QUASI-PERIODIC WIGGLES OF MICROWAVE ZEBRA STRUCTURES IN A SOLAR FLARE

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Abstract

Quasi-periodic wiggles of microwave zebra pattern (ZP) structures with periods ranging from about 0.5 s to 1.5 s are found in an X-class solar flare on 2006 December 13 at the 2.6–3.8 GHz with the Chinese Solar Broadband Radio Spectrometer (SBRS/Huairou). Periodogram and correlation analysis show that the wiggles have two to three significant periodicities and are almost in phase between stripes at different frequencies. The Alfvén speed estimated from the ZP structures is about 700 km s\(^{-1}\). We find the spatial size of the wave-guiding plasma structure to be about 1 Mm with a detected period of about 1 s. This suggests that the ZP wiggles can be associated with the fast magnetoacoustic oscillations in the flaring active region. The lack of a significant phase shift between wiggles of different stripes suggests that the ZP wiggles are caused by a standing sausage oscillation.

Key words: Sun: flares – Sun: oscillations – Sun: radio radiation

Online-only material: color figures

1. INTRODUCTION

Quasi-periodic pulsations (QPPs) are a frequently observed phenomenon in the electromagnetic emission generated by solar and stellar flares in a vast energy range from radio to hard X-ray and gamma-ray bands (see Nakariakov & Melnikov 2009; Nakariakov et al. 2010; Tan et al. 2010 for recent reviews). Typically, QPPs appear as a pronounced oscillatory pattern in the intensity of the radiation with typical periods ranging from a fraction of a second to several minutes. Also, QPPs have been found as oscillations of the Doppler shift of the emission lines associated with the hot plasma in flaring sites (Mariska 2006) or the density of the plasma (Kim et al. 2012). The variety of the characteristic periods and modulation depths of QPPs suggests that they can be caused by several different mechanisms, including wave–particle interaction (e.g., Aschwanden 1987), spontaneous or driven periodic regimes of magnetic reconnection (e.g., Tajima et al. 1987; Nakariakov et al. 2010), magnetohydrodynamic (MHD) oscillations (e.g., Nakariakov & Melnikov 2009), or oscillations in an equivalent LCR circuit (e.g., Zaitsev & Stepanov 2008). Revealing the mechanisms responsible for the production of QPPs remains an important task in the context of our understanding of the basic physical processes operating in solar and stellar flares.

Another interesting phenomenon of flaring microwave emission is the zebra pattern (ZP) structures of the broadband spectral observations: sets of almost-parallel stripes superposed on microwave type II and IV bursts with slow frequency drifting and variations (e.g., Chernov 2006). A similar phenomenon is an “evolving emission line” (EEL), which, in contrast with the ZP, consists of a single emission stripe in the dynamical spectrum (Chernov et al. 1998; Ning et al. 2000a). There is no broadly accepted interpretation for the ZP, although recent observational findings favor the model associating ZP with the coherent generation of upper-hybrid waves at multiple double plasma resonances (DPRs) in a non-uniform plasma (Zheleznyakov & Zlotnik 1975). In this model, the frequency separation of adjacent stripes in a ZP is directly proportional to the electron gyrofrequency and hence to the magnetic field strength. This property provides us with a unique method for measuring the coronal magnetic field. The model based upon the double plasma resonance is supported by some observational evidence (e.g., Zlotnik et al. 2003; Chen & Yan 2007; Chen et al. 2011; Yu et al. 2012). However, other proposed mechanisms, e.g., based upon the whistler wave packets (e.g., Chernov 2006) and trapped upper-hybrid Z-mode waves (LaBelle et al. 2003) have not been ruled out. In addition, very recently Karlický (2013) proposed a new model that links ZP with propagating compressive MHD waves.

Analysis of some ZPs indicates the presence of periodic modulation. In particular, Chernov et al. (2005) found that the intensity of ZP stripes observed on 2002 April 21 pulsed quasi-periodically—the bright ZP stripes consisted of separate short-duration pulses with a period of about 30 ms. Pulsations of the same intensity in adjacent stripes were found to be similar. The detected periodicity was associated with the oscillatory nonlinear interaction of whistlers with ion–sound and Langmuir waves. That ZP event obtained great attention and the QPPs of this intensity have been considered in several follow-up studies that addressed temporal characteristics of the pulses and their polarizations (e.g., Chen & Yan 2007; Kuznetsov 2008). Chen & Yan (2007) proposed that the pulsations were associated with relaxation oscillations in a system of an electron beam and plasma waves. Kuznetsov & Tsap (2007) linked the pulsations with the periodic injection of electron beams. Kuznetsov (2008) interpreted the quasi-periodic patterns in terms of downward-propagating fast magnetoacoustic waves. A similar model was recently employed to interpret the phenomenon of fiber bursts in the dynamical spectra of flare-generated radio emissions (Karlický et al. 2013). Variations of the intensity with longer periods, about 275 ms, were detected in the event on 1998 April 15 by Ning et al. (2000a).

