Periodicity of Twisting Motions in Sunspot Penumbral Filaments

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Received ; accepted

Abstract. We study the periodicity of twisting motions in sunspot penumbral filaments, which were recently discovered from both space (SOT/HINODE) and ground-based (SST) observations. A sunspot was well-observed for 97 minutes by the SOT/HINODE in the G-band (4305 Å) on 12 November 2006. By use of the time-space-gradient applied to intensity space-time plots, the twisting structures can be identified in the penumbral filaments. Consistent with previous findings, we find that the twisting is oriented from the solar limb to disk center. Some of them show a periodicity. The typical period is about ∼4 minutes, and the twisting velocity is roughly 6 km s^{-1}. However, the penumbral filaments do not always show the periodic twisting motions during the time interval of the observations. Such behavior seems to start and stop randomly with various penumbral filaments displaying the periodic twisting during different intervals. The maximum number of the periodic twists is 20 in our observations. Studying this periodicity can help us to understand the physical nature of the twisting motions. The present results enable us to determine observational constraints on the twisting mechanism.

Keywords: Sunspot, Dynamics

1. Introduction

Studying sunspot dynamics is one way to investigate the nature of sunspots. Previous spectroscopic observations showed that sunspots exhibit a characteristic flow field in the penumbra (e.g. Evershed 1909). This is the so-called "Evershed flow", which is a nearly horizontal outward flow of gas that takes place in the photospheric layer of the penumbra. The Evershed flow is explained as the siphon flow based on the concept of interchanging convection via magnetic flux tubes (e.g. Jahn and Schmidt 1994). This proposal subsequently demonstrated by simulations (e.g. Schlichenmaier and Collados 2002; Schlichenmaier and Solanki 2003). Recently, high-spatial resolution observations from the Solar Optical Telescope (SOT) (Ichimoto et al. 2004; **Tsuneta et al. 2008**) on HINODE (Kosugi et al. 2007) reveals new sunspot structures and dynamics (Ichimoto et al. 2007), and similar findings are further seen in ground-based observations from the Swedish 1-m Solar Telescope (SST) (Zakharov et al. 2008). They found apparent motions of intensity structures across penumbral filaments for several sunspots away from disk center. These apparent motions are observed in the penumbra, which is located in a direction perpendicular to the symmetry line connecting the sunspot center and the solar disk center, and are hardly seen in the limb-side and disc-center-side penumbra. The twisting motions are found to be always in the direction from the limb toward disk center for both sides of the sunspot and irrespective of whether the sunspot is East or West of the meridian. This is the most striking recent discovery about the Evershed flow. These apparent twisting motions are neither an actual twist nor a helical motion of individual penumbral filaments. Therefore, these observations are difficult to reconcile with (twisting) flux tubes but are consistent with overturning convective flows in gaps (Spruit and Scharmer 2006). Such convective flow patterns are indeed seen in the simulations (Rempel, Schussler, and Knolker 2009).

The cause of the apparent twisting motions of the penumbral filaments is still not clear. Observed properties of twisting motions should yield observational constraints on theories. For example, the properties of the periodicities of the twisting motions. Ichimoto et al. (2007) mentioned such motions as having a periodicity, which has been not explored in detail until this time. In this paper, we statistically study the periodicity of twisting motions in the different penumbral filaments of a sunspot.

2. Observations and Measurements

The data that we use here are from the SOT aboard HINODE, which obtains diffraction-limited images with a 50-cm aperture telescope from a Sun-synchronous orbit. SOT allows us to observe sunspot dynamical activities in the photosphere and chromosphere with stable diffraction-limited image quality. We obtained image sequences of a sunspot in active region NOAA 10923 on 12 November 2006, taken by the SOT Broadband Filter Imager (BFI) at 4305 Å . The spatial resolution of the BFI is about 0.2 arcsec (or 150 km on the solar surface), and the temporal cadence is 20 s. This sunspot was well observed from 08:37 UT to 10:14 UT (97 minutes) and shows well-developed penumbral dynamics. Figure 1 shows the sunspot image at 08:37:32 UT. The sunspot center is located at E28S7 with a heliocentric angle of 30°. Some of the data from this series of observations (blue continuum) have been presented by Ichimoto et al. (2007).

