WHAT HELIOSEISMOLOGY TEACHES US ABOUT THE SUN

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ABSTRACT

Helioseismology uses observations of oscillations of the solar surface to determine the internal structure and dynamics of the Sun, providing critical knowledge about the mechanisms of solar variability and activity cycles. The recent advances based on observations from SOHO spacecraft and GONG network have allowed us to study both long-term changes of the global structure and circulation and short-term variations associated with developing active regions, sunspots and coronal activity. In particular, the global helioseismology results have revealed 1.3-year variations of the rotation rate in the tachocline, but found no indication of 11-year variations. Studies of the meridional circulation have shown formation of additional meridional cells of flows converging toward the activity belts, thus, questioning the flux-transport theories of the solar cycle. It is found that sunspots as cool objects appear to be only 4-5 Mm deep, but accumulate significant heat in the deeper layers, and also form converging downflows. Large active regions are formed as a result of multiple flux emergence, and no evidence of large-scale emerging Ω-loop has been found. This paper presents a brief review of these and some other results of helioseismology, analysis techniques, and perspectives.

Key words: helioseismology, differential rotation, global circulation, solar radius, active regions, synoptic maps, subphotospheric velocity field; magnetic reconnection.

1. INTRODUCTION

In the past decade, helioseismology has provided important insights in the internal dynamics of solar variability on the global and local scales. The continuous monitoring by the GONG ground-based network and the MDI instrument on SOHO has revealed significant variations of the solar structure and dynamics with the activity cycle. Two regions, the tachocline and the upper convective boundary layer, are particularly critical for understanding the solar variability. Both of these regions are characterized by strong rotational shears. The helioseismic observations of the tachocline have provided evidence of puzzling 1.3-year variations of the rotation rate. Rich dynamics correlated with the magnetic activity have been revealed in the upper convective layer. Of particular interest are variations of the global circulation pattern, zonal flows ("torsional oscillations") and meridional circulation, and their interaction with large-scale converging mass flows around active regions. These variations are studied by constructing 3D synoptic maps of subphotospheric flows. On the local scale, strong sound-speed variations and vortex shear flows are observed beneath sunspots and active regions. The key questions are: How is the internal dynamics of the Sun related to the magnetic field patterns, energy transport and irradiance variations? What are the mechanisms of the global circulation and local vortex mass flows? How does the subsurface dynamics lead to unstable magnetic topologies?

2. GLOBAL AND LOCAL HELIOSEISMOLOGIES

Helioseismology provides a set of tools for probing the solar interior by observing oscillations of the solar surface. These can divided into two broad categories: global and local helioseismology. Global helioseismology utilizes frequency of normal modes (resonant waves) of the entire Sun while the local helioseismology uses local properties of solar oscillations, such as wave travel times, in various areas of the Sun (Fig. 1). Solar oscillation have typical periods between 3 and 10 min, with maxi-
Figure 2. a) The power spectrum of solar oscillations obtained from MDI Doppler measurements of solar oscillations as a function of angular degree $l$ of spherical harmonics, which is related to the horizontal wavelength, $\lambda_l = R_0/(l + 1/2)$, and cyclic frequency $\nu$. The lowest ridge corresponds to f-mode, and the higher ridges to p-modes. b) The power spectra of the oscillation modes of $l = 200$ observed in Doppler velocity (top) and continuum intensity from SOHO/MDI.

Figure 3. a) The cross-covariance function of solar oscillations ('time-distance diagram') as a function of acoustic waves travel time and distances on the solar surface. b) The cross-covariance function for distance 30°.

The frequencies are measured by fitting the mode lines in the oscillation power spectrum (Fig.2). The spectral lines are asymmetrical because of the localization of the oscillation source close to the surface, and a correlated component of the granulation fluctuations in the intensity signal (Nigam and Kosovichev, 1999). The mode frequencies are measured using long time-series spanning, typically, 72 days of uninterrupted observations (Schou et al., 2002). This allows to achieve the relative precision of $10^{-5}$ to $10^{-6}$, and make inferences about the deep interior including the solar core. Because of averaging over the long periods of time and symmetric properties of normal modes, this method ('global helioseismology') provides information only about the azimuthally averaged components of the solar structure and angular velocity as a function of latitude and radius.
Figure 4. The relative deviations of the sound-speed inside the Sun from a standard solar models: a) a cut-away view (positive deviations are dark, negative - light), b) the radial dependence (the horizontal bars show the radial resolution, the vertical ones indicate formal error estimates).

