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Hinode “a new solar observatory in space”

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Since its launch in September 2006, the Japan-US-UK solar physics satellite, Hinode, has continued its observation of the sun, sending back solar images of unprecedented clarity every day. Hinode is equipped with three telescopes, a visible light telescope, an X-ray telescope, and an extreme ultraviolet imaging spectrometer. The Hinode optical telescope has a large primary mirror measuring 50 centimeters in diameter and is the world’s largest space telescope for observing the sun and its vector magnetic fields. The impact of Hinode as an optical telescope on solar physics is comparable to that of the Hubble Space Telescope on optical astronomy. While the optical telescope observes the sun’s surface, the Hinode X-ray telescope captures images of the corona and the high-temperature flares that range between several million and several tens of millions of degrees. The telescope has captured coronal structures that are clearer than ever. The Hinode EUV imaging spectrometer possesses approximately ten times the sensitivity and four times the resolution of a similar instrument on the SOHO satellite. The source of energy for the sun is in the nuclear fusion reaction that takes place at its core. Here temperature drops closer to the surface, where the temperature measures about 6,000 degrees. Mysteriously, the temperature starts rising again above the surface, and the temperature of the corona is exceptionally high, several millions of degrees. It is as if water were boiling fiercely in a kettle placed on a stove with no fire, inconceivable as it may sound. The phenomenon is referred to as the coronal heating problem, and it is one of the major astronomical mysteries. The Hinode observatory was designed to solve this mystery. It is expected that Hinode would also provide clues to unraveling why strong magnetic fields are formed and how solar flares are triggered. An overview on the initial results from Hinode is presented. Dynamic video pictures captured by Hinode can be viewed on the website of the National Astronomical Observatory of Japan (NAOJ) at http://hinode.nao.ac.jp/index_e.shtml.

1 Hinode Spacecraft

The Hinode spacecraft (Kosugi *et al.*, 2007; see Fig. 1), previously known as Solar-B, was successfully launched in September 2006 from the Uchinoura Space Center in Japan using an M-V launch vehicle. On 25 October 2006, it started its scientific operation. Its orbit is a sun-synchronous orbit that provides 9-month continu-

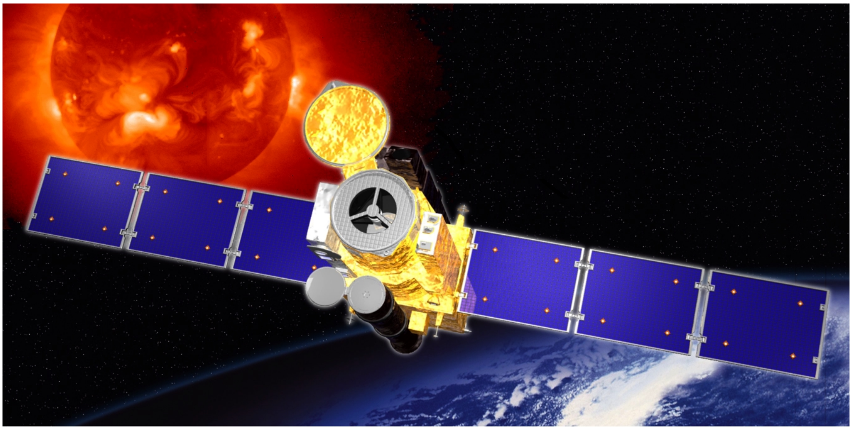

Fig. 1. Image of the Hinode spacecraft in orbit. (Courtesy of NAOJ, JAXA, and NASA.)

ous observations. It comprises an observatory style set of instruments that function together with the aim of answering the following mission science goals:

- To understand the process of magnetic field generation and transport.
- To investigate the processes responsible for energy transfer from the photosphere to the corona.
- To determine the mechanisms responsible for eruptive phenomena such as flares and coronal mass ejections.

Hinode is designed to answer the fundamental question of how magnetic fields are formed and how they interact with the atmosphere to create the activity that we observe on the sun. This subsequently addresses all phenomena that have an impact on the Sun-Earth system, such as the formation of the solar winds (both slow and fast), triggering of flares and coronal mass ejections, formation and maintenance of filaments and prominences. This review summarizes how the new results from Hinode are addressing these critical questions as well as probing fundamental physical processes that will have applications in many other scenarios across the universe.

