The Solar Interior
From the perspective of an observer

Phil Scherrer

Stanford University

pscherrer@solar.Stanford.edu

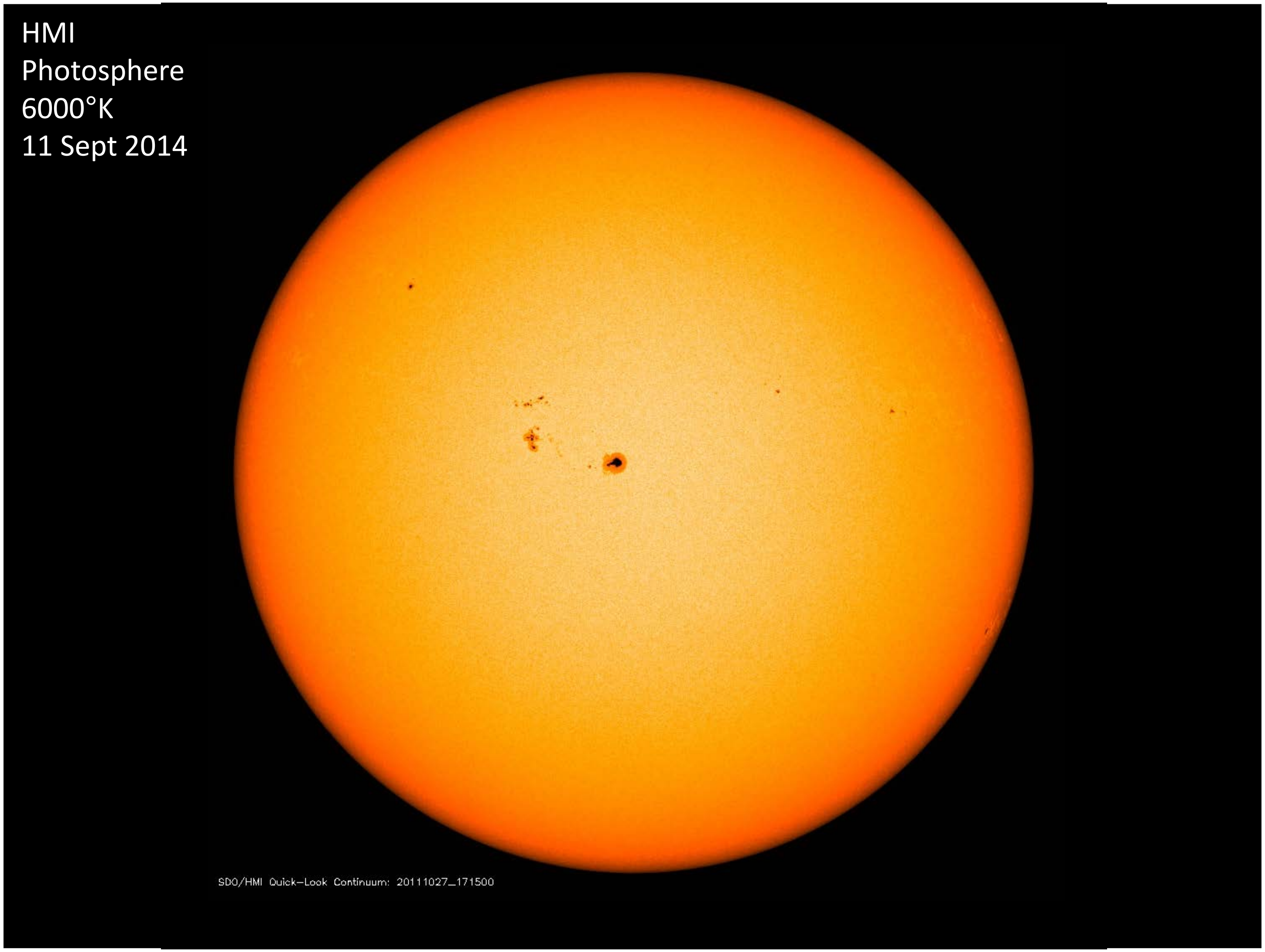
We are here

Sun is way over there

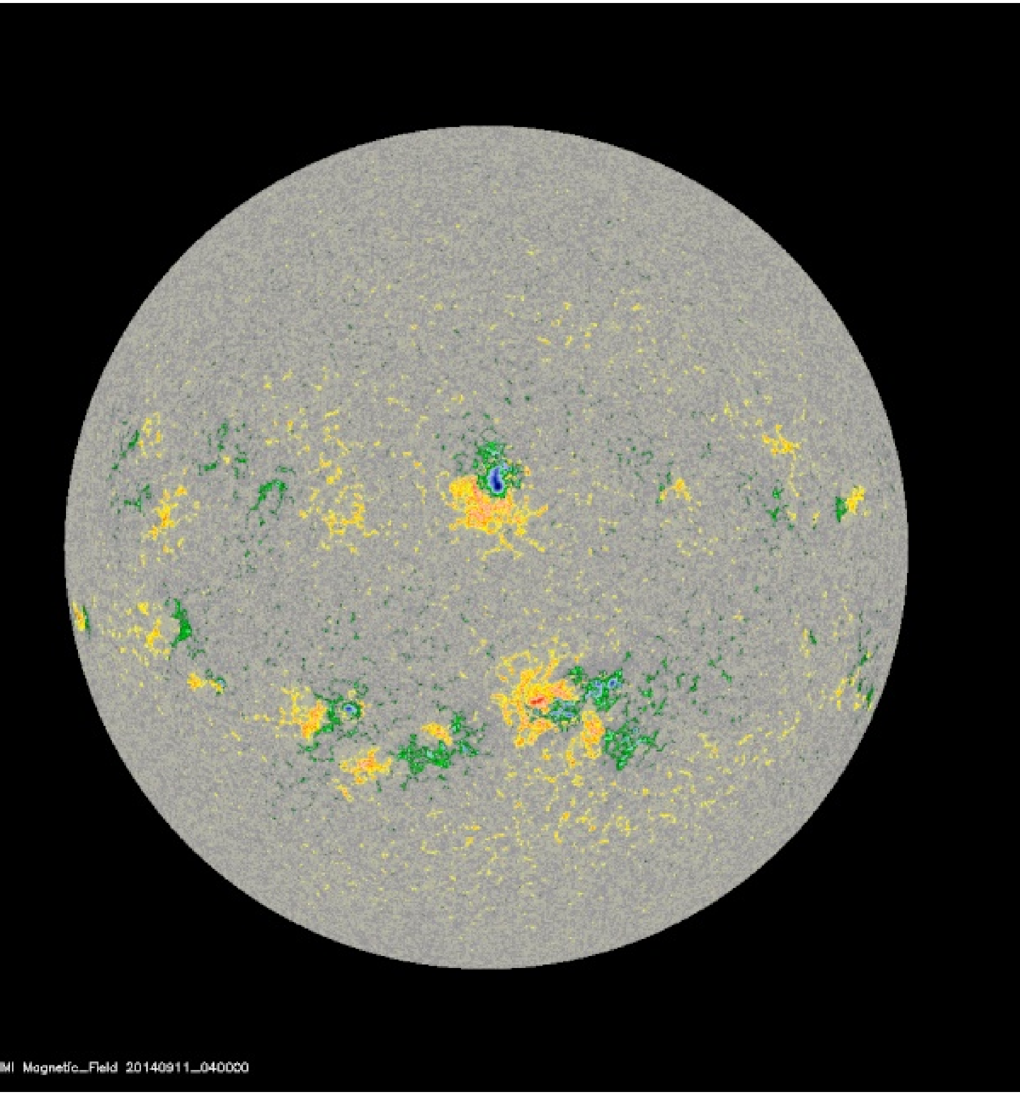
Why We Care About the Solar Interior

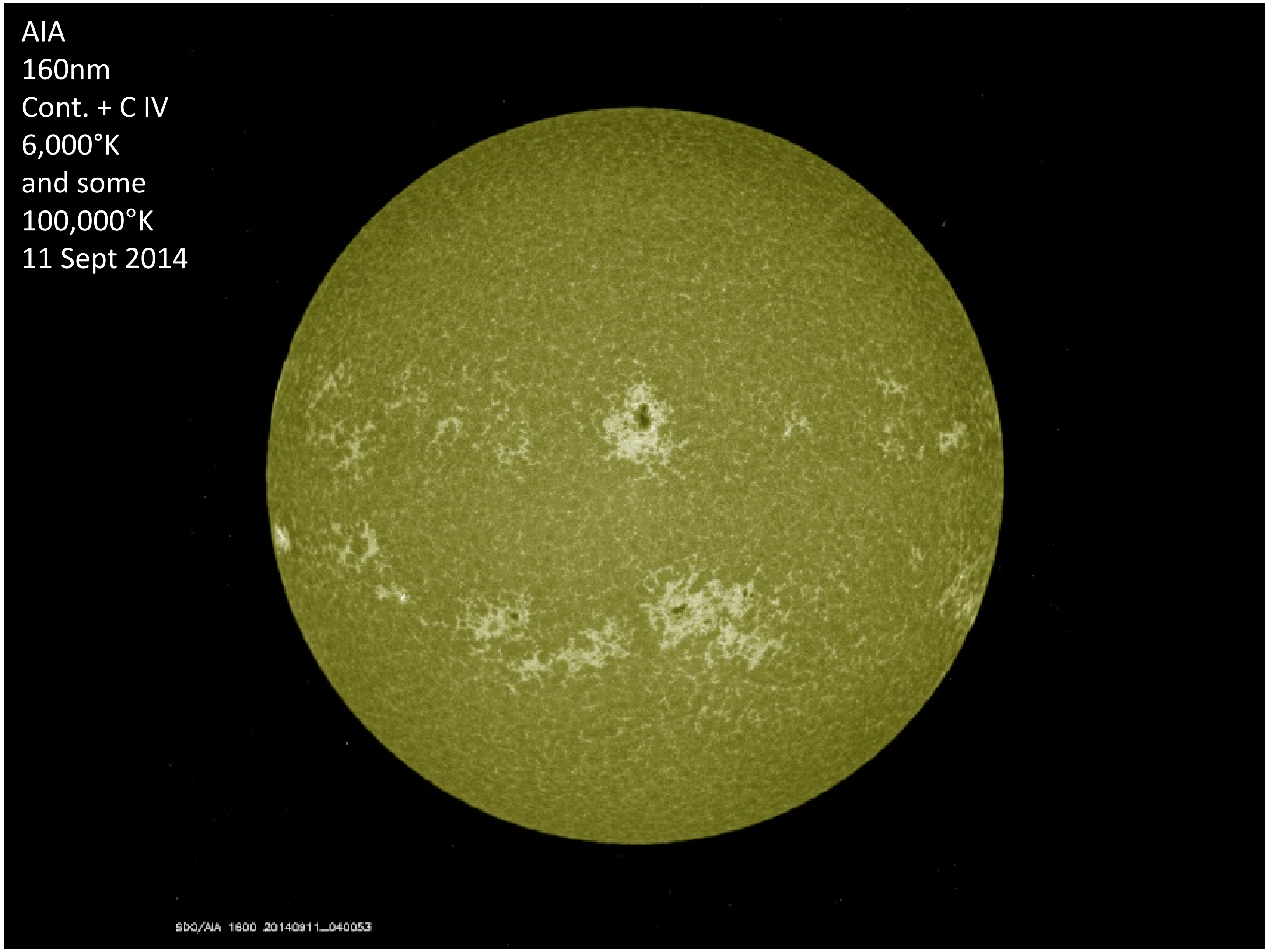
- The Earth is in the Sun's extended atmosphere.
- Dynamic effects of magnetic fields emerging from the solar interior cause disruptions throughout the heliosphere.
- These disruptions, e.g. "Space Weather", cause disruptions to human technological systems – which we increasingly depend on.
- To understand the origins of these magnetically driven events and possibly them we must look to the solar interior.
- It is also fun to look inside a star.
  - Oh, I mean it is an intellectual challenge…

