The Origin and Characteristics of Solar Acoustic Oscillations

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Abstract

It is generally accepted that solar acoustic (p) modes are excited by near-surface turbulent motions, in particular by downdrafts and interacting vortices in intergranular lanes. Recent analysis of Solar Dynamics Observatory data by Zhao et al. (2015) revealed fast-moving waves around sunspots, which are consistent with magnetoacoustic waves excited approximately 5 Mm beneath the sunspot. We analyzed 3D radiative MHD simulations of solar magnetoconvection with a self-organized pore-like magnetic structure, and identified more than 600 individual acoustic events both inside and outside this structure. By performing a case-by-case study, we found that acoustic sources surrounding the magnetic structure are associated with downdrafts. Their depth correlates with downdraft speed and magnetic field strength. The sources often can be transported into deeper layers by downdrafts. The wave front shape, in the case of a strong or inclined downdraft, can be stretched along the downdraft. Inside the magnetic structure, excitation of acoustic waves is driven by converging flows. Frequently, strong converging plasma streams hit the structure boundaries, causing compressions in its interior that excite acoustic waves. Analysis of the depth distribution of acoustic events shows the strongest concentration at 0.2–1 Mm beneath the surface for the outside sources and mostly below 1 Mm inside the magnetic region, that is, deeper than their counterparts outside the magnetic region.

Key words: magnetohydrodynamics (MHD) – methods: numerical – Sun: interior – Sun: magnetic fields – Sun: oscillations – waves

1. Introduction

The turbulent nature of solar convection leads to the excitation of numerous acoustic waves observed in the photosphere with a characteristic frequency of 3 mHz (known as 5 minute oscillations) in the quiet-Sun regions and 5 mHz (or 3 minute oscillations) in sunspot umbrae, with transitions to 5 minute oscillations in sunspot penumbralae (Beckers & Schultz 1972). The observed signals represent superpositions from individual sources in the turbulent magnetoconvection. The origin and characteristics of these oscillations have been investigated mostly in terms of resonant modes, both observationally (e.g., Renda et al. 1999; Schmidt et al. 1999; Komn et al. 2000) and theoretically (e.g., Stein 1967; Ulrich 1970; Goldreich & Kumar 1990; Goldreich et al. 1994; Musielak et al. 1994; Georgobiani et al. 2000). Observations of individual acoustic events (Goode et al. 1992; Strous et al. 2000; Hoekzema et al. 2002; Bello González et al. 2010) in the intergranular lanes suggest that the excitation mechanism can be associated with strong local cooling and downflows (Rast 1995, 1999). Different authors have estimated the acoustic source depth. For instance, it was suggested that the sources can be located at a depth of 75 ± 50 km from analyzing the power spectra of the velocity and intensity oscillation modes from SoHO/MDI (Nigam & Kosovichev 1999); 200 km or less from comparing 1D piston-like simulations with phase shifts observed in an absorption line profile (Goode et al. 1992); 300 km or deeper from analysis of observed and modeled oscillation power spectra (Kumar & Lu 1991); 120–350 km and 700–1050 km for dipole and quadrupole acoustic sources from modeling the asymmetry of modal lines in the power spectrum (Kumar & Basu 1999).

Our previous 3D radiative hydrodynamic simulations of quiet-Sun regions demonstrated that acoustic events could be associated with the ubiquitous interaction of vortices formed primarily in the intergranular lanes (Kitiashvili et al. 2011, 2012). Such vortices are found in high-resolution observations (e.g., Bonnet et al. 2008, 2010). In these hydrodynamic simulations the acoustic sources also were found in the subphotospheric layers at a depth of 100–300 km. Another mechanism of wave excitation by small granule collapse was suggested by Skartlien et al. (2000), who estimated the source location in the height range above a cooling layer 500 km thick.

The detection of fast-traveling waves in the frequency range of 2.5–4.0 mHz around sunspots with an estimated source location approximately 5 Mm beneath a sunspot (Zhao et al. 2015) recently was supported by the simulations of Felipe & Khomenko (2017), who performed a parametric study by placing artificial localized sources at various depths and compared the surface wave speed with the observations. However, due to the uncertainty of the helioseismology analysis, the location of the acoustic sources relative to the subsurface magnetic structure, as well as the mechanism of wave excitation in the deep layers, remained unclear.

