

Scientific Insights from *SOHO*, 2003 -2005: Helioseismology and Solar Interior

New solar abundances, helioseismic model of the Sun and neutrino problem

Recently determined heavy element abundances¹⁻³ have led to significant changes in our understanding of the internal structure and constitution of the Sun. It turns out that the standard solar models calculated with the new abundances are significantly different from the helioseismic results which were in a good agreement with the previous solar models. Figure 1 shows the relative difference between the MDI measurements of the sound-speed profile inside the Sun and various solar models. The solid curve shows the difference for a standard solar model with the previously known solar composition. The dotted curve shows this difference for the standard model computed with the new composition which has lower abundances of oxygen and iron as determined spectroscopically by Asplund¹).

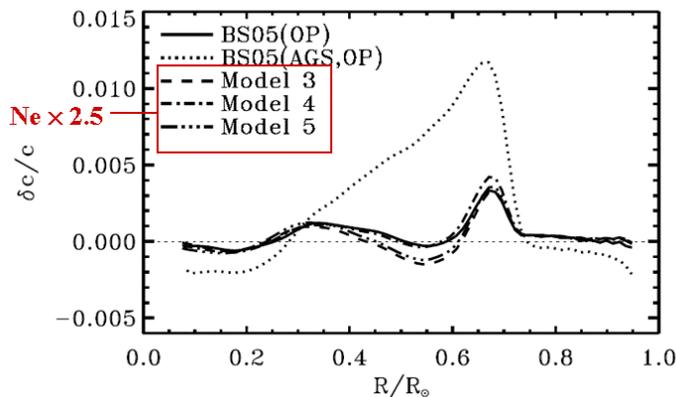


Figure 1. Relative sound-speed differences, between some selected solar models and helioseismological results from MDI data. The BS05(OP) (solid curve) is a standard solar calculated with the previously known abundances of helium (0.2725) and heavier elements (0.0188). Model BS05(AGS,OP) (dotted curve) is a solar model calculated with the newer and lower heavy-element abundances (Y=0.2599, Z=0.0140). Models 3, 4, and 5 are calculated with the

increased relative abundance of neon show an agreement with helioseismology data which is comparable to that of the previous standard solar model, BS05(OP). Trail-and-error method was used in order to find a composition mixture that fits well the helioseismological data without exceeding the quoted uncertainty⁴ in any of the abundance determinations except for neon and argon.

This discrepancy represents a new challenge for helioseismology and solar modeling, and also affects the predicted neutrino fluxes⁵⁻⁸. One possible solution is to increase the relative abundance of neon by a factor of 2.5⁹. This may compensate for the lack of oxygen and iron as shown in Fig.1 by Models 3-5 calculated by Bahcall et al⁵.

Obviously, more precise helioseismic measurements of the solar structure are required to provide more accurate constraints for the solar composition. This can be achieved by using longer time series of observations of solar oscillations for measuring the frequencies of acoustic (p) modes (and correcting these for the solar-cycle variations).

Variations of the subsurface structure with the activity cycle and solar irradiance

Helioseismic observations from space provide unique opportunity for measuring oscillation frequencies of surface gravity waves (f-mode) of medium angular degree l , which represent a very sensitive indicator of variations of the stratification just below the surface of the Sun. These data are very important for diagnostics of the solar-cycle effects below the surface and mechanisms of the total irradiance variations. The medium- l f-modes are not observed from the ground because of their relatively low amplitude. Figure 2 shows the estimates of the variations of the radius of the subsurface layers of the Sun with the activity cycle, obtained by Lefebvre and Kosovichev¹⁰, following the theory of Dziembowski and Goode¹¹. It appears that the changes in the solar stratification due the solar activity are not uniform with depth. There is an evidence of a compression layer at the depth of 7 Mm (0.99 R). It is intriguing that the most significant changes occur below the solar surface. According to these inferences, the Sun is smaller at the activity maximum, and the variations of the surface radius do not exceed 2 km.

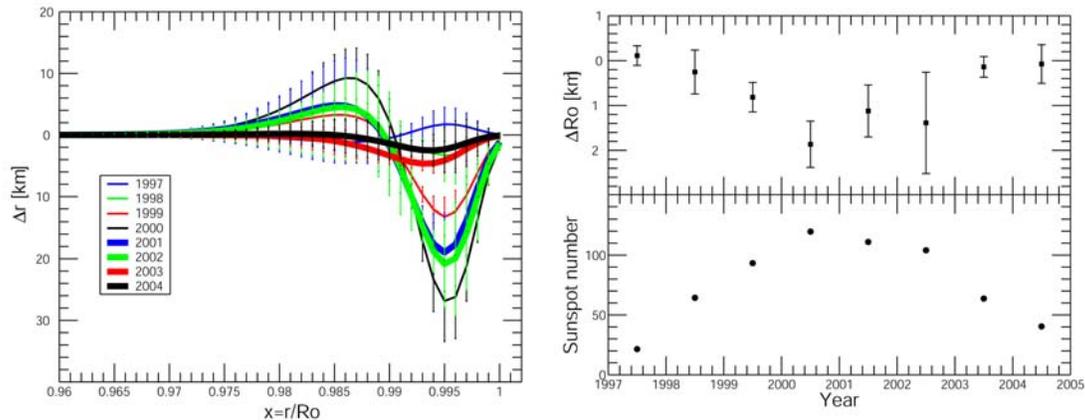


Figure 2. Left panel shows changes of the radius of subphotospheric layers with the solar cycle (relative to the solar minimum values of 1996) for the whole period of SOHO/MDI observations, inferred by helioseismic inversion of frequencies of f-modes (surface gravity waves). Right panel shows the solar radius estimated at the surface changes in antiphase with the sunspot number, meaning that the Sun becomes smaller at the activity maximum.

