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Magnetic Field Elements at High Latitude: Lifetime and Rotation Rate

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Abstract Using one-minute cadence time-series full disk magnetograms taken by the SOHO/MDI, we have studied the magnetic field elements at high latitude (poleward of 65° in latitude). It is found that an average lifetime of the magnetic field elements is 16.5 h during solar minimum, much longer than that during solar maximum (7.3 h). During solar minimum, number of the magnetic field elements with the dominant polarity is about 3 times as that of the opposite polarity elements. Their lifetime is 21.0 h on average, longer than that of the opposite polarity elements (2.3 h). It is also found that the lifetime of the magnetic field elements is related with their size, consistent with the magnetic field elements in the quiet sun at low latitude found by Hagenaar *et al.* (*Astrophys. J.* 511:932, 1999). During solar maximum, the polar regions are equally occupied by magnetic field elements with both polarities, and their lifetimes are roughly the same on average. No evidence shows there is a correlation between the lifetime and size of the magnetic field elements. Using an image cross-correlation method, we also measure the solar rotation rate at high latitude, up to 85° in latitude. The rate is $\omega = 2.914 - 0.342\sin^2\phi - 0.482\sin^4\phi$ μrad s^{-1} sidereal. It agrees with previous studies using the spectroscopic and image cross-correlation methods, and also agrees with the results using the element tracking method when the sample of the tracked magnetic field elements is large. The consistency of those results strongly suggests that this rate at high latitude is reliable.

Keywords Magnetic element, lifetime · Solar rotation · Sun's polar region

1. Introduction

A better understanding of the Sun's polar field is helpful to advance our knowledge on the solar dynamo. Usually the polar regions are occupied by many magnetic concentrations. Those magnetic field elements have been intensively studied. In a series of research

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based on the high-resolution videomagnetograph data from the Big Bear Solar Observatory (BBSO) (*e.g.*, Lin, Varsik, and Zirin, 1994; Zhang, Zirin, and Marquette, 1997; Varsik, Wilson, and Li, 1999; Varsik *et al.*, 2002), it was found that during the solar maximum, the polar regions are occupied by an equal number of the positive and negative magnetic field elements, while during the solar minimum, one polarity is dominant by a ratio of 4:1. They also found that (1) at solar minimum, the polar fields are stronger than the quiet equatorial field, but not greater than the fields in the equatorial unipolar regions (probably the coronal holes); and (2) the background fields in the polar regions are of mixed polarities but show a net weak field opposite in sign to the dominant polarity. This is similar to the coronal holes in which Zhang, Ma, and Wang (2006) found networks are dominant by one polarity but the inter-network elements are over-numbered by those with the opposite polarity. Those studies imply that, during solar minimum, the magnetic fields in the polar regions tend to have properties similar to those in the low latitude coronal holes. Using the chromospheric magnetograms taken by the Synoptic Optical Long-term Investigations of the Sun (SOLIS), Raouafi, Harvey, and Henney (2007) studied the distribution of the magnetic field elements. The chromospheric magnetograms are particularly suitable to study the magnetic field elements at high latitude because of the canopy structure. They found that the area density distribution of the magnetic flux decreases close to the pole. This trend is more pronounced for larger elements. Very recently, *Hinode* provided a precise measurement of the vector magnetic field that makes it possible to study the field configuration at high latitude. A detailed analysis carried out by Tsuneta *et al.* (2008) shows that most large patches have fields vertical to the local surface. The field strength is as strong as 1 kG. They further discovered that the polar region is also covered with ubiquitous horizontal fields, which agrees with the work done by Harvey *et al.* (2007) who found ubiquitous and dynamic horizontal fields in the quiet Sun over the solar disk (see also Lites *et al.*, 2008). Much effort has also been made to link dynamics of the magnetic field elements and coronal phenomena at high latitude, such as plumes, X-ray bright points, and X-ray jets (*e.g.*, Deforest *et al.*, 1997; Wang, 1998; Cirtain *et al.*, 2007; Raouafi *et al.*, 2008). The nature of the solar polar regions is still an important topic that deserves further investigation.

