A Fast-Moving Wave Implying Acoustic Wave Sources beneath Sunspots Surface

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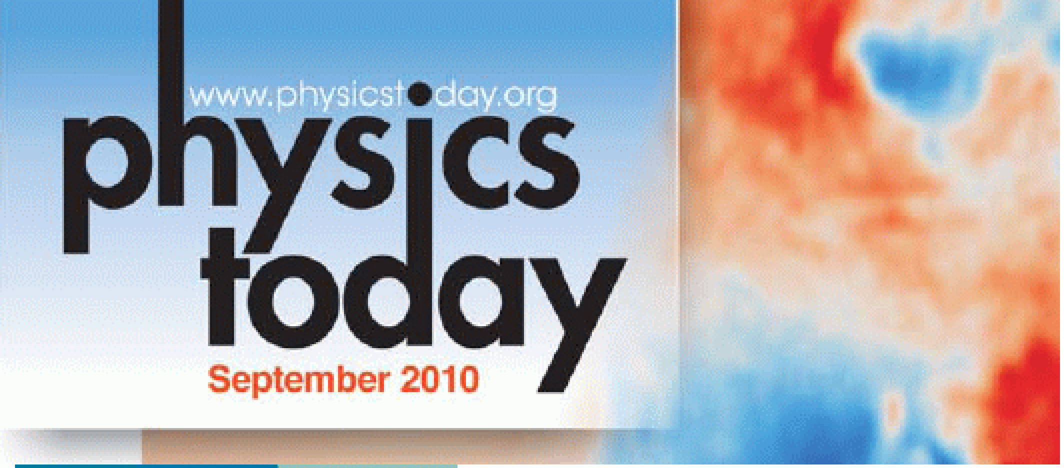
Reconstructing how waves propagate by computing cross-correlations has become a popular practice in geo- and helioseismology



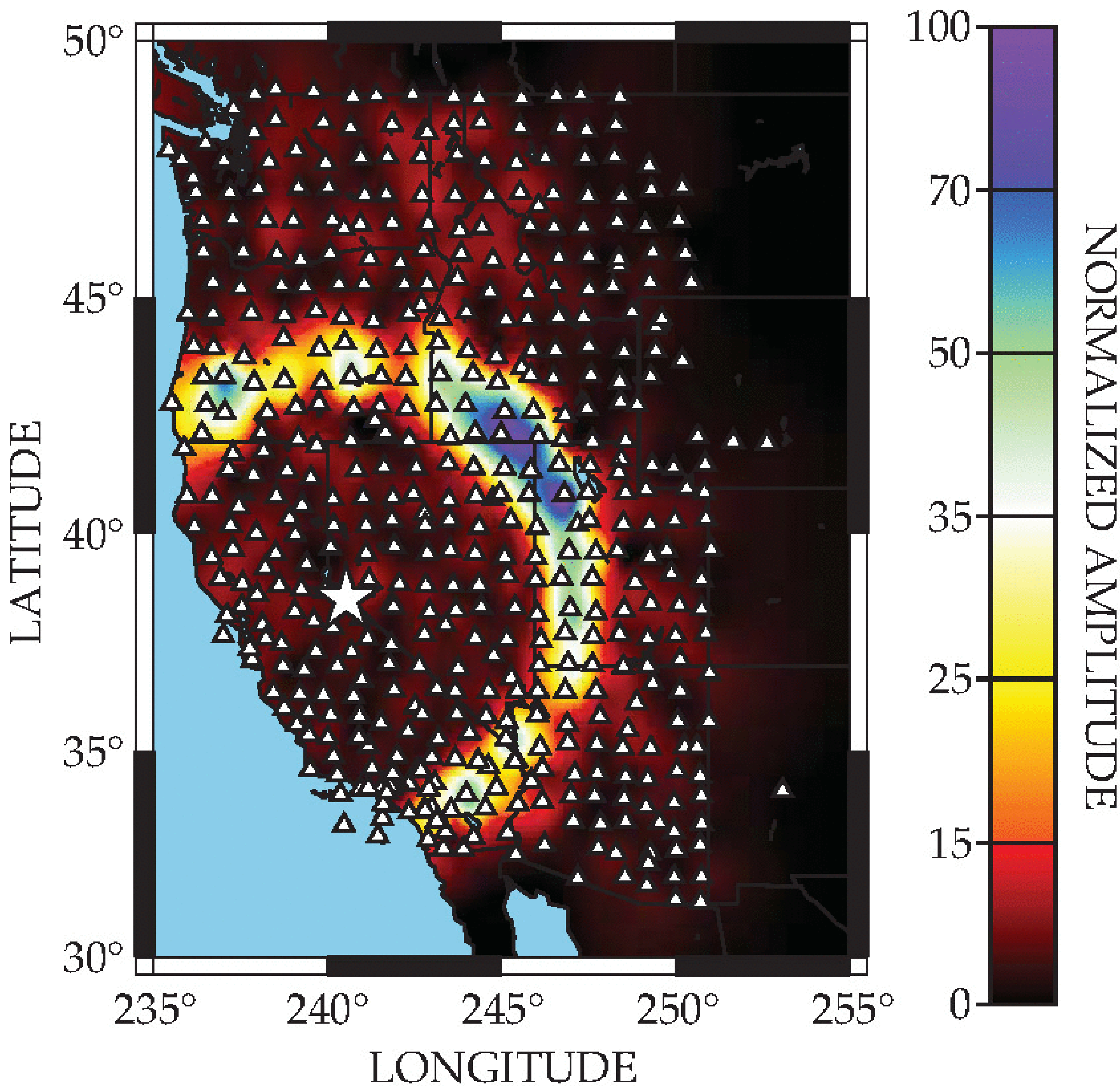
feature article

Imaging with ambient noise

Roel Snieder and Kees Wapenaar

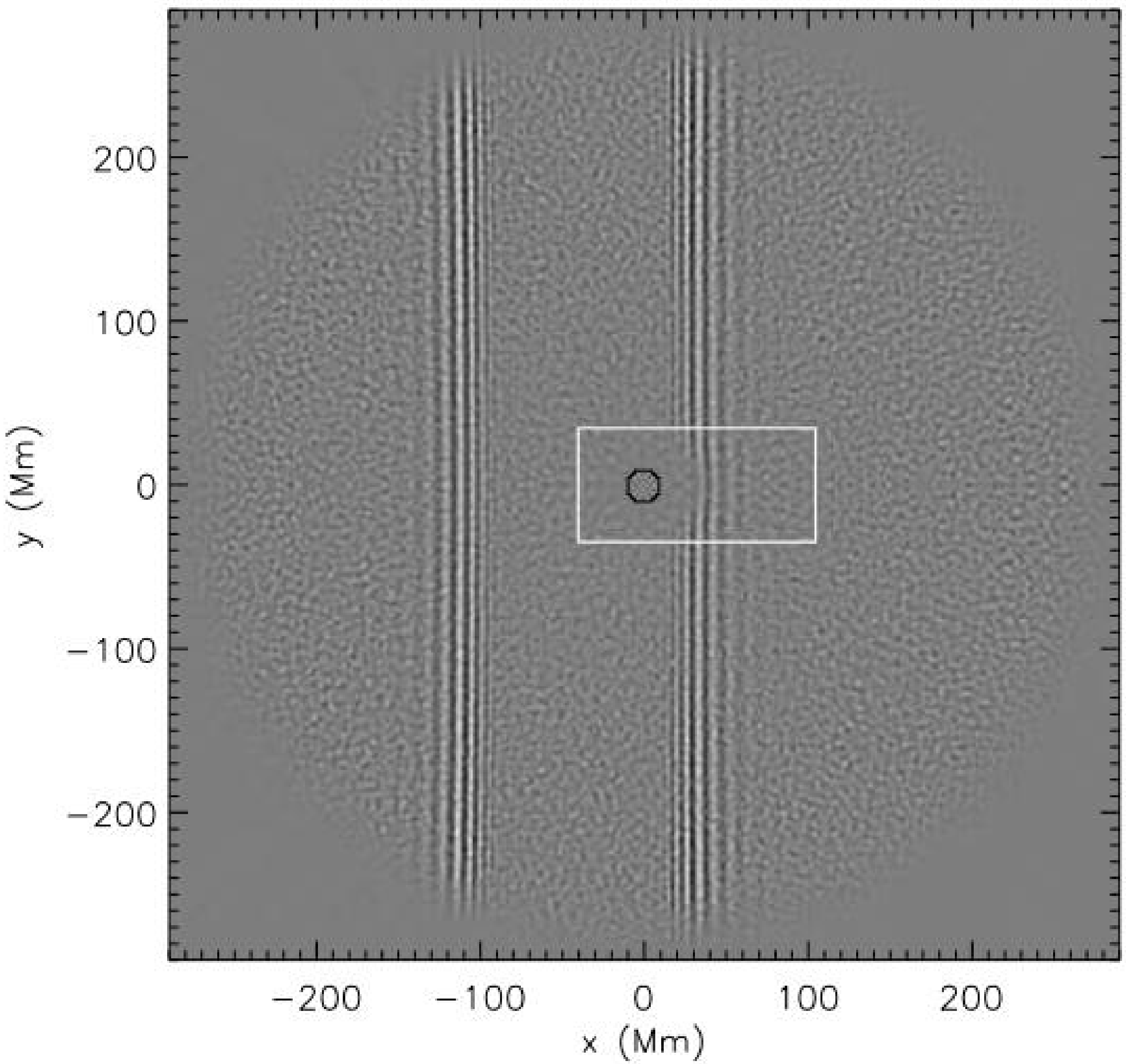
Whether noise is a nuisance or a signal depends on how it's processed. By cross-correlating noise recorded at two sensors, researchers can retrieve the waves that propagate between them and extract details about the intervening medium.

Roel Snieder is the W. M. Keck Distinguished Professor of Basic Exploration Science and director of the Center for Wave Phenomena at the Colorado School of Mines in Golden. **Kees Wapenaar** is a professor of applied geophysics at Delft University of Technology in Delft, the Netherlands.



Through cross-correlating seismic noise signals, generated by ocean waves and recorded by US Seismic Array, one is able to reconstruct seismic waves as if an earthquake happens at Lake Tahoe.

