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Multilevel Observations of the Oscillations in the First Active Region of the New Cycle

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Abstract For the first time, a multiwavelength investigation of the oscillation dynamics in a solar facula from its birth to decay was carried out. We performed spectral observations of active region NOAA 12744 at the Horizontal Solar Telescope of the Sayan Solar Observatory in the Hα, He I 10830 Å, and Si I 10827 Å lines. We used Solar Dynamics Observatory (SDO) line-of-sight magnetic field data and the 1600 Å, 304 Å, and 171 Å UV channels. At the early stages of the facula evolution, we observed low-frequency (1 – 2 mHz) oscillations concentrated in its central part. In the lower solar atmosphere, this was registered in the intensity, line-of-sight velocity, and magnetic field signals. These frequencies were also observed in the transition region and corona (304 Å and 171 Å channels). At the maximum development phase of the facula evolution, the low frequency oscillations closely reproduced the coronal loop structures forming above the active region. At the decay phase, the spatial distributions of the observed frequencies resembled those found in and above the undisturbed chromospheric network. Our results indicate a direct relation of the low frequency oscillations observed in the lower solar atmosphere with the oscillations in the coronal loops, which happens probably through the loop footpoints.

Keywords Faculae · Oscillations, solar · Waves, propagation

1. Introduction

Faculae are the most frequent expression of solar activity. They appear as large bright areas that harbor high magnetic field flux. They are always observed in active regions (ARs), both containing sunspots and those not related to them. Faculae precede the emergence of sunspots and remain during the whole lifespan of ARs up to the sunspot decay and even after it. Due to their surface area and abundance, faculae affect the energy balance between

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solar atmospheric layers, and their influence may happen through wave mechanisms. Studying the oscillation characteristics in faculae is a relevant problem of solar physics. To date, numerous studies have addressed this problem (Orrall, 1965; Sheeley and Bhatnagar, 1971; Khomenko et al., 2008; Kobanov and Pulyaev, 2011; Kolotkov et al., 2017). Note that analyzing the spatial distribution of oscillations in faculae is more difficult than in sunspots due to a more complicated magnetic field topology: faculae often contain several separated magnetic knots of different polarities. The evidence of the strength and direction of the magnetic field is highly diverse. Narayan and Scharmer (2010) analyzed polarimetric observations of a facula with a high spatial resolution and found a number of magnetic features: micropores, bright points, ribbons, flowers, and strings. Solov'ev and Kirichek (2019) identified three main magnetic structures: small-scale flux tubes, knots, and pores. Rabin (1992), Martínez Pillet, Lites, and Skumanich (1997), Guo et al. (2010) claim that vertical magnetic fields dominate faculae, while Ishikawa et al. (2008) found that small horizontal magnetic structures prevail in them. Blanco Rodríguez and Kneer (2010), based on polar facula observations in the Fe I 1.5 μm line, found two magnetic structure types: one with a strength of 900 – 1500 G and the other of strengths lower than 900 G. While the structures of the first type are vertical, those of the second type show arbitrary angles. The situation becomes even more complicated when one considers the changes in the characteristics following the evolution of a facula. The first indications of a new solar activity cycle can be observed in the emerging faculae.

While the processes accompanying the evolution of ARs have been discussed quite thoroughly in the contemporary publications (van Driel-Gesztelyi and Green, 2015, and the references therein), studies of the oscillation dynamics during the facular AR evolution are almost non-existent. With this study we are trying to fill this gap.

This work is dedicated to the multiwavelength study of oscillations in a solar facula registered as NOAA 12744—the first AR of the new solar activity Cycle 25. The goal of this work is to reveal the most characteristic features of the oscillation processes in a facula at an early stage of the activity cycle and to establish which frequencies dominate in the transition region and corona in different phases of the active region evolution.

2. Instruments and Data

We used data from the Solar Dynamics Observatory (SDO: Pesnell, Thompson, and Chamberlin, 2012). The Atmospheric Imaging Assembly (AIA: Lemen et al., 2012) onboard SDO obtains full-disk images of the Sun in a number of ultraviolet spectral channels with a 0.6″ spatial resolution and 12 to 24 s time cadence. For the analysis, we chose the 1600 Å, 304 Å, and 171 Å channels, which represent the chromosphere, transition region, and corona, respectively. We also used the Helioseismic and Magnetic Imager (HMI: Scherrer et al., 2012) measurements of the line-of-sight magnetic field.

