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The Influence of Eruptive Processes in Active Regions on Oscillations of the Magnetic Field Parameters in Sunspot Umbrae

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Abstract—For three events, the effect of eruptive processes in active regions on the characteristic of magnetic field oscillations in sunspot umbrae has been studied. Eruptive processes include solar flares and coronal mass ejections. The power spectra of oscillations of each analyzed parameter of the magnetic field in each sunspot of the studied active region (AR) are constructed, and, in general, for the entire AR. It was found that at certain stages the eruptive process has a noticeable effect on the power spectrum of oscillations of the magnetic field parameters in sunspot umbrae. It is shown that the power of the eruptive process, which is characterized by the X-ray flare, affects the features of the magnetic field oscillations in sunspot umbrae. The results obtained for ARs with eruptive processes are compared with the results for ARs without eruptive processes. The analysis of the influence of eruptive processes on the magnetic field oscillations in sunspot umbrae was carried out for the AR as a whole, and for some sunspots with the strongest response. For different events, the oscillation power spectrum was compared with the intensity maximum A_{max}, frequency f_{m}, which accounts for the maximum A_{max}, and the frequency power spectrum width df.

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1. INTRODUCTION

It is known that solar flares can affect the characteristics of sunspots (Wang et al., 2005; Liu et al., 2005; Wang, Zhao, and Zhou, 2009; Li et al., 2009; Ravindra et al., 2011). The cited papers show that as a result of a solar flare, the shape, structure, and brightness of sunspot penumbra change significantly. It has also been established that a solar flare can lead to a sudden shift of the sunspot (Xu et al., 2017) and to sunspot rotation (Liu et al., 2016). The effects of solar flares on the magnetic field in sunspot umbra (Petrie, 2013) and in sunspot penumbra (Griñón-Marín et al., 2020) have been found. The features of the strong influence of powerful solar flares on the properties of the magnetic field in the sunspot umbrae were studied by the authors (Zagainova and Fainshtein, 2017, 2022; Zagainova et al., 2022).

It follows from our analysis that the changes in the characteristics of the magnetic field in the sunspot umbra with time usually occur nonmonotonically and often have an oscillatory character. In this case, a spectrum with periods from several minutes to several hours (long-period oscillations) is distinguished, see (Griñón-Marín et al., 2020) and Table 1 in it with citations of such papers, as well as (Efremov et al., 2016).

In our papers, apparently for the first time, the study of the influence of eruptive processes on the characteristic of magnetic field oscillations in the sunspot umbra have been performed (Zagainova and Fainshtein, 2021; Zagainova and Fainshtein, 2022; Zagainova et al., 2022). This paper continues our research of this type. Below are the results of the first stage of our research, where, using the example of three events with powerful solar flares and fast CMEs, we studied the features of the effects of eruptive processes on the properties of the magnetic field in sunspot umbra for each active region selected for analysis as a whole, when such an effect is averaged over all sunspots in the AR. The results we obtained are compared with the results for active regions without eruptive processes.

2. THE DATA AND METHODS OF THEIR ANALYSIS

The magnetic properties of sunspot umbrae were found using vector measurements of the magnetic field with the HMI instrument (Schou et al., 2012) aboard the Solar Dynamic Observatory (SDO; Pesnell et al., 2012). The spatial resolution of the CCD-matrix of the HMI magnetograph is 0.5″ and the temporal resolution during field vector measurements was

12 min. To solve the problem of π-uncertainty in finding the transverse component of the magnetic field, which is necessary when finding the components of the magnetic field, we used the relatively accurate and fast method proposed in (Rudenko and Anfinogentov, 2014).

In this work, the oscillation power spectra are analyzed for the following characteristics of the magnetic field in the sunspot umbra: (1) the minimum angle α_{min} between the magnetic field vector **B** and positive normal **n** to the surface of the Sun; (2) the average within the sunspot umbra angle $\langle\alpha\rangle$; (3) the maximum B_{max} and (4) average value $\langle B\rangle$ of the magnetic induction module in sunspot umbra. We note that if the magnetic field at the measurement point had a negative polarity (i.e., the field at this point is directed towards the Sun), the angle α was determined from the ratio $\alpha = 180° - \alpha$mes, where αmes is the measured angle between **B** and the normal to the surface of the Sun.

The practical angle α at some point of sunspot umbra was found from the relation $\cos(\alpha) = |Br|/B$, where *Br* is the radial component of the field and *B* is the modulus of magnetic induction at this point. *Br* was determined using field characteristics that are found from vector field measurements by the HMI tool: the magnetic induction modulus *B*, the angle of inclination of the magnetic field vector to the line of sight δ and the azimuth ψ, i.e., the angle measured in the sky plane counterclockwise from the columns of the CCD matrix to the transverse field component obtained by projecting the vector **B** to the plane of the sky. Finding *Br* was described in detail in our paper (Zagainova et al., 2022).

An analysis of the power spectra of fluctuations in the magnetic field parameters in sunspot umbrae was carried out on AR NOAA 11261 of August 4, 2011, on AR NOAA 11429 of March 7, 2012, and on AR NOAA 12673 of September 6, 2017. According to the Geostationary Operational Environmental Satellite (GOES) these solar flares were M9.3, X5.4, and X9.3, and the linear projection velocities of the coronal mass ejections associated with them were 1315 km/s, 2684 km/s, and 1571 km/s, respectively. For comparison, we analyzed the power spectra for a period of 12 hours and for each half of this interval in NOAA 12686 on October 28, 2017 in the absence of solar flares and coronal mass ejections in this time interval.

The power spectra of oscillations of four characteristics of the magnetic field in sunspot umbra were plotted for each AR (i.e., the oscillation power spectra were averaged over all ARs sunspots. In what follows, for such power spectra, in some cases, for brevity, we will use the phrase “ARs power spectrum”). The oscillation power spectrum was found for a time interval of 12 hours; the middle of this was at the beginning of solar flare.