Reconstructing Helioseismic Waves



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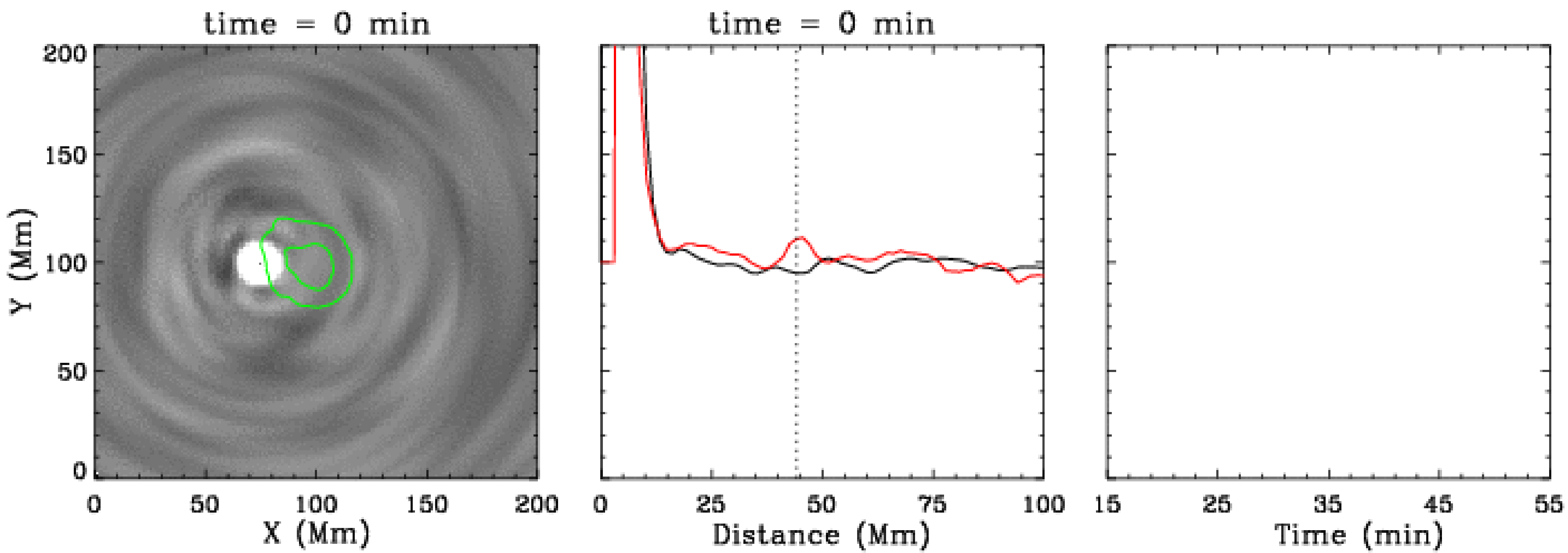
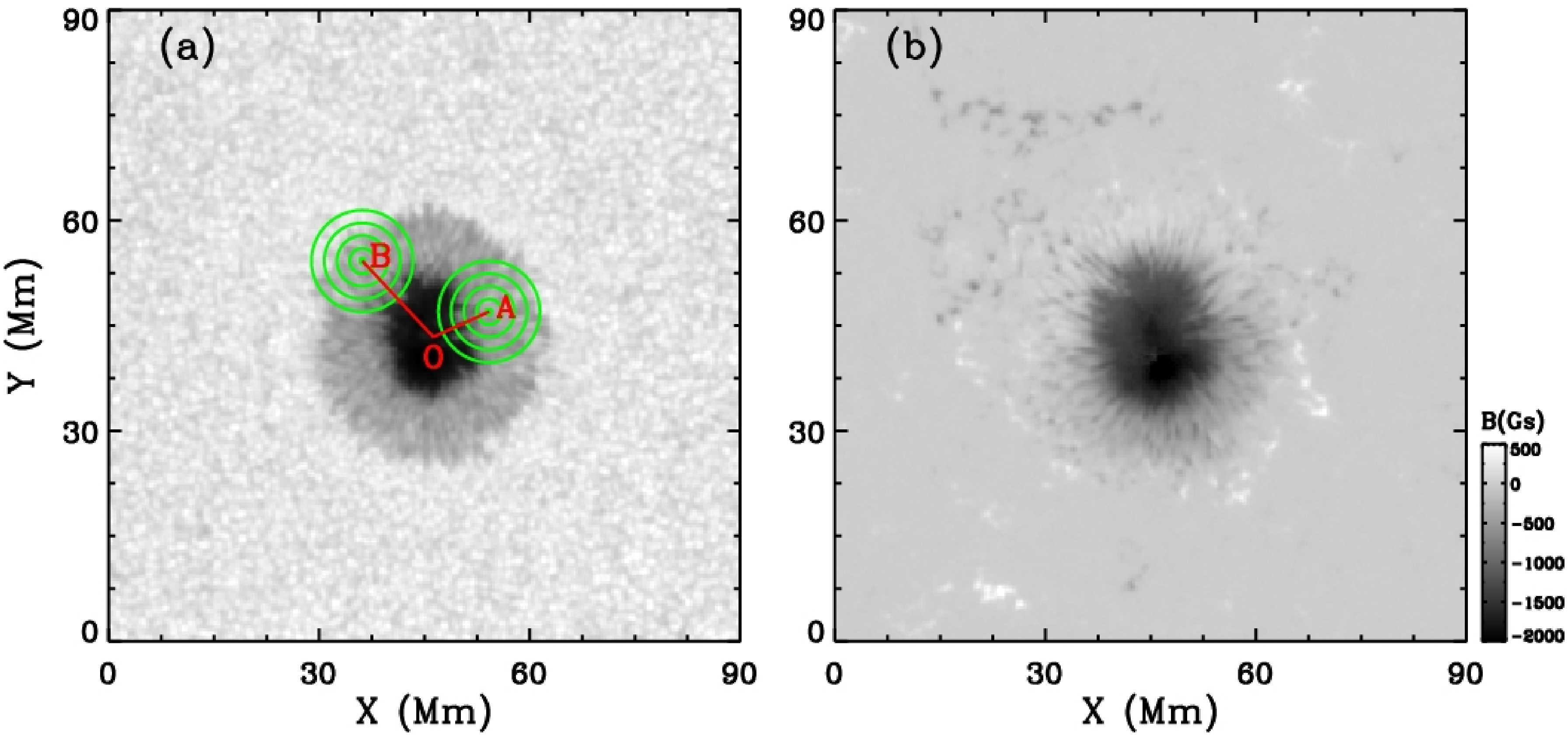
Reconstructed Wave from A Virtual Source: How Acoustic Wave Interacts with A Sunspot



Left: Reconstructed helioseismic wave, excited at the boundary of the sunspot, showing how helioseismic wave interacts with a sunspot. *Middle*: A horizontal cut through the sunspot center from the left panel. *Right*: Oscillations seen at the wavefront passing the sunspot center (*Zhao et al. 2011*, *Solar Physics*).

Wave Sources inside Sunspots

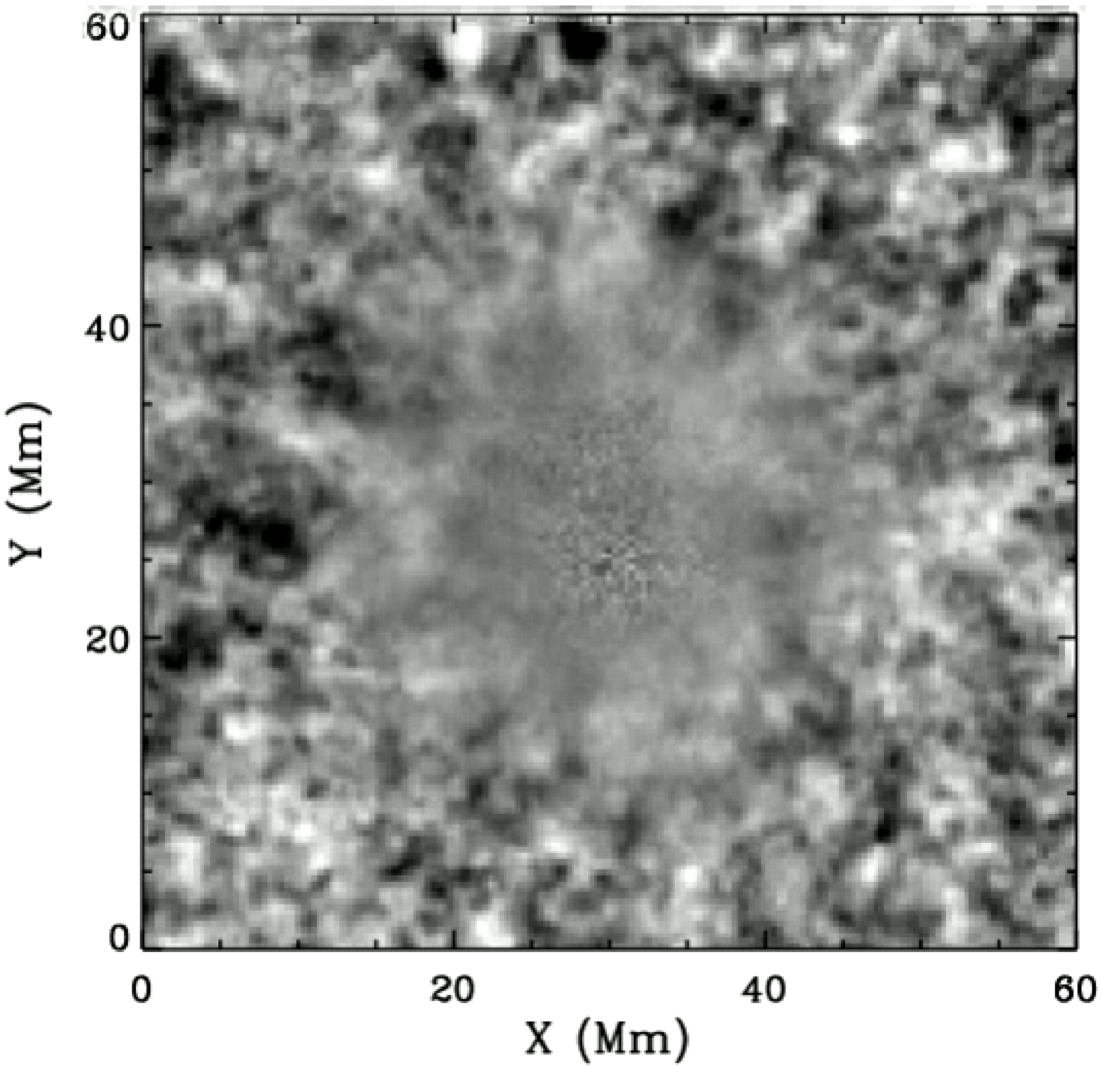


Theoretically, one is able to reconstruct how waves propagate away from every single location inside the sunspot. But practically, due to the limited observational time and other noises, one is only able to study reconstruct the waves using all locations inside the sunspot. To do that, one needs to overlap points *A* and *B*, rotate the wavefield to align directions of *OA* with *OB*, and then average wavefields from these two sources. Repeat for all locations.

