Long quasi-periodic oscillations of sunspots and small-scale magnetic structures

Victoria Smirnova

TURUN YLIOPISTO
UNIVERSITY OF TURKU
Turku 2020

University of Turku
Faculty of Science and Engineering
Department of Physics and Astronomy

Research director
Prof. Juri Poutanen
Dept. of Physics and Astronomy
University of Turku
Turku, Finland

Supervised by
Dr. Alexandr Riehokainen
Dept. of Physics and Astronomy
University of Turku
Turku, Finland

Prof. Rami Vainio
Dept. of Physics and Astronomy
University of Turku
Turku, Finland

Reviewed by
Dr. Alexei Pevtsov
National Solar Observatory
Boulder, CO
USA

Assoc. Prof. Petr Jelinek
Faculty of Science
University of South Bohemia
České Budějovice, Czech Republic

The originality of this thesis has been checked in accordance with the University of Turku quality assurance system using the Turnitin Originality Check service.

ISBN 978-951-29-7942-4

Preface

Acknowledgments

This work has been carried out at the Department of Physics and Astronomy at University of Turku. The ERASMUS MUNDUS Program and CIMO fellowship Program are acknowledged for financial support.

I am eternally grateful to Prof. Esko Valtaoja who has gave me the possibility to start the collaboration with University of Turku. I express my sincere gratitude to Prof. Harry Lehto and Prof. Juri Poutanen for the support during my visits in Tuorla Observatory. I would like to thank Dr. Juha Kallunki for the support in solar data processing. Many thanks to Prof. Rami Vainio, who spent his time not only carefully reading my thesis. He has gave me helpful comments and advises during the thesis preparation. His support gave me the possibility to understand some special things I haven't dealt with before.

And I am eternally grateful to Dr. Alexandr Riehokainen, who was my scientific advisor during my career as a scientist. We started our collaboration in 2009. It was an incredible ten-year Journey to the West through Space and Time. Without him, that work would not have happened.

I am grateful to Prof. Alexei Pevtsov and Prof. Petr Jelinek who carefully reviewing my thesis. I would like to thank Prof. Miroslav Bárta, who is my opponent.

I would like to thank our collaborators in Pulkovo Observatory, especially Prof. Alexander Solov'ev, Vyacheslav Efremov, Leonid Parfinenko, Polina Strekalova, Juri Nagovitsyn, Alexander Stepanov, Ivan Zhivanovich. Many thanks to Dr. Dmitrii Kolotkov and Prof. Valery Nakariakov from University of Warwick for the fruitful collaboration.

I would like to thank Dr. Valery Nagnibeda, who was my first supervisor in Saint-Petersburg State University. He has gave me possibility to became an astronomer.

Finally, I wish to thank my family, especially my father Valery who aroused in me an interest in astronomy, my husband Konstantin who always supports me, and my mother Natalia. You have kept me alive.

Turku, January 2020

Victoria Smirnova

"Your teacher for a day is your father for the rest of your life." – Chinese proverb

To my Finnish father Alexandr R.

Abstract

This thesis presents the investigations and the interpretation of long quasi-periodic oscillations with periods more than 30 minutes observed in the magnetic field of sunspots, as well as, at millimeter radio emission nearby sunspots. Additionally, the same phenomenon of long quasi-periodic oscillations was studied for the magnetic field of small-scale magnetic structures related to the facular knots observed in solar chromosphere.
Two different methods of data processing are used to obtain the quasi-periodicity. The first method is the traditional Wavelet transform, and the second method is the Empirical Mode Decomposition (EMD).
Firstly, long quasi-periodic oscillations of the millimeter (37 GHz) radio emission of active regions above sunspots were obtained with periods in the interval of 1-5 hours. The same periods were obtained for the magnetic field of the sunspots observed in these active regions. The time-lags between the magnetic field oscillations and the millimeter radio emission oscillations were derived in the interval of 15-30 minutes. The interpretation of observed oscillations and lags was done by using the so-called "three-fluxes" model. Secondly, the non-stationary long quasi-periodic oscillations of the magnetic field of facular knots were obtained with periods in the interval of 30-260 minutes. The interpretation of the observed periodicities was done by using the modelling of oscillations of the system with a time-varying rigidity.
Three-fluxes model together with the shallow sunspot model gave the physical interpretation of the observed long quasi-periodic oscillations of the millimeter radio emission and the magnetic field of sunspots. Hydrostatic rebuilding of physical parameters of millimeter radio source modulated by the oscillations of the magnetic field of a sunspot as a whole describes the observed lags between the time series in the interval of 15-30 minutes, when the radio emission delay relatively to the magnetic field variations.
In the other case, the shallow sunspot model could not be directly used to provide the interpretation of the observed oscillations of facular knots. This requires a number of physical parameters, that have not been observed yet (the analog of Wilson's depression of the sunspot, the lower boundary of the facular knot). In this case, the model of the facular knot as the system with the time-varying rigidity is in good agreement with the observed dynamics of these objects, and it could be the first step to the new analytical model of the facular knot that will consider the dynamical properties of this small-scale object.

Tiivistelmä

Väitöskirja käsittelee Auringon pitkien, yli 30 minuutin mittaisten kvasijaksollisten värähtelyjen havaintoja ja niiden tulkintaa. Värähtelyjä havaittiin auringonpilkkujen magneettikentässä ja millimetriaalloilla auringonpilkkujen lähellä. Lisäksi tutkittiin pitkiä kvasijaksollisia värähtelyjä magneettikentän pienen skaalan rakenteissa. Nämä rakenteet liittyvät Auringon kromosfäärissä havaittujen kirkkaiden kohtien, ns. fakuloiden solmukohtiin. Työssä käytetään kahta erilaista analyysimenetelmää kvasijaksoisuuden havaitsemiseksi: tavallista aallokemuunnosta sekä empiiristä moodihajotelmaa (EMD). Työssä havaittiin millimetrialueella (37 GHz) radiosäteilyn pitkiä kvasijaksollisia värähtelyjä Auringon aktiivisilta alueilta auringonpilkkujen yläpuolella. Näiden värähtelyjen jaksonajat ovat 1-5 tunnin väliltä. Samat jaksot havaittiin aktiivisilla alueilla havaittujen aurinkopilkkujen magneettikentän värähtelyille. Aikaviiveeksi magneettikentän värähtelyjen ja radiosäteilyn millimetriaaltojen värähtelyjen välillä saatiin 15-30 minuuttia. Havaittujen värähtelyjen ja viiveiden tulkinta tehtiin ns. kolmivuomallilla. Työssä havaittiin myös fakuloiden solmujen magneettikentän epävakaita pitkiä kvasijaksollisia värähtelyitä, joiden jaksonajat olivat 30-260 minuuttia. Fakuloiden solmujen havaittujen jaksonaikojen tulkinta tehtiin käyttämällä värähtelymallia, jossa systeemin jäykkyys vaihteli ajallisesti. Auringonpilkkujen millimetriaaltohavaintojen ja auringonpilkkujen magneettikentän havaintojen pitkien kvasijaksollisten värähtelyjen fysikaalinen tulkinta perustui kolmivuomallin ja matalan aurinkopilkkumallin yhdistelmään. Auringonpilkkujen magneettisten muutosten moduloima millimetriradiolähteen fysikaalisten parametrien hydrostaattinen rekonstruktio kuvaa hyvin aikasarjojen välisiä havaittuja viiveitä alueella 15-30 minuuttia. Fakuloiden solmujen värähtelyiden tapauksessa samaa mallia ei voitu suoraan käyttää, sillä tämä vaatisi tietoa useista fysikaalisista parametreista, joita ei ole vielä havaittu (Wilsonin auringonpilkkualeneman analogia, fakuloiden solmun alareuna). Tässä tapauksessa fakuloiden solmun värähtelymalli, jossa järjestelmällä on ajasta riippuva jäykkyys, on sopusoinnussa solmujen havaitun dynamiikan kanssa. Työ muodostaa ensimmäisen askeleen kohti uutta analyyttistä fakulasolmumallia, joka ottaa huomioon systeemin dynaamiset ominaisuudet.

Articles included in this thesis

This thesis is based on the experimental work carried out at the Department of Physics and Astronomy, University of Turku. The thesis consists of an introductory part and of the following publications:

[**P1**] V. Smirnova, A. Riehokainen, A. Solov'ev, J. Kallunki, and A. Zhiltsov: *Long quasi-periodic oscillations of sunspots and small-scale magnetic structures*, A&A **552**, A23 (2013).

[**P2**] V. Smirnova, V. Efremov, L. Parfinenko, A. Riehokainen and A. Solov'ev: *Artifacts of SDO/HMI data and long-period oscillations of sunspots*, A&A **554**, A121 (2013).

[**P3**] V. Smirnova, A. Riehokainen, A. Solov'ev and J. Kallunki: *Time delay effect between long quasi-periodic oscillations of 37 GHz radio sources and the magnetic field of the nearest sunspots*, Astrophysics and Space Science **357**, 149 (2015).