Following Ichimoto et al. (2007), we also use space-time plots to show the twisting motions in the penumbral filaments of the sunspots. **As mentioned before, these apparent motions of intensity fluctuations in penumbral filaments are seen from the limb-side to the disk center-side of filaments.** So we firstly use a slit parallel to this direction, such as slit 1 in Figure 1. Figure 2 (top) shows space-time plots of the G-band intensity at slit 1 for 97 minutes. **The zero of the Y-axis indicates the limb**

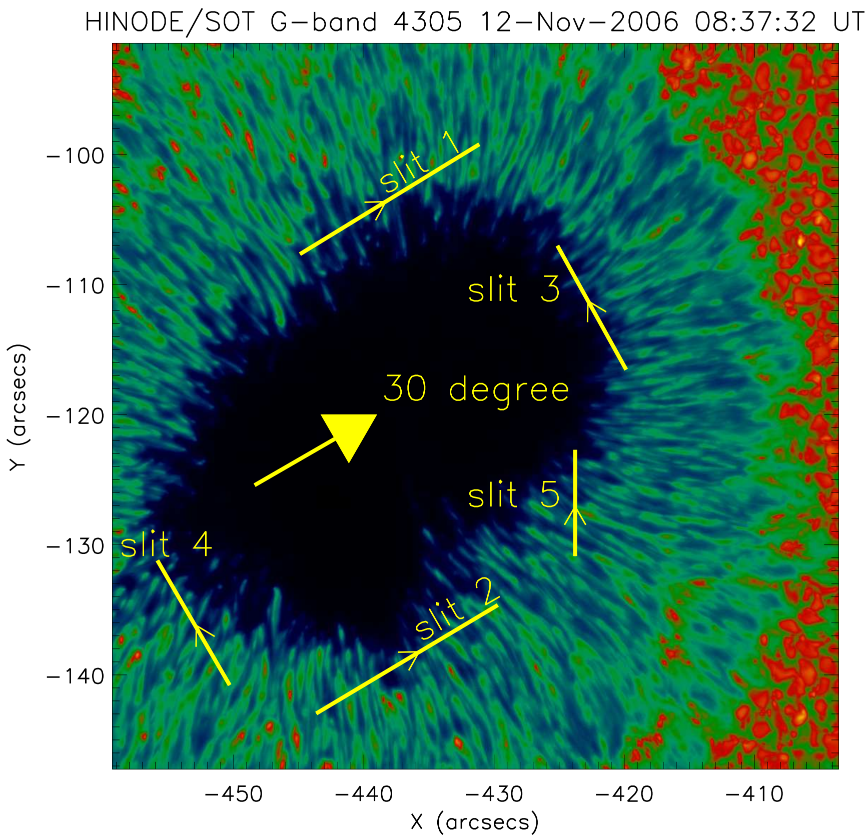

Figure 1. G-band image at 4305 Å of the sunspot on 12 November 2006 obtained from the SOT BFI on HINODE. Top and right are toward solar north and west, respectively. The arrow at the center of sunspot indicates the direction toward the solar disk center. Five slits were used in the paper, and the arrows represent the slit directions.

side end of the slit. More than 14 bright filaments were included, and the apparent twisting structures can be seen, for example, at a height of 25 Mm. Because the slit points toward the disk center, the twisting motions are expected from the slit bottom (solar limb) to top (toward the disk center). The twisting motions start at one side of filaments, and end at another side. Therefore, such structures are oblique in the space-time plots. However, the problem is that the individual twisting structure is difficult to discern from such intensity plots. In order to study the periodicity of the twisting motions, we firstly take the time derivative of the space-time plots. The bright and dark filaments are displayed as before, as shown in the middle panel of Figure

2. Then the space-gradient is performed in a direction from the slit bottom to top, as shown in Figure 2 (bottom). The twisting motions are clearly displayed, and each individual twisting structure can be identified. Thus, the individual twisting structures are separated into two strips, the bright one is beneath the dark one. The former indicates the edge of the intensity increase from slit bottom to top, while the latter denotes the intensity decreasing to that edge.

