

Time-Distance Helioseismological Studies over Solar Active Regions

Junwei Zhao
Alexander G. Kosovichev

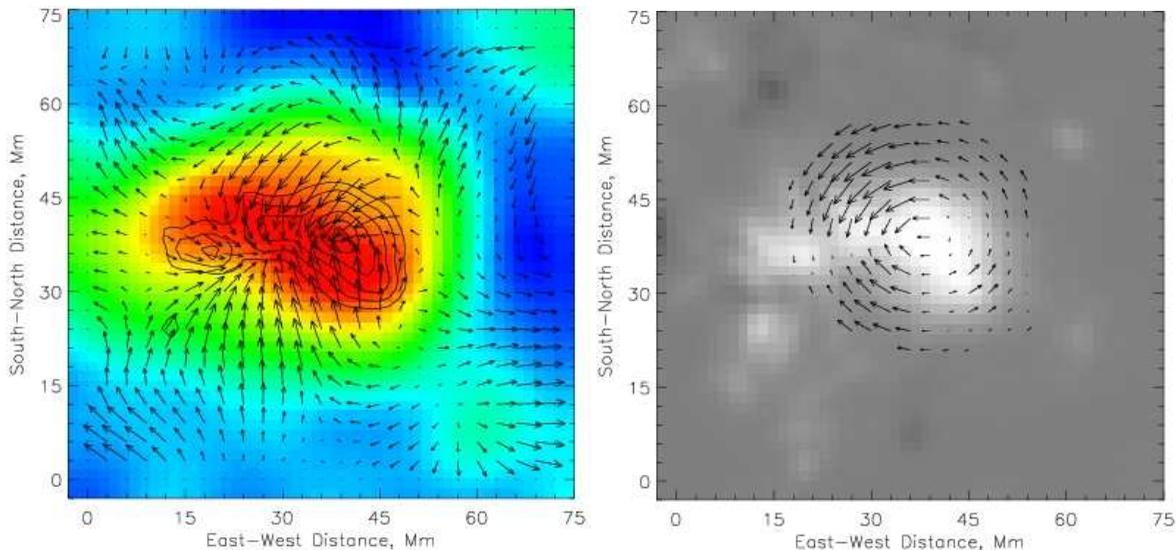
*Hansen Experimental Physics Laboratory,
Stanford University, Stanford, CA94305-4085*

Outline

- What can time-distance helioseismology do?
 - Derive three-dimensional subsurface velocity
 - Infer subsurface structures
 - Compute subsurface kinetic helicity
- Apply time-distance techniques on AR8210
 - Rotational flows were found around the sunspot
 - Kinetic helicity was found increasing before the X1.0 flare
- Summary

What Can Time-Distance Helioseismology Do (1)? Derive Subsurface Flow Fields of Active Regions

(Zhao & Kosovichev 2003, ApJ, 591, 446)



Subsurface flow fields (*left*) and the tangential components of the flow fields (*right*). The longest arrow in each plot is approximately 450 m/s.

Numerical Simulation of Twisted Magnetic Flux Emergence

(Magara & Longcope 2003, ApJ, 586, 630)