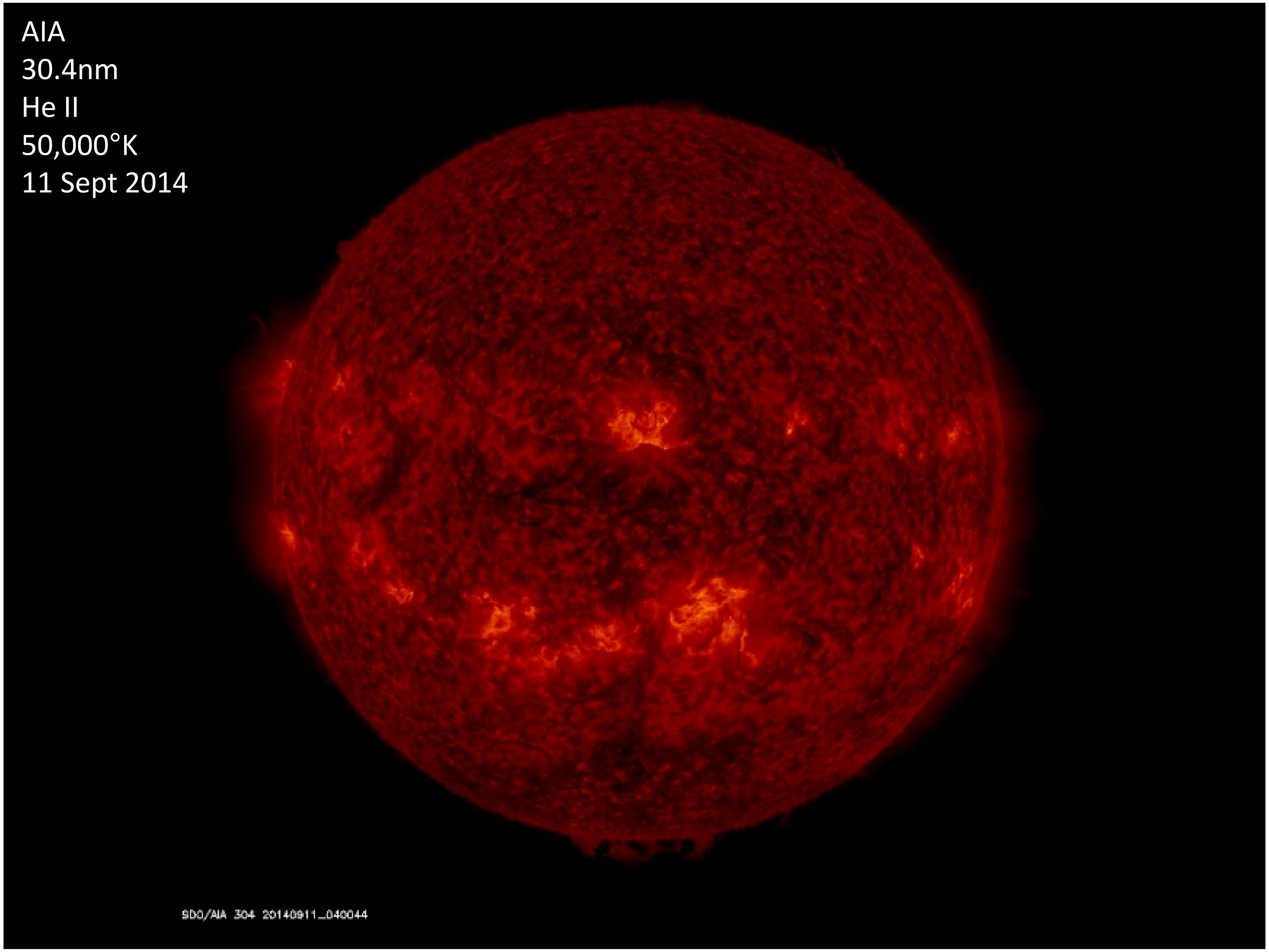
- But first a quick look at the exterior.

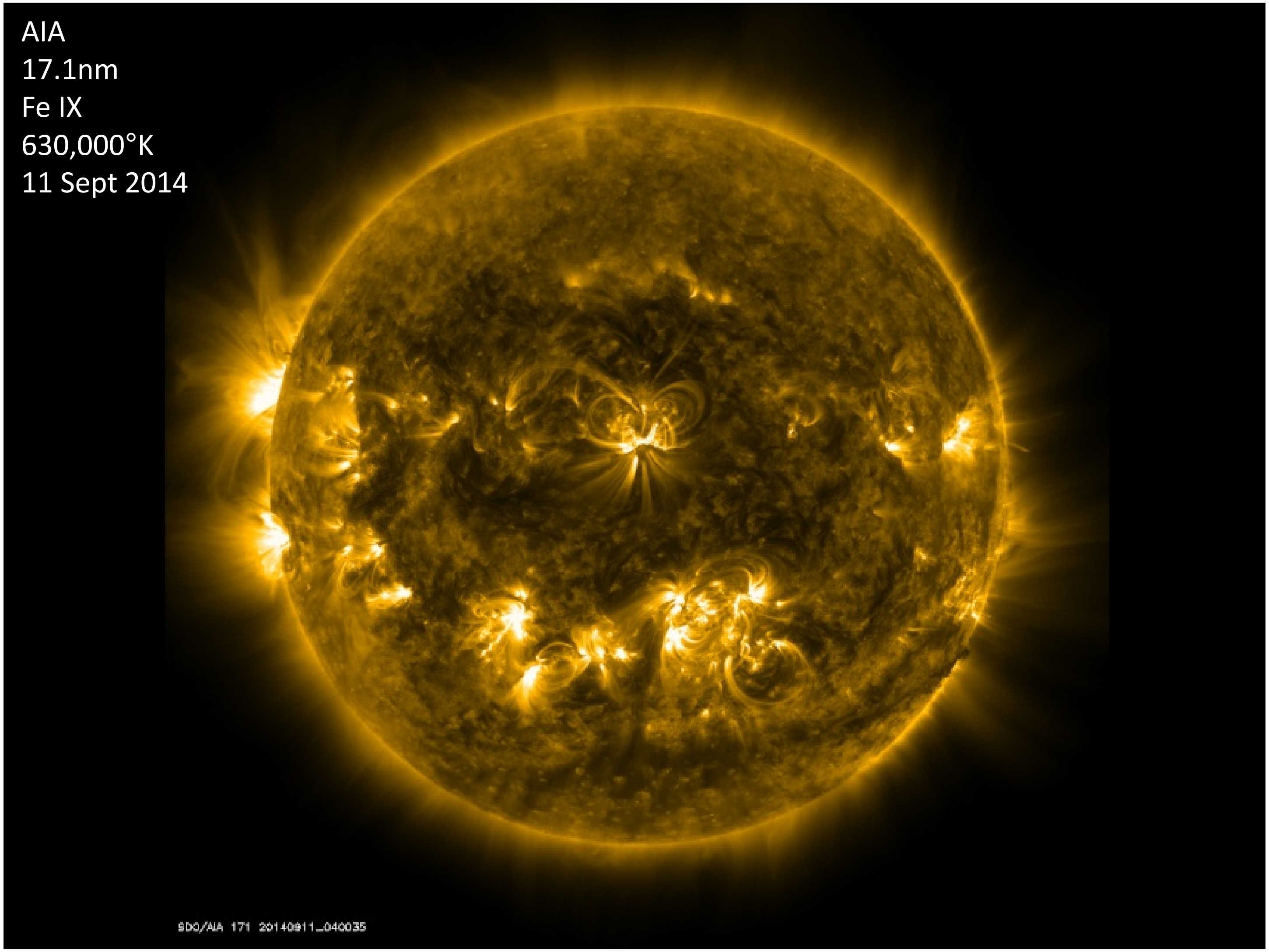

HMI
Photosphere
6000°K
11 Sept 2014
SDO/HMI Quick-Look Continuum: 20111027_171500

HMI
Magnetic Field
Green +
Yellow -
11 Sept 2014




AIA
160nm
Cont. + C IV
6,000°K
and some
100,000°K
11 Sept 2014
SDO/AIA 1600 20140911_040053


AIA
30.4nm
He II
50,000°K
11 Sept 2014
SDO/AIA 304 20140911_040044


AIA
17.1nm
Fe IX
630,000°K
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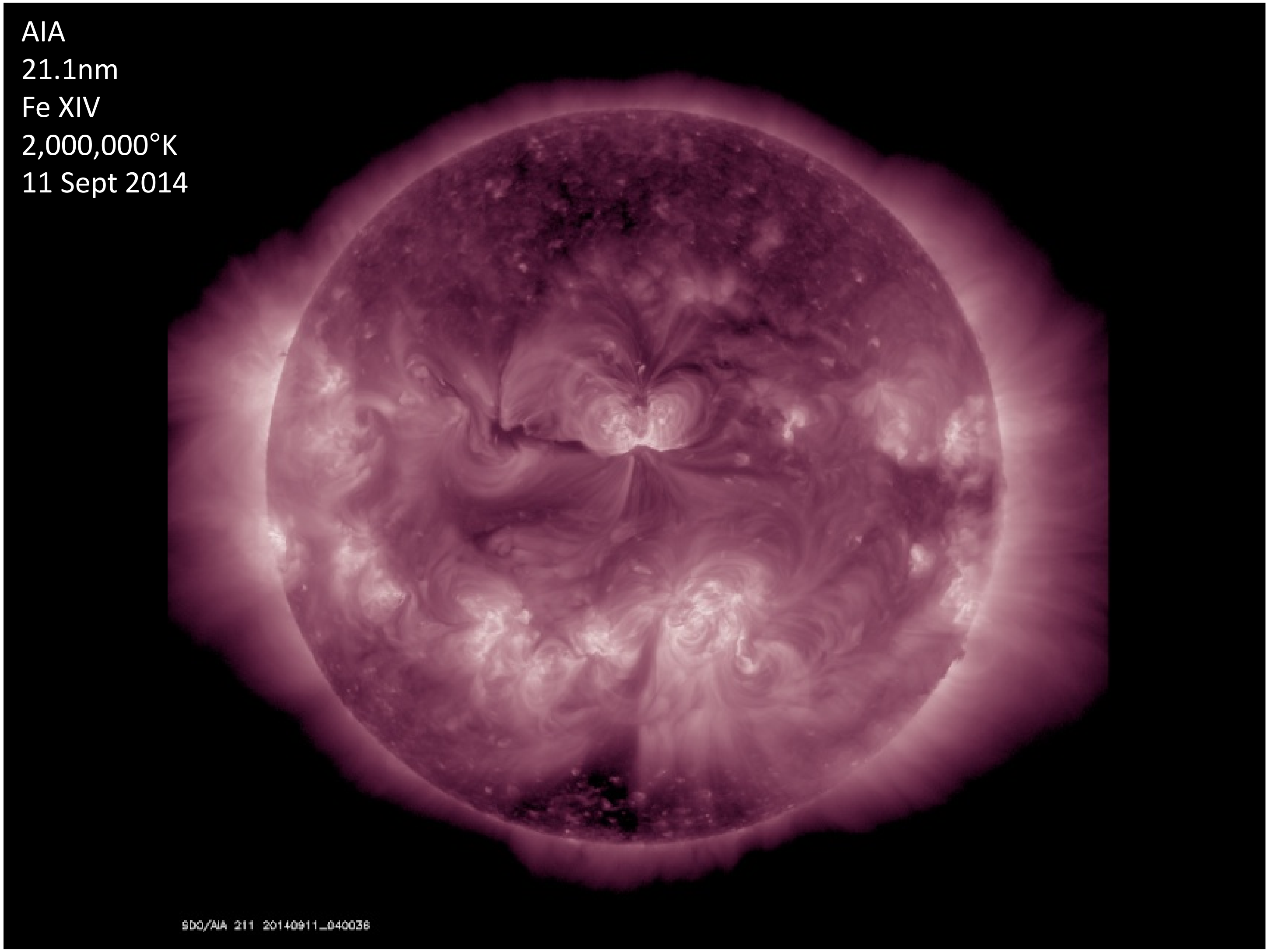
SDO/AIA 171 20140911_040035