[**P4**] D. Kolotkov, V. Smirnova, P. Strekalova, A. Riehokainen and V. Nakariakov: *Long-period quasi-periodic oscillations of a small-scale magnetic structure on the Sun*, A&A **598**, L2 (2017).

[**P5**] V. Efremov, A. Solov'ev, L. Parfinenko, A. Riehokainen, E. Kirichek, V. Smirnova, Y. Varun and I. Bakunina: *Long-term oscillations of sunspots and a special class of artifacts in SOHO/MDI and SDO/HMI data*, Astrophysics and Space Science **363**, 3 (2018).

[**P6**] A. Solov'ev, P. Strekalova, V. Smirnova, and A. Riehokainen: *Eigen oscillations of facular knots*, Astrophysics and Space Science **364**, 2 (2019).

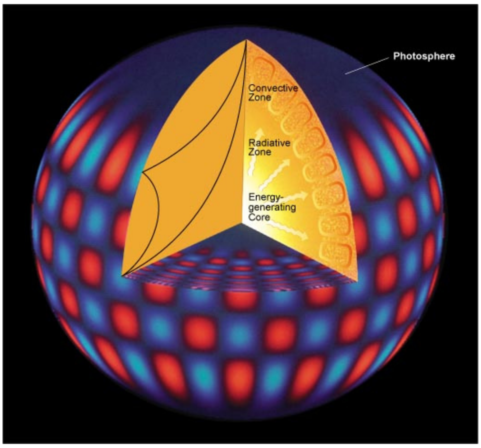
Contents

1 Introduction: Quasi-periodic oscillations of solar formations

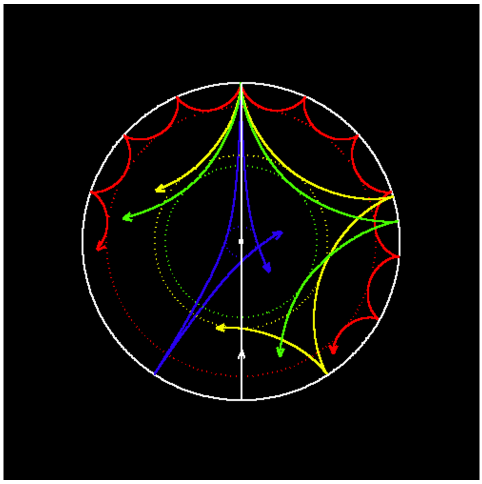
Quasi-periodic oscillations observed at different layers of solar atmosphere have been actively studied for decades. The interest is due to the complex dynamics of the solar active regions, where the turbulent plasma motions with the magnetic fields lead to energy storage for solar flares and provide coronal heating [3].

The oscillatory phenomenon of solar formations has been previously investigated, for example, by [25], [64], [44]. The review of solar oscillatory phenomena is presented in [29]. Authors have studied some parts of the oscillatory spectrum at the interval of periods from several seconds to 3-5 and 10-25 minutes. The interval of periods 3-5 minutes are observed at all layers of the solar atmosphere, as well as, in coronal loops [35]. It is easy to explain this periodic component by the propagation of magnetohydrodynamic waves (MHD) that was proposed in numerous analytical and numerical models [32], [36], [20]. The periods in the interval of 10-25 minutes, observed in active regions, sunspots and also in small-scale structures, was explained by several authors as the influence of granulation motions and the turbulent flows, which propagate under the solar photosphere [21]. Recently, the existence of long quasi-periodic component in the oscillatory spectrum of solar magnetic structures, with periods from 30 minutes to several hours, has been established [15], [35] [33]. These long-period oscillations have also been observed in the magnetic field variations as well as in the line-of-sight velocity of sunspots [11]. Simple estimations show that it is not possible to explain these long-period oscillations by the propagation of MHD waves through the solar active region [52]. Another mechanism should be responsible for the generation of such long periods.

A more complex situation prevails concerning the investigation of small-scale magnetic structures, where the long quasi-periodic oscillations were observed in the magnetic field with periods 80-250 minutes [27]. These structures have a typical size of 3-10 arcseconds and usually correspond to the bright formations observed in solar chromosphere as facular knots [62]. The small-scale magnetic structures have a complex dynamics during their lifetime: they could be involved in granulation and supergranulation motions. On the other hand, there are long-lived structures (lifetime is 10-30 hours). Thus, one could suggest that this type of a stable structure could oscillate as a whole near the position of the equilibrium with such long periods [59]. So, it is difficult to provide unambiguous interpretation to the observed long-period oscillations.



A



B

Figure 1. A: the alternating patches represent gas moving down (red) and up (blue). B: Wave harmonics (l) which penetrate the interior of the Sun. $l = 0$ - white curve, $l = 2$ - blue, $l = 20$ - green, $l = 25$ - yellow, $l = 75$ - green. (Courtesy of J. Christensen-Dalsgaard and Ph. H. Scherrer.). Image source: https://ase.tufts.edu/cosmos/print$_i mages.asp?id = 25$.

Solar oscillatory phenomenon is actively investigated by methods of helioseismology. Helioseismology studies the solar interior by analyzing oscillations and waves propagation on the solar surface. The solar interior is transparent to acoustic (sound) waves that are excited by turbulent convection below the photosphere and travel with the speed of sound (Fig.1). The travel times of acoustic waves depend on physical parameters of the internal layers like temperature, density, velocity of mass flows [30], [71]. The measurements and the analysis of Doppler velocity established the existence of 5-minutes oscillations defined as horizontal standing waves propagating on the photosphere (Fig.2).

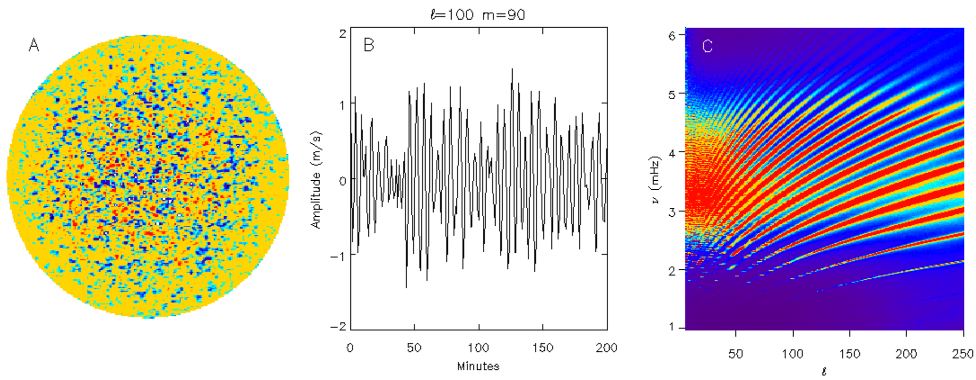


Figure 2. Figure from the GONG website (Harvey et al. 1996). A: the line-of-sight velocity map after removing the rotation of the Sun. B: the example of time series of one of the spherical harmonic. C: The spectrum of spherical harmonics. Image source: https://www.stat.berkeley.edu/ stark/Seminars/Aaas/helio.htm.

2 Sunspot: structure

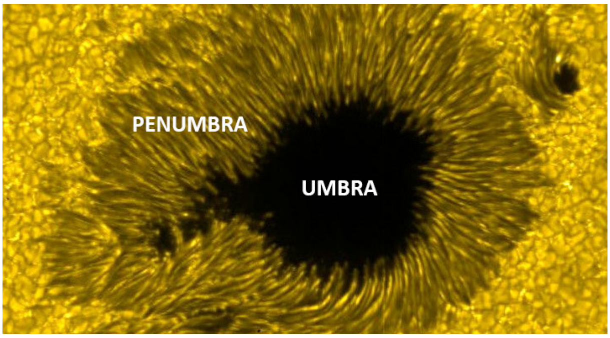


Figure 3. The sunspot visible structure with umbra and penumbra. Image source: https://www.spaceweatherlive.com/en/help/what-are-sunspots.

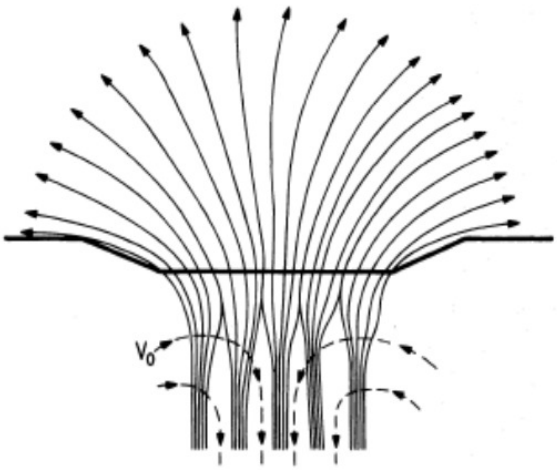


Figure 4. The structure of sunspot magnetic field lines provided by Parker [41].