These results raise questions about possible mechanisms of wave excitation in subsurface layers in the presence of magnetic fields and about the distribution of acoustic sources in the presence of magnetic structures. A natural way to investigate this problem is to analyze 3D realistic MHD simulations, which model the turbulent plasma dynamics, radiation, and magnetic effects with a high degree of realism, allowing one to look at the physical processes that are hidden from direct observations. In this paper, we analyze the simulation data of Kitiashvili et al. (2010), which reproduced the spontaneous formation of a dynamically stable self-organized magnetic structure. The structure resembles the concentrations of magnetic fields observed as solar pores. They are more dynamic and smaller than sunspots but nevertheless...
allow insight into the nature of deep acoustic sources. In this paper, we identify and examine acoustic waves in the simulation domain and consider possible sources of their excitation as well as the effects of magnetic fields.

The paper starts with a brief overview of the MHD simulation setup (Section 2) and a description of the formation and dynamics of self-organized pore-like magnetic structures. Then we describe the properties of the acoustic waves identified both outside and inside a pore (Section 3). A statistical analysis of the acoustic sources is presented in Section 4, followed by a discussion of the analysis results and conclusion in Section 5.

2. Numerical Simulations

We use 3D radiative MHD simulations of the upper convection zone and the low atmosphere obtained with the StellarBox code (Wray et al. 2015, 2018). The StellarBox code is a high-order fully compressible MHD solver. It uses a Large Eddy Simulation (LES) formulation for subgrid-scale turbulence modeling and includes a fully coupled radiation solver, assuming local thermodynamic equilibrium (LTE). The radiative transfer between fluid elements is calculated for four spectral bins using the long-characteristics method. The boundary conditions are periodic in the horizontal directions. The bottom and upper boundaries are closed for flows ($V_z = 0$) and open for radiative energy flux.

In the simulations, we first calculated a fully developed regime of hydrodynamic solar convection using a standard solar model for the initial conditions. Then, a uniform vertical magnetic field, $B_0^z = 100$ G, was added to the simulation domain. The boundary conditions for magnetic field maintained only the mean magnetic field strength, with no artificial structure imposed. The simulations revealed the spontaneous formation of a compact, 1–2 Mm in horizontal size, pore-like structure with a magnetic field strength of 1.5–1.7 kG at the photosphere, and about 5–7 kG in deeper layers (Figure 1). The self-organization process responsible for the development of pore-like structures is described by Kitiashvili et al. (2010). In the present simulations with a domain size of $6.4 \times 6.4 \times 5.5$ Mm, only one structure was formed. The simulation domain includes a 5.2 Mm thick upper part of the convection zone and about 300 km above the photosphere. The grid-spacing was $\Delta x = \Delta y = \Delta z = 25$ km. To model unresolved turbulent dissipation we use the Smagorinsky subgrid turbulence model. Our analysis showed that the compact magnetic structures are maintained by strong converging downdrafts, resembling Parker’s cluster sunspot model (Parker 1979) and local helioseismology inferences (Zhao et al. 2010), which revealed the filamentary subsurface structuring of a sunspot and converging flows. However, we note that the simulated magnetic structures are much smaller and more dynamic than sunspots. The properties of these self-formed magnetic structures correspond to pores. Because in the simulations acoustic waves are reflected from the bottom boundary, we primarily focus on the wave dynamics in the 3 Mm deep subsurface layer. We exclude from analysis wave excitation events for which the excited wave interferes with waves reflected from the bottom boundary.

3. Acoustic Waves in Subsurface Layers

The simulated magnetic structures are evolving and very dynamic. The complexity of the dynamics and the small size of the computational domain prevent us from performing a cross-correlation time–distance analysis similar to the observational analysis of Zhao et al. (2015). Instead, the simulation data allow us to study individual wave fronts and the corresponding excitation events in the subsurface layers. To capture the propagating acoustic wave fronts, we calculate the time difference of the gas pressure fluctuations, normalized by the square root of the mean pressure suggested by Stein (1967): $p^* = \Delta_t(p'')$, where $p'' = (p - \bar{p})/\sqrt{\bar{p}}$, and $\Delta_t$ denotes the time difference between subsequent moments of time.

