence of scattering polarization in the Lyman-α line (Kano et al. 2017). The Lyman-α wings, which are insensitive to the Hanle effect, show scattering polarization perpendicular to the solar limb with a clear center-to-limb variation (CLV) as predicted theoretically (Belluzzi et al. 2012). However, the Lyman-α core, where the Hanle effect acts, does not show the CLV, in contrast to theoretical calculation with the currently available one-dimensional (1D) and three-dimensional (3D) solar atmospheric models (Trujillo Bueno et al. 2011; Štěpán et al. 2015). Although the interpretation of scattering polarization is not straightforward, the signature of the Hanle effect has been detected (Ishikawa et al. 2017) and new information on the magnetic field in the upper chromosphere and the transition region is being obtained.

The flight of CLASP2 (Chromospheric LAyer SpectroPolarimeter 2) has been approved by NASA and scheduled for 2019. By refitting the successfully recovered instrument, this second flight is aimed at performing spectropolarimetric observations of the Mg II h and k lines which are also candidates for exploring the magnetic field in the upper chromosphere (Belluzzi and Trujillo Bueno 2012; Alsina Ballester et al. 2016; del Pino Alemán et al. 2016). In the Mg II h and k lines, the circular polarization signals induced by the Zeeman effect can be measured in the strongly magnetized region, and this additional measurement will provide magnetic field information. Thus, in the second flight, circular and linear polarization will be examined. By completing these two CLASP missions (CLASP1 and 2), the effectiveness of UV spectropolarimetry in opening new avenues in solar physics will be investigated.

21.3.2 Balloon Experiment: SUNRISE

The balloon-borne solar telescope SUNRISE (Fig. 21.3) is a project aimed at obtaining high-quality solar data in terms of spatial resolution and polarimetric accuracy that are not affected by the Earth's atmosphere. SUNRISE is a stratospheric balloon mission that carries a 1 m aperture optical telescope. A flight altitude above 35 km allows it to perform (1) observations in the UV range that is inaccessible from a ground-based telescope and (2) high-precision polarimetric measurements without being affected by atmospheric seeing (Barthol et al. 2011; Solanki et al. 2010). The flight observations of SUNRISE were performed twice in 2009 and 2013 and provided many results on the dynamics on the solar surface, such as fine-scale magnetic structures resolved with an 0.1 arcsec (smaller than 100 km) resolution (Lagg et al. 2010) and the ubiquitous appearance of vortex motion on the surface (Steiner et al. 2010). More than 50 refereed papers based on data obtained from these two flights have been published. The SUNRISE mission was mainly led and developed by research groups in Germany and Spain. In the third flight that we are now proposing, our Japanese group will participate to develop the new infrared spectropolarimeter SCIP (Sunrise Chromospheric Infrared spectroPolarimeter) (Katsukawa et al. 2015, 2016). The 1 m aperture of the SUNRISE telescope can achieve 0.2 arcsec resolution (equal to the *Hinode* resolution) at near-infrared spectral lines such as Ca II

Fig. 21.3 SUNRISE balloon-borne stratospheric telescope. The 1 m aperture telescope is mounted on a gondola

854 nm and K I 769 nm, which have strong sensitivity to the Zeeman effect in the upper photosphere and the chromosphere. By having broad wavelength coverage to include many spectral lines originating from the photosphere to the chromosphere, we can obtain 3D magnetic field structures connecting the photosphere and the chromosphere. These magnetic structures and their temporal evolution are critical to determine the energy transfer and dissipation from the photosphere to the chromosphere under seeing-free conditions. A key engineering goal is to realize high polarimetric accuracy down to 0.03% by utilizing techniques developed for *Hinode*, CLASP, and SOLAR-C, including precise synchronization between the polarization modulator and cameras, efficient and precise polarization optics, and structural and thermal design of the spectrograph. The third flight, planned for 2020, will establish the scientific feasibility of chromospheric field measurements and develop the strong international collaboration required to realize SOLAR-C.

21.3.3 Wide Variety of Small-Size Experiments

Observations of solar coronae have revealed that unresolved fine-scale dynamics probably have a key role in coronal heating. It is thus strongly required to improve the spatial and spectral resolution as well as the wavelength coverage in UV and X-ray coronal observations. Here we introduce some rocket experiments that aim to develop critical techniques required for future coronal observations and are critically important for planning future spacecraft missions. The Hi-C (High-Resolution Coronal Imager) rocket experiment conducted by NASA realized an innovative instrument that achieved a high resolution of 0.2 arcsec in an EUV (Extreme UltraViolet) imaging observation of the corona (Kobayashi et al. 2014). The Hi-C flight experiments were performed twice in 2012 and 2016. The High-Resolution Coronal Imager (HCI) proposed for SOLAR-C is an evolutionary successor of Hi-C. The FOXSI (Focusing Optics X-ray Solar Imager) is an instrument carried by a sounding rocket aimed at conducting imaging and spectroscopic observations in the X-ray region (below 15 keV) with focusing optics. The flight experiments of FOXSI were performed twice, in 2012 and 2014, to capture very hot plasma [hotter than 10 million Kelvin (MK)] in microflares and in active regions (Ishikawa 2016). The Japanese group is in charge of the development of the X-ray detectors aboard FOXSI. A new X-ray detector that uses a fast readout complementary MOS (CMOS) sensor and allows imaging spectroscopic measurements in the soft X-ray region is now under development for the third flight in 2018.

The advanced observational techniques developed by these small space projects are essential for future instruments planned for small-to-large spacecrafts, such as SOLAR-C. We are mapping a strategy to realize the next-generation solar physics mission in the next solar maximum around 2025 by international collaboration, considering various opportunities including small-size spacecrafts.

