Hinode SP Vector Magnetogram of AR 10930 and Its Cross-Comparison with MDI

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Abstract

We present one Hinode Spectropolarimeter (SP) magnetogram of AR 10930 that produced several major flares. The inversion from Stokes profiles to magnetic field vectors was made using the standard Milne–Eddington code. We successfully applied the Uniform Shear Method for resolving the 180° ambiguity to the magnetogram. The inversion gave very strong magnetic field strengths (near 4500 gauss) for a small portion of area in the umbra. Considering that the observed V-profile of 6301.5 Å was well-fitted as well as a direct estimation of the Zeeman splitting results in 4300–4600 gauss, we think that the field strengths should not be far from the actual value. A cross-comparison of the Hinode SP and SOHO MDI high resolution flux densities shows that the MDI flux density could be significantly underestimated by about a factor of two. In addition, it has a serious negative correlation (the so-called Zeeman saturation effect) with the Hinode SP flux density for umbral regions. Finally, we could successfully obtain a recalibrated MDI magnetogram that has been corrected for the Zeeman saturation effect using not only a pair of MDI intensity and magnetogram data simultaneously observed, but also the relationship from the cross-comparison between the Hinode SP and MDI flux densities.

Key words: Sun: magnetic fields — Sun: photosphere — Sun: sunspots

1. Introduction

The Hinode satellite (formerly Solar-B, Kosugi et al. 2007) is a very complicated and modernized one for studying solar activity with three advanced solar telescopes. It was launched on 2006 September 22 and has continuously provided us with the most excellent quality of data. The Solar Optical Telescope (SOT: Shimizu 2004; Tsuneta et al. 2007) on board Hinode is the largest and most advanced solar telescope flown in space. The SOT consists of the main 50 cm aperture telescope (Optical Telescope Assembly, OTA: Suematsu et al. 2007) and the focal plane package (FPP: Tarbell et al. 2007). The combined SOT system is optimized for accurate measurements of the vector magnetic field in the photosphere and the dynamics of both the photosphere and the chromosphere associated with the magnetic fields. Especially, the SOT has an unprecedented 0″2 resolution for observations of solar magnetic fields. Its great advantage is that polarization signals are free from the seeing effect and have excellent photometric accuracies.

We present in this paper an analysis of a vector magnetogram of AR 10930 taken by the Hinode Spectropolarimeter (SP). This active region produced several strong flares, including three X-class flares. It was the most active region during the first half year of the Hinode mission.

The SOHO MDI (Scherrer et al. 1995) has been providing us with excellent Dopplergrams and magnetograms since 1995. The MDI magnetograph has two different modes of spatial samplings: 0″6 pixel size for the high-resolution mode and 2″ for the full-disk mode. It is a filter-based magnetograph. It has a wide field of view (about 600″ by 600″ for the high-resolution mode) as well as a very good temporal cadence (typically one minute). However, there is a problem in the calibration of Stokes polarization signals to magnetic fields, as discussed below. It would thus be useful to make a cross-comparison between the MDI and Hinode SP magnetograms. The calibration of MDI magnetograms is based on a direct measurement of the spectral line splitting of Ni 6767.8 Å in magnetic fields due...
to the Zeeman effect. Five-point spectral images were taken sequentially in left and right circular polarization signals by placing a quarter-wave plate retarder in the beam before the filter. These sequential measurements produce Dopplergrams in both left and right circular polarizations and can be used to form a ‘center-of-gravity’ displacement of the line profile, which is directly proportional to the magnetic flux density. More detailed descriptions on the calibration process are well described by Berger and Lites (2003).

One calibration problem of filter-based magnetographs is the Zeeman saturation problem; that is, the circular polarization signal from a filter-type magnetograph may have a negative correlation with the longitudinal magnetic field strength in strong field regions (Sakurai et al. 1995). In this study, we confirmed that this problem is very serious, and then developed a way to correct for it using a pair of MDI intensity and flux density maps, simultaneously observed, as well as a relationship from a cross-comparison between the MDI magnetogram and the Hinode SP magnetogram. We demonstrated that the recalibrated MDI magnetogram without the Zeeman saturation effect is very consistent with the Hinode SP magnetogram.

The paper is organized as follows. In section 2, we describe the data, calibration, and methodology. Results are given in section 3. Finally, a brief conclusion and discussion are presented in the last section.

