Long-term Variation of the Solar Polar Magnetic Fields at Different Latitudes (Postprint)

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Abstract

The polar magnetic fields of the Sun play an important role in governing solar activity and powering fast solar wind. However, because our view of the Sun is limited in the ecliptic plane, the polar regions remain largely uncharted. Using the high spatial resolution and polarimetric precision vector magnetograms observed by Hinode from 2012 to 2021, we investigate the long-term variation of the magnetic fields in polar caps at different latitudes. The Hinode magnetic measurements show that the polarity reversal processes in the north and south polar caps are non-simultaneous. The variation of the averaged radial magnetic flux density reveals that, in each polar cap, the polarity reversal is completed successively from the 70° latitude to the pole, reflecting a poleward magnetic flux migration therein. These results clarify the polar magnetic polarity reversal process at different latitudes.

Full Text

Preamble

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Long-term Variation of the Solar Polar Magnetic Fields at Different Latitudes

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Abstract

The polar magnetic fields of the Sun play an important role in governing solar activity and powering fast solar wind. However, because our view of the Sun is limited to the ecliptic plane, the polar regions remain largely uncharted. Using high spatial resolution and polarimetric precision vector magnetograms observed by Hinode from 2012 to 2021, we investigate the long-term variation of magnetic fields in polar caps at different latitudes.

The Hinode magnetic measurements show that the polarity reversal processes in the north and south polar caps are non-simultaneous. The variation of the averaged radial magnetic flux density reveals that, in each polar cap, the polarity reversal is completed successively from 70° latitude to the pole, reflecting a poleward magnetic flux migration. These results clarify the polar magnetic polarity reversal process at different latitudes.

Key words: dynamo – Sun: magnetic fields – Sun: photosphere

1. Introduction

Exploring the solar poles represents a great frontier in solar physics and is vital for understanding the drivers of long-term solar cycles, short-term solar activity, fast solar wind, space weather, and stellar cycles [**?**]. As the primary determinant, the Sun's polar magnetic fields are considered a direct manifestation of the solar interior and serve as seed fields for the global dynamo that produces the solar cycle [**?**]. Due to our location in the ecliptic plane, large projection effects limit precise measurement of magnetic fields in the Sun's high-latitude regions when observed from or near Earth.

Since polar magnetic fields are dominated by small-scale magnetic flux concentrations, accurately measuring them remains an outstanding challenge. Pioneering observations of the polar regions provided only longitudinal magnetic field measurements, assuming the polar magnetic fields to be approximately radial [**?**, **?**, **?**]. Vector magnetic field measurements can obtain detailed information about polar magnetic structure. The vector magnetic field of the solar polar region was first systematically measured with a ground-based instrument in 1997 [?]. However, atmospheric seeing makes it difficult for ground-based telescopes to provide accurate measurements of magnetic fields near the solar poles. Consequently, we lack knowledge about the long-term variation and spatial distribution of precise magnetic fields in the polar caps.

As a space mission, the Hinode satellite [?] provides high spatial resolution and polarimetric precision observations of polar vector magnetic fields [?, ?, ?, ?]. Hinode has routinely measured polar vector magnetic fields over a solar cycle, giving us a unique opportunity to investigate their long-term variation. Using ten years of vector magnetic field observations from 2012 to 2021 carried out with the Spectro-polarimeter (SP; [?]) of the Solar Optical Telescope (SOT; [?]) aboard Hinode, we study the long-term variation of solar polar magnetic fields at different latitudes.

2. Observations and Results

As one of the most important facilities onboard Hinode, SOT/SP measures vector magnetic fields in the photosphere with high spatial and spectral resolution. We use Hinode/SP polar observations released at ISEE, Nagoya University. The Hinode data adopted in this study are listed in Table 1 . The pixel size in the east-west direction (i.e., the SP scanning direction) is approximately 0.30 arcseconds, and that in the north-south direction (i.e., along the slit) is almost 0.32 arcseconds.

The magnetic field data were retrieved from the SP full Stokes profiles of Fe I 630.15 nm and 630.25 nm by applying Milne-Eddington inversion [?]. The retrieved magnetic data were then processed to resolve the 180° ambiguity [?] and to obtain the radial magnetic field component [?].