Figure 2 (bottom) shows that five penumbral filaments exhibiting periodic twisting motions, marked by G1, G2, G3, G4 and G5. Those are the five we choose to study in detail here, and each individual twisting structure is indicated by an arrow. It is clear that some filaments display twisting motions without a periodicity. Note that the other three periodic twisting filaments at heights of 40, 65 and 95 Mm are not studied here. **Consistent with the earlier findings by Ichimoto et al. (2007), the individual twisting starts at the outside (limb-side edge) of the bright filament, and ends at the inside (disk-center-side edge).** When an individual twisting ends, almost at the same time, a new twisting motion starts at the other side of penumbral filament, as shown in the five samples identified. This observation indicates that the apparent twisting motions in the penumbral filaments are not a helical motion. In other words, the adjacent twisting motions in the same penumbral filament represent the behaviors of different flows of different mass. Meanwhile, we have to pay attention to the fact that these penumbral filaments do not show periodic twisting motions with the same interval, and the number of periodic twisting structures are 5 (G1), 9 (G2), 5 (G3), 8 (G4) and 19 (G5), respectively. On the other hand, more than 6 penumbral filaments in Figure 2 show twisting motions without a periodicity, or irregularly, and even do not show twisting motions.

As in Figure 2, Figure 3 shows the space-time plots of intensity and the space-time-gradient along slit 2, which is parallel to slit 1, but located at the opposite side of the sunspot. **Again the origin of the Y axis is the limb side end of the slit.** The time-gradient plots are not shown in Figure 3. In total, 15 filaments are included. Also, five samples of periodic twisting penumbral filaments are chosen, and they are identified by G6, G7, G8, G9 and G10. The apparent twisting motions are expected as before, along the slit direction from the bottom to top (from the limb to disk center). Each individual twisting is marked by an arrow. Note here that the other 4 periodic twisting filaments are not studied at heights of 27, 67, 85 and 110 Mm. **As expected from the previous findings, the twisting direction is from the limb to disk center again.**

According to the findings of Ichimoto et al. (2007), the twisting motions are hardly seen in the limb-side and disc-center-side penumbra. In order to confirm this result, we use another two slits, 3 and 4, at these two sides, along the direction perpendicular to the line connecting the sunspot and