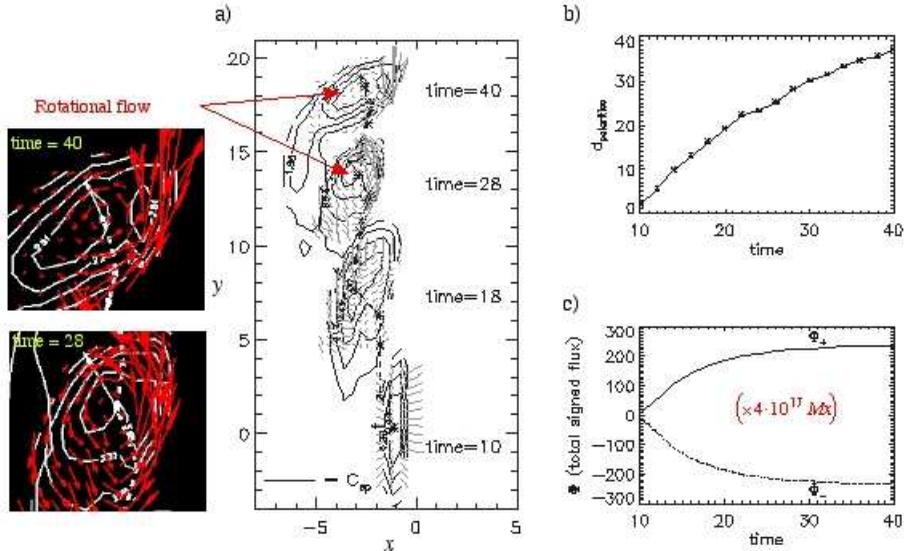
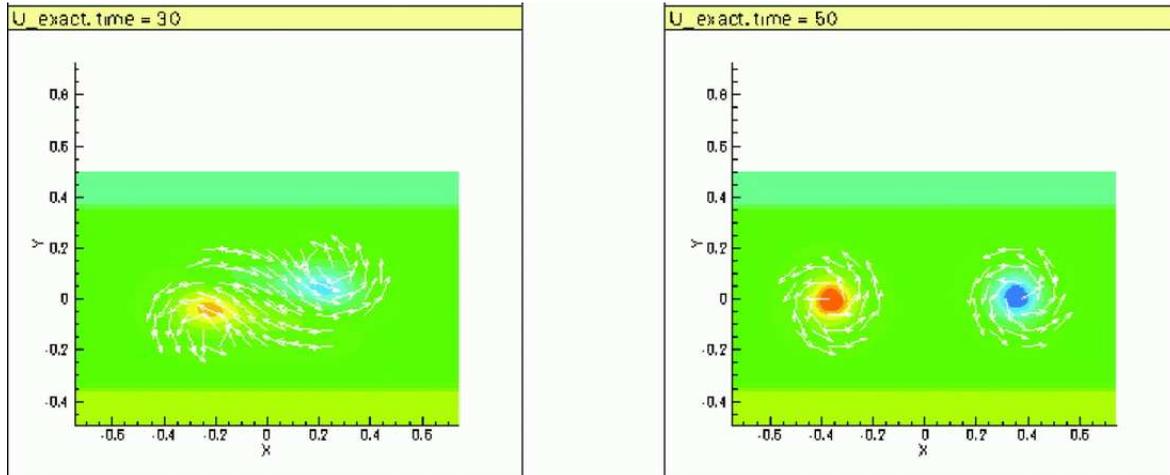


Fig. 2 (a)-Temporal development of positive magnetic polarity region in the photosphere. A thick broken line traces the peak flux area of positive magnetic polarity from $t = 10$ to $t = 40$. Contours show vertical magnetic flux while black arrow represents the velocity of peak flux area. Gray arrows show the velocity field relative to the velocity of peak flux area. These are obtained at $t = 10, 18, 28,$ and 40 . (b)-Time variation of the distance between the peak flux areas of positive and negative polarities. (c)-Time variation of the total amount of positive and negative magnetic flux in the photosphere.