Sunspot is a localized structure visible on the solar photosphere as a dark area relative to the surface in white light observations. The temperature of sunspots is about 1500 K lower than the ambient photosphere, which is about 6000 K. One of the main property of the sunspot is strong magnetic field. According to the observational results, the magnetic field of a sunspot is complicated, containing two basic parts: the umbra with the sufficiently homogeneous magnetic field, and the penumbra, which has a highly dynamical filamentary structure with a weak magnetic field (Fig.3). The description of the magnetic structure of a sunspot and its penetration into the convective zone was proposed by Parker [41]. According to this model the sunspot is a cluster of magnetic flux tubes compressed together by the lateral pressure of the environment (Fig.4). A few hundred kilometers under the photosphere, the magnetic flux tube of the sunspot is divided into vertical strands. Between these strands weak plasma flows may exist, that create some extra lateral compression. But the structure of the subsurface layers of a sunspot was not clearly described in the Parker's model.

At present, the structure of sunspots is investigated by local helioseismology [71], [39]. Local helioseismology analyzed frequency and phase shifts of oscillations and variations in wave travel times in subsurface layers. It requires of high-resolution observations of solar oscillations [30].

Recent observations of subsurface layers of a sunspot obtained by methods of local helioseismology established a complex structure of the magnetic field and plasma dynamics under the visible sunspot configuration (Fig. 5). It is seen that inside the sunspot magnetic flux tube the vertical distribution of temperature changes at depths of about 4 Megameters (Mm). Here, a sharp transition takes place between the relatively cold plasma of a sunspot and the underlying very hot area of plasma, which is overheated to about 1000 K in comparison to the environment [56].

2.1 Shallow sunspot: formation, stability and long-period oscillations

To understand the nature of the existence of the overheated zone under the sunspot interior, the description of a sunspot formation should be provided. The process of a sunspot formation is usually described by the emergence of new magnetic flux consisting of magnetic elements of different polarity ([52], Fig. 6). When the vertical magnetic field B_z exceeds the value of the equipartition field B_{eq} the convective heat transport is slowed down. The equipartition field is the maximum value of the magnetic field at which convection is still possible. The equipartition means that the density of the magnetic energy is equal to the density of the kinetic energy. We could consider plasma with density ρ_0 and with a speed of convection V_{conv}. At the level of solar photosphere [61]: ($\tau \approx 1$): $\rho_0 = 2 \times 10^{-7}$ g cm^{-3}, $V_{conv} \approx 1$ km s^{-1}, $B_{eq} \approx \sqrt{4\pi\rho_0 V_{conv}^2} \approx 200$ G.

The value of the magnetic field strength of about 200 G is a threshold value. Stronger magnetic field suppresses convection, and then the temperature in this area begins to decrease [56], [57].

At the top of the overheated region, the overlying flows meet the plasma flows from the overheated region, which are supported by the convection. The underlying flows transmit part of their momentum to the overlying streams in the layers of the interaction

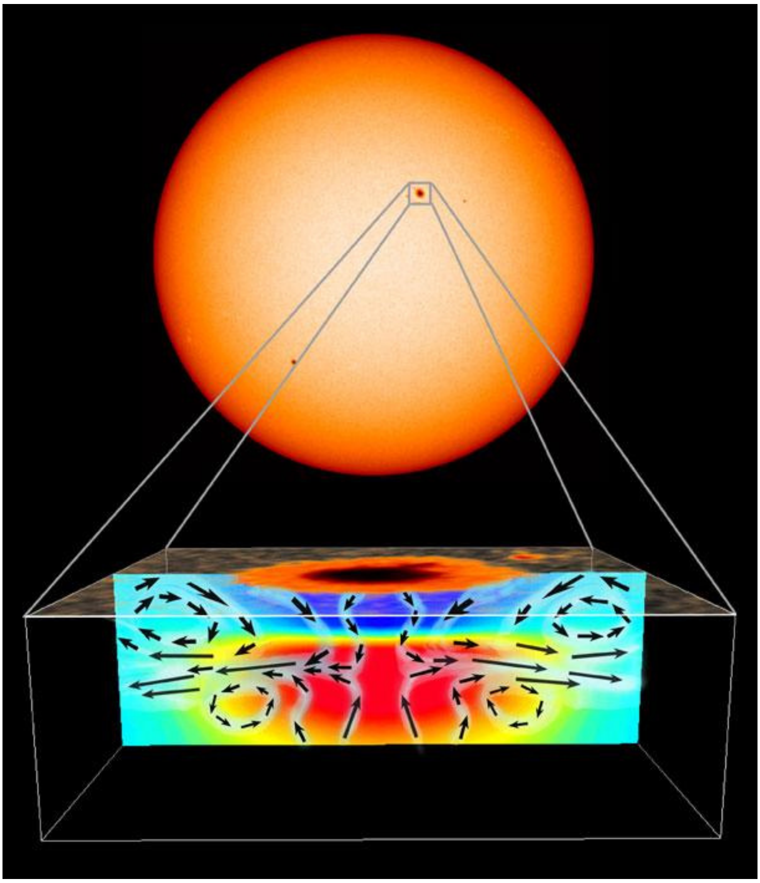


Figure 5. Sub-photospheric structure of a sunspot obtained by local helioseismology Colors represent temperature distribution, and arrows represent the flow structure beneath a sunspot. (Courtesy of the SOHO MDI consortium. SOHO is a project of international cooperation between ESA and NASA.) Image source: https://ase.tufts.edu/cosmos/print$_{i}mages.asp?id = 25$.

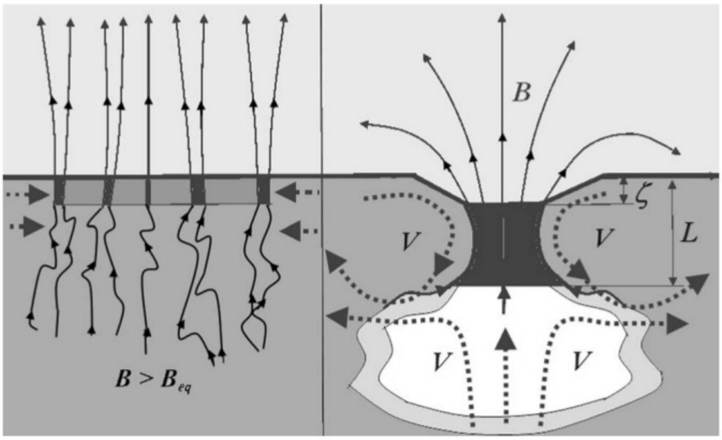


Figure 6. The sunspot formation. Left: when the vertical magnetic field exceeds the equipartition field B_{eq} , convection suppressed. The flux tubes are compressed due to the pressure difference $(P_{ex} - P_{in}) > 0$. Right: Formation of a Wilson depression of depth ζ. White area represents the overheated region of plasma. L is the sunspot effective depth ([56]). Image source: [56].

of flows, and plasma streams will be stabilized (Fig.6). Thus, three basic processes are responsible for the sunspot formation:

1. The suppression of convective heat transfer by a magnetic field. 2. The formation of the spot due to the pressure difference. During the convergence of the magnetic field lines of a sunspot the thermal energy of the spot is reduced, and its magnetic energy grows. 3. Formation of an overheated zone under the sunspot. Here a Wilson depression is formed due to the vertical redistribution of the mass of the gas (the deficiency of the gas density occurs over the sunspot). This process is important for the energy balance of the sunspot. It is interesting to note that the overheated zone under sunspots was predicted by Parker in 1974 [40], and other authors [45], [38]. Local helioseismology gave the possibility to estimate the lower boundary of a sunspot and provided the measurements of the velocity of sub-surface flows. These flows manifest the regular streams convergent to the spot. In this case, these flows of plasma should play an important role in maintaining the stability and equilibrium of a sunspot [19].