Due to the 7.25° tilt angle of the solar rotation axis with respect to the ecliptic plane, the south and north poles are tilted toward Earth every March and September, respectively [?]. To observe the solar poles at a large viewing angle, Hinode's observation dates for the south pole are primarily in March, while those for the north pole are in September. For each polar cap each year, we use a dataset consisting of approximately 10 magnetograms with roughly 3-day intervals (see Table 1). The fields of view of the polar magnetograms cover latitudes from about $±$67° to $±$90° and beyond. Each magnetogram observed from the Hinode viewpoint can be projected to a top-down view from above the solar pole, which is necessary to correctly show the size distribution and spatial extent of polar magnetic patches. Figure 1 [Figure 1: see original paper] shows an example illustrating the projection from the Hinode view to the polar view. For a given observed magnetogram, we calculate the longitude and latitude of each pixel, then warp the magnetogram to the polar view image via interpolation.

Figure 2 [Figure 2: see original paper] displays the landscape of radial magnetic fields in the north and south polar caps over ten years. For the north polar cap (Figure 2(a)), the magnetic field in 2012 was dominated by negative polarity. The magnetic field then became weak, large magnetic concentrations became rare, and both negative and positive concentrations spread across the polar cap in 2015. By 2019, the north polar cap was dominated by strong magnetic elements with positive polarity. In 2021, although the dominant field remained positive, the number of strong positive flux concentrations decreased. Conversely, the south polar cap (Figure 2(b)) in 2012 was dominated by positive magnetic elements. In 2015, the number and average size of major positive concentrations decreased and many negative concentrations appeared. As the south polar field reversed, the strength of the negative polarity field became strong in 2019, then decreased. In 2021, the dominant positive polarity became somewhat weak.

We also use 13-month smoothed monthly hemispheric sunspot numbers from the Sunspot Index and Long-term Solar Observations (SILSO; online sunspot number catalog[9]). The 13-month smoothed monthly sunspot number and the averaged magnetic flux density above 70° latitude are shown in Figure 3 [Figure 3: see original paper]. The averaged radial magnetic flux density is calculated as $\sum_{ij} B_{r,ij} S_{ij} / \sum_{ij} S_{ij}$, where $B_{r,ij}$ is the radial magnetic flux density and S_{ij} is the corrected real area in each pixel i within the latitude range $\pm(70-90)^{\circ}$ and longitude range $[-90, 90]^{\circ}$ in each magnetogram j (approximately 10 magnetograms) every year for the north and south polar caps.

The total sunspot number curve (Figure 3(a)) contains two peaks. The first peak corresponds to the maximum sunspot number in the northern hemisphere (Figure 3(b)), and the second corresponds to that in the southern hemisphere (Figure 3(c)). In the northern hemisphere, the sunspot number reached maximum in August 2011. The polarity reversal in the north polar cap took place first and was completed in March 2013 (Figure 3(b)). The sunspot number in the southern hemisphere reached maximum in April 2014, and the polarity reversal in the south polar cap was completed in August 2014, approximately one and a half years after that near the north pole (Figure 3(c)).

After the polarity reversal in the north polar cap, the averaged flux density maintained a quite weak level of about 0.5 Mx cm^{-2} until the end of 2015. In the north polar cap, the averaged flux density reached its peak (3.7 Mx cm^{-2}) at the end of 2019, i.e., at the epoch of solar minimum (Figure 3(b)). While in the south polar cap, the maximum (-4.0 Mx cm^{-2}) of the averaged flux density occurred much earlier, in 2017 (Figure 3(c)).

To investigate the variation of magnetic fields at different latitudes, we average the radial flux density within every 5° from $±$70° latitude to the poles. Figure 4 [Figure 4: see original paper] shows the long-term variation of radial magnetic flux density at different latitudes in the north and south polar caps. The polarity inversion time marked by each vertical line indicates completion of the reversal process in each latitude range. For both the north and south polar caps, the magnetic field in the latitude range $\pm(70-75)^{\circ}$ changed polarity first, followed by successive polarity reversals at higher latitude ranges; i.e., higher latitudes correspond to later polarity reversals. In the north polar cap, the reversal times in the latitude ranges 70°–75°, 75°–80°, 80°–85°, and 85°–90° are approximately January 2013, April 2013, May 2013, and July 2013, respectively (Figure 4(c)). While in the south polar cap, the reversal times in the latitude ranges $-(70-75)^{\circ}$, $-(75-80)^{\circ}$, $-(80-85)^{\circ}$, and $-(85-90)^{\circ}$ are approximately April 2014, August 2014, November 2014, and May 2015, respectively (Figure 4(d)). The polarity reversal in the north and south polar caps lasted for almost half a year and one year, respectively.

