Hinode: A New Solar Observatory in Space

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The third Japanese solar observing satellite, SOLAR-B, was launched on 2006 Sep 23 from the Uchinoura Space Center of JAXA and it was named ”*Hinode*” (sunrise). *Hinode* carries three major telescopes: Solar Optical Telescope (SOT), X-Ray Telescope (XRT), and Extreme-ultraviolet Imaging Spectrometer (EIS). These telescopes have been built in an international collaboration of Japan, US, and UK for understanding the formation mechanism of the solar corona, mechanism of dynamic events such as solar flares and coronal mass ejection, and general magnetic activities on the sun. All telescopes have started their commissioning activities after the successful launch of the spacecraft. The performance of the spacecraft that supports the diffraction-limited SOT observations and the first-light observation of each telescope are briefly introduced.

Keywords: astronomy, solar physics, space science

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1. Introduction

Hinode (SOLAR-B; Figure 1 and Table 1) [1] is the third Japanese solar observing satellite that follows *Hinotori* (ASTRO-A) and *Yohkoh* (SOLAR-A). It was successfully launched on 2006 Sep 23 from the Uchinoura Space Center (USC) of JAXA with the 7th M-V vehicle. It carries three telescopes: Solar Optical Telescope (SOT), X-Ray Telescope (XRT), and EUV Imaging Spectrometer (EIS). These telescopes are developed with significant participation of US, and UK. Using these telescopes we try to understand why the solar corona consisting of 10^6 K plasmas are produced outside the colder plasmas and why dynamic events like solar flares and coronal mass ejections (CME) occur with producing high-energy particles. This paper briefly introduces the *Hinode* science goals and the new solar observatory dedicated to solar physics in space.

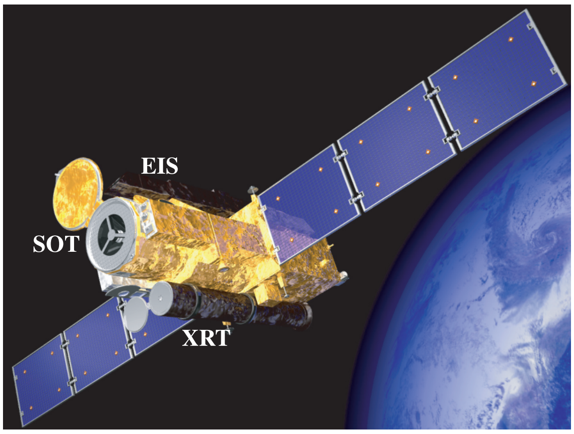

Fig. 1 Solar observing satellite, *Hinode* (SOLAR-B).

2. *Hinode* Science

Soft X-ray observations of *Yohkoh*, the previous Japanese solar observing spacecraft, has revealed that the solar corona is filled with very dynamic events. These events occur with a large topological change in the coronal magnetic fields. The *Yohkoh* observations showed some evidence to support magnetic reconnection as driver for energy release in the dynamic events. The coronal velocity fields around the reconnection site are expected to be measured in the next step. Regarding the energy build-up process of such events the change of magnetic field topology in the corona needs to be understood from the detailed vector magnetic field measurements on the photosphere. The *Yohkoh* observations also showed a close relationship between general coronal features and magnetic fields on the photosphere in quantitative manners. However, both spatial and temporal resolutions were not high enough to do understand why the solar corona is heated to 10^6 K. Especially, we strongly felt that observations of the photospheric magnetic fields with sub-arcsec spatial resolution is required in coordination with the coronal observations of higher spatial resolution than *Yohkoh* observations. The limiting factor of the spatial resolution in the photospheric magnetic field measurements for the ground-based observations is the earth’s atmospheric seeing blur. After investigating observing conditions of the ground-based observatories at the best seeing site and potential capability of image restoration technique, we decided to propose an optical telescope, working in the visible light range, to the next solar satellite mission, SOLAR-B. A wide variety of science targets are possible by having an optical telescope with sub-arcsec resolution.

All the solar outer atmospheric layers that can directly be observed by incoming photons are observed with

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Table 1 Characteristics of the *Hinode* spacecraft.