3. RESULTS

3.1. The Strong Influence of Eruptive Processes on the Behavior of Various Characteristics of the Magnetic Field in Some Sunspot Umbrae

It was noted above that, according to our results (Zagainova et al., 2021; Zagainova et al., 2022), eruptive processes can have a strong effect on the properties of the magnetic field in some sunspot umbrae. In this case, the characteristics of the magnetic field in different sunspots change in different ways: the more sunspots occur in the AR, the more options for variations of the field parameters with time exist. In Fig. 1 examples are given of the strong influence of eruptivee processes on the characteristics of the magnetic field in some sunspot umbrae, α_{min}, $\langle\alpha\rangle$, B_{max}, and $\langle B\rangle$. The response to eruptive processes manifests itself in a noticeable change in the behavior of the magnetic field characteristics with time after the onset of a solar flare. For example, for the event of September 6, 2017, α_{min} in the time interval Δt = 30 min before and after the outbreak changed by more than 15°, and B_{max} changed by more than 1000 G (Figs. 1a, 1b). For the event of March 7, 2012, $\Delta\alpha_{min}$ in the time interval Δt = 30 min before and after the start of the outbreak was ~ 35° and ΔB_{max} ~ 1000 gauss (Figs. 1c, 1d). Let us also consider variations in the magnetic field parameters in AR NOAA 12686 of October 28, 2017, where, in the absence of solar flares and CMEs, pores and two sunspots were observed during this time period (see Fig. 2) (one of which had a degenerate penumbra, Figs. 2a, 2b). The B_{max} values changed monotonously. For α_{min} one can note fluctuations relative to the average for the entire observation period of 12 hours at short time intervals of Δt < 60 min.

3.2. Comparison of the Power Spectra of Oscillations of Magnetic Field Parameters in Sunspot Umbrae Obtained for Each AR selected for analysis as a Whole

In this work, we also compared the power spectra of oscillations of the analyzed characteristics of the magnetic field in sunspot umbrae, obtained as a whole for each considered AR, i.e., power spectra averaged over all sunspots of each AR. This made it possible to estimate how large the contribution to the power spectrum of ARs sunspots is, in which the influence of eruptive processes on the feature of fluctuations of the analyzed parameters most significantly and determine whether the contribution of such sunspots to the “AR power spectrum” is decisive.

Let us consider in more detail the comparison of the power spectra of oscillations of the magnetic field parameter α_{min} for three selected ARs with eruptive processes and without them (Fig. 3). Based on the given dependencies in Fig. 3, several conclusions can be drawn. It can be seen that the power spectra of oscillations α_{min} in the selected sunspot groups differ

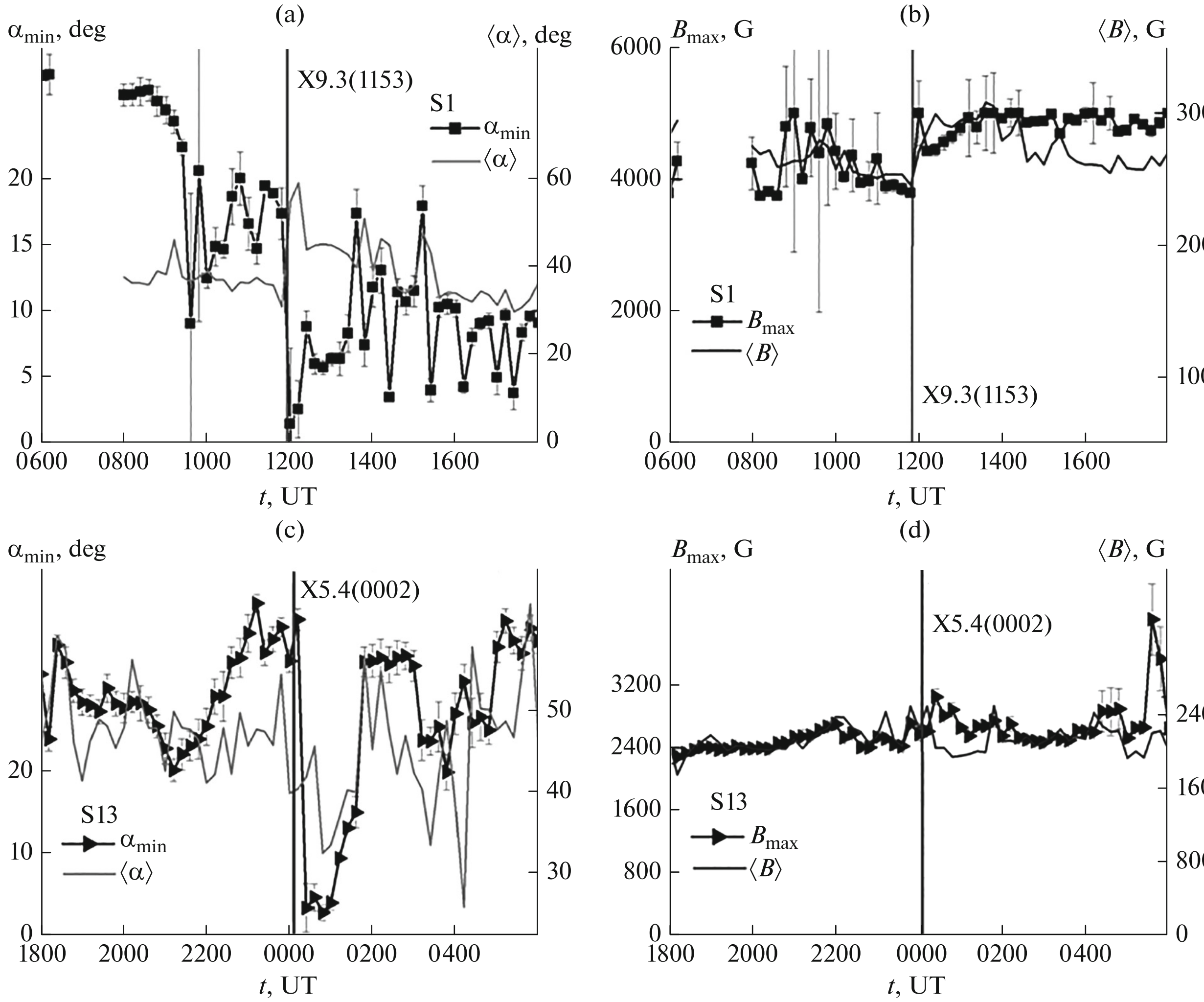

Fig. 1. Examples of the strong influence of eruptive processes on the characteristics of the magnetic field in some sunspot umbrae in AR NOAA 12673 on September 6, 2017 (a, b) and AR NOAA 11429 on March 7, 2012 (c, d), where (a) and (c) are the dependences $\alpha_{min}(t)$ (thick line with markers) and $\langle\alpha\rangle(t)$ (thin solid line), (b) and (d) are the dependencies $B_{max}(t)$ (thick line with markers) and $\langle B\rangle(t)$ (thin solid line).

significantly. For the power spectrum α_{min} in the AR without eruptive processes is characterized by the absence of some spectral lines on the oscillation power spectra (i.e., the power spectrum is not continuous) compared with the power spectra of oscillations for events with eruptive processes, i.e., there are no fluctuations on a large sample of frequencies from the entire spectrum of selected frequencies. The power spectra of oscillations α_{min} in the AR with eruptive processes have intensity maxima A_{max} at different low frequencies, and, further, the intensity in all cases decreases nonmonotonically with increasing frequency f. On each graph in Fig. 3 for ARs with eruptive processes we determined the "width" of the power spectrum df, i.e. the frequency of the spectral line that is most noticeable in intensity from the origin. Definition examples of df are shown in Figs. 3 and 4. For ARs without eruptive processes it is not possible to define df due to lack of continuity in the power spectrum α_{min}. Similarly, power spectra of oscillations of the maximum magnetic induction B_{max} were constructed for the studied ARs (Fig. 4).