Another less-studied type of ZP modulation is the periodic quasi-coherent oscillating drift of the spectral stripes, also called “wiggling.” In the unusually long radio event on 1992 February 17 observed with ARTEMIS, OSRA, and IZMIRAN in the 100–500 MHz band, Chernov et al. (1998) detected pronounced wiggling of the ZP with a period of about three minutes, with a frequency variation amplitude of about 5 MHz. The relative amplitude of the spectral variation was 2%. It was linked with
the possible variation of the emitting plasma density by about 4% or of the magnetic field by 2%, or a combination of both. An EEL observed simultaneously with the ZP showed a similar variability. In the event of 1998 April 15 observed with Huaireou at about 3 GHz, Ning et al. (2000a, 2000b) and Chernov et al. (2001) found that the central frequencies of the stripes fluctuated on a typical timescale of 0.5 s and 1.5–2 s in two different time intervals. In the shorter period case, three stripes were found to wiggle synchronously by about 200 MHz with a relative frequency variation of about 6%. It was estimated to correspond to the relative variation of the magnetic field of 10% or the density of about 6%. In the longer period case, the spectral amplitude of the oscillations was 80 MHz, from 3.41 GHz to 3.49 MHz. A similar wiggling evolution of ZP stripes can be associated with either an impulsively generated fast magnetoacoustic wave train (e.g., Roberts et al. 1984; Nakariakov et al. 2004) or with a standing sausage mode of a fast magnetoacoustic resonator (e.g., Kopylova et al. 2007; Zaitsev & Stepanov 2008; Nakariakov et al. 2012), or result from the passage of a perpendicular fast wave through a randomly structured coronal plasma (Nakariakov et al. 2005). All these mechanisms are of great interest for MHD coronal seismology, as they bring us the unique information about fine, unresolved structure of the coronal plasma and can rarely be studied in the EUV band because of its insufficient time resolution.

The aim of this paper is to perform a detailed study of the quasi-periodic wiggles in a microwave ZP observed in a solar flare. In Section 2, the instrumentation and the data analyzed are described. In Section 3, we present the findings that are then discussed in Section 4.

2. OBSERVATIONAL DATA

The flare analyzed in this paper occurred on 2006 December 13 in NOAA active region 10930 located on disk (S05W33). It was a typical two-ribbon flare that reached the GOES level X3.4/4B class at about 02:40 UT (Isobe et al. 2007; Yan et al. 2007). This flare was observed by Solar and Heliospheric Observatory (SOHO), Hinode, and RHESSI satellites. It was also well observed by the ground-based Chinese Solar Broadband Radio Spectrometer (SBRS/Huaiirou; Tan et al. 2007; Yan et al. 2007) and the Nobeyama Radioheliograph (NoRH). SBRS/Huaiirou (Fu et al. 1995, 2004; Yan et al. 2002) is a robust solar radio spectrometer that measures the total flux density of solar microwave emission on both left- and right-handed circular polarization (LHCP and RHCP) at three frequency bands: 1.10–2.06 GHz (time resolution of 5 ms and frequency resolution of 4 MHz), 2.6–3.8 GHz (8 ms and 10 MHz), and 5.20–7.60 GHz (5 ms and 20 MHz). NoRH can provide imaging observations at frequencies of 17 GHz and 34 GHz (Nakajima et al. 1994). Thirteen ZP structures were recorded by SBRS/Huaiirou at 2.6–3.8 GHz during the flaring process in the discussed event (Yu et al. 2012). Here we focus on the time interval 02:40–03:05 UT after the soft X-ray emission maximum. Two long-lasting ZPs were detected at 02:43:00–02:43:20 UT (ZP1) and 03:03:00–03:03:20 UT (ZP2) that show quasi-periodic spectral wiggling of the ZP stripes (see Figures 1(a)–(b)).