Numerical Simulation of Twisted Magnetic Flux Emergence

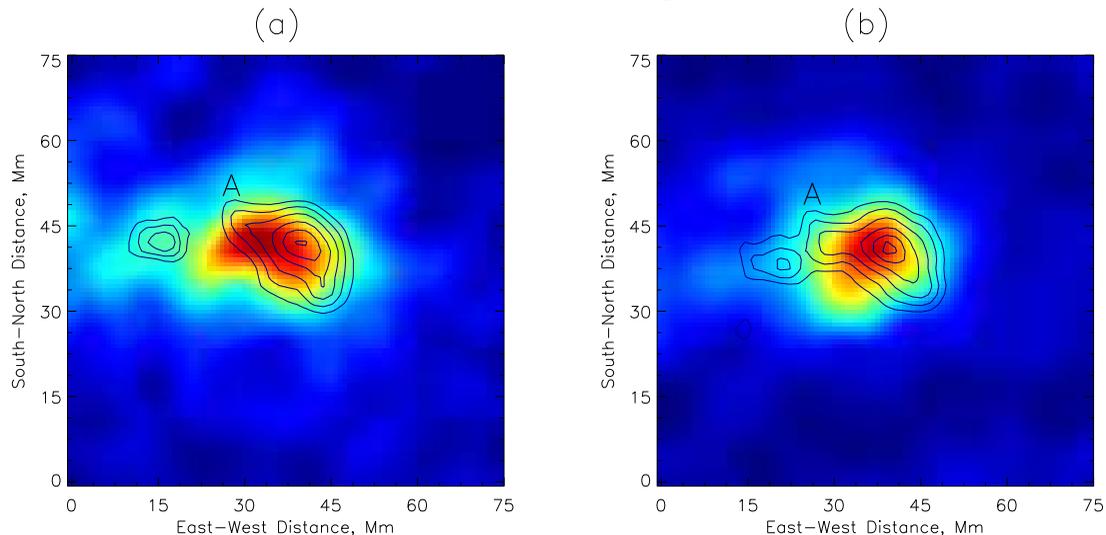
(Gibson, Fan, Mandrini, Fisher, & Demoulin 2004, ApJ, 617,600)



Another numerical simulation also shows rotational flows around emerging twisted magnetic fluxes.

What Can Time-Distance Helioseismology Do (2)? Map Interior Structure of Active Regions

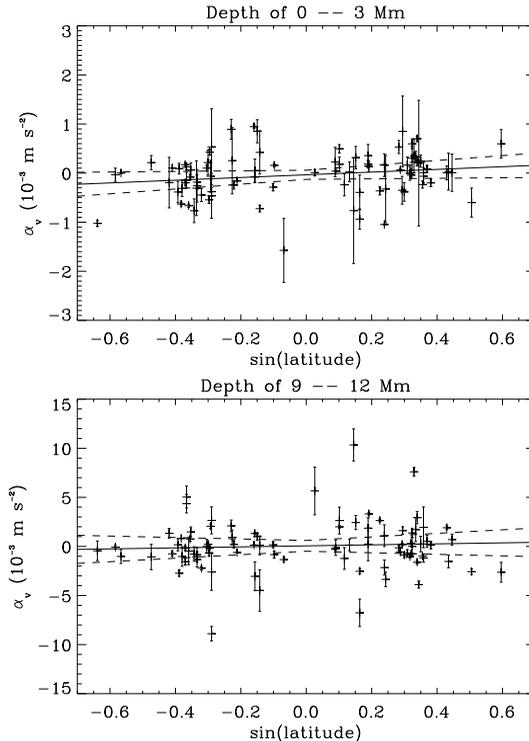
(Zhao & Kosovichev 2003, ApJ, 591, 446)



Background image shows the interior sound-speed structure of a rotating sunspot, and the contours show the photospheric magnetic field. Subsurface structures disclose that this rotating sunspot has a twisted structure on both observational days.

What Can Time-Distance Helioseismology Do (3)?