By analyzing changes of the oscillation frequencies of the solar acoustic (p) modes, obtained from SOHO/MDI data, Dziembowski and Goode¹² concluded that the Sun not only becomes smaller at the activity maximum but also cooler in the subsurface layers. However, measurements of the total solar irradiance from the VIRGO instrument on SOHO indicate during the same period the total solar irradiance increased with the increasing solar activity. The solution to the puzzle why the smaller and cooler Sun radiates more is that the solar structure becomes more corrugated because of the nonuniform distribution of magnetic field. The deviations from the spherical structure can be also estimated from the helioseismology data, in particular, from frequency splitting, and from the full-disk continuum intensity images. By putting together these constraints Dziembowski and Goode were able to put an upper limit on the possible increase of the solar irradiance due to the solar activity. This limit is shown by yellow line in Figure 3 which also shows the irradiance variations during the past four hundred years assuming

that variations in the past track those over the past two cycles (blue curve), and the changes that could explain the climate variations and might be caused by some unknown long-term processes on the Sun, as suggested by Foukal et al¹³.

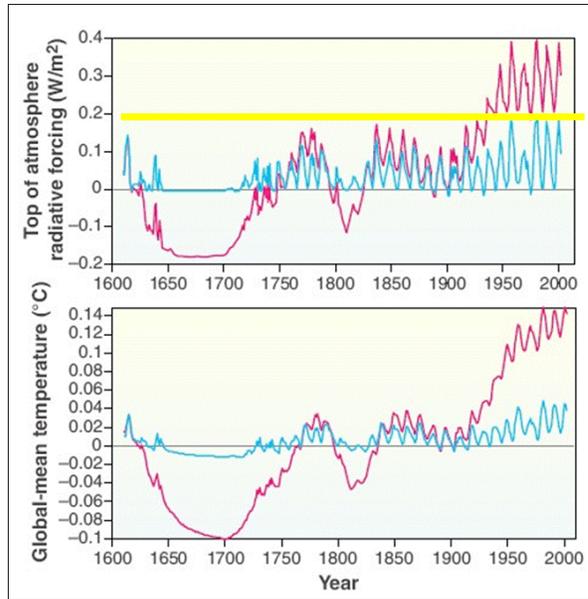


Figure 3. The upper blue curve shows the irradiance variation assuming variations in the past track those over the last two cycles and the red curve includes the putative long term component. Note that from here on we take the terrestrial perspective in which the mean irradiance is about 340 watts/m². This is translated to temperature changes using the NCAR model (paper by Foukal, et al¹³). With the long term trend, one can account for part of the cooling over the first half of the 20th century and the depths of the Maunder minimum. Foukal et al deny the presence of the long-term component on phenomenological grounds (the magnetic network discovered by Hale in the 1890s would have disappearing during the 1920s).

Evidently, the helioseismology limit significantly constraints possible irradiance changes. Now that we understand the physics of irradiance change, we can put a hard lower limit on the irradiance change (yellow line). Increases in irradiance are bound directly by increases in activity. Since higher activity cycles are shorter and there is Greenland ice core data showing a roughly cycle going back 100,000+ years, it is unlikely that the Sun's irradiance over historical times was much greater than it is now. Thus, we are left with a mystery...how can there be terrestrial signatures of the solar cycle when the irradiance changes are too small to matter? It is extremely important to carry out joint helioseismology and irradiance observations on SOHO for the declining phase of the current solar cycle and during the transition to the new cycle.

Changes in the large-scale dynamics (subsurface solar weather) with the solar cycle

New methods of local helioseismology (time-distance helioseismology, helioseismic holography and ring-diagram analysis) provide unique three-dimensional view of the solar interior. The 3-D imaging of the solar interior requires uninterrupted series of stable Dopplergrams of relatively high resolution such as provided by the MDI instrument in the full-disk and high-resolution modes. Attempts to apply these methods (particularly, time-distance helioseismology and helioseismic holography) for analysis of helioseismology data from the ground-based networks have not been as successful as analysis of the MDI data.

Sub-photospheric flow maps provided by these techniques are called "subsurface space weather". SOHO observations revealed a fascinating picture of the large-scale subsurface

dynamics of the Sun, dramatically changing with the solar cycle¹⁴⁻¹⁹. Figure 4 gives an example of the changes in the subsurface flow pattern for two solar rotations during the solar minimum (upper panel) and solar maximum (lower panel).

