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Oscillations of a Giant Solar Tornado

Fatemeh Hashemi-Nasab[1] · Neda Dadashi[2] · Nasibeh Alipour-Rad[3] · YousefAli Abedini[4]

[1] Department of Physics, University of Zanjan, P.O. Box 45195-313, Zanjan, Iran; email: fatima.hashemi@gmail.com
[2] Department of Physics, University of Zanjan, P.O. Box 45195-313, Zanjan, Iran email: dadashi@znu.ac.ir
[3] Department of Physics, University of Zanjan, P.O. Box 45195-313, Zanjan, Iran
[4] Department of Physics, University of Zanjan, P.O. Box 45195-313, Zanjan, Iran

Abstract.

Solar magnetic tornadoes are known to be one of the mass and energy transport mechanisms from the lower solar atmosphere into the upper layers of the solar corona. A bright spiral structure with two arms is observed using high-cadence EUV images of 171, 193 and 304 Å channels of Atmospheric Imaging Assembly (AIA) aboard the Solar Dynamics Observatory (SDO) on 10th of July 2011 for three hours. The structure studied here looks bright in front of dark background emissions. The rotational energy budget of this tornado is estimated using three different approaches. Results showed the rotational energy ranges between 1.95×10^{18} erg to 3.36×10^{19} erg. After correcting for the solar differential rotation, the oscillatory behaviour of the structure is studied using FFT technique. Results show four different regimes of oscillations: 3-min, 5-6 min, 8-11 min, and 15-17 min. The showed origin of each of these oscillations are discussed.

Keywords: Sun: Corona, Sun: Tornado, Sun: UV radiation, Sun: Oscillations

1 Introduction

Convective flows at the surface of the Sun can result in the braiding and twisting of the magnetic field lines. This scenario is suggested to be one of the most effective mechanisms in the heating of the solar atmosphere [1]. A large number of these magnetic vortex flows that are driven convectively had been observed in the photosphere [2, 3, 4]. Atmospheric swirl motions got more attention since Wedemeyer et al. 2009 [5] detected such vortex movement in the chromosphere using high resolution images from 1-meter Swedish Solar Telescope (SST), [6]. These vortices were studied both in numerical and theoretical simulations [7, 8]. Both studies suggested that the vortex tubes originate either in the granules or in the intergranule areas [9]. These magnetized vortex structures in the solar atmosphere are called solar tornadoes. As it is described, the formation mechanism(s) of the solar tornados is totally different from the terrestrial tornadoes. These giant structures appear like huge vortex flows or twisting cables in chromosphere and corona [10]. Wedemeyer et al. 2012 found the imprints of these vortex flows (or swirl motions) in the transition region and coronal lower layers. Therefore, it is found that the solar tornadoes connect the convection zone to the upper layers of the solar corona, directly, in a unique magnetic structure. They suggested that the solar tornados could be considered as energy (or even possibly matter) injection channels from the lower layers to the upper layers of the solar atmosphere [11, 12].

Su et al. 2012 suggest that the solar tornados are the vertical legs of solar prominences (barbs). They propose that rotating magnetic structure caused by the photospheric vortex flows, can generate giant tornados [13]. On the other hand, Panesar et al. 2013 [14] propose another mechanism for the formation of solar tornados. They suggest that the dynamic tornado happens as a response of magnetic field of a helical prominence to the cavity expansion. However, the giant tornado studied here is not related to any prominence structure.

Throughout the last two decades, vast variety of waves are discovered inside the coronal structures [15, 16]. To study the tornado structure properties, and investigate the possible signatures of wave-base phenomena [17, 18] in coronal heating through this structure, we use Fast Fourier Transformation (FFT) technique on the light curves of different parts of this tornado in 171 Å EUV images of AIA/SDO to obtain the prevalent intensity frequencies. Propagating waves and periodic motions are classified as small amplitude oscillations and large ones. If their velocity is faster than 20 kms^{-1}, they are classified as small-amplitude and if they are slower, they are grouped as long-amplitude [19].