Ground-based observations by the Horizontal Solar Telescope at the Sayan Solar Observatory complement the SDO data. The working aperture diameter of the main mirror is 80 cm. The Earth's atmosphere limits the spatial resolution to 1 – 1.5 arcsec, and the spectral resolution varies between 4 and 8 mÅ depending on the wavelength. A detailed description of the telescope can be found in Kobanov (2001) and Kobanov, Chelpanov, and Kolobov (2013). The lengths of the series varied between 135 and 210 min, and the cadence was 3.2 s. In the observations, we used three spectral lines: the chromospheric He I 10830 Å and Hα lines and the photospheric Si I 10827 Å.

3. Morphology and Evolution of the Active Region

The first AR of the solar activity Cycle 25 emerged on the disk on 6 July 2019 at the southern hemisphere close to the eastern limb (S27° E55°). During the first six hours after the first appearance of the magnetic flux, it rapidly developed into a quite big facula (approximately 50″ in diameter based on the images in the 1600 Å channel). After that, pores appeared in the AR. The new AR was given number NOAA 12744.

On 8 July, the facula started to expand. It separated into head and tail parts of negative and positive magnetic polarities, correspondingly. On this day, the pores disappeared, and the facula started to divide into several cores.

The 171 Å channel images showed a blurred picture of forming coronal loops. The region continued to grow on 10 July 2019 in the 1600 Å and 304 Å images, while a clear structure of closed coronal loops formed in the 171 Å channel.

Starting from 11 July, the loop structures in the 171 Å images grew more blurred and elongated. During the next two days, the loop structure continued to disintegrate, and by the end of this period (01:00 UT on 14 July), they disappeared completely.

On the eighth day after the facula appeared, it decayed: it almost merged into the surrounding chromospheric network in the 1600 Å channel.

It must be noted that on 14 July at 01:00 UT after the decay, magnetic reconnection occurred followed by a local brightening in the coronal lines and in the upper chromospheric channels. A new loop structure developed above the facula rapidly within an hour. The newly activated region lived for two more days, during which the decay process repeated and concluded by a complete disappearance of the active region. By this time the region approached the western limb.

We divided the evolution of the facula into five phases based on the SDO/AIA images. The first phase (*emergence*) is characterized by the appearance of small brightenings at an area of increased magnetic field concentration. The second phase (*growth*) is distinguished by a rapid expansion of the bright elements. During the third phase (*maximum development phase*), a stable coronal loop structure is observed in the 171 Å channel; the surface area and brightness of the facula are at their maxima. The fourth phase (*decline*) is characterized by a decrease in the brightness and the number of coronal loops. During the fifth phase (*decay*), the coronal loop structure completely disappears.

We carried out the observations at the ground-based telescope on 7, 8, 10, and 11 July, which corresponded to the emergence, growth, maximum development, and decline phases of the facula evolution. We lack ground-based observations for the fifth phase—the decay.

4. Results

4.1. Oscillation Dynamics in the LOS Velocity and Intensity

The AIA telescope onboard SDO provides two-dimension images in UV and EUV channels, which we used to construct spatial distributions of the dominant oscillation frequencies (Figure 2). These distributions show which frequencies dominated at each point of the facula during each of the five development phases. The dominant frequency ν_d at each spatial point was determined as the frequency for which the integrated oscillation power in the $\nu \pm 0.5$ mHz range shows the maximum value. The white areas in the panels correspond to the spatial points whose oscillation power did not reach the $3\sigma^2$ level.