There are three instruments onboard Hinode, the Solar Optical Telescope (SOT), the X-ray Telescope (XRT), and the EUV Imaging Spectrometer (EIS), each measuring critical parts of the sun's atmosphere from the surface (photosphere) to the chromosphere, the transition region and finally the outer and hottest part of the atmosphere, the corona.

1.1 The Solar Optical Telescope (SOT)

SOT is the first large optical telescope flown in space to observe the sun (Tsuneta *et al.*, 2008a). It has an aperture of 50 cm and achieves an angular resolution of $0.25''$ (175 km on the sun) covering a wavelength range from 480–650 nm. It consists of

2 components, the Optical Telescope Assembly (OTA: Suematsu *et al.*, 2008) and the Focal Plane Package (FPP). The FPP includes the narrow-band (NFI) and the wide-band (BFI) filtergraphs and the Stokes spectropolarimeter (SP). This complex instrument allows measurements of the magnetic field both in the longitudinal and transverse directions, Doppler shifts, and imaging in the range from the low photosphere through to the chromosphere very accurately under precise calibration (Ichimoto *et al.*, 2008).

1.2 The X-ray Telescope (XRT)

XRT is an advanced solar X-ray telescope (Golub *et al.*, 2007; Kano *et al.*, 2008) with the highest angular resolution of $2''$. It is a Wolter Type III grazing incidence telescope that uses 2 reflections to focus soft X-rays onto a CCD array. It can provide both full sun and partial disk images. Filters ranging in thickness by a factor of 10,000 provide a huge dynamic range able to measure very weak features in coronal holes and very large flares. The temperature range extends from 1 million K to 30 million K. This temperature range is much wider than that of the soft X-ray Telescope on board Yohkoh.

1.3 The EUV Imaging Spectrometer (EIS)

EIS is an imaging spectrometer (Culhane *et al.*, 2007) built by a consortium consisting of UCL-MSSL, RAL, NRL, GSFC, UiO, and NAOJ. EIS was designed to probe the dynamics and composition of the solar atmosphere with a spatial resolution of $1''$. For observations, it uses two EUV wave-bands which were chosen to measure plasma with temperatures ranging from 50,000 K to 20 million K. EIS is a flexible instrument with the ability to measure high-resolution spectra along with imaging achieving velocity resolutions of several km/s, and it can also observe fast cadence (seconds) monochromatic images. The two wave-bands cover a total of 90 Å containing at least 500 spectral lines of which 55% are identified to come from previously known atomic transitions (Brown *et al.*, 2007).

In the following sections, highlights of the new results from Hinode during its initial operational phase are introduced.

2 New Views of the Solar Atmosphere (Photosphere/Chromosphere/Corona)

Figure 2 shows images of the sunspot and the sun’s surface captured by the optical telescope. The sizes of the sunspot range from between several thousand kilometers to several tens of thousands of kilometers. By enlarging the sun’s image further, structures called granules can be seen, as shown in Fig. 2, in which bubbling gases flow in swirls of convection over an area measuring about 1,000 km. Small white spots seen between the granules correspond to strong magnetic fields. It is still a mystery how these structures were formed, but thanks to Hinode, it has become possible to observe these changing features for the first time. Figure 3 shows a side view of the sun with a sunspot positioned along the edge. Bright emissions appear frequently around the sunspot, and material jets up like a fountain to an altitude of 20,000 km.

Hinode shows magnetic field structures in a new light. A spectacular example is solar prominences. These are large-scale, cool structures that lie surrounded by the hot corona. It has been suggested that these are caused by plasma trapped in hor-