One of the most frequent oscillation obtained out of the FFT analysis in our work is 3 minute oscillations that could be related to the presence of Type II spicules in the background of the studied tornado. In general, there are two types of spicules: Type I spicules, the classic ones, with maximum velocities of $15-40\ km/s$, and typical lifetimes of $150-400$ seconds, appear almost everywhere all over the suns' surface in the chromospheric temperature range [20, 21]. Type II spicules have shorter life times of $50-150$ seconds with higher velocities of $30-110\ km/s$, rise up to coronal lower (even middle) heights [20, 22].

In the present paper, the oscillation properties of a gaint solar tornado is studied. We describe the observations in Sect. 2. Energy estimation of this giant tornado is discussed in Sect. 3. In Sect. 4 using the FFT technique, we investigate the periodic behaviour of the different parts of this tornado. The obtained prevalent frequencies and their possible roots are discussed in this section. Finally, the conclusions are summarized in Sect. 5.

2 Observation and Data Analysis

The Atmospheric Imaging Assembly (AIA, Lemen et al. 2012) [23] on board Solar Dynamic Observatory, (SDO, Pesnel et al. 2012) provides full-disk images of the sun with high spatial and temporal resolutions of 0.6 arcsec and 12 seconds in the EUV wavelength range of 94, 131, 171, 193, 211, 304 and 335 Å . The giant tornado is observed on the 10th of July 2011, 00:00:00 UT to 03:00:00 UT in the 171 Å channel nearby the west limb of the sun. It looks like a bright ellipse with two arms (Fig. 1). Level 1 images of AIA 171 Å channel during the mentioned time are obtained with the cadence of 12 seconds and calibrated using the SolarSoftWare (SSW) standard routine *aia_prep.pro* and corrected for the differential rotation of the sun with the help of *derot_map.pro* routine. The center of this giant solar tornado is obtained by fitting an ellipse function to the AIA 171 Å image to be at solar coordinates of (825″,235″) with respect to the solar center with coordinates of (0″,0″).

The STEREO-A images (with separation angle of 98 degrees from SDO on this date) helped us to have a perpendicular look at this structure and eliminate the projection effects. The tornado surface in STEREO-A images looks to have a circular shape rather than an elliptical one (Fig. 2). From the point of view of STEREO-A, the center of this tornado located at (-538″,186″). The round shape of the tornado surface in STEREO-A point of view images allows us to measure the radius of this structure to be 15″ (Fig. 2).

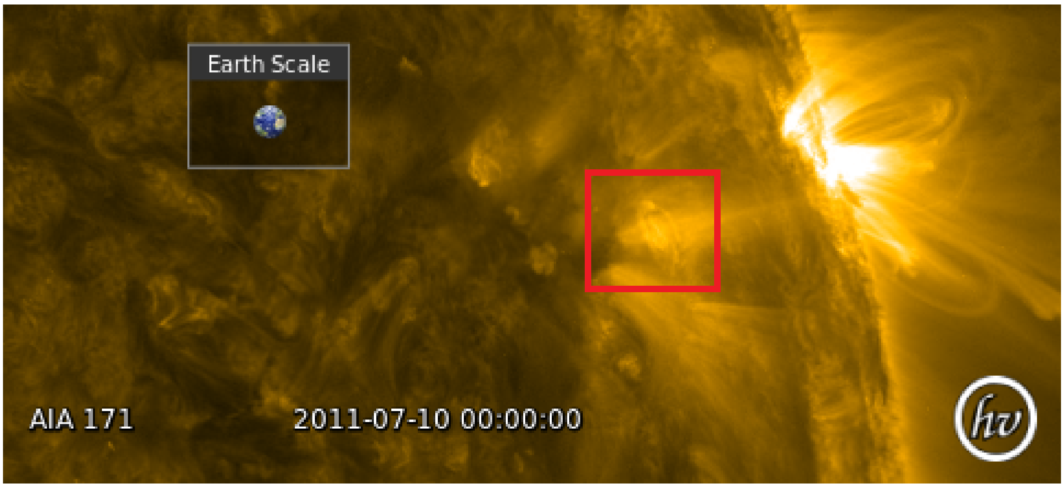

Figure 1: Fe IX 171 Å AIA image on 2011-07-10, 00:00:00 UT. The gaint tornado nearby the west limb of the sun is outlined by the red box. An Earth scale image is over-plotted to represent the size of this gaint tornado in comparison to the size of the Earth.

