Hinode observations of flares and active region emergence

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Abstract. After observing the quiet Sun during a long and deep minimum, Hinode’s observing priority is now the active Sun, i.e., flares and active regions. Because of its small field-of-view instruments and telemetry restrictions, capturing major flares with good observing coverage needs challenging efforts on operation planning for Hinode and we have been using the latest available AIA and HMI full-Sun images for targeting. Also, capturing the initial phase of large-scale emerging flux activities is not easy for Hinode without having the forecast of flux emergence before they are visible on the surface. Nevertheless, Hinode has some good examples of observations of such events. In this paper, we briefly discuss two specific observations; X-class flares in March 2012 and a large-scale flux emergence in December 2009. The Stokes polarimetry data for the flares presented in this paper reveals significant gas flows along the neutral line of the sheared magnetic distributions and the change of magnetic field inclination at the areas where penumbral development and disappearance was observed with the occurrence of the flares. The flux emergence and the sunspot formation presented were well monitored by the Hinode three telescopes from the beginning through the end of the emergence. Of particular interest is the finding of a precursory signature in the chromosphere preceding the appearance of sunspot penumbra.

1. Towards better Hinode observations of emerging active regions

Hinode [1], launched on September 2006, has been observing the Sun to understand the processes of magnetic field generation, the processes responsible for energy transfer from the photosphere to the corona, and the mechanisms responsible for heating, dynamics and eruptive phenomena. The Solar Optical Telescope (SOT) [2, 3, 4, 5] provides observations at 0.2-0.3 arcsec resolution of magnetic and velocity fields at the solar surface, while the EUV Imaging Spectrometer (EIS) [6] and the X-Ray Telescope (XRT) [7, 8] provide EUV spectroscopic data and soft X-ray images, respectively, for diagnosing thermal properties and dynamics in the corona. Their observing field of views are limited to the target of interest, in order to obtain high spatial resolution and high precision, and thus they are complementary to the AIA and HMI full-Sun images from the Solar Dynamics Observatory.

The snapshot successfully acquired during the transit of Venus became one of the Hinode’s famous pictures in 2012. The impressive image (Figure 1) called attention from the public and Japanese major newspapers published this colorful image on the top page. This image was quickly distributed through the internet media. A honorable note was attached to the picture in one media site (gizmodo): ”Not only this image wins the internet for the most amazing image
of the Venus transit, but to me it’s also one of the most impressive images in the history of astronomy and space exploration. The scale and the feeling left me in awe.”

With the Hinode telescopes, we observed quiet regions including coronal holes and ephemeral regions without sunspots during a long and deep minimum (2007-2009), but we were surprised that quiet regions are full of dynamical natures of magnetic structures. From 2009, the Sun started to show the appearance of new-cycle active regions on the surface and produce flares (Table 1). In order to investigate the active Sun with Hinode, active regions, especially regions with the potential to create flares, are given the highest observing priority. Capturing major flares with good observing coverage, however, is operationally challenging because Hinode has narrow field-of-view instruments and strong limitation on telemetry volume due to onboard X-band modulator malfunction [9]. Telemetry resources should be also shared with synoptic observations performed repeated on a regular basis and non-flare observations proposed by the international user community (called HOP, Hinode Operation Plan). The selection of active regions for the observations is made by checking AIA and HMI full-Sun images available at the time of selections. We may also consider the Maximum Millennium Flare Watch target designation. As soon as possible after the issuance of a Maximum Millennium Flare Watch, we attempt to follow that target and use flare watch observing sequences. In addition, the Hinode team may declare “Hinode flare watch” to shift all resources to observations of flare-potential regions.

2. Flare observations

Hinode data have been extensively analyzed for three X-class flares during December 2006, producing more than 30 papers in refereed journals. After four years of solar quietness, the Hinode telescopes started to capture major flares from 2011. Table 1 shows the statistics for all flares recorded in the SolarSoft flare list (SSW list), in which not only X-, M-, and C-class flares but also B- and A-class flares are included. The number of flares acquired with the XRT, SOT
filtergraph (FG) and EIS is based on the Hinode flare catalog; flares are counted as successful flares in this table, if more than one sample (image for XRT and SOT or map for EIS) is acquired during the time of the event and the flare location is within the instrument field of view [10]. More than half of the flares were captured with the large field-of-view XRT, but only a limited number of flares were captured with the narrow field-of-view SOT and spectroscopic instrument EIS.