Launch time	2006 Sep 23 6:36 JST
Launch vehicle	JAXA M-V-7 rocket
Size (L × W × H)	2 m × 1.6 m × 3.8 m
Weight	893 kg including thruster fuel
Orbit	Sun-synchronous orbit at the end of orbit maneuvers
Altitude:	680 km
Inclination:	98.1 deg
Telescopes	Solar Optical Telescope (SOT) X-Ray Telescope (XRT) EUV Imaging Spectrometer (EIS)
Attitude control	three axis stabilized attitude control
Average data rate	300-400 kbps
Downlink stations	JAXA USC (N31°) in Japan and SvalSat (N78°) in Norway

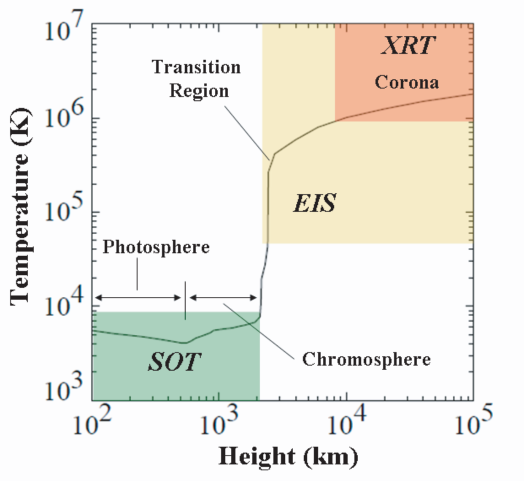

Fig. 2 Model of the solar atmosphere and regions where *Hinode* instruments can observe.

the *Hinode* scientific instruments: photosphere and chromosphere with SOT, the transition region with EIS, and corona with XRT and EIS as shown in Figure 2. The principal science goals of *Hinode* are:

1. To understand the processes of magnetic field generation and transport (why there are magnetic fields on the sun).
2. To investigate the processes of energy transfer from the photosphere to the corona for the heating of the chromosphere and corona (why the chromosphere and corona are so hot).
3. To determine the mechanisms responsible for eruptive phenomena, such as flares and CME (why flares and CME occur).

These science goals are to be addressed by research from closely coordinated observations among the *Hinode* SOT, EIS, and XRT.

3. *Hinode* Science Instruments

To achieve the science goals, the challenging high performance of science instruments was set. All the science instruments have higher performance for the previous spacecraft missions, of course. Although each telescope has a high spatial resolution, among the three telescopes SOT has the highest spatial resolution of 0.2-0.3 arcsec (150-220 km on the sun). This is the extremely challenging target in the space environment.

SOT [2, 3] consists of an aplanatic Gregorian optical telescope of 50 cm aperture with diffraction-limited performance and a focal-plane package, operating in the visible light range (380-670 nm). This is the largest aperture solar observing telescope ever flown in space, which can deliver the seeing-free solar images, not disturbed by the earth's atmosphere. The solar image on the CCD detectors cannot be stabilized by the spacecraft attitude control alone, so that SOT has a closed-loop image stabilization system consisting of a tip-tilt mirror driven by piezoelectric devices and a correlation tracker, which is a system to detect displacement of the image on the focal plane by solar granular cell patterns on the photosphere. A CFRP (carbon fiber reinforced plastics) with a very low thermal expansion coefficient is used to main telescope structures to stabilize the position of the secondary mirror to the primary mirror. The photosphere and chromosphere are observed with broad and narrow bandpass filter imagers for high-cadence imaging observations and the photospheric vector magnetic fields are studied with a spectropolarimeter in details. Continuous observations of small-scale magnetic fields on the sun, which is an important key to understand the energy input to the corona, have never been achieved before SOT/*Hinode*. See the details in Ichimoto (2007) [7].

XRT [4] is a grazing-incidence X-ray telescope that has a three-times better spatial resolution with 1 arcsec pixel sampling and an order of magnitude higher sensitivity for the low-temperature corona of 1-2 MK, compared with the performance of the soft X-ray telescope on-board *Yohkoh*. All coronal phenomena with temperatures of 1-30 MK are studied in detail with the best performance that has ever been achieved. See the details in Kano (2007) [8].