The flows of plasma with an average speed V make a significant contribution to the pressures balance if: $\rho V^2/2 \approx P$, or $V^2 \approx c_s^2$, where

$$c_s^2 = \frac{\gamma P}{\rho} = \frac{\gamma RT}{\mu}, \tag{1}$$

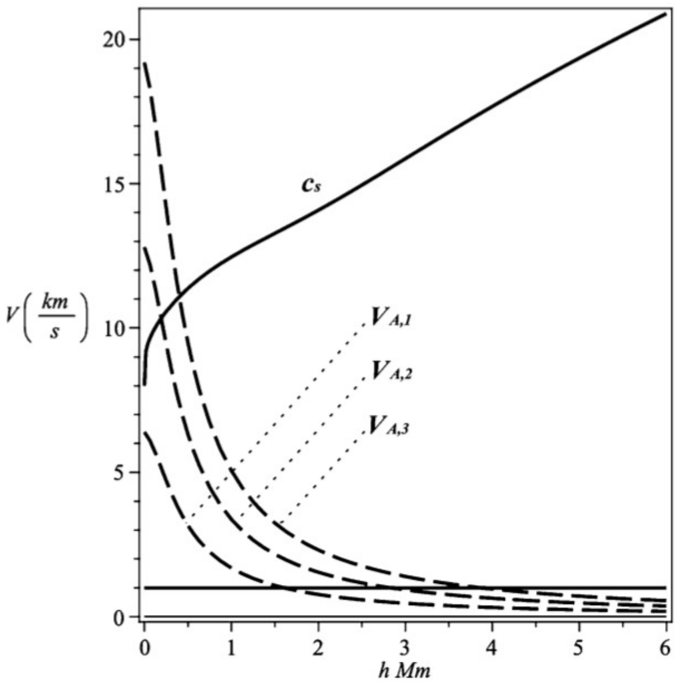


Figure 7. The sound speed c_s. Dashed lines represents Alfvèn speeds calculated as functions of the depth of the convective zone. $V_{A,1}$ corresponds to magnetic field of 2000 G, $V_{A,2}$ - to 4000 G, and $V_{A,3}$ to 6000 G. The Alfvén speeds fall below the level of 1 km s^{-1} at depths of about 2-4 Mm. [61]. Image source: [56].

where γ is the adiabatic index. Typically $c_s \approx 8$ km s^{-1} is the sound speed in the photosphere. In the convection zone $c_s > 20$ km s^{-1}. According to results of local helioseismology, the averaged speed of subsurface flows near the spot is about 1 km s^{-1} [28], [29], [30].

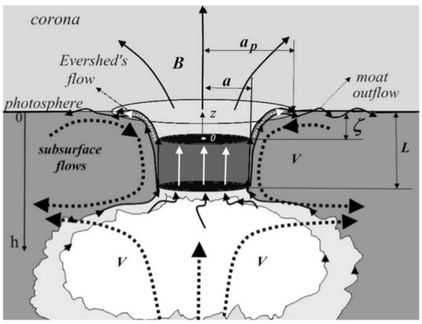
In the region $h \geq L$, the magnetic flux tube should expand with a depth. When the condition $\frac{\rho V^2}{2} \geq \frac{B^2}{8\pi}$ or $V^2 \geq V_A^2$ is satisfied ($V_A = \frac{B}{\sqrt{4\pi\rho}}$ is the Alfvén speed), the geometric structure of the magnetic field is change due to plasma flows.

Figure 7 represents the Alfvén speed behaviour in the convective zone. The influence of plasma flows becomes sufficient at the depth of about 4 Mm. Here the sunspot magnetic flux tube is expanded sharply.

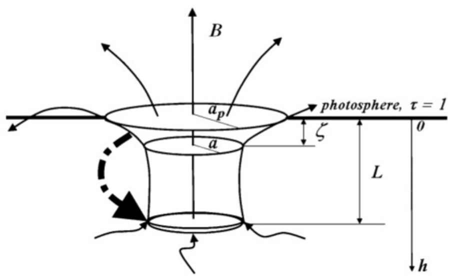
A theoretical analysis of the equilibrium of the vertical magnetic flux tube provided by [55] shows that a horizontal balance of the magnetic tube at the upper edge of the overheated area could be realized if the magnetic tube will expand very quickly with depth. Here the sign of the pressure difference $P_{ex} - P_{in}$ changes at the boundary between the sunspot and the overheated area that expands the flux tube. Local helioseismology data show that at a depth of about 4 Mm the pressure difference $P_{in} - P_{ex}$ is about $1 - 2 \times 10^7$ dyn cm^{-2}. The gas pressure difference between the overheated magnetic flux tube and the environment can be compensated by the sharp horizontal expansion of the sunspot magnetic tube. So, below the depth of 4 Mm, the sunspot magnetic flux tube has an irregular structure. Therefore, the level $L \approx 4$ Mm can be considered as the lower boundary of the sunspot. It should be noted, that the value L is defined only as the energetic boundary. The pressure difference $P_{in} - P_{ex}$ remains negative above the level $h = L$ when the magnetic field significantly larger than B_{eq}.

The model of the sunspot proposed by Parker [41] describes the sunspot structure from the visible layers to the boundary $L = h$. The shallow sunspot model describes analytically the subsurface levels of a sunspot in accordance to the data obtained with local helioseismology [54], [55], [56], [57]. The independent successful numerical simulations have also shown the existence of the overheated area under the sunspot at the level of about 4 Mm [46].

The schematic representation of the magnetic structure of a round unipolar sunspot (A) and it's geometrical structure (B) is presented in Fig. 8, in accordance to the "shallow sunspot" model. According to the shallow sunspot model, long quasi-periodic oscillations of magnetic field and line-of-sight velocities of sunspots are associated with the slow vertical displacements of a sunspot as a whole.



A



B

Figure 8. A: The sunspot magnetic structure (unipolar spot). ζ is the depth of the geometric depression; L is the lower boundary of a sunspot; a is the umbra radius; a_p is the sunspot radius with a penumbra. The maximum value of the magnetic field presented by the white dot. Dotted lines is the The subsurface plasma flows. B: A mass of the gas is moved away from the region of Wilson depression to the depth L (the scale of Wilson depression is enlarged) [56]. Image source: [56].

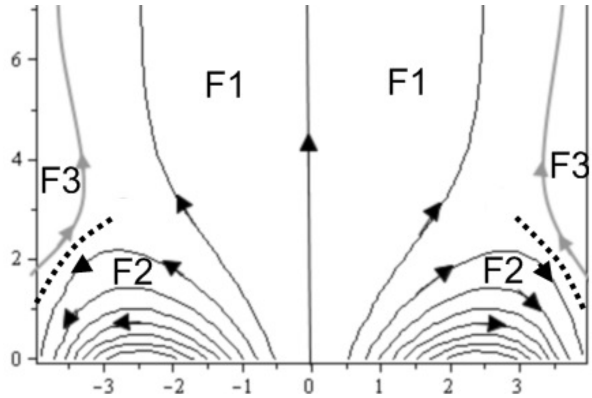


Figure 9. Typical magnetic structure of axisymmetrical sunspot with the well-defined penumbra in which the Evershed flows are circled onto the photosphere near the sunspot. Image source: [1].

3 Modulation of millimeter radio emission above sunspots: Three fluxes model

It has been suggested by several authors that microwave interspot radio sources are generated due to the accelerated particles that fill in a magnetic loop in the solar chromosphere and lower corona [1], [2], [6]. These particles are stored at the top of the magnetic loop, and, partly thermalized, release the observed microwave radio emission. But how the accelerated particles could exist without the visible flare activity near the sunspots? To answer this question of the typical magnetic structure of a sunspot with a penumbra should be analysed (Fig. 9). The magnetic flux of the sunspot could be separated on two parts: the flux F1 that extends to the solar corona, and the flux F2 which closes in the photosphere. But in the active region where the sunspot is located an ambient flux F3 also exists. The flux F3 usually has the same magnetic field polarity as in the spot, but its magnetic field is significantly weaker (300-400 G). In areas where the magnetic field of sunspot umbra is separated on F1 and F2, a separatrix appears between fluxes F2 and F3. Here the magnetic fields of different polarities meet each other to provide small-scale magnetic reconnections. Numerous current sheets are formed in the region of fluxes where plasma is thermalized. But the thermalization of plasma is relatively weak due to: high plasma density ($\beta = 1$) and because magnetic fields in the penumbra are fragmented into the thin filaments which are permanently mixed. Because of it, the magnetic reconnections are sporadic, with a dynamical character [1].

Therefore, the magnetic reconnections leads to the appearance of Dricer's (sub-

Dricer's) electric fields that accelerate particles (electrons). They are the physical reason of the formation of the interspot radio sources [51]. But the real configuration of a sunspot is usually not ideal. More realistic configuration has the sunspot where a largest part of the flux F1 is circled onto the other sunspot of different polarity, or onto the area of the opposite polarity.

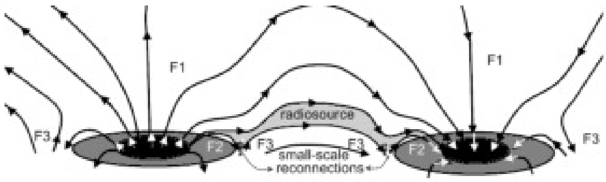


Figure 10. Schematic representation of a bipolar sunspot group. In areas where fluxes F2 and F3 meet each other the small-scale current sheets are generated accelerated particles. These particles are accumulated in the top of magnetic loops and formed the interspot radio sources. Image source: [1].

In the low-laying loops the magnetic field is stronger than in the high loops, which exist at the upper chromosphere and the corona. That leads to the more effective magnetic reconnections providing sufficiently energetic particles, which could thermalize plasma to the X-ray temperatures [66]. In the highest loops the magnetic field is weak and it could trap a relatively small part of the accelerated particles. But these particles emit thermal and cyclotron radio emission. In [66] the authors noted that the X-ray loops near the sunspots are always laying lower than microwave loops. The accelerated particles are accumulated at the tops of magnetic loops. The formation of a radio source is due to the partial or full thermalization of these particles. Thermal radio emission is produced if the thermalization is full, and weak gyrosynchrotron emission could be generated due to partial thermalization. It should be noticed that millimeter radio sources are usually characterized as thermal emission sources [23].