2. Data and Methodology

2.1. Data and Calibration

We use the magnetogram of the NOAA Active Region AR 10930 (S06W06) taken by the Hinode SP and the SOHO MDI. The Hinode SP uses two magnetically sensitive Fe I lines at 6301.5 and 6302.5 Å and the nearby continuum. Spectra are read out continuously at a rate of 16 times per rotation of the polarization modulator. The raw spectra are added and subtracted on board in real time, generating Stokes $IQUV$ spectral data. Its spectral resolution is about 30 mÅ and its sampling size is about 21.5 mÅ. Basic reductions (dark, flat, polarization, wavelength correction, etc) were applied to raw data by using a procedure developed by B. Lites (Tarbell et al. 2007). An inversion from the Stokes profiles to magnetic field vectors was done by a non-linear least-squares method (Skumanich & Lites 1987), which minimized the difference between an observed profile and a theoretical profile of the Stokes parameter, derived from the radiative transfer equation for polarization radiation. The Hinode SP observation was made from 13:50 to 15:39 UT on 2005 December 11 with an $\sim 0\.'16$ spectrograph slit and an $\sim 0\.'15$ stepsize. The observing field of view was about $195^\circ$ by $165^\circ$. It produced a polarimetric accuracy of about 0.1% with normal mode sampling. The line-of-sight component of the SP magnetogram was compared with the MDI magnetogram.

For a cross-comparison between the Hinode SP and SOHO MDI magnetograms, we took a high-resolution MDI magnetogram observed at 15:39 UT on the same day. The last part of the Hinode SP magnetogram was nearly-simultaneously obtained with the MDI data. The alignment between the two magnetograms was done by shifting the Hinode SP magnetogram to have the largest correlation between both flux densities. Therefore, its accuracy is about the single pixel size (0´6) of the MDI magnetogram, or more. A mis-alignment is probably caused by the observing time difference and the error of the SP step size.

The FITS header information of the Hinode SP data gives a 0´1476 (x-axis) stepsize and a 0´1585 (y-axis) pixel size, which were taken from a pre-launch ground measurement. Chae et al. (2007) independently estimated these pixel sizes (0´153 and 0´161) from a comparison between the Hinode SP and the Hinode FG/NFI (Filtergram/Narrowband Filter Imager) images. These authors assumed that the pixel size of the NFI image, which was taken in a $2 \times 2$ summing mode, is 0´16 by 0´16. We obtained 0´151 and 0´161 from a comparison between the Hinode SP and the MDI high-resolution data. Our estimation values are slightly larger than the ground-based measurement.

2.2. Uniform Shear Method for 180° Ambiguity

The 180° ambiguity is attributed to the fact that the polarization signals of the two antiparallel transverse fields are identical to each other, since transverse measurements from the magnetograph provide only the plane of the linear polarization. To resolve this ambiguity, we adopted the Uniform Shear Method (USM: Moon et al. 2003), which is a relatively simple three-step procedure. Moon et al. (2003) showed that this method could be successfully applied to several active regions that produced major X-ray flares.

Here, we briefly summarize its methodology as follows. The first step is to apply the potential field method, in which the observed transverse fields are taken to be closer to the potential field calculated from the measured line-of-sight magnetic field as a boundary condition using a Fourier-expansion method. The second step is that the observed transverse fields are taken to be closer to the most probable magnetic shear angle. In practice, the most probable shear angle is determined with several steps, which include (1) finding the local maximum of the shear angle distribution, (2) performing a Gaussian fit to the distribution, and (3) minimizing the number in the distribution tail. This second step minimizes any discontinuities in the number distribution of magnetic shear angle from a statistical point of view. Finally, we use an objective criterion, such that an observed transverse vector field is closer to a mean transverse vector for a surrounding local area. The computing time for resolving the ambiguity of the Hinode SP magnetogram (1281 by 1024 pixels) is about 9.6 s with SUN Ultra 20.

3. Results

3.1. Vector Magnetogram

Figure 1 shows an intensity image taken from the Hinode SP data of AR 10930 on 2006 December 11. It shows a big sunspot and a nearby small sunspot. It is noted that there are highly sheared penumbral fibrils between both sunspots. We can also see numerous small sunspots or pores outside the sunspots. Figure 2 shows the ambiguity-resolved vector fields for strong magnetic field areas (600 by 600 pixels). A careful examination of the direction of transverse fields shows that
the resolution of the 180° ambiguity is reasonably made for nearly all areas. For example, the direction of the transverse field smoothly changes from the center of the positive polarity sunspot to that of the negative polarity sunspot without any significant discontinuities. A comparison between figures 1 and 2 also shows that the transverse field directions follow the pattern of penumbral fibrils very well, especially near the highly sheared polarity inversion line.