EIS [5, 6] is an imaging spectrometer working at two extreme-ultraviolet wavelength ranges, 17-21 and 25-29 nm. These wavelength ranges contain many emission lines that are formed at $T = 10^{4.7} - 10^{7.3}$ K. The line-profile spectroscopy with narrow slits or an imaging observation with wide slits is possible. The spectral resolution $\lambda/\Delta\lambda$ is about 4000 for the narrowest slit observation. Motions of hot plasmas and the process of plasma heating to coronal temperatures are investigated with this novel high-sensitivity spectrometer. See the details in Watanabe (2007) [9].

4. Performance of Spacecraft

To achieve the high-performance telescopes, the pointing stability of the spacecraft is largely improved from the previous spacecrafts that have ever been flown. The followings are taken into account.

1. Improvement of a sun sensor to have sub-arcsec resolution.
2. Reduction of mechanical disturbance from mechanical sensors and actuators for attitude controls.
3. Adoption of an optical bench unit made of a CFRP with high-heat conduction coefficient.

To detect the direction of a spacecraft pointing to the sun in a high accuracy of 1 arcsec at any time, the high resolution sun sensor is mandatory. To detect the spacecraft pointing jitter for a short duration of 10 sec gyroscopes are used. The so-called momentum wheels are used to move the spacecraft to desired pointing directions. These are mechanical components and create a high-frequency mechanical disturbance that affects the image blur of SOT images. The mechanical disturbance is reduced in components level. To stabilize the pointing direction of each telescope during an orbit, the high stability of spacecraft structure for the thermal distortion is required. The optical bench structure on which all telescopes and sun sensors are mounted is made of a CFRP with high-heat conduction coefficient.

Large format CCDs are used in all telescopes as detectors: $4\,\mathrm{K} \times 2\,\mathrm{K}$ pixels for SOT, $2\,\mathrm{K} \times 2\,\mathrm{K}$ pixels for XRT, and $2\,\mathrm{K} \times 1\,\mathrm{K}$ pixels for EIS. The cadence of exposures is an order of a few second to 10 seconds for the fastest case, so that huge image data are produced from each telescope. A readout of CCD partial area is possible to reduce the size of data to be transmitted to the ground, but the total size of data is still large. Since these huge data cannot be sent from the spacecraft to the ground as they are, the data have to be compressed before transmitting to the ground. The design study in the early design phase showed that a compression with hardware is required to achieve high-cadence SOLAR-B observations. We newly developed a hardware chip dedicated to 12-bit depth JPEG compression with DPCM loss-less compression for space application.

5. Mission Design to Launch

Just after the success of the *Yohkoh* mission, the conceptual design study for the next solar satellite mission has started by the SOLAR-B working group in 1994, continuing the *Yohkoh* science operation. After the approval by government in 1998, the SOLAR-B mission started in 1999 with US and UK international partners. The proto-model test of electronics was executed in 2001 and the checks of the mechanical and thermal test models were conducted in 2002. Through these tests the validity of the initial design and the test method were confirmed.

All the flight models were first assembled in Sep 2004 and the electrical and mechanical interface checks were executed. All the flight models were de-integrated in Dec 2004 and were integrated again in July 2005 for the final performance test after fixing problems. All the performance tests were completed in July 2006 and the spacecraft moved to the launch site in Aug 2006 (Figure 3). After the final test on the rocket was eventually finished, the spacecraft was successfully launched with the JAXA M-V-7 rocket on 2006 Sep 23 as shown in Figure 4. The spacecraft was named *Hinode* (sunrise in Japanese) by the project manager, late Professor Kosugi.

Fig. 3 *Hinode* spacecraft at the launch site, USC.

Fig. 4 Launch of *Hinode*: 2006 Sep 23 6:36 JST.

6. On-Orbit Operation before the First Light

The initial orbit injection of the spacecraft by the M-V rocket was almost perfect and the spacecraft sensors could easily find the sun. The initial orbit is an elliptical orbit with a low perigee altitude and the spacecraft orbit