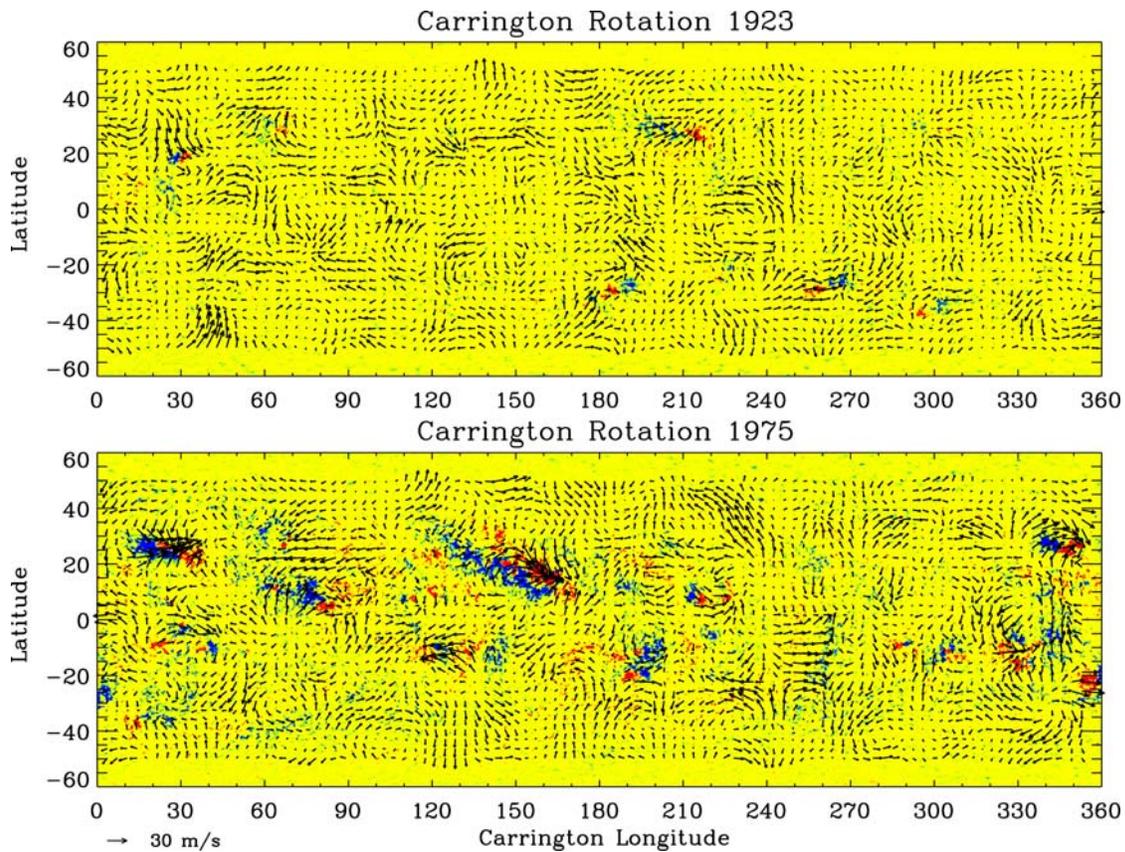


Figure 4. Synoptic maps of large-scale subphotospheric flows obtained from SOHO/MDI during the activity minimum (upper panel) and activity maximum (lower panel). The color background shows the corresponding synoptic maps of the photospheric magnetic field positive (red) and negative (blue) polarities. Evidently, magnetic activity of the Sun is associated with substantial changes of the subsurface flow patterns ('subsurface solar weather').

The synoptic flow maps are obtained from the MDI Dynamics Program run during continuous contacts with SOHO, and represent a valuable source of information about the mechanisms of solar activity in the interior^{15, 18}. These maps are provided to the solar physics community and are being studied along with the traditional synoptic maps of solar magnetic fields and new coronal EUV maps constructed from the SOHO/EIT data²⁰. The synoptic studies of the Sun are particularly important for understanding the basic mechanisms of the solar dynamo and links to the coronal and heliospheric activity.

Global circulation, solar dynamo and prediction of the solar cycle

The internal differential rotation and meridional circulation are the most important components of the solar dynamo. The dynamo models of the solar cycle predict that the toroidal magnetic field of the Sun, which is the source of active regions and sunspots, is generated by the differential rotation and that the polarity of the dipole poloidal field is reverse every 11 years due to the magnetic flux transport to the polar regions by the meridional flow. Helioseismic observations for SOHO/MDI and also from the ground-based network GONG have detected changes in the zonal flow pattern in the convection zone of the Sun²¹, shown in Fig.5.

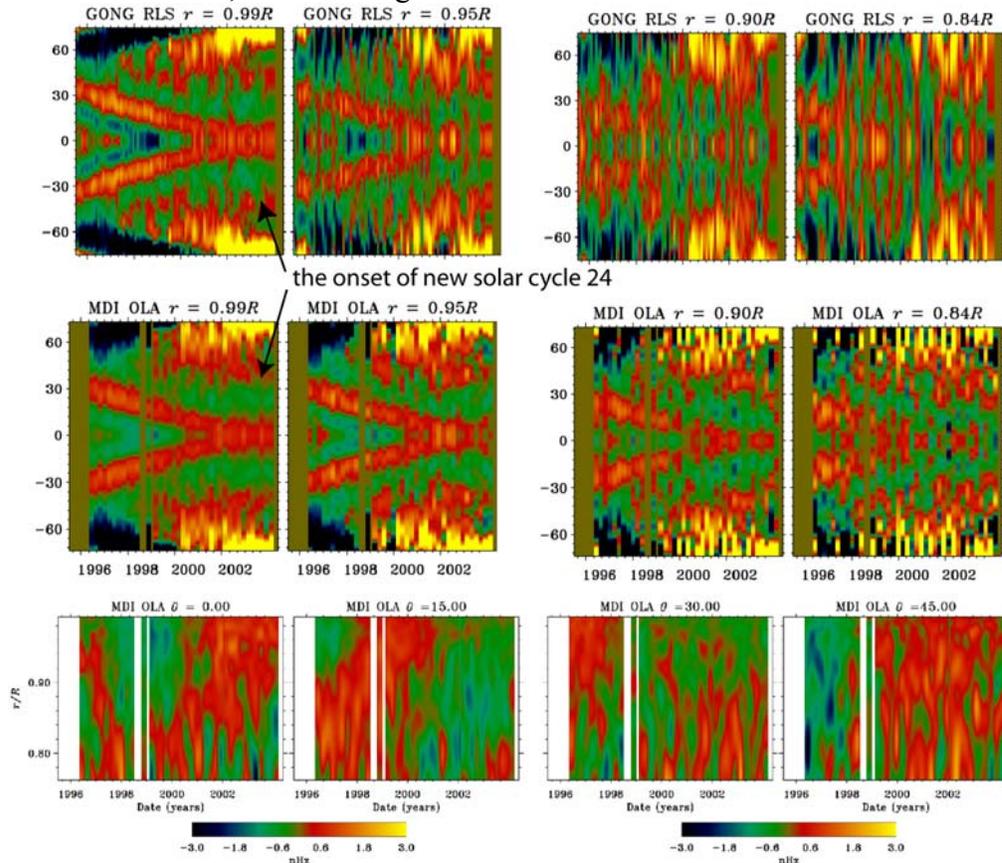


Figure 5. Time-latitude (top and middle panels) and time-radius maps of the zonal flows (“torsional oscillations”) obtained by helioseismic inversions from GONG and MDI data.

The zonal flows play important role for solar activity because active regions tend to appear in the transition shear layers between faster (red) and slower (green) streams. MDI observations (middle and bottom panels) provide better resolution in deeper layers. However, it is essential to continue this type of helioseismology measurements from both MDI and GONG because these independent observations provide confidence in detection of weak but very important features, such as appearance of new branches of torsional oscillations at high latitude in 2002, indicating the onset of the next solar cycle, well before the appearance of sunspot regions of the new cycle. The MDI observations indicate that these new branches originate in the deep convection zone. The origin of the evolving zonal flows is not yet understood.

