Chapter 8

Relationship Between Rotational Speed and Magnetic Fields

8.1 Introduction

It is well-known that sunspots and other solar magnetic features rotate faster than the surface plasma (Howard & Harvey, 1970). The sidereal rotation speeds of weak magnetic features and plages (Howard, Gilman, & Gilman, 1984; Komm, Howard, & Harvey, 1993), individual sunspots (Howard, Gilman, & Gilman, 1984; Sivaraman, Gupta, & Howard, 1993) and sunspot groups (Howard, 1992) have been studied for many years by different research groups by use of different observatory data (see reviews of Howard 1996 and Beck 2000). Such studies are deemed as diagnostics of subsurface conditions based on the assumption that the faster rotation of magnetic features was caused by the faster-rotating plasma in the interior where the magnetic features were anchored (Gilman & Foukal, 1979). By matching the sunspot surface speed with the solar interior rotational speed robustly derived by helioseismology (e.g., Thompson et al., 1996; Kosovichev et al., 1997; Howe et al., 2000a), several studies estimated the depth of sunspot roots for sunspots of different sizes and life spans (e.g., Hiremath, 2002; Sivaraman et al., 2003). Such studies are valuable for understanding the solar dynamo and origin of solar active regions. However, D'Silva & Howard (1994) proposed a different explanation, namely that effects of buoyancy and drag coupled with the Coriolis force during the emergence of active regions might lead to the faster rotational speed.

Although many studies were done to infer the rotational speed of various solar magnetic features, the relationship between the rotational speed of the magnetic features and their magnetic strength has not yet been studied. In this chapter, we present our results on the relationship between the residual rotational speed and magnetic strength of weak magnetic features on the solar surface. The residual rotational speed relative to the mean rotational speed of the solar plasma is determined by time-distance helioseismology just beneath the solar surface.

8.2 Data Reduction

Same datasets and inversion results are used as in Chapter 7. One full Carrington rotation is selected from each year, from 1997 until 2002, for time-distance helioseismological analysis in this study.

At the start of each Carrington rotation, we select from the solar surface a central meridian region of 30° wide in longitude and from −54° to 54° in latitude with 512 minutes nearly uninterrupted Dopplergram observation. Time-distance measurement and inversion are carried out for this selected region to derive the horizontal velocities from the photosphere to a depth of 12 Mm (see Chapters 3 and 7). Then, another 512-minute central meridian region observed 8 hours after the first one is processed in the same way. Such procedure is repeated till the end of the Carrington rotation. Approximately 90 such regions are processed for each rotation. Only the flow maps of the upper layer, $0-3$ Mm in depth, are used in this study. The pixel size at this depth is 0.24 heliographic degrees (or 2.9 Mm), though the spatial resolution may be slightly greater. Such a high spatial resolution enables us to overlap the horizontal flow maps over the corresponding magnetic field maps to study the relationship between the rotational speed of solar magnetic features and their magnetic strength. Figure 8.1 shows one example of the flow maps overlapping the corresponding magnetograms.

MDI also provides magnetograms with 96-minute cadence during the Dynamic Campaign periods. For each selected Carrington rotation, about 90 magnetic field