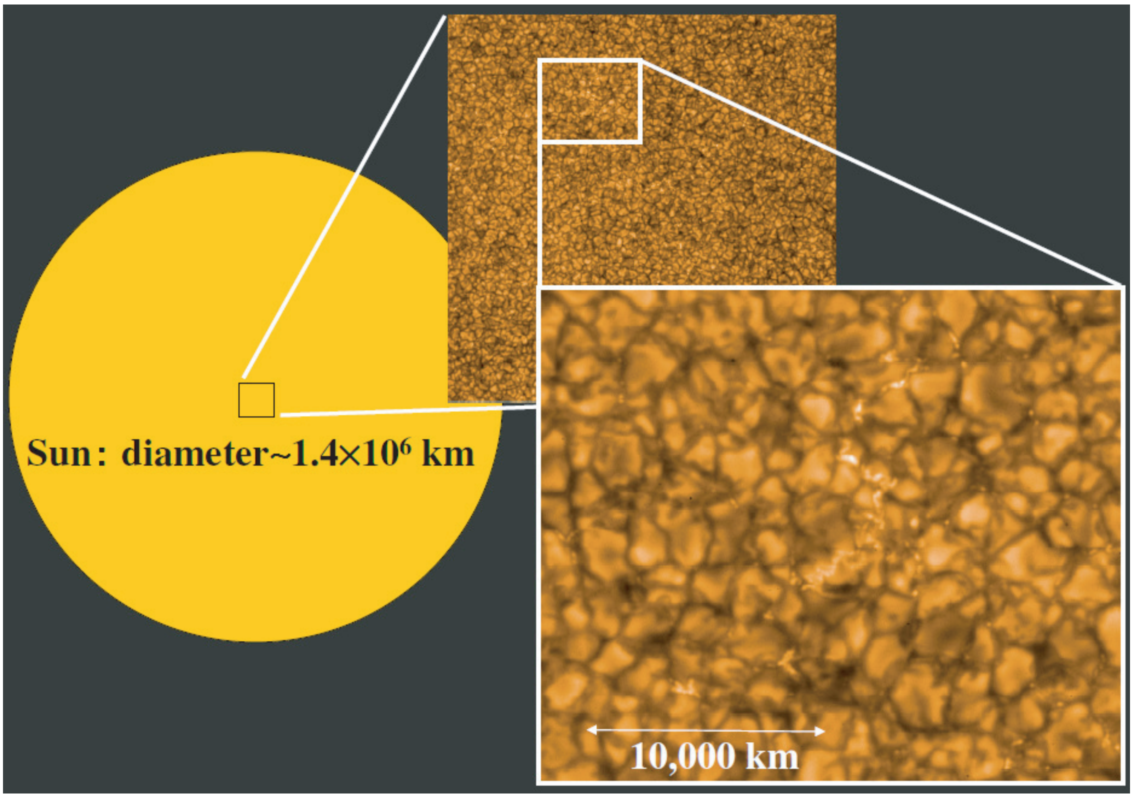

Fig. 5 SOT first-light image at 430 nm.