AIA
21.1nm
Fe XIV
2,000,000°K
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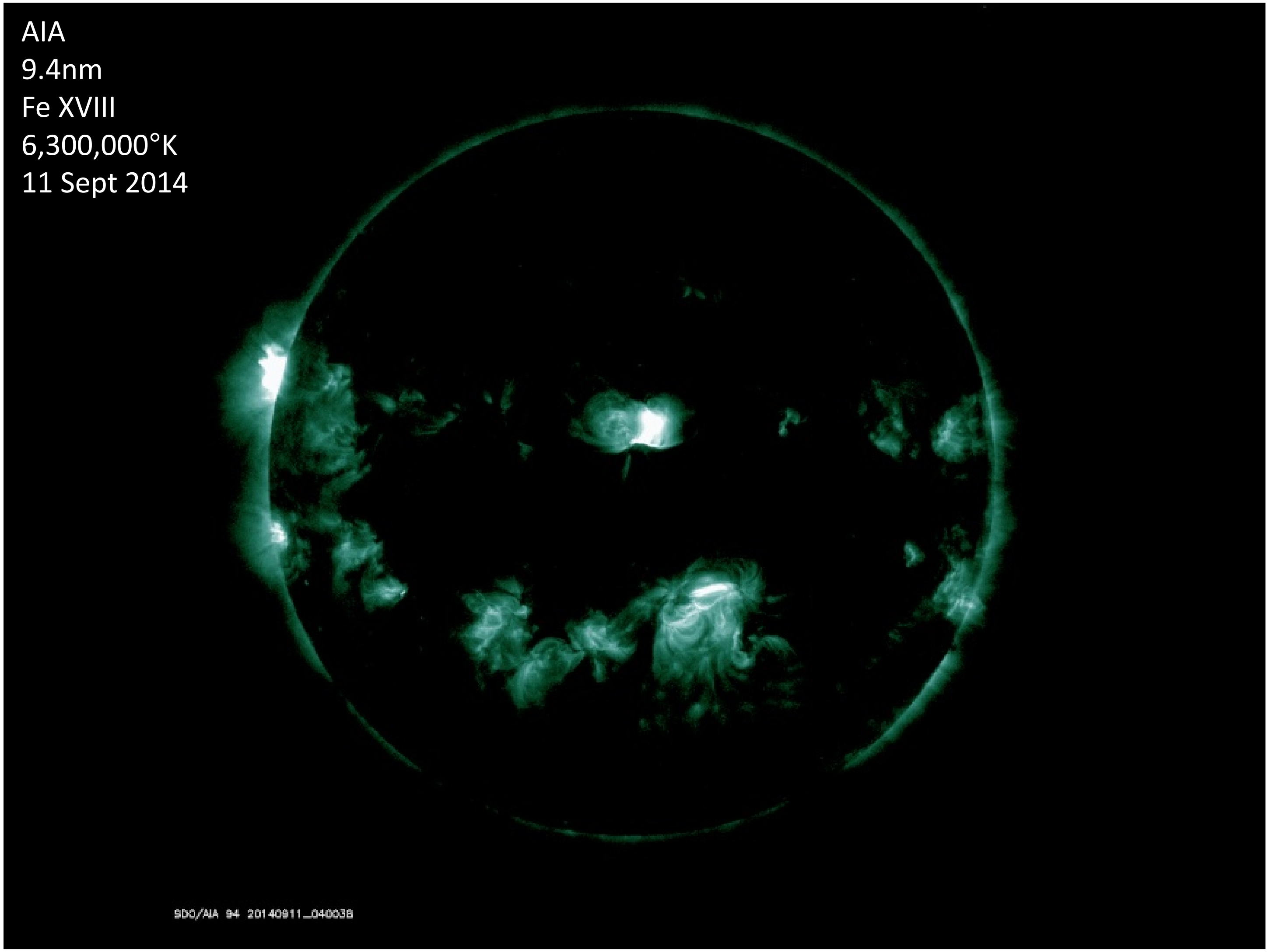
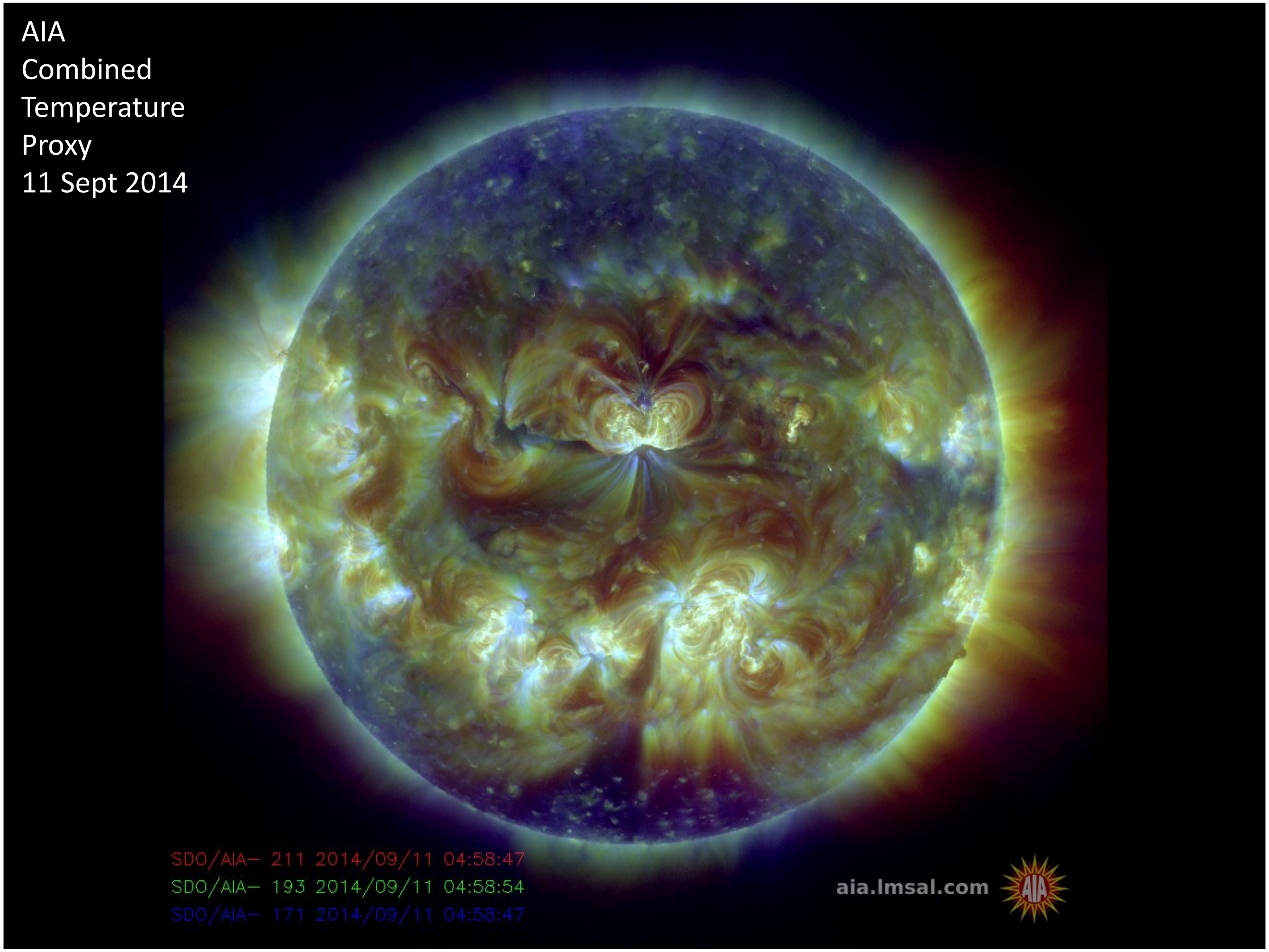
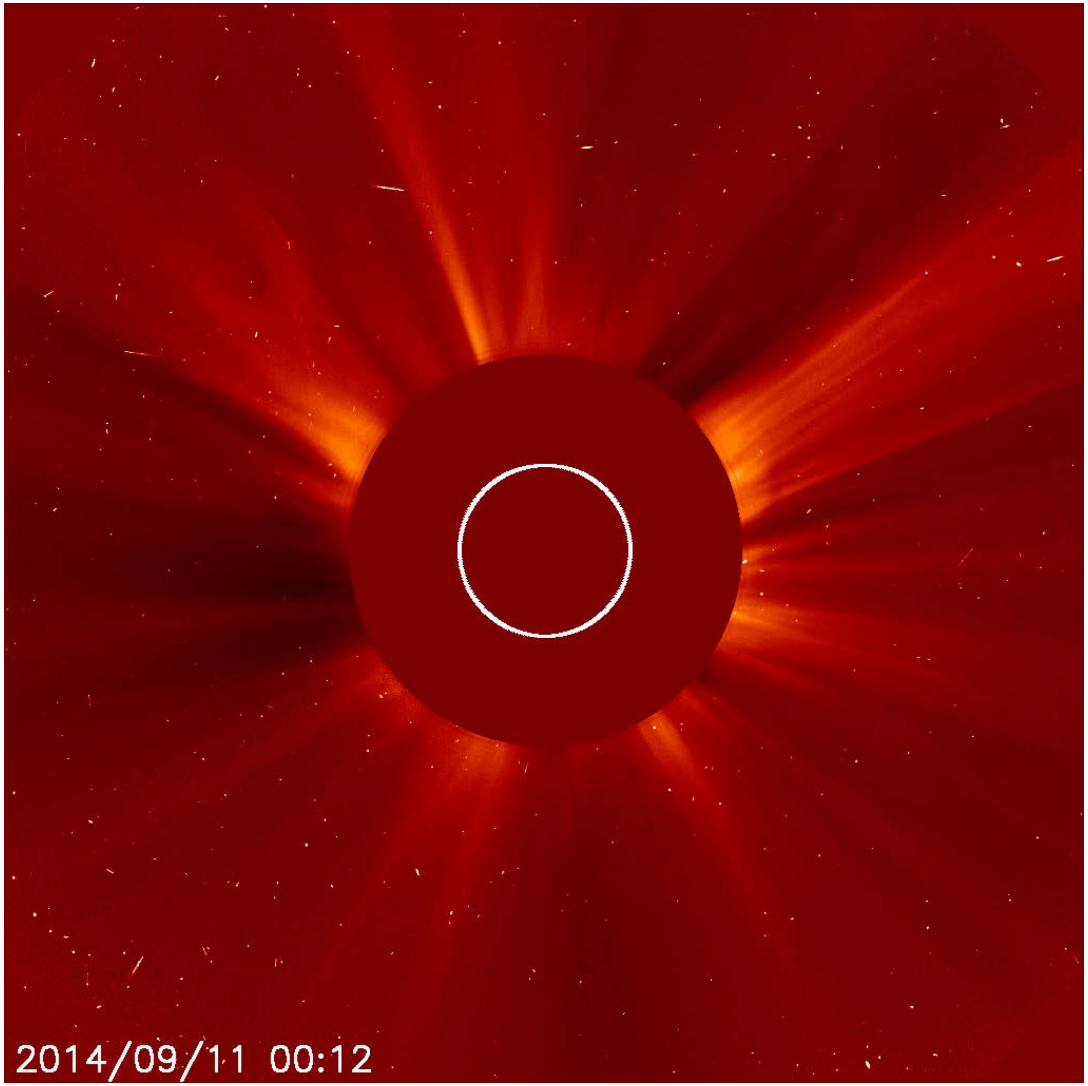
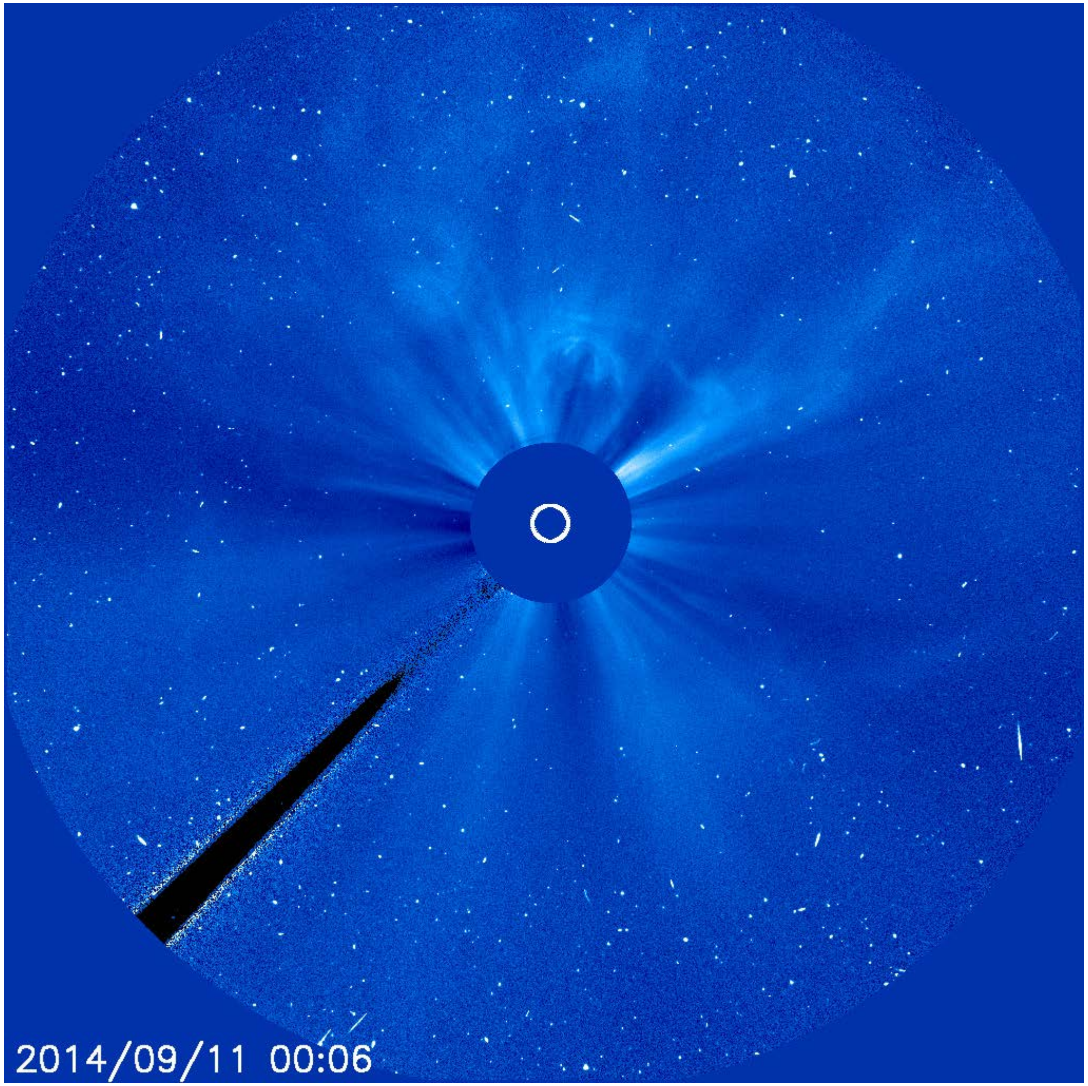
SDO/AIA 211 20140911_040036


AIA
9.4nm
Fe XVIII
6,300,000°K
11 Sept 2014
SDO/AIA 94 20140911_040038


AIA
Combined
Temperature
Proxy
11 Sept 2014
SDO/AIA- 211 2014/09/11 04:58:47
SDO/AIA- 193 2014/09/11 04:58:54
SDO/AIA- 171 2014/09/11 04:58:47
aia.lmsal.com