Data

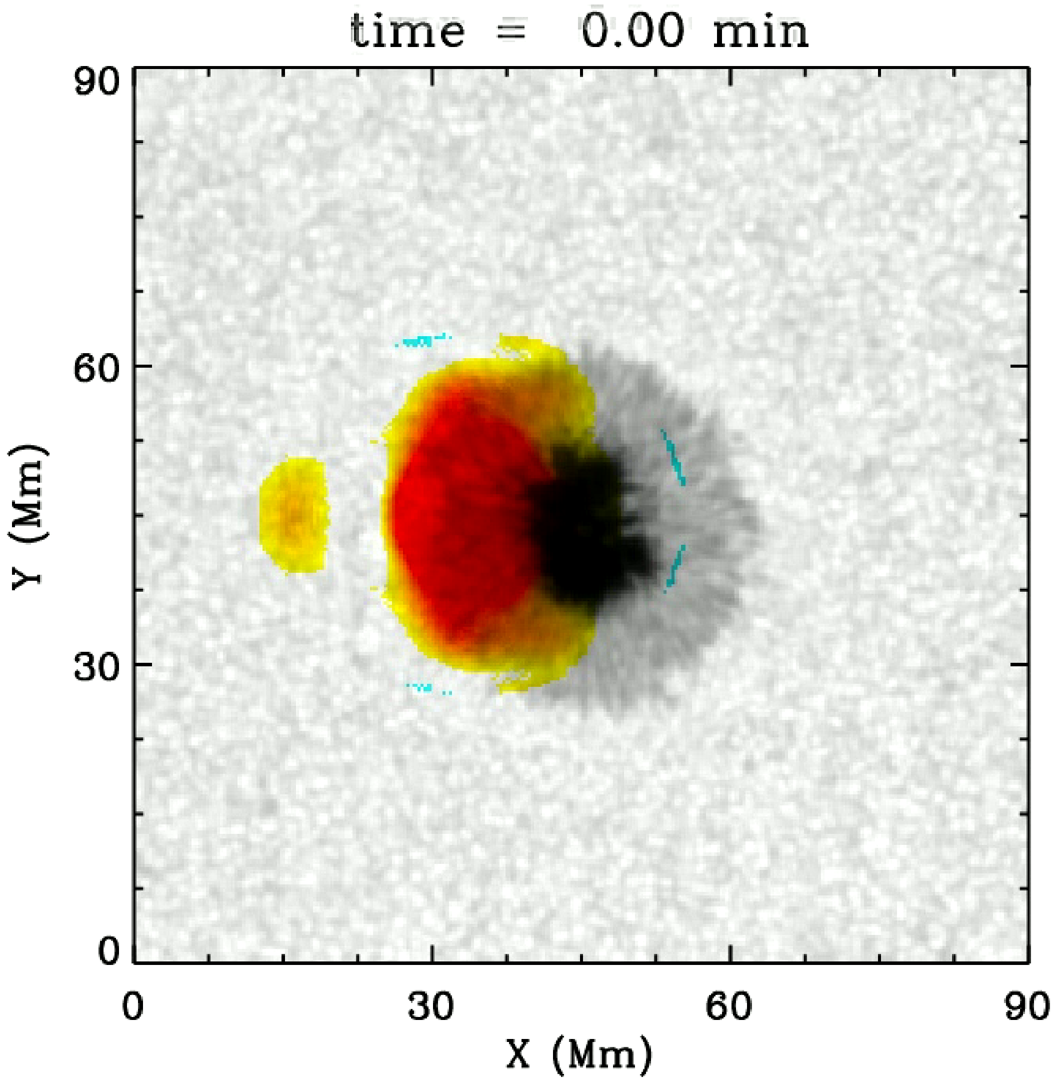
- The sunspot, located inside AR11312, is round (i.e., presumably axisymmetric) and stable during its passage through the disk. We use 5 days' continuous observations, from 2011 October 8 to 12, of HMI and AIA to analyze.
- HMI Doppler velocity gives the best S/N, and most results presented here are from the Doppler velocity.
- HMI line-core intensity, line-depth, and continuum, and AIA 1700Å data are also used. Result are qualitatively similar to those using Doppler.
- Waves from sunspot umbra and penumbra are qualitatively similar regarding the properties of the waves we discuss. In the following, we only present results from the penumbra, as it gives better S/N.

Doppler Velocity: Running Differences



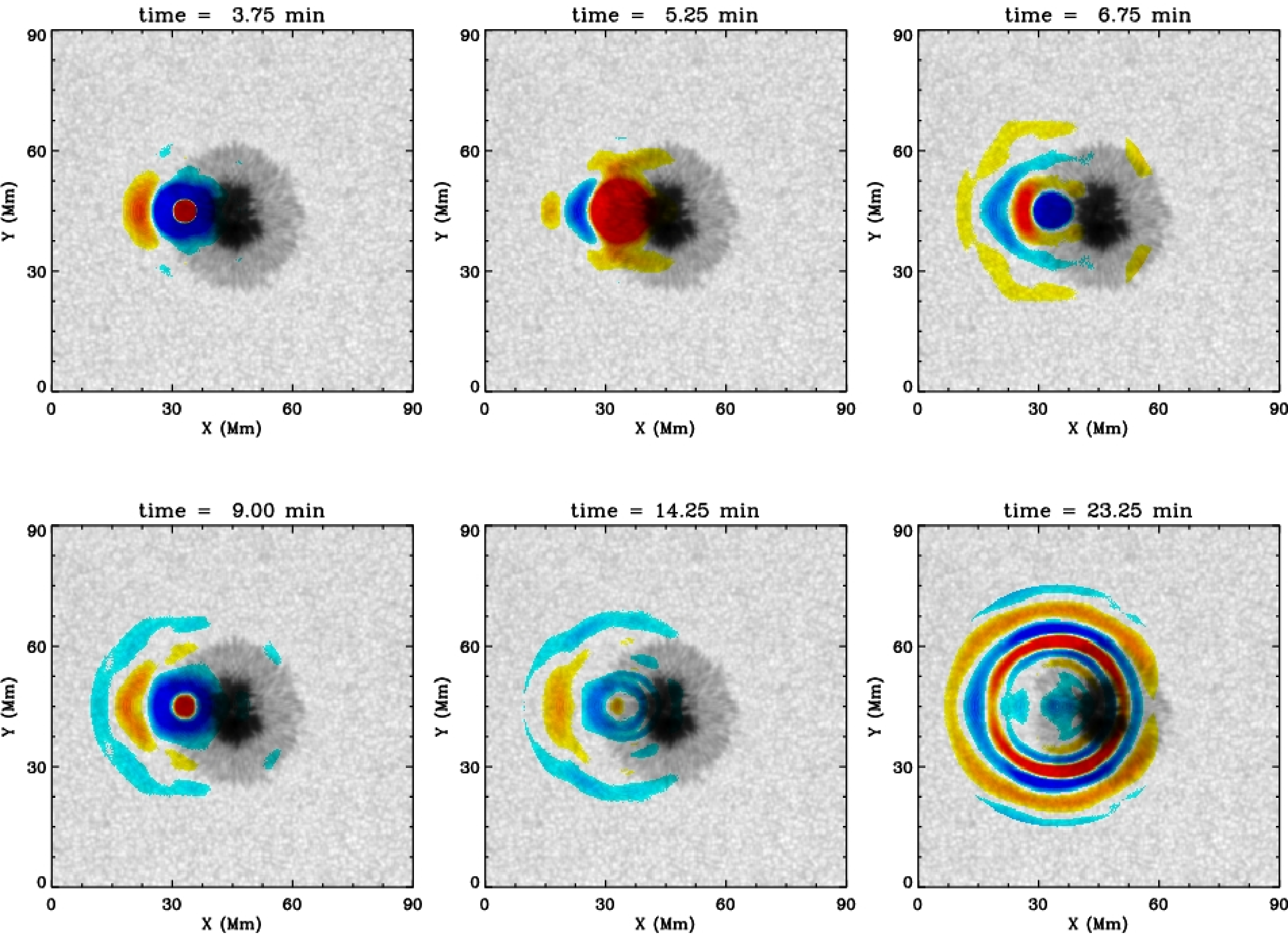
Movie of Doppler velocity basically shows acoustic wave propagating into the sunspot region. That is because waves traveling into the sunspot often have stronger amplitudes than waves traveling out.

Fast-Moving Wave from Inside to Outside of the Sunspot



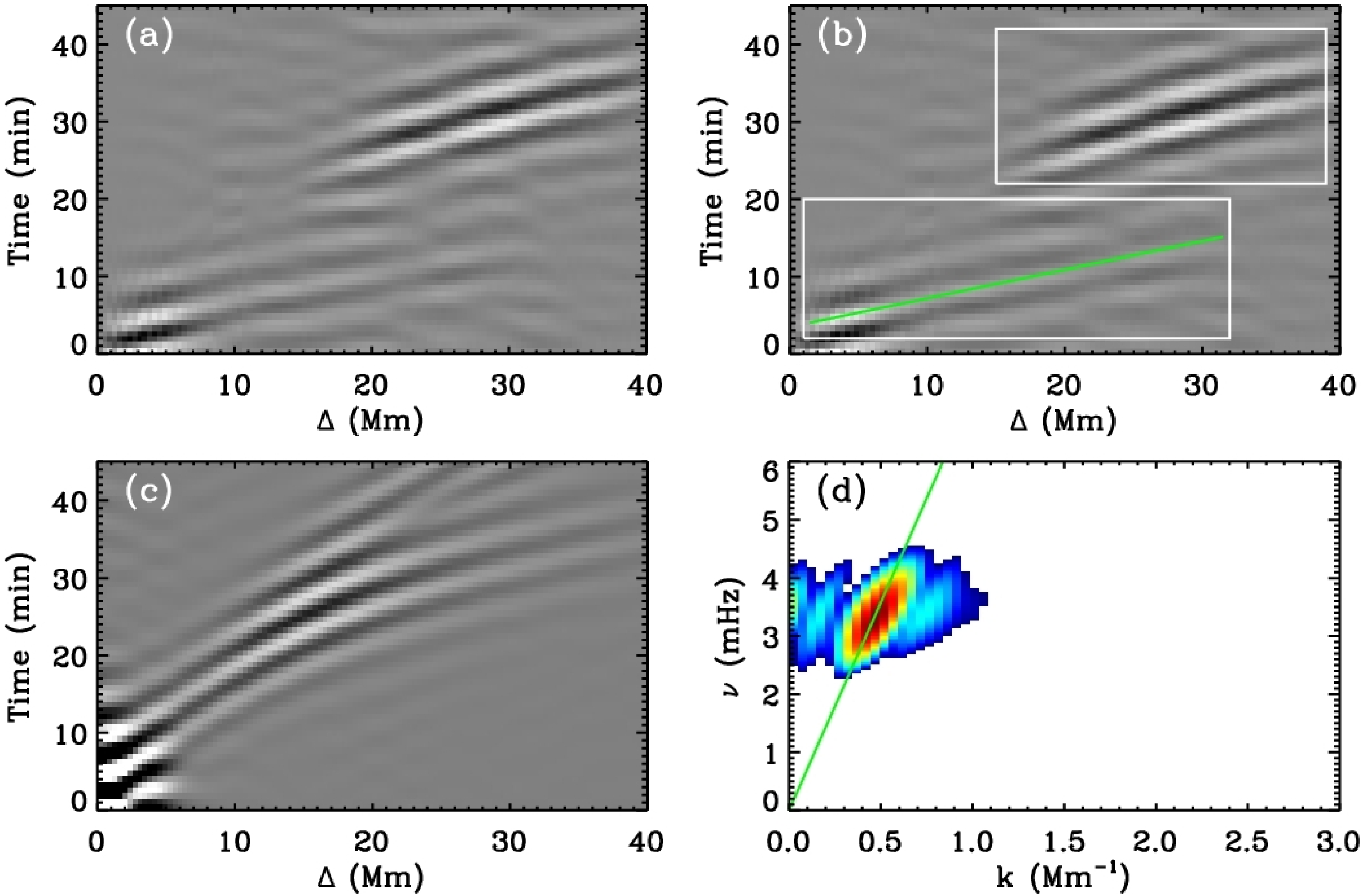
1. Two types of waves are visible: one is fast-moving wave along the sunspot's radial direction, and the other is helioseismic wave traveling in all directions.