MDI magnetic field measurements during the dynamic campaign program are specifically useful to study evolutionary characteristics of the magnetic field elements on the polar regions, because the magnetograms (1) are full disk, (2) have a cadence of 1 min, and (3) a long time coverage from several days to months. The lifetime of the magnetic field elements and the rotation rate at high latitude are two topics that these data can help to address. There have been some prior studies to measure the high latitude magnetic field element lifetime. Deng, Wang, and Harvey (1999), after tracking 1300 magnetic field elements at high latitude, found that the lifetime of the elements varies from several hours to more than 58 h. Varsik, Wilson, and Li (1999) reported that the lifetime of the magnetic field "knots" is longer than 7 h but shorter than 24 h. Benevolenskaya (2007) found "the polar magnetic field elements have a tendency to be present for about 1 – 2 days". Based on the *Hinode* observation, Tsuneta (2009) estimated the lifetime of the elements to be within 10 to 15 h. Thus, it is useful to give a statistical measurement of the lifetime of the magnetic field elements on the polar regions. The solar rotation rate at high latitude has also been measured using various methods, such as spectroscopic (*e.g.*, Howard and Harvey, 1970; Becker, 1978), image cross-correlation (*e.g.*, Cram, Durney, and Guenther, 1983; Snodgrass, 1983; Strous and Simon, 1998; Meunier, 2005), and element tracking (*e.g.*, Howard, 1978; Zhang, Zirin, and Marquette, 1997; Deng, Wang, and Harvey, 1999; Benevolenskaya, 2007). In this paper, we measure the magnetic field element lifetime and rotation rate at high latitude.

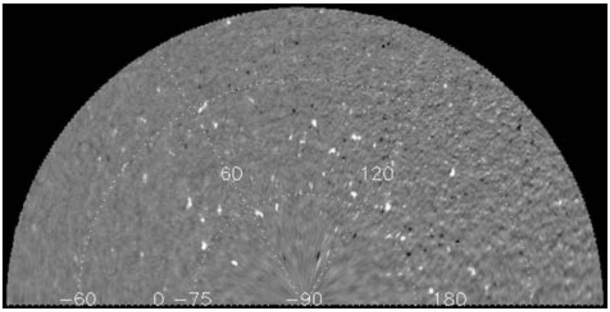


Figure 1 Solar polar field from the southern pole down to −51 degree in latitude. The data were taken by MDI on 16 March 2007. The image shown here is an average of 30 magnetograms centered at 13:52 UT.

2. Data and Methodology

We use three data sets taken during solar maximum (2001 and 2002), and three data sets taken during solar minimum (2007 and 2008) to measure the lifetime of the magnetic field elements at high latitude. The data were taken in March or April when the solar north pole tilted away from the earth. In this way, we are able to observe magnetic field on the south pole. All the data were taken during the dynamic program in which MDI provided full disk magnetograms every minute. The time coverage of those data is from two weeks to one month. For the new calibrated magnetograms produced from a set of filtergrams collected during a 30-s time interval (so-called 1-min magnetograms), the noise level is about 26.4 gauss. The noise is not uniform over the whole disk. It is about 30 gauss near the top limb, and 35 gauss near the bottom limb. In this work, the measured line-of-sight magnetic field is converted to the radial field under an assumption that the field is purely radial. To minimize the noise, only the values greater than 35 gauss are converted. To estimate the lifetime of the magnetic field elements, we first transform the magnetograms to the heliographic coordinates, and, after removing the solar rotation effect, average 30 remapped images to suppress the noise. The averaged data are then remapped onto the polar region, as shown in Figure 1. A movie is made from those data. The solar rotation rate used here is the feature tracking result in Meunier (2005). We choose this rotation rate because we are tracking the magnetic field elements to measure their lifetime. With this movie, we manually track each magnetic field element to measure the lifetime. First, we identify a magnetic field element, then play the movie forward and backward to find the appearance and disappearance times of the selected element. The lifetime of this element is defined here as the time interval between those two instants. We repeat this procedure using another movie with a higher cadence. This movie is made by the averaged images from ten remapped magnetograms taken in 10 min. So the uncertainty of the lifetime is about 30 min.