2014/09/11 00:12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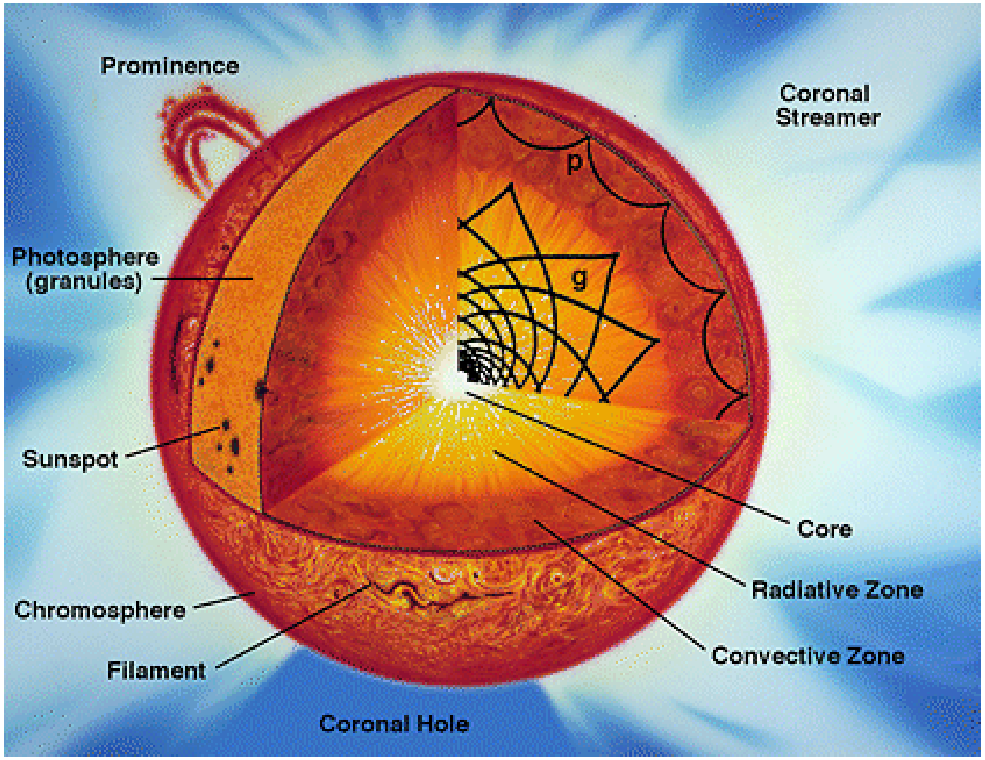
Quick stats and overview

- Things you already know
  - Radius 6.96×10^5 km
  - Age 4.5×10^9 years
  - Mass 2×10^{30} kg
  - 73.4% hydrogen, 24.8% helium by mass.
  - Luminosity 3.85×10^{26} J/s
  - Center is 15.7 million °K.
  - Surface temperature: 5,800 °K.
  - Corona temperature: 1 to 10 million °K.



Handy Numbers

- Mm = 10^6 m is handy unit for Sun
- Radius = 696 Mm, 953 arc-sec
- Diameter 1887 arc-sec in July to 1952 arc-sec in January
- Supergranule ~ 30 Mm
- Sunspot ~ 5 – 30 Mm
- Granule ~ 1 Mm
- 1 AU – average distance to Sun 150,000 Mm
- 1 arc-sec disk center at 1 AU = 0.73 Mm
- Rotation 25.38 days, ~ 27.27 days at Earth at 16 degrees
- HMI pixel 365km, AIA pixel 438km at 1AU

Solar Core

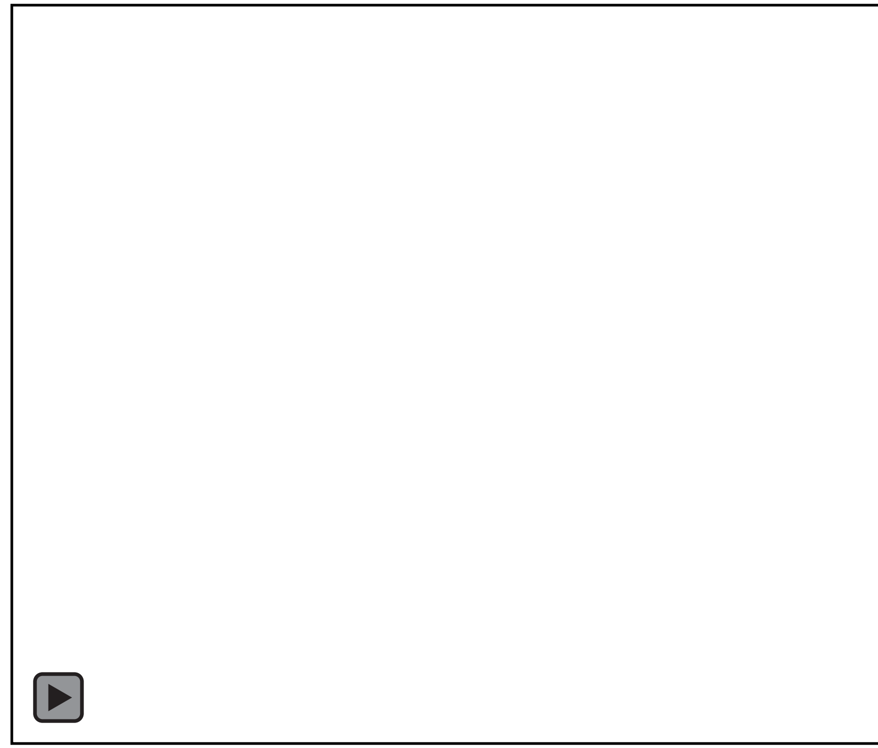
- Hydrogen nuclei fuse to make Helium nuclei
- Via complex reaction chains the net effect is 2 H -> 1 He + energy
- From luminosity we know that 4.3×10^9 kg/s of H is converted to He
  - Which is 0.007% per 10^9 years
- The Sun is big, this is < 300watt/m^3, like a compost pile.
- The energy is in gamma rays
- Neutrinos are byproduct, long story
- How we know
  - Stellar Models
  - Neutrinos
  - Helioseismology – more later…
- Found about 1/3 expected neutrinos. After stellar model calculations
- Models confirmed by helioseismology. Solution was that physics was wrong – neutrinos have mass, thus finite lifetimes, they change kinds between there and here.

Radiative zone

- Gamma rays -> X-rays -> lower energy photons takes hundreds of thousands of years random walk to get through the core and radiative zone
- Thermal time scale is c. 30 million years.
- Stable against convection, probably buoyancy waves, aka gravity waves like at the ocean surface are possible.
- At cooler height where H and He and heavier atoms are no longer fully ionized and opacity increases.
- This is the transition to convection zone where energy is carried up by turbulent convection.
- Buoyancy waves convert to convection and any standing or resonant g-modes are evanescent in the convection zone. Too bad since they would sample the deep interior better than acoustic waves.

Convection Zone

- This is where it gets interesting and time scales go from millions of years to tens of years to months to days to minutes.
- For processes that take place in minutes to hours, such as acoustic waves the interior up to near the photosphere can be considered to be a perfect gas. Computational life is simple. Sort of....
- See: http://www.cora.nwra.com/~werne/eos/text/convection_zone.html



Numerical Model of Convection Zone

Radial Magnetic Field in a rotating convective spherical shell. Color legend: Dark tones for the negative polarity and bright tones for the positive polarity.

http://lcd-www.colorado.edu/sabrun/movies.html

Photosphere

- Transition from simple to complex, gets ‘simple’ again well above.
- All the nice approximations that make calculations easy, or at least tractable, fail here. It is the place for observations and numerical simulations.
- Spectral line wings and continuum at top of granulation
- Line core above granulation (most photospheric lines)
- Below the photosphere the gas dominates, above the magnetic field dominates the structure.
- Photosphere and Chromosphere are perhaps worst places to observe in terms of complex physics.
- But it is where all the light comes from…

Photosphere – Some Numbers

Surface Gas Pressure (top of photosphere): 0.868 mb
Pressure at bottom of photosphere (optical depth = 1): 125 mb
Effective temperature: 5778 K
Temperature at top of photosphere: 4400 K
Temperature at bottom of photosphere: 6600 K
Temperature at top of chromosphere: ~30,000 K
Photosphere thickness: ~500 km
Chromosphere thickness: ~2500 km
Sun Spot Cycle: 11.4 yr.

Photosphere Composition:

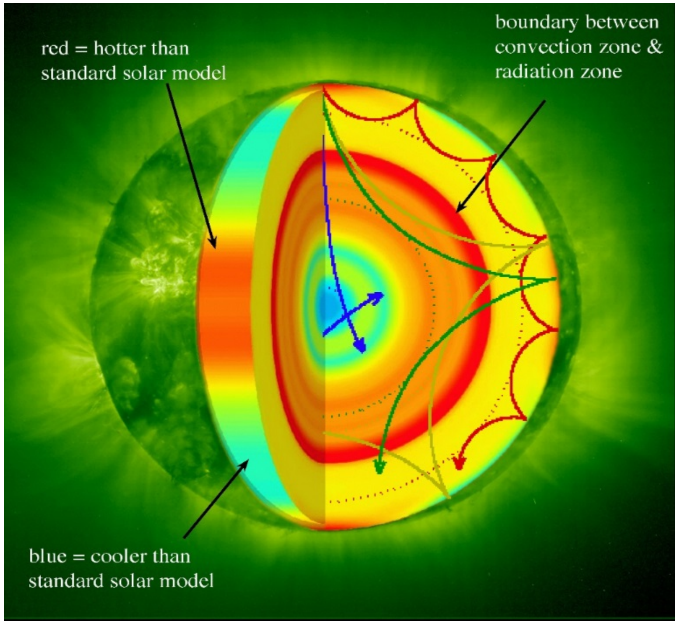
Major elements: H - 90.965%, He - 8.889%
Minor elements (ppm): O - 774, C - 330, Ne - 112, N - 102
Fe - 43, Mg - 35, Si - 32, S - 15

Helioseismology – What Is It?

Helioseismology is the study of solar interior by analysis of the propagation of sound waves through the Sun's interior.

The Sun is filled with acoustic waves with periods near five minutes.

These waves are refracted upward by the temperature gradient and reflected inward by the drop in density at the surface



The travel times of these waves depends on the temperature, composition, motion, and magnetic fields in the interior.

The visible surface moves when the waves are reflected enabling their frequency, phase, and amplitude to be measured.

Analysis of travel times over a multitude of paths enables inference of internal conditions.

Helioseismology – Quick Overview

- The Sun and most stars are filled with acoustic waves.
- These waves, in the Sun at least, are excited by the small (Mm) convective cells at the surface.
- The waves travel in all directions in the interior and with frequencies below a “cutoff frequency” reflect from near the surface.
- The waves have lifetime sufficient to travel through and around the Sun and the superposition of many wave packets can be detected as normal modes of oscillation.
- Analysis of the measured frequencies of these modes is referred to as “global helioseismology”
- Physical inferences are made by comparing measured frequencies to those calculated from solar models.

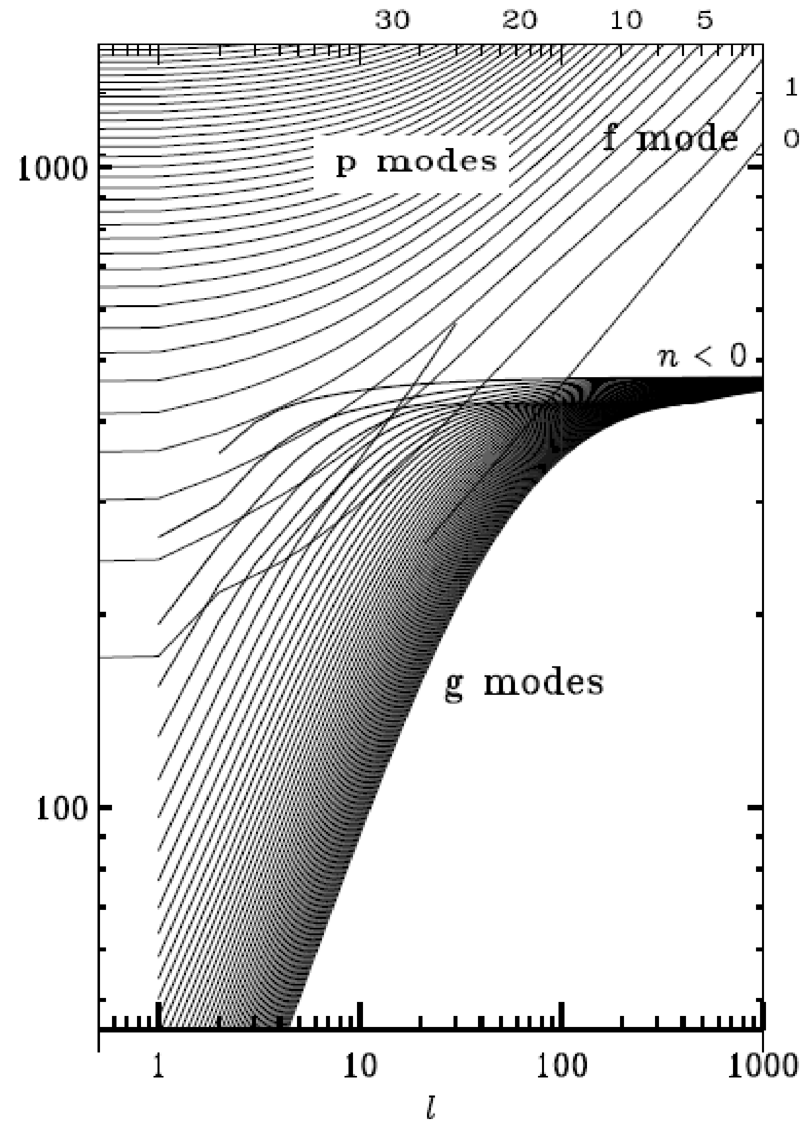
Solar interior wave modes

Cyclic frequencies as functions of degree *l*, computed for a normal solar model.

