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Behaviour of oscillations in loop structures above active regions

D.Y. Kolobov *, N.I. Kobanov, A.A. Chelpanov, A.A. Kochanov, S.A. Anfinogentov, S.A. Chupin, I.I. Myshyakov, V.E. Tomin

Institute of Solar-Terrestrial Physics, SB RAS, Lermontov St., 126-a, Irkutsk 664033, Russia

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Abstract

In this study we combine the multiwavelength ultraviolet–optical (Solar Dynamics Observatory, SDO) and radio (Nobeyama Radioheliograph, NoRH) observations to get further insight into space-frequency distribution of oscillations at different atmospheric levels of the Sun. We processed the observational data on NOAA 11711 active region and found oscillations propagating from the photospheric level through the transition region upward into the corona. The power maps of low-frequency (1–2 mHz) oscillations reproduce well the fan-like coronal structures visible in the Fe IX 171 Å line. High frequency oscillations (5–7 mHz) propagate along the vertical magnetic field lines and concentrate inside small-scale elements in the umbra and at the umbra–penumbra boundary. We investigated the dependence of the dominant oscillation frequency upon the distance from the sunspot barycentre to estimate inclination of magnetic tubes in higher levels of sunspots where it cannot be measured directly, and found that this angle is close to 40° above the umbra boundaries in the transition region.

Keywords: Sunspots, oscillations; Faculae, oscillations; Magnetic topology; Coronal loops

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1. Introduction

The waves in solar magnetic structures play an important role in processes of the energy exchange. Moreover, the properties of the medium, i.e. the solar atmosphere, can be determined by studying the wave propagation. This affects such problems as the origin of the solar magnetic fields, coronal heating, flares, wave propagation in plasma with different magnetic field topology, and others. From the observation driven point of view the problems above depend on our knowledge of the magnetic field distribution with height, plasma velocity, temperature and their variations. Because direct measurement of these parameters is a considerable challenge, in practise one has to use different tools to get a comprehensive picture of the atmosphere structure in active regions and processes therein. The seismological study of the active regions is one of such unique tools (Bogdan and Judge, 2006; De Moortel and Nakariakov, 2012). Different methods were developed to explore magnetic geometry of the sunspots and to estimate the magnetic field inclination angle in the transition region and in the corona (Jess et al., 2013; Yuan et al., 2014b; Kobanov et al., 2015). Coronal seismology provides a capability to determine the magnetic field strength in coronal closed magnetic structures (Nakariakov and Ofman, 2001). Another opportunity is radio magnetography (Gelfreikh, 2004). The radio emission is naturally connected with magnetic field providing an instrument to study the 3D-structure of the sunspot atmosphere. Joint observations in radio and optical spectral ranges have a great potential (Kislyakov et al., 2006), that has not been implemented yet. One can trace the wave train propagation and utilise magnetic field extrapolation to the corona to

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* Corresponding author.
E-mail address: kolobov@iszf.irk.ru (D.Y. Kolobov).

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estimate the effective height of the radio emission, which can be used to qualify the formation heights of the lines in UV and optical spectral ranges. New facilities like the Siberian Solar Radio Telescope (SSRT, Lesovoi et al., 2012), the Chinese Spectral Radioheliograph (CSRH, Yan et al., 2013), and others will provide new possibilities for observing the Sun's radio emission in the multifrequency mode.

Sunspot oscillations were extensively studied in the past decades (see reviews by Lites (1992), Solanki (2003), Bogdan and Judge (2006) and Jess et al. (2015)). Recent studies are based on multiwavelength observations and focus on determining the wave propagation speed (Felipe et al., 2010; Abramov-Maximov et al., 2011; Kiddie et al., 2012; Chandra et al., 2015), wave dynamics (Sych et al., 2012; Sych and Nakariakov, 2014; Zhugzhda and Sych, 2014), and related phenomena like jets, penumbral filaments, umbral flashes (Yurchyshyn et al., 2014, 2015; Pozuelo et al., 2015; Madsen et al., 2015; Louis et al., 2014; Maurya et al., 2013), light bridges (Yuan et al., 2014a; Yang et al., 2015) and also flares (Sych et al., 2014). Due to the circular symmetry, sunspots provide an opportunity to study the wave propagation processes in the presence of magnetic fields. In sunspot umbra, five-minute oscillations dominate at the photospheric level, and three-minute ones prevail in the chromosphere (Kobanov, 1990; Kentischer and Mattig, 1995; Sigwarth and Mattig, 1997; Rouppe van der Voort et al., 2003; Kobanov et al., 2009; Reznikova and Shibasaki, 2012). Oscillations with longer periods (10–15 min) manifest themselves at the peripheral part of the sunspots. Other magnetic field regions, e.g. facula show very different behaviour of the spatial-frequency dependence (Kobanov and Pulyaev, 2007; Centeno et al., 2009). Detecting and studying the coronal counterparts of these waves and quasi-periodic pulsations are relevant for the problem of energy flux transfer to the upper atmosphere.