The rotation rate is measured using an image cross-correlation method. Again, the magnetograms are transformed to the heliographic coordinates, and 60 remapped images are averaged. Here, we do not remove the solar rotation effect. The averaged images are then divided into strips along the latitude with a bin size of 5°. A cross-correlation is employed to the corresponding strips that are from a pair of the remapped magnetograms with a certain time lag. Here we choose a time lag of 2 h. The cross-correlation code, *cross_cor_taylor.pro*, which is part of a predecessor to the Fourier local correlation tracking (FLCT) code (Fisher and Welsch, 2008), can find the peak of the cross-correlation function to sub-pixel accuracy. Shown in Figure 2 is an example of a pair of strips that range from 67.5° to 72.5° in latitude. The strips are from the averaged remapped magnetograms centered at 08:09 UT and 10:09 UT of 4 March 2008, respectively.

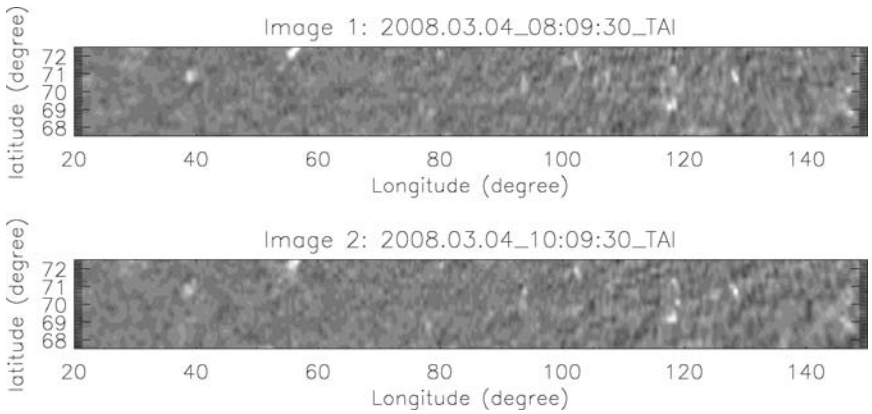


Figure 2 A pair of strips from two averaged magnetograms with a time lag of 2 hours. An image cross-correlation technique is applied to these data.

3. Results

3.1. Lifetime of the Magnetic Field Elements at High Latitude

Shown in Figure 3 are distributions of the lifetime of the magnetic field elements during solar maximum (grey histogram) and solar minimum (black histogram). We find that at solar maximum most magnetic field elements have a lifetime less than 10 h, while at solar minimum there are many magnetic field elements that live much longer, up to 100 h. A statistical result is shown in Table 1. Average lifetimes of the magnetic field elements with unsigned, positive, and negative polarity are given by the first three columns of Table 1. The error here is one standard deviation. The fourth and fifth columns are percentages of the magnetic field elements with positive and negative fields. The average lifetime of the elements during solar minimum is 16.5 ± 16.0 h, much longer than that during solar maximum (7.3 ± 6.6 h). During solar minimum, the magnetic field elements with positive field, the dominant polarity in the south pole, have a lifetime of 21.0 h on average, while the average lifetime of the negative field elements is only 2.3 h. The ratio of the positive field elements and negative field elements is about 3:1. During solar maximum, the lifetimes and numbers of the positive and negative field elements are approximately the same on average. This agrees with the previous studies (*e.g.* Lin, Varsik, and Zirin, 1994; Varsik, Wilson, and Li, 1999).

At solar minimum, the lifetime of the positive field elements decreases slightly as a function of latitude, while the lifetime of the negative field elements appears not to depend on latitude (right panel of Figure 4). Raouafi, Harvey, and Henney (2007) found that the area density distribution of the polar flux elements decreases toward the pole independent of the flux element size. However, this trend is more pronounced for larger flux concentrations. Since the area of the magnetic field elements is correlated with their lifetime, as will be shown in below, our result is consistent with theirs. For a comparison, we also place in the left panel the same plot for solar maximum. Shown in Figure 5 are scatter plots of lifetime versus area of the magnetic field elements for solar maximum (left) and minimum (right). The solid lines are a linear fitting to the data. The Pearson correlation coefficient is 0.57 for solar maximum and 0.80 for solar minimum. Similar to the correlation between active regions' total unsigned magnetic flux and area (see, *e.g.*, Dikpati, Toma, and Gilman, 2006),

Table 1 Lifetime of the magnetic field elements at high latitude during solar minimum and maximum.

