Hinode "A New Solar Observatory in Space"

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1. MAGNETIC FIELD AND COSMOS

It is a remarkable and fascinating fact that a solitary star like the Sun emits intense X-rays from its outer atmosphere. Observations with Japan-US Yohkoh satellite [1] show that all the sporadic heating from major flares to ubiquitous tiny bursts in the solar corona is due to magnetic reconnection; a process to efficiently annihilate magnetic fields with opposite direction into heat, jets and non-thermal acceleration. Magnetic field does dissipate in the corona with time scale 10^{12} faster than that of the classical Ohmic dissipation. Though this leads to an attractive conjecture that the solar corona in general is heated by ensemble of tiny bursts ([2, 3] and references therein), precise mechanism for the heating of solar corona and acceleration mechanism of solar wind is, however, unknown.

These activities on the surface of the star are driven by magnetic field created by interaction of flow and fields below the photosphere (dynamo mechanism). The magnetic field strength on the surface of the sun exceeds 1 kG, while that at the bottom of the convection zone may reach 100 kG. They are too strong, far stronger than the *equi-partition magnetic field strength*, whose energy is the same as that of the local convection motion. Though a dynamo mechanism can amplify field strength upto the equi-partition field strength, it is perceived not possible to have field strength beyond the threshold. Such too-strong magnetic field can be found elsewhere in the universe, namely pulsers (10^{12}G), magneters (10^{15}G), galaxies and clusters of galaxies (a few micro G), which is again too strong in terms of that in early universe (10^{-17}G, [4]). Dynamo mechanism for the sun and these objects is poorly understood.

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2. HINODE SPACECRAFT

The Hinode spacecraft ([5], see Fig. 1), previously known as Solar-B, was successfully launched in September 2006 from the Uchinoura Space Center in Japan using a JAXA's M-V launch vehicle. On 25 October 2006, it started its scientific operation. Its orbit is a sun-synchronous orbit that provides 9-month continuous observations. It comprises an observatory style set of instruments that function together to answer the fundamental question of how magnetic fields are formed and how they dissipate to create the solar corona. 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 with intense non-thermal particle acceleration and coronal mass ejections, formation and maintenance of filaments and prominences.

The concept of Hinode is that two X-ray and EUV telescopes observe the dissipation part of the magnetic life-cycle history, while the visible light telescope observes generation and transport of magnetic field simultaneously. Hinode is the Japan's third solar mission with participation of NASA and UK STFC (then PPARC). Observations of Sun from space in Japan started with Hinotori satellite as early as 1981. Hinotori took the hard X-ray images of solar flares above 20 keV for the first time. This is followed by highly successful Yohkoh mission, which carries both hard

Fig. 1: Image of the Hinode spacecraft in orbit.

and soft X-ray telescopes. The Hinode mission is designed based on Yohkoh results and recent progress in ground-based astronomy. 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.

2.1. The Solar Optical Telescope (SOT)

SOT is the first large optical telescope flown in space to observe the sun [6]. 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 380-650 nm. It consists of 2 components, the Optical Telescope Assembly (OTA: [7]) 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 [8].

2.2. The X-ray Telescope (XRT)

XRT is an advanced solar X-ray telescope [9, 10] with the highest angular resolution of 1". It is a Wolter Type I 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/EUV Telescopes on board Yohkoh, SOHO and TRACE.

2.3. The EUV Imaging Spectrometer (EIS)

EIS is an imaging spectrometer [11] built by a consortium consisting of UCL-MSSL, RAL, NRL, GSFC, UiO, and NAOJ. EIS was designed to probe the dynamics of the solar atmosphere with a spatial resolution of 1". 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 [12].

3. A NEW OBSERVATIONS ON SOLAR MAGNETIC FIELD

Magnetic field carries energy through waves and fluctuation, and can store energy. It dissipates stored energy with magnetic reconnection, and induces MHD instability and eruptions. Another aspect of magnetic field is that it suppresses cross-field transport for mass and heat, and suppress convection i.e. energy transport. In the following sections, highlights of the new results from Hinode during its initial operational phase are introduced.