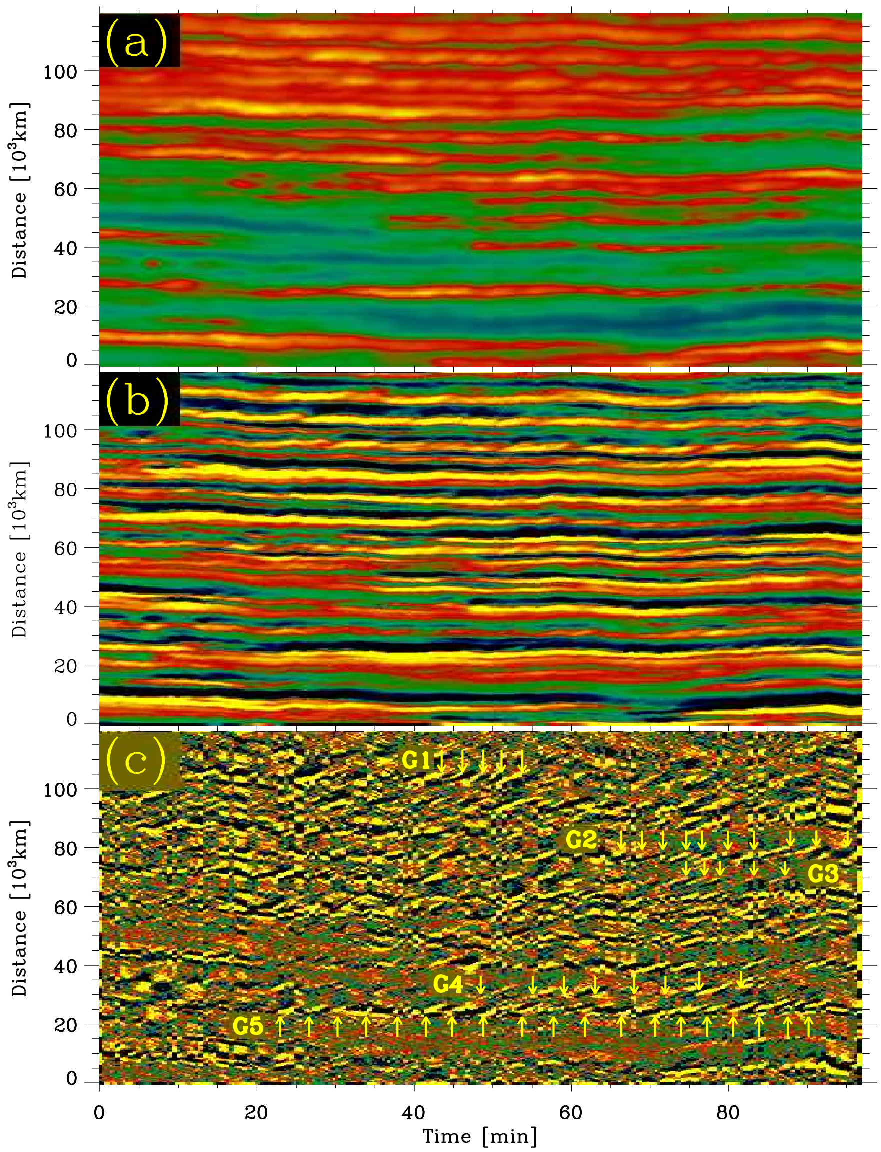

Figure 2. Space-time plots along slit 1 across the penumbral filaments. (a) G-band intensity; (b) the time-derivative (or gradient) of intensity; (c) the space-time-gradient of intensity.