	Lifetime (all) [hour]	Lifetime (positive) [hour]	Lifetime (negative) [hour]	Numbers (positive)	Numbers (negative)
Minimum	16.5 ± 16.0	21.0 ± 17.5	2.3 ± 1.5	76.1%	23.9%
Maximum	7.3 ± 6.6	7.2 ± 7.2	7.5 ± 5.8	53.5%	46.5%

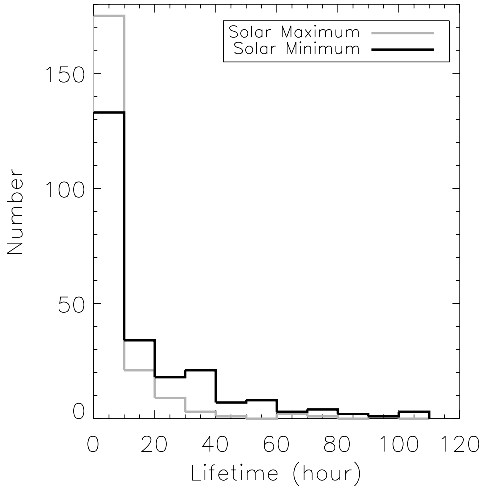


Figure 3 Distributions of lifetime of the magnetic field elements at high latitude for solar maximum (grey histogram) and solar minimum (black histogram).

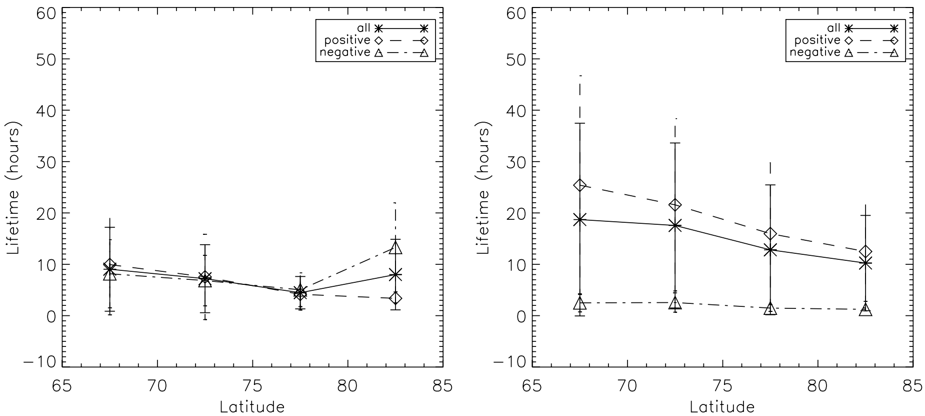


Figure 4 Average of the magnetic field element's lifetime as a function of latitude for solar maximum (left) and solar minimum (right). The grey and black lines represent the lifetimes for the negative and positive magnetic field elements, while the thick black line is for all the magnetic field elements.

it is found that the flux of the magnetic field elements is closed related with their area (see Figure 6). Therefore, we can conclude that the lifetime of the magnetic field elements is also related with their flux. This agrees with the findings by Hagenaar *et al.* (1999), who showed a correlation between lifetime and flux of the magnetic concentrations in the quiet Sun at low latitude.