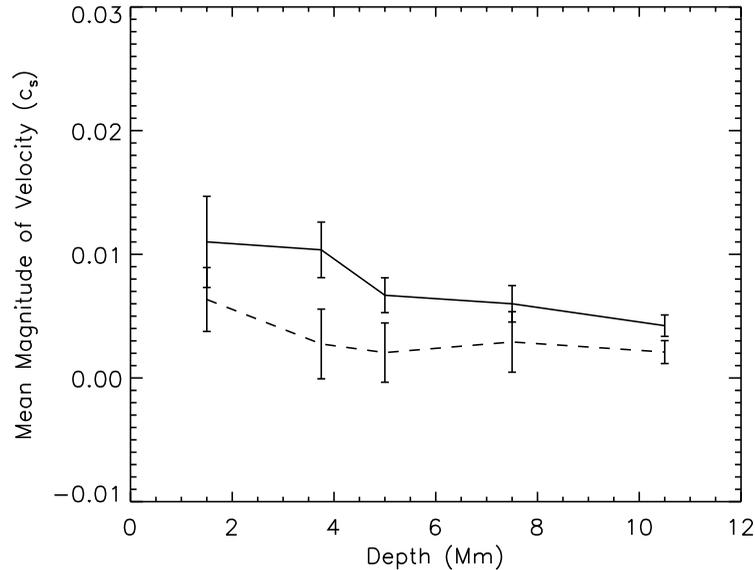
Compute Subsurface Kinetic Helicity



- A total of 88 active regions from MDI observations have been studied
- We have performed statistical studies of subsurface kinetic helicity over two different depths
- At the depth of 0 – 3 Mm, 58.1% (66.7%) ARs have negative (positive) kinetic helicity in southern (northern) hemisphere
- At the depth of 9 – 12 Mm, 55.8% (55.6%) ARs have negative (positive) kinetic helicity in southern (northern) hemisphere

Error Estimation of Flow Fields Derived from Time-Distance Helioseismology

(Zhao & Kosovichev 2003, ApJ, 591, 446)

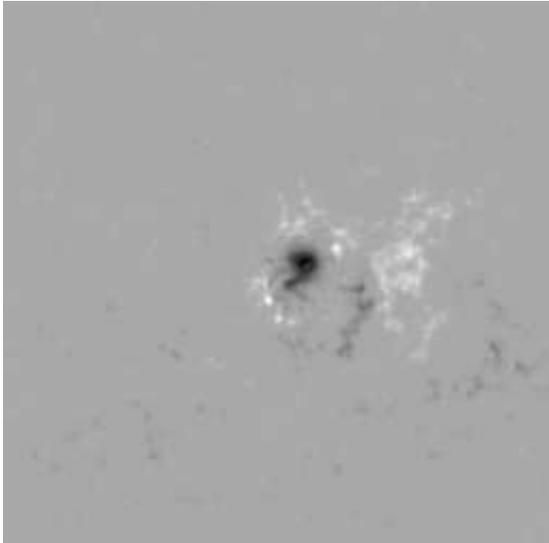


Errors from time-distance helioseismology are significant. And Occasionally, it may even be wrong in flow directions.

How Valid Are Time-Distance Results?

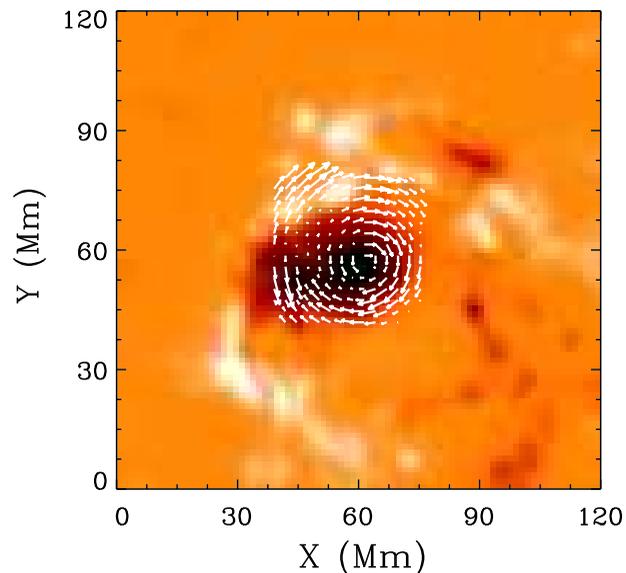
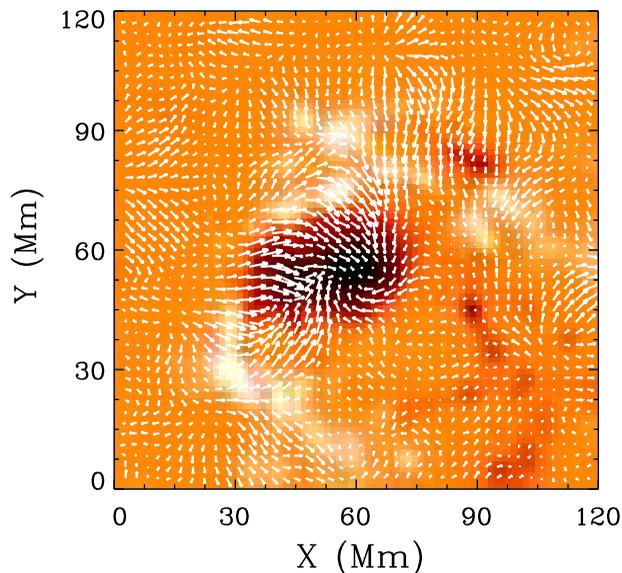
- Cross-Check Time-Distance Results with Other Helioseismological Results
 - Compare our results of solar rotational rate with that obtained by global helioseismology
 - Compare our large-scale results, including rotational and meridional flows, large-scale flows with ring-diagram analyses results
 - Compare high-resolution results with acoustic holography results (in collaboration with Doug Braun)
 - Generally, those results agree well, though discrepancies remain in some aspects
- Apply Our Technique on Numerical Simulation Data and Check Self-Consistency
 - There are possibilities that all helioseismological results give similar wrong results. Therefore, it is necessary to check the validity of our technique on numerical simulation data
 - The requirement of the numerical simulation data is pretty high: sufficient duration, sufficient spatial scales with nice spatial resolution, and with acoustic information