3.1. Identification of the Acoustic Waves

Automatic detection of acoustic sources in highly turbulent conditions is difficult in terms of defining identification criteria and detection thresholds. Our attempts to develop an automatic identification procedure led to misidentification of events with unrelated dynamics and multiple counts of the same events. Similarly, the automatic identification of wave fronts is problematic because of gas pressure variations in the surrounding turbulence. Therefore, we performed visual identification of the acoustic events beneath the solar photosphere primarily using the time differences of the normalized gas pressure perturbations, $p^*$. To simplify the identification procedure, we first search for wave-like patterns in a horizontal slice below the most turbulent granulation layer (see, e.g., Figure 2, upper panels) and then track the wave patterns backward in time to obtain a first guess of the source.

Figure 1. Temperature (panel a) and vertical magnetic field (panel b) distributions in the photosphere in the vicinity of the pore-like magnetic structure. Panel (c) shows a vertical slice of the vertical magnetic field through the structure at $x = 4.64$ Mm.)
coordinates. Then we track the wave fronts in vertical slices to estimate the source depth (Figure 2, bottom panels) and to determine if the source is moving into deeper layers. Finally, we shift back and forth between vertical and horizontal planes to determine the location of each source more precisely and to estimate the location uncertainty. In some cases, if a source...
moves fast enough it can produce separated wave patterns at different depths. In addition, we removed analysis cases that have strong interference with wave fronts reflected from the bottom boundary. Also, in some cases acoustic waves are excited close to each other and form joint wave fronts. These sources are also excluded from analysis due to difficulties in separating them and high uncertainty in time and location. This approach worked well outside or near the boundary of the magnetic structure.

The identification of a source location inside the magnetic structure is more challenging because strong turbulent flows make it impossible to track the wave fronts from their origin. Therefore, in the first step we look for wave fronts propagating from the pore, and determine possible locations and the time excitation of their sources, taking into account the shapes of the wave fronts. After this, we check the source dynamics inside the pore to make a more precise estimate. In this way we improve the accuracy of the source depth estimate. Due to the pore’s filamentary structure, local compressions by occasionally strong converging plasma streams can excite several waves between different magnetized bundles at about the same time, which are observed as a single wave front outside the pore.

Figure 4. Evolution of the acoustic-wave energy flux density with depth (columns) and time (rows). The time difference between snapshots is 1 minute. The color scale is in a range from $-10^{11}$ to $3.7 \times 10^{11}$ erg cm$^{-2}$ s$^{-1}$.
Using this procedure, we estimated the locations for more than 600 acoustic events, both inside the pore and in the surrounding region in the 5 hr run. The actual number of acoustic events is probably larger due to the nature of turbulence and because several waves can be excited by a single source.

The analysis is performed event-by-event. The typical uncertainty of the determination of the source location is about 100 km. But sometimes the uncertainty can be very high (up to $0.5 - 1$ Mm), even in cases of clear wave front identification, e.g., when several interacting downdrafts that are close to each other drive the excitation of several waves, making it impossible to identify individual sources. Often, these excitation events produce joint wave fronts. Therefore, all excitation events with source location uncertainties of more than 100 km are removed from the statistical analysis. Also, we excluded from the statistical analysis most of the sources located below a depth of 3 Mm because of interference with waves reflected from the bottom boundary and limited tracking ability.

3.2. Acoustic Waves in the Vicinity of a Pore

As discussed above, acoustic waves are excited both outside and inside the magnetic structure. Acoustic events outside the pore are ubiquitous and are usually associated with downflows. Figure 2 illustrates an example of propagating acoustic waves excited outside the pore structure. The wave fronts are shown in a horizontal plane at a depth $z = -1.5$ Mm below the photosphere (upper row) and in a vertical slice at $x = 2.36$ Mm, with a cadence of 30 s between the snapshots. For acoustic-wave visualization, we use time differences of the normalized gas pressure perturbation, $p'$ as defined by Stein (1967). The isocontours in the top panels of Figures 2(a)–(c) correspond to a 500 G vertical magnetic field at the photosphere, $z = 0$ (red contours), and at a depth of 1.5 Mm (blue contours). Note that the chosen horizontal and vertical slices do not cross the acoustic source location, because otherwise strong turbulent flows would make it difficult to identify and track the wave front. The source in this case is located near the pore boundary, which occurs quite frequently. Figure 3 shows in detail the preceding dynamics in the vicinity of the downdraft associated with the acoustic event shown in Figure 2. It reveals a strong local increase in negative plasma divergence in the downdraft before the excitation of acoustic waves. Also, we found that the identified acoustic source at a depth of about 600 km below the photosphere is transported by the downflows into deeper layers with a speed of about 1.5 km s$^{-1}$.