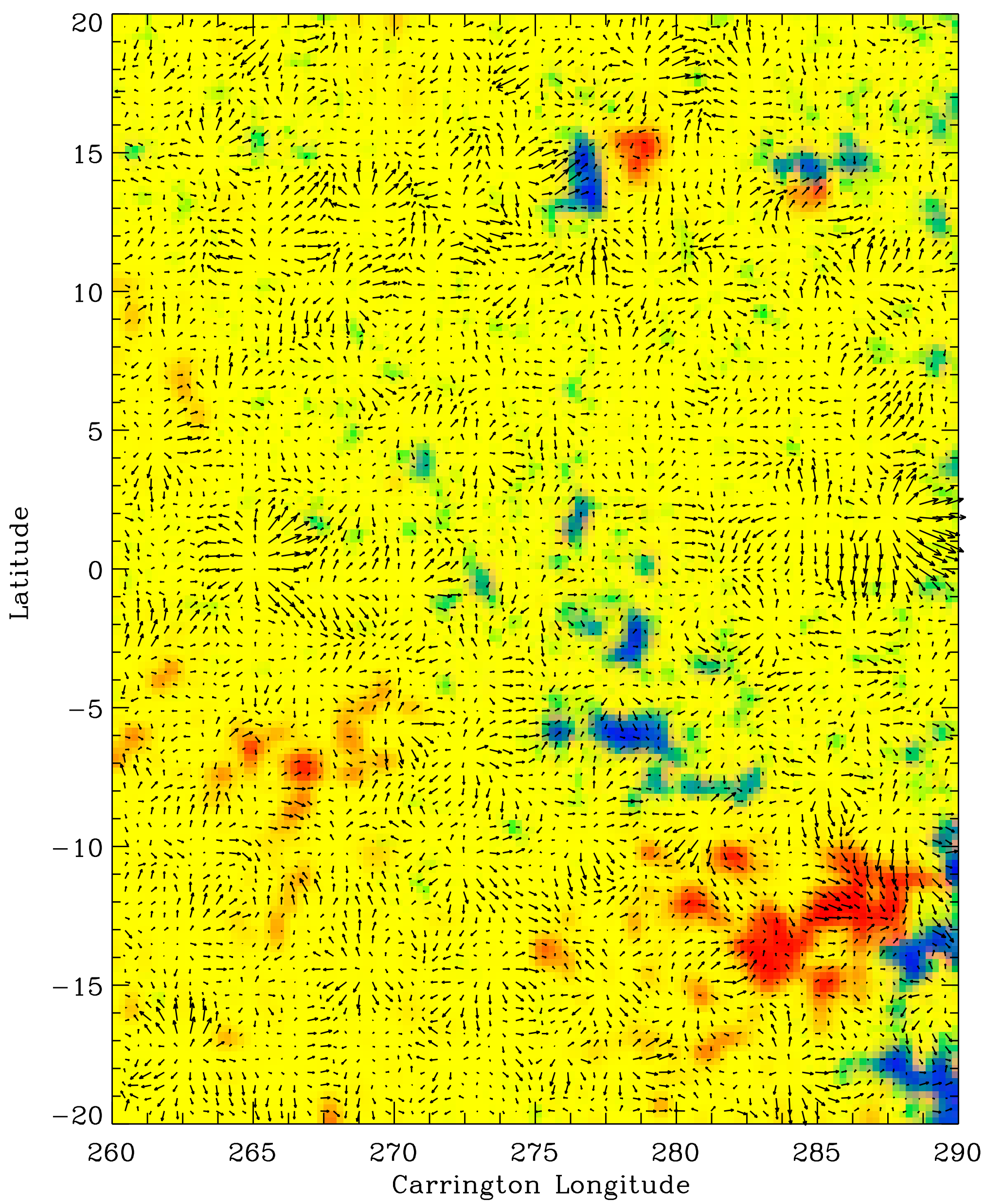

Figure 8.1: An example of the horizontal flow maps overlapping the corresponding magnetograms. The horizontal flows are plotted after 2×2 rebin in order to show the vectors clearly, and the magnetogram is kept at the original resolution. The plot shows a solar region at the disk center averaged from 08:00UT to 16:31UT of April 5, 2002.

maps are obtained covering the the same spatial regions and same temporal periods as those of the corresponding flow maps. In this study, we consider only weak magnetic features with magnetic field strength less than a few hundred Gauss, for which the parameter $\beta = 8\pi p/B^2 \gg 1$, thus magnetic field does not directly affect the plasma flows. Sunspots may have different origins and rotational speed compared to weak magnetic features, such as magnetic networks and plages. Therefore, in order to study the dependence of rotational speed on magnetic strength for weak magnetic features, all sunspots are masked out from the magnetic maps, but plages and other weak magnetic features surrounding the sunspots are kept.