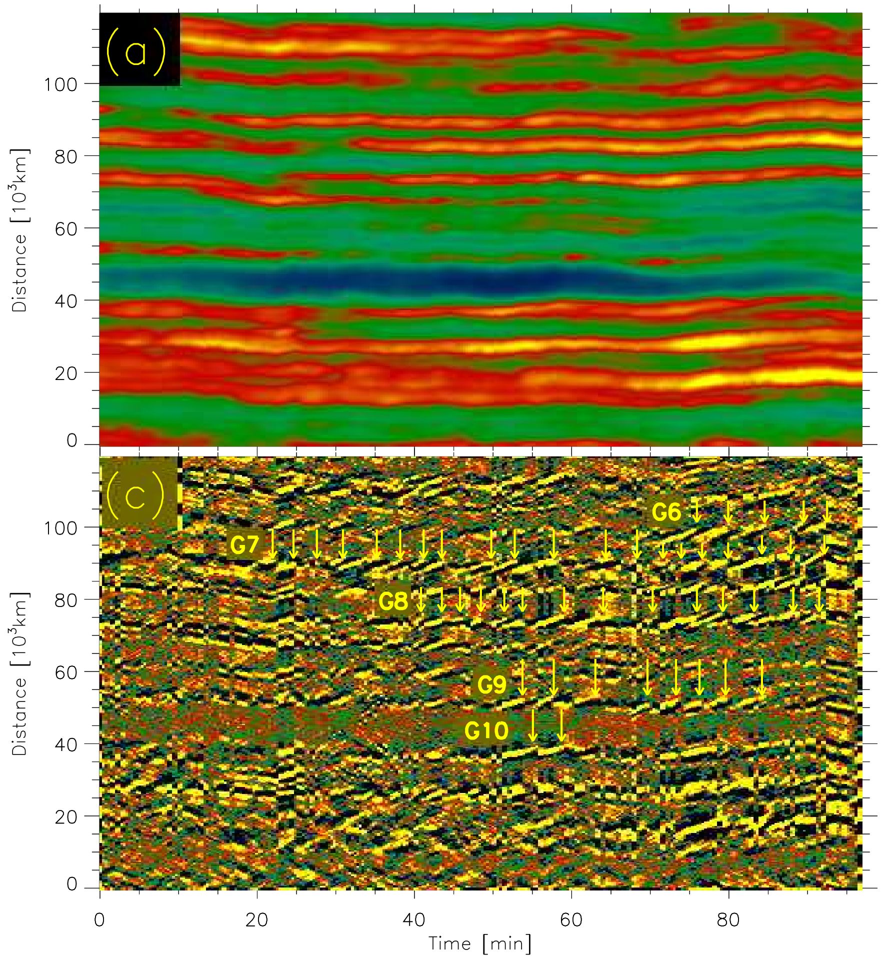

Figure 3. Space-time plots along the slit 2 across the penumbral filaments. (a) G-band intensity; (c) the space-time-gradient of intensity.

disc center. As in Figure 3, Figures 4 and 5 show the the space-time plots of intensity and the space-time-gradient along slits 3 and 4, respectively. Only one (G11) of the 11 penumbral filaments shows an apparent periodic twisting motion, as indicated by arrows to each of the individual twisting structures, although there are two filaments showing very weak twisting motions at 35 Mm (the time axis from 20 to 80 minutes) and 54 Mm (from 75 to 85 minutes) on the slit 3. **Only two (G12 and G13) of 9 filaments on the limb-side penumbra are found to show an apparent periodic**