We continue studying the space-frequency stratification of the oscillation processes in the sunspot atmosphere (Kobanov et al., 2015). We extend the analysis with new sunspot data, including those obtained in radio emission, and compare the results with magnetic field extrapolation.

2. Observational data and methods

The paper is result of the investigation into the sunspot oscillations observed at different wavelengths representing several heights of the solar atmosphere from the photosphere to the corona. We used the data from two observatories in this study: Solar Dynamics Observatory (SDO, Lemen et al., 2012; Scherrer et al., 2012; Woods et al., 2012) and Nobeyama Radioheliograph (NoRH, Nakajima et al., 1994). The data were selected to cover height scale from the photosphere to the corona.

The sunspot had regular circular shape (Fig. 1, left panel). The observation was performed on 2013 April 6 00:00–04:20 UT and there was no flare activity at this period; a C1.7 flare occurred on 10:58 UT.

We chose four spectral bands provided by the Atmospheric Imaging Assembly (AIA) for the analysis: Fe IX 171 Å and Fe XII, XXIV 193 Å (coronal heights), He II 304 Å (transition region) and 1700 Å (upper photosphere, Fig. 1, middle panel). The Helioseismic and Magnetic Imager (HMI) data were used to obtain the magnetic field at the photospheric level in the Fe I 6173 Å line, which is formed at the 100–150 km height (Fleck et al., 2011; Parnell and Beckers, 1969). The vector magnetic-field components were computed using the code of Very Fast Inversion of the Stokes Vector (Borrero et al., 2011). The SDO data sets were prepared using the `aia_prep` and `hmi_prep` SolarSoft routines. The sunspot was observed near the central meridian (W03S17), which allowed us to minimise the projection effect on the analysis of oscillations at different heights. We corrected the magnetic field angle to the solar normal within the planar approximation using equation (Gary and Hagyard, 1990):

$$\varphi = cos\gamma cos\varphi' + sin\gamma sin\varphi' cos\theta \tag{1}$$

where γ is the angle between the line of sight and the solar normal; φ' is the observed field inclination angle; θ is the azimuthal angle corrected for the line-of-sight deviation from the central-meridian plane (Fig. 1, right panel).

The radio data are the sequence of the 17 GHz NoRH images with the 20-s effective cadence and the 5″ spatial resolution. The images were synthesised with the "Koshix" algorithm on the Solar Data Analysis System. To increase the signal-to-noise ratio, the number of integration frames for synthesis was set to 10. The images were cropped to include the sunspot area (400 × 400″). Then, the images were co-aligned using the cross-correlation technique and smoothed over spatial dimensions. The maximum brightness temperature in the sunspot does not exceed 29,000 K and the degree of polarisation is about 25%. Thus, the polarised emission at 17 GHz in this image is most likely due to optically thin thermal bremsstrahlung. The line-of-sight magnetic field was estimated by the method proposed by Gelfreikh (2004).

To study space-height properties of the sunspot oscillations we used the method described in Kobanov et al. (2015) that is suitable for circular sunspots. To calculate the cut-off frequency, we used the equation (Bel and Leroy, 1977; McIntosh and Jefferies, 2006; Botha et al., 2011):

$$f_c = \frac{g_0 \gamma \cos\varphi(r)}{4\pi v_s} \tag{2}$$

where f_c is the cut-off frequency; $g_0 = 274\ \mathrm{m\,s^{-2}}$ is the gravitational constant; v_s is the speed of sound; $\gamma = \frac{5}{3}$ is the adiabatic index; $\varphi(r)$ is the dependence of inclination angle on the barycenter distance. Using Eq. (2) and empirical ratio $f_c = 0.81\mathrm{F(r)\ mHz} - 1\ \mathrm{mHz}$ for the 304 Å line