Figure 5. a) The contours of equal rotation rate inside the Sun. b) The variations of the rotation rate in the tachocline (0.72R) and the upper radiative zone (0.63R) obtained from the GONG (circles) and MDI (triangles) data.

The methods of 'local helioseismology' are based on much shorter time series of solar oscillations and, thus, are less precise. However, they probe the three-dimensional structure and dynamics of the Sun. The most complete diagnostics is provided by time-distance helioseismology (e.g. Kosovichev and Duvall, 1997), which is based on measurements of travel times of acoustic waves for different distances corresponding to one skip of the ray path (see Fig.1). The travel time depends on the wave speed along the ray path, and, thus, it is used to infer the distributions of the sound-speed and flow velocities. The travel times are determined by fitting the cross-covariance function of the oscillation signals observed for a chosen range of distances on the surface. The typical cross-covariance function (Fig. 3) displays a set of ridges corresponding to packets of acoustic waves travelling through the interior between different distances on the surface. The lowest ridge corresponds to single-skip wave paths between two points; the second ridge is formed by waves travelling to the same distances along a two-skip path with an intermediate surface reflection ('second skip' waves), and the higher ridges corresponds to multiple skips. The phase and group travel times are measured by fitting a wavelet to the wave packets (Fig. 3b).

So far, most inversions of the observed travel-time variations was made using a ray-path approximation, which raised some concerns about the accuracy of the inferences. However, the recent results based on Fresnel-zone sensitivity kernels which take into account the finite wave-length effects confirmed the ray-theory results (Jensen et al, 2001). The major effect is found in changes of the vertical scale: the solar structures may be deeper than they appear in the ray-path inversion results. However, this conclusion needs to be verified by using a more accurate theory based on a Born-approximation, which is currently under development (Birch and Kosovichev, 2000; Gizon and Birch, 2002).

The time-distance helioseismology uses 2-8 hours long time series of solar oscillation. The 8-hour series provide robust measurements of the acoustic travel times for the
depth range of 0-30 Mm below the surface. The typical spatial resolution is about 2 Mm.

3. INTERNAL STRUCTURE AND ROTATION OF THE SUN: VARIATIONS WITH SOLAR CYCLE

The sound-speed structure of the Sun inferred by inversion of mode frequencies shows a remarkable agreement with the standard solar model (Fig. 4). The most significant deviations are observed in three regions: the energy-generating core, the base of the convection zone, and near the surface. The cause of the deviations is not completely understood, but they can be explained by some additional material mixing and turbulence effects, not included in the standard solar model. The measurements of the rotation rate have revealed strong radial gradients, rotational shear layers, at the base of the convection zone (so-called tachocline) and near the surface (Fig. 5a).

The solar-cycle variations of the sound speed are reliably measured only in the near-surface layer. The detection of variations in the tachocline region where the solar dynamo is commonly believed to be operated, is difficult because the contribution of magnetic fields to the sound speed is quite small compared to the high gas-dynamic pressure. However, the variations of the rotation rate in the tachocline, associated with the dynamo processes, may be sufficiently large for helioseismic observations. Indeed, the inversion results of Howe et al (2000) provide evidence for variations of the rotation rate with the amplitude of about 1% and the period of 1.3 years (Fig. 5b). The anticipated 11-year signal is not observed. However, the amplitude of these variations seems to decrease at the solar maximum. It is intriguing that similar 1.3-year are observed in the surface sunspot data (Krivova & Solanki, 2002). However, the connection between the surface magnetic field and tachocline is not yet established.

Another interesting phenomenon associated with the solar cycle, so-called 'torsional oscillations', well-known from the surface magnetic and Doppler observations (Howard and Labonte, 1980; Ulrich, 2001), are found to be extended through the upper half of the convection zone (see Fig. 6), and perhaps, even deeper in the polar regions (Vorontsov et al, 2002). The active regions tend to emerge in the shear layer formed by these flows (with the positive angular velocity gradient towards the equator). The observations of these flows at the solar minimum and their great extent made problematic the previous explanations based on the Lorentz force, and have led to a suggestion that these flows may be caused by temperature variations associated with deep magnetic structures evolving with the solar cycle (Spruit, 2003). Clearly, further investigation of these flows is one of the top priorities of helioseismology.