Fig. 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. Fig. 3 shows a side view of the sun with a sunspot positioned along the edge. Bright emissions appear frequently around the sunspot, and mate-

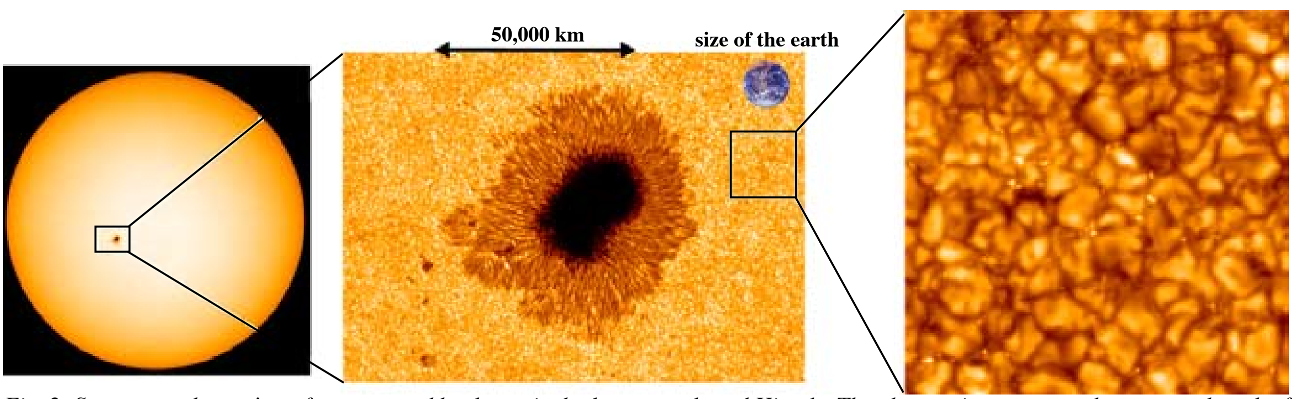

Fig. 2: Sunspot on the sun's surface captured by the optical telescope onboard Hinode. The observations were made at a wavelength of 460 nm. (The colors in the image have been artificially enhanced and differ from the actual colors.) Convection called granules can be seen in the photosphere (right). 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.)

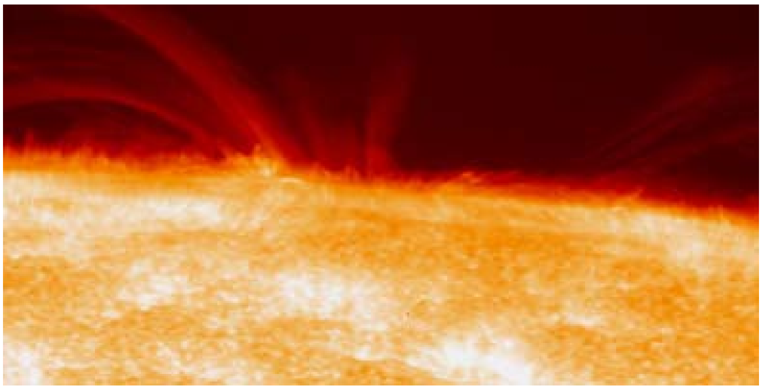

Fig. 3: Dynamic solar activities around the sunspot as seen through the optical telescope; substances of temperatures of several tens of thousands of degrees are being sprayed into the solar atmosphere. (Courtesy of NAOJ, JAXA, and NASA.)

rial jets up like a fountain to an altitude of 20,000 km.

Hinode shows magnetic field structures in a new light, and two major discoveries being made by Hinode are reported here.

3.1. Super Equi-Partition Field

The photospheric magnetic flux tubes with kG field strength and spatial scale of a few 100 km are ubiquitously found across the entire solar surface. Those flux tubes appear as small bright points in Fig. 1. The field strength should have been limited by the equi-partition magnetic energy (typically 400 G) corresponding to the kinetic energy density of the granular flows. Thus, further intensification is necessary to explain the kG field strength flux tubes. A theory was that the plasma in flux tubes emerged from below cools and falls due to suppression of heat, and the flux tube narrows until the magnetic pressure of the evacuated flux tube balances with the surrounding gas pressure. This process referred to as *convective collapse* has been studied for almost 30 years, and is finally confirmed with Hinode [13]. We find a good coincidence between the field strength intensification and the downward motion. The initial field strength of 400 G is intensified up to 2,000 G as the downflow grows to 6 km s^{-1} in 150 s. Convective collapse ubiquitously takes place in the convective atmosphere, and is an essential ingredient for formation of flux tube with intense magnetic field.