In the other case, quasi-periodic and relatively slow variations of the sunspot magnetic field are transferred as excitations along the magnetic field lines from the lower-lying spot to the millimeter radio sources. The time needed for these excitations to propagate along the magnetic loop from the spot to the source are observed as a time delay effect [51]. In order to estimate the average velocity of excitation propagation from the spot to the radio source, one should determine the half-length of the magnetic loop, at the top of which the radio source is formed. This half-length is $l = \sqrt{L^2 + H^2}$, where L is the distance from the projection of the radio source position on the photosphere to the closest boundary of the sunspot penumbra. We assumed that the height of the radio source above the photosphere is $H = 2$ Mm. The length of the projection of L from the sunspot penumbra boundary to the maximum value of radio emission of the nearby radio sources was provided by [51] for seven sources. The calculated values of half-length of the magnetic loops l lay on the interval of 11300-23800 km. The velocity of excitation propagation in the loop along the magnetic field lines was estimated as $V = l/\Delta T_{corr}$, where ΔT_{corr} is the time-delay observed between oscillations of the magnetic field of a sunspot and the millimeter radio emission at 37 GHz. Based on the experiments, we have obtained $V = 12.1 \pm 1.8$ km s^{-1}.

The obtained velocity should probably be associated with the average sound speed in the magnetic loop. This is related to the fact that millimeter emission of radio sources is of a purely thermal nature. Therefore, in order for it to be modulated efficiently, the incoming excitation should alter the plasma temperature-density characteristics in the source. This process may be completed in no less than the propagation time of acoustic waves or slow magnetoacoustic waves (with its velocity is equal to the sound speed $c_s = \sqrt{\gamma \frac{RT}{\mu}}$ that propagates along the half-length of the loop). If the obtained velocity of 12 km s^{-1} is interpreted as the acoustic wave velocity, the temperature averaged over the magnetic loop that connects the spot to the radio source equals 11000 K.

Near-spot and interspot radio sources are connected to a spot by the magnetic field lines. These sources are formed due to thermalization of accelerated particles produced in small-scale current sheets (Fig.10). Quasi-periodic variations of the magnetic field of the spot are transferred to the radio source along the magnetic field lines with the speed of sound. These variations are modulate the slow changes of plasma parameters at radio source. In other words, the eigen oscillations of the sunspot provided the hydrostatic rebuilding of the parameters in the millimeter radio source.

4 Separated facular knots: long quasi-periodic oscillations

Solar facular knots are regarded as relatively stable and long-lived active formations with a size from 4 to 10 arcsecs and having a fine magnetic structure with magnetic field strengths from 250 G to 1000 G [63]. These separated, stable and long-lived formations are located at the junctions of several convection cells of supergranulation. In these cells radial-horizontal plasma flows connect several parts of magnetic facular elements (magnetic flux tubes) into intersupergranular lanes, sweeping them, due to the frozen-in field in the plasma, to the edges of the cells [34]. Facular knots are usually observed in chromospheric spectral lines as bright formations (Fig. 11).

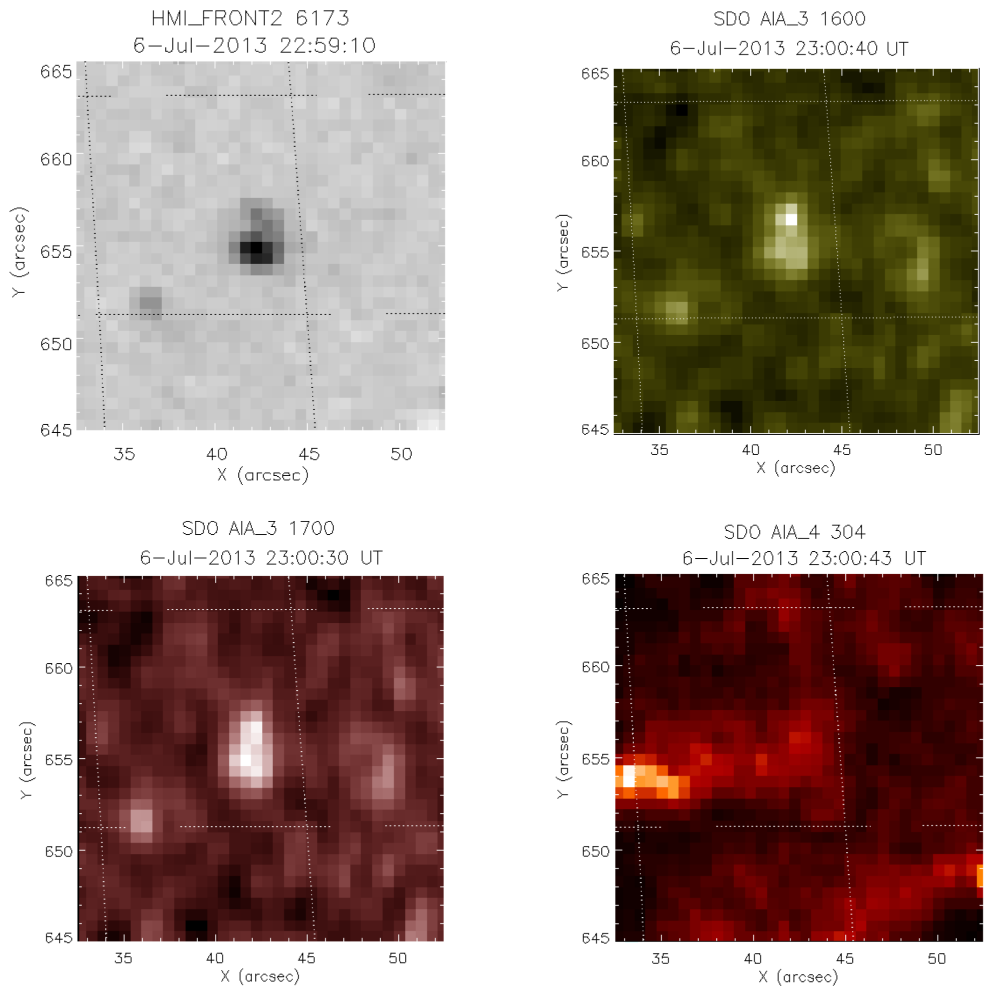


Figure 11. Facular knot in different spectral lines.

Quasi-periodic oscillations in small-scale solar magnetic structures (sizes of about

4-10 arcsecs), such as faculae and pores, are less studied than sunspots. This is because the observations with high temporal resolution were unavailable due to the insufficient temporal resolution of the ground-based instruments. However, using the newest satellite observations with a high spatial and temporal resolutions, we are able to investigate the oscillatory spectrum of small-scale structures which are observed in different layers of the solar atmosphere. Recently [4] quasi-periodic oscillations in the facular magnetic knots with periods of about 3 minutes were revealed. Additionally, the authors identified periods of about 5-11 minutes above the facula periphery regions in the 304 Å spectral line. The detected spatial and temporal distribution of the oscillations was proposed by the authors to be caused by the magnetic field line topology in facular regions. Oscillations with the periods about 5 minutes which depend on the magnetic field dynamical properties of a facular region were found in [24]. In [16] oscillations with periods from 3 to 20 minutes in the intensity of two isolated magnetic pores were detected and interpreted in terms of propagating slow magnetoacoustic sausage waves. Variations of facular brightness was found to be dependent on the convective motions in a facular region in [31]. There, the periodicities of about 5 minutes were detected. The longest periods of oscillations defined in small-scale solar elements do not exceed 30 minutes.

One of the main goals of the study of quasi-periodic oscillations of facular knots is the construction of an adequate model of a solitary facular knot that satisfies the existing observations. The construction of such a model primarily requires knowledge of the magnetic field structure, density, temperature, and pressure distribution in the object. It is also necessary to take into account the lifetime of the structure, its stability, and its equilibrium. Therefore, long quasi-periodic oscillations provide information about the evolution of facular knots during the lifetime.

4.1 Oscillatory modes of facular formations

Previous studies have shown the existence of quasi-periodic variations of the magnetic field of such small-scale structures, with periods from few minutes to 5-6 h [33]. Variations (within 25 minutes) were related to the influence of ascending granulation cells on the structures [21]. The interpretation of longer periods (80-200 min or longer) remains questionable. Quasi-periodic variations of the magnetic field of the facular knots with periods above 1 hour have been studied by several authors (see, for example: [27], [62], [58], [60]). In the work [27], such long periods of oscillations were explained by the influence of supergranulation movements on the structure. But, the lifetime of the granules is about 5-10 minutes. The lifetime of supergranules is about 1.5-2 days. These lifetimes have a different timescales that do not correspond to the obtained periods of oscillations in the interval of 80-250 minutes. This oscillatory character was also explained by the mechanism of vortex separation in the turbulent plasma of the solar atmosphere [36]. The physical interpretation of long periods of up to 250 minutes could not be presented in frames of a suggestion of a propagation of MHD waves [21].