A Case Study: AR8210



- A rotating active region
- Study period: from 00:00UT, 1 May to 23:59UT, 3 May, 1998
- A few solar flares occurred in this region, including an X1.0 at 13:40UT on 2 May
- Time-distance computations give three dimensional subsurface velocities

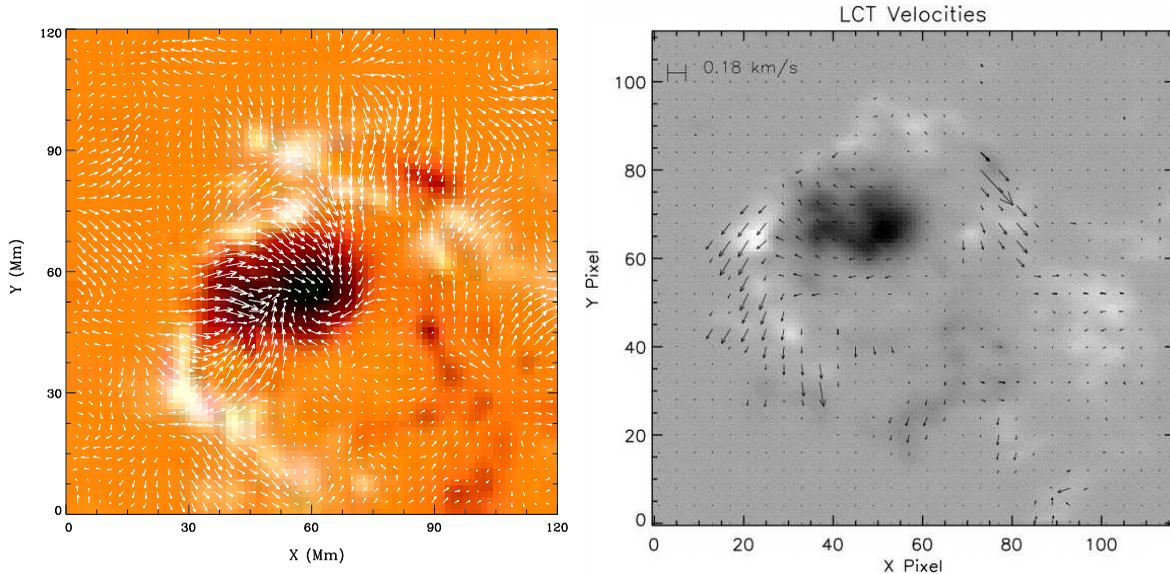
Subsurface Flow Fields at Depth of 1.0 Mm



Subsurface flow fields at a depth of 1.0 Mm (*left*) and the tangential components of the flow fields (*right*). Rotational flows around the sunspot are apparent. The longest arrows represent approximately 500 m/s (*left*) and 300 m/s (*right*).