In general, the acoustic sources are often associated with braking of the downdrafts due to their interaction with the denser plasma of the deep layers. The shape of wave fronts is often distorted by surrounding turbulence and sometimes can be stretched and inclined along the downdrafts. In the case of multiple acoustic sources located near each other (when several interacting downdrafts merge together), usually we can identify a joint wave front that behaves as if from a spatially distributed single source. Because of the complicated local downdraft dynamics, to study the propagation of source-related disturbances we consider the time–space evolution of the acoustic-wave energy flux density induced by turbulent flows, defined as $F_{ac} = V_{i} (p - \bar{p})$ (Eckart 1960; Musielak et al. 1994). Figure 4 shows the downward propagation of turbulent...
disturbances associated with the acoustic flux from a source depth of $-1.15 \text{ Mm}$ to $-1.82 \text{ Mm}$ with a speed of $3–4 \text{ km s}^{-1}$. These disturbances accompany the downdrafts and reveal swirling motions. The yellow–white color corresponds to flux values above $2 \times 10^{13} \text{ erg cm}^{-2} \text{s}^{-1}$. The mean acoustic-wave energy flux at the photosphere is about $5 \times 10^{8} \text{ erg cm}^{-2} \text{s}^{-1}$. This is one order of magnitude higher than the flux estimated from a mixing-length solar model by Musielak et al. (1994).

3.3. Acoustic Waves inside the Magnetic Structure

The unsteady dynamics of the pore represents strong interactions of several highly twisted magnetic bundles with strengths up to $5–7 \text{ kG}$ in the subsurface layers (Figure 5). As suggested by Parker (1979), these interacting bundles can make magnetic structures more stable in time. Figure 6 shows the evolution of time differences of the normalized gas pressure $p^*$ and reveals the appearance of nearly circular patterns centered inside the pore. These regions in the pore “body” experience increases and decreases of $p^*$. To track the local time evolution of variations of $p^*$ we plot them as a function of time (Figure 7), where each plot corresponds to an independent event and shows variations of $p^*$ with a characteristic period of 2–3 minute, corresponding to an acoustic-wave source. As seen from Figure 6, despite the quasiperiodic enhancement of fluctuations inside the pore, it is very difficult to identify wave fronts because of surrounding turbulence. However, averaging the gas pressure perturbations, say in the $y$-direction, across the pore, and smoothing them, can significantly improve the signal-to-noise ratio. Figure 8 illustrates wave excitation inside the pore and an expanding perturbation as a ringlike wave pattern. Another way to capture the wave is to plot the time–space diagram. Because the pore evolves in time and also can freely move in the computational domain, we perform tracking of the pore at the photosphere. Then we transform the simulation data to polar coordinates and average over the azimuth (Figure 9). Note that in most cases it is better to average only over a certain range of azimuth, where turbulent flows are not strong. Because the time–space diagrams can be obtained for each depth, they are also used as an additional criterion for estimating source depth. Figure 9 shows a series of ridges in the time–space diagram that represent propagation of

![Figure 6](image_url)
acoustic waves with a speed of 14 km s\(^{-1}\) about 1.2 Mm below the photosphere.

Our analysis is primarily based on variations of the time difference of normalized gas pressure fluctuations \(p^*\). The enhancement of this quantity inside the pore (e.g., Figure 6) reflects local movements of the magnetic flux bundles that form the structure as they are being pushed by surrounding converging flows. In fact, the converging flows accompany the pore dynamics all the time and maintain its structure. In general, the internal filamentary structure of the pore (Figure 5) evolves rather slowly, without strong external perturbations from the converging flows of the surrounding plasma. Nevertheless, frequently the converging flows become locally much stronger, squeezing the magnetic bundles and causing strong local variations in gas pressure. Such local shifts of the bundles are detected in the enhancement in the time difference of gas pressure fluctuations (Figure 6). The process is illustrated in Figure 10 as a time sequence (left to right panels) of the gas pressure perturbations (upper row), \(p'\), and the flow divergence, \(\text{div}U\) (middle and bottom rows). The middle column corresponds to the moment of time illustrated in Figure 6(a) as the time difference of \(p'\).