Another interesting problem is the variation of the solar radius with the solar cycle. This is important for understanding the mechanism of irradiance changes. An accurate estimate of the solar radius is provided by the f-modes (Schou et al 1997). However, this radius is not directly related to the photospheric radius, but measures the

Figure 6. Solar-cycle variations of the zonal flows ('torsional oscillations') at various depth inferred from the MDI data (light regions correspond to faster flow, and dark - to slower flow).
Figure 7. a) The subsurface density profiles of the standard solar model ('mode 1') and inferred by calibrating the surface gravity waves (f-mode) frequencies observed from MDI ('seismic models'). The star on the model curve indicates the photospheric radius used in the model calculations; and the diamond on the seismic model curve shows the corresponding 'seismic radius', which follows from the f-mode calibration. b) Variations of the seismic radius with the solar cycle for two cases of data analysis when the surface structure changes not included ('γ1 neglected', the upper set of points), and included (the lower set).

location of a subsurface zone of adiabatic convection with steep density gradient, 4–5 Mm deep (Fig. 7a). The f-mode show that this zone located approximately 300 km deeper than predicted by the standard solar model. However, between this zone and the photosphere there is a zone of superadiabatic convection, the structure of which is rather uncertain. For its observation, it is necessary to accurately measure frequencies of high-degree modes (l = 300 – 1000), and this task has not been achieved. For the theory, it is necessary to develop a robust theory of convective energy transport. If the standard mixing-length theory is used than the photospheric solar radius is about 300 km less than the observed apparent radius of the Sun, 659.99 Mm. The solar radius estimated by this f-mode calibration procedure is known as "seismic solar radius".

Further analysis by Goode & Dziembowski (2002) has found evidence that the seismic radius decreased by about 1.8 km/year during the raising phase of the solar cycle, in 1997–2000 (Fig. 7b). Comparing this result with the independently measured photospheric radius could provide an important insight into the solar-cycle variations of the superadiabatic zone thermodynamics and irradiance variations. However, unfortunately, the direct observations of the apparent solar radius are rather uncertain because of various systematic errors (Noel, 2001); and the results vary from -40 km/year to +150 km/year. The results of 3-year measurements from SOHO/MDI are consistent with an increase of about 5.8 km/year. Certainly, more data, both helioseismological and photometric, are needed to solve this important problem of the solar cycle.

4. SYNOPTIC MAPS OF SUBPHOTOSPHERIC FLOWS AND SOLAR-CYCLE DYNAMICS

The time-distance technique has provided detailed maps of subphotospheric flows. The oscillation data for these maps are full-disk 1024×1024-pixel Dopplergrams provided by the MDI instruments on SOHO during 2-month continuous contacts with spacecraft (so-called Dynamics Program). Therefore, only 2 Carrington synoptic maps of subphotospheric flows are available for each of the 7 years of SOHO observations (Zhao and Kosovichev, 2003). Despite the limited temporal coverage these new maps provided a tremendous amount of information about the mass motions of various scale associated with the solar activity and cycle. The spatial resolution is about 3 Mm (0.24 heliographic degrees), the depth coverage is 0–12 Mm, and the temporal integration time for each central-meridional tile is 8 hours.

These maps allow us to investigate both the global-scale flows (zonal flows and meridional circulation) and convective flows of the supergranular scale and larger. Figure 8 shows two maps of large-scale flows obtained by averaging the original synoptic flow maps in 15° × 15° regions separated by 3.75° to simulate the resolution of another local helioseismology method - ring-diagram analysis (Haber et al., 2002). These maps reveal systematic large-scale converging flows around active regions. Even small active regions develop distinct patterns of large-scale plasma flows towards them in the subphotosphere. The comparison between the time-distance and ring-diagram results gives a high correlation coefficient of about 0.8. However, there some differences in the large-scale flow patterns which can be attributed to the differences in the horizontal and depth resolutions and temporal integration (the ring-diagram method requires 24-day integration time for measurements).