3.2. Horizontal Magnetic Field and Local Dynamo Process

The surface of the Sun is essentially covered with concentrated (< 1") vertical magnetic flux tubes with field strengths of kG as shown above. This paradigm is challenged by Hinode: Hinode discovered *transient horizontal magnetic fields* [Fig. 4], which are characterized by horizontal field with random direction, size as small as convection cell, life time as short as convection turnover time, magnetic field strength smaller than equi-partition strength. These unique properties are completely different from those of the vertical magnetic elements. The horizontal fields are ubiquitous, regardless of the quiet sun or active regions, and their total magnetic flux is larger than that of vertical fields. It appears that convection layer has an inherent property to produce such horizontal fields. We call this *local dynamo process* ([14] and references therein). It is totally unknown at this point how this new dynamo process and its resultant horizontal fields are related to global dynamo process, which produces sunspots.

4. DYNAMIC X-RAY CORONA

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 sun viewed through the X-ray [Fig. 5] is completely different from that seen in the visible light

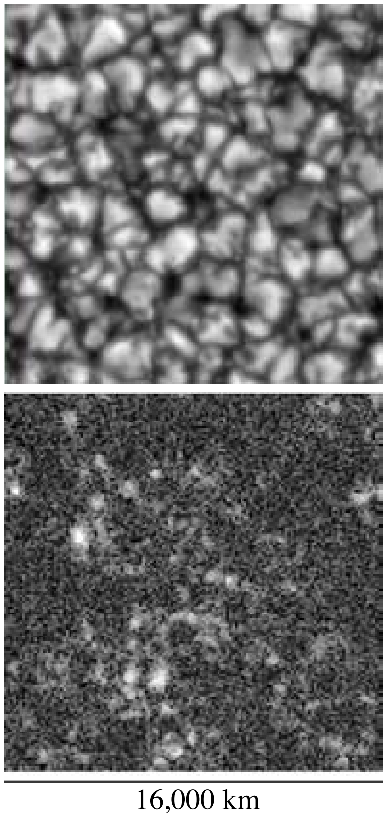

Fig. 4: (upper panel) granule (convection) pattern in white light. (lower panel) transient horizontal magnetic field. Bright while color corresponds to field strength of 200 G or beyond. (Courtesy of R. Ishikawa of NAOJ.)

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.

There is now the possibility that the results of the observations of Hinode may be used to solve the coronal heating problem. Hinode has revealed there are strong *vertical and horizontal* magnetic fields outside sunspots, and strong coronal activity even 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. Hinode expects 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 either nano-flares and/or some form of magneto-hydrodynamic waves propagating open field lines are responsible for the heating of corona.

EIS has the capability of obtaining physical information of the coronal plasma, such as temperature, density, and velocity. An interesting discovery with EIS is the high-speed upflows at footpoints of coronal loops in active regions [15] and weakly emitting outflows at the edge of active regions in open magnetic field configurations [16, 17], both of which have upflow velocities exceeding 100 km/s. Interestingly, broad EUV emission lines are found in these upflow regions, suggesting the presence of unresolved fine-scale dynamic structures that reflects how heating energy is deposited. EIS has also revealed that a typical coronal filling factor in active region loops is about 10% from its density diagnostic capability [18], which determines the electron density of various structures in the transition region and corona with unprecedented statistics.

5. PROMINENCE, SPICULE AND WAVES

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 ground-based observations, but Hinode now appears to be opening the door to these waves being observed in many different circumstances.

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 plasmas maintained in coronal horizontal magnetic field-line configurations. Observations show horizontal threads of plasma which have oscillatory behavior with periods around 170 s. This is consistent with Alfvén wave propagation which may possibly heat the surrounding corona [19]. What comes as a surprise is that prominences in the quiet Sun show dark upward flows that are turbulent and move at speeds of 20 km/s [20]. The existence of these flows is a real challenge to the current MHD understanding of prominences as they are inconsistent with the magnetic sustainment of heavy low-temperature plasma against gravity.