Figure 3 shows a histogram of the magnetic shear angle for the ambiguity-resolved vector fields. It demonstrates that the histogram approximately follows a normal distribution, which is important in determining whether the ambiguity resolution is properly performed. The major assumption of the USM is that the number distribution of the magnetic shear angle approximately follows a normal distribution, whose validity has been demonstrated for several active regions (Moon et al. 2003 and this paper). A closer look at the histogram shows that there are two components: around 0° and about −90°. That is, the “0°” comes from most of the areas at which magnetic fields are nearly potential, and the “−90°” corresponds to the polarity inversion line area at which the transverse fields are nearly parallel to the polarity inversion line. For this magnetogram, the final estimate of the most probable shear angle described in the last section is about −32° from the second step of the USM.

Figure 4 shows a line-of-sight current-density map derived from the vector magnetogram. For its estimation, we used...
the transverse fields with 10 pixel (1:6) boxcar smoothing, and then took the four-point differentiation method. Without such a smoothing, the resulting current density map would be too noisy to identify some current density kernels. It is found that there are noticeable electric currents along the polarity inversion line with high magnetic shear. In addition, we can see numerous kernels of the electric current density in the weak field regions, which are quite different from low-resolution ground-based observations in which such kinds of small-scale current density structures might be smoothed out due to some seeing effects and/or smoothing methods. If reality, such electric current kernels may be related to coronal heating. To draw a more solid conclusion, a further careful investigation is necessary. It is also noted that the levels of the line-of-sight current density kernels from the Hinode SP magnetograph are several times higher than those from ground-based solar magnetographs (Gary & Demoulin 1995).

3.2. Cross-Comparison with MDI

Figure 5 shows a comparison of a Hinode SP line-of-sight magnetogram (13:50 UT–15:39 UT) and a MDI high resolution one (15:39 UT). There are two major differences. Firstly, there are many detailed magnetic structures in the Hinode SP magnetogram. First of all, the magnetic structure in the penumbral fibrils are clearly discernible and very consistent with the structure shown in figure 2. Secondly, for the MDI magnetogram there is evidently the Zeeman saturation effect in the sunspot umbral area. Especially, because the center of the largest sunspot has a similar magnetic flux density with the background flux density, we think that it can not be real.

Figure 6 shows a cross-comparison between the Hinode SP ($M_{SP}$) and the MDI flux densities ($M_{MDI}$), where $M_{SP}$ is defined as the multiplication of line-of-sight magnetic field ($B_{los}$) and the magnetic filling factor ($f$). For convenience, we use “gauss” instead of Mx cm$^{-2}$ to express the flux densities. For $-2000 \leq M_{SP} \leq 2000$ gauss of the Hinode SP flux densities, there is a relatively good correlation between both flux densities, except for very weak field regions. The maximum time difference between two observations (Hinode SP and MDI) is about 110 min (15:39–13:50). An analysis of fields outside the sunspot may be almost useless, because a small-scale flux moves over to be distances comparable to mesogranule size (about 7000 km) in about 30 minutes.

We note that the maximum value of the Hinode SP magnetic flux density is nearly 4500 gauss, and that this value is noticeably higher than that of typical ground-based magnetograms by at least 1000 gauss. A careful inspection of the inversion fitting result (not shown here) for the Stokes profiles near the center of a sunspot shows that the result should be looked at with care because of serious contamination of the spectrum with molecular lines, and worse photon statistics in the umbra. But, as far as the V-profile of 6301.5 Å is concerned, the fitting is successful. Independently, we estimated the Zeeman splitting, itself of 6301.5 Å, as 4300–4600 gauss, which is very consistent with the value from the inversion code. Thus we think that the field strength around 4500 gauss should not be far from the real value.

In figure 6, the Zeeman saturation effect is more clearly seen. That is, the flux density of MDI has a negative correlation with that of the Hinode SP for strong field regions larger than about 2000 gauss. For the worst case, about 4500 gauss in the Hinode SP magnetogram corresponds to about 200 gauss. For a given field of view, the MDI magnetic fluxes are $6.0 \times 10^{22}$ Mx for positive polarity and $1.2 \times 10^{22}$ Mx for negative polarity, respectively. The Hinode SP magnetic fluxes are $1.3 \times 10^{22}$ Mx for positive polarity and $2.6 \times 10^{22}$ Mx for negative polarity, respectively. That is, the Hinode SP magnetic flux is about twice the value of the MDI flux. This fact may imply that the magnetic helicity transport rate based on a time series of MDI measurements can be significantly underestimated, roughly by a factor of four, since the magnetic helicity is roughly proportional to the square of magnetic flux density (Chae 2001).

Figure 7 shows the relationship between the Hinode SP and MDI flux densities for three different areas. For convenience, the sunspot region A corresponds to regions where there is a negative correlation in figure 6 due to the Zeeman saturation effect. The sunspot region B covers the biggest sunspot in the field of view, except for the sunspot A area. The weak
Fig. 6. Cross-comparison between the Hinode SP line-of-sight and the MDI flux densities; $M_{SP}$ is defined as a product of the line-of-sight magnetic field and the magnetic filling factor.