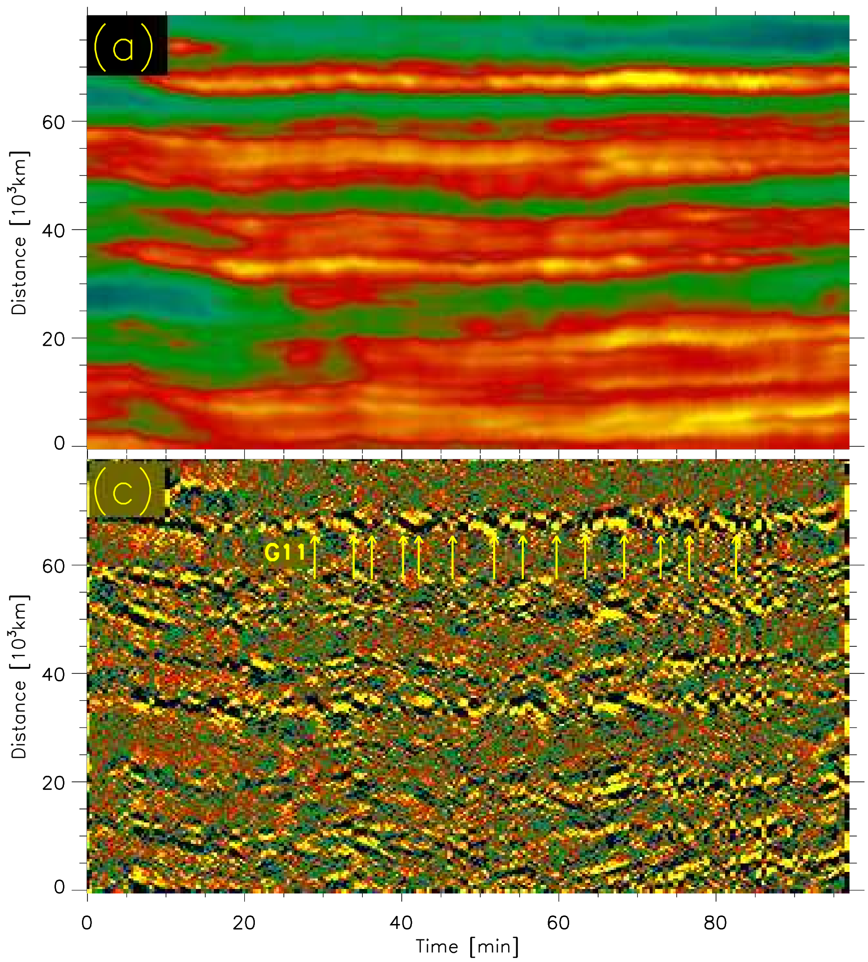

Figure 4. Same as in Figure 3, but along the slit 3 in Figure 1.

twisting motion in Figure 4. The twisting direction is from the limb side to disk center again, i.e. from the slit top to bottom along the slits 3 and 4.

3. Results

The apparent periodic twisting motions are more frequently seen in the penumbra located in the direction perpendicular to the symmetry line connecting the sunspot and disk center (slits 1 and 2) than the limb-side and

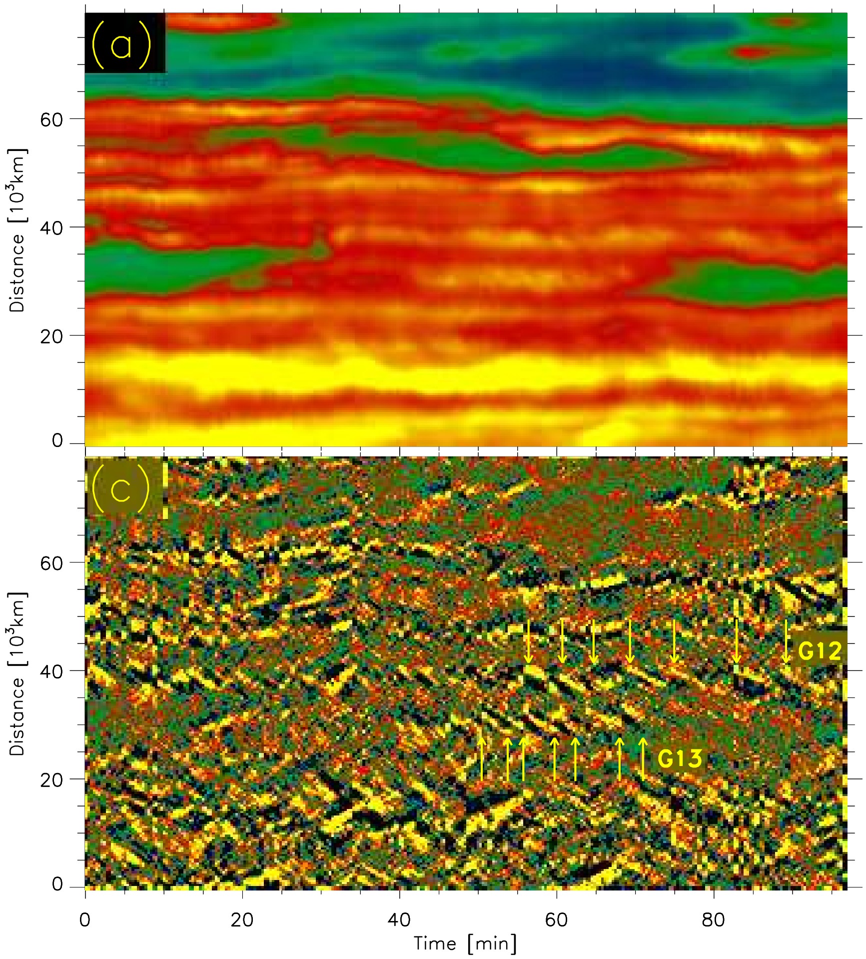

Figure 5. Same as in Figure 3, but along the slit 4 in Figure 1.