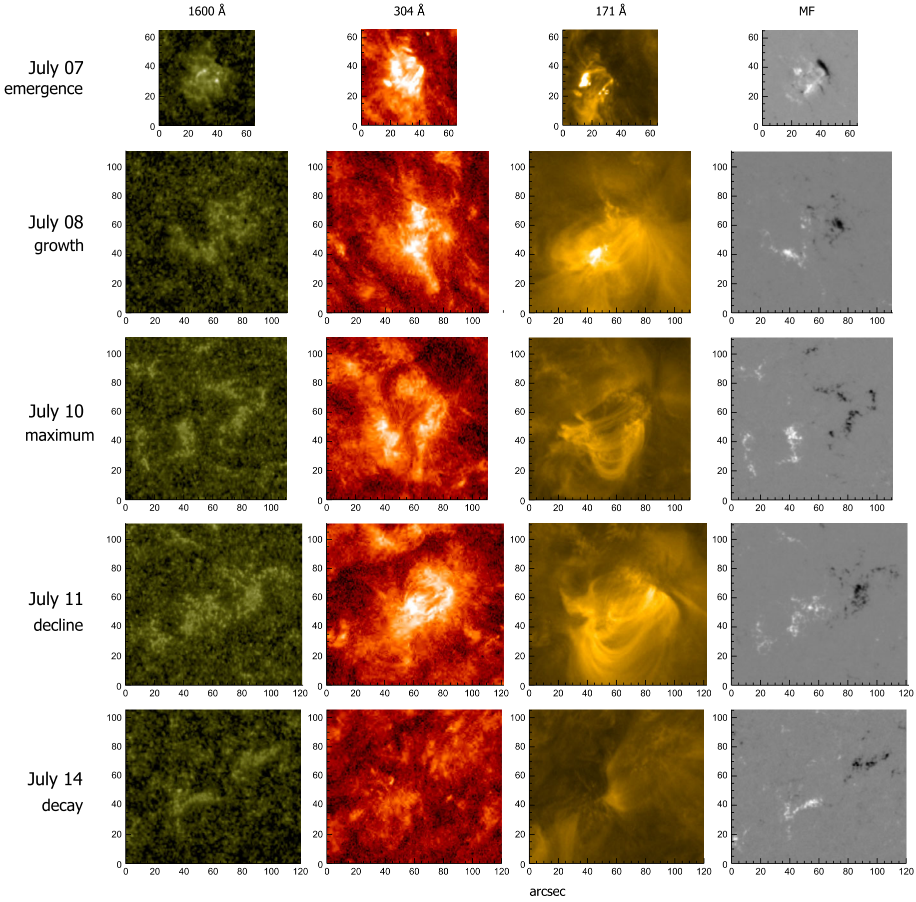

Figure 1 Snapshots of the facula in the three AIA channels and HMI magnetograms for the five phases of the active region evolution.

For four out of the five facula evolution phases that we specified, we have ground-based spectral observations in the Si I 10827 Å (upper photosphere), He I 10830 Å and Hα (chromosphere) lines.

We analyzed the spectra in the $1-8$ mHz range. The restriction at the lower end was imposed by the fast evolution rate of the active region, which may lead to significant changes in its structure during the time series. The frequencies over 8 mHz showed insignificant power.

Numerous earlier works have noted the dominance of the five-minute oscillations in faculae at the photospheric and chromospheric levels (Deubner, 1974; Teske, 1974; Balthasar, 1990; De Pontieu, Erdélyi, and De Moortel, 2005). In our case, however, the emergence phase showed the oscillation power concentration in the lower-frequency range ($1-2$ mHz) in the central part of the facula. This clearly shows in the oscillation spatial distribution in the HMI magnetic field signals and in the 1600 Å (Figure 2). The lower frequencies also dominate in the spectra of our ground-based line-of-sight (LOS) velocity observations in the Hα and He I 10830 Å lines, over the central part of the facula, at its first evolution phase