4.2 Analytical description of long-period oscillatory modes

We assumed that the magnetic field and the area of the facular knot can vary in time during the observations. Also the effective mass of the system can be changed. So, we can consider the facular knot as a system with a time-varying rigidity. Such system is characterized by a variable character of the response to external disturbances. Let's consider the equation of small linear oscillations of the system:

$$\ddot{x} + 2\beta\dot{x} + W^2(t)x = 0, \tag{2}$$

where x is the parameter of the system - the averaged magnetic field strength, β is the coefficient of the friction, $W^2(t)$ is the effective elasticity of the system. In the case when $W^2 = \lambda^2 q(t)$ where λ is constant, we can obtain the approximate solution of (2) ($\beta = 0$) by WKB method ([37], formula 14.28):

$$x(t) \approx \frac{C_1 \cos[\lambda \int \sqrt{q} dt] + C_2 \sin[\lambda \int \sqrt{q} dt]}{\sqrt[4]{q}}. \tag{3}$$

We postulate the exact solution of (2) in the form:

$$x(t) = A_0 \exp[(\gamma - \beta)t] \cos[\omega(t) \cdot t + \phi_0], \tag{4}$$

where A_0 is the amplitude of the oscillations, γ is the increment/decrement of oscillations, $\omega(t)$ is the time varying frequency and ϕ_0 initial phase. Inserting the law of motion (4) into (2), we obtain:

$$W^2(t) = (\omega + \dot{\omega}t)^2 - \gamma^2 + \beta^2, \tag{5}$$

$$\frac{d(\omega + \dot{\omega}t)}{dt} = -2\gamma(\omega + \dot{\omega}t). \tag{6}$$

If $(\omega + \dot{\omega}t) \equiv \frac{d}{dt}(\omega t) = u$, we have: $u = \omega_0 \exp(-2\gamma t)$, where ω_0 is some characteristic constant frequency. After the second integration:

$$\omega t = \frac{\omega_0}{2\gamma} \exp(-2\gamma t) - \phi_0. \tag{7}$$

At $t = 0$, the phase of oscillations is $\phi_0 = \frac{\omega_0}{2\gamma}$. From equations (5) and (7):

$$W^2 = \omega_0^2 \exp(-4\gamma t) - \gamma^2 + \beta^2 \tag{8}$$

and the $x(t)$ is:

$$x(t) = A_0 \exp[(\gamma - \beta)t] \cos\left[\frac{\omega_0}{2\gamma} \exp(-2\gamma t) + \phi_0\right]. \tag{9}$$

The function $W(t)$ is a variable function of time, depending mainly on the coefficient γ: it decreases with time if $\gamma > 0$, and grows when $\gamma < 0$. Here, W is a complex function of parameters of the system. It can vary significantly in time. This suggests that during the observational period, not only the magnetic field and the area of the facular knot can change. Also the depth of immersion of the facular knot into the photosphere, that is reflected on its effective mass could vary in time.

5 Observations and methods of data processing

5.1 Millimeter radio emission observations

Studies of millimeter radio emission have a special place in present radio astronomy. This range provides the opportunities for a comprehensive study of the Solar system, and more distant astronomical objects. The most important parameters of the observed solar elements, their spatial distribution and fine structure can be obtained by the methods of millimeter radio observations. Therefore, high-frequency observations are complex both from a technical and methodological point of view. This imposes serious restrictions on the technical characteristics of the equipment of the instruments used. The Earth's atmosphere has a strong influence on the signal quality in the millimeter range, since the absorption coefficient significantly increases as the signal passes through atmospheric layers (Fig.12). Millimeter and submillimeter waves are fairly absorbed in the clouds, so radio astronomical observations in this range are almost impossible in cloudy weather. In the absence of cloudiness, water vapor and oxygen play a major role in the absorption of radio waves [23].

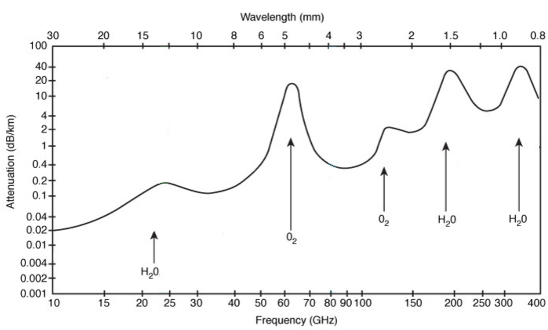


Figure 12. Atmospheric absorption at the sea level. Image source: https://safenetforum.org/t/what-are-your-business-ideas-for-the-safe-network/25034/61.

The molecular absorption coefficients of radio waves in H_2 O and O_2 are calculated over the entire millimeter range [23]. However, in order to take into account the effect of the atmosphere on the signal as well as possible, you need to know the total absorption on the line of sight. Usually the flat-layered model of the atmosphere, which is valid at zenith angles $\Phi \leq 85\,\text{deg}$ is used.

The line-of-sight full absorption is: $\gamma = \Gamma_a \sec\Phi$, where $\Gamma_a = k_b H_b + k_k H_k$ is the zenith optical depth. Here k_b and k_k - are the radio waves absorption coefficients due to H_2O and O_2 at the sea level, H_b and H_k the effective path length of the water vapor and oxygen [8]. For the transparency windows in millimeter range ($\lambda = 8, 3.4, 2.3, 1.4$ mm) we could assume $k_b(h) = \exp(-h/H_b)$, where h is the heigth above the sea level. The value H_b depends weakly on the air temperature and on h, and could change from winter to summer in the interval of $1.48 - 1.56$ km [23].

In connection with the above, the requirements for the sensitivity of the receiving equipment in the millimeter range, to the methods of observation and their primary processing should be quite high. At present, ground-based radio telescopes and radio interferometers are used for short-wave observations of astronomical objects [7]. However, the multitude of tasks facing large systems around the world most often do not allow concentrating on long-term observations of the same object. Therefore, single full-turn antennas still play an important role not only as elements of radio interferometers with very-long bases (VLBI), but also help to solve the tasks of independent long-term observations of individual radio sources.

5.2 Metsähovi radio telescope

The Metsähovi RT-14 radio-telescope is a Cassegrain-type antenna. The diameter of the RT-14 is 13.7 m. The telescope could work in range of $2 - 150$ GHz (13.0 cm - 2.0 mm). The telescope provides two observational methods: solar mapping and the tracking of the chosen region. At present the 37 GHz receiver is used for solar observations. The beam size of the antenna is 2.4 arcminutes. The sensitivity of the receiver is 0.2 solar flux units (s.f.u.). The temporal resolution is 0.1 s [67].

5.3 Helioseismic and Magnetic Imager (SDO/HMI)

Solar Dynamics Observatory (SDO) spacecraft is located in a geosynchronous, inclined (28.5 deg) orbit. Also the spacecraft traces an "eight" spanning 57 degrees in latitude at an altitude of 36 000 km along the meridian 102 deg W. These characteristics provided a variable component with a period of 12 and 24 hours due to the Doppler effect.
The Helioseismic and Magnetic Imager (HMI) instrument is on-board the SDO. This instrument provides the measurements of solar magnetic fields and Doppler velocities every 45 s [47]. The spatial resolution of HMI is 1 arcsecond. A data processing manual and the description of SDO/HMI is presented in [48], [49], [9], [68]. Full-disk solar maps of the line-of-sight magnetic field could be obtained by using the Joint Science Operation Centre (JSOC) HMI-AIA Science Data Processing.

5.4 Methods of data processing

5.4.1 Wavelet transform

The Wavelet analysis is the most popular method for the investigation of the distribution of periods of quasi-periodic oscillations in time in various signals. In other words, it enables to study the signal behaviour both in the time and in the frequency domain. Here the signal analyzed by "mother" function (Ψ), as well as, by the changing of the time delay (τ) and the scale (s). The continuous Wavelet transform is defined as [65]:

$$W_x^{\Psi}(\tau, s) = \frac{1}{\sqrt{|s|}} \int_{-\infty}^{+\infty} x(t) \Psi^* \left(\frac{t-\tau}{s} \right) dt, \tag{10}$$

where the (*) indicates the complex conjugate. Mostly the Morlet wavelet is used as a mother function to analyse non-stationary signals. This is because it has the minimum value of the square in frequency-time resolution, i.e. the maximum frequency resolution [10]. The Morlet function is defined as:

$$\Psi(t) = \pi^{1/4} e^{i\omega_0 t} e^{-t^2/2}, \tag{11}$$

where ω_0 is the dimensionless frequency [13].