Fig. 7. Relationship between the Hinode SP line-of-sight and MDI high resolution flux densities for three different areas (top, sunspot region A having the Zeeman saturation effect, middle, sunspot region B, and bottom, weak magnetic field region).

Fig. 8. Comparison of the MDI intensity (15:43 UT) and the absolute value of the MDI flux density (15:42 UT).

The slopes between the MDI and the Hinode SP flux densities are 0.50 (correlation coefficient, $r = 0.93$) for sunspot region B and 0.35 ($r = 0.79$) for the weak field regions, respectively.

3.3. Recalibration of MDI Flux Density

As shown in figures 5 and 6, the MDI flux density measurements in the sunspot umbra region are very problematic due to the Zeeman saturation effect. In this study, we recalibrated the MDI flux density as follows. Figure 8 shows a comparison of the absolute value of the MDI flux density (15:42 UT) and the MDI intensity (15:43 UT) near-simultaneously observed. These observations were made only several minutes later than the Hinode SP magnetogram observation. As generally expected, the absolute value of MDI flux density has a negative correlation with the MDI intensity for a high-intensity area larger than about 900. For the remaining area, both quantities have positive correlations, which are caused by the Zeeman saturation effect. Secondly, we applied two different formulae (two upper panels of figure 7) to two different areas (the higher intensity area with MDI intensity $> 900$ and the remaining area in figure 8). For the higher intensity area, the linear regression between the MDI and Hinode SP flux density for $-2000 \leq M_{SP} \leq 2000$ gauss was used to recalibrate the MDI flux density. For the lower intensity area, a quadratic relation for each polarity was applied, as shown in the top panel in figure 7. Figure 9 shows a comparison of the re-calibrated MDI and Hinode SP flux densities. Both flux densities have a quite good correlation ($R = 0.91$) with each other. Such a good correlation demonstrates that MDI flux densities can be reasonably re-calibrated using a pair of MDI intensity and magnetic data as magnetic field area corresponds to weak field regions including numerous small sunspots and pores, which are located at the right-hand side of two main sunspots. In the sunspot region A with the Zeeman saturation effect, the MDI magnetic flux density can be expressed as

$$M_{MDI} = -4913 - 2.30M_{SP} - 2.4 \times 10^{-4}M_{SP}^2.$$

(1)
Fig. 9. Comparison of the re-calibrated MDI and Hinode SP flux densities.

well as a cross-comparison relationship between the MDI and Hinode SP flux densities, as far as this sunspot is concerned.

4. Conclusion and Discussion

We have presented a Hinode Spectropolarimeter magnetogram of AR 10930. It shows very detailed magnetic field structures that have never been reported. We made a cross-comparison between Hinode SP and SOHO MDI high-resolution magnetograms. The main results and their implications can be summarized as follows:

1. A careful examination of the transverse fields shows that the $180^\circ$ ambiguity is reasonably solved by the Uniform Shear Method. The vector magnetogram shows that transverse fields are highly sheared near the polarity inversion line, resulting in strong vertical current density kernels. We also note numerous kernels of current density in the weak field regions, which may be related to coronal heating. A time-series Hinode SP data set would be very valuable for studying the magnetic field evolution and several activity quantities (e.g., vertical current density, linear force-free coefficient, magnetic shear, net magnetic forces, etc.) in that it can provide us with the most excellent quality of data.

2. The inversion fitting gives very strong magnetic field strengths (near 4500 gauss) near the sunspot center. Since the observed V-profile of 6301.5 Å is well fitted as well as a direct estimation of the Zeeman splitting results in 4300–4600 gauss, we think that the field strength around 4500 gauss should not be far from reality. This is very impressive in that the field strength is at least 1000 gauss larger than the typical value commonly adopted. To draw a more definite conclusion, a more detailed investigation is necessary.

3. A cross-comparison of the Hinode SP and SOHO MDI high-resolution flux density maps shows that the MDI flux density could be significantly underestimated for penumbral regions by about a factor of two. More seriously, the MDI flux density has a serious negative correlation (the Zeeman saturation effect) with the Hinode SP flux density for the umbral regions. For the observing field of view including AR 10930, the MDI magnetic flux is underestimated by about factor of two and the magnetic helicity by about a factor of four, as described in the previous section. Finally, we successfully obtained a re-calibrated MDI magnetogram, which was corrected for the Zeeman saturation effect by using a pair of MDI intensity map and magnetogram simultaneously observed as well as the relationship from a cross-comparison between the Hinode SP and MDI flux densities.

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