The twisting magnetic bundles are dynamically coupled. This makes them more stable, so they evolve more slowly than surrounding flows. The surrounding converging flows (Figure 10, middle and bottom rows) make such interactions even stronger. Strong local enhancements of converging streams (light blue colors in \(\text{div}U\), Figure 10) in one or more areas initiate local compression of the magnetic structure and its expansion. Because such local impacts quickly come to involve the whole pore, the horizontal location of the compression cannot be determined precisely and certainly cannot be considered a point source. Nevertheless, the depth of the acoustic source can be determined by tracking the wave fronts back in time to their origin, analyzing the time differences of gas pressure fluctuations and using time–space diagrams. In the next section we will use the identified acoustic sources to investigate statistical correlations of various properties.

### 4. Statistical Properties of Acoustic Sources

We separately consider acoustic events beneath the solar surface in areas of strong magnetic field (inside the pore) and in weak fields. To perform a statistical study we consider only the last 5 hr of the data set, to avoid the pore-formation stage. From the statistical analysis we exclude acoustic events in the following cases: (1) the excited wave interferes with a wave reflected from the bottom boundary; (2) the acoustic source is close to the bottom boundary so that it is not possible to properly track the wave front; and (3) the uncertainty of the source location is greater than 100 km (e.g., due to a high concentration of several sources in areas with interacting downdrafts). In this study more than 600 events have been identified, and in most cases the localization error does not

![Figure 7. Examples of local temporal variation of \(p^*\) inside the pore, revealing the appearance of oscillations with 2–3 minute periods.](image)
Because of this uncertainty, we compare the mean physical properties in the vicinity of the source location by averaging over a 100 km$^3$ volume (Figure 11). The distribution of the identified sources as a function of depth and magnetic field strength shows a clear separation between events associated with the pore dynamics in strong field regions (red dots) and events located outside the pore in areas of weak magnetic field (blue dots). There are a few cases of acoustic events that are associated with the pore dynamics but located in areas with weak magnetic field (Figure 11(a)). These exceptions reflect the natural dynamics of the pore filamentary structure, because in layers below 2 Mm the “roots” of the magnetic structure can split into two or more substructures with a weak magnetic field between the bundles.

The relative distribution of the sources in terms of the time difference of normalized gas pressure perturbations generally reveals stronger fluctuations in the pore (Figure 11(b)). Pressure fluctuations in weak-field areas are stronger closer to the solar photosphere, and their strength decreases with depth. The sources in the strong magnetic field areas lie in a relatively narrow range of gas pressure fluctuations, while in the weak-field areas the distribution of pressure fluctuations is much broader (Figure 11(c)). Vertical velocity fluctuations in the vicinity of the acoustic sources located in the pore are about 1 km s$^{-1}$ and weakly decrease with depth. Outside the pore areas, the vertical velocity of the sources has a broad distribution and rapidly decreases with depth (Figure 11(d)).

The histogram of the acoustic source distribution with depth shows that most of the sources outside the magnetic structure are located around 0.5 Mm beneath the surface and that the number of excitation events quickly decreases with depth (blue bars, Figure 12). Acoustic waves inside the magnetic structure are excited in a broad range of depths, from 1 to 2 Mm (red bars). The number of acoustic events deeper than 2.5 Mm is likely underestimated due to selection effects.

5. Discussion and Conclusion

Recent local helioseismology inferences show signatures of acoustic waves (Zhao et al. 2015) excited in sunspot areas at a
depth of about 5 Mm, much deeper than was found in previous studies of acoustic-wave excitation in quiet-Sun regions (e.g., Goode et al. 1992; Kumar 1994; Kumar & Basu 1999; Nigam & Kosovichev 1999; Kitiashvili et al. 2011). In this paper, we used results of 3D radiative MHD simulations to investigate the excitation of acoustic waves in a stable, self-organized pore-like magnetic structure and to compare with acoustic sources in weak-field regions outside this structure. The magnetic structure is spontaneously formed from an initial uniformly distributed 100 G vertical magnetic field (Kitiashvili et al. 2010). The mean magnetic field strength of the pore is about 1.5–1.7 kG at the photosphere and reaches 5–7 kG below the solar surface. The subsurface structure of the pore consists of several highly twisted magnetized bundles. The structure is maintained due to surrounding downdrafts converging around the pore. In the analysis we used the last 5 hr of the simulation when the structure was fully developed and stable. We performed a case-by-case study and identified more than 600 individual excitation events both inside and outside the pore.