5.4.2 Empirical Mode Decomposition (EMD)

The empirical mode decomposition (EMD) is iteratively decompose the signal into natural harmonics by using a shift-factor (local time-scale of the real signal) [18]. EMD method does not use the harmonic functions (as sine, cosine, or wavelets) as a basis. Due to its adaptive nature, EMD is suitable for analysing nonlinear variations [18].

Application of the EMD technique to the average magnetic field time-series allows us to extract several intrinsic empirical modes from the signal. We can estimate periods of the empirical modes as $P = 2N/n$. Here N is the total length of the analyzed signal; n is the number of extrema in a mode. Also, EMD may indicate a random nature of empirical modes [14]. Writing the power spectral density S as a function of the frequency f as $S = 1/f^{\alpha}$ [70], [26], we are able to compare the modes with the white and coloured noises. Recently it was shown [26] that the energy E of the intrinsic modes obtained from synthetic coloured noise time-series is connected with the mean period of the modes.

6 Results (summary of the publications)

All articles included in this thesis are dedicated to the investigation of long quasi-periodic oscillations of observed physical parameters of sunspots and small-scale magnetic structures with periods more than 30 minutes.

6.1 Long quasi-periodic oscillations of sunspots and nearby magnetic structures

This article was aimed to investigate the long quasi-periodic oscillations of the averaged value of the line-of-sight component of the sunspot magnetic field. We analysed five active regions with sunspots using data obtained from SDO/HMI and from the Metsähovi RT-14 radio-telescope at 37 GHz frequency. The periods in the interval of 200-400 minutes were found in the time-series of the magnetic field and radio emission. The analysis of time-series of the magnetic field and the radio emission showed that the oscillations with periods of 200-400 minutes occur in phase, but the radio emission variations are delayed relative to the magnetic field variations. Time lags of 15-18 minutes were found. We proposed the modulation mechanism of radio emission at high levels is the magneto-hydrostatic rebuilding of radio sources caused by slow time-variation of the sunspot magnetic field. The interpretation of observed long periods was also given with the "shallow sunspot" model, which represents the sunspot as a stable, isolated magnetic structure, which could oscillate as a whole near the position of equilibrium.

6.2 Artifacts of SDO/HMI data and long-period oscillations of sunspots

In this article the periodic artifacts with periods of 12 and 24 hours found in SDO/HMI data series were investigated. These artifacts appeared in long time-series during the analysis of quasi-periodic variations of sunspots. It was found that these artifacts are well detected in the regions of weak magnetic fields. The artifitial harmonics do not significantly affect to the long-period oscillations of sunspots if the maximum value of the magnetic field of the spot is less than 2000 G. If the magnetic field is higher than 2000 G, the amplitude of artifacts grows and become significant.

6.3 Time delay effect between long quasi-periodic oscillations of 37 GHz radio sources and the magnetic field of the nearest sunspots

In this article we continued the detailed investigations of the time-delay effect observed between the variations of the magnetic field and the radio intensity at 37 GHz. For seven active regions several parameters were found: periods of oscillations of the magnetic field and radio emission; time-delays obtained with the cross-correlation analysis, time-delays obtained as the time propagation of the acoustic disturbances from the sunspot to the radio source for temperatures of 10000 K, 11000 K and 12000 K; the half-length of the magnetic loop where the radio sources are originated. All time-delays were very close. The interpretation of these time-delays and the description of the relation between sunspots and radio sources observed at 37 GHz was given with the "free-fluxes" model.

6.4 Long-period quasi-periodic oscillations of a small-scale magnetic structure on the Sun

This article represents the study of long-period non-linear variations of the magnetic field of the solar small-scale magnetic structure. To obtain the period of variations the Empirical Mode Decomposition method was used. The obtained modes were tested with the synthetic noises (white, pink and red), and the significant mode with the period of 80-260 minutes was found. This mode showed non-linear character with the growing amplitude and period. We interpreted such oscillatory phenomenon in terms of the vortex shedding appearing during the emergence of the magnetic flux of the structure. Such long period oscillations could be induced by the dynamical interaction of small-scale magnetic structures with the supergranula cells.

6.5 Long-term oscillations of sunspots and a special class of artifacts in SOHO/MDI and SDO/HMI data

A special class of artifacts named pixel-to-pixel (p2p) were described in this article. These artifacts appear when we track the pixel on the CCD matrix, i.e. when the image moves along the pixel matrix. We found the period of p2p artifact for SDO data of about 3 minutes. The results of the detailed analysis of two types of p2p artifact show that the integral parameters of the source observed with the CCD matrix should be used for studying of quasi-periodic oscillations of source parameters instead of the maximum values of the source obtained from the one pixel. Artifact neutralization is possible only if we analyse the source-average values of physical parameters. Several tests confirmed the existing of oscillations of physical parameters of sunspots, independent of the artifacts. For example, the simultaneous analysis of sunspot magnetic field and ultraviolet intensity of its umbra showed the same periods of oscillations.

6.6 Eigen oscillations of facular knots

Long-period non-linear oscillations of the magnetic field of small-scale magnetic structures as facular knots were analysed in this article. Three regimes of oscillations were found: the increasing of the amplitude and the period; the decreasing of the amplitude and the period; and the growth and decrease of the amplitude and period alternate one another. The theoretical interpretation of these regimes of oscillations of facular knots was proposed. We suggested the facular knot as a system with the time-varying rigidity. The oscillations of the system with the time-varying rigidity were estimated. The comparison of the observed and estimated oscillatory modes shown good agreement. It was shown that even if objects retain their structural identity, their physical parameters can vary significantly. The variations of the parameters could change the response of the system to the external disturbances that lead to the changing of the character of observed oscillations. Obviously, the rigidity of the facular knots is a complex function of physical parameters of the system. It vary in time significantly during the observations. Also, the depth of immersion of the facular knot into the photosphere, which is directly reflected on its effective mass, could vary in time.

7 Conclusions

The thesis aimed to provide the analysis and the interpretation of long quasi-periodic oscillations of the magnetic field of sunspots and the penetration of these oscillations into the high levels of solar atmosphere, which was observed at millimeter radio waves. Also, we analyzed the long quasi-periodicity at small-scale magnetic structures like facular knots and pores. We provided the interpretation of long-period oscillations of sunspots as well as the long-periodical component observed in the oscillatory spectrum of facular knots in frames of model of a shallow sunspot (periods from 60 minutes and more).

So-called "three-fluxes model" is the additional part of the shallow sunspot model. This model explains the formation and the long-period oscillations of radio sources, which lay in the solar chromosphere, nearby spots.

Extrapolating the shallow sunspot model to the facular knots, we met some difficulties, like the incomplete knowledge of a number of physical parameters (mass of the object, lower boundary) that should be included in the model. Because of that, firstly, we carefully analyzed the dynamics of facular knots based on the observations of the magnetic field variations, and the intensity variations at UV spectral lines. We obtained three types of non-linear long-period oscillatory modes with periods from 25 to 250 minutes: 1. The period and the amplitude increase with time; 2. The period and amplitude decrease with time; 3. The changing regime of the growing and the decreasing of the period and the amplitude, as the beats, where the period of oscillations does not depend on the amplitude. All observed modes were interpreted in terms of oscillations of the system with the time-varying rigidity [59]. The second step is to estimate theoretically the values of periods of oscillations comparable with the observed long periods. Using the estimations of characteristic frequency of oscillations of a facular knot provided by [59], and based on the assumption that the lower boundary of a facular knot L is about 1 - 2 Mm, we obtained the period $T = 150$ minutes. This value is in the good agreement with the observed periods.

8 Outlook

Future work will directed to the statistical investigations of facular knots and pores. There are still several questions concerning the evolution and the physical parameters of these small-scale magnetic structures: 1. what is the typical lifetime of facular knots? 2. how these objects distributed on the Sun during the solar cycles? 3. what is the structural evolution of these objects? 4. how the intensity of facular knots is changes with the height? 5. if these objects are long-lived, what factors provide its stability? There is no adequate theoretical model of a separated facular knot with a lifetime is more than 5 hours. New analytical and numerical model of a facular knot will be proposed based on the observational results of the dynamical properties of these objects, and on the theoretical suggestions which was described in the thesis.

One of the important question which will be investigated in our future work is the new theoretical model of the dissipation of a sunspot. This process has a complex character when the system of a sunspot loose its stability and the equilibrium. New theoretical interpretation of the sunspot dissipation process will give the possibility to describe the sunspot evolution in more detail.

References

[1] Bakunina, I.A., Abramov-maximov, V.E., Nakariakov, V.M., Lesovoy, S.V., Soloviev, A.A., Tikhomirov, Y.V., Melnikov, V.F., Shibasaki, K., Nagovitsyn, Y.A., Averina, E.L. 2013, PASJ, 65, 13.