Analysis of the power spectra for all considered parameters of the magnetic field sunspot umbrae made it possible to draw several more important conclusions. It turned out that the characteristics of the power spectra depend on the power eruptive process, which we characterized by the maximum radiation power from the flare region in the soft X-ray range I_{SXR}, or, equivalently, the X-ray score of a solar flare (Fig. 7). These characteristics include: a) the maximum intensity of the power spectrum A_{max}; b) the "width" of the power spectrum df; c) the frequency f_m, at which the maximum intensity A_{max} is observed in the AR power spectrum. The feature of the depen-

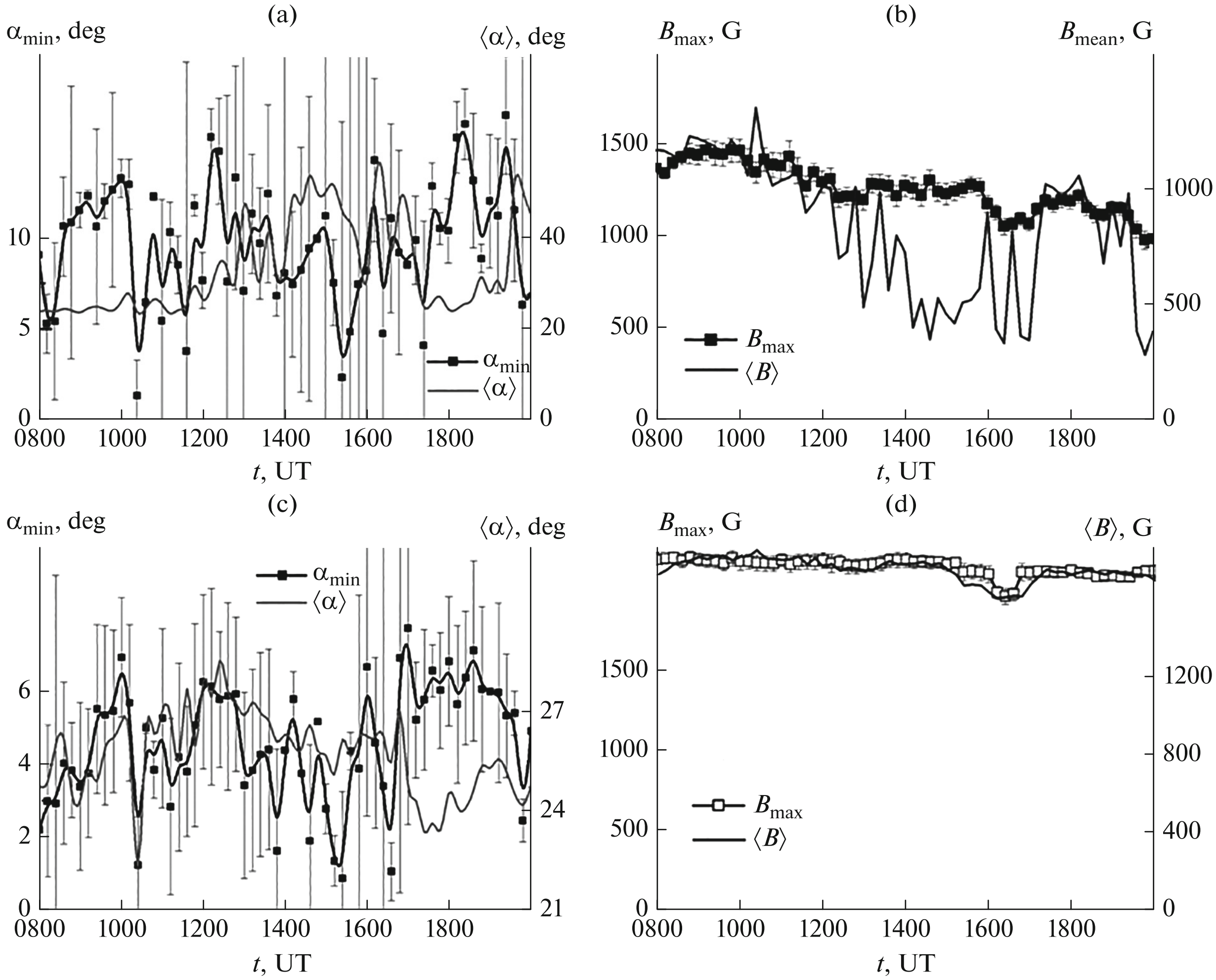

Fig. 2. An example of evolutionary changes in the magnetic field parameters in two sunspot umbrae in NOAA 12686 dated October 28, 2017, in which no solar flares and CMEs were observed during the period under consideration.

dence of the indicated characteristics of the power spectrum with I_{SXR} differs for different field parameters in sunspot umbrae.

From Fig. 7 it follows that for the maximum intensity of the oscillation power spectrum A_{max} such characteristics of the magnetic field in sunspot umbrae as α_{min}, $\langle\alpha\rangle$, and B_{max} vary monotonically with an increase in the maximum power of soft X-rays I_{SXR}. For the $\langle B\rangle$ dependence $A_{max-\langle B\rangle}$ (I_{SXR}) turned out to be nonmonotonic. Let us pay attention to the fact that for α_{min} and $\langle\alpha\rangle$ dependencies $A_{max-\alpha min}$ (I_{SXR}) and $A_{max-\langle\alpha\rangle}$ (I_{SXR}) turned out to be decreasing (with an increase in I_{SXR} magnitude A_{max} decreases), and for the B_{max} dependence $A_{max-B max}(I_{SXR})$ is increasing.

The dependencies $f_m(I_{SXR})$ and $df(I_{SXR})$ for the power spectra of the oscillations of α_{min} and B_{max} are increasing monotonicaly with an increase in the maximum intensity of soft X-ray radiation I_{SXR} out of the solar flare initiation area (i.e. with an increasing solar flare power) f_m and df increase. Let us note the important result that follows from Figs. 4–6 and is reflected in Fig. 7: f_m values for the power spectra of different characteristics of the magneticfield in the sunspot umbrae differ, just as they differ for the same parameters of the magnetic field in sunspots in different events.