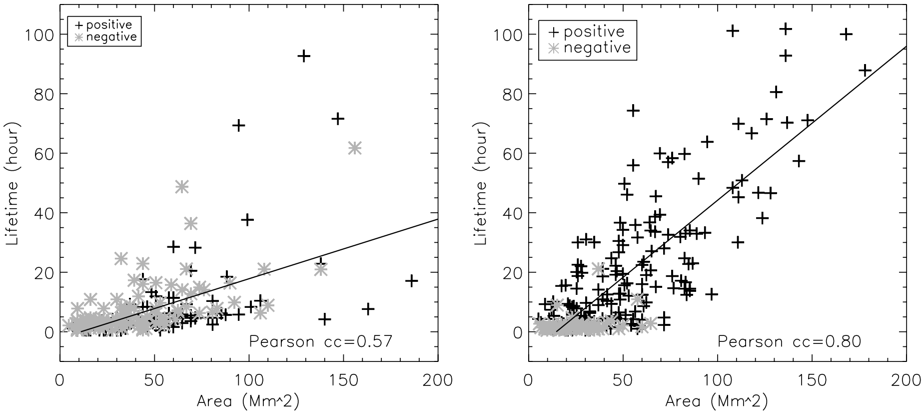
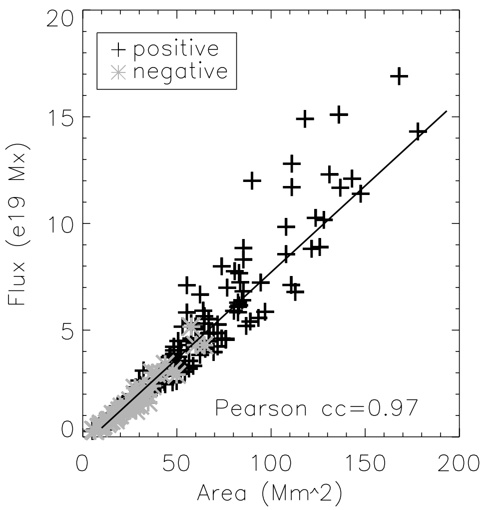


Figure 5 Lifetime versus size of the magnetic field elements for solar maximum (left) and solar minimum (right). A linear fit is applied to the data that is shown with a straight line. It is $y = -2.2 + 0.2x$ for solar maximum and $y = -7.6 + 0.52x$ for solar minimum. The fitting is much better for solar minimum. The Pearson correlation coefficient is 0.57 for solar maximum, and jumps to 0.80 for solar minimum.

Figure 6 Scatter plot of the magnetic flux and area of the magnetic field element for solar minimum. A linear fit shown here in straight line is $y = -0.40 + 0.08x$. The Pearson correlation coefficient is 0.97.



3.2. Solar Rotation Rate at High Latitude

We only use one data set taken in March 2008 to measure the solar rotation because the data were taken during solar minimum, and there were no outstanding data gaps in this period. The time coverage of the data is 28 d, from March 3 to 31. The data taken during solar maximum are not suitable for the image cross-correlation method because the lifetime of the magnetic field elements is too short.

The rotation rate at high latitude, up to 85°, is determined from the pairs of the averaged magnetograms with a 2-h time lag. In total we measured 159 pairs of magnetograms. The final result is the median of those measurements. Shown in Figure 7 is a comparison of the rate between this work (black diamonds) and previous results from various methods. The error bars are one standard deviation. It agrees with the results from the image cross-