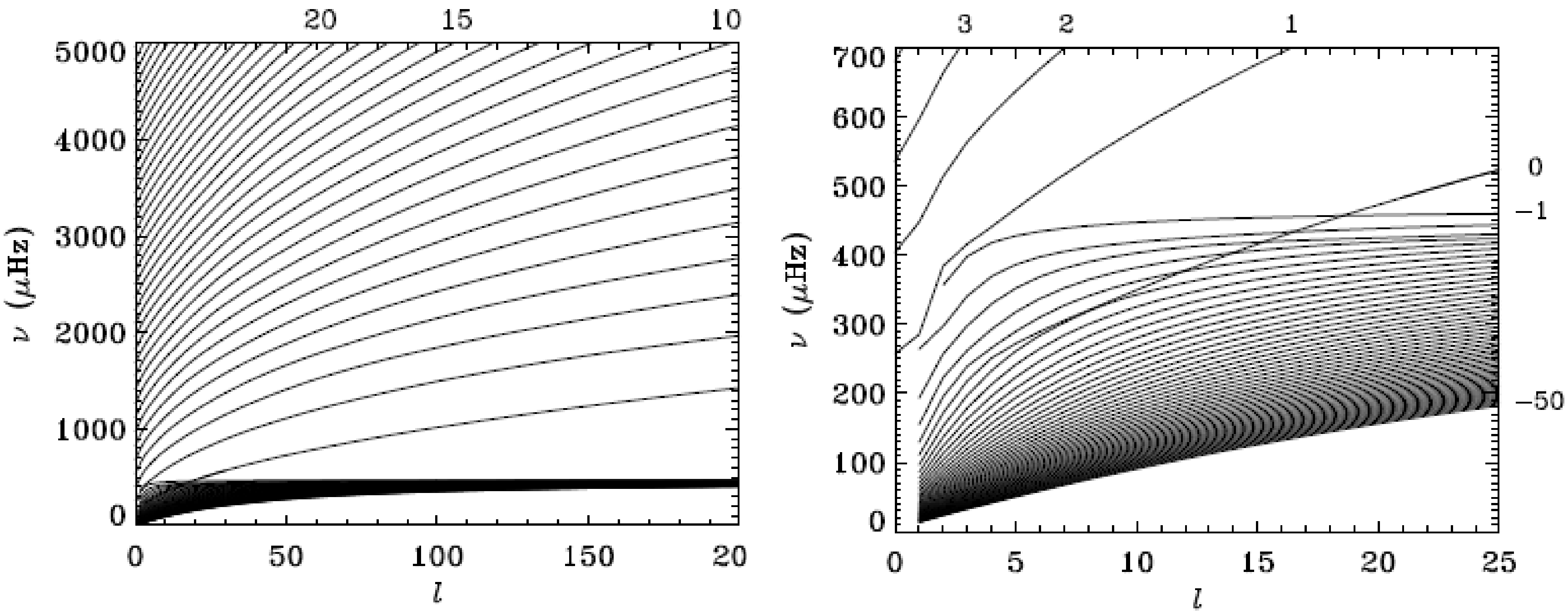
From "Lecture Notes on Stellar Oscillations", Joergen Christensen-Dalsgaard, 5th edition, 2014. Read this!

g modes are internal buoyancy modes, not yet observed (probably).
f mode is a surface gravity wave.
p modes are acoustic waves.

Modes are labeled by radial harmonic n, degree l, and order m.

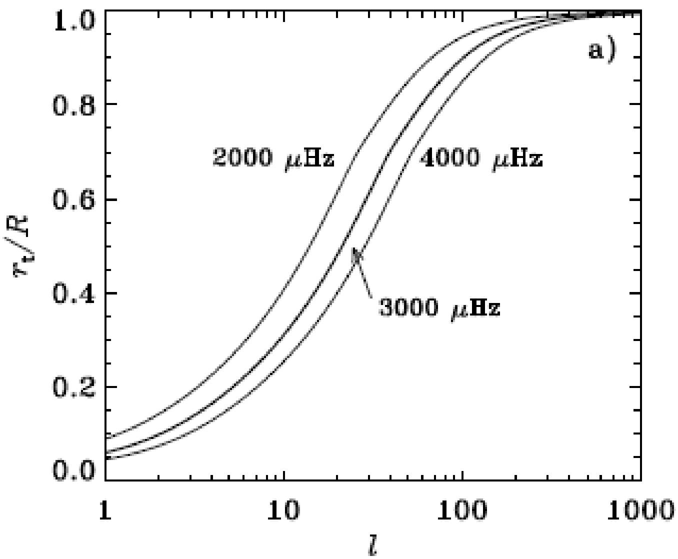


Linear views of same

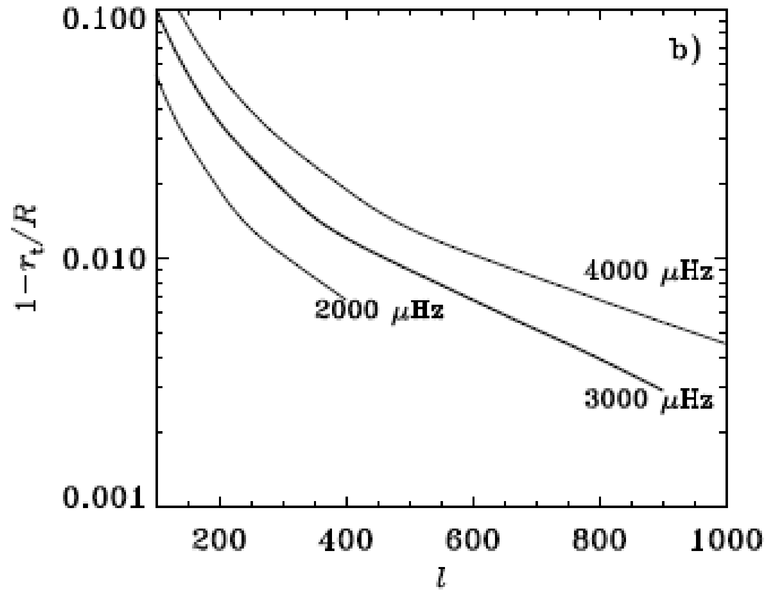


At low *l* the modes are nearly equally spaced, at higher *l* low radial number n they are nearly parabolas.

Lower turning points



Only low degree modes penetrate into the radiative zone



High degree modes only sample the near surface region

Where c is sound speed, $c = \omega/k$. We can separate radial and horizontal components of $\boldsymbol{k}$ as $|\boldsymbol{k}|^2 = k_r^2 + k_h^2$. Lower turning point is where radial part of wavenumber k_r vanishes. Using the relation $k_h^2 = l(l+1)/r$ we see that $r_t^2 = l(l+1)\, c^2(r_t)/\omega^2$. Thus deeper with increasing frequency and lower *l.*

Sample ray paths. From JCD.

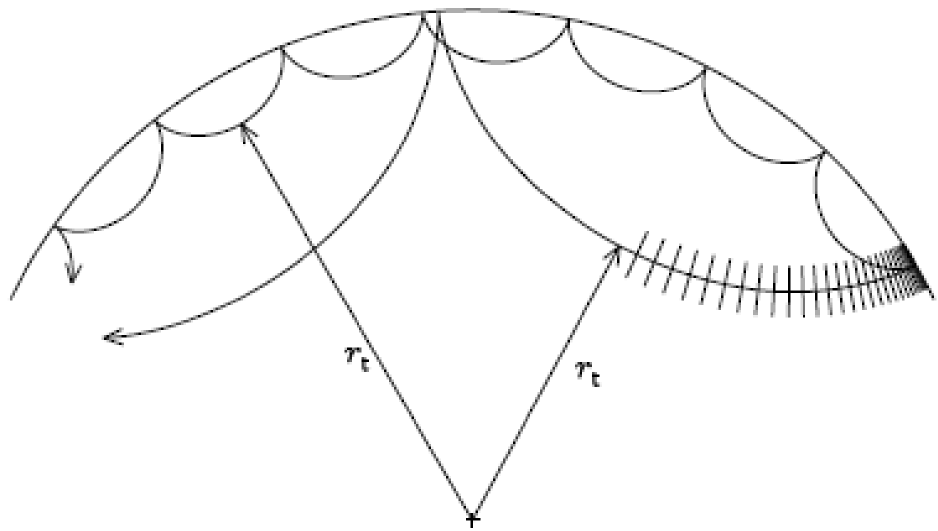
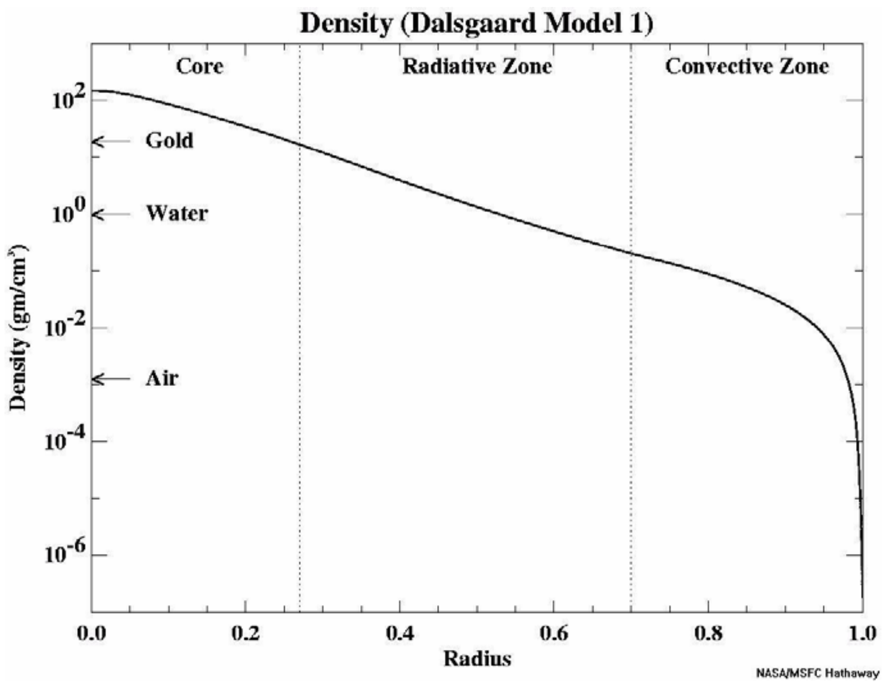
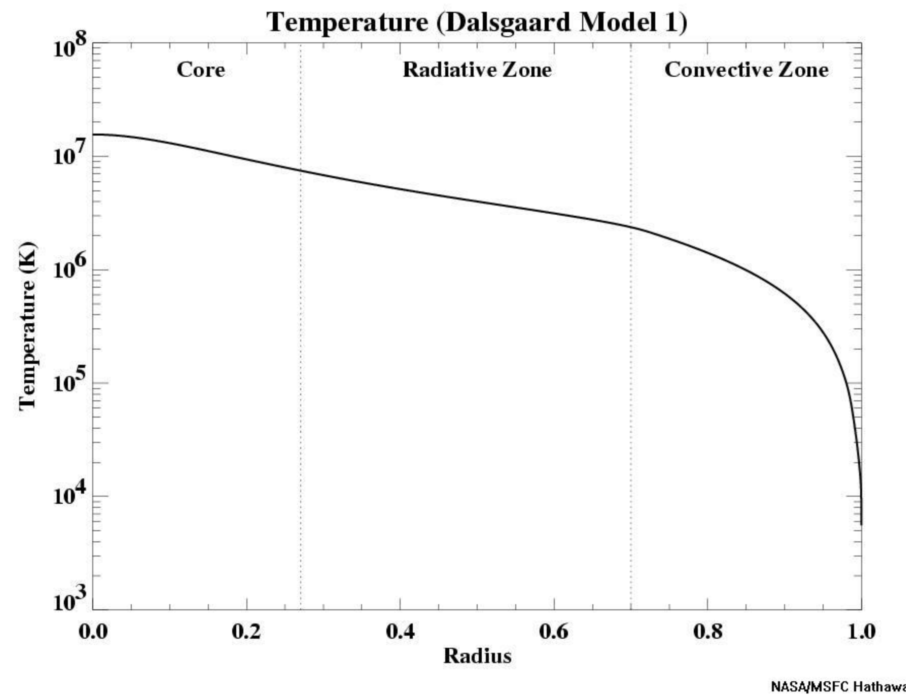


Figure 5.4: Propagation of acoustic waves, corresponding to modes with $l = 30$, $\nu = 3\,\mathrm{mHz}$ (deeply penetrating rays) and $l = 100$, $\nu = 3\,\mathrm{mHz}$ (shallowly penetrating rays). The lines orthogonal to the former path of propagation illustrate the wave fronts.