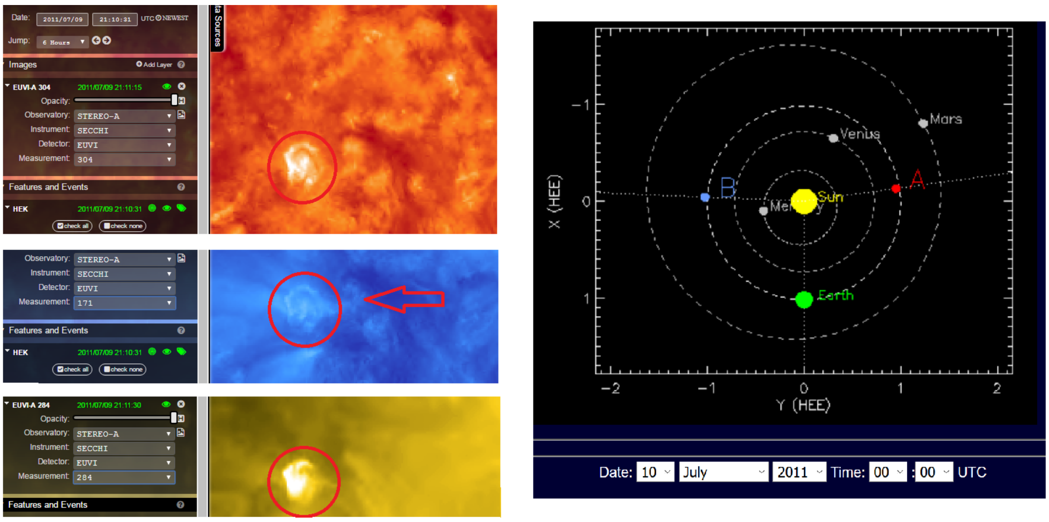

Figure 2: Right Panel represents an schematic of the separation angle of STEREO-A (the red circle labelled with A) and AIA/SDO (which rotates in an orbit around the Earth and could be considered at the Earth position, the green circle) around the Sun at the time of observation which is 98 degrees.
Left panel (from the top to the bottom) represents the tornado on 2011-07-09 at 21:10:31 UTC as observed in the 304, 171, and 284 Å channels of STEREO-A. The circular shape of the tornado is apparent in contrast to the elliptical shape from the AIA/SDO point of view (the projection effect).

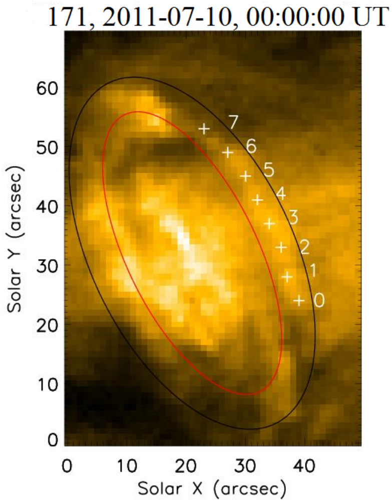

Figure 3: An ellipse is fitted to all the three hours of AIA data from 2011-07-10, 00:00:00 to 03:00:00 UTC to measure the solar tornado rotation velocity.