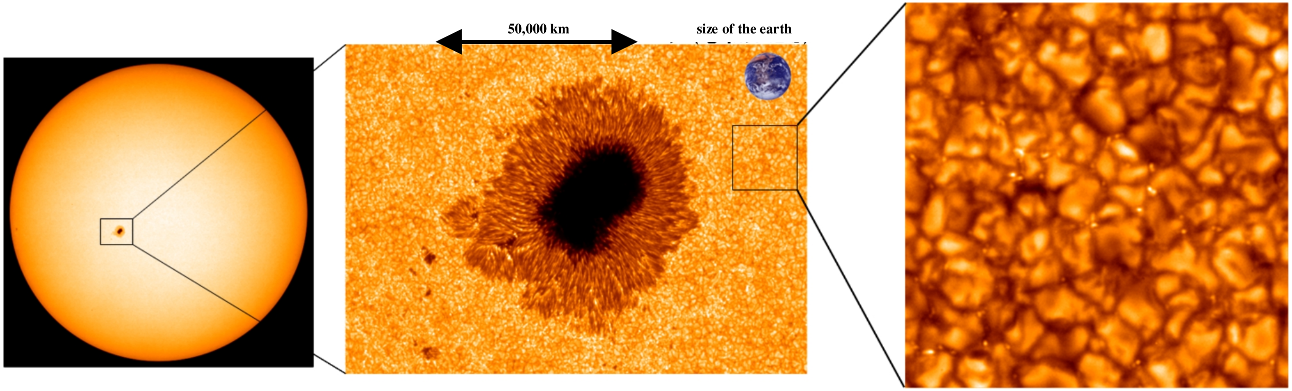

Fig. 2. Sunspot on the sun’s surface captured by the optical telescope onboard Hinode. The observations were made at a wavelength of 460 nm. (The colors in the image have been artificially enhanced and differ from the actual colors.) Convection called granules can be seen in the photosphere (right). Small spots between the convection cells are magnetic elements (the minimum unit of a magnetic field) that have an exceptionally strong magnetic field. (Courtesy of NAOJ, JAXA, and NASA.)

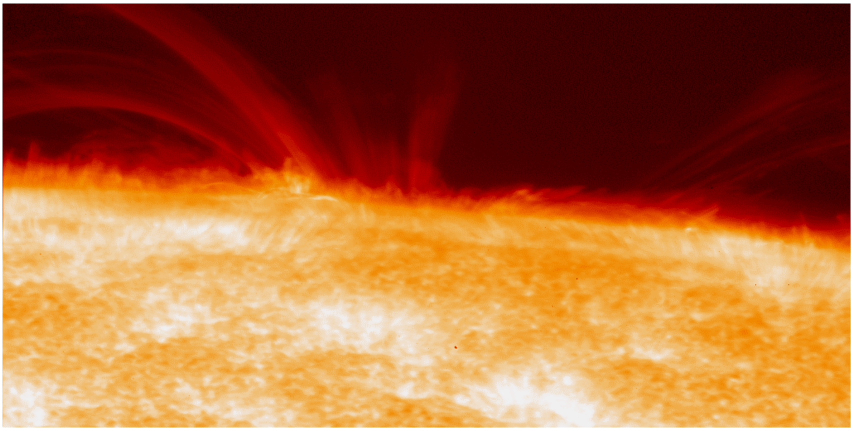

Fig. 3. Dynamic solar activities around the sunspot as seen through the optical telescope; substances of temperatures of several tens of thousands of degrees are being sprayed into the solar atmosphere. (Courtesy of NAOJ, JAXA, and NASA.)

izontal magnetic field-line configurations. Observations show horizontal threads of plasma which have oscillatory behavior with periods around 170s which is consistent with Alfvén wave propagation which may possibly heat the surrounding corona (Okamoto *et al.*, 2007). What comes as a surprise is that these threads show dark upward flows that are turbulent and move at speeds of 20 km/s (Berger *et al.*, 2008). The existence of these flows is a real challenge to the current MHD understanding of prominences as they are inconsistent with the idea of a low-Beta (where Beta is the ratio of gas to magnetic pressure) plasma lying in horizontal magnetic fields.

While the optical telescope observes the photosphere/chromosphere, the X-ray telescope captures images of the corona and the high-temperature flares that range from between several million and several tens of millions of degrees. The telescope has achieved the greatest spatial resolution in history, and it has captured coronal structures that are clearer than ever. The sun viewed through the X-ray (Fig. 4) is completely different from that seen in the visible light range. The area around the sunspot, where the strong magnetic fields exist, is referred to as an active region, from which X-rays further radiate. Many stripes can be seen around the active region, which represent the magnetic lines of force that spread upward from the photosphere.

The source of energy for the sun is in the nuclear fusion reaction that takes place at its core. The temperature drops closer to the surface where the temperature measures about 6,000 degrees. Mysteriously, the temperature starts rising again above the surface and the temperature of the corona is exceptionally high at several millions of degrees. This is the so-called coronal heating problem, and it is one of the major astronomical mysteries involving something of a lower temperature being able to heat something of a higher temperature.