The left panel in Figure 2 shows the full disk EUV image at 195 Å obtained by the Extreme-ultraviolet Imaging Telescope (EIT; Delaboudinière et al. 1995) onboard SOHO during the decay phase of the flare with an inset of the TRACE (Handy et al. 1999) image at 195 Å showing the post-flare loop arcade with explosive features at the time of ZP2. The right panel shows the NoRH 17 GHz full disk intensity image and an inset of the enlarged 17 GHz image superposed with a 34 GHz image. The source region of the radio emission at 17 GHz has approximately the same position as the EUV arcade structure in the flare region during the decay phase with the maximum situated in the northeast of the arcade, between the opposite footpoints of 34 GHz radio sources. The spatial separation of the footpoints is about 50 arcsec. The NoRH 17 GHz full disk image shows that AR 10930 is a unique strong radio emission source on the solar disk in this flare event, indicating that the radiation of the ZPs possibly comes from the flare core region.

The extended duration \((t > 15 \text{s})\) of ZP1 and ZP2 makes it possible to study their long-term variation, including the wiggling of individual spectral stripes. To analyze the oscillatory patterns in ZPs, we need to extract the ZP stripes from the background emissions in the raw microwave spectrogram. Specific steps of the data processing are illustrated in Figure 1. The microwave dynamic spectrograms of ZP1 and ZP2 in the LHCP are shown in Figures 1(a)–(b). Note that the RHCP spectrograms are not used for large saturation in the low-frequency range \((<2.9 \text{GHz})\). The first step of processing is to remove the trend of the background emission to make the bright stripe-like features prominent. For that, a running average smoothed over 10 pixels is subtracted from the frequency profile at each instant of time. We subsequently apply a low-pass filter to smooth out the separate spike-like structures in the stripes. We then use the thresholding method to segment the stripe features as shown in Figures 1(c)–(d). The following step is the data series extraction. We fit a Gaussian to the frequency profile of each stripe and then normalize the Gaussians to their amplitudes so that the brightness of stripes is uniform. This procedure removes the information about the amplitude modulation of the signal while highlighting the frequency modulation. The centers of the Gaussian peaks give us the unique information about fine, unresolved structure of the coronal plasma and can rarely be studied in the EUV band because of its insufficient time resolution.

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3. RESULTS

The presence of wiggling oscillatory patterns in the two microwave ZPs is seen in the time variation of the spectral skeletons. To quantify this finding, we performed periodogram and autocorrelation analyses of the $f_N$ and $\Delta f_N$ time profiles of the extracted stripes. The $f_N$ time profiles were first smoothed by 30 points (0.24 s) to remove high-frequency noise and then detrended by subtracting the signal $f_N$ smoothed with a 100 point (0.8 s) boxcar. The detrended time profiles are shown in Figures 1(g)–(h). Note that the smoothing of $f_N$ attenuates the signal amplitude of oscillation. The oscillation amplitude of $f_N$ without smoothing is about 20 MHz, larger than the frequency resolution of the spectrum (10 MHz). Power spectra of the pre-processed signals were obtained with the use of the Lomb–Scargle periodogram (e.g., Scargle 1982; see the left panels of Figures 3–4). The spectra contain significant peaks above the 99.99% confidence level. Additional confirmation of the significance of the detected oscillations was obtained by the application of Fisher's randomization test (Linnell Nemec & Nemec 1985; Yuan et al. 2011). The calculation of the spectral peaks for 200 permutations confirmed that the significance of the main peaks was greater than 99%. To avoid the appearance of artificial periodicities due to the smoothing procedure, we calculated the periodograms of the $f_N$ time profiles obtained for a set of noise-removing boxcars (10, 20, 30 points) and trend-removing boxcars (60, 70, 80, 100 points; see Kupriyanova et al. 2010 for a discussion of this method). The positions of pronounced spectral peaks in the periodograms do not show any dependence on the smoothing width, implying that these spectral peaks are not artifacts of the smoothing.

Figure 3(a) presents the periodograms of the $f_N$ time profiles of four highest-frequency stripes in ZP1 with the long-term trend removed. There are two well-pronounced spectral peaks in the vicinities of 0.70 and 1.20 Hz ($P_1 \sim 1.43$ s and $P_2 \sim 0.83$ s) that are seen in all four stripes. The four auto-correlation functions versus time lag (Figure 3(b)) show evident in-phase periodic behavior over several periods. The four auto-correlation functions, the period $P_1$ is well seen in all stripes, while the period $P_2$ is pronounced only in $f_3$ and $f_4$. Figure 3(c) presents the periodograms of time profiles of detrended spectral difference of the stripes $\Delta f_N$. The three profiles of $\Delta f_N$ show different periodic
behaviors with three dominant peaks in the vicinities of 0.86, 1.58, and 1.90 Hz (1.16, 0.63 and 0.53 s). In Figure 3(d), the auto-correlation functions of detrended \( \Delta f_s \) show still significant though less pronounced periodic oscillatory patterns than were obtained for the central frequencies of the stripes. The spectral differences \( \Delta f_{3,4} \) between the second and third stripes and the third and the fourth stripes (dashed and dotted curves, respectively) have periods that are apparently two times shorter than the difference between the first and second stripes \( \Delta f_2 \).