2. The fast-moving wave seems to terminate at about 30 Mm from the sunspot center, or 15 Mm beyond the sunspot boundary.

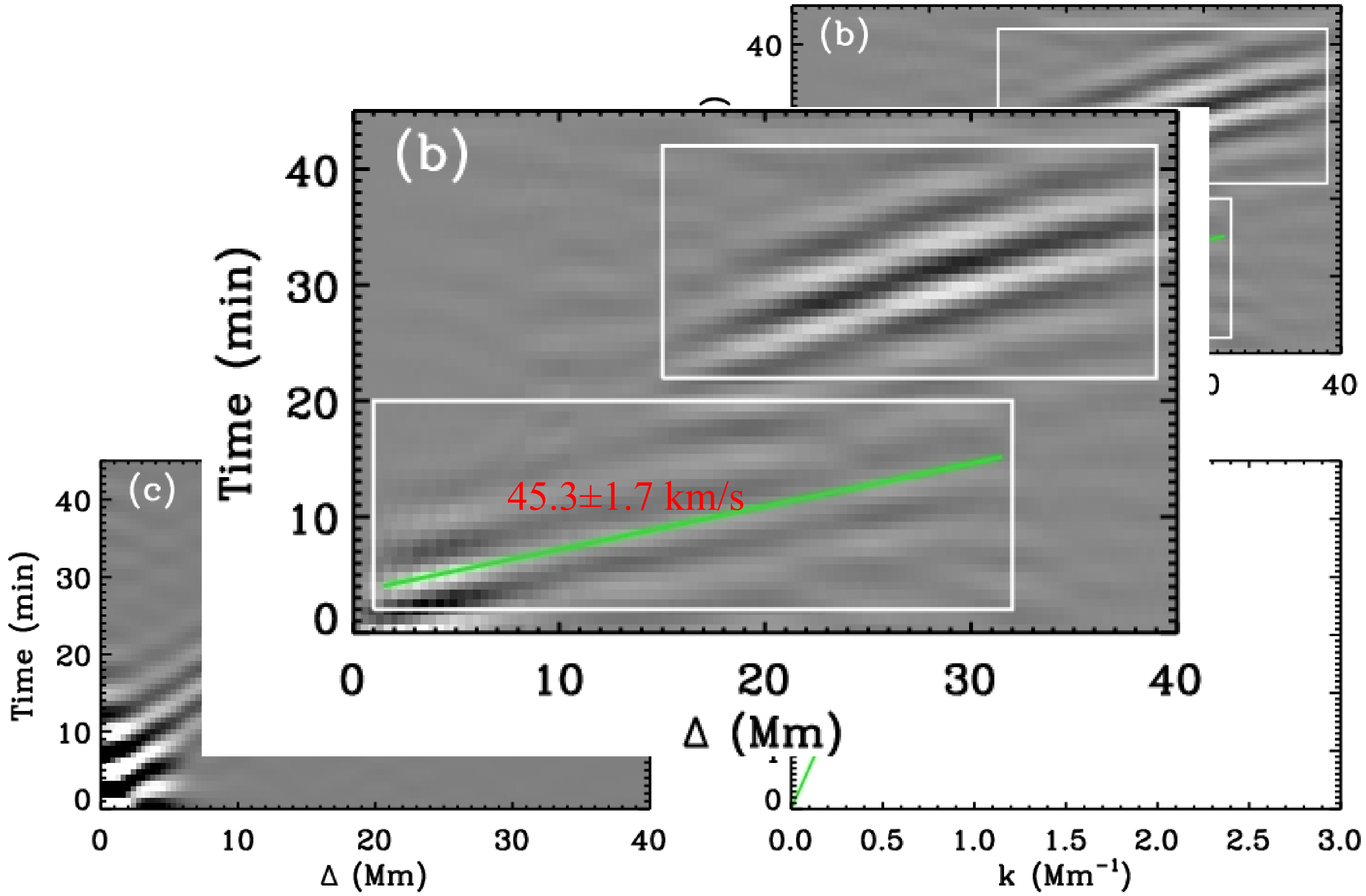


time = 3.75 min
time = 5.25 min
time = 6.75 min
time = 9.00 min
time = 14.25 min
time = 23.25 min
Y (Mm)
X (Mm)
0
30
60
90

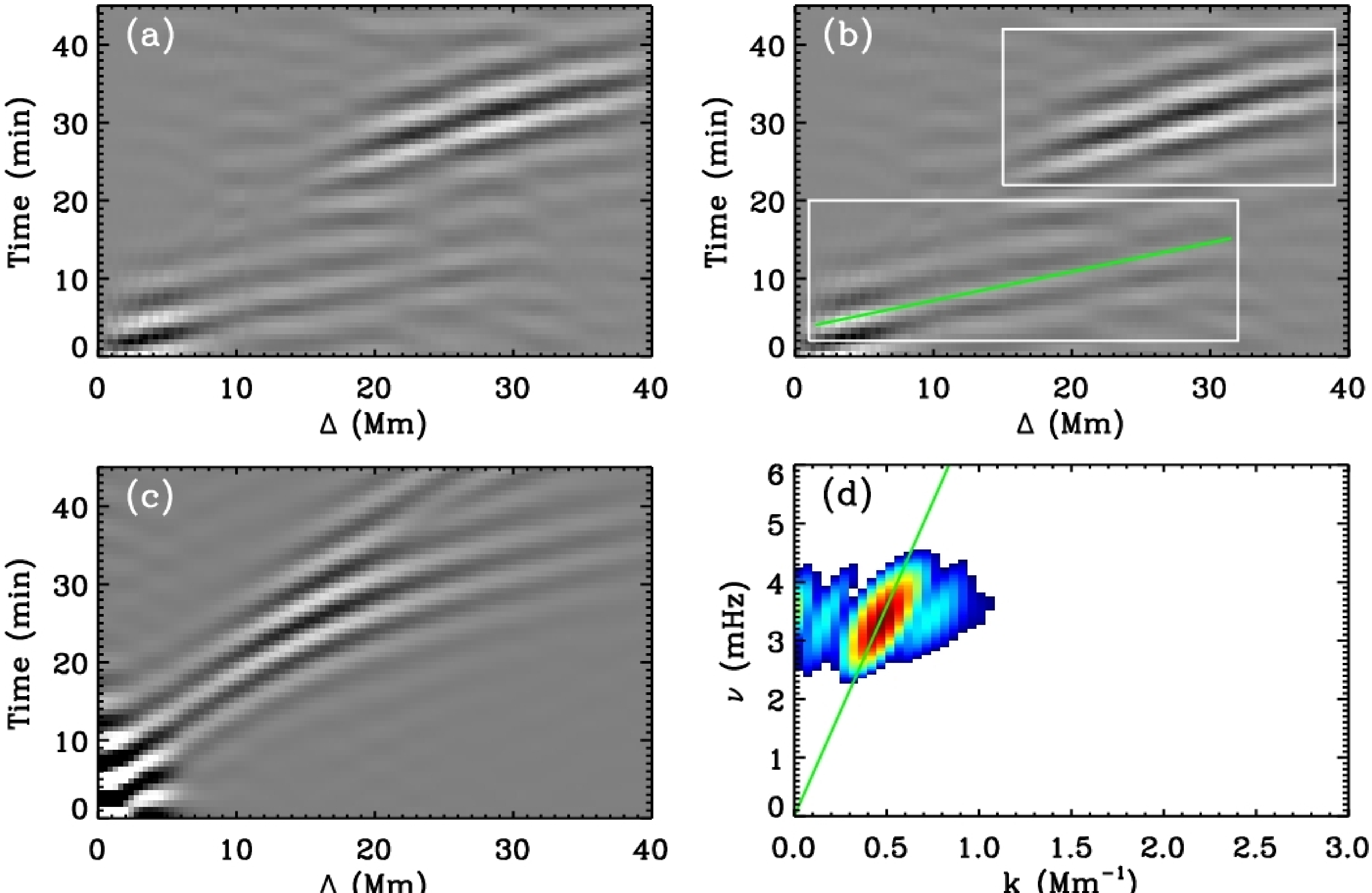
Time-Distance Relation and Power Spectrum



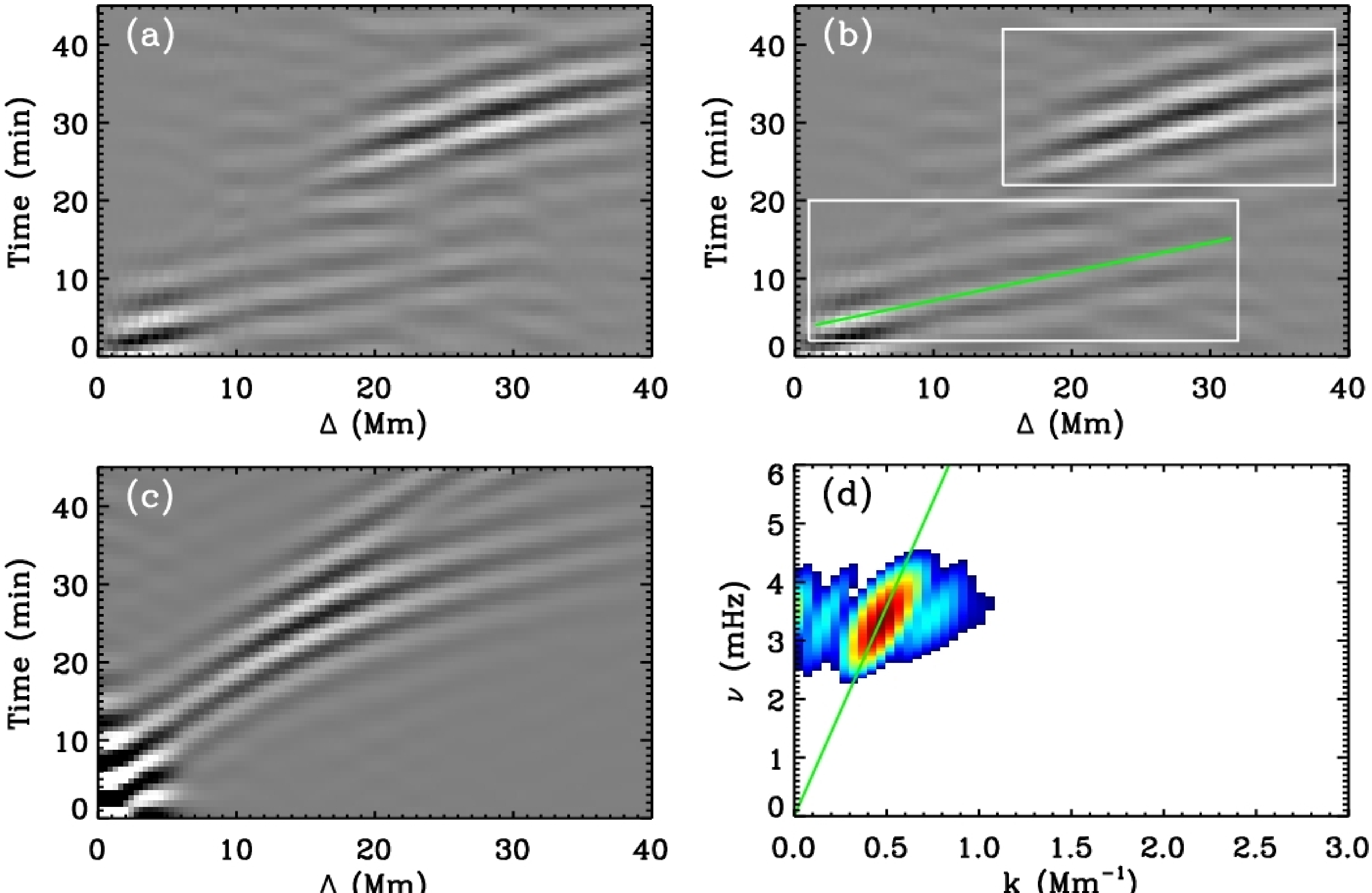
Time-Distance Relation and Power Spectrum