There is now the possibility that the results of the observations of Hinode may be

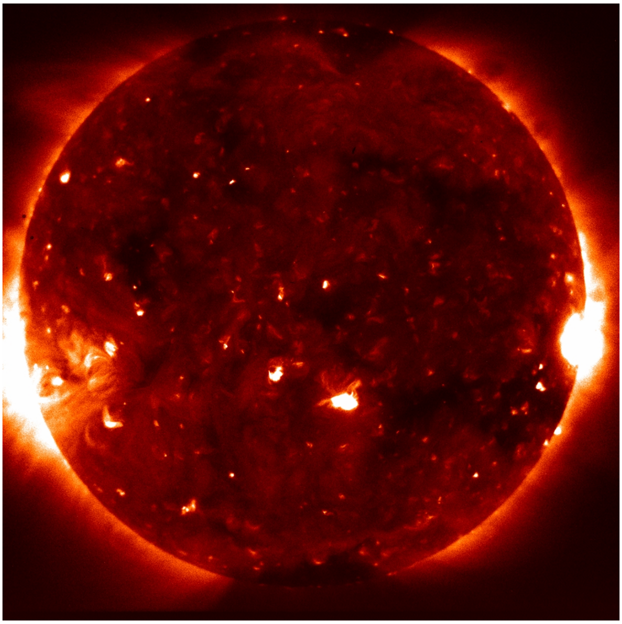

Fig. 4. X-ray images of the entire solar surface photographed by the X-ray telescope onboard Hinode. A punctuate structure called an X-ray bright point was identified for the first time, which revealed that the corona is made up of magnetic loops. (Courtesy of NAOJ, JAXA, and NASA.)

used to solve the problem. Hinode has revealed there are strong magnetic fields and strong corona activity in areas without the sunspot. Sources of X-rays are scattered here and there on the photosphere, and it still remains a mystery as to how they were formed. Scientists expect to understand the solar corona heating mechanism by comparing such information with information on the magnetic fields obtained by the optical telescope. The current hypothesis is that there are areas on the photosphere where there is a strong magnetic field, and the corona is being vigorously heated by the magnetic energy. An explanation of the specific mechanism is now anticipated. In the near future, there may also be clues to unraveling why such strong magnetic fields are formed and how solar flares are generated.

EIS has the capability of obtaining physical information of the coronal plasma, such as temperature, density, and velocity. Broad EUV emission lines might correspond to some turbulent or non-thermal processes critical to understand energy transfer, for example, coronal heating. The fact that the most turbulent regions which we have been studying for decades can actually be seen outside the bright loops has huge implications on how the atmosphere of the sun is heated and sustained. The processes that make loops bright may not actually be the key to understanding the atmosphere as a whole. This is also seen in the quiet corona where weak emission regions have measured outflows of 100 km/s (Dere *et al.*, 2007). Another discovery is that the density of very weak emission regions can be high, which suggests that the observed active region is surrounded by weakly emitting high-density loops. The weak regions often show large line widths in the EUV spectral lines (Doschek *et al.*, 2007).

3 Alfvén Waves and Solar Wind Source

The activity on the sun is known to be driven by the magnetic fields that are prevalent everywhere. Hinode has higher temporal, spatial and velocity resolution than any satellite previously and is probing wavelength regimes that have never had such continuous time coverage available. This has allowed us to measure waves in the atmosphere in a way we have been unable to do before. In 1947 Alfvén predicted the existence of magnetic waves caused by the constant movement due to convection on the surface of the sun. The convection disturbs the magnetic fields causing waves and may then be damped in the corona providing an energy source that may create enough heating for the atmosphere and energy to accelerate the solar wind. Attempts to measure Alfvén waves have been ambiguous in previous missions, but Hinode now appears to be opening the door to these waves being observed in many different circumstances.

The chromosphere is highly structured as can be seen in Fig. 2. At the solar limb, spiky features known as spicules are seen in abundance. Now with Hinode, observations can be made continuously without being concerned about seeing conditions as is the case with ground-based telescopes. De Pontieu *et al.* (2007a) have analyzed these spicules and found that there are two types. The first type is formed when global oscillations and convective flows leak into the atmosphere causing shocks. These have timescales of minutes and show persistent upward and downward motions. The type II spicules (named straws) have lifetimes of seconds, are much thinner and move plasma at speeds of over 100 km/s. These seem to be related directly to the magnetic reconnection process. However both types of spicules show a swaying behavior strongly indicative of Alfvén waves. They show amplitudes and periods that are consistent with simulations of the generation, propagation and dissipation of Alfvén waves from the photosphere to Earth orbit (De Pontieu *et al.*, 2007b), and they have enough energy to power the solar wind.