Figure 3. Periodograms and auto-correlation functions of QPP components of (a) and (b) the stripe frequency \( f_N \), and (c) and (d) the frequency separation \( \Delta f_N \) of two neighboring stripes in the ZP1. Horizontal lines in the periodograms indicate a 99.99% confidence level.

Figure 4(a) shows the periodograms of the detrended \( f_N \) time profiles of the four highest-frequency stripes in ZP2. Two pronounced common peaks are seen in the vicinities of 1.20 and 1.70 Hz (\( P_2 \sim 0.83 \) s and \( P_3 \sim 0.59 \) s). The periodicity of \( P_2 \) is not detected in the detrended time profile of \( f_2 \). The auto-correlation functions of the detrended \( f_N \) time profiles all have pronounced oscillatory patterns over several periods (Figure 4(b)). Periods \( P_2 \) and \( P_3 \) are present in the auto-correlation function of \( f_1 \), \( f_3 \), and \( f_4 \). Figure 4(c) presents the
periodograms of time profiles of detrended $\Delta f_{\text{fs}}$, showing an obvious peak at 1.20 Hz ($P_2 \sim 0.83$ s). The auto-correlation functions in Figure 4(d) have a similar periodicity for all the three $\Delta f_{\text{fs}}$.

Additionally, as we can see in Figures 3 and 4, the periodograms and auto-correlation functions of the detrended $f_{\text{fs}}$ and $\Delta f_{\text{fs}}$ time profiles in ZP1 and ZP2 all have a well-pronounced common spectral peak at the period $P_2 \sim 0.83$ s. The observed amplitude of the frequency variation in the ZP wiggles is about 20 MHz, about 0.7% of the central frequency.

To establish phase relations between the periodic wiggles of neighboring stripes, we calculate the cross-correlation coefficients of the detrended time profiles of $f_{\text{fs}}$. For ZP1, the highest cross-correlation coefficients—0.86 between stripes 1 and 2, 0.85 between stripes 2 and 3, and 0.85 between stripes 3 and 4—are obtained for the time lags less than 0.01 s. Likewise, for ZP2, the highest cross-correlation coefficients are 0.79 between stripes 1 and 2, 0.56 between stripes 2 and 3, and 0.84 between stripes 3 and 4 for the time lags 0.12 s, $-0.02$ s, and $-0.02$ s, respectively. Thus, we can accept that the ZP wiggles occur almost in phase, as in all cases the time lag is found to be much smaller than the oscillation period and is likely to be attributed to noise.

4. DISCUSSIONS AND CONCLUSION

Analysis of the fine spectral structure of individual stripes in two microwave ZPs observed with SBRS/Huaireou shows that central frequencies of the stripes perform quasi-periodic oscillations (wiggling) in the range from about 0.5 s to 1.5 s. Simultaneously, the oscillations are found to have two to three significant periodicities. Similar periodicities are detected in the spectral differences of neighboring ZP stripes. The frequency variation amplitude is about 20 MHz, giving a relative amplitude of 0.7%. Both the wiggling periods and amplitudes are consistent with previous reports of this effect in Chernov et al. (1998, 2001) and Ning et al. (2000a, 2000b). Wiggling of neighboring stripes is found to be almost in phase.

The detected periods are of the order of the transverse Alfvén or fast magnetooacoustic transit time in active region loops and other plasma non-uniformities (for a typical spatial scale of 1 Mm and Alfvén speed of 1 Mm s$^{-1}$). This timescale plays an important role in the physics of MHD wave interaction with structured plasma. In particular, an impulsively excited fast magnetooacoustic disturbance of a coronal loop or a current sheet develops in a quasi-periodic wave train with a period about the same as the transverse fast magnetooacoustic transit time (Roberts et al. 1984; Nakariakov et al. 2004; Jelinek et al. 2012). Also, this timescale is a typical period of standing sausage fast magnetooacoustic modes of such a loop in a leaky regime (Kopylova et al. 2007; Nakariakov et al. 2012). Thus, it is reasonable to assume that the observed periodicities could be connected with MHD wave dynamics.