21.4 Ground-Based Observations

Space missions are required to focus on measurements that can never be realized from the ground and aim at obtaining maximum scientific outcome under considerable resource constraints. If a space instrument will observe the Sun in visible or near-infrared wavelengths, it is critically important for the planner to clarify the ultimate limitation of ground-based observations and to make extensive verification of the flight instrument and its products using ground facilities. In this regard, the role of the ground-based observations for developing and realizing fascinating space missions becomes more important. The advantages of ground-based observation against space missions are its abilities to employ a very large-size instrument, to use highly flexible observation setups in existing facilities, and to conduct century-long data acquisition using synoptic observation instruments. With these advantages, ground-based observations are expected to: (1) exhibit an extremely high spatial resolution with a big telescope, (2) develop new methods of plasma characterization by highly flexible spectropolarimetric observations, and (3) perform long-term monitoring observations to accumulate a historic record of the solar activity to study the mechanism of the solar cycle and solar forcing on the Earth's environment.

A 4 m-aperture solar telescope (DKIST, Daniel K. Inouye Solar Telescope) is now under construction in Maui island of Hawaii and planned for completion in 2019. A project for a large solar telescope (EST, European Solar Telescope, 4 m

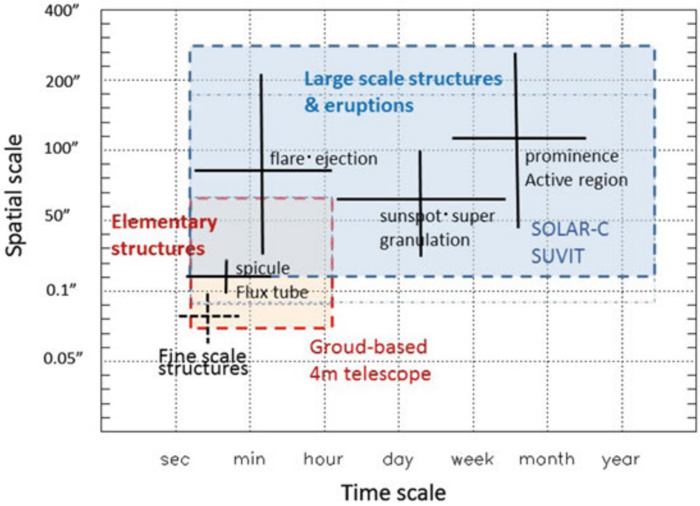

Fig. 21.4 Spatial and temporal scales covered by a 1 m space telescope and 4 m ground-based telescope

aperture) is also in progress in Europe. Both of these are expected to achieve an extremely high spatial resolution below 0.1 arcsec (approximately 70 km on the Sun) in imaging and spectroscopic observations and open a new window to the unexplored world of fundamental plasma processes in elementary magnetic structures on the Sun. Recently ALMA (Atacama Large Millimeter/submillimeter Array) has started observations of the Sun. It is strongly expected that ALMA will provide new methods to characterize thermal states of chromospheric fine-scale structures and high-energy electrons in flares with an unprecedented spatial resolution in submillimeter wavelengths, although its spatial and temporal coverage is rather limited. In contrast to large-size ground-based telescopes that observe the fine-scale elementary structures with the highest-ever spatial resolution like microscopes, the optical telescope aboard SOLAR-C covers large spatial and time scales at a high spatial resolution with the highest spectropolarimetric accuracy (see Fig. 21.4). The synergy of space and ground-based observations will ensure revolutionary progress in our understanding of the Sun.

Using the advantages of medium-size ground-based solar telescopes and their highly flexible usage, studies on the methodology for diagnosing 3D magnetic fields and experiments on the optical components that will be implemented in future space missions are conducted. For this purpose, a new multi-wavelength spectropolarimeter installed on the Domeless Solar Telescope (DST) at the Hida observatory of Kyoto University provides spectropolarimetric data of various photospheric and chromospheric lines in visible and near-infrared wavelengths simultaneously, which are used for developing an algorithm to reconstruct 3D magnetic fields from the photosphere to the chromosphere and for evaluating the diagnostic capability of spectral lines that will be observed by SUNRISE and SOLAR-C.

Additionally, a network observation project aimed at promoting space weather forecast is ongoing with a participation of Japanese space- and ground-based facilities. The project (PSTEP, Project for Solar-Terrestrial Environment Prediction) aims to understand the occurrence of eruptions on the Sun and their propagation to the Earth as a whole. PSTEP involves the coordinated observation of magnetic field of dark filaments by the Solar Flare Telescope at NAOJ, the velocity field of filament eruption using Solar Magnetic Activity Research Telescope (SMART) at the Hida observatory, shock waves propagating in the corona using the radio spectrometer at NICT (National Institute of Information and Communications Technology), the disturbance in the solar wind with the IPS (interplanetary scintillation) system at Nagoya University, and the magnetic field in active regions using *Hinode*. PSTEP is expected to build a foundation for the next-generation space weather forecasting system.

21.5 Summary

Solar observation in Japan has a history of approximately 100 years beginning with the start of solar photography in Tokyo Astronomical Observatory in 1917. Since the 1950s, ground-based solar telescopes have been constructed at Norikura, Mitaka, Kwasan, Okayama, and Hida. Since the 1980s, the solar observation satellites, Hinotori, *Yohkoh*, and *Hinode* have been successfully launched, and they have played a leading role in solar physics worldwide. In the current era, the size and cost of the required future flagship instruments are considerable, and solar physicists worldwide share a common understanding that an extensive international collaboration is necessary to realize a large-size next-generation solar physics mission. In this manuscript, we have discussed the prospects of solar observation in the next 10 years by focusing on the ongoing and future projects in Japan. Our goal is to realize a revolutionary space mission (SOLAR-C) with a worldwide international collaboration and the support of ground-based observatories.

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