Figure 9 shows a portion of a full-resolution flow map obtained by the time-distance method. On this map, one can easily identify the divergent supergranular flows and strong converging flow in magnetic regions. These observations reveal the great complexity and richness of subphotospheric flows on the smaller scale, which also display a remarkable organization on the larger and global scales. The multi-scale organization of subphotospheric flows is one of the important lessons of helioseismology.
Indeed, by simply averaging these complex synoptic flow maps over longitude we obtain the zonal flows ("torsional oscillations") familiar from surface Doppler and magnetic data and global helioseismology. In addition, to the important cross-check between the two types of helioseismology, the time-distance maps allow us to investigate the North-South asymmetry of the zonal flows, and also to derive the meridional component (Zhao and Kosovichev, 2003).

Figure 10 illustrates the rotation rate, velocity of the meridional and zonal flows in the subphotosphere obtained from the 1995 MDI synoptic maps. The zonal flows are obtained by subtracting a parabolic fit representing the standard differential rotation law from the rotation rate curve. The study of the evolution of these flows has confirmed the results of global helioseismology and surface observations that the zonal flows migrate toward the equator, and that the magnetic activity belts are located in the shear layers where the velocity gradient toward the equator is positive (Fig. 11a).

The meridional flows from the equator to the poles are of the order of 20 m/s, and remain poleward during the whole period of SOHO/MDI observations, covering the rising phase of the solar cycle. In addition to the regular meridional flow that exists at the activity minimum, extra meridional circulation cells are found in each hemisphere (Fig. 11b). These cells correspond to large-scale regular flows converging in the activity belts.

The extra meridional circulation cells associated with the magnetic activity in addition to the widely known single meridional cell from the equator to the pole may have some interesting implications for the dynamo theory. It is recognized that the meridional circulation may play some important roles in the regeneration of poloidal magnetic field and angular momentum transportation, and the accurate measurements of meridional flows have helped the numerical simulation of the solar dynamo theory. The additional meridional circulation cell found in this study may help to transport more magnetic flux to the activity belts, but may hamper the flux to transport into the polar regions.

The mystery of the solar activity belts migrating toward the solar equator remains not fully understood, and it perhaps is caused by the migrating converging meridional ow cells. On the other hand, the converging flows and hence the downdrafts in the activity belts, may result from the hydrodynamic effects associated with cooling in magnetic regions, as recently predicted by a geostrophic flow (Spruit 2003). Or perhaps, the converging flows and downdrafts are just a global-scale manifestation of the...
Figure 9. A portion of the full-resolution subphotospheric synoptic map of horizontal flows at depth 0-3 Mm, for Carrington rotation 1988 (March 30 - April 26, 2002). The background is the corresponding synoptic map of the photospheric magnetic field (white - positive polarity, and black - negative polarity).
Figure 10. Differential rotation, meridional circulation, vorticity and zonal flows below the photosphere (depth 0-3 Mm) as a function of latitude, obtained by averaging time-distance synoptic maps of horizontal flows observed in 1998.

Figure 11. a) Zonal flows obtained at the depths of 3 – 4.5 Mm (solid curves) and 6 – 9 Mm (dash dot curves) for different Carrington rotations from SOHO/MDI Dynamics Program data. The shaded regions represent the locations of activity belts. The error bars show the standard deviations of data from which the zonal flows are averaged. For clarity, only a few error bars are selected for display, and the error bars for the depth of 6 – 9 Mm are not shown but have similar scale. b) Meridional flows obtained at the depths of 3 – 4.5 Mm (solid curves) and 6 – 9 Mm (dash dot curves) from the same data. (Zhao & Kosovichev, 2003)
strong converging flows and downdrafts in regions with strong magnetic fields.

The vorticity distribution is largely linear relative to the latitudes with small deviations. Calculations show that the vorticity results mainly from the differential rotation. The vorticity inside supergranules and at the supergranular boundaries caused by the Coriolis force is approximately one order of magnitude smaller than vorticity from the differential rotation, apparently due to the cancellation of the opposite sign of vorticity in the supergranular converging and divergent flow regions. Since the vorticity is connected with the kinetic helicity, which is directly related with the solar dynamo, this may imply that the local vorticity caused by the Coriolis force does not have much contribution to the generation of the solar magnetism compared to the differential rotation in the global scale. The deviation of the vorticity distribution from its linear, it has a valley in the activity belt of Southern hemisphere and a peak in the activity belt of northern hemisphere.