8.3 Results

For each Carrington rotation, the mean latitudinal rotational speed is derived from all the flow maps of East-West velocity, and then subtracted from each flow map to get residual velocity maps. A scatter plot can be made for the magnetic field strength (the absolute value) of each pixel, between latitude $-30°$ to $30°$, and the corresponding residual East-West velocity. In order to increase the signal to noise ratio, we combine data points from six maps to make one such scatter plot. Figure 8.2(a) presents an example of the scatter plot. The residual velocity of individual elements can be eastward or westward, but the West-directed velocities clearly dominate over the East-directed flows with the increase of magnetic strength. To infer the dependence of the residual rotational speed of magnetized plasma on the magnetic strength, we average the East-West velocity of all pixels in 5 Gauss bins, from 0 to 600 Gauss. The average rotational velocity as a function of magnetic strength is plotted as the solid curve in Figure 8.2(a). For one Carrington rotation, we have approximately 15 such scatter plots, hence 15 functions of residual rotational speed relative to the magnetic strength. The averages are made again from these 15 functions to derive one function for the whole Carrington rotation which is shown in Figure 8.2(b). This plot shows the residual rotational velocity as a function of magnetic strength for Carrington rotation CR1964 of 2000. This function is nearly linear: the rotational speed increases with the magnetic field strength. By use of the weak magnetic features as tracers,

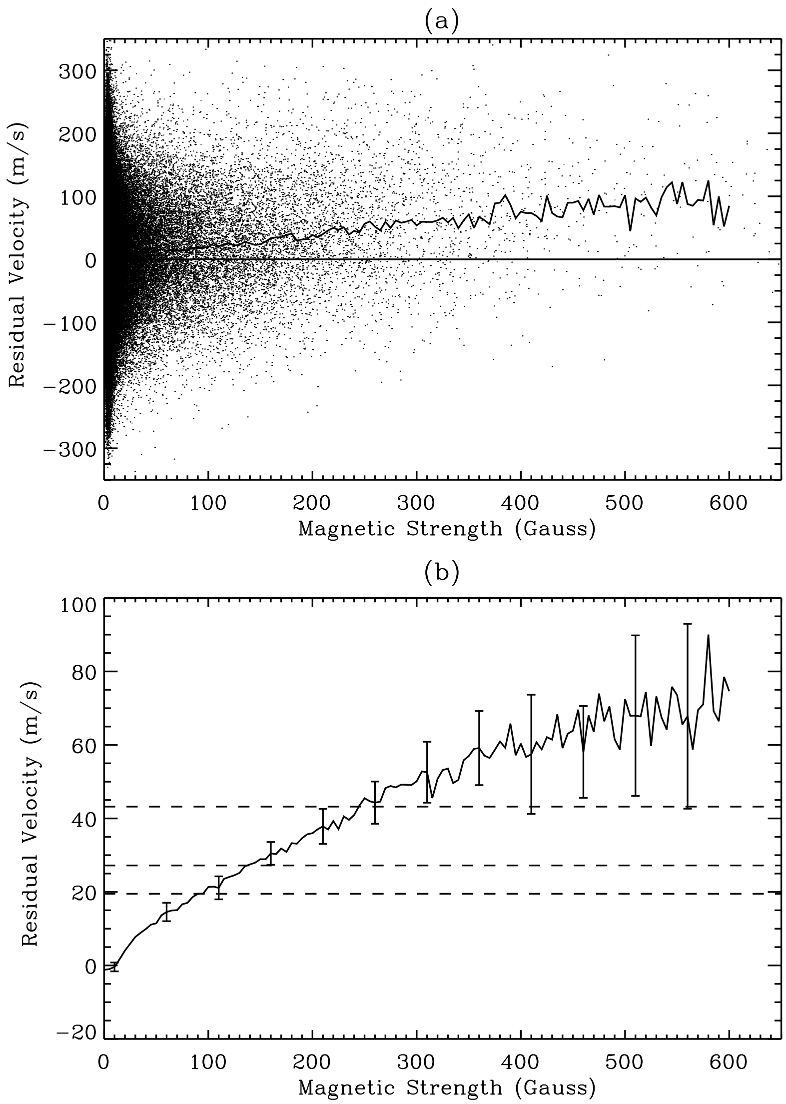

Figure 8.2: (a) Scatter plot of the residual East-West velocity versus the magnetic field strength for six 512-minute observation periods, in Carrington Rotation 1964 in 2000. The solid curve is an average of the residual velocities in 5 Gauss bins. (b) The average residual rotational velocity as a function of magnetic strength for CR1964. The error bars show one standard deviation of all 15 curves obtained for this solar rotation (for clarity, error bars are only displayed every 50 Gs). From the lower to upper, the three horizontal dashed lines represent the residual equatorial rotational speed of magnetic features inferred from Mt. Wilson data (Snodgrass & Ulrich, 1990), MDI data (Meunier, 1999) and Kitt Peak data (Komm, Howard, & Harvey, 1993), respectively.