Compare Subsurface Flows from Helioseismology with Surface Flows from ILCT

(ILCT results from Welsch et al. 2004, ApJ, 610, 1148)

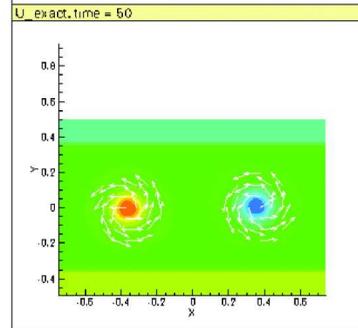
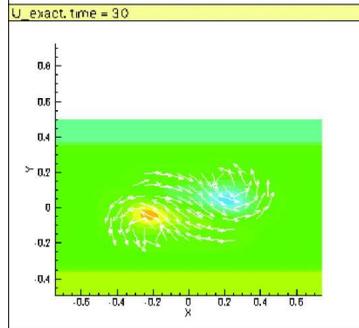
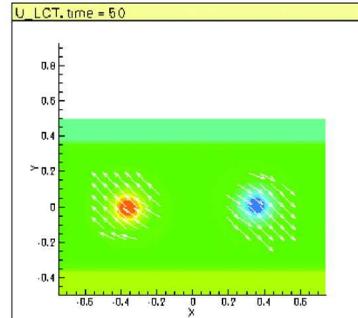
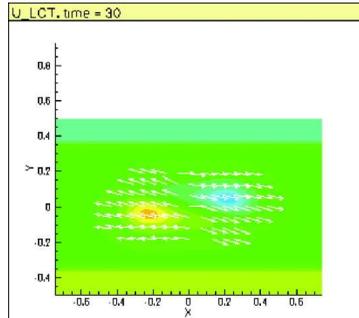


The flow fields from both techniques are pretty much different except that both plots show the rotational flows.

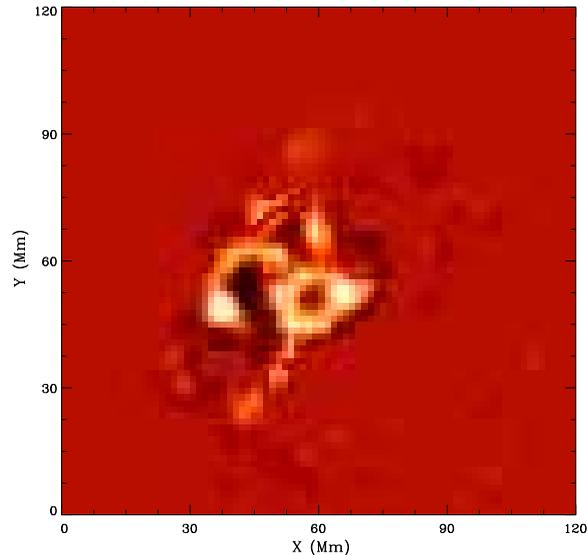


LCT May Underestimate Rotational Flows

(Gibson, Fan, Mandrini, Fisher, & Demoulin 2004, ApJ, 617,600)