From Figs. 4–6 you can see that the maximum intensity of vibrations A_{max} in the power spectrum of the ARs for different parameters of the magnetic field in the sunspot umbrae appears at different frequencies f_m. It turned out that for the parameters $\langle\alpha\rangle$ and B_{max} the frequency f_m, increases monotonically with increasing I_{SXR} (Fig. 7(g, h)). For α_{min} and $\langle B\rangle$ the relationship between f_m and I_{SXR} turned out to be nonmonotonic and rather chaotic. Therefore, we do not present it.

Analysis of the power spectra in Figs. 4–6 led to the conclusion that there are dependencies between $A_{max-B max}$ and $A_{max-\alpha min}$ (Fig. 8(a)), between $A_{max-\langle\alpha\rangle}$

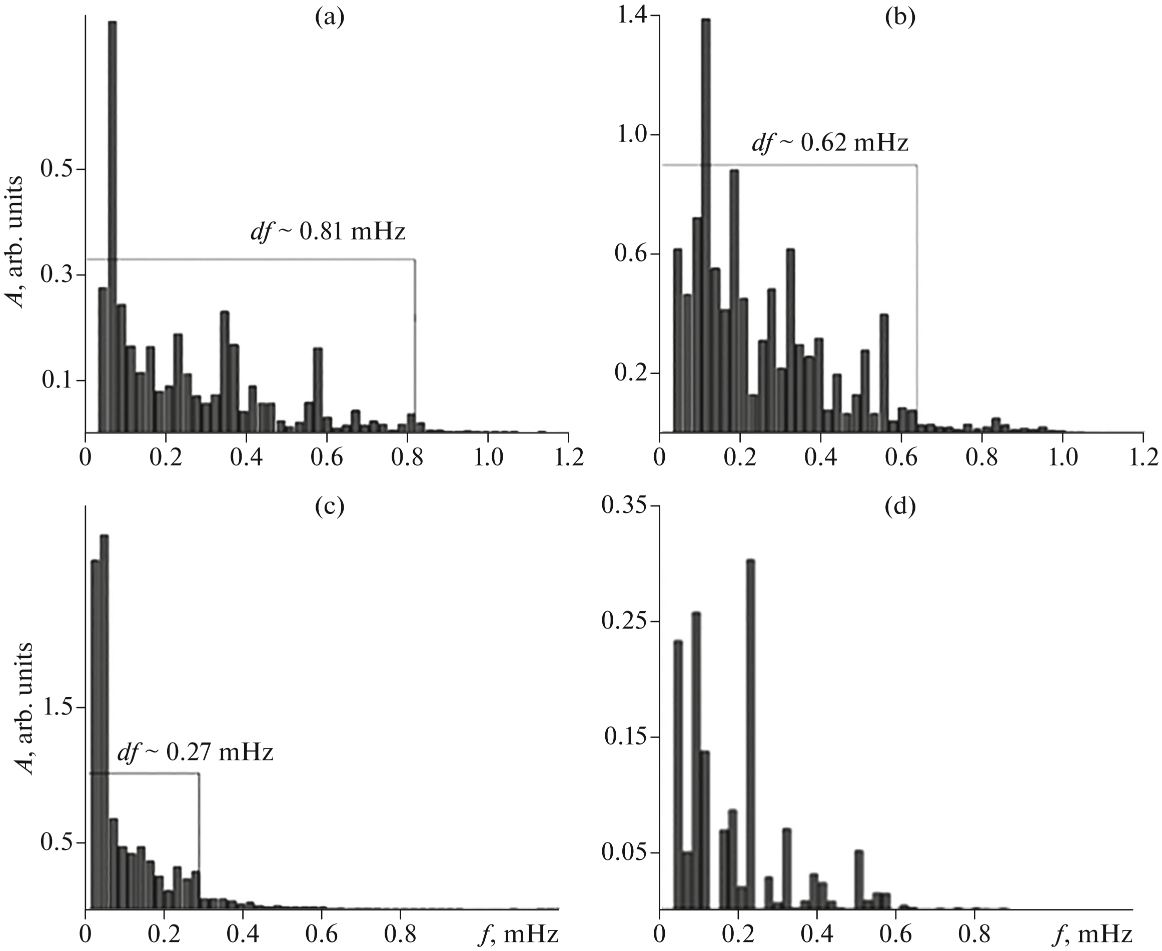

Fig. 3. The AR power spectra for α_{min}, where (a) is for the event of September 6, 2017, (b) is for the event of March 7, 2012, (c) is for the event of August 4, 2011, (d) is for the event of October 28, 2017.

and $A_{max-\langle B\rangle}$ (Fig. 8(b)), as well as between A_{max} and f_m (Figs. 8c–8f) for all considered parameters of the field in sunspot umbra, as well as the width of the power spectrum *df* with the amplitude of the oscillation power spectrum α_{min} and B_{max}. Let us pay attention to the fact that the relationship between the oscillation amplitudes $A_{max-Bmax}$ and $A_{max-\alpha min}$ (Fig. 8a) and between $A_{max-\langle\alpha\rangle}$ and $A_{max-\langle B\rangle}$ (Fig. 8(b) is decreasing: as the parameter on the horizontal axis increases, the value of the parameter on the vertical axis decreases. We note that a similar relationship was obtained in the work of the authors of this paper (Zagainova et al., 2017) between B_{max} and α_{min} in the umbra of the leading and following magnetically coupled sunspots: on average over the sample of analyzed events, with increasing α_{min} B_{max} decreases. A similar correlation was obtained between $\langle B\rangle$ and $\langle\alpha\rangle$. These dependences turned out to be most distinct for leading sunspots. We assume that the same nature of the connection between B_{max} and α_{min} on the one hand, and $A_{max-Bmax}$ with $A_{max-\alpha min}$ on the other hand, and similarly, the similarity of the relationship $\langle B\rangle$ with $\langle\alpha\rangle$ and links $A_{max-\langle\alpha\rangle}$ with $A_{max-\langle B\rangle}$ are not random, but are physically determined.

The maximum intensity locations for the event without eruptive processes on the charts in Fig. 7 and Fig. 8 are not given, because they are "knocked out" from dependencies for events with eruptive processes. Thus, for example, for the parameter α_{min} the maximum value of A_{max} was ~0.23 at f_m = 0.23116 mHz, for parameter $\langle\alpha\rangle - A_{max}$ = ~0.12 at f_m = 0.11558 mHz, for parameter $B_{max} - A_{max}$ = ~286 at f_m = 0.092246 mHz, for the parameter $\langle B\rangle$ we have A_{max} = ~870 at f_m = 0.06935 mHz.