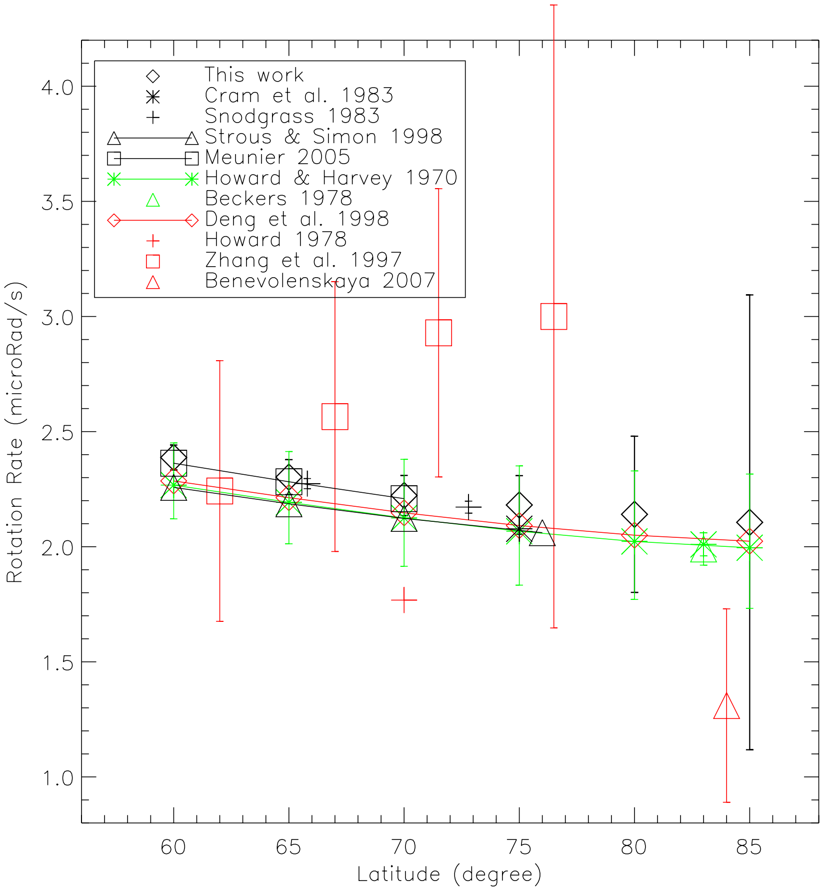


Figure 7 The solar rotation rate at high latitude derived from previous studies using various methods, including element tracking (red), image cross-correlation (black), and spectroscopic (green), in comparison with the result from this work (black diamonds).

correlation method, the same method used in this work (in black), and the spectroscopic method (in green). It also agrees with the result of Deng, Wang, and Harvey (1999) who used the element tracking method to manually track 1300 magnetic field elements (red line with diamonds). Significant discrepancy can be seen between this work and the results from the element tracking method by Howard (1978) (red cross), Zhang, Zirin, and Marquette (1997) (red squares), and Benevolenskaya (2007) (red triangle). One possible interpretation is that the sample of the tracked magnetic field elements in those studies is small: the random motion of the elements may contaminate the results.

We extend this measurement down to the low latitude. Shown in the left panel of Figure 8 is the median of those 159 measurements (the black diamonds). The error bars are one standard deviation. A least-square polynomial fit is employed, and we obtain a differential rotation profile as $\omega = 2.914 - 0.342\sin^2\phi - 0.482\sin^4\phi$ μrad s^{-1} sidereal. This profile is plotted with the thick solid black line. Also shown in that plot are the profiles from previous work using the image cross-correlation method, the same method used in present work. The dashed lines are the differential rotation profiles derived by Snodgrass and Ulrich (1990) us-

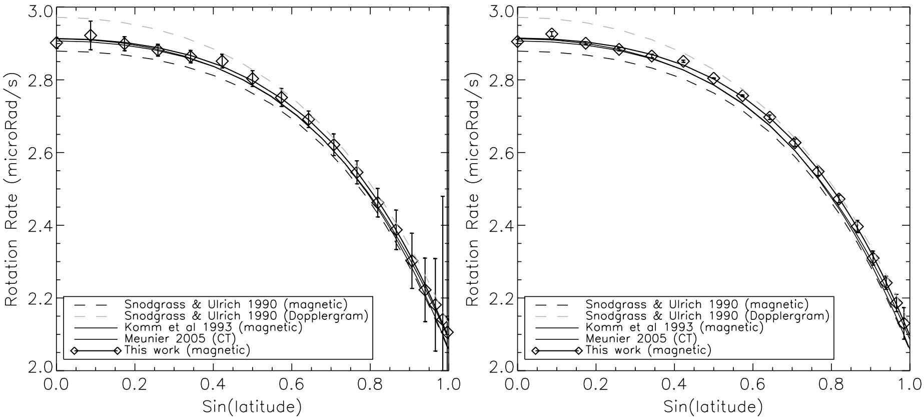


Figure 8 Left: The differential rotation rates from previous studies using the image cross-correlation method only, in comparison with the result from this work (the solid thick line with diamonds). The rate is derived to be $\omega = 2.914 - 0.342\sin^2\phi - 0.482\sin^4\phi$ µrad s^{-1} sidereal. Right: Average of the differential rotation profiles from various time lags from 1 hour to 5 hours (the solid thick line with diamonds), in comparison with the previous studies using the image cross-correlation method only.

ing the magnetograms (black) and Dopplergrams (grey) taken at Mount Wilson Observatory. The solid line is derived by Komm, Howard, and Harvey (1993) using the magnetograms taken at Kitt Peak. The triple-dot-dashed lines are derived by Meunier (2005) by using MDI magnetograms. Basically, the profile derived from this work (the thick solid line with diamonds) matches well with those results, especially the results from Komm, Howard, and Harvey (1993) and Meunier (2005). Agreement improves significantly at high latitude.