Consider the DPR model (see, e.g., Zheleznyakov & Zlotnik 1975; Kuznetsov & Tsap 2007) as the mechanism responsible for the generation of ZPs. According to the DPR model, the microwave ZP structure is likely to be interpreted as a great enhancement of electrostatic upper-hybrid waves at certain resonance levels where the upper-hybrid frequency $f_{\text{uh}}$ is equal to the harmonics of electron cyclotron frequency $f_{\text{ce}}$:

$$f_{\text{uh}} = (f_{\text{pe}}^2 + f_{\text{ce}}^2)^{1/2} \simeq s f_{\text{ce}},$$

(1)

where $f_{\text{pe}}$ is the plasma frequency of electrons and $s$ is an integer harmonic number. We would like to stress that the index $s$ used here is different from the index $N$ used above. Enumeration of the observed ZP stripes with index $N$ begins from the stripe of the highest observed frequency, while some higher-frequency stripes can be missing. Hence, $N = s - M$, where $M$ is the number of missing stripes.

If the plasma density and the absolute value of the magnetic field, and hence the electron plasma and cyclotron frequencies, vary with height, there are several spatially separated levels.
where the DPR condition is satisfied. Radio emissions from different DPR levels come at the local upper-hybrid frequencies. The emissions from different DPR levels form different individual stripes of the ZP structure. When taking into account the different DPR levels come at the local upper-hybrid frequencies.

The Astrophysical Journal between neighboring ZP stripes at harmonics s and s + 1 is respectively, that are non-uniform in the vertical direction. In the DPR model, the polarization will be very weak; the emission possibly generates from the coalescence of two excited plasma waves.

Taking that in the DPR resonant layer, the electron cyclotron emission frequency of the stripe. For the analyzed event, this gives us a magnetic field of 50 G.

As discussed in the DPR, the oscillation of the ZP stripes is caused by a propagating magnetoacoustic wave, neighboring ZP stripes, separated by several Mm, would be positioned at approximately 10 Mm. In the case of the slow magnetoacoustic wave, taking into account that in the corona the sound speed is lower than the Alfvén speed, the wavelength becomes even shorter than 1 Mm. Thus, if the oscillation is caused by a propagating magnetoacoustic wave, neighboring ZP stripes would wiggle with a significant phase difference that is not detected. Consequently, we rule out the interpretation of the ZP wiggling in terms of propagating waves. On the other hand, in a global standing mode, all segments of the wave-guiding plasma non-uniformity oscillate in phase. Moreover, in a global sausage mode of sufficiently thin field-aligned plasma non-uniformities, the period is determined by the transverse size of the plasma non-uniformity and is almost independent of its longitudinal size (Kopylova et al. 2007; Nakariakov et al. 2012). Taking that the period of the detected oscillations is 1 s, we obtain that the required spatial size of the wave-guiding plasma non-uniformity with the estimated value of the Alfvén speed is about 1 Mm. This value is a typical minor radius of an active region loop. Consequently, the observed ZP wiggling can be associated with fast magnetoacoustic oscillations in the flaring active region. Moreover, the established lack of a significant phase shift between oscillations of different stripes that are coming from different spatial locations indicates that the MHD oscillation is likely to be standing. The above suggests that the detected ZP wiggles are caused by a standing sausage oscillation. This conclusion is supported by the finding that both the instantaneous frequencies of individual stripes and their spectral separations oscillate with the same periods. This is consistent with a sausage oscillation that perturbs both the plasma density and magnetic field (Nakariakov et al. 2012).

More information could be obtained from the analysis of the phase relationship between the instantaneous frequencies of individual stripes and their spectral separations, but such a study requires an observational example of a ZP with higher-amplitude wiggling.