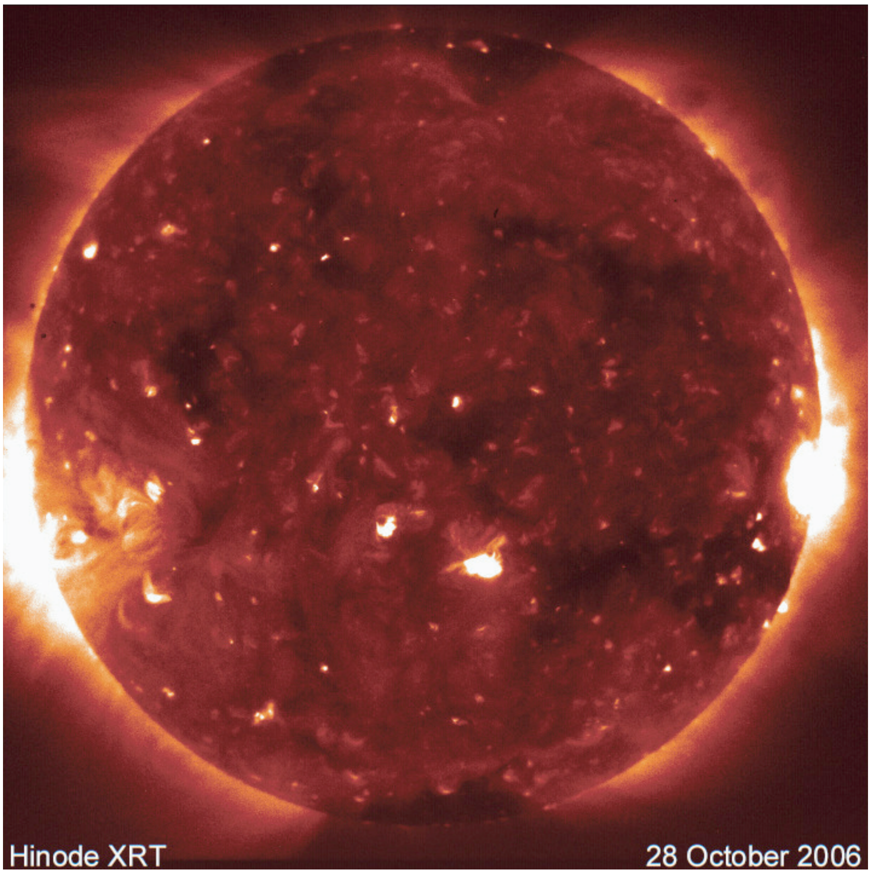

Fig. 6 XRT first-light X-ray image.

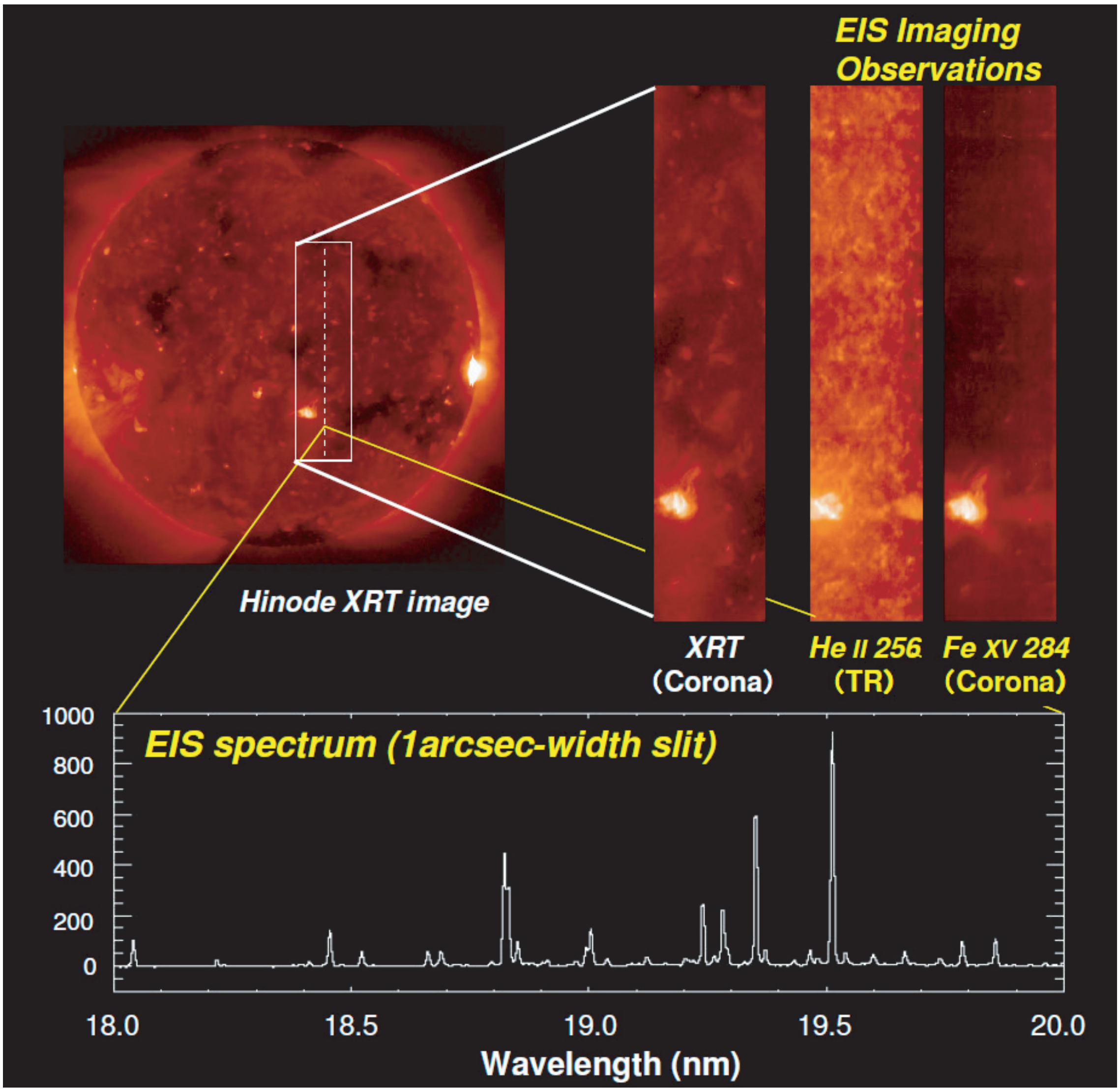

Fig. 7 EIS first-light EUV images and spectrum.