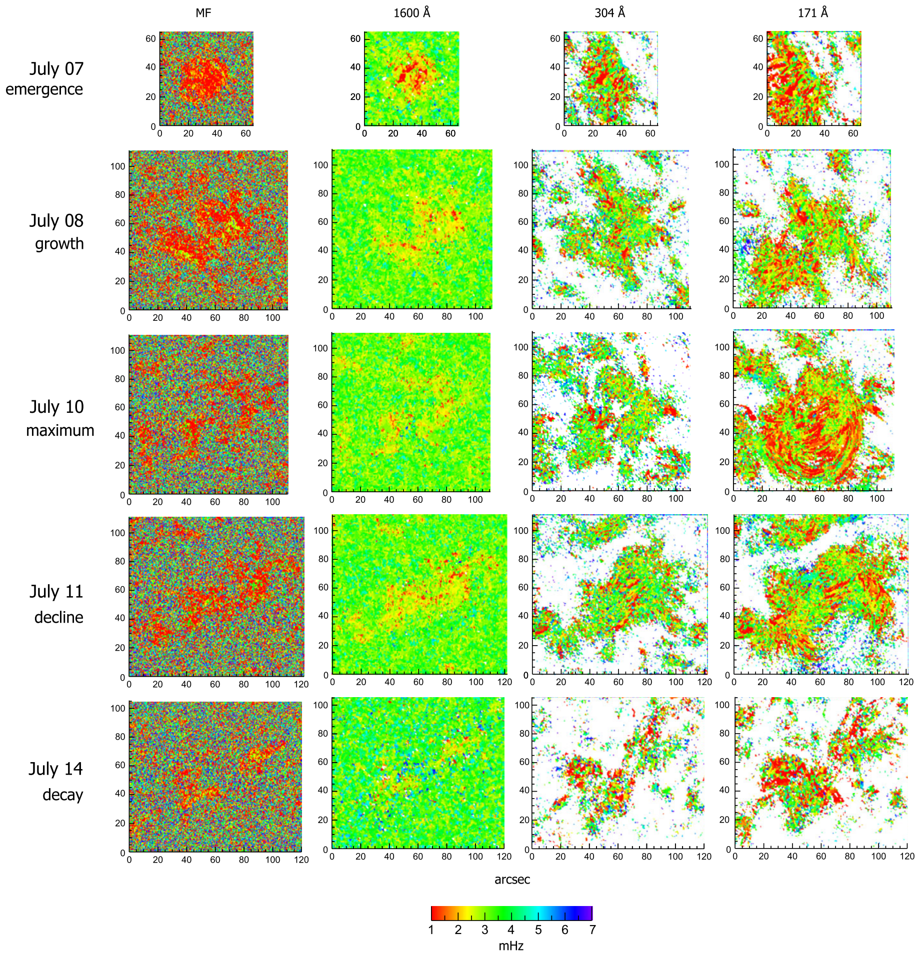

Figure 2 Maps of the dominant frequencies in the facula in the HMI LOS magnetic field signals and in the three studied AIA channels at the five phases of its evolution.

(Figure 3). Concentrations of elements with the lower-frequency oscillations are seen in the 304 Å and 171 Å as well.

Appearance of the lower frequencies in the chromosphere above faculae are mainly attributed to the decrease in the cut-off frequency in the areas of inclined magnetic field (Michalitsanos, 1973; Bel and Leroy, 1977). However, Khomenko et al. (2008), Khomenko and Calvo Santamaria (2013), and Centeno, Collados, and Trujillo Bueno (2009) indicate that the cut-off frequency may decrease even in the areas of vertical magnetic field due to changes in the radiative relaxation time (Roberts, 1983). We believe that both effects could be working in facula atmospheres.

In the 1600 Å dominant frequency distribution of the emergence phase, a ring of higher frequency (up to 8 mHz) interspersions surround the core of the facula. We observe the same pattern in the ground-based spectra of the chromospheric lines; at a distance of $10''$ to $15''$ from the central part of the facula, strong peaks manifest in the 6 – 8 mHz range (Figure 4).

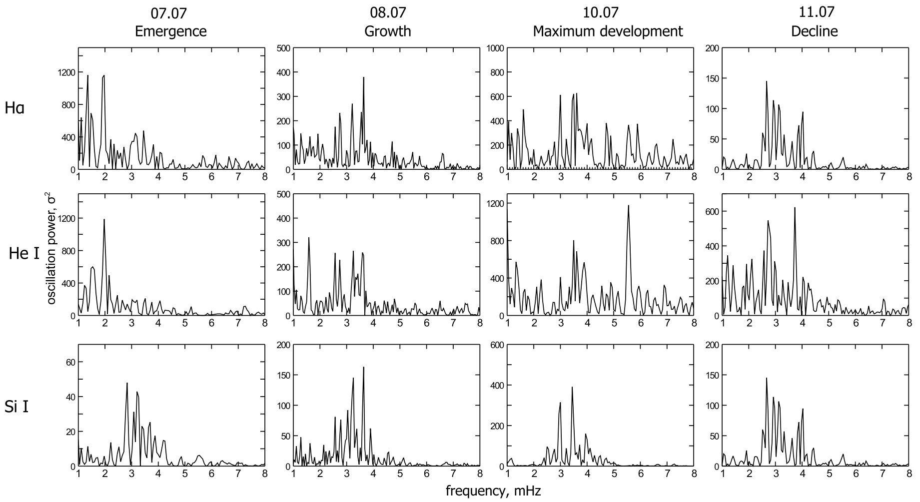

Figure 3 Line-of-sight velocity oscillations in the central part of the facula based on the ground-based data.