3 Energy Estimation of the tornado

In addition to the thermal energy, tornadoes have other budget of energy because of their rotation. In continue, we estimate these extra energies from three approaches:

1. On the first approximation, we just calculate the kinetic energy through this extra rotation velocity (apart from the thermal velocity), $E_k = \frac{1}{2}Mv^2$. To calculate the circular rotation velocity of the tornado, we extracted a 100×100 pixel^2 area in the AIA 171 Å channel's data, that covers the tornado structure and fitted an ellipse function to the each time step of AIA images (during the three hours of the study) to investigate the evolution of the structure (Fig. 3). The results show the structure is at-least rotated about 0.43″, and 1.67″ in the solar X and solar Y directions (during the three hours) counter-clockwise, respectively. This means that the rotating velocity of the tornado at its surface is $v = 126 \pm 40\ m/s$. The typical height of a tornado is about 100″ (about 72,500 km), with the obtained radius of 15″ (about 10,875 km). If we consider a cylindrical shape for the tornado, its volume is $V = \pi\, r^2\, h = 2.69 \times 10^{28}\ cm^3$, and the electron number density in the corona is about 10^9 to 10^{10} particle per cm^3, then the mass of the tornado could be calculated as $M = m_e nV = 2.46 \times 10^7$ to $10^8\,kg$, where m_e is the electron mass. The energy estimation from this approach is obtained as $E_k = \frac{1}{2}Mv^2 = 1.95 \times 10^{18}$ to $10^{19}\,erg$ [25].

2. On the 2nd approximation, we consider the tornado as a solid cylinder rotating around its central axis with the moment of inertia, I. The total energy in this case is $E_t = E_k + E_r$, where $E_r = \frac{1}{2}I\omega^2$, $I = \frac{1}{2}Mr^2$, $\omega = v/r$. The energy in the second estimation is calculated as $E_t = (1.95 + 0.97) \times 10^{18}$ to $10^{19}\,erg$ [25].

3. On the 3rd approximation, we can consider the tornado as a hallow cylinder with internal and external radius of r_1=10″ and r_2=15″ rotating around the central axis. The moment of inertia in this case is calculated though $I = \frac{1}{2}m(r_1^2 + r_2^2)$. The total energy in this estimation is calculated to be $E_t = (1.95 + 1.41) \times 10^{18}$ to $10^{19}\,erg$ [25].

Theses amount of estimated energies for a single tornado are not very large in the solar energy scale. However, high occurrence frequency of these tornados could build up a considerable energy source for the solar atmosphere heating budget.

4 Periodic Behaviour of The Tornado

To investigate the presence of any wave or oscillations in this giant tornado structure, we selected a couple of 3×3 pixels^2 boxes all over the tornado structures, and applied the Fast Fourier Transform technique to the light curves of each box and obtained the dominant frequencies. Figure 4 represented the selected boxes over the different parts of the tornado structure. Many different right loops, bright arms, central H-shape bright area, and some dark areas (overall about 200 boxes) are selected and studied. To make a better comparison with the possible large scale oscillations, three, and four extra large boxes are selected and studied over the bright, and dark areas, respectively (Fig. 5).

The details of the all obtained frequencies over the all selected boxes can be find at Hashemi-Nasab master thesis [26]. As few samples, the obtained frequencies over the tornado ellipse circumference, and the central H-shape are listed in the Tables 1 and 2, respectively. In general, four different frequency regimes are obtained over this tornado structure:

1. The 3 minutes oscillations which are mostly observed over the tornado's bright loops. These oscillations could be a possible evidence of the presence of type II spicules that are risen up to the coronal temperatures and became observable in AIA 171 Å channel. These type of spicules could be driven by releasing the magnetic tension in the lower layers of the solar atmosphere and could affect the solar corona in different manners [27].

2. 5 to 6 minutes oscillations that are frequently seen in both the bright and dark areas of the tornado. They could be the signatures of p-mode oscillations. P-mode frequencies are the solar global surface oscillations which have irregular nature and support the idea of leaking to corona loops; However, there are differences between oscillations in loops above sunspots and plages [16]. Photospheric flux tubes which rise from granules make buffeting sounds and the transverse waves travel through the field lines and permeate into the upper atmosphere [24].

