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Hinode "A new solar observatory in space"

Saku Tsuneta*
Hinode Science Center and Advanced Technology Center,
National Astronomical Observatory of Japan, Mitaka, Tokyo 181-8588, Japan

Abstract. The road to Hinode is briefly reviewed. Some science highlights of the Hinode mission are described, and the plan following Hinode is presented.

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1. Introduction

It is fascinating that a solitary star like the Sun emits intense X-rays from its outer atmosphere. The hot coronae with sporadic energy release in the form of heating, particle acceleration and eruptions above the surfaces of late-type stars are driven by magnetic fields.

Hinode (Kosugi et al. 2007) comprises an observatory-style set of instruments that function together to answer the fundamental questions of how magnetic fields are formed and how they dissipate to create the hot solar corona. The concept of Hinode is that the X-ray and EUV telescopes (Narukage et al. 2011; Culhane et al. 2007) observe the dissipation part of the magnetic life-cycle, while the visible light telescope (Tsuneta et al. 2008a) simultaneously observes the generation and transport of the magnetic fields.

Hinode is Japan's third solar physics mission, and three major space agencies (JAXA, NASA and ESA) and 11 institutions in four countries have contributed to its construction and operation. The concept design of the Solar-B (the then code name) was developed in 1994–1995. Ten years later, in September 2006, after years of hard work by numerous individuals, the Hinode spacecraft was successfully launched. First-light images and movies were just stunning. Hinode has worked perfectly ever since, bringing an outstanding progress in astronomy.

*email: saku.tsuneta@nao.ac.jp

The Solar-B project had been a difficult but enjoyable project for me and, I believe, for many other people who had been involved in the programme. Indeed, the programme had developed over ten years from an ambitious and fragile programme in its infancy to one of the most sophisticated solar physics missions in the world.

The number of Hinode papers in refereed journals reaches 456 (June, 2011), and the publication rate is growing even 5 years after its launch. The contribution from the Asian countries (especially India, Korea, and China in addition to Japan) is becoming comparable to that from USA and the European Union.

Following Hinode, the Solar-C mission is being considered. There is still a long way ahead of us, and we anticipate the launch of the Solar-C in 2010s. I stress the importance of the vigorous pursuit of the complementary efforts: large and small space programmes, space and ground-based missions, observations and theory/simulations.

2. Highlights of the Hinode mission

I briefly describe a few important discoveries so far made by Hinode. The choice is subject to my personal bias. I should mention that we tend to rediscover what has been discovered with ground-based telescopes. Here, the discovery refers to identification and substantial understanding of new properties. These discoveries include among others (1) Transient horizontal magnetic fields (Lites et al. 2008; Ishikawa & Tsuneta 2011), (2) emergence of helical flux ropes (Okamoto et al. 2008) , (3) Intense polar magnetic fields (Tsuneta et al. 2008b; Ito et al. 2010), (4) waves in photosphere and chromosphere (De Pontieu 2008; Fujimura & Tsuneta 2009; Okamoto & De Pontieu 2011), (5) convective collapse (Nagata et al. 2008; Stenflo 2010), (6) dynamic chromosphere driven by magnetic reconnection (Shibata et al. 2007; Shimizu et al. 2009), (7) fine structures in prominence (Berger et al. 2011; Okamoto et al. 2010), and (8) enhanced width of coronal emission lines (Hara et al. 2009).

2.1 Transient horizontal magnetic fields (Lites et al. 2008; Ishikawa & Tsuneta 2011)

Transient horizontal magnetic fields (hereafter referred to as THMFs) correspond to the apexes of emerging small magnetic loops with sizes comparable to or smaller than granulation cell. Their sizes never exceed that of the granular convection cell where they emerge. They manifest themselves in the linear polarization signal, and are ubiquitous in the quiet Sun. They are short-lived with time scale smaller or comparable to the time scale of granulation. The boundaries of the meso-granulation harbour THMFs, while usual vertical fields are concentrated around the boundaries of the meso-granulation and super granulation. This non-uniform presence of THMFs in terms of granulation, meso-granulation and super-granulation has not yet been explained.

The origin of the quiet Sun magnetism would be related to THMFs. THMFs apparently reach chromosphere and possibly corona, and the remnant vertical 'footpoints' (in the photosphere) are subject to convective collapse (Hasan 1985; Stenflo 2010). Such footpoints may be transported from the inter-network region to its boundary region by supergranular outward flow. This sequence of evolution starts with small emerging bipolar fields. Chromospheric and coronal magnetic fields associated with the supergranular transport of their footpoints may become quite complex, and there is implication here to the chromospheric and coronal heating problem.

The intrinsic magnetic field strength of THMFs is smaller than the equipartition magnetic field strength (600–700 G) of granular motion, whereas those for the usual vertical magnetic patches often exceed the equipartition magnetic field strength. This suggests that the THMFs are generated by a local dynamo process associated with granular motion. The histogram of the intrinsic magnetic field strength for THMFs is exactly the same between the quiet Sun and the polar region, supporting this possibility. This, however, should be further confirmed by other observations, given the importance of the implication. A key observation to check whether this is the case would be to study the spatial variation all over the Sun and the time variation over the solar cycle with Hinode. Note that only Hinode has spatial resolution and stability good enough to detect the THMFs over extended period of time.