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.* (2007) [21] 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. Both types of spicules show a swaying behavior strongly indicative

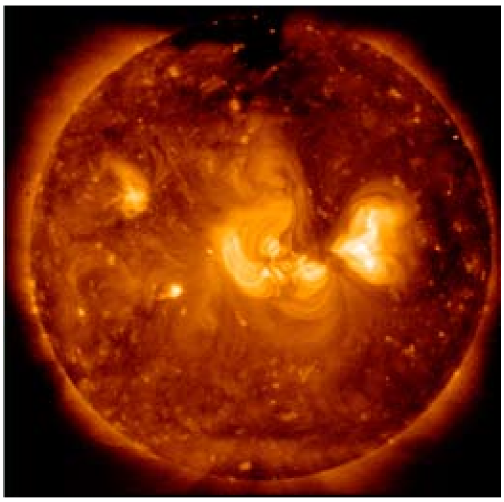

Fig. 5: X-ray images of the entire solar surface photographed by the X-ray telescope onboard Hinode. A punctuate structure called an X-ray bright point was identified for the first time, which revealed that the corona is made up of magnetic loops. (Courtesy of NAOJ, JAXA, and NASA.)

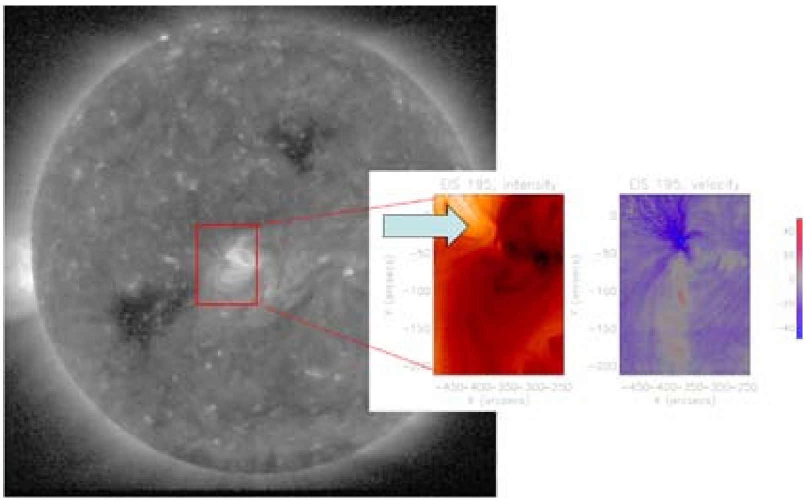

Fig. 6: The right hand side shows a full sun XRT image with the box showing the EIS FOV. The left EIS image is the intensity and the right image is the Doppler velocity. The blue arrow shows the source of the strongest outflow. (i.e., [25], [17].)

of Alfvén waves. They show amplitudes and periods that are consistent with the p-mode 5 min oscillation [22], 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 even within the coronal holes. One explanation of the formation of jets involves a scenario in which emerging flux from below the surface reconnects with coronal holes. Hinode now has the ability (thanks to its higher spatial resolution) to observe jets in significantly more detail to study basic physical processes [23]. 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 [24]. The characteristics of these jets are consistent with plasma being ejected at the Alfvén speed, which is a direct observation of the outflow jet from the reconnection site. These small jets may carry as much as a tenth of the mass necessary for the solar wind.

These observations clearly show that Alfvén wave or magneto-hydrodynamics waves are ubiquitous in chromosphere and in corona, and this opens up a new research field to understand its role in the heating and acceleration of coronal plasma, and to diagnose the Sun from below photosphere through corona with seismic approach.

6. SOLAR WIND AND POLAR REGION

The sun supplies a huge amount of plasma into interplanetary space as solar wind. 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 acceleration. 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 [25] 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. Fig. 6 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. 6). The region of weakest emission at the top of the active region shows the strongest velocities [17]. 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 may be 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.* (2008) [26] 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. 7]. 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.