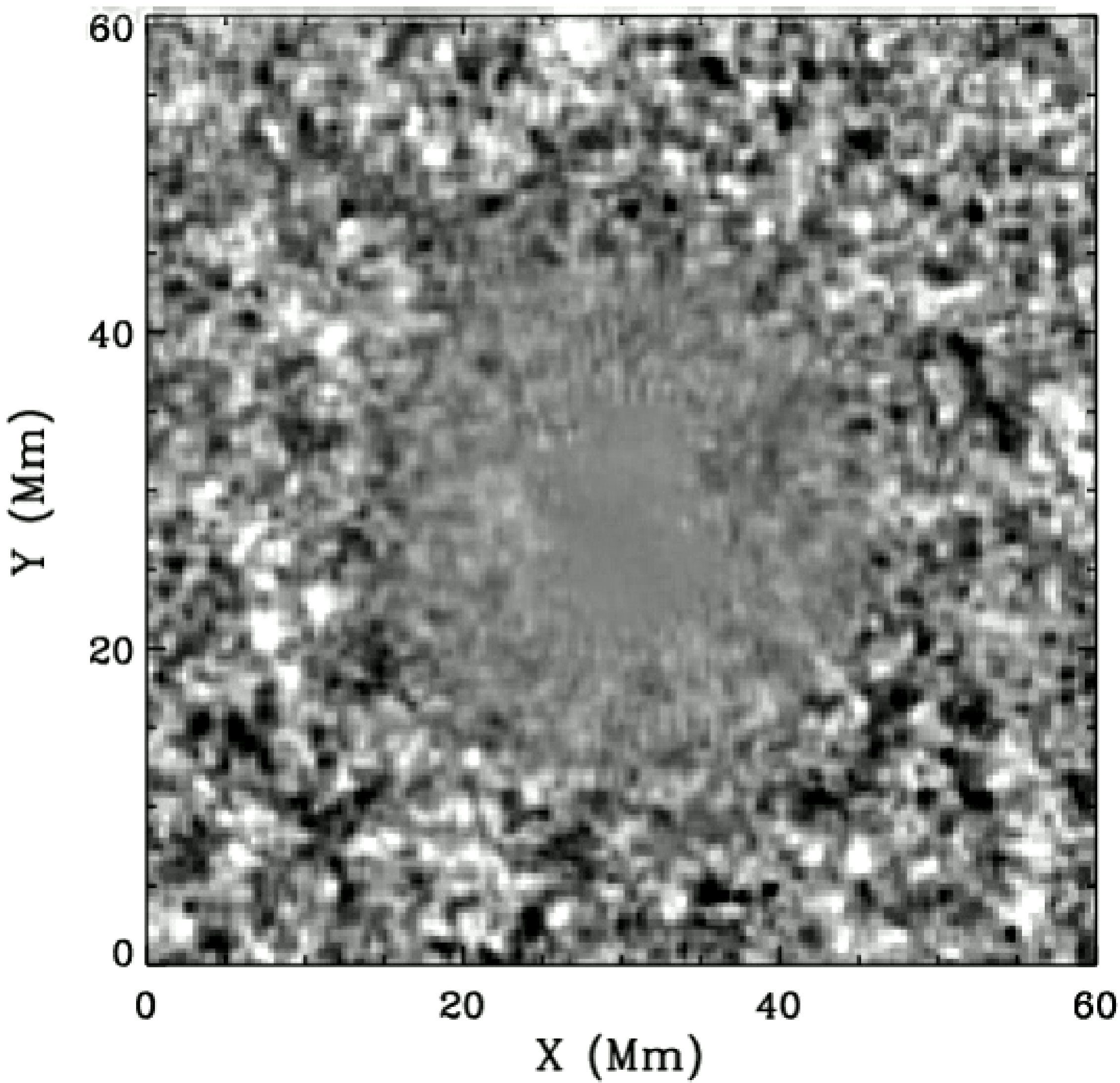
Time-Distance Relation and Power Spectrum



Time-Distance Relation and Power Spectrum

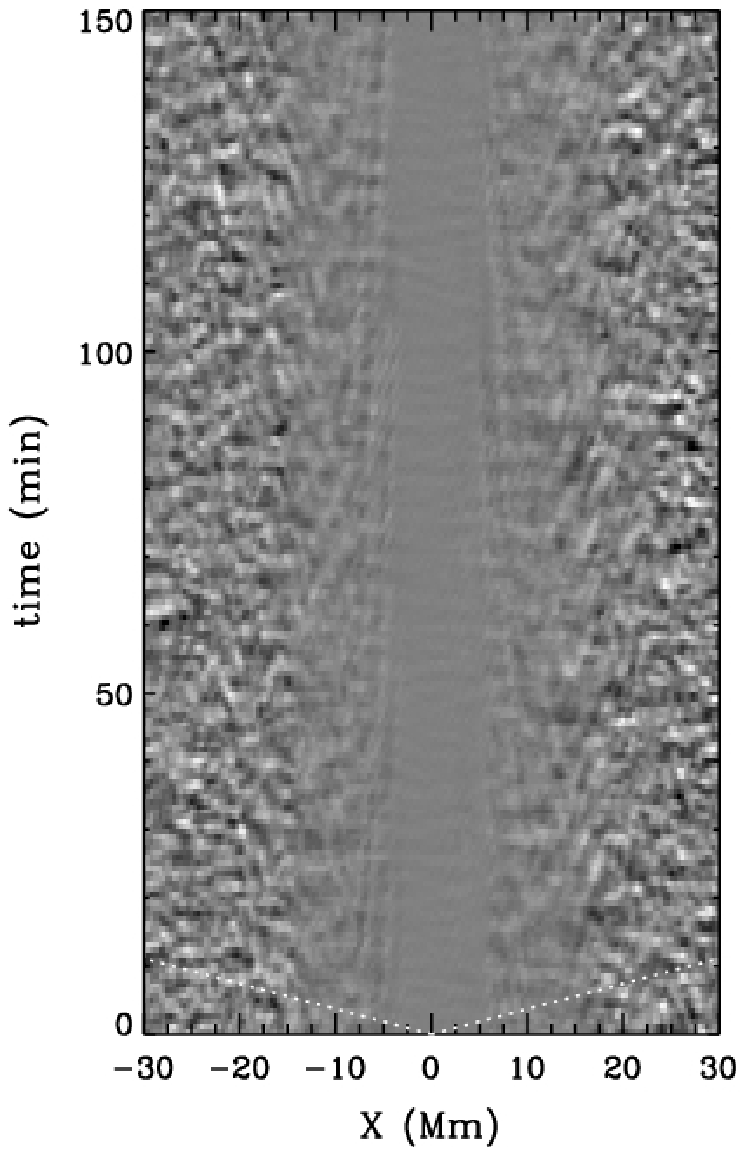


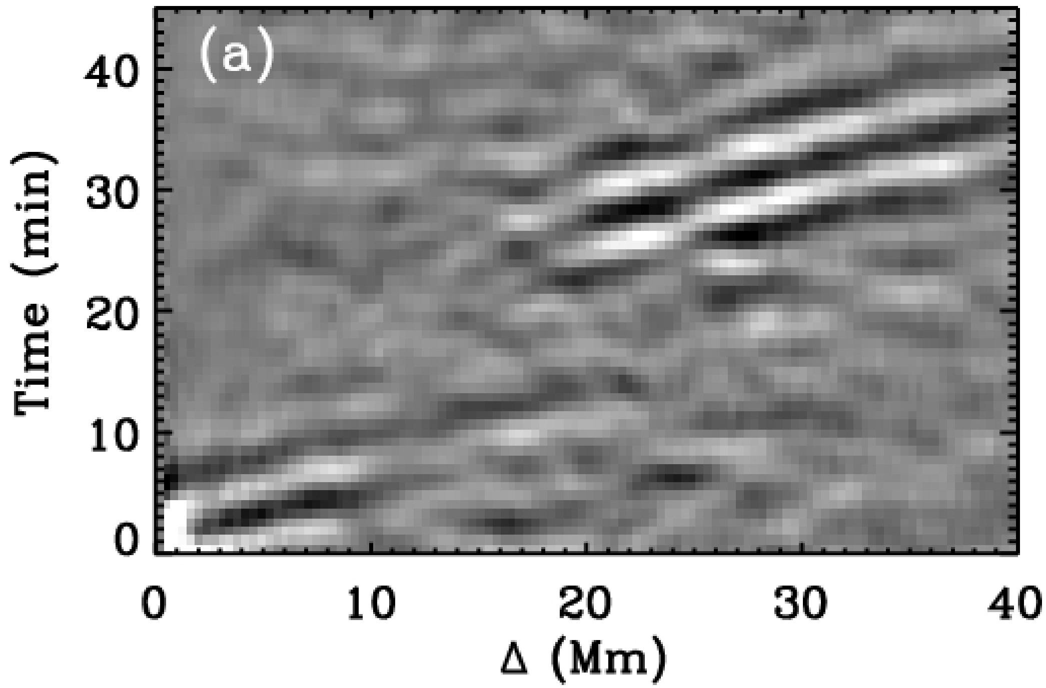
Continuum Intensity: Running Differences