The seed magnetic fields created by the Biermann battery process after the start of the reionization phase of the universe are very weak, but are intensified to the observed magnetic fields of the order of μG, which are the present-day magnetic fields of galaxies and clusters of galaxies, with turbulence associated with the formation of the proto-galaxies (Kulsrud 2005). The local dynamo process as observed with Hinode may be a very basic process that connects very weak seed fields in early universe to the present-day relatively strong magnetic fields.

2.2 Emergence of helical flux ropes (Okamoto et al. 2008, 2010)

Hinode found emergence of a helical rope in an active region. It emerged along the neutral line with a slight helical structure. The neutral line is the only location where such a helical flux rope can appear to have the 'sliding door'. The flux rope with correct helicity can appear without reconnection, which destroys the emerging flux rope with the existing oppositely directed vertical magnetic fields. If this is the case, such flux ropes are expected to emerge in other locations, but cannot be seen due to reconnection with existing vertical magnetic fields. The emergence of such helical flux ropes may provide implication on the convection zone and solar dynamo.

The emerged flux rope was closely related to the formation of a prominence and coronal cavity seen in soft X-rays. Berger et al. (2011) reported that the temperature of the flux rope entering the corona already had the temperature as high as 1 MK, suggesting efficient coronal heating. The intrinsic magnetic field strength of the helical flux rope in the photosphere was around the equipartition magnetic field strength (600–700 G) with a low filling factor of approximately 0.2. A sea-serpentine modulation due to individual convective motion was seen. The properties of the weakly helical flux rope and those of THMFs are obviously completely different, but I notice some similarities between the two such as intrinsic magnetic field strength, low filling factor, and the very horizontality of magnetic fields. There may be a causal relationship between these two in the convection zone: the horizontal flux ropes may somehow be the more organized form of randomly directed THMFs.

2.3 Intense polar magnetic fields (Tsuneta et al. 2008b; Ito et al. 2010)

Polar faculae have been believed to be due to intense magnetic fields even without very direct observations. The magnetism of the polar regions is revealed with the Hinode high resolution observations of the extreme limb for the first time. The polar region consists of scattered kG magnetic patches whose polarities are the same and are consistent with the known polarity of the polar region. Smaller weaker patches have both polarities. Such kG patches with mixed polarities are seen in the supergranular boundaries with smaller size and sparse distribution in the quiet Sun as well.

These kG patches in the polar region sometimes emerge as unipolar patches via the amalgamation of smaller patches. The disappearance of such magnetic patches is just the reverse process: disappearance of unipolar fields or disintegration to smaller patches. The life time of these patches is 1–10 hours, while the overall number of kG patches in the polar region appears to be maintained providing stable global poloidal magnetic fields. This indicates that the magnetic flux smaller than the detection limit of Hinode is gathered by the swirl-like flow field, which may be a final form of meridional flow. It is important to obtain information of both magnetic fields and the flow fields simultaneously to understand the formation process of the kG patches. The process is by no means trivial.

Since polar regions are occupied by these eminent unipolar kG patches and smaller bipolar fields, the field lines leaving the photosphere and reaching to the heliosphere may come from a few tens of kG patches in the polar region. This means that the fast solar wind comes from these kG patches. A rapid expansion of the flux tubes from the kG patches in the transition region may provide higher cutoff frequency of the Alfven waves propagating along the field lines from the kG patches, making the kG patches chimney for the Alfven waves to accelerate solar wind.

The discovery of these kG patches in the polar region solves a puzzle of the solar dynamo. Simulations of flux tube dynamics in the convection zone suggest that the toroidal magnetic field at the bottom of the convection should be as strong as 10^5 G (D'Silva & Choudhuri 1993; Fan, Fisher & DeLuca 1993). It would be impossible for the differential rotation of the Sun to generate such a strong field within the solar cycle beginning with a weak poloidal field. On this ground, Choudhuri (2003) predicted that the poloidal field should get concentrated in intermittent magnetic flux bundles of high field strength, which is now beautifully confirmed by this Hinode discovery.

Hinode has been regularly observing both polar regions, and we are seeing stable south pole and north pole whose polarity is about to change. This will be reported elsewhere.

2.4 Waves in photosphere and chromosphere (De Pontieu 2007; Fujimura & Tsuneta 2009; Okamoto & De Pontieu 2011)

Transverse waves are found in prominences and in spicules. These waves are found in the high-resolution movies by following the motions of the thin threads consisting of active region prominences and the spicules. These waves have a single frequency suggesting standing waves, but they turn out to be propagating waves as far as waves propagating along spicules are concerned. It is important to obtain magnetic and velocity fluctuations to better understand the nature of these transverse waves. Hinode spectro-polarimeter clearly identifies kink and/or sausage waves propagating along the thin flux tubes in the photosphere. The way to observe these photospheric waves is close to the in-situ observations of geomagnetic environment. The detected waves are superpositions of upward-moving and downward-moving waves with almost equal amplitude. A small leakage flux may provide the energy required to heat the corona. We, however, note that if the low filling factor of such flux tubes has to be taken into account to estimate the total flux into the overall corona, it may be too small to maintain the corona.