Meridional circulation of the Sun determined from the synoptic flow maps (Fig.4) in the upper convection zone is shown in Figure 6.

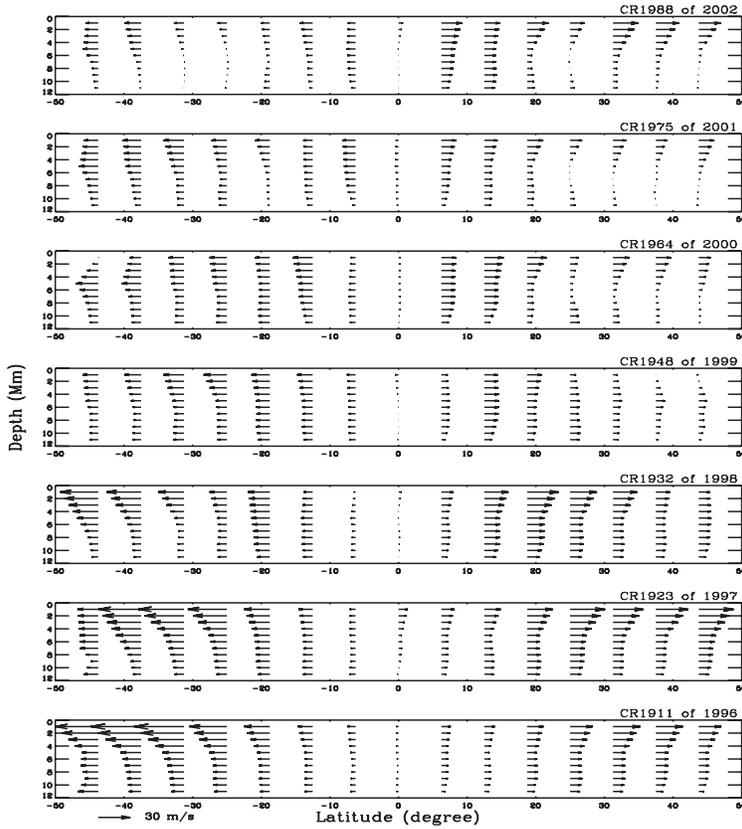


Figure 6. Meridional flow maps in the upper convection zone as a function of depth and latitude for different Carrington Rotation periods in 1996-2002 show substantial decrease of the flow speed during the solar maximum (1999-2002).

These measurements^{19, 22} discovered that the meridional flow slows down as the solar cycle progresses. After the solar maximum in 2001 the flow speed becomes higher again. This discovery is important for the flux-transport dynamo theories which assume that the magnetic polarity reversal in the Sun's polar regions are caused by the transport of magnetic flux by the meridional flow. The slowing down of the meridional flow results in a delay of the next solar cycle. According to the dynamo theory calculations²³ the next solar cycle will start in late 2007 or in 2008 (Fig.7) . This is 6-12 months later then the previously predicted time.

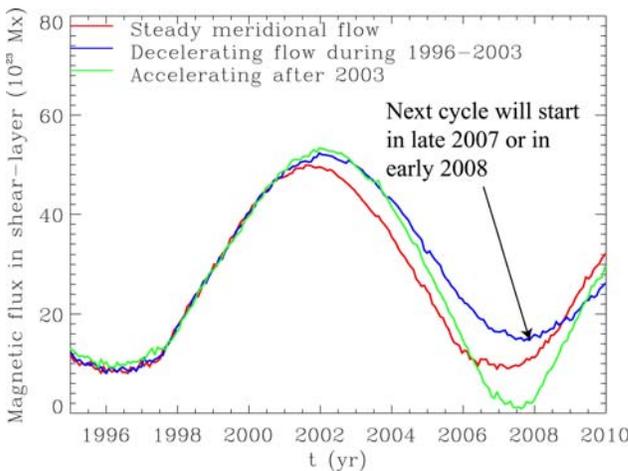


Figure 7. Magnetic field flux calculated using a dynamo model for various models of the meridional flow. The results for the meridional flow determined from the MDI helioseismology data (blue) predict that the near cycle will start in late 2007 or 2008.

Evolution of active regions

Local-domain helioseismic studies have revealed global-scale flows beneath the solar surface. These flows of Solar Subsurface Weather (SSW) are complex and exhibit rich time dependence. Maps of SSW made with ring analysis reveal large-scale patterns of converging and diverging flows, as well as large jets and circulation patterns. Previous studies have observed these phenomena in the vicinity of active regions, but questions remain regarding correlations between flow patterns and active region characteristics. Most active regions show converging flows near the surface but exhibit greater variation at depth (Fig. 8). Some of the active regions are marked by inflows at all depths, some possess surface inflows and deeper outflows, and some show strong jets. Such flow variations among different active regions are quite striking²⁴.