disk-center-side penumbra (slits 3 and 4). Table-1 lists the parameters of the penumbral filaments with the apparent periodic twisting motions, including their duration, period, spatial scale and twisting velocities. The penumbral filaments show various numbers of twists in their motions. We find that the maximum numbers of twisting motions is 20 (G7 in Figure 3) in our data set. Here, the duration (4240 s) is the time interval, and it includes the 20 twisting structures. The periods are average values from the duration and twisting numbers. Our results show this value is between 155 s and 330 s, with an average value of 230 s. The spatial scale shows the width of the

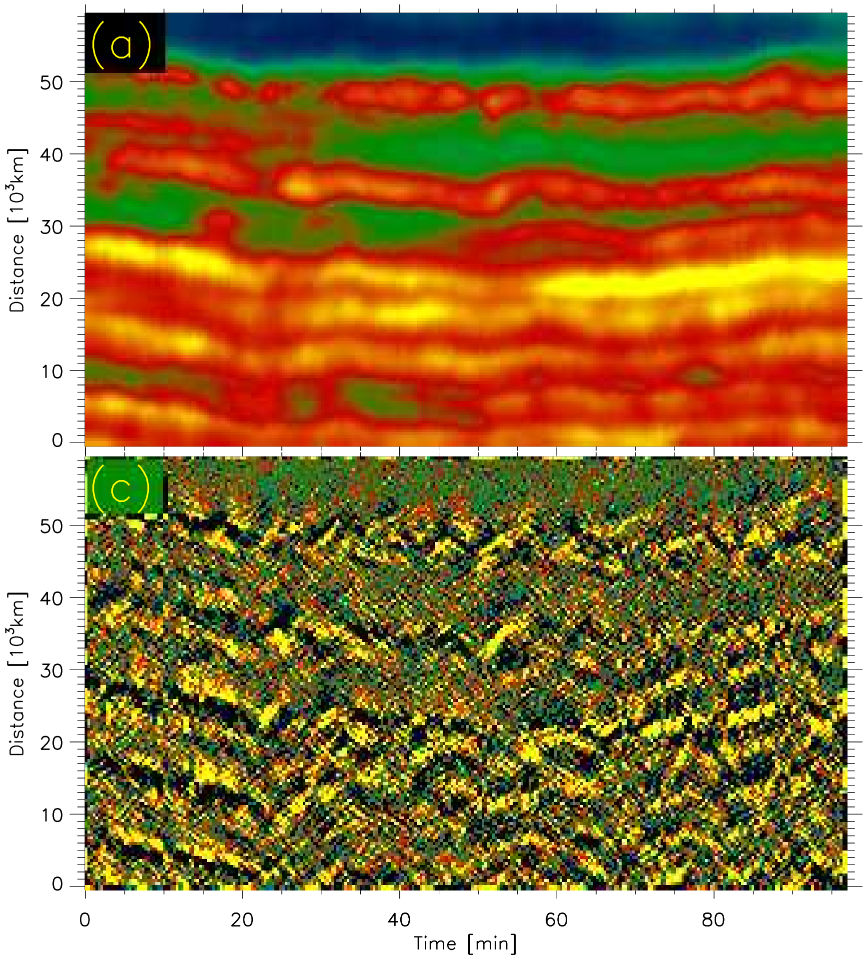

Figure 6. Same as in Figure 3, but along the slit 5 in Figure 1.

penumbral filaments along the slit direction as being from 1050 km to 1350 km. And the twisting velocity computed from the spatial scale and average period is between 4.1 km s^{-1} and 7.7 km s^{-1}, with an average value of 5.6 km s^{-1}.

We analyze the twisting motions of the penumbral filaments along two opposite directions, i.e., parallel or perpendicular to the direction from the limb to disk center. It is an interesting question whether the twisting motions are able to be seen along an oblique direction. Figure 6 shows the space-time plots along slit 5 that runs

Table I. Parameters of the twisting motions of the penumbral filaments. Duration is the time interval over which the twisting motions are identified; Spatial scale shows the width of penumbral filaments along the slit direction.