[2] Bakunina, I.A., Melnikov, V.F., Solov'ev, A.A., Abramov-Maximov, V.E. 2014, Sol. Phys. 290, 37

[3] Bogdan, T. 2000 Sunspot Oscillations and Seismology, Encyclopedia of Astronomy and Astrophysics, Edited by Paul Murdin, article id. 2299. Bristol: Institute of Physics Publishing, 2001.

[4] Chelpanov, A. A., Kobanov, N. I., & Kolobov, D. Y. 2015, Astronomy Reports, 59, 968

[5] Cheung, M. C. M., Moreno-Insertis, F., & Schüssler, M. 2006, A&A, 451, 303

[6] Chorley, N., Hnat, B., Nakariakov, V.M., Inglis, A.R., Bakunina, I.A. 2010, Astron. Astrophys. 513, 27

[7] Christiansen U., Hogbom I. 1972, Radiotelescopes, Mir, 255

[8] Chukin V.V. 2004, Monography, RGGMU, 107

[9] Couvidat, S., Schou, J, Shine, R. A., et al. 2012, Sol. Phys., 275, 285

[10] Daubechies, I. 1992, Ten lectures on wavelets, Society for industrial and applied mathematics

[11] Efremov, V.I., Parfinenko, L.D., Solov'ev, A.A. 2010, Sol. Phys. 267, 279

[12] Efremov, V. I., Parfinenko, L, D., Solov'ev, A. A. 2012, Geomagnetism and Aeronomy, 52, 1055

[13] Farge, M., 1992: Wavelet transforms and their applications to turbulence. Annu. Rev. Fluid Mech., 24, 395–457.

[14] Flandrin, P., Rilling, G., & Goncalves, P. 2004, IEEE Signal Processing Letters, 11, 112

[15] Foullon, C., Verwichte, E., & Nakariakov, V. M. 2009, ApJ, 700, 1658

[16] Freij, N., Dorotovic, I., Morton, R. J., et al. 2016, ApJ, 817, 44

[17] Gelfreikh, G. B., Nagovitsyn, Y. A., & Nagovitsyna, E. Y. 2006, PASJ, 58, 29

[18] Huang, N. E., Shen, Z., Long, S. R., Wu, M. C., Shih, H. H., Zheng, Q., Yen, N. C., Tung, C. C., and Liu, H. H., 1998, Proc. Roy. Soc. Lond. A, 454, 903

[19] Hulburt, N.E., Rucklidge, A.M. 2000, Mon. Not. R. Astron. Soc. 314, 793

[20] Jelinek, P.; Karlický, M.; Van Doorsselaere, T.; Bárta, M. 2017, ApJ, 847, 98J

[21] Jess, D.B., Morton, R.J., Verth, G, Fedun, V., Grant, S.D.T., Giagkiozis, I. 2015, Sp.Sc.Rev., 190, 1-4, 103

[22] Jess, D.B., Verth, G. 2016, Washington DC American Geophysical Union Geophysical Monograph Series 216, 449, 1502.06960

[23] Kislyakov A. G. 1970, Physics-Uspekhi, 101, 4, 607

[24] Kobanov, N., Kolobov, D., & Chelpanov, A. 2015, Sol. Phys., 290, 363

[25] Kobrin, M. M., Pakhomov, V. V., & Prokofeva, N. A. 1976, Sol. Phys., 50, 113

[26] Kolotkov, D. Y., Anfinogentov, S. A., & Nakariakov, V. M. 2016, A&A, 592, A153

[27] Kolotkov, D.Y., Smirnova, V.V., Strekalova, P.V., Riehokainen, A., and Nakariakov, V.M., 2017, A&A 598, L2.

[28] Kosovichev, A. G. 2006, Adv. Space Res., 38, 876

[29] Kosovichev, A.G. 2009, Space Sci. Rev. 144, 175

[30] Kosovichev, A.G. 2012, Sol. Phys. 279, 323

[31] Kostik, R. & Khomenko, E. 2016, A&A, 589, A6

[32] Kshevetskii, S.P., Solov'ev, A.A. 2008 Astron. Rep. 52, 772

[33] Martínez González, M.J., Asensio Ramos, A., Manso Sainz, R., et al., 2011, Astron. J. Lett., 730, 2, L37

[34] Mehltretter J.P. 1974, Sol. Phys. 38, 43

[35] Nakariakov, V.M., Stepanov, A.V.A.: In: Klein, K.-L., MacKinnon, A.L. (eds.) 2007, Lecture Notes in Physics, vol. 725, p. 221

[36] Nakariakov, V.M., Aschwanden, M.J., & van Doorsselaere T. 2009, A&A, 502, 661

[37] Nayfeh, Ali H. 1981, A Wiley-Interscience Publication, New York: Wiley

[38] Obridko, V.N. 1985, Sunspots and Complexes of Activity. Nauka, Moscow, pp. 255

[39] Parchevsky, K. V., & Kosovichev, A. G. 2009, ApJ, 694, 573

[40] Parker, E.N. 1974, Sol. Phys. 36, 249

[41] Parker, E.N. 1979, Astrophys. J. 230, 905

[42] Parker, E.N. 1979, Cosmical Magnetic Fields. Part I. Claredon Press, Oxford, pp. 608

[43] Parker, E.N. 2008, Space Sci. Rev. 144, 15

[44] Pevtsov, A.A., Berteo, L., Tlatov, A.G., Kilcik, A., Nagovitsyn, Yu.A., Cliver, E.W. 2014, Sol. Phys. 289, 593

[45] Ponomarenko, Y.B. 1972, Sov. Astron. 16, 116

[46] Rempel, M. 2012, Astrophys. J. 750, 62

[47] Scherrer, P. H., Schou, J., Bush, R. I., et al. 2012, Sol. Phys., 275, 207

[48] Schou, J., & Larson, T. P. 2011, SPD Meeting 42, 16.05, BAAS, 43

[49] Schou, J., Scherrer, P. H., Bush, R. I., et al. 2012, Sol. Phys., 275, 229

[50] Smirnova, V., Riehokainen, A., Solov'ev, A. A., & Kallunki, J. 2015, AP&SS, 357, 2, 149

[51] Smirnova, V.V., Riehokainen, A., Ryzhov, V., Zhiltsov, A., & Kallunki, J. 2011, A&A, 534, A137

[52] Smirnova, V., Riehokainen, A., Solov'ev, A., Kallunki, J., Zhiltsov, A., Ryzhov, V. 2013, A&A, 552, 23

[53] Smirnova, V., Efremov, V.I., Parfinenko, L.D., Riehokainen, A., Solov'ev, A.A. 2013, A&A, 554, A121, 7

[54] Solov'ev, A. A., & Kirichek, E. A. 2008, Astrophys. Bull., 63, 169

[55] Solov'ev, A. A., & Kirichek, E. A. 2009, Astron. Rep., 53, 675

[56] Solov'ev, A., Kirichek, E. 2014, Astrophys. Space Sci. 352, 23

[57] Solov'ev, A.A., Kirichek, E.A. 2015, Astron. Lett. 41, 211

[58] Solov'ev, A.A., Kirichek, E.A., Efremov, V.I. 2017, Geomagnetism and Aeronomy 57, 1101

[59] Solov'ev, A. A., & Kirichek, E. A. 2019, MNRAS, 482, 4, 5290

[60] Solov'ev, A. A., Strekalova P.V., Smirnova V.V., Riehokainen A. 2019, Ap&SS, 364, 29S

[61] Stix, M. 2004, The sun: an introduction, 2nd ed., by Michael Stix. Astronomy and astrophysics library, Berlin: Springer, ISBN: 3540207414

[62] Strekalova, P.V., Nagovitsyn, Yu.A., Riehokainen, A., and Smirnova, V.V., 2016, Geomagn. Aeron. (Engl. Transl.), 56, 8, 1052.

[63] P. V. Strekalova, Yu. A. Nagovitsyn, and V. V. Smirnova, 2018, Geomagn. Aeron. (Engl. Transl.), 58, 7, 893.

[64] Thomas, J. H., Cram, L. E., & Nye, A. H. 1984, ApJ, 285, 368

[65] Torrence, C., & Compo, G. P. 1998, Bull. Am. Meteorol. Soc., 79, 61

[66] Tun, S.D., Gary, D.E., Georgoulis, M.K. 2011, ApJ, 728, 1, 1, 16

[67] Urpo, S. 1982, Observing methods for the millimeter wave radio telescope at the Metsaehovi Radio Research Station and observations of the Sun and extragalactic sources. Ph.D. Thesis. Helsinki University of Technology, Espoo, Finland

[68] Wachter, R., Schou, J., Rabello-Soares, M. C., et al. 2012, Sol. Phys., 275, 261

[69] Wilhelm, K. 2009, Landolt Börnstein, 4115

[70] Wu, Z. & Huang, N. E. 2004, Proceedings of the Royal Society of London Series A, 460, 1597

[71] Zhao, J., Kosovichev, A. G., & Duvall, Jr., T. L. 2001, ApJ, 557, 384