was modified to have a circular sun-synchronous orbit by firing the spacecraft thruster gas. By three orbit maneuvers we could successfully set the spacecraft in the sun-synchronous orbit. The orbit altitude and inclination at the end of maneuvers are 680 km and 98.1 deg.

After the orbit maneuver we turned on science instruments one by one. The status of the spacecraft and science instruments was OK and the door deployment operation and the following start of observation were the last step for the first light of each telescope. Everything was almost perfect.

7. First Light Images from *Hinode*

Figure 5 shows the SOT first-light image obtained in the visible light range at 430 nm (G-band). The structure of the solar photosphere is clearly seen. The cell-like structures, surrounded by dark lanes, are called granules in the solar physics community, showing convective patterns like the so-called Bénard cell. Smaller bright points between granules, the solar physicists call them G-band bright points, are also clearly resolved. These are the points of strong magnetic field concentration and are what we definitely need to see in details without the earth's atmospheric seeing blur. From this image we confirm the diffraction-limited performance of SOT. See other SOT initial results in Ichimoto (2007) [7].

Figure 6 shows the XRT first-light image. The solar activity in Oct 2006 is at the solar activity minimum in the 11-year solar cycle, so that big active regions with sunspots are not on the solar disk. A few small active regions are seen in the X-ray image with many tiny bright points that the solar physicists call X-ray bright points, which are the site of the magnetic interactions of opposite magnetic polarities in the corona through magnetic reconnection process. From the close-up of each X-ray bright point in the XRT image the tiny structure is found to be small loop structures. This is one of the achievements from XRT as the highest-resolution X-ray imager. The number of X-ray bright points is much larger than that seen in *Yohkoh* soft

X-ray images. This is because the XRT sensitivity in 1-2 MK plasmas is largely improved. See other XRT initial results in Kano (2007) [8].

Figure 7 is the EIS first-light images and spectrum with an XRT image for showing the observing region on the sun. A wide slit was used in the EIS imaging observation (He II and Fe XV) of 10 sec exposure duration. A high-cadence EUV imaging observation is possible by these imaging observations to detect dynamic events. He II 25.6 nm image shows the structure of the solar transition region (TR) at $T \sim 0.05$ MK. The bright points seen in this image correspond to the sites of strong magnetic fields on the photosphere, suggesting the close relationship between magnetic fields and TR structures. Fe XV 28.4 nm image shows coronal features of 2 MK plasmas and it is quite similar to the XRT image. The spatial resolution of EIS imaging observations in two EUV wavelength ranges is largely improved from observations in previous missions. Images obtained from these imaging observations are also used for co-alignment between SOT and EIS images and between XRT and EIS images. A spectrum from the EIS short wavelength band is shown at the bottom of Figure 7. The high-count rate and high spectral resolution are confirmed and detailed plasma diagnoses are possible by the performance. See other EIS initial results in Watanabe (2007) [9].

8. Summary

The SOLAR-B spacecraft, dedicated to solar physics studies, was developed by ISAS/JAXA with extensive support of NAOJ and in an international collaboration with US and UK. It spent 8 years from the start of the mission after the mission design studies of 5 years that were executed prior to the mission approval. Much higher performance of the spacecraft than that of previous spacecrafts is required to achieve the mission goals. The spacecraft was successfully launched on 2006 Sep 23 by the last JAXA M-V vehicle and the SOLAR-B spacecraft was named “*Hinode*” (sunrise) by the project manager, late Professor Kosugi. The first-light images show the achievement of the fundamental performance of each telescope. After initial observations for the post-launch verification the initial science observations have started since 2006 Dec. We expect that enormous new scientific outputs will soon appear.

Acknowledgements

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