Solar Model Density and Temperature vs Depth





Density from center to surface, from 10^2 to 10^{-6}

Temperature from center to surface, from 1.5×10^7 to 5×10^3

From JCD, Model ‘S’ data is available at http://users-phys.au.dk/jcd/solar_models/

Solar Model 'S' by Joergen Christensen-Dalsgaard

http://users-phys.au.dk/jcd/solar_models/

```
# sound speed, etc for Model S (Christensen-Dalsgaard et al. 1996)
#
#  r/R      c (cm/sec)   rho (g/cm^3)  p (dyn/cm^2)    Gamma_1     T (K)
#
 1.0007126 6.8643880e+05 3.2924832e-09 9.4557639e+02  1.6407053 4.3481956e+03
 1.0007047 6.8657305e+05 3.4690527e-09 9.9627728e+02  1.6413612 4.3484914e+03
 1.0006968 6.8670653e+05 3.6565446e-09 1.0501248e+03  1.6419969 4.3488194e+03
 1.0006888 6.8684063e+05 3.8555865e-09 1.1073017e+03  1.6426175 4.3491832e+03
 1.0006807 6.8697749e+05 4.0668379e-09 1.1679998e+03  1.6432328 4.3495866e+03
 1.0006726 6.8712024e+05 4.2909950e-09 1.2324234e+03  1.6438552 4.3500339e+03
 1.0006645 6.8726374e+05 4.5288000e-09 1.3007889e+03  1.6444595 4.3505299e+03
…
 0.0014480 5.0466295e+07 1.5386289e+02 2.3489111e+17  1.6682847 1.5667737e+07
 0.0014288 5.0466263e+07 1.5386369e+02 2.3489205e+17  1.6682845 1.5667756e+07
 0.0014098 5.0466228e+07 1.5386447e+02 2.3489289e+17  1.6682847 1.5667775e+07
 0.0013911 5.0466228e+07 1.5386501e+02 2.3489373e+17  1.6682845 1.5667793e+07
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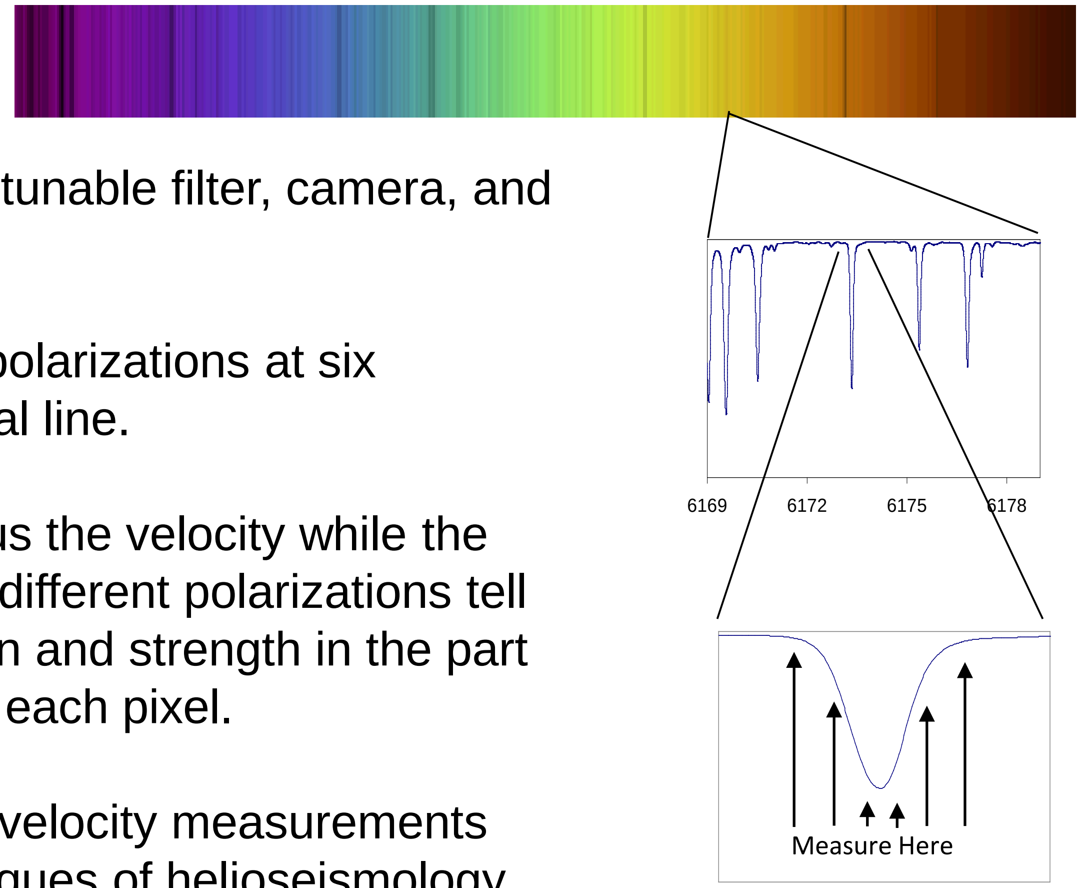
HMI – How It Works



HMI consists of a telescope, tunable filter, camera, and necessary electronics.

HMI images the Sun in four polarizations at six wavelengths across a spectral line.

The position of the line tells us the velocity while the shape changes of the line in different polarizations tell us the magnetic field direction and strength in the part of the Sun's surface seen by each pixel.

Long gap-free sequences of velocity measurements are needed to use the techniques of helioseismology.