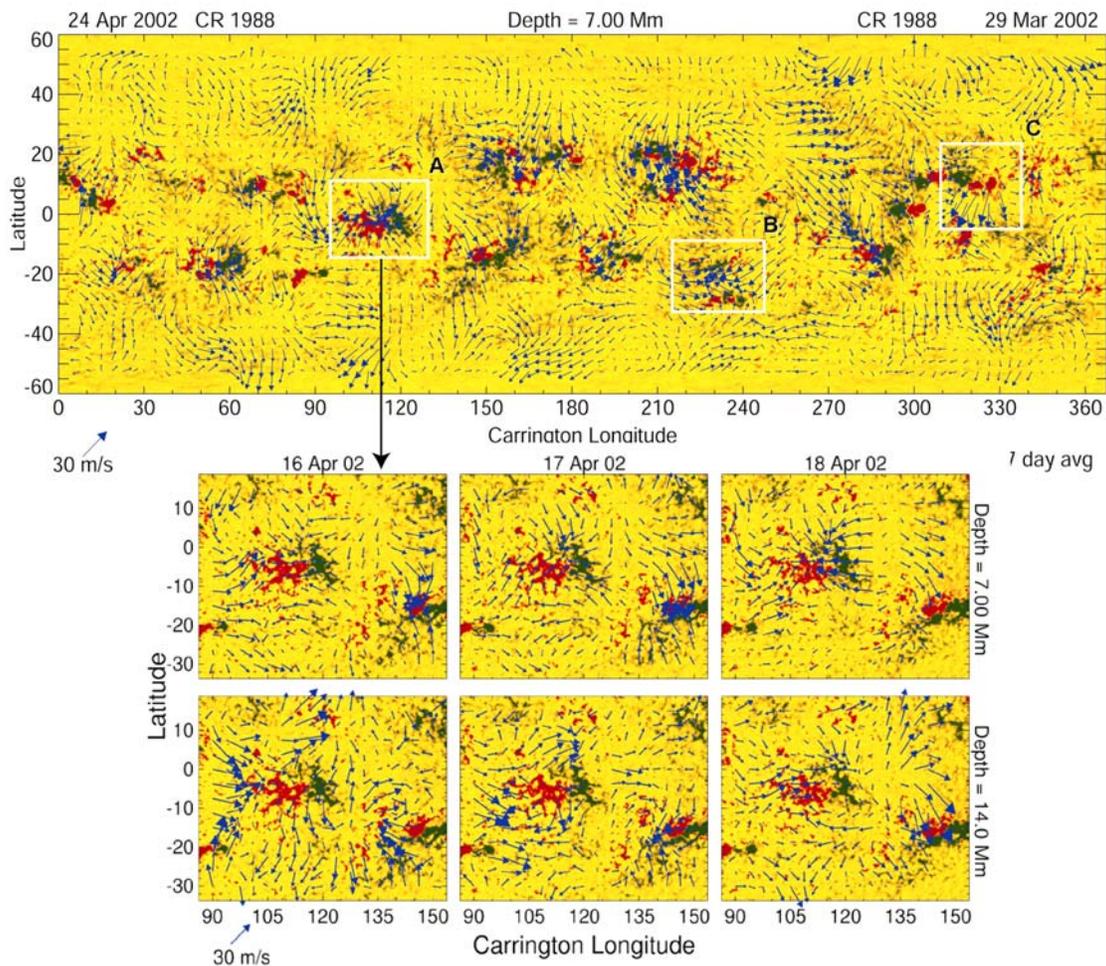
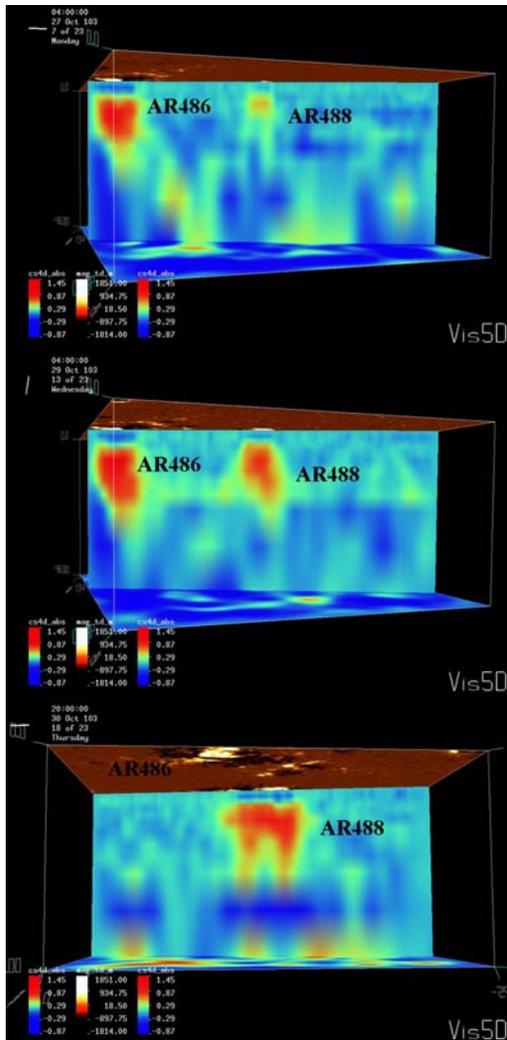


Figure 8. Synoptic maps of subsurface velocity fields at depth 7 Mm (upper panel) obtained from the SOHO/MDI full-disk (Dynamics) data. Large scale flows in the vicinity of active regions display a variety of flow phenomena. Three flow types are shown here: Region A (NOAA 9907) shows converging flow at shallow depths and diverging flow at deeper layers (the lower panels). Region B (9904) is marked by converging flows at all depths. Region C (9885) displays diverging flows at all depths.

We have begun a systematic statistical study of SSW flows around active regions observed during MDI dynamics observing programs. The primary goal is the understanding of the life cycle of active regions and relationship between the internal dynamics of active regions and their magnetic structure and flaring and CME activity at various phases of the solar cycle. Patterns of flow behavior that may precede rapid magnetic reconfiguration are of particular interest to us. Large-scale flows could however lead to a gradual evolution of magnetic topology until a highly unstable configuration is achieved, which then rapidly reconnects.



In addition to the flow fields, local-area helioseismology provides three-dimensional images of sound-speed perturbations associated with developing active regions²⁵⁻²⁷. Figure 9 illustrates the evolution of the sound-speed in the upper convection zone for a large complex of activity in October 2003. This complex of activity produced a series of X-class flares. Analysis of the helioseismology data provide evidence that the large active regions are formed not from a single large Omega-loop structure, but rather as a result of repeated emergence of magnetic flux in the same region from the deep convection zone over extended period of time. The depth of this “nest” zone is not known yet, but it is probably at least 48 Mm deep.

Figure 9. Growth and formation of sunspots of NOAA 10488, October 27-31, 2003, was studied by time-distance helioseismology from SOHO/MDI data. Subsurface sound-speed maps of AR10486-488 (higher sound speed – red, lower –blue; top panel - magnetogram) show formation of a giant loop-like structure as a result of multiple flux emergence events. The lower horizontal panel is 48 Mm deep. The top panel shows the MDI magnetogram.