5. SUNSPOT STRUCTURE AND MASS FLOWS

Sunspots are the main source of the solar irradiance variations and solar disturbances. However, the mechanisms of sunspot formation and stability are not understood. Time-distance helioseismology provides an unique opportunity for investigating the internal structure and dynamics of sunspots. The initial results shown in Fig. 12 have indicated that the region of decreased sound speed, associated with cooler temperature of sunspots, is extended to 4–5 Mm below the photosphere, and that in the deeper layers the sound speed is greater than in the surrounding plasma (Kosovichev et al., 2000). The sound speed can be increased because of a higher temperature or strong magnetic field. These two effects have not been separated, but the main factor is higher temperature (approximately by $3 \times 10^5$ K) because the magnetic field should be about 20 kG to make the dominant contribution to the sound speed. Given the magnetic flux conservation this would lead to a much smaller area of the sunspot structure below 5 Mm, which is not found in the observations. Probably, the deep higher temperature zone is formed by accumulation of the heat flux under sunspots. It is interesting to note that the helioseismic observations reveal deep connections ("fingers") between the main sunspot and surrounding pores of the same magnetic polarity as the spot. Pores of the opposite polarity (e.g. C) are not connected to the spot.

The observations of the higher-temperature regions raise the question why the temperature excess in the photosphere around sunspots is very small (Kosovichev et al., 2002). The answer can be in the specific convective flow pattern beneath the sunspot, also inferred by helioseismology (Fig. 13, 14a). These observations have found evidence for strong converging downflows of the relatively cool plasma from the solar surface to the depth of 4–5 Mm. These flows may prevent the heat flux from emerging around sunspots and creating bright rings in the photosphere. In the deeper layers of the hotter plasma, the flow pattern is dominated by diverging upflows. A detailed investigation of the flow map shows that in the deep layers the plasma appears to be flowing through the sunspot structure. This provides evidence that in the deep layers (below 4–5 Mm) the sunspot structure is not monolithic, and probably, represents a cluster of sparsely distributed flux tube as suggested by Parker (1979).

The recent numerical simulations of magnetoconvection around sunspot-like magnetic structures by Hurlbut & Rucklidge (2000) provide results that are generally consistent with the observations (Fig. 14b). However, both the model and the observations shown in Fig. 13, do not reproduce the well-known Evershed effect which is interpreted as plasma outflow in penumbra. The Evershed effect is observed by using in the time-distance analysis surface gravity waves (f-mode), which are more sensitive to the near surface flows than the acoustic (p-modes) employed to image the deep layers. This provides evidence that the Evershed effect is a very shallow phenomenon. In the model, Hurlbut & Rucklidge suggested that the
Figure 13. The mass flows in a sunspot area at the depth of 0–3 Mm (a) and depth of 6–9 Mm (b). The arrows show the magnitude and directions of the horizontal flows, and the background gray-scale map shows the vertical flows (light color indicates downflow). The contours at the center correspond to the umbra and penumbra boundaries. The longest arrow represents 1.0 km/s in panel a), and 1.6 km/s in panel b). The vertical cut in panel c) is made through the sunspot center with the cut direction of East-West. The range covered by the line arrows indicate the area of umbra, and the range covered by the dotted arrow indicate the area of penumbra. The longest arrow represents 1.4 km/s. (Zhao et al 2001).

Figure 14. a) Schematic picture showing the axisymmetrical flow pattern beneath the sunspot shown in Fig. 13. The background image shows the sound-speed variation (in this case, the light color corresponds to negative perturbation, and the dark color shows positive perturbations beneath the surface). The top panel shows a white-light image of this sunspot. b) Mass flow in an axisymmetrical MHD model.

Figure 15. Image of the acoustic wave speed in an emerging active region in the solar convection zone obtained from the SOHO/MDI data on January 12, 1998, from 02:00 to 04:00 UT, using time-distance helioseismology. The horizontal size of the box is approximately 560 Mm, and the depth is 18 Mm. The (mostly) transparent panel on the top is an MDI magnetogram showing the surface magnetic field. The vertical and bottom panels show perturbations of the sound speed which are approximately in the range from -1.3 to +1.3 km/s. The positive variations are dark, and the negative ones are light. A large active region formed at this location within a day after these observations.
Figure 16. The potential magnetic field model of NOAA AR 9393: a) pre-flare configuration 4:00 UT, b) close to the maximum (12:40 UT) configuration 12:00 UT and c) post-flare configuration. The active quasi-separatrices are presented by heavy lines and are numbered 1, 2, 3, see text. Solar north is up and west is to the right. Field of view is 300'' × 300''.