How to Measur

HMI “Dopplergram”

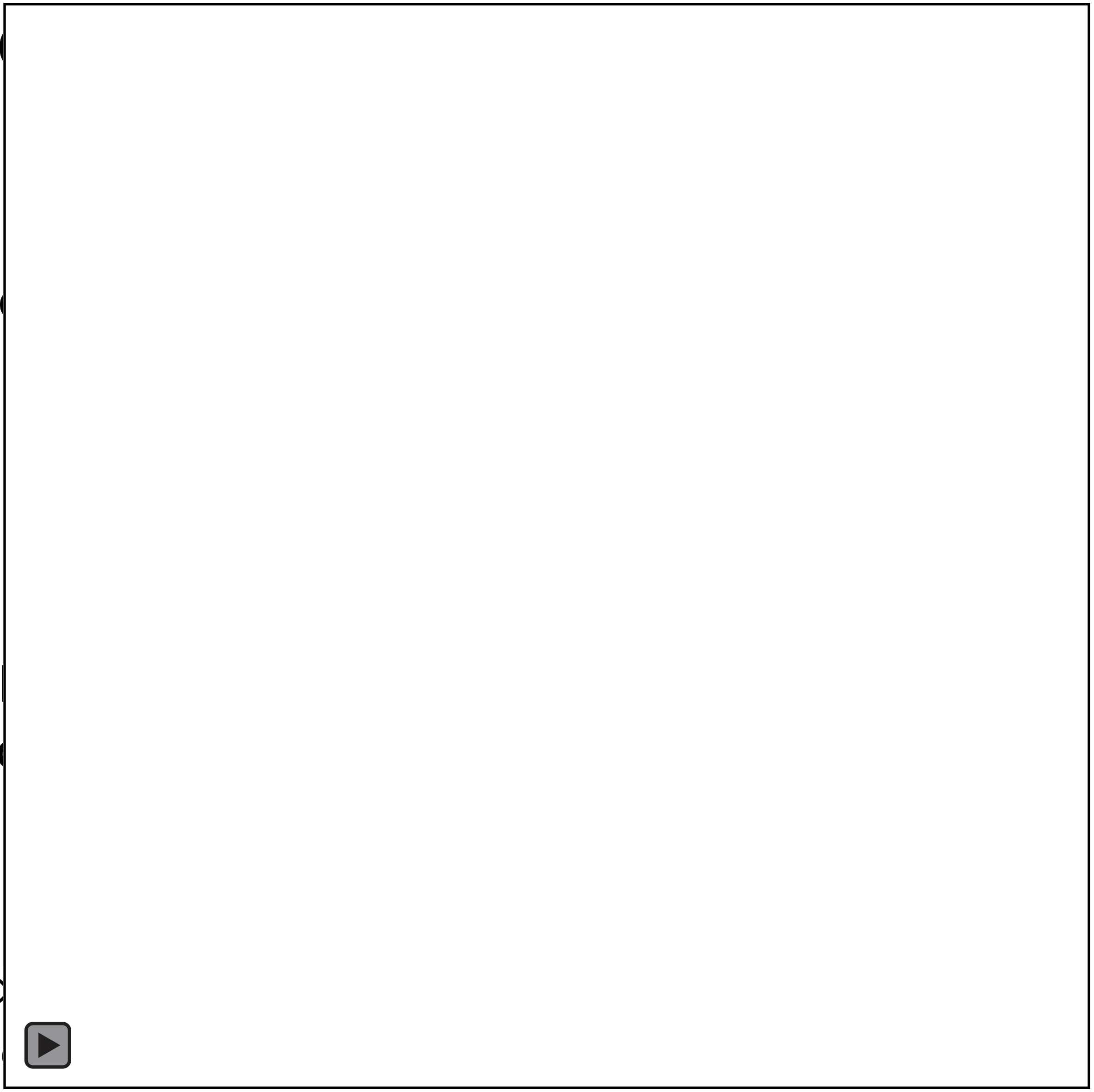
Images of motion of the lay
that the light comes from

Dark=moving to you

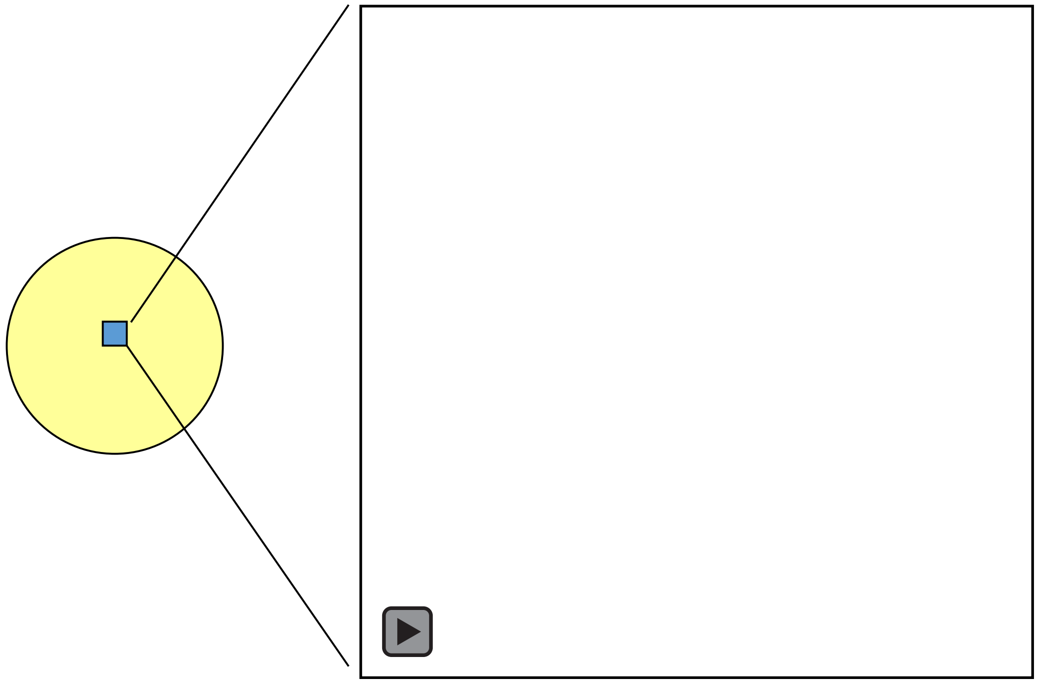
Light=moving away

HMI makes 4096x4096 pixel
images in 6 wavelengths an
polarizations for the “Doppl
camera with a 45s cadence.

Velocity, magnetic field, and
continuum intensity, line wi
and line depth are computed.

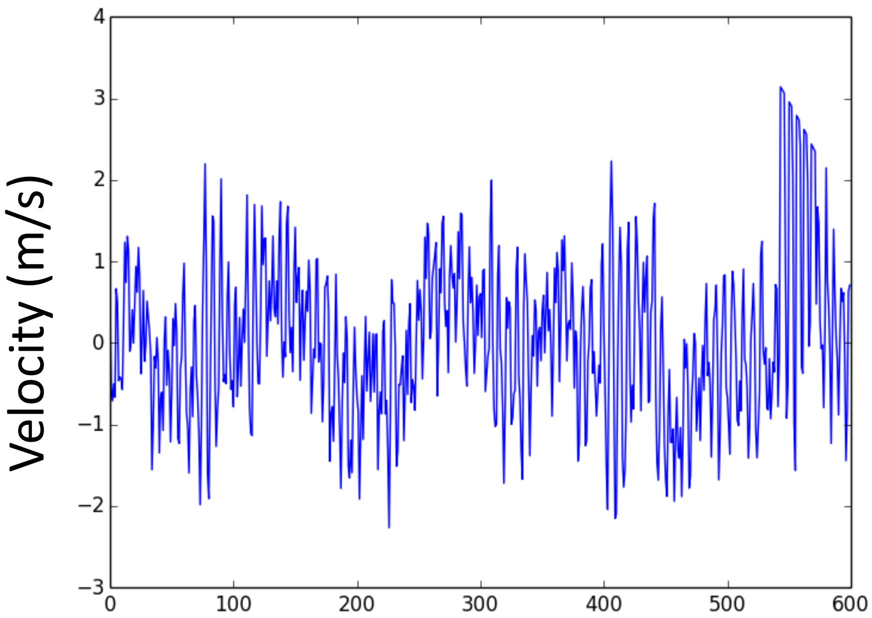


Close-up of Sun's surface motion

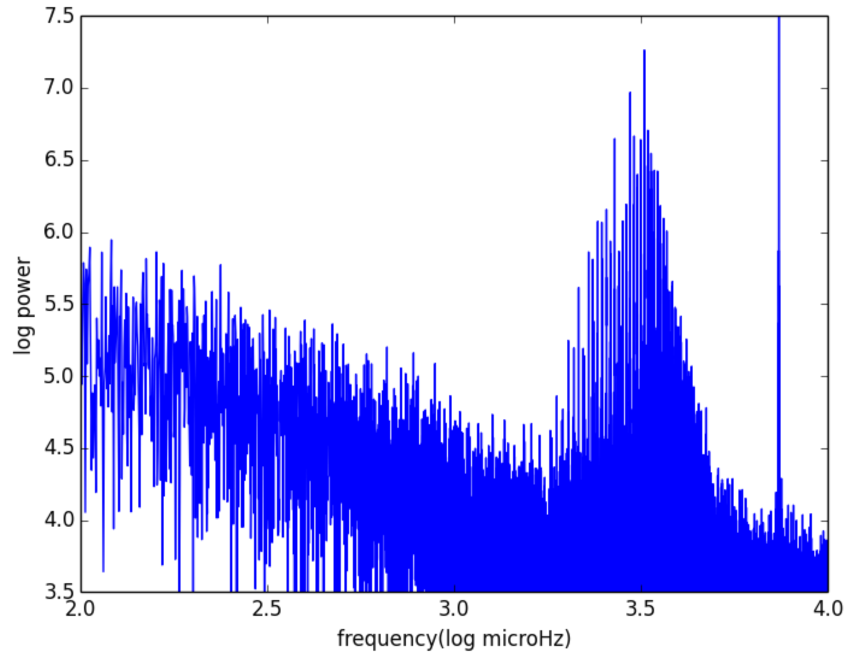


Lighter is motion into Sun, darker is upward motion

Sun as a Star Average Velocity



Time in 45s samples

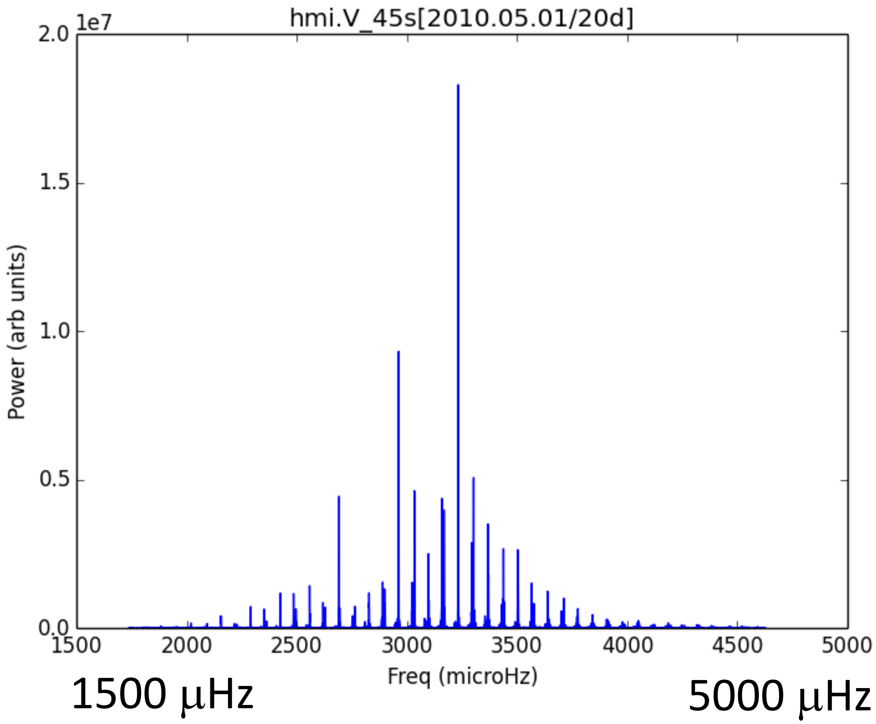


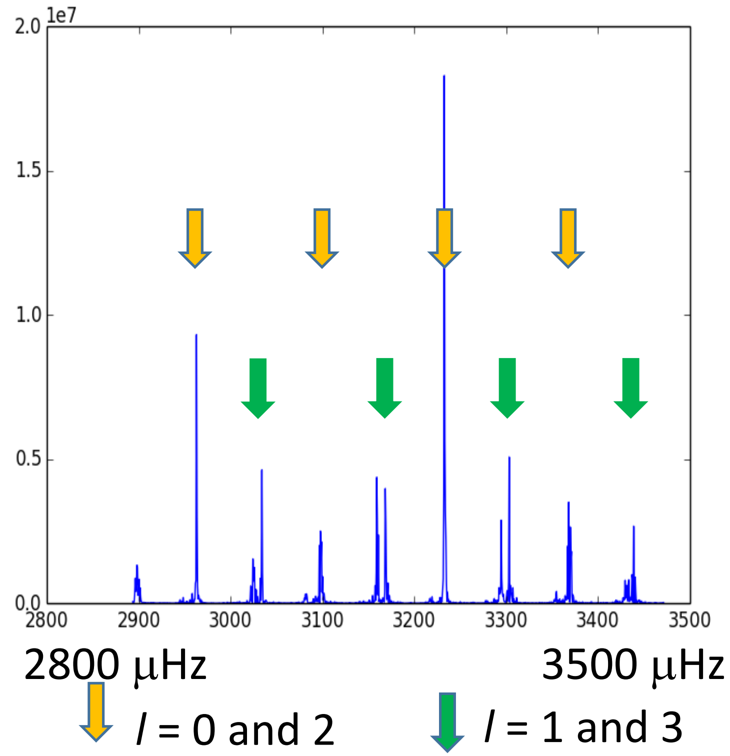
Power spectrum as log-log plot

HMI Disk average velocity, 7.5 hour sample from May 2010
Plots from sample analysis Python program

Sun as a Star Seismology

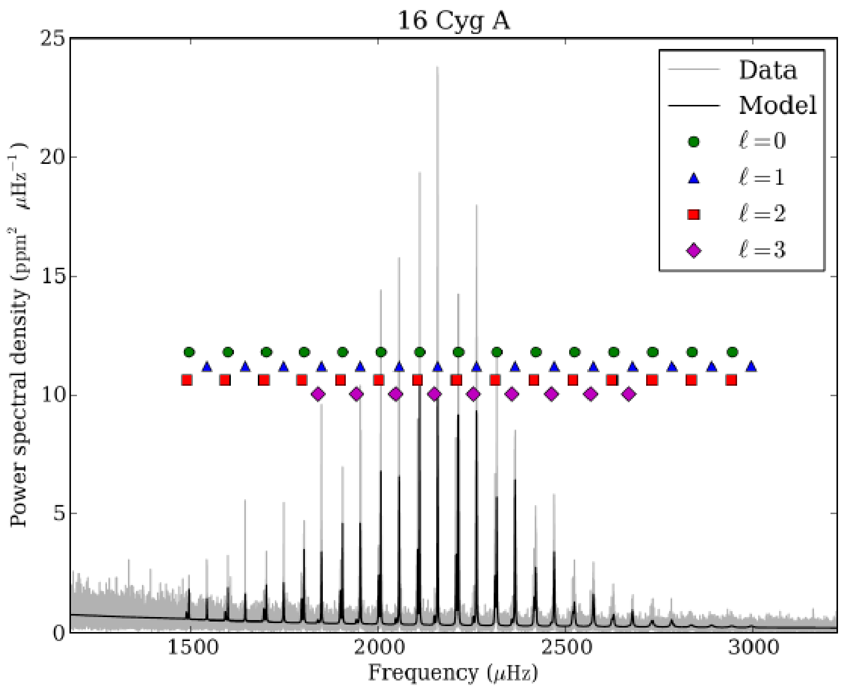
Sun as a Star p-mode spectrum for 20 days

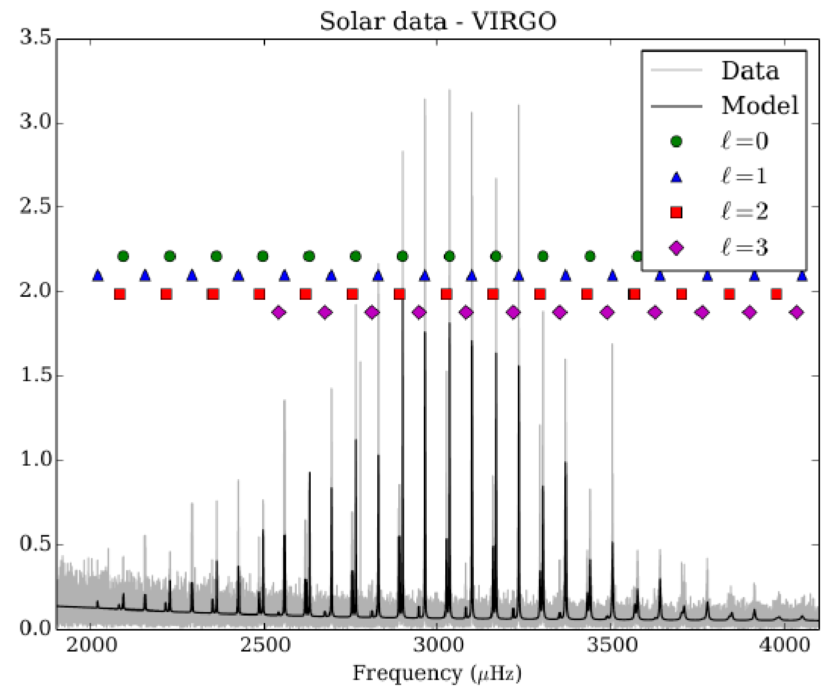




The 135 μHz "large" separation gives information about the whole star, the *l*=1 – *l*=3 small separation gives information about the core.

Kepler: Solar analog





	16 Cyg A	16 Cyg B	16 Cyg Bb
Age (Gyr)	6.8 ± 0.4^{a}	6.8 ± 0.4^{a}	6.8 ± 0.4
Mass	1.11 ± 0.02^{a} $M_\odot$	1.07 ± 0.02^{a} $M_\odot$	2.38 ± 0.04^{c} M_{Jup}
Radius	1.243 ± 0.008^{a} $R_\odot$	1.127 ± 0.007^{a} $R_\odot$	-
$B - V$	$0.64^{b} \pm 0.01$	$0.66^{b} \pm 0.01$	n/a
Orbital Period	$> 13000^{c}$ yr	$> 13000^{c}$ yr	798.5 ± 1.0^{c} days
Eccentricity	0.54 to 1^{d}	0.54 to 1^{d}	0.689 ± 0.011^{c}
Orbital Inclination (°)	100 to 160^{d}	100 to 160^{d}	$45/135^{c}$

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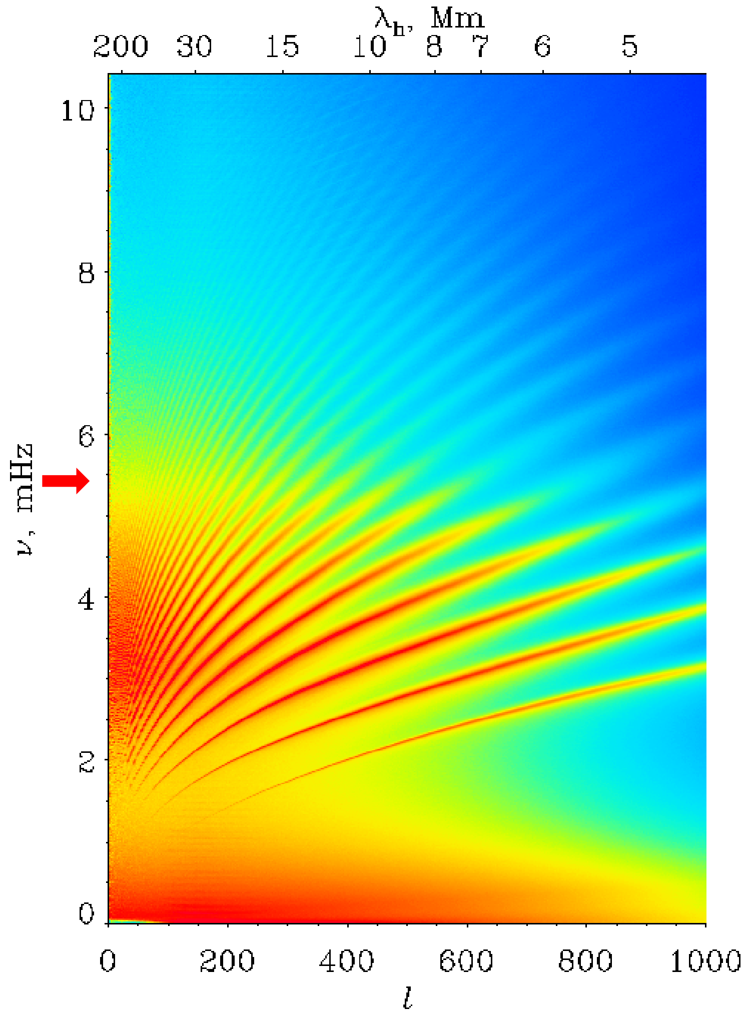
Observed Oscillations, SOHO/MDI

- *l-n* diagram for the Sun. This is for about 1 day.