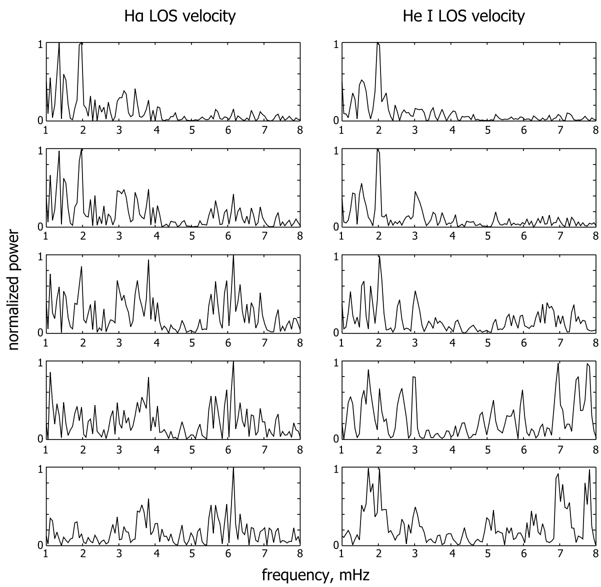

Figure 4 Line-of-sight velocity oscillations in the chromosphere in the central part of the facula at its emergence phase and at points farther away from it (from top to bottom).

One should note that in this case we see a pattern opposite to that observed in sunspots, where high frequencies reside in the center of the umbra, and the dominant frequency gradually decreases closer to the outer edges of a sunspot; the lowest frequencies are found outside of the penumbra (Kobanov, 2000; Kolobov, Chelpanov, and Kobanov, 2016). In sunspots, such a frequency distribution is attributed to the geometrical shape of the magnetic field—vertical at the center and more and more inclined to the edges—and to the cut-off frequency related to it.

In the facula, however, the shift to the higher frequencies lacks the gradual transition through the middle-range frequencies. The spectra show only two frequency domains with strong peaks: the lower frequencies around 2 mHz and higher frequencies around 7 mHz. In the areas out of the core of the facula, the high-frequency peaks grow, and the power in the central part of the spectra (3.5 – 5.5 mHz) remains quite low in all the areas of the facula (Figure 4). To answer the question whether such behavior is typical of the early stages of a solar cycle or it characterizes the birth of an active region at any stage of a cycle will require numerous observations of the oscillation dynamics in faculae throughout a whole cycle.

The magnetic field topology dramatically influences the distribution of the dominant frequencies in the photospheric and chromospheric facular levels. Kostik and Khomenko (2013) studied the oscillation period dependence on the field strength in individual parts of a facula. They concluded that the dominant oscillation period in the photosphere and low chromosphere increases in the areas with the increased strength of the underlying magnetic field. Chelpanov, Kobanov, and Kolobov (2016) found that the power of the high-frequency oscillations increased at the locations of strong magnetic field. The mismatch of these results could be explained by the fact that Kostik and Khomenko (2013) used the full-vector data, while Chelpanov, Kobanov, and Kolobov (2016) used the LOS component. The lower frequencies are usually associated with an inclined field. Besides, the observations in the two studies were carried out in different sets of spectral lines and with time series of different lengths. We should also note that the facula observed in Kostik and Khomenko (2013) was at the last stage of its evolution: it had disintegrated; its surface area had decreased, and the magnetic field strength had weakened compared to its maximum development phase three days before.

Starting from the growth phase, the main oscillation power in the LOS velocity signals in the chromosphere shifted towards the five-minute range. A similar shift is observed in the 304 Å and 171 Å channels (Figure 2), where in the dominant frequency distributions, the five-minute oscillations occupy extensive areas in the facula.

During the maximum development phase, the oscillation power in the 5 – 6 mHz range increases at the lower levels. This is especially noticeable in the LOS velocity signals of the He I line (Figure 3). In the maximum phase, the coronal 171 Å line distribution is largely occupied with the low-frequency oscillations (1 – 2 mHz) that reproduce the loop structures that had formed by this time. This suggests that in the 171 Å line we see mostly the horizontal apexes of the loops, and that low-frequency oscillations are associated with such structures. Note that the spatial distribution of the low frequencies represents a picture averaged over the time series, while the images in Figure 1 are snapshots, thus one should not expect a complete visual match.