Comparing Fig. 3, Fig. 7b, and Fig. 8a for parameter $\langle\alpha\rangle$, we can conclude that the more powerful the eruptive process is, the more clearly the periods of oscillations of the parameter $\langle\alpha\rangle$, amounting to several hours. As the solar flare power decreases, the duration of the "dominant" period decreases (i.e., the period corresponding to the frequency f_m) on the oscillation power spectrum $\langle\alpha\rangle$, i.e., AR power spectrum for parameter $\langle\alpha\rangle$ with an increase in the solar flare

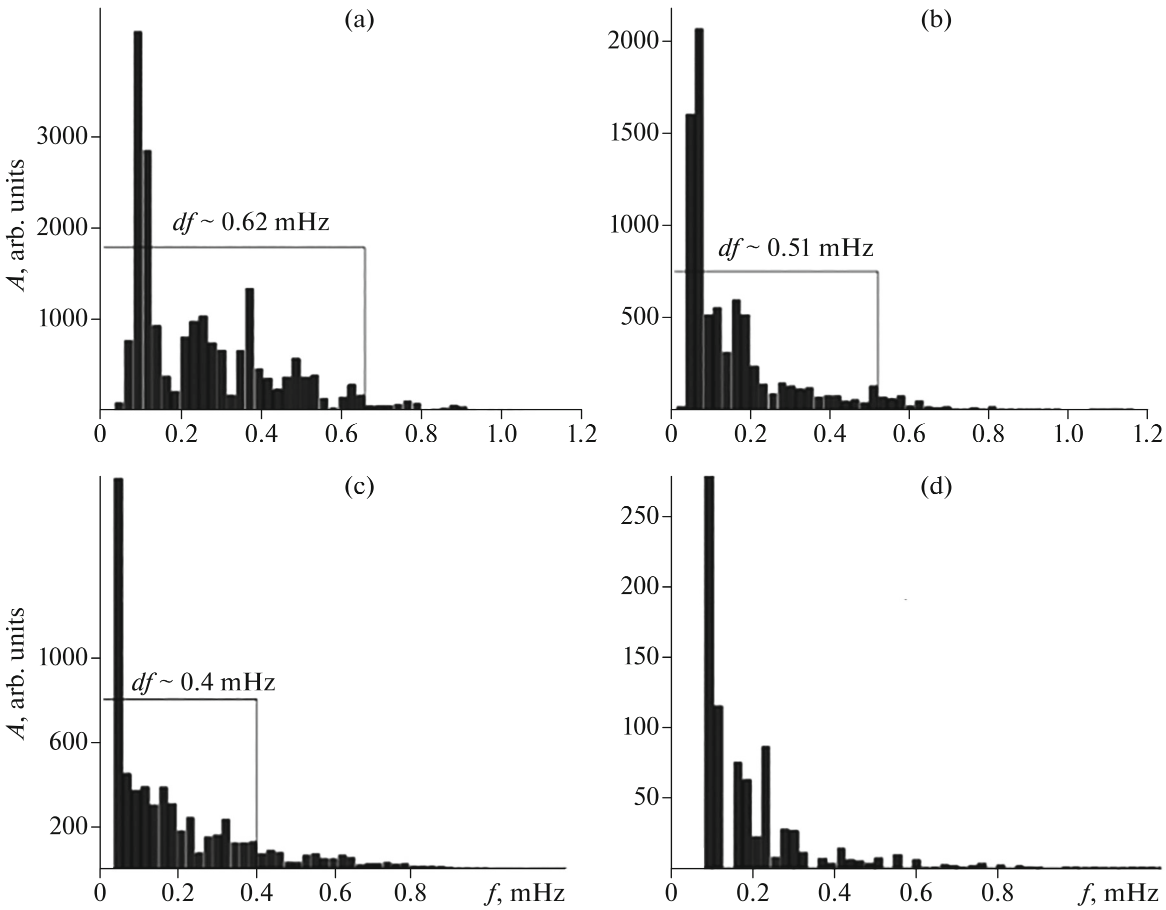

Fig. 4. The AR power spectra for B_{max}. Note: see symbols in Fig. 3.

power, it "saturates" with high (in frequency) harmonics. In this case, the maximum intensity of oscillations A_{max} takes the largest values for the event with the smallest power eruptive process, on August 4, 2011 with a solar flare of X-ray M9.3. Such a pattern in the behavior of A_{max}, in this case, allows us to speak about a more reliable identification of "dominant" periods in the AR power spectrum for events with less powerful solar flares. Accordingly, the higher the solar flare power is, the more difficult it is to distinguish on the dependencies $\langle\alpha\rangle(t)$ of oscillatory process with a dominant frequency.

Despite the outward similarity of the dependences of the maximum intensity of the AR power spectrum on the X-ray flare index for the parameters α_{min} and $\langle\alpha\rangle$ (compare Figs. 8a and 8b), for the parameter α_{min} significant difference should be noted. It can be traced when comparing the dependencies in Fig. 4b and Fig. 6b: on the latter, we can clearly distinguish the maximum of the dependence $f_m(A_{max})$ for the event of March 7, 2012, although the dependences of the maximum intensity of oscillations $A_{max\_\alpha min}$ and $A_{max\_\langle\alpha\rangle}$ from the solar flare power are close. This also makes it possible to draw a conclusion about a more reliable identification of "dominant" periods in the AR power spectrum for events with less powerful flares. The "dominant" frequency f_m can be determined not only by the X-ray intensity of the solar flare, but also by the power of the initiated CME. We recall that for the event of March 7, 2012 the linear mass ejection velocity was 2684 km/s, which is higher than for other events with eruptive processes.

For the dependence of the maximum intensity of vibrations B_{max} from time to time, the relation is valid: the lower the X-ray solar flare power is, the lower the maximum intensity of the AR power spectrum is. Comparing Fig. 2c, Fig. 4c, and Fig. 6c it turns out that for the parameter B_{max} the AR power spectrum with an increase in the solar flare power is "saturated" with high-frequency harmonics. For the event of September 6, 2017, the highest intensity A_{max} on the AR power spectrum for parameter B_{max} has fluctuations with a period of ~3 hours, while for the event of August 4, 2011, it was ~6 hours.

For the parameter $\langle B\rangle$, the relationship between the solar flare power and the intensity maximum A_{max} is absent.