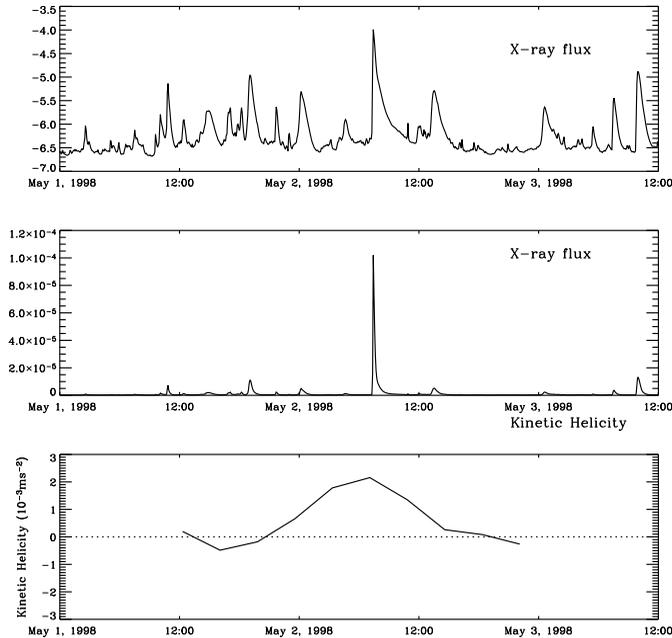


Computation of Subsurface Kinetic Helicity



Map of kinetic helicity computed as $v_z(\partial v_y/\partial x - \partial v_x/\partial y)$ from the previous subsurface flow field figure, with only magnetic field strength greater than 100 Gs included.

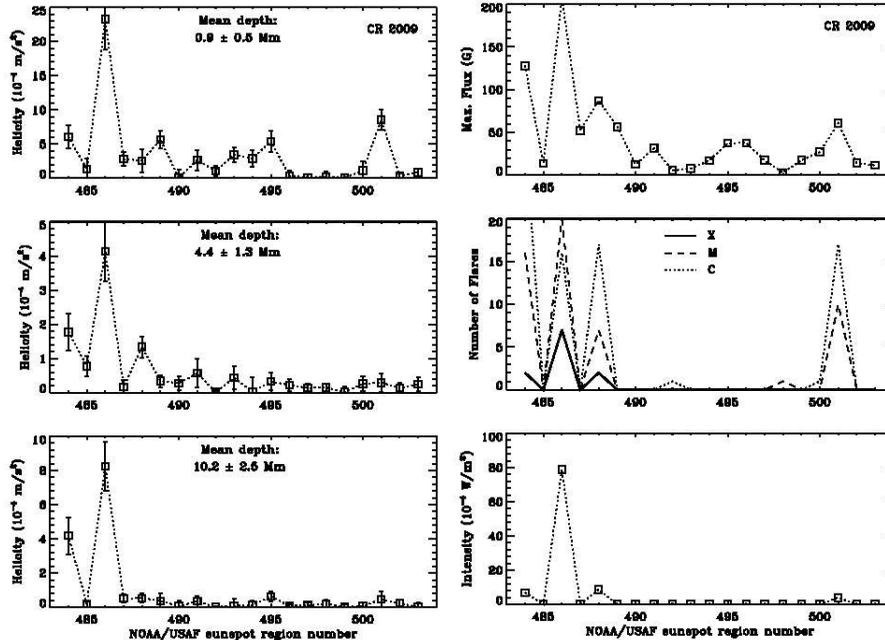
Evolution of Subsurface Kinetic Helicity



It seems kinetic helicity keeps increasing before the major flare, and peaks at approximately the same time as the flare X1.0.

Correlation Between Subsurface Kinetic Helicity and Flares

(Komm et al. 2005, ApJ, in press)



Very nice correlations were found between the mean subsurface kinetic helicity and the number of solar flares in the same active region.

It Would Be Very Interesting If ...

- If subsurface kinetic helicity and photospheric magnetic helicity are measured for same active regions during same observational periods for sufficient number of events, so that correlations between subsurface kinetic helicity and magnetic helicity may be established
- If subsurface kinetic helicity can be observed well before major flares for sufficient number of events, so that statistical studies may be performed to see if there is positive correlation
- If subsurface numerical simulation data with acoustic information can be provided to us to test the validity and accuracy of time-distance helioseismology results.

Summary

- Time-distance helioseismology can provide subsurface flow fields, subsurface structures and subsurface kinetic helicity
- Such measurements may be used to study connections with major solar flares, and may be used as eruption predictors
- Subsurface kinetic helicity can also be statistically studied associated with magnetic helicity, so as to better understand turbulence inside solar convection zone
- Meanwhile, efforts to cross-check with results from other helioseismological techniques, and to obtain useful numerical simulation are ongoing to ensure the validity and accuracy of time-distance results