Table 1. Number of flares in Hinode data (courtesy of K. Watanabe)

| All classes | XRT | SOT(FG) | EIS | SSWlist |
|-------------|-----|---------|-----|---------|
| 2006 (25 Oct-) | 160 | 171 | 68 | 432 |
| 2007 | 443 | 267 | 209 | 713 |
| 2008 | 24 | 8 | 7 | 134 |
| 2009 | 125 | 83 | 65 | 320 |
| 2010 | 690 | 264 | 125 | 1248 |
| 2011 | 1269 | 464 | 276 | 2389 |
| 2011(-31 Oct) | 1010 | 390 | 245 | 1958 |
| total | 3721 | 1647 | 995 | 7194 |
| percent of SSW | 51.7% | 22.9% | 13.8% |

Table 2. Number of major flares included in Table 1 (courtesy of K. Watanabe)

| GOES class | XRT | SOT(FG) | EIS | SSWlist |
|-------------|-----|---------|-----|---------|
| X | 14 | 10 | 7 | 19 |
| M | 143 | 70 | 53 | 260 |

The number of successful X- and M-class flare detections are given in Table 2 and details of the successful X-class flares are listed in Table 3. The table gives GOES class, location on the solar disk, and number of images (for XRT and SOT) or raster-scanning maps (for EIS) during the flare period. “Flare mode” in remarks means that the telescopes might perform observations with high-cadence flare watch program. The onboard mission data processor analyzes XRT flare patrol images for large intensity increases indicative of a flare [8]. If a flare is found a flare flag is issued that allows the telescopes to terminate their pre-scheduled sequence and switch to a flare watch program.

3. 7 March 2012 X5.4/X1.3 flares
These flares occurred in the complex active region NOAA 11429. XRT images show a bright sheared feature along the neutral line, suggesting a sheared structure in the coronal magnetic fields. The X5.4 peak was observed as strong heating in a local loop structure existing along the neutral line. This compact brightening evolved into the formation of a large flare arcade. This morphological change was triggered by the X1.3 flare.

For accurate determination of magnetic fields and dynamics at the photosphere, SOT acquired Stokes-polarimeter (SP) [11] maps every a few hours. The SP yields the full-polarization states
Table 3. Hinode’s X-class flares in 2006-2012 (courtesy of K. Watanabe)

| Flare date/time | GOES | Location  | XRT | SOT (FG) | EIS | Remarks |
|-----------------|------|-----------|-----|----------|-----|---------|
| 2006/12/06 18:29 | X6.5 | S05E57    | 0   | 30       | 0   |         |
| 2006/12/13 02:14 | X3.4 | S07W22    | 44  | 44       | 1   |         |
| 2006/12/14 21:07 | X1.5 | S06W46    | 84  | 80       | 1   |         |
| 2011/02/15 01:44 | X2.2 | S20W10    | 116 | 102      | 0   | Flare mode |
| 2011/03/09 23:13 | X1.5 | N08W11    | 54  | 0        | 0   | Flare mode |
| 2011/08/09 07:48 | X6.9 | N14W69    | 59  | 0        | 0   |         |
| 2011/09/06 22:12 | X2.1 | N14W18    | 82  | 0        | 0   | Flare mode |
| 2011/09/24 09:21 | X1.9 | N13E61    | 0   | 0        | 6   |         |
| 2011/11/03 20:16 | X1.9 | N21E64    | 122 | 118      | 0   | Flare mode |
| 2012/01/27 17:37 | X1.7 | N33W85    | 447 | 381      | 7   | Flare mode |
| 2012/03/05 02:30 | X1.1 | N19E58    | 220 | 275      | 0   | Flare mode |
| 2012/03/07 00:02 | X5.4 | N18E31    | 296 | 6        | 0   | Flare mode |
| 2012/03/07 01:05 | X1.3 | N15E26    | 63  | 0        | 0   |         |
| 2012/07/06 23:01 | X1.1 | S13W59    | 161 | 0        | 1   | Flare mode |
| 2012/07/12 15:37 | X1.4 | S13W03    | 278 | 43       | 1   | Flare mode |
| 2012/10/23 03:13 | X1.8 | S13E58    | 60  | 101      | 3   | Flare mode |

Figure 2. Two physical parameters derived from SOT Stokes-polarimeter data. Left: $B_z$, the magnetic flux component vertical to the solar surface. Contours give the position of flare ribbons seen in Ca II H images at initial phase (7 March 2012 00:07:25 UT). Right: Doppler shift of the Fe I 630.15 nm line. Red is away from the observer and blue is toward the observer. The arrow gives the direction to the solar disk center.
Figure 3. Measured Doppler velocity compared with the inclination of magnetic flux. The inclination is the angle on the local coordinate frame; 0 and 180 deg is vertical to the solar surface and 90 deg is horizontal orientation. Red points are Doppler features (higher than 1 km/s) observed along the neutral line. Blue points are from the penumbral areas where Evershed flow signatures are observed. Contours represent the density of data points in the entire field of view.

Figure 4. Continuum images recorded before and after the X5.4 flare. The change of magnetic field inclination is given for one location where penumbra disappeared (values given in the left image) and four locations where penumbra developed (in the right image).
negative and positive polarities) exist. Remarkable is strong Doppler shift signals (the order of $\pm 5$ km/s, which corresponds to the sound speed at the photosphere) distributed along the neutral line. The strong Doppler shift signals are dominantly observed in horizontally or highly inclined magnetic fields (Figure 3), indicating that gas flows are excited in horizontal flux tubes. Investigating the roles of these gas dynamics may be important for understanding dynamics and triggering mechanisms of flares.