The ultimate goal of these studies is to reveal the mechanisms of formation and decay of active regions, and predict their growth and lifetime. For this it is necessary to observe more active regions with the MDI Dynamics observing program.

Subphotospheric dynamics of flaring active regions

It is not known at present whether large-scale flows of subsurface space weather contribute to the possibility of flaring and CMEs or whether the real culprits are far smaller scales. Various techniques of local helioseismology are being used to search for subphotospheric processes related to the flaring activity. Of particular interest are measurements of the kinetic vorticity and helicity which may be related to generation of electric currents and magnetic helicity, and also detection of subsurface shearing flows which can cause shear of magnetic field and trigger instabilities. The initial results indeed show evidence for both the helicity variations and shearing flows. While the large-scale helicity variations of active regions can be measured from both MDI and GONG data, the smaller-scale shear flows have been detected only from the MDI data by the time-distance technique.

In the example, shown in Figure 10, Komm et al²⁸ used daily and synoptic flow maps from MDI data covering the disk passage of AR 10486 in October-November 2003. In the synoptic maps, a strong signal in each of the vorticity components and hence in the kinetic helicity is found at the location of the active region during the epoch when the flares occur. This signal is absent from the same location in the synoptic maps before and after the flares occur. In the daily flow maps, a systematic variation in the kinetic helicity was observed at the location of AR 10486 with large values before the flare event and small ones after the event that remain rather constant. These systematic variations in synoptic and daily maps might be subsurface signatures of the flare events.

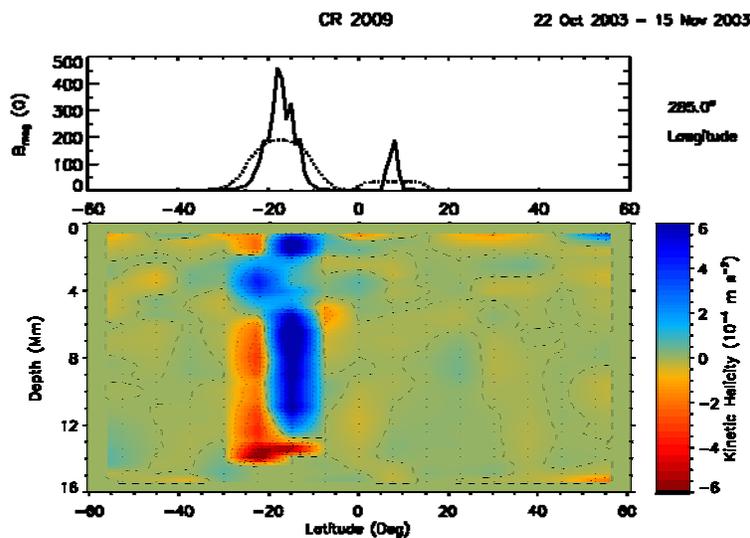


Figure 10. The kinetic helicity at 285° longitude in CR 2009 as a function of latitude and depth. Top: gross magnetic flux (solid curve) and averaged over 15° (dashed curve); bottom: kinetic helicity. The large values coincide with the location of the active region and they are significantly different from zero. The sign of the kinetic helicity remains the same at depths greater than about 5 Mm at the locations of AR 10486. Closer to the surface the sign changes with depth indicating a more complicated behavior.

The subsurface shearing flows in active regions have been detected by the time-distance helioseismology analysis of the MDI data^{29, 30}. These flows are observed at the depth of 4-5 Mm. The typical flow velocity is about 1 km/s. The precise effect of these flows on the structure and stability of magnetic fields of active regions, and their role in triggering flares and CME is not known. More observations, data analysis and numerical modeling

are necessary to establish this. However, the initial results, illustrated in Fig.11 for two solar flares, reveal intriguing flow patterns correlating with the place of flare magnetic energy release around neutral lines of the photospheric line-of-sight magnetic field.