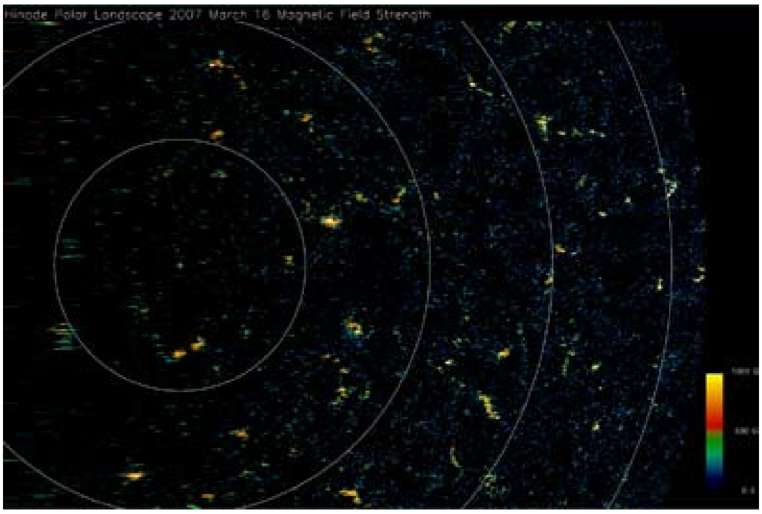

Fig. 7: South polar view of the magnetic field strength taken at 12:02:19-14:55:48 UT on 16 March 2007. The original observing field of view is 327.52" (east-west) by 163.84" (north-south) and was converted to a map seen from above the south pole. East is to the left, west is to the right, and the observation 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. (after [26].)

7. GIGANTIC 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 have complex structure.

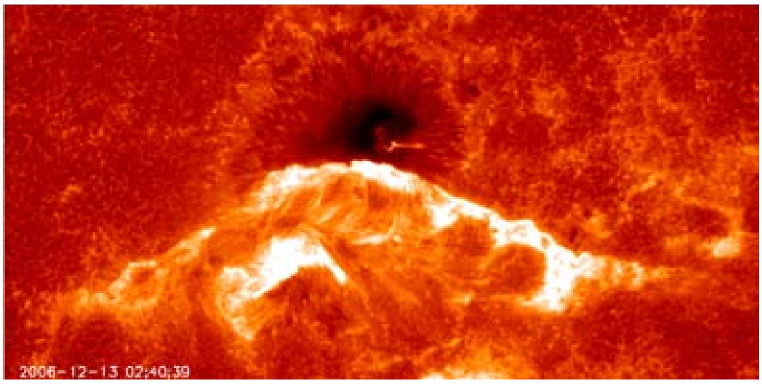

Fig. 8: Large solar flare captured by SOT on 13 December 2006. Two-Ribbon structure and some of post-flare loops between the two ribbons are clearly seen. (Courtesy of NAOJ, JAXA, and NASA.)

Although the sun is now 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 [27]. The impact on the corona above of this shearing motion could be seen [28]. 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. Fig. 8 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.

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) [29] 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 1,000 km/s were measured at ACE from this event.

The sun is in a period of minimum activity at the time of writing. Solar flares will start to occur more frequently as the sun heads toward its period of maximum activity around 2013-2014, 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.

8. MAGNETIC UNIVERSE

Recently, there is growing interest on the role and behavior of magnetic field in the universe. Topics include X-ray flares in proto-stars, galactic prominence and spicule [30], X-ray ridge emission near Galactic center, jets from accretion disks, non-thermal particle acceleration in clusters of galaxies, gamma-ray bursts, pulsers, and magnetors, relationship between magnetic field in early universe and galactic dynamo. As we saw here in this brief report, with rapid progress in space observations, we are able to observe and resolve fascinating magneto-hydrodynamics phenomena occurring on the Sun. Sun is, needless to say, a natural laboratory to be accessible through telescopes. Indeed, direct comparison with numerical simulation and theory becomes possible probably for the first time with the arrival of Hinode. We are entering a golden age in solar physics, and believe that progress in solar physics brings us with much better understating on the magnetic universe to which we all belong.

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