Figure 17. Horizontal velocity fields at different depths at 12:00 UT, March 28, 2001: A) 3.00 Mm B) 4.52 Mm, C) 6.42 Mm. The background image of each frame is MDI magnetogram at 12:00 UT. Solar north is up and west is to the right. Field of view is 300'' × 300''.

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Evershed effect is produced by almost horizontal flows along the magnetic field lines in penumbra just above the converging ("collar") flow. An important task of the future time-distance analysis is to combine the diagnostics based on p- and f-modes in a single uniform procedure and resolve the near-surface structure of sunspot flows.

6. EMERGING MAGNETIC FLUX, DEVELOPING ACTIVE REGIONS, AND LINKS TO CORONAL ACTIVITY

Detecting of developing active regions before they emerge on the solar surface and prediction of their evolution are of primary importance for space weather forecasts. A important lesson learned from helioseismology is that the emerging magnetic flux propagates so quickly that the standard 8-hour integration is not sufficient to follow the process of emergence. Reducing the integration time (similar to the exposure time in astronomy) lowers the signal-to-noise ratio and makes the inversion results more uncertain. Nevertheless, it is necessary to develop the time-distance measurements techniques which will provide the temporal resolution of 1-2 hours. Figure 15 shows a sound-speed image of an emerging active region obtained with a 2-hour time series. These results show that the emerging magnetic flux propagates with the speed at least 1.3 km/s in the upper 18 Mm of the convection zone. The sensitivity of the time-distance measurements is not yet sufficient for detecting emerging flux in deeper interior.

The investigation of the evolution of large active region for 3 solar rotation in March-May, 2001, have found no evidence for emergence of a large magnetic O-loop. In particular, no large scale outflows (that one would expect to accompany emergence of a large-scale structure) was observed. The active region was rather formed by multiple emergence of relatively small magnetic structures in the same region during an extended period of time. (Kosovichev & Duvall, 2002).

This active region produced a series of powerful solar flares. The relations between the flare morphology, magnetic configuration, and subphotospheric flows have been investigated by Dzifčáková et al (2003) and Kulinova et al (these Proc.) for 2 flares. The initial results indicate that most dynamics related to the magnetic configuration in the flares, probably, occur not at the photosphere, but at the depth between 2 and 6.4 Mm. The magnetic configuration calculated in the potential field approximation for M4.3 flare of March 28, 2001, is shown in Fig. 16, where the thick black curves show the location of magnetic quasi-separatrices (Priest and Demoulin, 1995). The corresponding flow maps at 3 depths are shown in Fig. 17. The most prominent feature in the flow maps at 3 Mm and 4.53 Mm (Fig. 17 A,B) is a fast plasma flow mostly along a quasi-separatrix in the central area. In the deeper layer, at 6.42 Mm, there is a flow across this quasi-separatrix. If these flows affect the motion of magnetic field lines and footpoints, then the motion across the quasi-separatrix could cause "magnetic flipping", leading to magnetic reconnection according to Priest and Demoulin (1995). It is interesting that another flare in this region had a similar flow pattern (Kulinova et al, these Proc.). The flow maps used in this study were obtained with 8-hour integration time. Obviously, better temporal resolution is necessary to make more definite conclusion, as well as vector magnetic field data. But, this new direction of helioseismic diagnostics which establishes links between the dynamics of the solar interior and coronal activity is very promising, and certainly will be developed in the future, particularly, when data from Solar Dynamics Observatory will become available.

7. CONCLUSION

In summary, helioseismology has provided tremendous amount of new information about the interior structures and dynamics related to the processes of solar activity of various scale, from the global dynamo to small-scale flow associated with solar flares. It has demonstrated a remarkable organization of small-scale dynamics into global processes, important links between the solar interior and exterior, and tremendous potential for new discoveries which will lead to better understanding of solar variability and activity.

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