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REFFERENCES

Aschwanden, M. J. 1987, SoPh, 111, 113
Chen, B., Bastian, T. S., Gary, D. E., & Jing, J. 2011, ApJ, 736, 64
Chen, B., & Yan, Y. 2007, SoPh, 246, 431
Chernov, G. P. 2006, SSRv., 127, 195
Chernov, G. P., Markeev, A. K., Poquerusse, M., et al. 1999, A&A, 334, 314
Chernov, G. P., Yan, Y. H., Fu, Q. J., & Tan, C. M. 2005, A&A, 437, 1047
Chernov, G. P., Yasnov, L. V., Yan, Y.-H., & Fu, Q.-J. 2001, ChJAA, 1, 525
Cooper, F. C., Nakariakov, V. M., & Williams, D. R. 2003, A&A, 409, 325
Delaboudinière, J.-P., Artzner, G. E., Brunaud, J., et al. 1995, SoPh, 162, 291
De Moortel, I., & Nakariakov, V. M. 2012, RSPTA, 370, 3193
Fu, Q., Qin, Z., Ji, H., & Pei, L. 1995, SoPh, 160, 97
Fu, Q. J., Ji, H.-Q., Qin, Z. H., et al. 2004, SoPh, 222, 167
Handy, B. N., Acton, L. W., Kankelborg, C. C., et al. 1999, SoPh, 187, 229
Isobe, H., Kubo, M., Minoshima, T., et al. 2007, PASJ, 59, 807
Jelinek, P., Karlický, M., & Murawski, K. 2012, A&A, 546, A49
Karlický, M. 2013, A&A, 552, A90
Karlický, M., Mészárossová, H., & Jelinek, P. 2013, A&A, 550, A1
Kim, S., Nakariakov, V. M., & Shibasaki, K. 2012, ApJ, 756, L36
Kopylova, Y. G., Melnikov, A. V., Stepanov, A. V., Tsap, Y. T., & Goldvarv, T.-B. 2007, AstL, 33, 706
Kupriyanova, E. G., Melnikov, V. F., Nakariakov, V. M., & Shibasaki, K. 2010, SoPh, 267, 329
Kuznetsov, A. A. 2008, SoPh, 253, 103
Kuznetsov, A. A., & Tsap, Y. T. 2007, SoPh, 241, 127
LaBelle, J., Treumann, R. A., Yoon, P. H., & Karlicky, M. 2003, ApJ, 593, 1195
Limnell Nemec, A. F., & Nemec, J. M. 1985, AJ, 90, 2317
Mariska, J. T. 2006, ApJ, 639, 484
Nakajima, H., Nishio, M., Enome, S., et al. 1994, IEEE, 82, 705
Nakariakov, V. M., Arber, T. D., Ault, C. E., et al. 2004, MNRAS, 349, 705
Nakariakov, V. M., Hornsey, C., & Melnikov, V. F. 2012, ApJ, 761, 134
Nakariakov, V. M., Inglis, A. R., Zimovets, I. V., et al. 2010, PPCF, 52, 124009
Nakariakov, V. M., & Melnikov, V. F. 2009, SSRv., 149, 119
Nakariakov, V. M., Pascoe, D. J., & Arber, T. D. 2005, SSRv., 121, 115
Ning, Z., Fu, Q., & Lu, Q. 2000a, A&A, 364, 853
Ning, Z., Fu, Q., & Lu, Q. 2000b, PASJ, 52, 919
Roberts, B., Edwin, P. M., & Benz, A. O. 1984, ApJ, 279, 857
Scargle, J. D. 1982, ApJ, 263, 835
Tajima, T., Sakai, J., Nakajima, H., et al. 1987, ApJ, 321, 1031
Tan, B., Yan, Y., Tan, C., & Liu, Y. 2007, ApJ, 671, 964
Tan, B., Zhang, Y., Tan, C., & Liu, Y. 2010, ApJ, 723, 25
Williams, D. R., Phillips, K. J. H., Rudawy, P., et al. 2001, MNRAS, 326, 428
Yan, Y. H., Fu, Q. J., Liu, Y. Y., & Chen, Z. J. 2002, in The 10th European Solar Physics Meeting, Solar Variability: From Core to Outer Frontiers, Vol. 1, ed. A. Wilson (ESA SP-506; Noordwijk: ESA Publication Division), 375
Yan, Y. H., Huang, J., Chen, B., & Sakurai, T. 2007, PASJ, 59, 815
Yu, S., Yan, Y., & Tan, B. 2012, ApJ, 761, 136
Yuan, D., Nakariakov, V. M., Chorley, N., & Foullon, C. 2011, A&A, 533, A116
Zaitsev, V. V., & Stepanov, A. V. 2008, PhyU, 51, 1123
Zheleznyakov, V. V., & Zlotnik, E. Y. 1975, SoPh, 44, 461
Zlotnik, E. Y., Zaitsev, V. V., Aurass, H., Mann, G., & Hofmann, A. 2003, A&A, 410, 1011