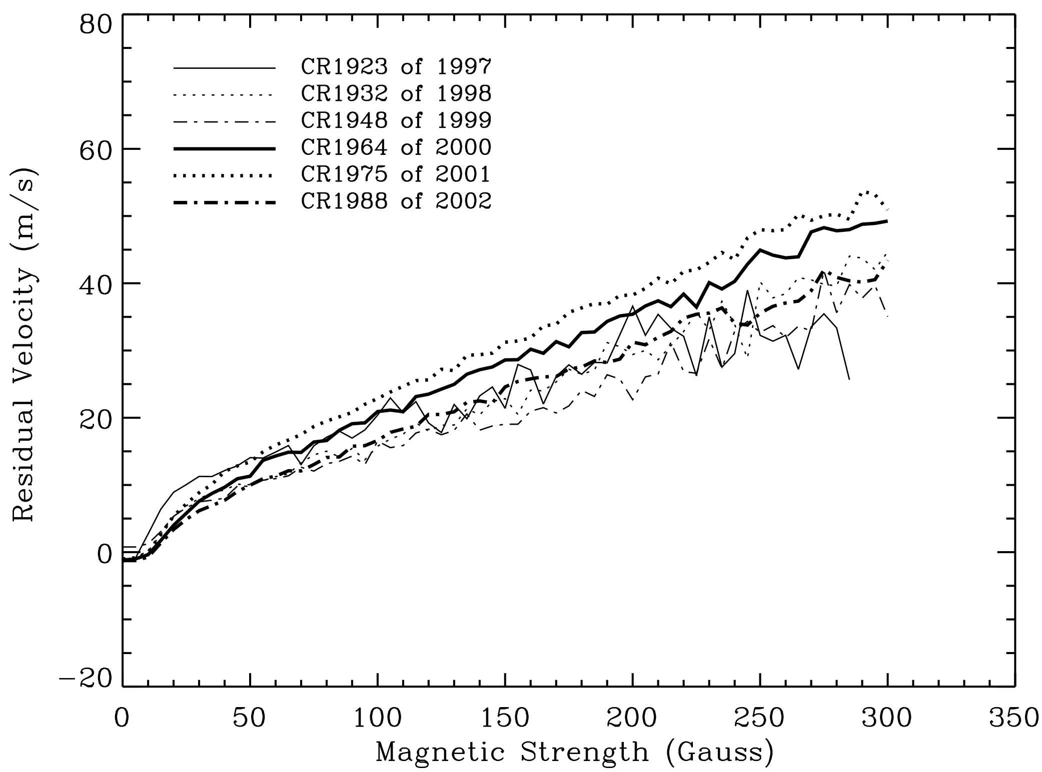

Figure 8.3: Residual rotational velocity as a function of the magnetic field strength for all studied Carrington rotations. For clarity, the error bars are not displayed, but they are similar as in Figure 8.2(b) except of CR1923 which has slightly larger error bars.

various researchers have derived slightly different rotational rate of magnetic features. For comparison, three previous results derived by different researchers are plotted in Figure 8.2(b), all of which fall in the ranges of the residual velocity function.

Following the same procedure, we derive the residual rotational velocity as a function of magnetic strength for each Carrington rotation selected from 1997 to 2002. Figure 8.3 presents all these functions covering 0 to 300 Gauss, beyond which data become very noisy for Carrington rotations in solar minimum years. Clearly, all the functions display approximately a linear relationship between the residual rotational velocity of weak magnetic features and their magnetic strength. However, these functions for different Carrington rotations are not the same, but seem to vary

