New Astronomy 51 (2017) 86–95

Contents lists available at ScienceDirect

New Astronomy

journal homepage: www.elsevier.com/locate/newast

Statistical research of the umbral and penumbral oscillations

Xinping Zhou, HongFei Liang*, QiuHuan Li, WenJia Zhang, WenHui OuYang

Yunnan Normal University, Physics Division, Kunming 650011, Yunnan, China

HIGHLIGHTS

- Extreme values related to umbral and penumbral oscillations have different distributions.
- The trough values related to umbral oscillations is a normal distribution symmetrical about zero.
- Crest and trough values related to penumbral oscillations are a pair of skewed distribution symmetrical about zero.
- Umbral and penumbral oscillation may be produced by same waves with a period of 312s.

ARTICLE INFO

Article history:
Received 5 April 2016
Revised 26 July 2016
Accepted 9 August 2016
Available online 24 August 2016

Keywords:
Sun: sunspot
Sun: oscillation
Method: statistics

ABSTRACT

Observation of the main sunspot of AR11692 were carried out with the 1m New Vacuum Solar Telescope (NVST) located on the Fuxian Solar Observatory (FSO) with the $H\alpha$ on 2013 march 13. The high cadence $H\alpha$ intensity images show that running waves formed periodically within umbra, and propagate outwards with the shape of partial arcs. The running waves run across the umbra-penumbra boundary and disappear at the outer edge of the penumbra eventually. Confusingly, the period of the running waves within umbra is half of that within penumbra, i.e., the former is a typical 3-min oscillation with a period of 156s and the latter is typical 5-min oscillation with a period of 312s. To investigate the nature of the umbral and penumbral oscillations, we selected 300 sample points from the umbra and 150 sample points from the penumbra, respectively, of the sunspot to analyze the distributions of the extreme values related to the intensity profiles of the sample points. It is found that there are significant difference between the distributions of the extreme values related to umbral and penumbral oscillation intensity profiles. When a possible steady solar radiation, which was replaced by the average of troughs of the umbral oscillation intensity profile, was filtered from the umbral oscillation intensity, the distribution of the trough values is a normal distribution symmetrical about zero, the distribution of the crest values is a skewed distribution. When another possible steady solar radiation, which was replaced by the average of the penumbral oscillation intensity profile, was filtered from the penumbral oscillation intensity, while the distribution of the crest values and trough values were a pair of skewed distribution symmetrical about zero. According to the statistical characteristic of umbral and penumbral oscillations, an interpretation seemingly no having physical meaning was used to explain the statistical results. The possible interpretation for the phenomenon is that the pair of oscillations with different period in the intensity are produced by a same wave with a basis oscillation period of 312s. The basis wave can be expressed as $Z(x,y,t) = A(x,y)cos(\omega t+\theta)$, where $\omega = (2\pi)/312$ is the angular frequency of the wave. In the umbra, the intensity due to the wave is proportional to the square of the displacement of the wave, $I^U = a_2Z^2 = \frac{a_2}{2}A^2(x,y)[1+cos(2\omega t+2\theta)]$, while the intensity in the penumbra due to the wave is proportional to the basis wave, $I^P = a_1Z = A(x,y)cos(\omega t+\theta)$. Correspondingly, the period of the intensity within umbra is $T_U = 156s$, while the period of the intensity within penumbra is $T_P = 312s$.

1. Introduction

Over the years, a wide range of oscillatory phenomena have been observed in various regions of the sun. A well-developed sunspot typically consists of a dark central region called the umbra which is surrounded by a less dark annular region called the penumbra. Sunspot oscillation phenomena have been observed at varying atmospheric heights since Beckers and Tallant (1969) first discovered umbral flashes in the *Ca II* & *K*. Three years later ,umbral oscillations both in photosphere (Bhatnagar et al., 1972) and in the chromosphere (Beckers and Schultz, 1972; Giovanelli, 1972) were revealed. Running penumbral waves were first realize by Zirin and

---

* Corresponding author.
E-mail address: lhf@ynao.ac.cn (H. Liang).

http://dx.doi.org/10.1016/j.newast.2016.08.007
1384-1076/

Stein (1972) and independently by Giovanelli (1972); 1974) by using filtergrams obtained in the wings of $H\alpha$. Since then many observations of running penumbral waves have been reported, running waves moving from the outer edge of the umbra to the penumbra. The horizontal propagation speed of penumbral waves is typically in the range of 10 $\sim$ 20km/s which is close to the sound speed in the chromosphere and the of the Alfven speed in the photosphere. Running penumbral waves have horizontal wavelength in the range 2350 $\sim$ 3800km, azimuthal extents arcs of 90° $\sim$ 180° sometimes attaining even 360° and their oscillation period has peak within the 5-min band (Tziotziou et al., 2002). Early observations showed that umbral oscillations were generated as a whole within small sunspot umbrae, but also that they had several oscillating elements within larger umbrae (Beckers and Schultz, 1972; Phillis, 1975). Kobanov and Makarchik (2004) calculated the Doppler-velocity distributions in a sunspot as the intensity difference in the red and blue wings of $H\alpha$ and FeI 6569 Å, The evolution of the Doppler-velocity distribution indicated that running waves propagated from the umbral center to the outside with a phase velocity of 45 $\sim$ 60 km s^{-1}, and most of the waves terminated abruptly on the umbral boundary. Tziotziou et al. (2006) calculated that some umbral flashes led to umbral waves propagating outward at an average speed of about $19kms^{-1}$, the running waves crossed the boundary between umbra and penumbra and propagated as running penumbral waves at an average speed of $19kms^{-1}$. It is important to clarify the nature of the oscillation phenomena in active regions. However, the relationship between umbral oscillations and running penumbral waves is a controversial matter. Alissandrakis et al. (1992) detected waves that started in umbral elements and propagated through the penumbra. Tsiropoula et al. (1996); 2000) and Tziotziou et al. (2006) provided clear evidence of waves originating from the oscillation element inside the umbral and propagating through the penumbra, and Liang et al. (2011) found that running waves originate from wave sources at varying locations inside the umbra, and propagate outward while forming an ellipse or partial arcs. Christopoulou et al. (2000) claimed that there is not a clear relationship between umbral oscillations and running waves, and the running penumbral waves is not a continuation of umbral oscillations into the penumbra.