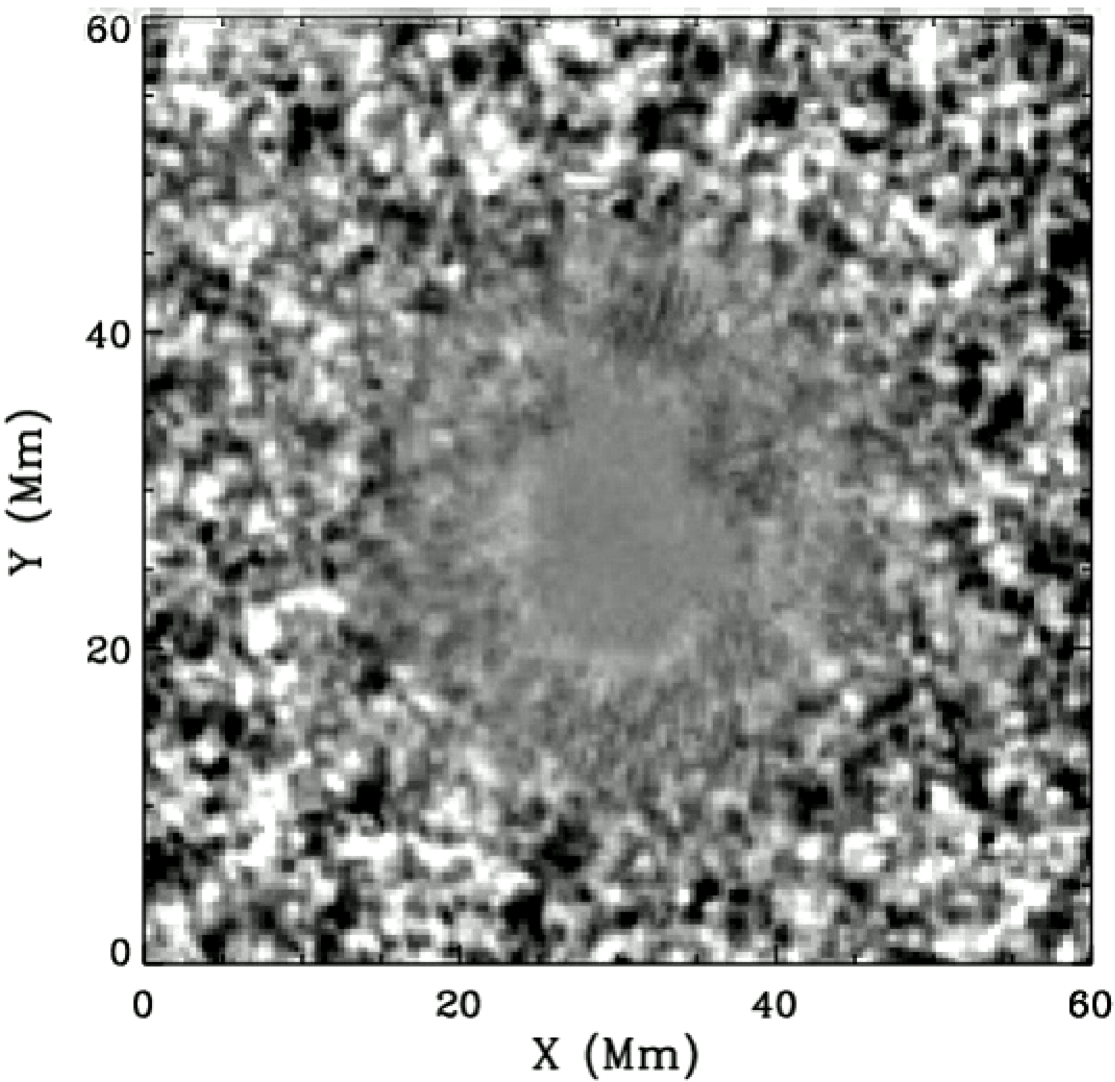
Movie of continuum intensity basically shows slowly outward moving features. There is no trace of the fast-moving wave visible in this movie.

Continuum Intensity: Time-Space Slice and Time-Distance Diagram



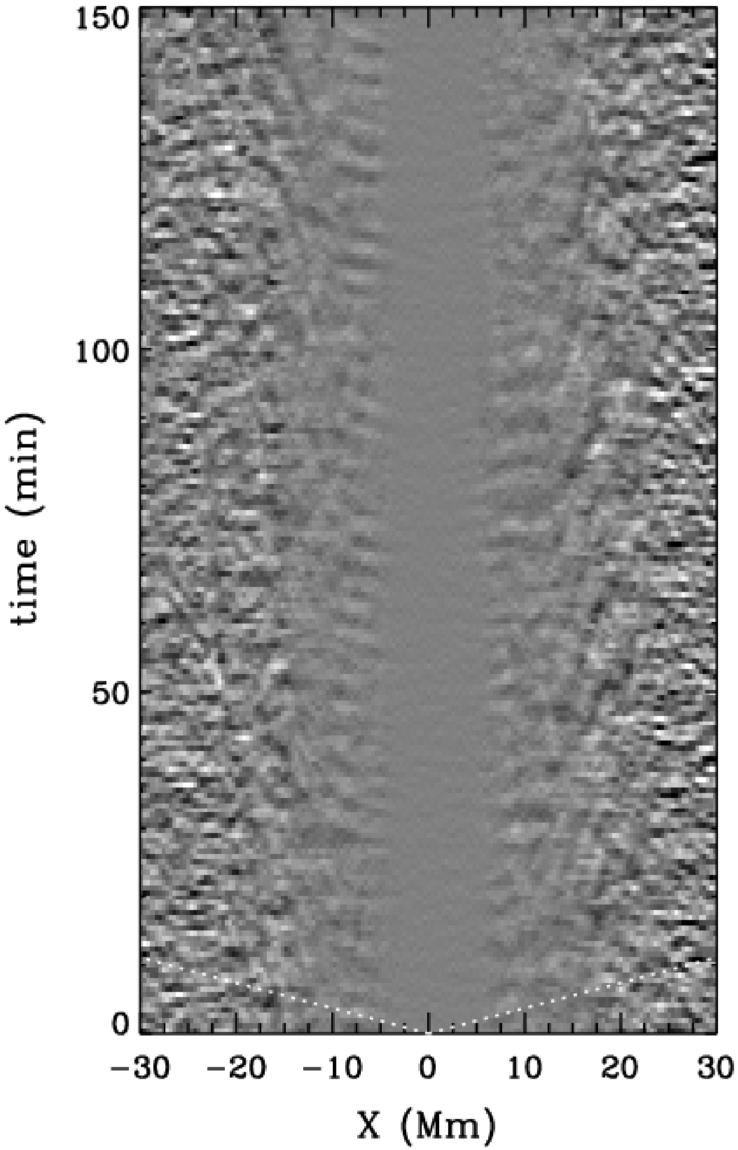


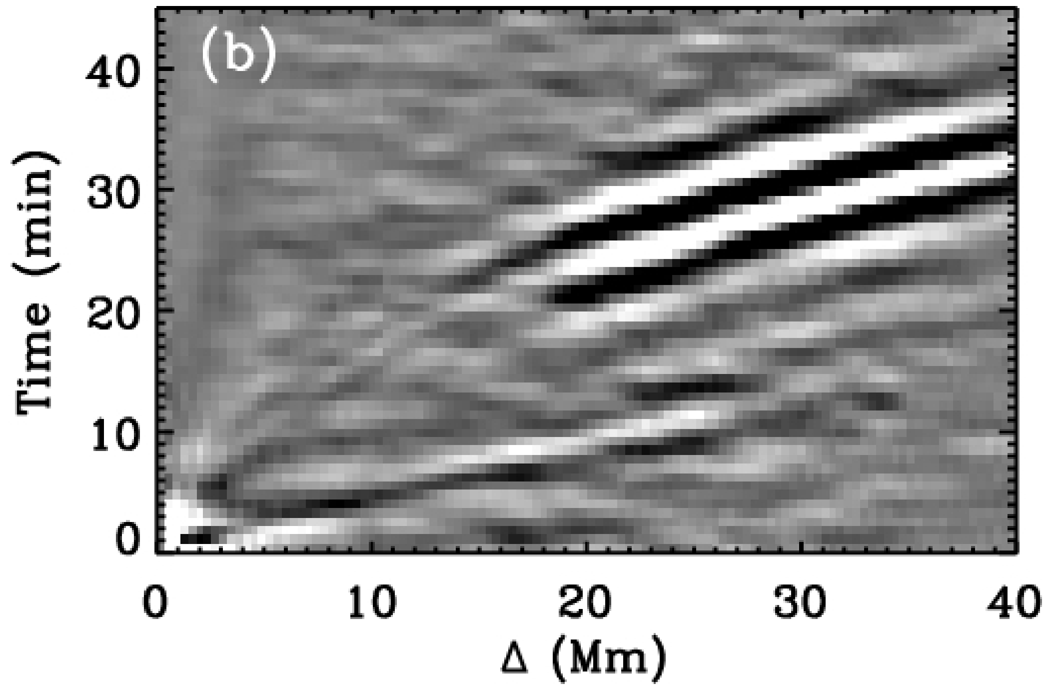
Line-Core Intensity: Running Differences



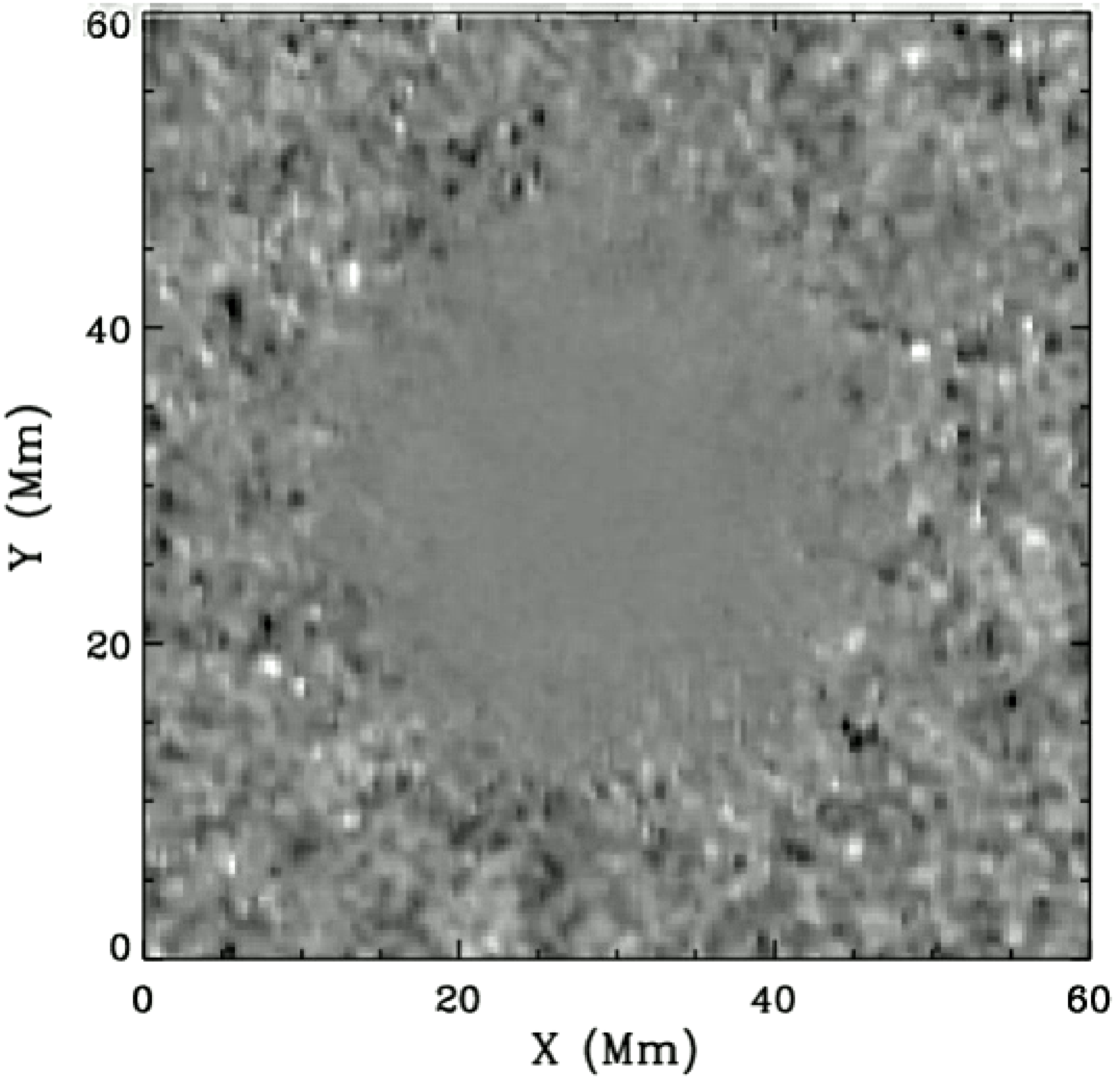
In the movie of line-core intensity, one is able to identify the fast-moving wave in the inner pebumbra, although our cross-correlation analysis shows the phenomenon actually expands from the umbra to 15 Mm beyond the sunspot boudary.