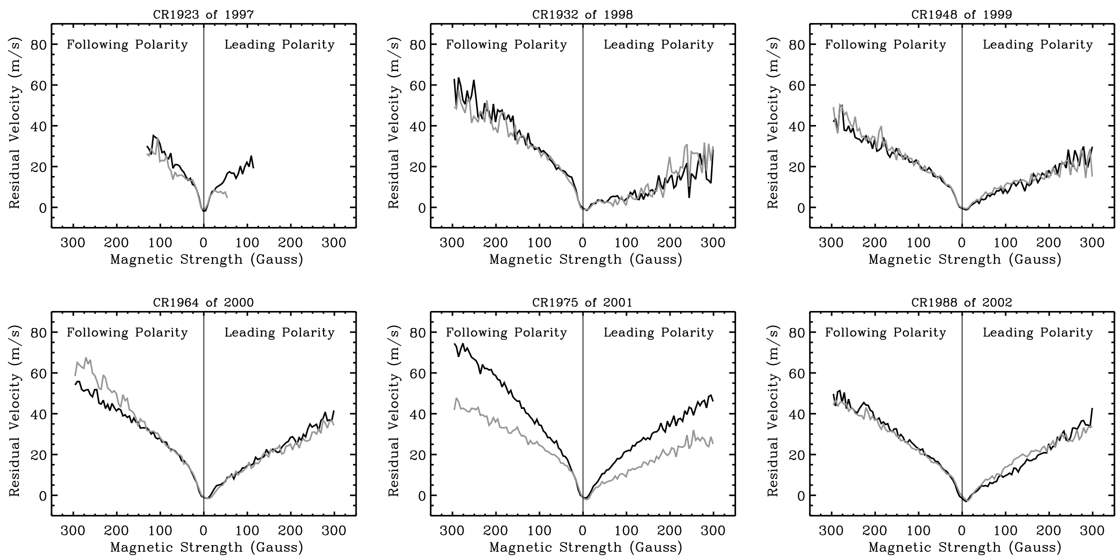

Figure 8.4: Residual rotational velocity versus the magnetic field strength for the leading and following polarities in both hemispheres. The black curves represent the functions for the Northern Hemisphere, and the gray curves represent the functions for the Southern Hemisphere.

with the phase of the solar cycle. The curves for the years 2000 and 2001, the maximum activity years, have the greatest slopes; the curves for the years 1997 – 1999 and 2002, when the solar activity was moderate, have smaller slopes. That is, the residual rotational speed of magnetic elements during the solar maximum years is faster than the speed of elements of same magnetic strength during the years with moderate activity. We have tried to derive such functions for various latitudes in each Carrington rotation, but did not find clear latitudinal dependence.

Magnetic features of leading and following polarities may have different residual rotational speed. By employing the similar procedure used above, we derive the rotational velocity of magnetic features separately for leading and following magnetic fields in both Northern and Southern hemispheres. Figure 8.4 presents the results. Except perhaps for CR1975 in 2001, the functions for the Northern and Southern hemispheres are strikingly similar. The differences in the two curves for CR1975 may result from the significantly different magnetic activity levels in the two hemispheres during this Carrington rotation: the Northern hemisphere had much stronger magnetic activity than the Southern hemisphere. The residual velocities for larger magnetic strength in CR1923 are not able to be derived reliably due to small number of pixels with larger magnetic strength. Nevertheless, for all the Carrington rotations studied covering from near the solar activity minimum to past the maximum of Solar Cycle 23, the plots show that the magnetic elements of the following polarity rotate faster than those of the leading polarity with the same magnetic strength. The increase of the residual rotational velocity with the magnetic strength is particularly fast for elements of the following polarity when the magnetic strength is less than ~ 50 Gauss.

8.4 Discussion

In this study, we have derived the rotational speed of magnetic features relative to the mean speed of the Sun's differential rotation as a function of magnetic field strength at different phases of the current solar cycle, and found that these functions are nearly linear for all Carrington rotations studied, from the solar activity minimum to maximum: the stronger the magnetic strength, the faster the magnetic elements rotate. Generally, this is consistent with the previous finding that sunspots rotate faster than plages, because one would expect sunspots are composed of magnetic elements with stronger magnetic strength than magnetic networks and plages.