3. 8 to 11 minutes oscillations might represent the penetration of the torsional Alfvén waves in some parts of the tornado. Torsional Alfvén waves are transverse incompressible waves that travel on flux tubes' surface, usually observed above the photospheric bright points and might be generated by the vortex motions in granules [4]. To check out this possibility, we made an artificial slit using the pixels marked by blue colour on the left panel of Fig. 6. On the right panel of this figure, we plotted the time-slice diagram of the AIA 171 Å intensities over this artificial slit for about 2 hours starting at 00:00:00 UTC. The bright periodic sinusoidal pattern appeared in the time-slice could be a sign of twisting movements of the plasma due to the torsional Alfvén waves.
   The period of these pattern is measured to be $T = 480$ seconds. The radius of the rotational movement r, shown in the right panel of Fig. 6 is calculated as $r \approx 4.8\ arcsec$. The velocity and angular frequency of this torsional movement could be calculated as $v = 2\pi r/T = 22.7\ km/s$, $\omega = 2\pi/T = 0.013\ rad/s$, respectively. This velocity classify

as small-amplitude oscillations [19]. Su et al. 2014 using the same technique with AIA 193 Å images, along with EIS spectral data obtained similar rotating structures in a tornado-like prominence with radius of 4.2 $arcsec$ and velocity of $v = 2\pi r/T = 5\ km/s$ [28].

4. 15 to 17 minute frequencies; The existence of these oscillations could be according to the presence of coronal bright points in the tornado's region. Coronal bright points occur due to magnetic reconnections while emerging and cancelling the magnetic fluxes [29].

5 Conclusion

A giant solar tornado is observed through the 171 Å AIA/SDO images on the 10th 0f July 2011 at 00:00:00 UTC for a duration of 3 hours. The radius of this tornado is obtained to be 15″. The linear rotation velocity of the tornado is calculated as $v = 126\ \pm 40\, m/s$, which categorizes it in the slow evolving phenomena of the solar corona. The rotating energy budget of this structure estimated from three approaches, ranges between $E_t = 1.95 \times 10^{18}\, erg$ and $E_t = 3.36 \times 10^{19}\, erg$.

Looking for any signatures of waves and oscillations in this tornado structure, about 200 small 3×3 pixel^2 boxed are selected. The normalized light curves of these boxes are investigated through FFT technique to obtain the prevalent frequencies. The results showed four different frequency regimes: 3 minutes oscillations that could be a sign of the presence of type II spicules in the studied area over the tornado bright loops [27]. 5 to 6 minutes oscillations could be a signature of the solar global p-modes [24]. 8 to 11 minutes oscillations could be the presence of torsional Alfvén waves in the tornado structure. Similar oscillations have been reported by Su et al. 2014 over another giant tornado [28]. 15 to 17 minutes oscillations that could be a sign of the coronal bright points occurring due to magnetic reconnections in the underlaying areas of the tornado [29].