Line-Core Intensity: Time-Space Slice and Time-Distance Diagram



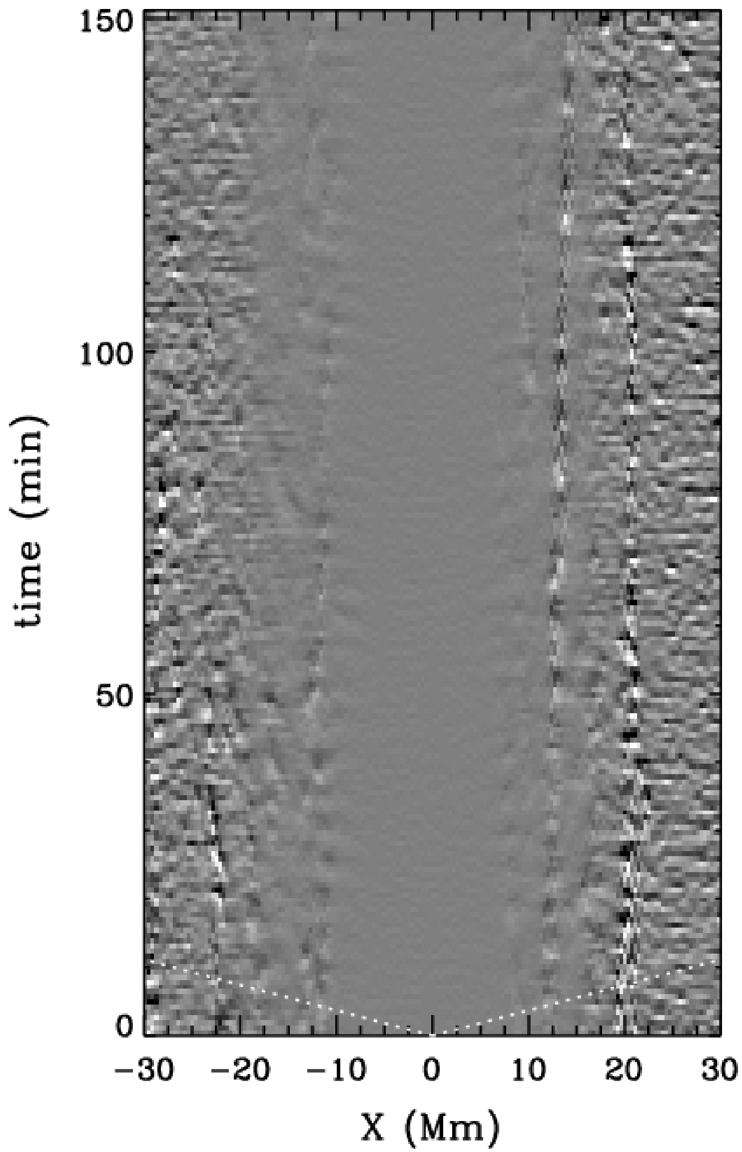


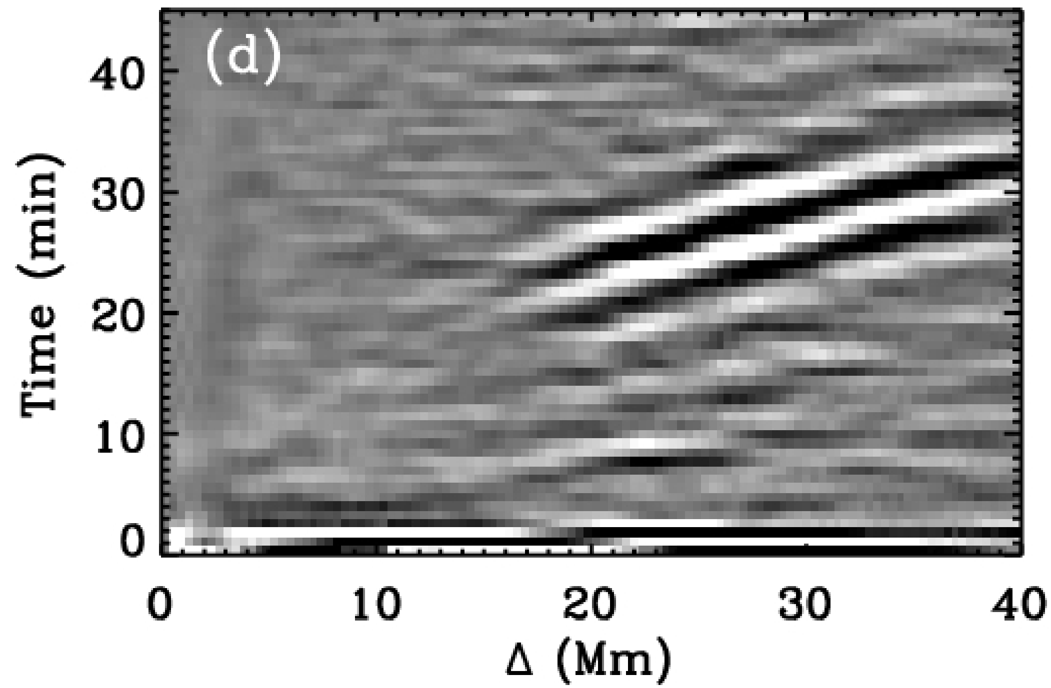
AIA 1700Å: Running Differences



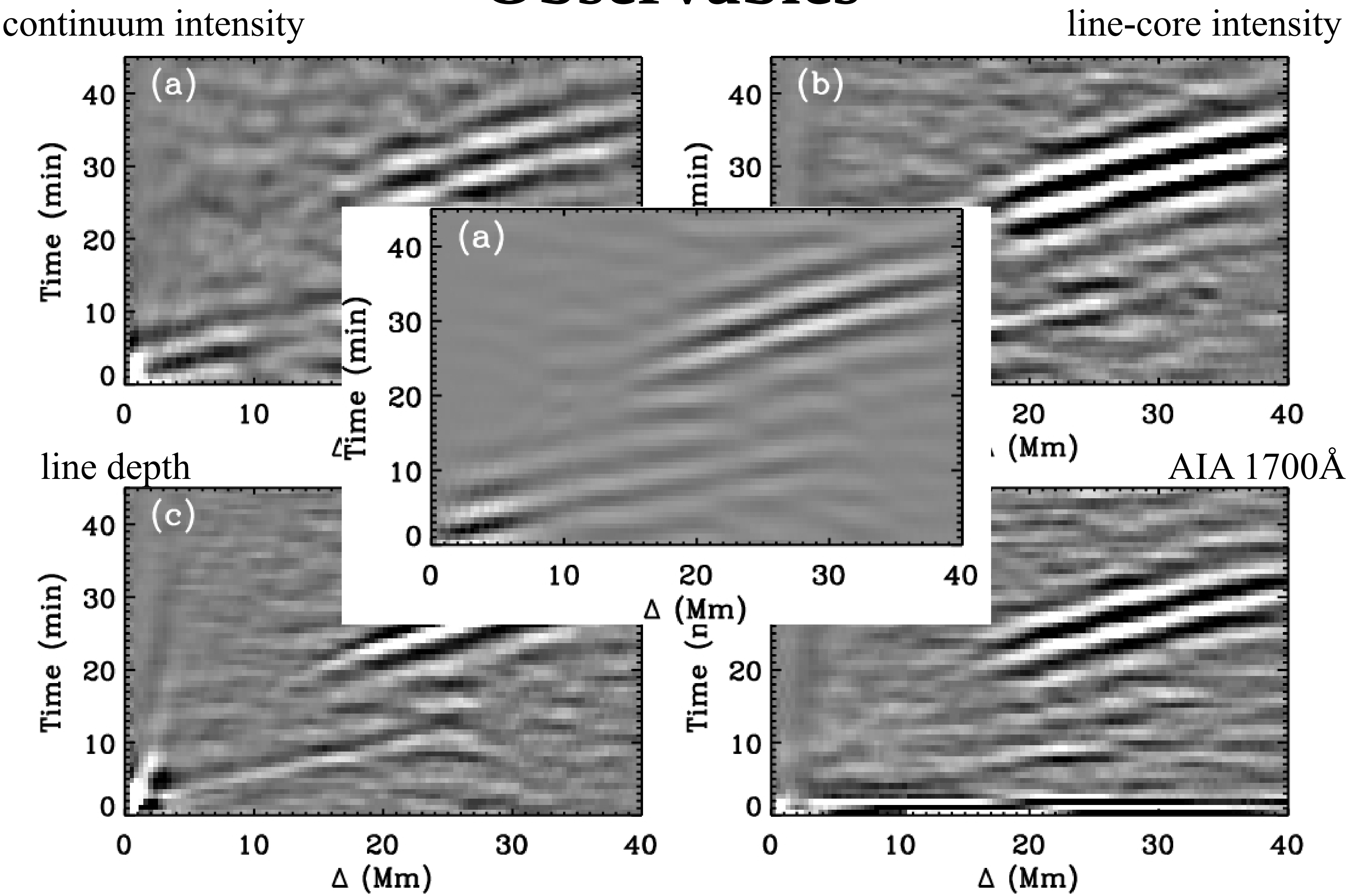
In the movie of AIA 1700Å data (low chromosphere), one is also able to identify the fast-moving wave through the pebumbra.