2.5 Convective collapse (Nagata et al. 2008; Stenflo 2010)

A process called convective collapse to enhance the magnetic field strength while maintaining the magnetic flux was proposed by Parker (1978), Spruit (1979) and Hasan (1985). A very clear observation to support the existence of such a process is finally found in the Hinode data. The example provided by Nagata et al. (2008) is by no means unique, but is ubiquitous (Stenflo 2010; Ishikawa & Tsuneta 2011). The quiet Sun magnetism (vertical fields) has bimodality in intrinsic field strength. Stenflo (2010) put it due to collapsed and uncollapsed magnetic fields. It is a very basic process that a cosmic flux tube increases its magnetic field strength beyond the local equipartition field that a dynamo process may ultimately reach in the convective environment.

2.6 Dynamic chromosphere driven by magnetic reconnection (Shibata et al. 2007)

It was recognized with the Yohkoh mission that magnetic reconnection, especially the type of reconnection proposed by Harry Petschek, plays a vital role in solar flares and micro-flares. Hinode discovered that magnetic reconnection takes place in the chromosphere, and is an apparent driver for the jets and fountains seen in the Hinode movies of the chromosphere. Though the precise magnetic configuration is not known, the signature of reconnection is apparent. The environment that is different from that of the corona includes dominance of neutral atoms, higher beta plasma (as compared with corona), much lower electrical conductivity (due to the lower chromospheric temperature) and possible complex magnetic geometry in the chromosphere. Magnetic reconnection in this parameter regime is a new topic in the study of astrophysical plasmas.

2.7 Fine structure in prominences (Berger et al. 2011; Okamoto et al. 2010)

Remarkable observations of prominence have been made with Hinode: the morphology of a prominence appears to be completely different between the active region prominence and the prominence in the quiet Sun. Active region prominences have somewhat organized horizontal fine threads implying a magnetic configuration. The formation of the active region prominence appears to be related to the emerging flux rope as clearly illustrated in Okamoto et al. (2010), while the quiet Sun prominence does not have the apparent signature of magnetic fields.

2.8 Enhanced width of coronal emission lines (Hara et al. 2009)

Enhanced widths of coronal emission lines are observed for an active region located near the disk center, while the enhancement is less significant for the same active region reaching the limb. This suggests the presence of the unresolved dynamic situation consisting of up-flows and down-flows near the footpoints of the coronal loops. We may be seeing a consequence of nanoflare-heated loops, or this may be a signature of the footpoint heating as suggested by De Pontieu et al. (2007).

3. Solar-C mission

The ISAS/JAXA Solar-C working group (WG) has been studying two options for Solar-C mission: the plan A (out-of-ecliptic mission) and the plan B (high resolution spectroscopic mission). We have recently decided that the plan B should have higher priority, and should be realized as the Solar-C mission.

The purpose of the Solar-C mission is to reveal the magnetic and plasma structures of the whole solar atmosphere from the photosphere throughout the corona, and to understand the mechanisms of chromospheric and coronal heating/dynamics and acceleration of the solar wind. It is our understanding that small scale processes related to waves, shocks and reconnection play an important role in the global phenomena of the Sun and the heliosphere, as we have seen in the previous section.

Our approach to implement this objective is through high resolution imaging spectroscopy for the entire solar atmosphere without gaps in temperature coverage where plasma might escape detection because of lack of instrumental sensitivity. Hinode clearly showed that the combination of high spatial resolution and spectroscopy (including spectro-polarimetry) is critically important both in the photosphere and in the corona. The strawman instruments for the Solar-C satellite include a larger visible light telescope that would obtain magnetic and velocity maps for the chromosphere and the photosphere, a high-throughput UV imaging spectrometer covering the chromosphere through the corona, and an X-ray/EUV (spectroscopic) telescope. The three instruments will seamlessly cover the photosphere through the corona. Such a wide spectroscopic coverage is not available with any mission so far launched. The Solar-C instruments will be characterized by high spatial and spectral resolution, high throughput, wide temperature coverage, and high time resolution, better than available from any existing missions. An Interim Report is available through the Solar-C web site. The document describes the current state of development for the Solar-C mission concept. As the programme progresses, we will continue to solicit new ideas and improvements to the mission definitions, especially from our colleagues outside Japan.

There is no question that the chosen Plan B is an outstanding mission that needs to be implemented. However, we also recognize the very important science goals of the plan A satellite, namely seismic investigation of the internal structure of the Sun and understanding of the dynamo process with possible heliospheric observations. Therefore both missions are important and attractive for the future of solar physics, and it will require a long time to be ready for one mission. We desire to continue activities for plan A as a Solar-D programme. This means that in parallel with the Solar-C development, we plan to allocate some resources to run the basic development programme for the Solar-D mission as well.

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