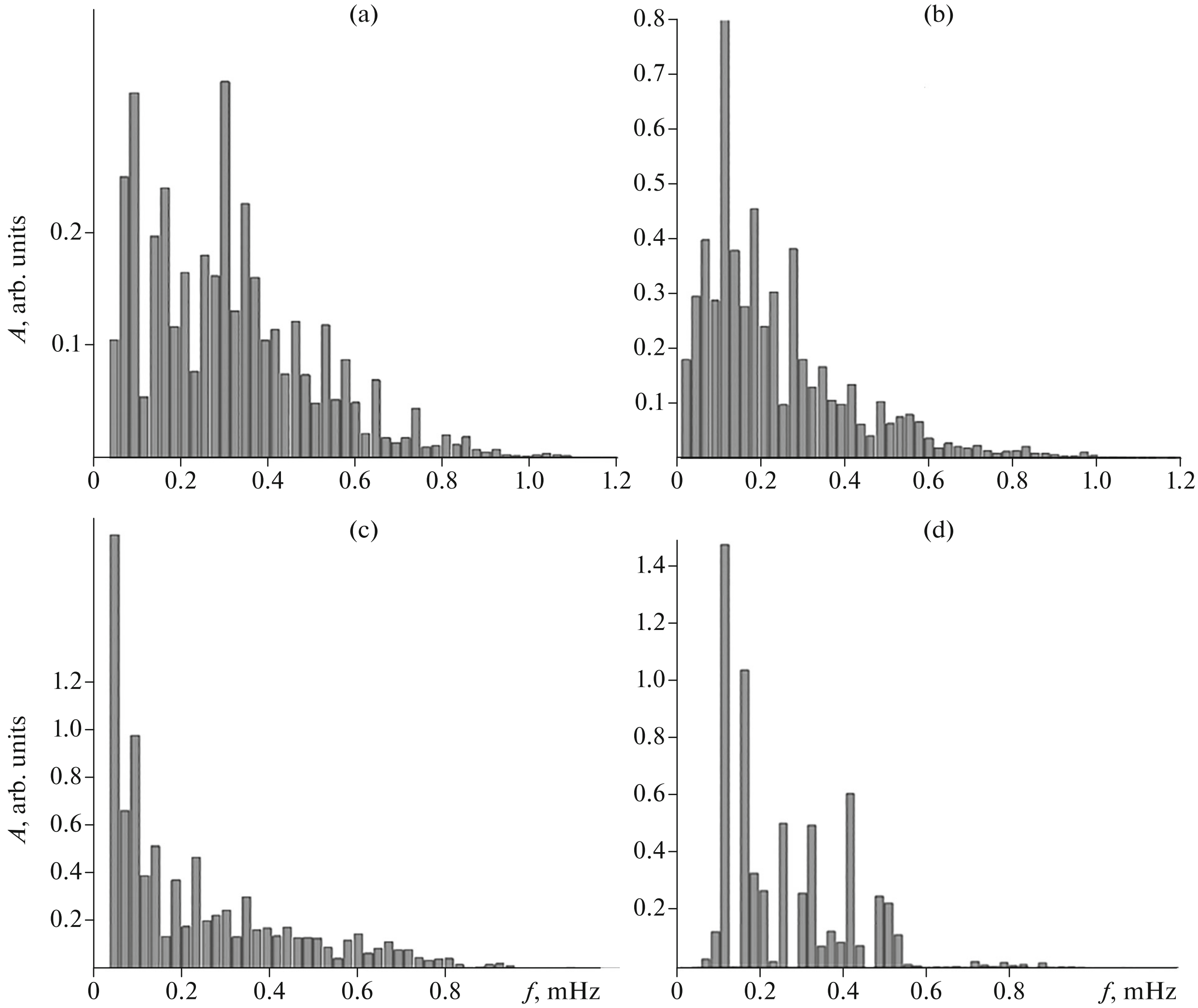

Fig. 5. The AR power spectra for $\langle\alpha\rangle$. Note: see symbols in Fig. 3.

4. CONCLUSIONS

Based on the examples of three events with powerful flares and fast coronal mass ejections in AR with sunspot groups, the effects of these eruptive processes on the character of oscillations (oscillation power spectrum) of several magnetic field parameters in sunspot umbrae has been studied. These magnetic field features include: (1) minimum angle α_{min} between the magnetic field vector **B** and positive normal **n** to Sun surface; (2) average within sunspot umbra angle $\langle\alpha\rangle$; (3) maximum B_{max} and (4) the average value $\langle B\rangle$ of the magnetic induction module in sunspot umbra. For comparison, we analyzed the AR power spectrum oscillations without eruptive processes. We have introduced the concept of the "AR power spectrum," which has the meaning of the AR power spectra averaged over all sunspots for oscillations of each investigated magnetic field parameter in sunspot umbrae. The main conclusions concerning the effect of eruptive processes on the power spectrum of oscillations of the considered magnetic field parameters in sunspot umbrae can be formulated as follows:

(1) The AR power spectra oscillations for each considered magnetic field parameter in sunspot umbrae in active regions selected for our analysis differ significantly.

(2) The characteristics of the power spectra depend on the intensity eruptive process, which we characterized by the X-ray solar flare power. These characteristics include:

— the conditional "width" of the power spectrum *df*, defined as the frequency of the most distant from the origin of the spectral line noticeable in intensity;

— the maximum intensity of the power spectrum A_{max};

— the frequency f_m, at which the maximum intensity A_{max} of the AR power spectrum occurs.