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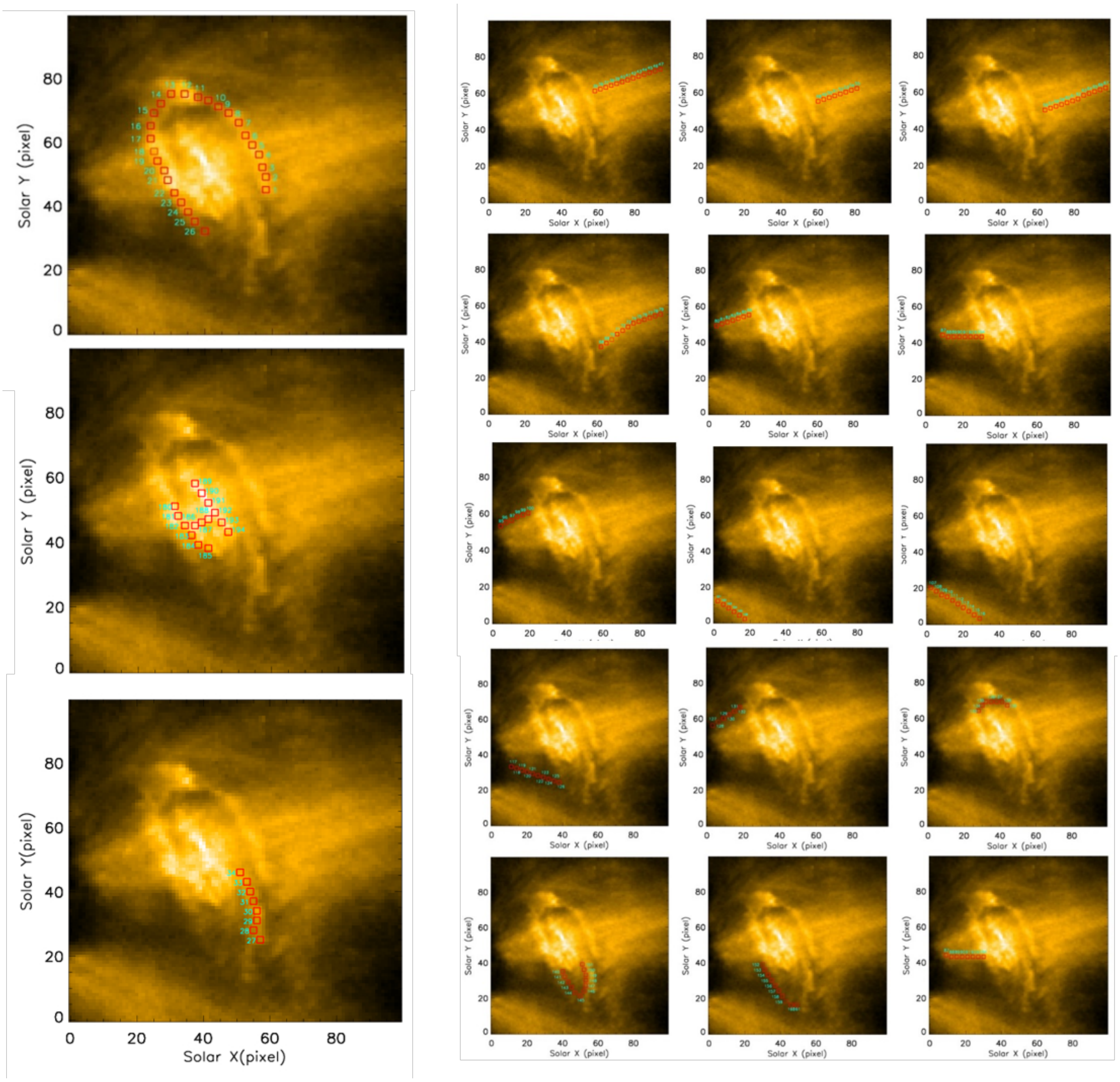

Figure 4: The larger images on the left side, show some of the the selected boxes over the ellipse circumference, central H-shape, and one of the bright arms. The rest fifteen smaller images on the right represent the different bright and dark loop structures over the tornado surface. A Fast Fourier Transformation is applied to all of these box light curves to obtain the dominant frequencies.