Jets of collimated, hot plasma have been observed for many years on the sun. These can occur in the active region loops that lie above sunspot groups or within the coronal holes. One explanation of the formation of jets involves a scenario in which emerging flux from below the surface interacts with coronal holes. Hinode now has the ability to observe jets in significantly more detail to study basic physical processes (Shimojo *et al.*, 2007). Jets in coronal holes have been observed to have speeds of 200 km/s. However, a new component that occurs at the beginning of the jet formation has been discovered, high speed, reaching 800 km/s, close to the Alfvén speed in the corona (Cirtain *et al.*, 2007). The characteristics of these jets are consistent with plasma being ejected at the Alfvén speed during a relaxation period following magnetic reconnection. These small jets carry as much as a tenth of the mass necessary for the solar wind.

The sun supplies a huge amount of plasma into interplanetary space as solar wind.

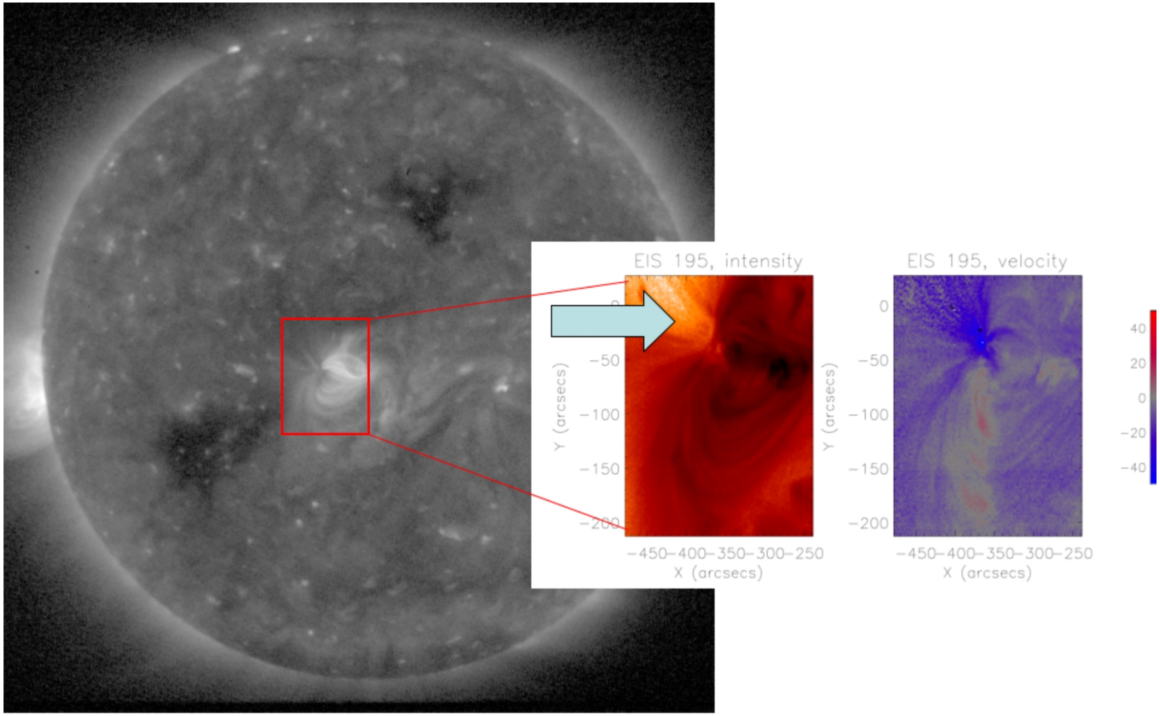

Fig. 5. The right hand side shows a full sun XRT image with the box showing the EIS FOV. The left EIS image is the intensity and the right image is the Doppler velocity. The blue arrow shows the source of the strongest outflow (i.e., from Sakao *et al*., Continuous Plasma Outflows from the Edge of a Solar Active Region as a Possible Source of Solar Wind, *Science*, **318**, 1585–1588, 2007, reprinted with permission from AAAS; Harra *et al*., 2008, reproduced by permission of the AAS).