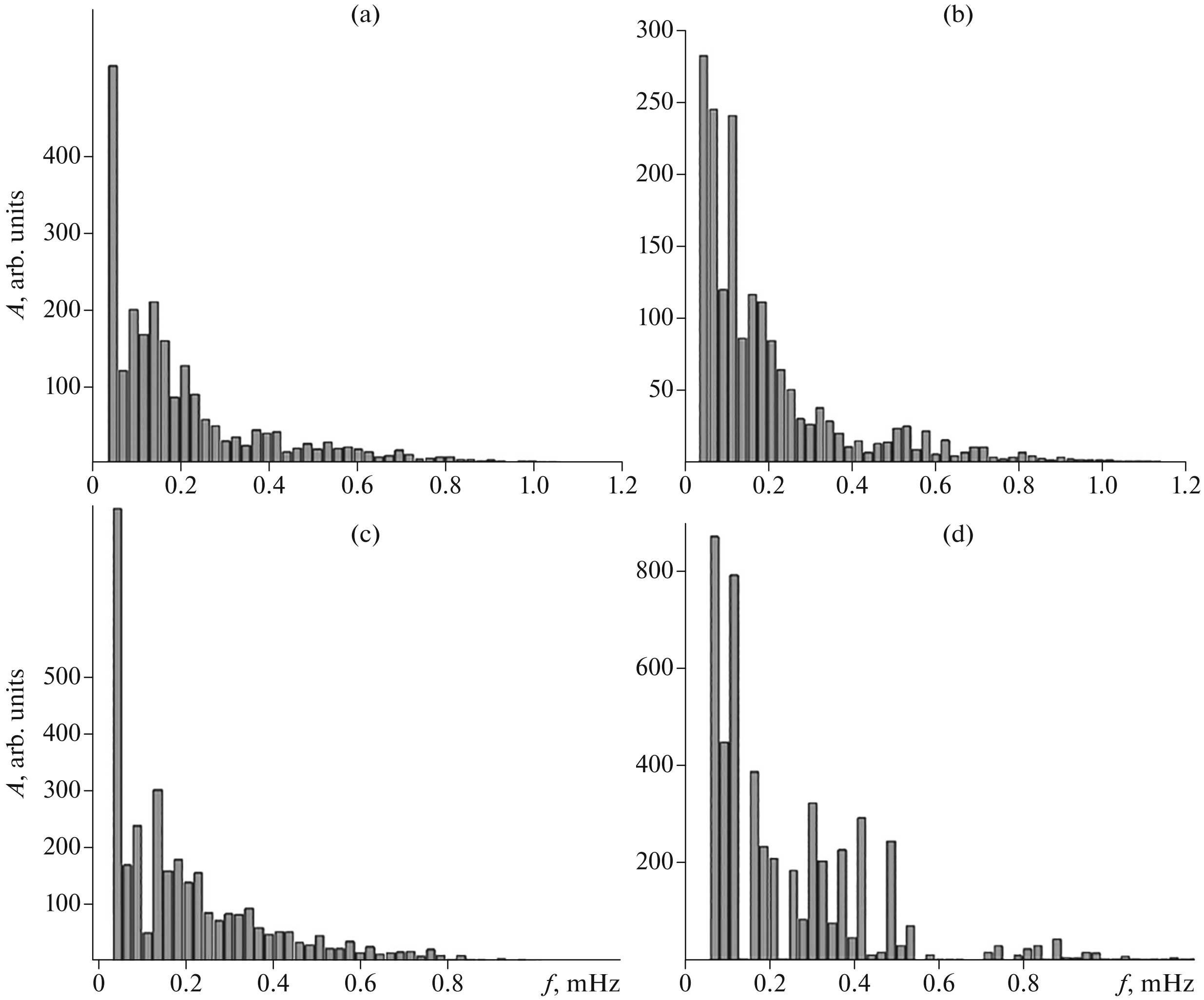

Fig. 6. AR power spectra for $\langle B \rangle$. Note: see symbols in Fig. 3.

In this case, the feature of the relationship between these characteristics of the power spectrum and the X-ray solar flare power differs for different magnetic field parameters in sunspot umbrae has been studied. The main trends are as follows: for dependencies $A_{max\_\ \alpha min}(I_{SXR})$ and $A_{max\_\langle\alpha\rangle}(I_{SXR})$, where I_{SXR} is the intensity of soft X-ray radiation (or, equivalently, the flare X-ray power), the maximum of the oscillation power spectrum decreases with increasing solar flare power. At the same time, the growth of I_{SXR} accompanied by an increase in $A_{max\_B max}(I_{SXR})$ and is nonmonotonically related to $A_{max\_\langle B\rangle}(I_{SXR})$. The "width" of the power spectrum df for parameters α_{min} and B_{max} grows with increasing I_{SXR}. In this case, the frequency f_m is determined by the solar flare power, then only for parameters $\langle\alpha\rangle$ and B_{max}.

A relationship has been established between various characteristics of the power spectrum: (1) between $A_{max\_\ \alpha min}$ and $A_{max\_B max}$, between $A_{max\_\langle\alpha\rangle}$ and $A_{max\_\langle B\rangle}$. Both dependences are characterized by a feedback between the parameters: with increasing $A_{max\_B max}$ and $A_{max\_\langle B\rangle}$ power spectrum amplitude $A_{max\_\ \alpha min}$ and $A_{max\_\langle\alpha\rangle}$ decrease. 2) The frequency f_m decreases with increasing $A_{max\_\langle\alpha\rangle}$ and increases with $A_{max\_B max}$. As $A_{max\_\langle B\rangle}$ grows the frequency f_m practically does not change. Finally, with the growth of $A_{max\_\ \alpha min}$ the frequency f_m changes nonmonotonically.

We studied the power spectra of oscillations of the analyzed characteristics of the magnetic field in the sunspot umbrae in the ARs, in which no solar flares were recorded for 12 hours with sufficiently fast mass ejections. It turned out that in this case the characteristics of the magnetic field are also subject to relatively strong oscillations, the maximum intensity of which can exceed the maximum intensity in the oscillation power spectrum for the event with the weakest of the considered solar flares on August 4, 2011.

It should also be noted that for power spectra αmin and Bmax, as the flash point increases, higher har-