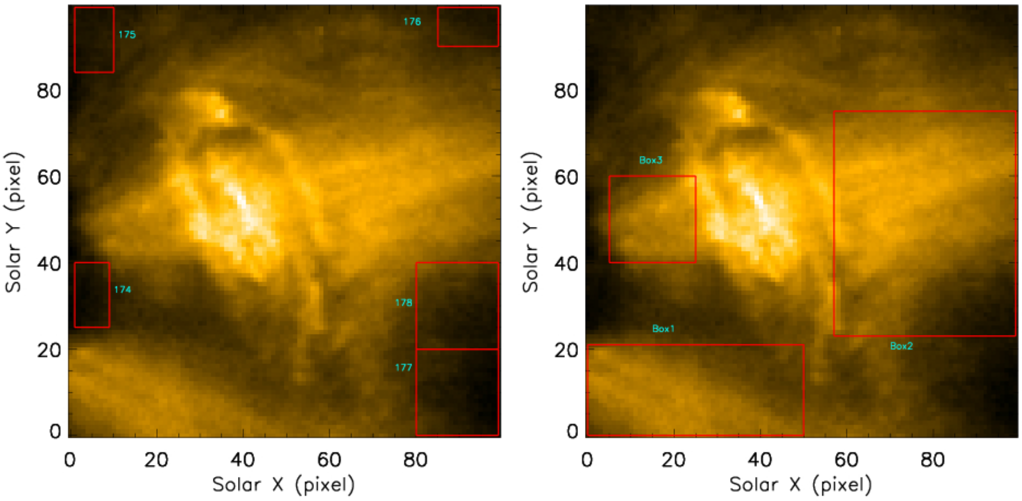

Figure 5: Right and left panels represent the three, and four extra large red boxes that are selected over the bright, and dark areas to investigate their prevalent intensity frequencies through FFT technique, respectively.

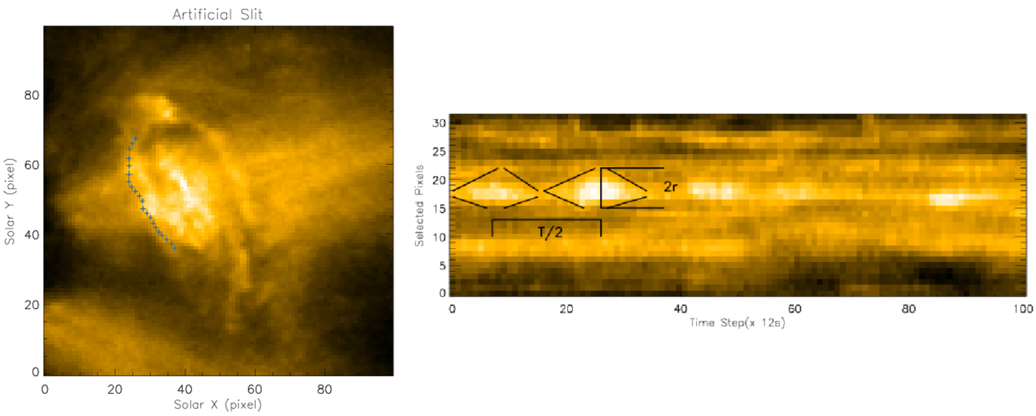

Figure 6: The blue colour marked pixels on the Left panel over-plotted on the AIA 171 Å image of the tornado, are used to make an artificial slit. The right panel represent the time-slice diagram of this artificial slit for about two hours starting at 00:00:00 UTC on the 10th of July 2011. Each time step represents 12 seconds. The period of the sinusoidal bright pattern is measured to be $T = 480$ seconds. The radius of the rotational movement r, is calculated as $r \approx 4.8$ $arcsec$

Table 1: The frequencies found in Ellipse shape of the tornado. Clearly, the 5 to 6 minutes oscillations are the most frequent signals inside the tornado and its background.

Box Number	Frequency (min)	Box Number	Frequency (min)
1	5-4	14	13-9-8-7
2	5-4-3-2	15	8-6
3	9-5-4-3-2	16	9-7-5-3-2
4	15-14-13-9	17	11-7-6-5-4
5	14-7-6-5	18	18-11-9-8
6	14-13-7-6-5-4-3	19	14-9
7	11-8-6-5-4	20	7
8	15-14-12-5-4	21	7-6
9	14-9-8-5-4	22	10-6-5-4-3
10	12-9-6-5	23	10-7-6-3
11	no signal found	24	3-5-6-11-14
12	13-10-7-6-5-4-3-2-	25	10-7-6-5-3
13	20	26	8-7

Table 2: The frequencies found in the center bright H-shape of the tornado.

Box Number	Frequency (min)	Box Number	Frequency (min)
180	no signal found	187	2-5-9-14-15-19
181	3-4-5-7-8-14	188	4-5-9-10-17
182	no signal found	189	3-4-5-6-7-13
183	no signal found	190	6-8-9-15
184	3-5-7-9-11-12-13-14	191	8-16
185	3-4-5-6-9-12	192	4-5-7-8-19
186	1-3-4-6	193	4-8-11

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