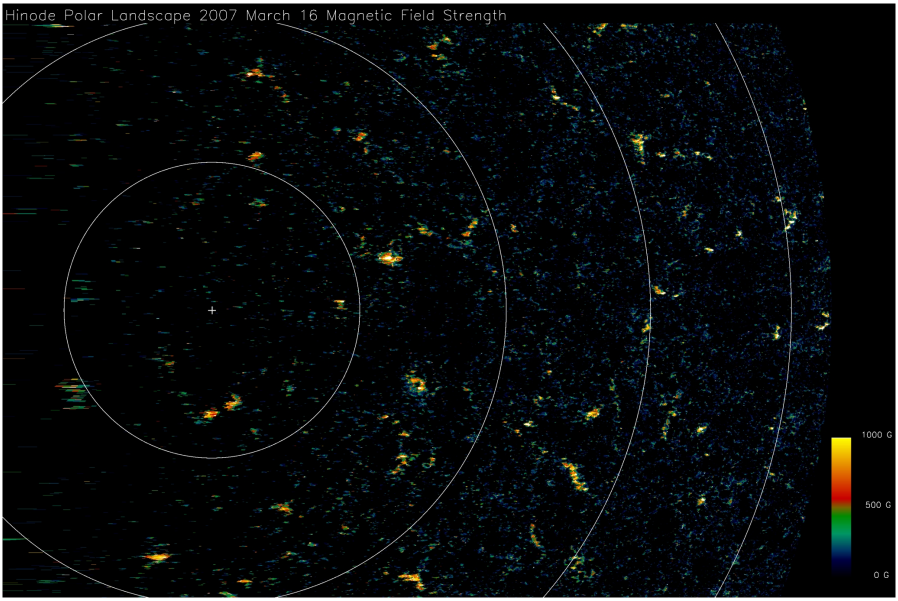

Fig. 6. South polar view of the magnetic field strength taken at 12:02:19–14:55:48 UT on 16 March 2007. The original observing field of view is 327.52″ (east-west) by 163.84″ (north-south) and was converted to a map seen from above the south pole. East is to the left, west is to the right, and the observation was carried out from the top down. Spatial resolution is lost near the extreme limb (i.e., near the bottom of the figure). The field of view for the line-of-sight direction (163.84″) expands to 472.96″ as a result of correction for foreshortening. The pixel size is 0.16″. Latitudinal lines for 85°, 80°, 75°, and 70° are shown as large circles, while the plus sign marks the south pole. The magnetic field strength is obtained for pixels meeting a given threshold. (From Tsuneta *et al.* (2008b). Reproduced by permission of the AAS.)

It is well known that the solar wind consists of two components, a fast solar wind that comes from predominantly coronal holes that have open magnetic fields, and a slow solar wind that comes from other open magnetic fields, such as the boundary of large-scale coronal holes and small-scale coronal holes even though its source has been debated for many years. Alfvén waves as mentioned above are also critical for solar wind formation. However, in this paper we focus on the source of solar wind.

The slow solar wind has fluctuating speeds between 200–500 km/s. XRT has observed persistent and steady flows directly at the edges of active regions (Sakao *et al.*, 2007) with speeds of over 100 km/s that persist for days. The mass loss rate was estimated to be 25% of the slow solar wind. Using EIS alongside this dataset, the real Doppler flows can be then observed. Figure 5 shows the XRT image for context alongside the EIS data. The EIS data show the intensity of the corona on the left-hand side. Now for the first time, the Doppler velocities can also be observed (on the right hand side of Fig. 5). The region of weakest emission at the top of the active region shows the strongest velocities (Harra *et al.*, 2008). Probing the magnetic field shows that this region is highly extended, most likely open fields caused by reconnection with a much smaller active region to the west of the one studied. These large-scale reconnections are of significant importance when aiming to understand the slow solar wind.

We have also new observations related to a fast solar wind. Tsuneta *et al.* (2008b) reported SOT observations of the magnetic landscape of the polar region of the sun with an extremely high spatial resolution and high polarimetric precision. Using a Milne-Eddington inversion, it was found that many vertically oriented magnetic flux tubes with field strengths as strong as 1 kG were scattered in latitude between 70° and 90° (Fig. 6). They all have the same polarity, consistent with the global polarity of the polar region. The field vectors have been observed to diverge from the centers of the flux elements, consistent with a view of magnetic fields that are expanding and fanning out with height. The polar region has also been found to have ubiquitous horizontal fields. The polar regions are the source of the fast solar wind, which is channeled along unipolar coronal magnetic fields whose photospheric source is evidently rooted in the strong-field, vertical patches of flux. We conjecture that vertical flux tubes with large expansion around the photospheric-coronal boundary serve as efficient chimneys for Alfvén waves that accelerate the solar wind.