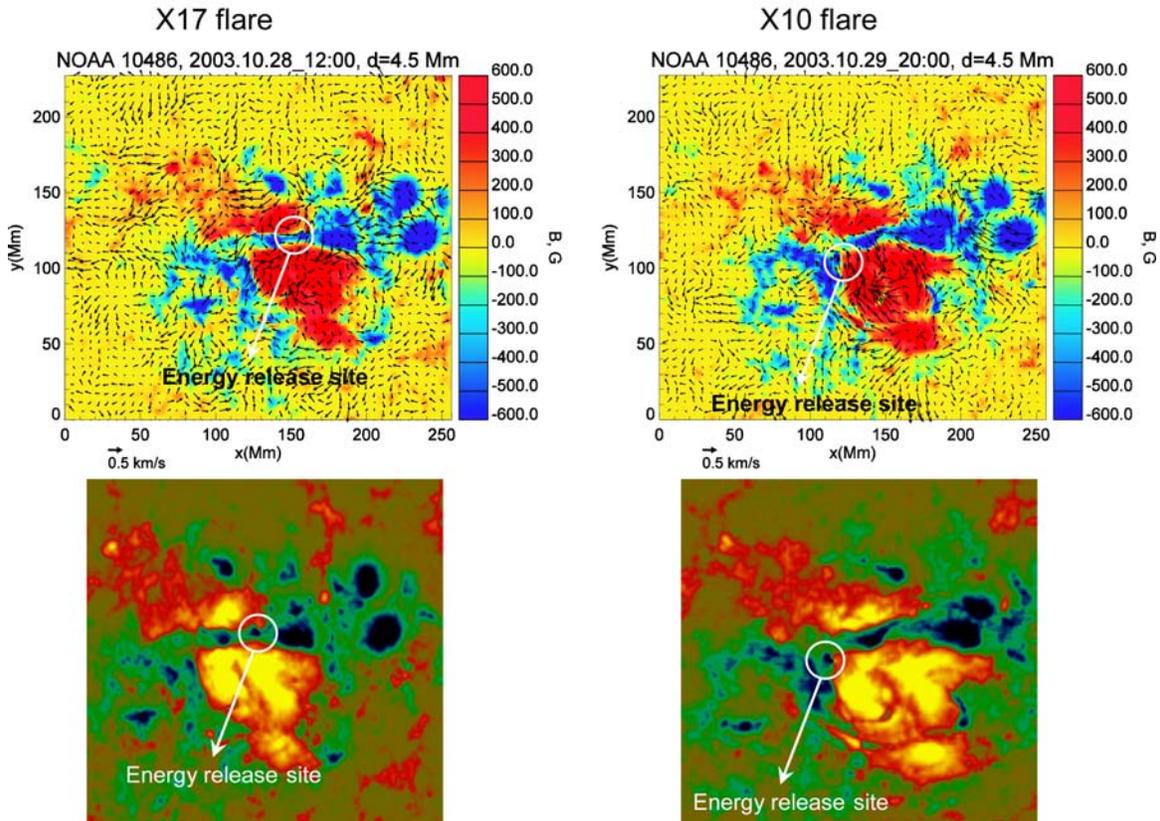


Figure 11. High-resolution maps of subsurface plasma flows obtained by time-distance helioseismology (top panels) and MDI magnetograms (background top and bottom images) during two solar flares: left, X17 (Oct. 28, 2003, 11:10 UT) and X10 flare (Oct. 29, 2003, 20:37 UT) During the flare strong plasma flows are observed at depth 4-6 Mm, shearing and converging in the magnetic neutral line region where the magnetic energy was released.

It appears that the shearing flows tend to appear in the neutral line regions where the magnetic field changes permanently during the impulsive phase of the solar flares. These observations indicate that the critical coupling between the subphotospheric plasma flows and magnetic fields happens at the depth of 4-5 Mm, and, thus, this region requires further detailed investigation, both from SOHO/MDI and theoretically by MHD simulations such as carried out by the CISM project.

Seismic response to solar flares

The seismic response to solar flares (“sunquakes”) is of significant interest because this phenomenon provides new information about the energy release and transport in solar flares, and also because of their potential for helioseismic diagnostics of sunspots and active regions. The sunquakes result in circular expanding waves on the Sun’s surface. The first sunquake was observed for a flare of July 9, 1996, the last X-class flare of the previous solar activity cycle and the first flare observed by SOHO³¹. However, subsequent observations from SOHO did not show new sunquakes since the start of the current solar cycle in 1996 until 2002.

The first evidence of the seismic flare signal in this solar cycle was obtained indirectly, through so-call “egression power” or changes in the oscillation power spectrum³². An example of the egression power maps obtained by the method of helioseismic holography from SOHO/MDI data is shown in Figure 12.

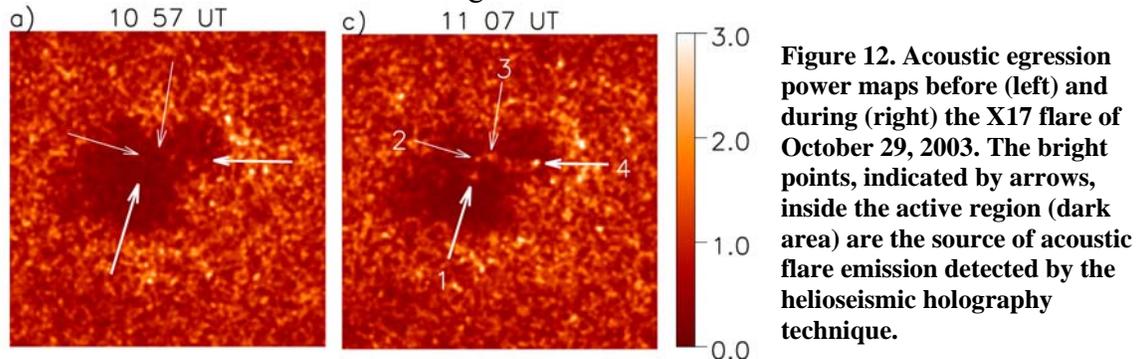


Figure 12. Acoustic egression power maps before (left) and during (right) the X17 flare of October 29, 2003. The bright points, indicated by arrows, inside the active region (dark area) are the source of acoustic flare emission detected by the helioseismic holography technique.

This flare of October 28, 2003, was the first flare of the current solar cycle, which produced seismic waves observed from SOHO/MDI. The upper panels of Figure 13 show the observational results for this flare. The left top panel shows a superposition of the MDI white-light image of the active region and the difference between two MDI Dopplergrams taken during the impulsive phase of this flare (11:03:30 and 11:02:30 UT). The Dopplergram difference shows the location of the initial flare impacts in the photosphere. The middle top panel shows the Dopplergram difference at 11:35 UT, which reveals two semi-circular fronts of expanding seismic waves. The top right panel shows the time-distance diagram for the first wave propagating South-East. The other panels of Figure 13 illustrate the sunquake events for two other flares of July 16, 2004, and January 15, 2005. The comparison of the sunquake images with RHESSI observations reveals a close association between the flare seismic waves and the hard X-ray source, indicating that high-energy electrons accelerated during the flare impulsive phase produced strong compression waves (shocks) in the photosphere, causing the sunquake³³. Figure 14 illustrate this sequence of events for the January 15, 2005, flare, from top to bottom. The high-energy electrons accelerated in the flare (presumably, high in the corona) produced hard X-ray impulse in the lower atmosphere and generated downward propagating shocks which hit the photosphere and generated the seismic waves.