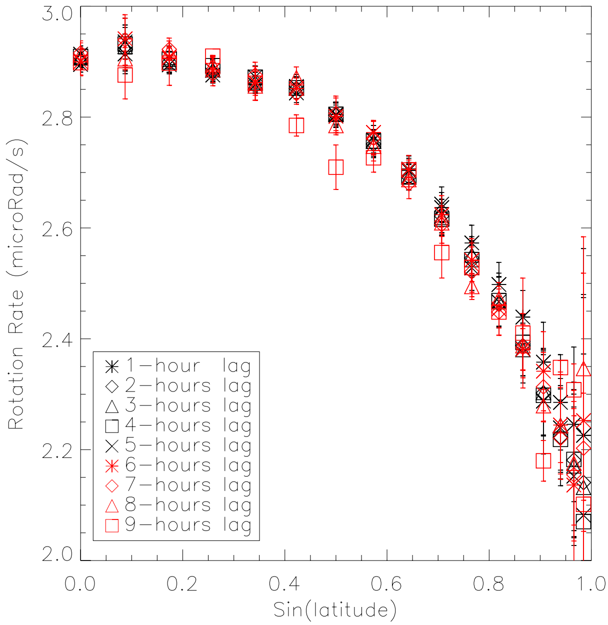
We also measure the rotation rate from pairs of magnetograms with different time lags. The average of the rates from different time lags, up to 5 h, suggests a differential rotation profile as $\omega = 2.914 - 0.322\sin^2\phi - 0.498\sin^4\phi$ µrad s^{-1} sidereal. This profile is presented in the right panel of Figure 8 (the thick solid black line with diamonds), together with the previous results from the same method. The error bars represent one standard deviation. They match each other well.

We plot in Figure 9 the rotation rates from different time lags, up to 9 h. The rates match each other pretty well until the lag becomes longer than 5 h. The median value of the lifetime of the magnetic field elements during solar minimum is 6.5 h. This implies that many magnetic field elements in a pair of magnetograms with a time lag of 5 h or more have already changed. In this way, the image cross-correlation method cannot accurately detect the shift of the magnetic field elements.

4. Conclusion

Using one-minute cadence time-series full disk magnetograms taken by MDI, we have studied the magnetic field elements at high latitude (poleward of 65° in latitude). The data were taken during solar maximum in March 2001, 2002, and April 2002, and solar minimum in March 2007 and 2008, when the solar north pole tilted away from the earth so that the south pole was well observed. It is shown that, during solar minimum, the south polar region is dominant by the magnetic field elements with positive polarity, consistent with the global

Figure 9 Differential rotation profiles from different time lags.



polarity of the polar region (see, *e.g.*, Tsuneta *et al.*, 2008). The number of the positive magnetic field elements is about 3 times as that of the negative ones, close to the 4:1 ratio found by Varsik, Wilson, and Li (1999). Their lifetime is 16.5 h on average. The average lifetime of the positive magnetic field elements is longer (21.0 h) than that of the negative field elements (2.3 h). A correlation is found between the lifetime and size of the magnetic field elements, which is consistent with the elements in the quiet sun at low latitude found by Hagenaar *et al.* (1999). During solar maximum, the positive and negative magnetic field elements equally occupy the polar regions, agreeing with Lin, Varsik, and Zirin (1994). Their lifetime is 7.3 h on average, much shorter than that during solar minimum. The average lifetimes for both polarity elements are comparable. And no correlation is found between the lifetime and size of the magnetic field elements.

The solar rotation rate at high latitude, up to 85°, is also measured to be $\omega = 2.914 - 0.342\sin^2\phi - 0.482\sin^4\phi\ \mu\text{rad}\,\text{s}^{-1}$ sidereal. The result agrees with the previous work using the image cross-correlation and spectroscopic methods, and also agrees with the results from the element tracking work when the sample of the tracked magnetic field elements is large, such as Deng, Wang, and Harvey (1999) (see Figure 7). This consistency strongly suggests that the rotation rate at high latitude is well determined.

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