The performed case studies showed that excitations of acoustic waves outside the pore are associated with convective downdrafts in the intergranular lanes, as was previously suggested. The depth of the excitation depends on the downdraft speed and the presence of magnetic field. The sources then often move downward together with the downdrafts, so that the wave front shape can be deformed along the downdrafts. Excitation of acoustic waves inside the pore is associated with interaction of magnetic bundles, when strong converging plasma streams hit the pore boundary, causing compression of the bundles and enhancements of the gas pressure. Several cases of wave excitation identified inside the pore are associated with weak local magnetic field and were located near the photosphere below 2 Mm. The origin of this phenomenon is in the filamentary structure of the pore. The local weak-field regions sometimes appear when the subsurface layers of the pore expand and the distance between the magnetic bundles increases. In deeper layers, the bottom part of the pore can split into several “roots.” In these cases, we found sources located near bifurcations in the pore’s body and likely associated with bundle dynamics.

The statistical distribution of the identified acoustic sources shows a clear separation between the acoustic events outside and inside the pore (Figure 12). In the area outside the pore, the sources are mostly located in the near-surface layers up to 1 Mm deep, with the distribution peak around 0.5–0.6 Mm. The number of events rapidly decreases with depth. Deeper sources outside the pore are associated with stronger downdrafts, stronger magnetic fields, and stronger cooling in the intergranular lanes (Figure 11).

Excitation of acoustic waves in the magnetic pore (or beneath the pore) is driven by the interactions of magnetic bundles. The distribution of acoustic sources with depth is much broader, and most of the identified events are located from 1 to 2.5 Mm below the photosphere (Figure 12). The maximum number excitation events was around 1.5 Mm below the photosphere. The rapid decrease of the identified acoustic sources below 2.5 Mm is likely due to limitations of the simulation setup and event selection as described in Section 3.

Recent detection of deep acoustic sources beneath sunspots at depths of about 5 Mm using the local helioseismology technique (Zhao et al. 2015) raised questions about the nature of the waves’ excitation. At the present time, due to the uncertainty of the helioseismic inferences, it is impossible to draw conclusions about the location of the detected sources relative to the magnetic structure. In particular, it is unclear if the sources are located at the boundary of or inside the sunspot. Previous helioseismology studies revealed signatures of a filamentary magnetic substructure beneath sunspots (Kosovichev 2009; Zhao et al. 2010) that support the theoretical model proposed by Parker (1979) and are consistent with our simulations (Kitiashvili et al. 2010). Our analysis suggests two possibilities of acoustic-wave excitation in magnetic structures that depend on the source location. In the case of the source location inside the structure, magnetic bundles are locally compressed by converging flows, causing pressure fluctuations. Because of the relatively small size of the modeled magnetic structure, interpretation of our results can be extended only to the most dynamical subsurface parts of sunspots and their periphery areas. In this case there is a possibility that the acoustic sources are located deep below sunspot penumbrae, near the the sunspot’s main body structure, or inside the structure where magnetic bundles are held together by converging flows. Another way to excite acoustic waves is the interaction of magnetic bundles in much deeper layers beneath the
Figure 10. Time evolution (from left to right) of the normalized gas pressure $p'$ (top row), and $\text{div}(U)$ (middle and bottom rows) across the pore and a horizontal slice at a depth of $-1.2$ Mm. The images reveal local disturbances and squeezing of the pore by converging flows that lead to excitation of waves inside the pore. The contour lines correspond to a vertical magnetic field of 500 G. The time difference between the snapshots is 1 minute.
sunspot umbrae. Which of these probabilities is most important needs to be determined in future large-scale simulations of sunspots. Despite current limitations, our results reveal a new mechanism of acoustic-wave excitation in concentrated magnetic structures (observed as pores and sunspots) associated with the interaction of magnetic bundles with deep converging flows that maintain these structures.

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