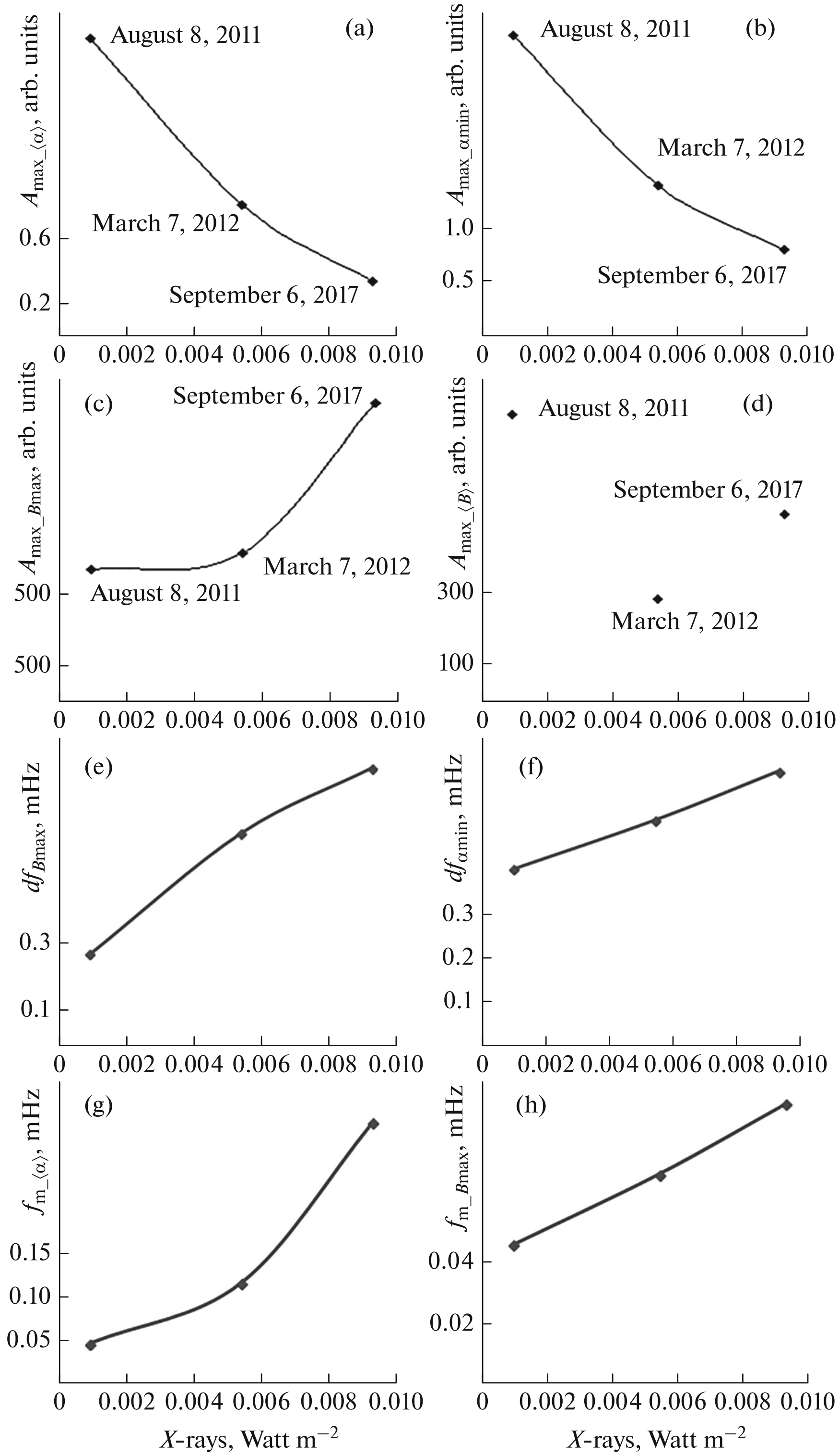

Fig. 7. The dependence on the intensity of soft X-ray emission from solar flare initiation area I_{SXR}: maximum power spectrum intensity A_{max} (a–d), power spectrum width df (e, f), frequencies of the maximum intensity of the power spectrum f_m (g, h). For the df and f_m dependencies the most reliable are shown.

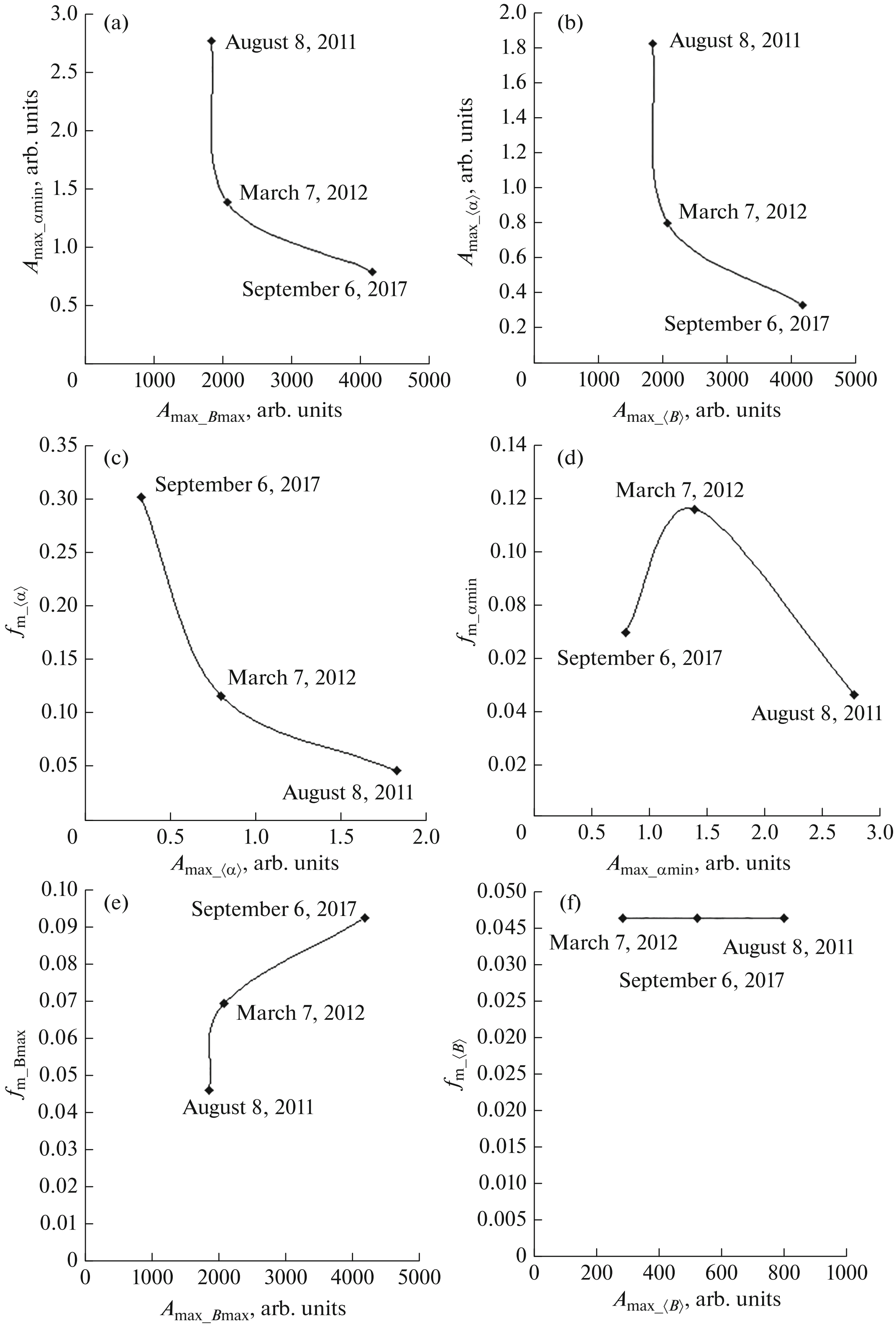

Fig. 8. The relationship between $A_{max-B\max}$ and $A_{max-\alpha\min}$ (a) and between $A_{max-\langle\alpha\rangle}$ and $A_{max-\langle B\rangle}$ (b), (c)–(f), the connection between f_m with A_{max} for the power spectra of oscillations of all considered magnetic field parameters in sunspot umbrae.

monics appear in the oscillation power spectrum and additional periods of oscillation appear.

We note that the results are preliminary and will be refined as the number of events considered increases. Using the example of only three events with eruptive processes, we tried to determine whether eruptive processes can affect the properties of the oscillations of the magnetic field parameters in sunspot umbrae. Such an effect has been found.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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