In this paper, we investigate the nature of the umbral and penumbral oscillations by using statistical methods. Based on the intensity profiles of the umbral and penumbral oscillations, we found that there are obvious differences between the distributions of the troughs and crests of these intensity profiles. These differences imply that the penumbral oscillation may be related to the umbral oscillations.

2. Observations and data reduction

A sunspot region (AR11692), located at the position $N07E38$ on the solar disk, was observed with the telescope NVST located on FSO on 2013 march 13. One hundred and ninety filtergrams were obtained by NVST with the line $H\alpha$ for a duration of 2328 (from 05:08:46 to 05:47:55) under good seeing conditions for most of the time. The data were obtained with a $1024'' \times 1024''$ CCD camera and the pixel size of the images was $0.15''$.The time interval between images is 12 s. The field of view that we used for analysis is 265 $\times$ 265 pixels containing the whole umbra and penumbra of the sunspot, which is shown as Fig. 1a. In Fig. 1a, the dotted white contour shows the $H\alpha$ umbra-penumbra boundary, the solid white contour shows the approximate outer penumbra boundary. Since the image is distorted by the proper motion of the sunspot during the observation, we used two-dimensional cross-correlation techniques to careful alignment of the images of our sequence, ensuring the possibility of a direct comparison between pixels in different images to the time series. In order to enhance time varying phenomenon in intensity images and remove the sharp intensity gradient between the penumbra and the umbra, we used a subtraction image processing technique (Christopoulou et al., 2000).

Running difference images were used to enhance the image-varying phenomena, and to make the waves much more noticeable. Due to the relatively slow propagation of running wave within the penumbra, we applied running difference images with a time interval of three frames (hereafter RDI3), RDI3=$imgae_{i+3} - image_i$, to enlighten oscillation in the sunspot, where $image_{i+3}$ and $image_i$ are the ith and $(i+3)$th intensity images (Liang, H.F. et al., 2012). As shown in Fig. 1b, there are four running waves originating from the wave source denoted by a white cross S_A. All of these waves are in a shape of partial arcs having azimuthal extent as large as 120°. To accurately investigate the umbral and penumbral associations, we selected 190 RDI3 to create a movie which vividly demonstrates many aspects of running wave. Bright regions periodically appear at almost the same location within the umbra denoted by the white cross S_A. The running waves propagate outward, forming partial arcs with azimuthal extent as large as 120° around the wave source S_A. The running waves run across the umbra-penumbra boundary and disappear at the outer edge of the penumbra eventually.

3. Period of the umbral and penumbral oscillations

To investigate the nature of the running waves, we selected 10 sample points, denoted by S_A, S_B, S_C et al., along the line $S_A - S_J$, which is the propagation direction of the running waves with obvious traces, to analyze the oscillation period of these sample points. The solid lines in Fig. 2 (first and third columns) show time profiles of the $H\alpha$ intensity at the ten sample points $S_A \sim S_J$ in Fig. 1, which illustrates the umbral and penumbral intensity variation mainly derived from the running waves originating from wave source S_A. To measure the oscillation period, the time profiles were transformed with FFT (Fast Fourier Transform) function using IDL. As shown in Fig. 2 (second and fourth columns), every power spectrum of the resulting transformation has one peak that appears as a spike. The frequencies at the spikes of the sample points $S_A \sim S_E$ are 6.4 mHz, of the sample points $S_F \sim S_G$ are 5.1 mHz, and of the sample points $S_H \sim S_J$ are 3.2 mHz, respectively. Base on the frequencies of the power spectra, the oscillation periods at the sample points $S_A \sim S_E$, $S_F \sim S_G$ and $S_H \sim S_J$ are 156 s, 195 s and 312 s, respectively. To confirm the oscillation periods, we kept the Fourier coefficients at the peaks in the power spectrum constant, set the other frequency element to zero, and then applied an inverse FFT to show the main period variation in the time profiles. The dotted lines in Fig. 2 (first and third columns) vary in manners similar to the solid lines in the same periods, which means the oscillation periods of the sample points are close to the correspond measured periods, $T_{S_A \sim S_E} = 156s$, $T_{S_F \sim S_G} = 195s$ and $T_{S_H \sim S_J} = 312s$. The results show that the oscillations of the sample points $S_A \sim S_E$ within umbra are a typical 3-min oscillation with period $T = 156s$, and the oscillations of the sample points $S_G \sim S_J$ within penumbra are a typical 5-min oscillation with period $T = 312s$. The period of umbra oscillations is exactly one half of that of the penumbral oscillations.

The above analysis show that FFT is a convenient method to measure the periods of the umbral and penumbral oscillations, however the significance level of the measured periods is not directly given in the analysis. In order to conveniently to analyze the oscillation periods and to give the significance level at the same time, the wavelet analysis, a common technique for analyzing localized variations of power within a time series, is a suitable method. This technique allows us to investigate the time dependence periods within the observed data. The details of the