At the last two evolution phases, the frequency distribution in the lower atmosphere levels is close to that in the elements of the undisturbed chromosphere network (Gontikakis, Peter, and Dara, 2005; Gupta et al., 2013). The loop structure in the corona disappears, and the lower-frequency areas become fragmented with higher concentration in the positive magnetic polarity area. At the decay phase, the low-frequency oscillations largely fade at the chromospheric level, and the higher frequencies of 5 – 7 mHz evolve around the areas of the magnetic field concentrations.

In the photospheric Si I line, oscillations with 3 – 4 mHz frequencies (five-minute oscillations) dominate at all the phases of the facula development.

In the spectra of the ground-based intensity signals, the main peaks are distributed in a wider frequency range. In the photosphere, the oscillation power concentrates around the 3 – 4 mHz, and in the chromosphere, the main peaks mostly seat in the 1 – 3 mHz range. In addition, the intensity spectra of the two chromospheric lines often differ significantly, as opposed to the velocity signals, where the oscillations of the He I and Hα lines behave similarly.

4.2. Oscillations in the LOS Magnetic Field Signals

The physical existence of the observed oscillations in the magnetic field signals is often doubted (Lites et al., 1998; Rüedi et al., 1999). Observations of oscillations in the magnetic field strength signals in faculae are rare. Nevertheless, results of such observations in the 1 – 7 mHz range are given in Muglach, Solanki, and Livingston (1995), Kobanov and Pulyaev (2007), and Chelpanov, Kobanov, and Kolobov (2016). Strekalova et al. (2016), Solov'ev et al. (2019), and Riehokainen et al. (2019) reported the presence of longer periods of tens and even hundred minutes. In our study, the changes in the magnetic field topology caused by the fast evolution of the active region restricted us to the 1 – 8 mHz range.

The main part of the facula area in the distribution of the magnetic field oscillations is occupied with low frequencies at the early stages of its development. The locations of the low frequencies correspond to the areas of moderate magnetic field strength within the facula. By the time of the decay, low and mid-range frequencies locate only close to the magnetic field concentration knots, and all the other areas between them are occupied with the background, which corresponds to the signals of low oscillation power. A similar spectral composition fills the areas of the quiet Sun around the facula.

Since we analyzed the line-of-sight component of the magnetic field strength, the angle at which the facula was observed changed in a quite wide range: the facula moved along 30° longitude from 50° east to the central meridian, and then to 40° west. Thus, the angle between the line of sight and the surface normal varied between 30° and 65°. This could have influenced the observed shape of the magnetic field frequency distribution.

4.3. Coronal Loop Oscillations

In the spatial distributions of the 171 Å channel dominant frequencies, the most prominent features are the structures of low frequencies that outline the coronal loops. This stands out mostly at the maximum phase of the facula evolution. The presence of low frequencies in the coronal loop spectra has been noted before (Wang et al., 2009; Aschwanden et al., 2002; Verwichte et al., 2009; Duckenfield et al., 2018). Kobanov, Kolobov, and Chelpanov (2015) and Kobanov and Chelpanov (2014) studied spatial distributions of oscillations above faculae; their analysis showed that the fan structures are clearly reproduced at the frequencies of 1 – 1.5 mHz.

Yuan et al. (2011) found frequencies between 0.2 and 0.6 mHz in the corona, as well as in the chromosphere above a sunspot, which indicates a long-period connectivity between these two layers. They suggested that these waves might be incited in the sunspot magnetic flux tubes by the g-modes. Restricted by the length of the time series, we observed shorter periods. However, we cannot exclude the same excitation mechanism, although in our case it is even more difficult to estimate the viability of this scenario, since the sub-photosphere magnetic field structure in faculae has been much less studied compared to sunspots.

Coronal loop spectra could be influenced, apart from the intrinsic intensity variations of the loop material, by the apparent changes in brightness caused by the transverse loop movements. Such movements are present in most active regions (Anfinogentov, Nakariakov, and Nisticò, 2015). Even a sub-pixel displacement of a loop changes the brightness of each separate pixel. Goddard et al. (2016) analyzed 58 kink oscillation events and found that 5-minute period oscillations were the most frequent; they found 8 – 12-minute oscillations as well.