Continuum images from the SP maps show both the decay and formation of sunspot penumbra in several areas at the time of these flares (Figure 4). Such rapid penumbral changes have been observed in other flares [12, 13]. The changes in field inclination at each penumbral change can be accurately evaluated with the SP data. Both cases shows that the field is changed toward the horizontal orientation in the region where penumbral changes are observed. This would be due to magnetic field restructuring associated with the flares.

4. Initial phase of large-scale emerging flux activities
Emerging processes of magnetic flux are another important target for observations during the time when the solar activity is high. Flux emergence is a key process for energy storage and the triggering of flares and microflares (transient brightenings) [14, 15]. We lack knowledge about magnetic field evolution and dynamics during the large-scale emerging flux activities, because of little number of high resolution observations available for the initial phase. Forecasting is not possible before the emerging flux elements appear on the photosphere, and only chance encounters enable narrow-field-of-view telescopes to properly point to the emerging site from before the start of emergence. In the period from 29 December 2009 through 1 January 2010, the SOT has continuously monitored the active region NOAA 11039. Fortunately, a large-scale emerging flux appeared in the SOT field of view on 30-31 December.

Sunspots were formed in a sequence of successive magnetic flux emergence to the solar surface. Pores, which are essentially small sunspots without penumbra (naked umbra), first formed at both edges of emerging flux regions, and then they developed to large sunspots with penumbra (see Figure 6). In this evolution, details of the penumbral formation are hidden in a veil of...
mystery. Figure 5 shows the morphological evolution of a pore (sunspot) formed at the leading edge of the emerging flux region in chromospheric Ca II H and photospheric G-band images taken every about 2 hours. Emerging flux activities happened at the east side of the spot, and remarkable chromospheric brightenings are associated with the elongated structure formed in the umbra. The penumbra formed in sectors; the penumbra was developed at the north side, and then it formed at the west and south.

In the Ca II H images, we noticed a zone between the umbra and ambient bright features before the penumbral formation (Figure 5). This zone appeared soon after the pore formation and was seen for about 10 hrs until the penumbral formation. The zone is annular with the width of 3”-5” and it exists at the outer side of the umbral edge (indicated by the dotted contour) on almost all the locations excepting the east side of the spot. The outer boundary of this zone is remarkably sharp. The penumbra was developed as if to fill the annular zone. The observations indicate that the annular zone is different from sunspot moat flow region and that it likely represents a structure in the chromosphere. A possible interpretation is that the annular zone may reflect the formation of a magnetic canopy at the chromospheric level overlying the region surrounding the umbra, much before the formation of the penumbra at the photospheric level (Figure 6). The magnetic structure observed as the annular zone goes down to the photospheric level, resulting in appearance of sunspot penumbra. This observation clearly showed the importance of magnetic structures at the chromospheric level in the development of photospheric sunspot penumbrae.

5. Final remark
As shown in the flare statistics tables, there are many unique Hinode datasets for X- and M-class flares. The field of view may be restricted in the flare region (a part of active region) but it is with high spatial resolution and precision. These data can be enhanced by combining with
complementary AIA and HMI full-Sun images and thus they can contribute to solar physics and space weather researches. We hope many researches use Hinode data more extensively in their researches.

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References
[1] Kosugi T et al. 2007 Solar Phys. 243 3
[2] Tsuneta S et al. 2008 Solar Phys. 249 167
[3] Suematsu Y et al. 2008 Solar Phys. 249 197
[4] Shimizu T et al. 2008 Solar Phys. 249 221
[5] Ichimoto K et al. 2008 Solar Phys. 249 233
[6] Culhane J L 2007 Solar Phys. 243 19
[7] Golub L et al. 2007 Solar Phys. 243 63
[8] Kano R et al. 2008 Solar Phys. 249 263
[9] Shimizu T 2009 The Second Hinode Science Meeting: Beyond Discovery-Toward Understanding ed. Lites B, Cheung M, Magara T, Mariska J. and Reeves K, Astron. Soc. Pac. CS-415 1
[10] Watanabe K, Masuda S, and Segawa T 2012 Solar Phys. 279 317
[11] Lites B W et al. 2013 Solar Phys. in press
[12] Wang H et al. 2004 Astrophys. J. 601 L195
[13] Deng N et al. 2005 Astrophys. J. 623 1195
[14] Shimizu T, Shine R A, Title A M, Tarbell T D, and Frank Z 2002 Astrophys. J. 574 1074
[15] Kano R, Shimizu T and Tarbell T D 2010 Astrophys. J. 720 1136
[16] Shimizu T, Ichimoto K, and Suematsu Y 2012 Astrophys. J. 747 L18