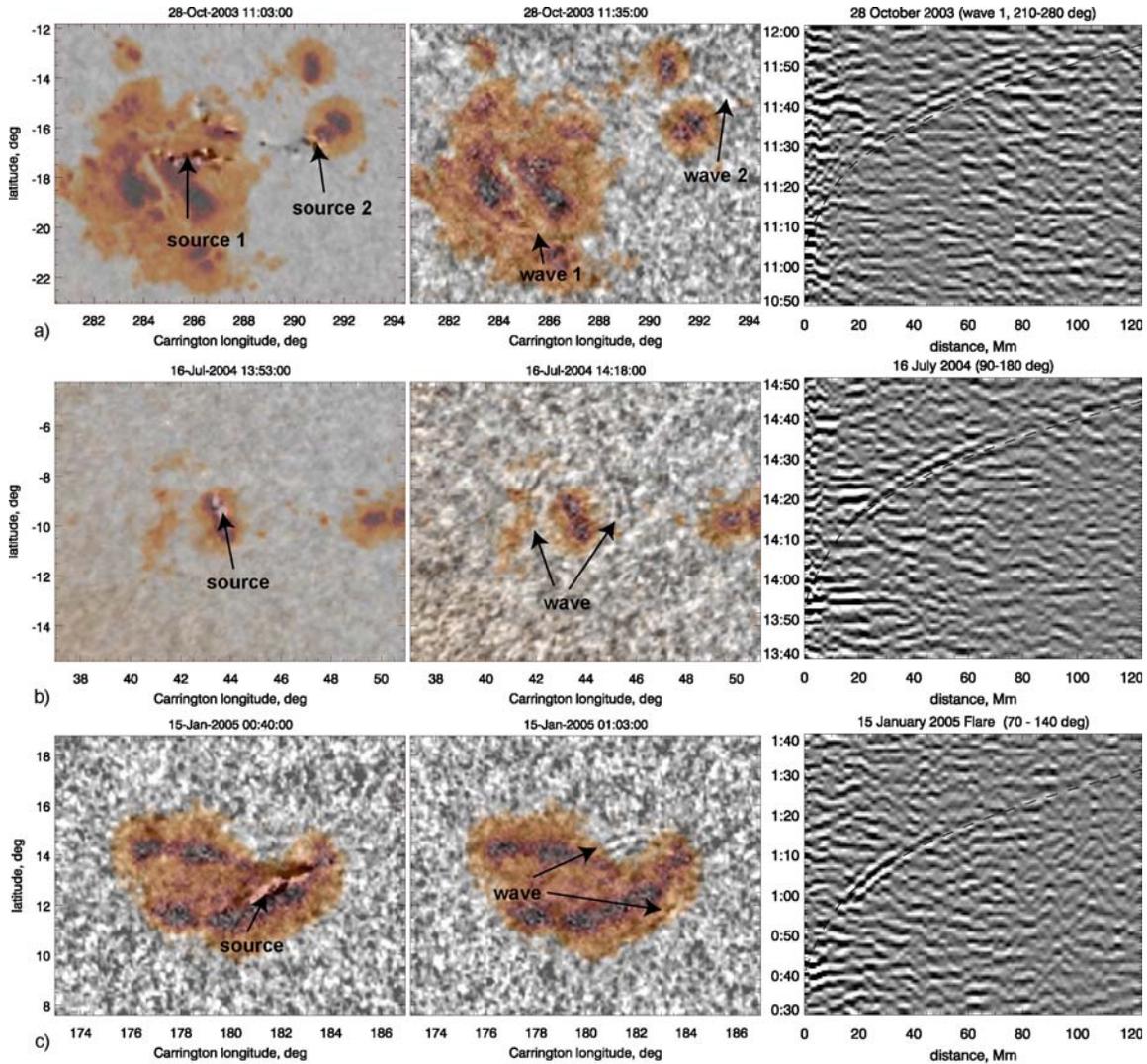
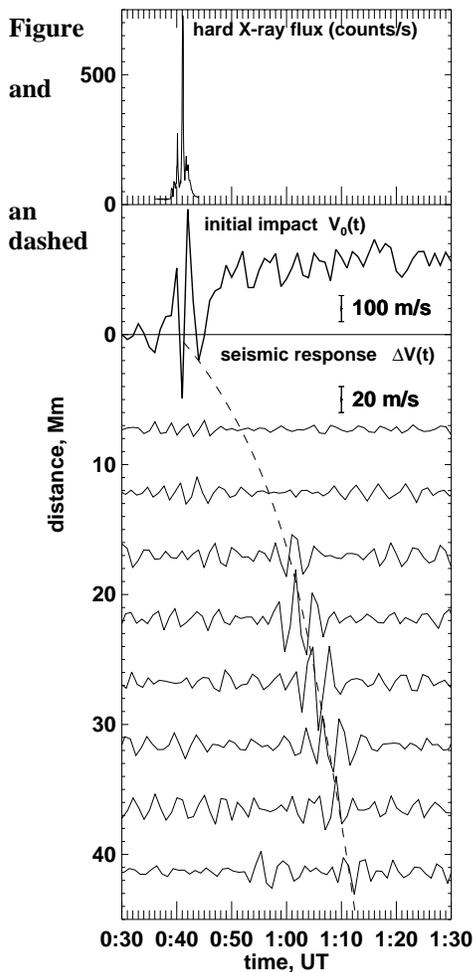


Figure 13. Observations of the seismic response of the Sun (“sunquakes”) to three solar flares: X17 of October 28, 2003 (top panels), X3 of July 16, 2004 (middle panels) and X1 flare of January 15, 2005. The left panels show a superposition of MDI white-light images of the active regions and locations of the sources of the seismic waves determined from MDI Dopplergrams, the middle column shows the seismic waves, and the right panels show the time-distance diagrams of these events. The dashed curve is a theoretical time-distance relation for helioseismic waves.

These new observations from SOHO and RHESSI provide unique information about the interaction of the high-energy particles accelerated in solar flares with solar plasma and the dynamics of the solar atmosphere during solar flares. These data also provide unique information about the interaction of acoustic (MHD) waves with sunspots, showing explicitly propagation of wave fronts through sunspot regions. This opens opportunity for developing new methods of helioseismology analysis of flaring active regions, similar to the methods of Earth-quake seismology.



14. The sequence of events during the flare of January 15, 2005. High-energy electrons accelerated in the solar flare interact with the lower atmosphere, producing hard X-ray emission (observed by RHESS) and shocks – initial hydrodynamic impact in the photosphere (observed by SOHO/MDI). Then, about 20 min after the initial impact expanding seismic wave was detected by SOHO/MDI. The curve shows a theoretical relation for helioseismic waves.

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