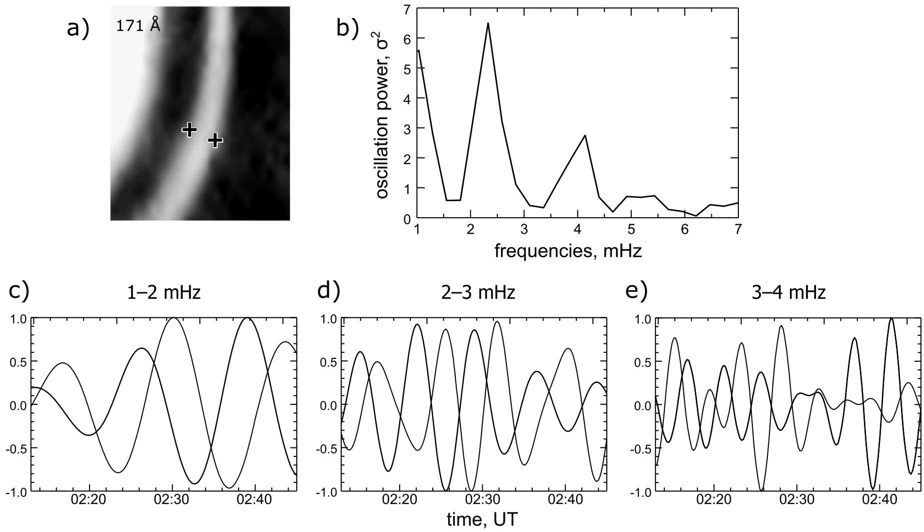

Figure 5 **a**) The 171 Å loop image with the reference points on the sides of the loop marked with crosses. **b**) Oscillation power spectrum of the 171 Å signal from a reference point. **c**–**e**) Signals from the points on the sides of the loop wavelet filtered in three frequency ranges.

Besides, the observed low frequencies could be related to the short lifetime of the loops. To exclude this factor from the analysis, we restricted the analyzed time series to the periods when the loops existed stably at one location. In the following example, we used a bright coronal loop that lit up during 32 minutes (02:13 UT to 02:45 UT) at the maximum development phase.

To distinguish the oscillations related to the loop displacements, we analyzed the signals from the points located on the sides of the loop central axis (Figure 5). In such signals, the oscillations caused by the loop displacements should be in antiphase, while the oscillations of the loop brightness should be in phase.

The power spectra are dominated by low frequencies accompanied by weaker peaks from 2 to 5 mHz. We used narrow-band wavelet filtration in order to separate different frequency oscillations. The oscillations of the 2 – 3 mHz and 3 – 4 mHz ranges have opposite phases. This implies that they result from the transverse displacements of the loop. The phase difference in the 1 – 2 mHz band differs from 180°, which indicates an input from other oscillation sources.

5. Conclusion

For the first time, we carried out a multiwavelength investigation of the oscillation dynamics in a solar facula from its birth to decay. During emergence phase of the facula evolution, low-frequency (1 – 2 mHz) oscillations concentrate in the center of the facula in the photospheric and chromospheric signals of the intensity, LOS velocity, and LOS magnetic field. This is most apparent in the spatial dominant frequency distribution in the chromospheric 1600 Å channel. In contrast, high-frequency (5 – 7 mHz) oscillations group at the edges of the emerging active region. We suggest that the occurrence of low frequencies could be considered as a precursor for the coronal loop structure development in a growing facula.

Later, at the more developed phases of the facula evolution, 5-minute oscillations dominate the photospheric and chromospheric levels.

The spatial distribution of the dominant frequencies in the corona (171 Å) is closely related to the coronal loop dynamics in the facula. During the maximum development of the coronal loop system these distributions are dominated by low frequencies. At these phases, the low-frequency distribution closely resembles the coronal loops. In the transition region, the low-frequency areas look more patchy: they concentrate around the footpoints of the coronal loops.

During the last phase of the evolution, the low frequencies in the chromosphere almost disappear, and high frequencies appear between the magnetic field concentration areas.

Our results confirm that the sources of low-frequency oscillations in coronal loops are located in the lower layers of the solar atmosphere.

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Disclosure of Potential Conflicts of Interest The authors declare that they have no conflicts of interest.

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