Filaments	Numbers of Twisting	Duration (s)	Period (s)	Spatial scale (km)	Velocity (km s^{-1})
G1	5	620	155	1200	7.7
G2	9	1740	218	1350	6.2
G3	5	760	190	1050	5.5
G4	8	2000	286	1500	5.2
G5	19	4060	213	1200	5.6
G6	5	1000	225	1350	6.0
G7	20	4240	223	1350	6.1
G8	14	2860	220	1200	5.5
G9	8	1840	263	1350	5.1
G10	2	220	220	1200	5.5
G11	14	3240	249	1050	4.2
G12	7	1980	330	1350	4.1
G13	7	1240	207	1200	5.8

across 8 inner penumbral filaments obliquely. It is parallel to the South-North direction. As expected from the previous findings, it is possible that the twisiting motions could be seen along the slit 6. Using the same method as before, however, we do not find apparent twisting motions with periodicity in these 8 penumbral filaments.

4. Conclusions and Discussions

We studied the periodicity of the recently discovered twisting motions of sunspot penumbral filaments. Among the SOT data set, a sunspot was well-observed for 97 minutes on 12 November 2006. Using space-time-gradient plots of the G-band intensity, the individual periodic twisting structures were identified. Firstly, our results are consistent with the previous findings of twisting directions being from the solar limb to the disk center. Such behavior is neither an actual twisting nor a helical motion. The adjacent motions are almost head-on-end. In other words, all of the twisting flows appear on the same side of the penumbral filaments, and disappear on the other side. **As a twisting-flow just ends, a new one starts simultaneously at**

the other side of the filament. Secondly, some apparent twisting motions display periodicity, where the average period is about 4 minutes. The twisting motions have a mean velocity of 6 km s^{-1}. A penumbral filament does not show periodic twisting motions over all of its lifetime. The start and end times of periodic twisting behavior are different for the various filaments. Thirdly, the apparent periodic twisting motions are hardly seen in both limb-side and disk-center-side of sunspot. According to our observations, only 3 of 20 filaments located at these two sides exhibit periodic twisting motions. To the contrary, more than half (17 of 29) filaments at slits 1 and 2 display periodic twisting structures. We do not find a fundamental difference between the periodic twisting motions for the penumbra on different sides of the sunspot.

The nature and origin of the apparent motions is still unclear. An interpretation of the twisting motions is an upflow of overturning convection, viewed from the side (e.g. Ichimoto et al. 2007; Zakharov et al. 2008). Therefore, the twisting motion being always from the limb to disk center must be an effect of viewing angle. With the limb-side part of these filaments hidden from view, **such flows will always appear to be in the direction of sun center direction when they are observed away from the disk center.** However, our result for the periodicity of twisting motions is an observational contrast to their theory. As noted earlier, the periodic twisting motions could represent a typical behavior of Evershed flows. Our observations that not all of twisting motions show a periodicity, and the periodic twisting motions start or end randomly in the penumbral filaments, **suggest a stochastic nature of the Evershed flow**.

Physical connection to the 4-min in penumbral filaments is not clear at all. It is possible that this periodicity contains physical information about the origin of the twisting. This observational property should be considered by the theorists in constructing their models. The 4-min periodicity is between the 3-min and 5-min periods, which are generally thought to be related the period of acoustic standing waves inside of the Sun.

Acknowledgements

HINODE is a Japanese mission developed and launched by ISAS/JAXA, with NAOJ as domestic partner and NASA and STFC (UK) as international partners. It is operated by these agencies in co-operation with ESA and NSC (Norway). W. Cao gratefully acknowledges the support of NSF through ATM-0847126, ATM-0745744, and NASA through NASA-NNX08BA22G. This work is also supported by NSF of China under grants 10603014, 10843005, 10833007, 40804034, 973 Program under grant 2006CB806302, and CAS Project under grant KJCX2-YW-T04.

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