AIA 1700Å: Time-Space Slice and Time-Distance Diagram





Time-Distance Diagrams from Different Observables



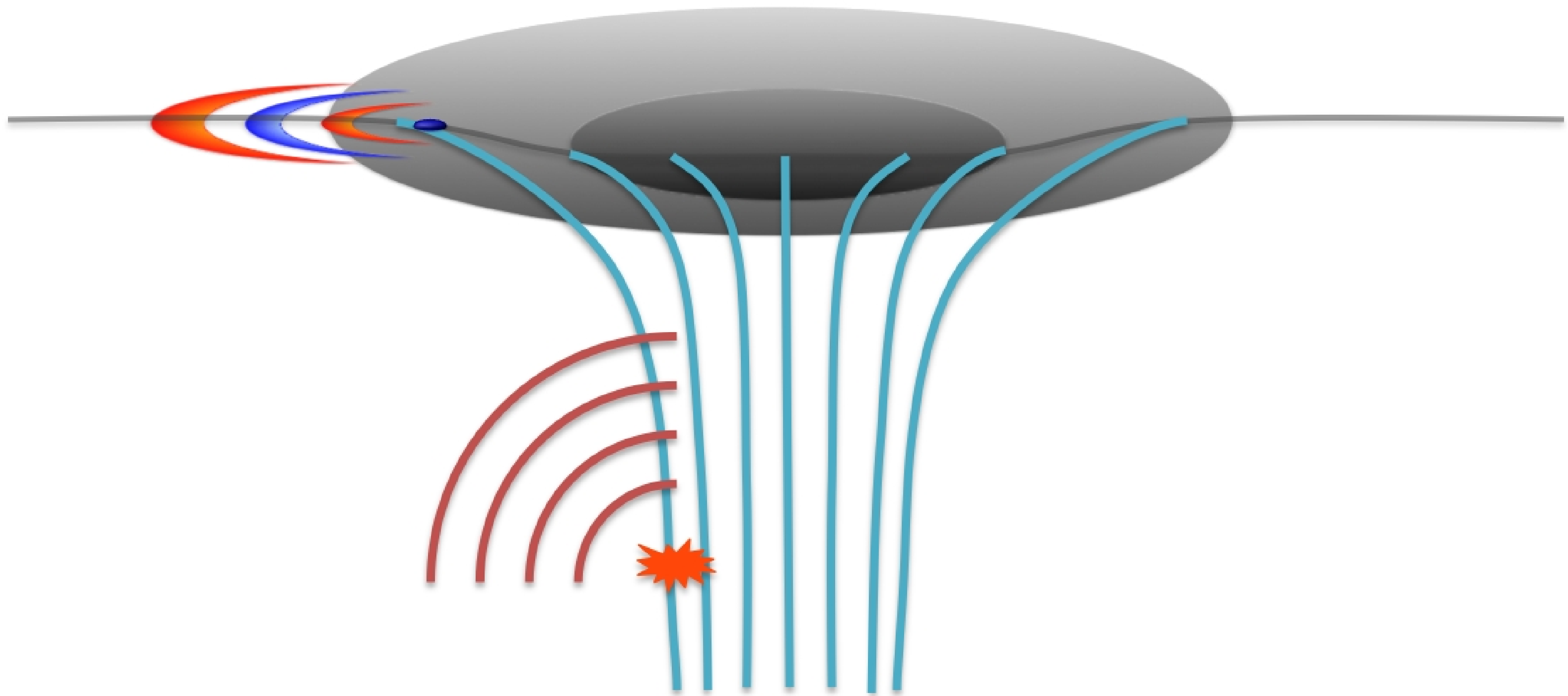
Observed Facts

- Visually, one cannot see this fast-moving wave in the HMI continuum intensity and Doppler data;
- However, in the HMI line-core intensity and line-depth data, one can identify this wave, but only in the inner penumbra;
- In AIA 1700Å data, one is able to see the fast-moving wave in the inner (or perhaps middle) penumbra.
- However, in all these data, the cross-correlation calculations show the same (or similar) fast-moving wave from the umbra extending to 15 Mm beyond the sunspot boundary.
- This fast-moving wave exists from the photosphere up to the lower chromosphere, and the property of the wave is only slightly different at different levels.

Questions to Answer

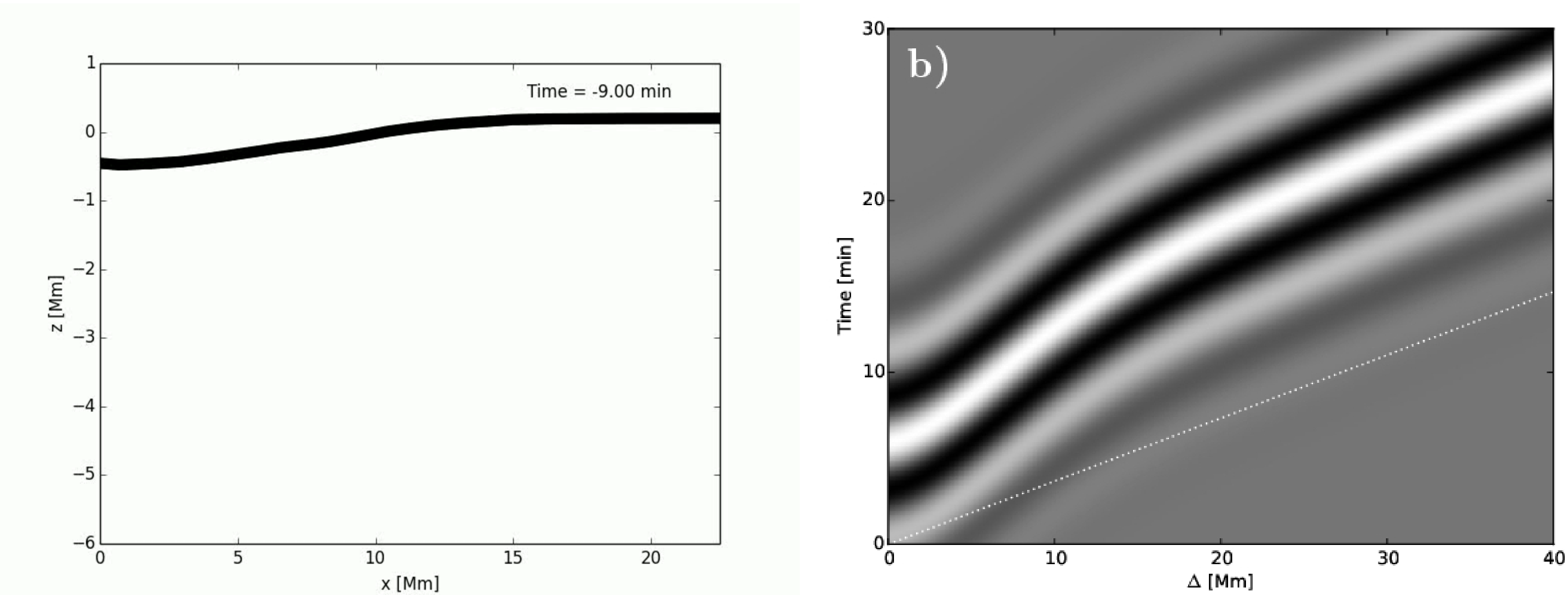
- Is this a new type of wave?
- What causes this fast-moving wave?
- How does this relate to the running penumbral wave observed in the chromosphere?

Interpretation: A Conjecture



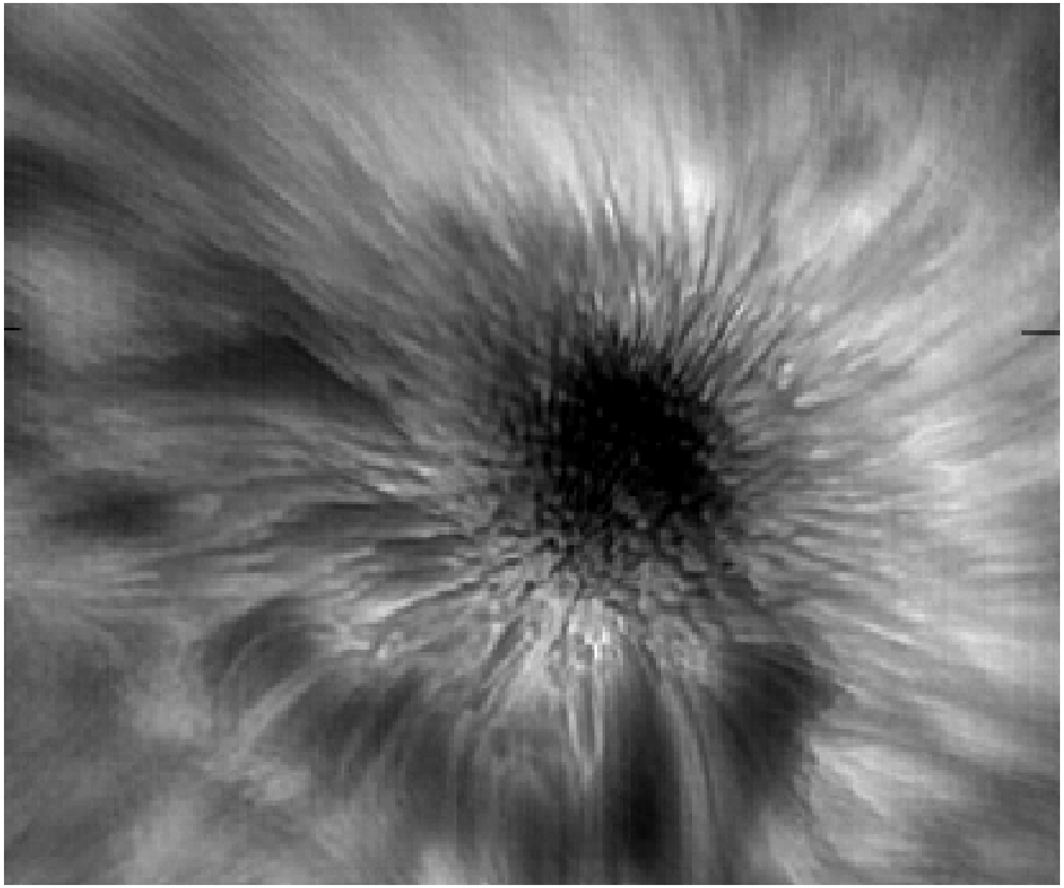
If somehow, there is a disturbance source at about 5 Mm beneath the umbra surface, acoustic waves will propagate toward all directions from that source.

Acoustic Wave from the Umbral Subsurface and Time-Distance Diagram in the Photosphere



This is not a simulation, but rather solving ray-theory equations, using a realistic sunspot model with magnetic field (Rempel et al. 2010) and at 3.0 mHz.

Running Penumbral Wave



Running penumbral wave (RPW) is a well-known phenomenon in the sunspot chromosphere (Zirin 1972), most notably in Hα. The typical speed of the wave is between 10-25 km/s, although there were also reports of faster speed.

Recently, Bloomfield et al. (2007) and Jess et al. (2013) explained the RPW as magnetoacoustic waves traveling along the inclined magnetic field lines, projected in the transverse direction

Overall Picture

The overall picture is, disturbances about 5 Mm beneath the sunspot umbra's surface excites magnetoacoustic waves. The waves sweep across the photosphere and lower chromosphere, forming the phenomenon that we see through cross-correlation computations. For the magnetoacoustic waves traveling along the inclined magnetic field lines, the projection in the transverse direction form the running penumbra waves observed in the chromosphere.

It seems to us that the photospheric fast-moving wave and the chromospheric running wave are caused by a same phenomenon but exhibited in different forms.

However, although a subsurface source seems reasonable to explain the observed fast-moving wave, we do not exclude other possible explanations.

For instance, Moradi & Cally (2014) demonstrated that helioseismic fast wave along inclined magnetic field lines could get reflected back from the chromosphere to the photosphere. Whether the reflected wave matches our observed time – distance relation remains to be investigated.

Potential Usefulness

If our interpretation is proved right, this newly observed wave will create a new window to study sunspots' subsurface structure and dynamics, because these waves originate directly from beneath the sunspots.

It is interesting to explore why there are such perturbation sources beneath sunspots umbrae.

It would be very interesting to investigate how this fast-moving photospheric wave connects with all other types of waves above the photosphere.