4 Solar Flare: 13 November 2006 Event

Also observed on the surface of the sun are explosive phenomena called solar flares that last for several minutes to several hours and the eruption of substances referred to as high-speed jets caused by the explosions. A magnetic field controls the activities in the corona, and large explosions take place frequently near the sunspot where magnetic field lines are in close proximity.

Although the sun is now in at the minimum of its activity level, we are still occasionally treated to an active region which produces solar flares. Such a region appeared in December 2006 just after the Hinode scientific operation started. Days before the large X-flare on 13 December 2006, the active region had been monitored. There was a large negative polarity sunspot, and to the south of it emerged a smaller positive polarity sunspot. Over the days of this evolution, the smaller sunspot rotated dramatically, colliding into the pre-existing sunspot (Kubo *et al.*, 2007). The impact on the corona above of this shearing motion could be seen (Su *et al.*, 2007). Just as the smaller sunspot was emerging, the coronal loops were lying perpendicular to the inversion line (marking out the separation between positive and negative polarity). At this stage the loops were essentially potential with little stored energy. By 12 December 2006, the story was completely different. At this stage the new sunspot had been emerging and rotating at the surface, dragging the field lines around, and causing the magnetic loops to become so sheared that they were now lying parallel to the inversion line. A few hours after this, a huge X-class flare took place there. Figure 7 shows an image of a gigantic flare captured by Hinode, which stretches to several tens of thousands of kilometers. Even more dynamic video pictures captured by Hinode can be viewed on the website of the National Astronomical Observatory of Japan (NAOJ) at http://hinode.nao.ac.jp/index_e.shtml.

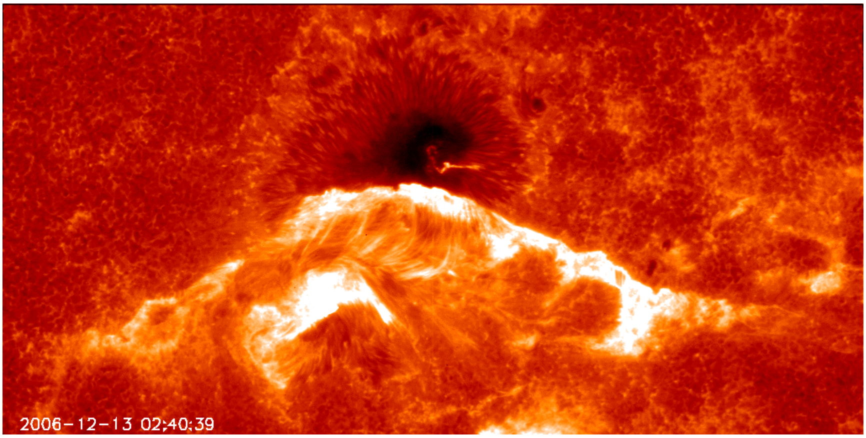

Fig. 7. Large solar flare captured by SOT on 13 December 2006. Two-Ribbon structure and some of post-flare loops between the two ribbons are clearly seen. (Courtesy of NAOJ, JAXA, and NASA.)

During this X-class flare, we measured directly for the first time what part of the atmosphere erupted away from the sun. Imada *et al.* (2007) analyzed the flare on 13 December 2006 and found that the strongest outflows were away from the main flare site. The force of the flare had ripped off some of the plasma from the sun. Interestingly, there seems to be a strong relationship between this outflow and the temperature of the plasma. The strongest outflows are from the hottest plasma which provides a constraint to the mechanism that forms this fast component to the solar wind. Speeds of 1000 km/s were measured at ACE from this event.

The sun is currently in a period of minimum activity. Solar flares will start to occur more frequently as the sun heads toward its period of maximum activity around 2012, when it will then undergo a transformation that will make it appear as a different star. Hinode is sure to change fundamentally the academic perspectives on solar observation through the analysis of clear and high-resolution images and spectroscopic data during the period of maximum activity that received for the first time.

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