It was suggested that the faster rotational rate of magnetic features could be due to the faster rotational rate of the solar interior where these features were anchored (Gilman & Foukal, 1979; Sivaraman et al., 2003). Following this suggestion, by matching the residual rotational velocity of magnetic features with the solar interior rotational rate from helioseismology studies (Howe et al., 2000a), we are able to derive the anchoring depth of the magnetic elements as a function of their magnetic strength. From our results, the magnetic features with a strength of 600 Gauss are rooted at a radius of approximately 0.95 $R_{\odot}$. Perhaps, this indicates that the weak magnetic features such as networks, plages may be generated in the surface shear layer which is located above 0.95 $R_{\odot}$, rather than in deeper convection zone; or perhaps, these features are formed by the dissipated magnetic elements of the decayed active regions which do not submerge deep into the solar interior. This is also in agreement with the local dynamo theory (e.g., Cattaneo, 1999) which suggested that weak and small-scale magnetic field on the Sun might be generated locally, very close to the solar surface. Furthermore, the linear dependence of the rotational speed on the magnetic field strength found in this study should be addressed by local dynamo theories.

However, there may be other explanations for the fast rotation of magnetic features, such as the Coriolis force in the course of magnetic emergence (D'Silva & Howard, 1994). The linear dependence of the residual rotational velocity on the magnetic strength may inspire us for other interpretations. Naively following the suggestion of Schüssler (1981) which was proposed to explain the global faster zonal flows known as "torsional oscillation" (Howard & LaBonte, 1980), the Lorentz force per unit volume f_L is proportional to $|B_{\mathrm{tor}}| \cdot |B_{\mathrm{pol}}|/L$, where B_{tor} is toroidal field, B_{pol} is poloidal field and L is the length scale of magnetic elements. Suppose that the kinetic energy density of the magnetized plasma, $\frac{1}{2}\rho v^2$, is achieved only from the influence of Lorentz force, one may expect $v \propto (|B_{\mathrm{tor}}| \cdot |B_{\mathrm{pol}}|)^{1/2}$. Intuitively, this may suggest the velocity is linearly proportional to the observed magnetic strength. However, this back-of-the-envelope interpretation does not explain the difference in the rotational speed of the leading and following polarities.

The following two factors may have played some roles in the linear relationship found in this study: 1) all the magnetic elements may rotate with the same speed, but the pixels observed by MDI may be composed of fast magnetic elements and slow unmagnetized plasma, hence our measurements are just averages of these two different speeds; 2) all magnetic features may rotate with the same speed, the unavoidable smoothing involved in the measurement and inversion procedure may reduce the speed of boundaries of these features. In both cases, one may expect the largest residual velocity should be less than or equal to the speed found by using magnetic features as tracers. However, Figure 8.2(b) clearly shows that this is not the case. Therefore, despite that the above two factors may inevitably contribute to the linear relationship found in this study, they do not play major roles, although we can not determine how much they contribute because the filling factor is unknown.

In this study, we have found that the functions of the residual rotational velocity versus the magnetic field strength have larger slopes for the solar maximum years (2000 and 2001) than for the intermediate activity years (Figure 8.3). By using sunspots as tracers, Gilman & Howard (1984) found that the residual rotational speed of sunspots was often faster in the activity maximum and minimum years than in the intermediate years. They interpreted the change of sunspots' rotational speed as resulting from the change of solar interior rotation rate with the solar cycle, but recent helioseismological studies did not show such significant change in the rotation rate. Our finding for the weak magnetic features is basically in agreement with the observations for sunspots: the magnetized plasma on the solar surface usually rotates faster during solar maximum years than during the years with moderate activity. This effect should not be related with or caused by the torsional oscillation, because the mean zonal flows are already removed from our data. Interpretation of this phenomenon may require more observational and theoretical studies.

Figure 8.4 suggests that for the same magnetic strength, magnetic features of the following polarity often have faster rotational speed than those of the leading polarity. Howard (1996) summarized previous results and showed that the leading sunspots often rotate faster than the following sunspots, but oppositely, the following portions of weak magnetic features are often faster than the leading portions. Our results confirm his conclusion. Howard (1996) suggested that the faster rotation of the following polarity might be caused by the faster diffusion to the East of the following magnetic flux, which would give an appearance of faster rotation of the following portions. However, our results are based on averaged plasma velocities of the magnetic elements rather than on tracking motions of specific magnetic features. Therefore, the faster rotation of the following polarity should not be just an apparent, but a real motion. This phenomenon may have some interesting implications in understanding magnetic network cancellation. The explanation of this observation may require more studies and improvement in the solar velocity measurements.