Moreover, in the north polar cap, the strongest magnetic flux density in the latitude range 85°–90° was observed in 2020, while those in the other lower latitude ranges were observed in 2019 (Figure 4(a)). In the south polar cap, the strongest magnetic flux density in the latitude range $-(85-90)^{\circ}$ occurred in 2018, while those in the other lower latitude ranges occurred in 2017 (Figure 4(b)).

3. Conclusions and Discussion

Using Hinode spectro-polarimetric observations from 2012 to 2021, we investigate the long-term variation of polar magnetic fields at different latitudes. The results show that the polarity reversal in the north polar cap took place first, and about one and a half years later, the magnetic polarity in the south polar cap began to reverse. We find that the magnetic field polarity in each polar cap reversed successively from 70° latitude to the pole at the epoch of solar maximum; i.e., higher latitudes correspond to later polarity reversal.

Polar magnetic fields are predominantly unipolar during most of the solar cycle and change polarity at the epoch of solar maximum [**?**]. The polarity reversal process is usually non-simultaneous in the north and south polar caps [**?**, **?**]. For solar cycle 24, many studies have investigated polar magnetic field reversals using data from the Wilcox Solar Observatory, the Solar Dynamic Observatory, the National Solar Observatory at Kitt Peak, etc., and as expected, the magnetic field in the north polar region began to reverse first [**?**, **?**, **?**, **?**]. Using Hinode vector magnetograms obtained between 2008 and 2012, [**?**] studied the variation of polar magnetic fields before the polar field reversal during solar cycle 24 and found that the net flux in the polar cap decreased during the rising phase, more rapidly in the north polar cap. As demonstrated in Figures 2 and 3, Hinode observations covering the reversal stage show that the polarity reversal in the north polar cap took place first, followed by the south polar cap. This result confirms that the reversal processes at the north and south poles are non-simultaneous, reflecting solar activity asymmetry between the two hemispheres [**?**, **?**].

The reversal in the north polar cap was completed about one year after the maximum hemispheric sunspot number, while the reversal time of the south pole coincided with the local cycle maximum in the southern hemisphere. In the north polar cap, the averaged flux density after polarity reversal remained at a quite weak level until the end of 2015 (Figure 3(b) and Figure 4(a)). This might be caused by the appearance of non-Joy and anti-Hale active regions (ARs) and remnant flux surges to the pole [**?**]. The averaged flux density in the north polar cap peaked at the epoch of solar minimum (Figure 3(b)), but the maximum averaged flux density in the south polar cap occurred much earlier, in 2017 (Figure 3(c)). This may be due to the prominent poleward surge during solar cycle 24 in the southern hemisphere caused by AR 12192 [**?**].

The polarity reversal times shown in Figure 4 reveal that higher latitudes correspond to later polarity reversal. The time lags among polarity reversals reflect magnetic flux migration from lower latitudes to the poles. The strongest polar magnetic density appeared earlier than those at lower latitudes, also implying the existence of poleward magnetic flux migration in the polar caps. Remnant magnetic flux from ARs migrates poleward and cancels the polar field of the old solar cycle, thus leading to polarity reversal in the polar caps [**?**].

As shown in Figures 1 and 2, the weakest magnetic fields in each north/south polar map are concentrated along the top/bottom edge of the map. It appears that the fall-off of magnetic field strength near the limb is likely caused by decreasing signal-to-noise ratio toward the limb. The effects of these signal-to-noise ratio problems are also visible in the plots of radial magnetic flux density versus time in Figure 4, particularly in the left panels. [**?**] analyzed equivalent Hinode/SP vector data processed at the High Altitude Observatory, discussed systematic errors and latitude-dependent changes in detail (with reference to longitudinal magnetogram data), and demonstrated the reversal of polar field polarity first at lower and then at progressively higher latitudes by constructing polar synoptic maps. The novelty in the present paper (besides the new Nagoya University dataset) is that magnetic flux densities are computed over separate latitude bands and plotted over time to show the latitude-dependent behavior.

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[9] https://sidc.be/SILSO/datafiles/

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