- The red arrow as at about the acoustic cutoff frequency, waves below this frequency are trapped below the photosphere.
- Peak in power at about 5 minutes period
- Mode lifetimes decrease with increasing frequency
- Tens of thousands of modes are observed with high s/n
- Analysis of frequencies use at least 72 day spans to achieve very accurate frequencies. SOHO/MDI has 73 such sets, SDO/HMI 22.



Solar Sound Speed vs Depth

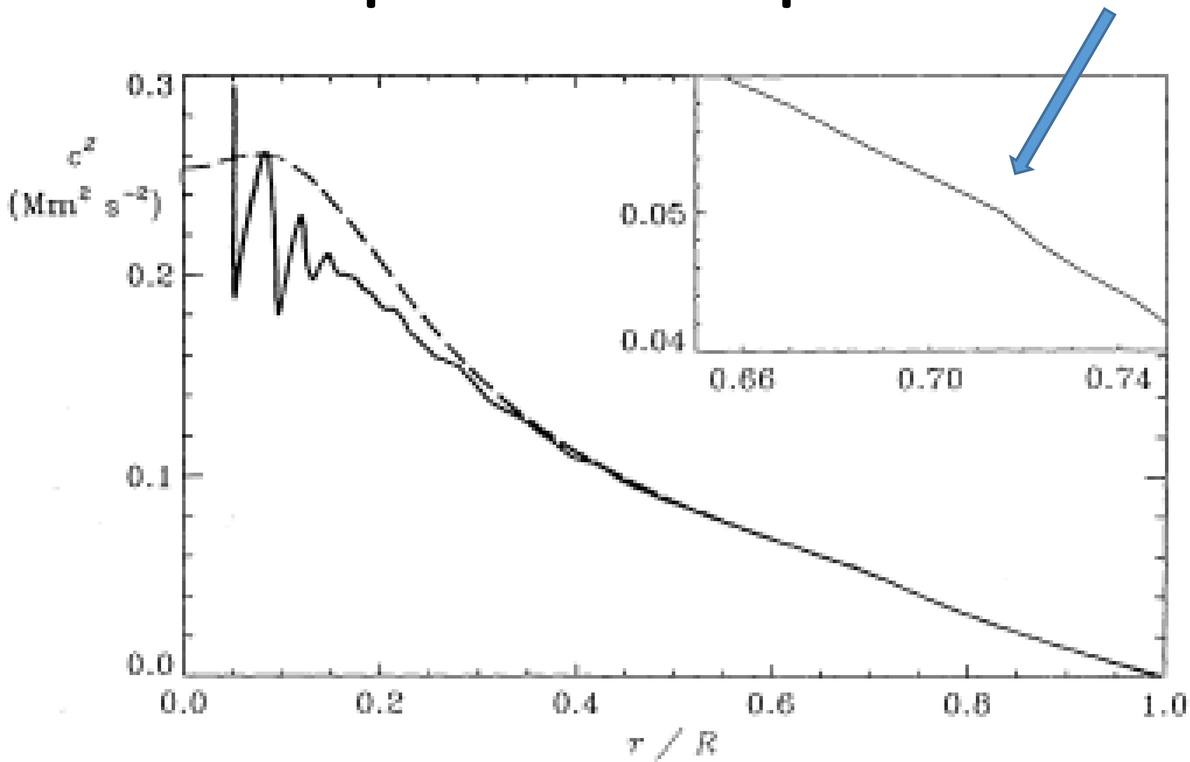


FIG. 1.—The sound speed in the Sun as inferred by Christensen-Dalsgaard et al. (1985) (*solid curve*); the dashed curve shows the sound speed in a standard solar model for comparison. The inset shows in greater detail the inferred sound speed near the base of the convection zone.

From JCD, Note the kink at 0.713 – this is the base of the convection zone

Helioseismic Inversions

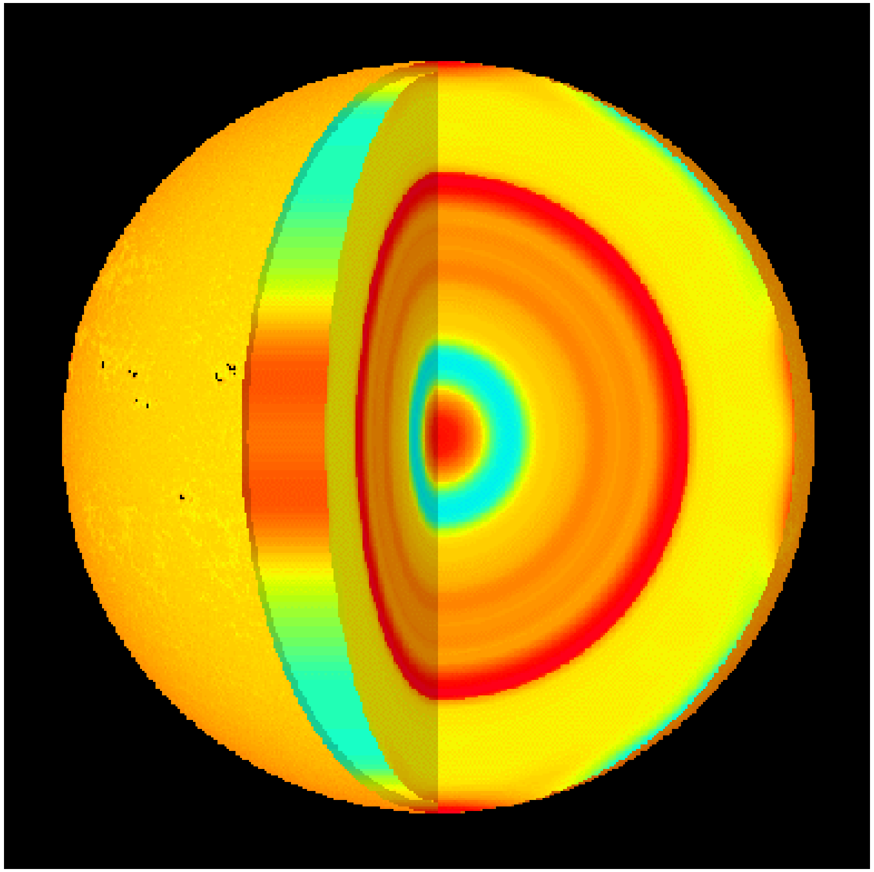
- Having a collection of mode frequencies does not directly give us details of the solar interior.
- The analysis process is one of iterating from a “forward problem” of computing frequencies from a solar model then constructing localized kernels to be used to estimate deviations from the model based on differences between model frequencies and observed frequencies.
- Using these kernels and the observed frequencies then is an “inverse problem” to infer the actual physical properties from the observations.
- See e.g. “Inversion methods in helioseismology and solar tomography” by A. G. Kosovichev

Journal of Computational and Applied Mathematics, Volume 109, Issues 1–2, 30 September 1999, Pages 1–39.
http://www.sciencedirect.com/science/article/pii/S0377042799001521

Solar Structure Variation from Models

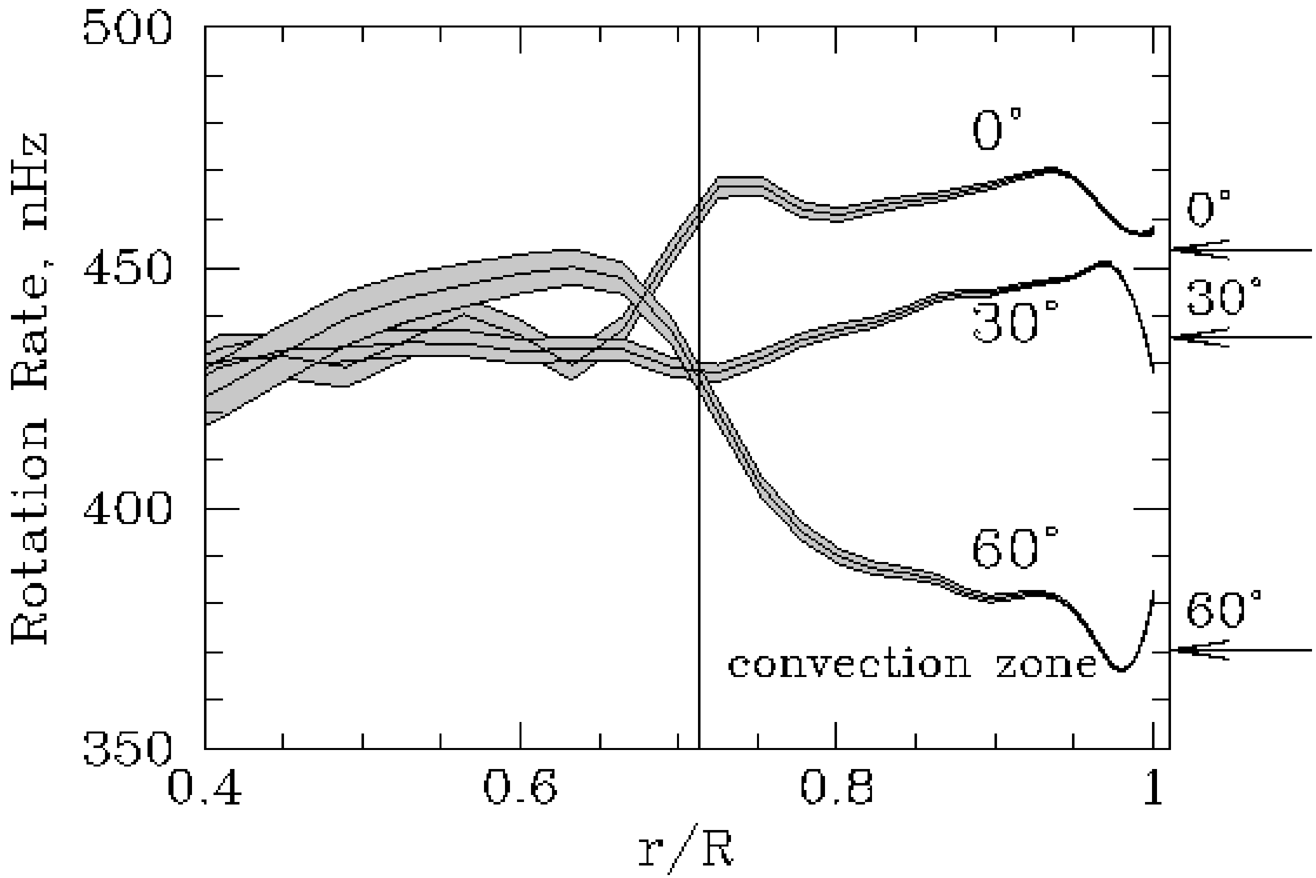
Sound speed difference from best model

Peak at base of convection zone is about 0.2%



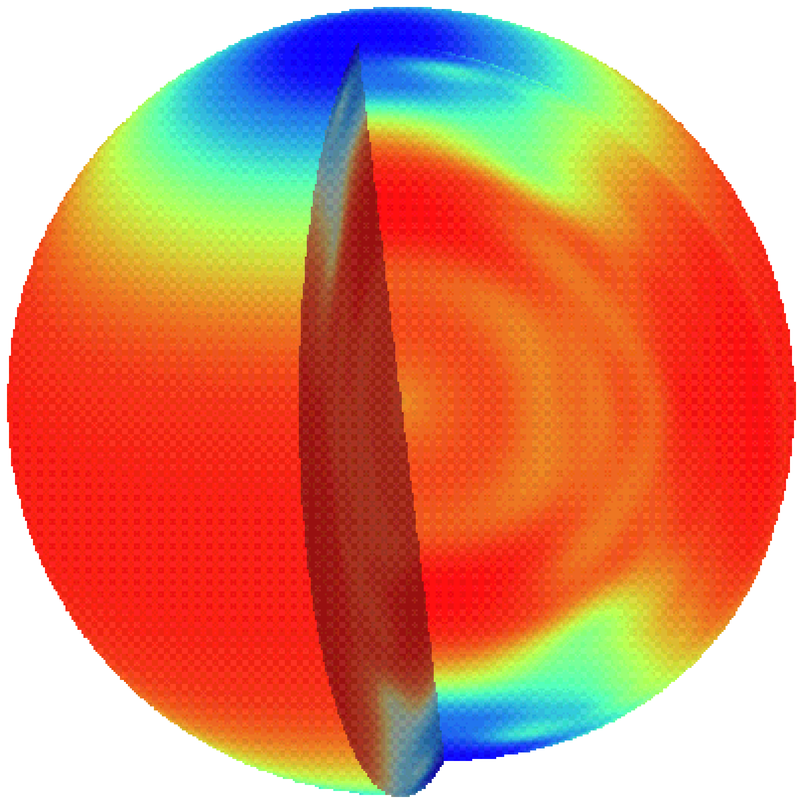
Red is faster, blue is slower than model

Observed Internal Rotation



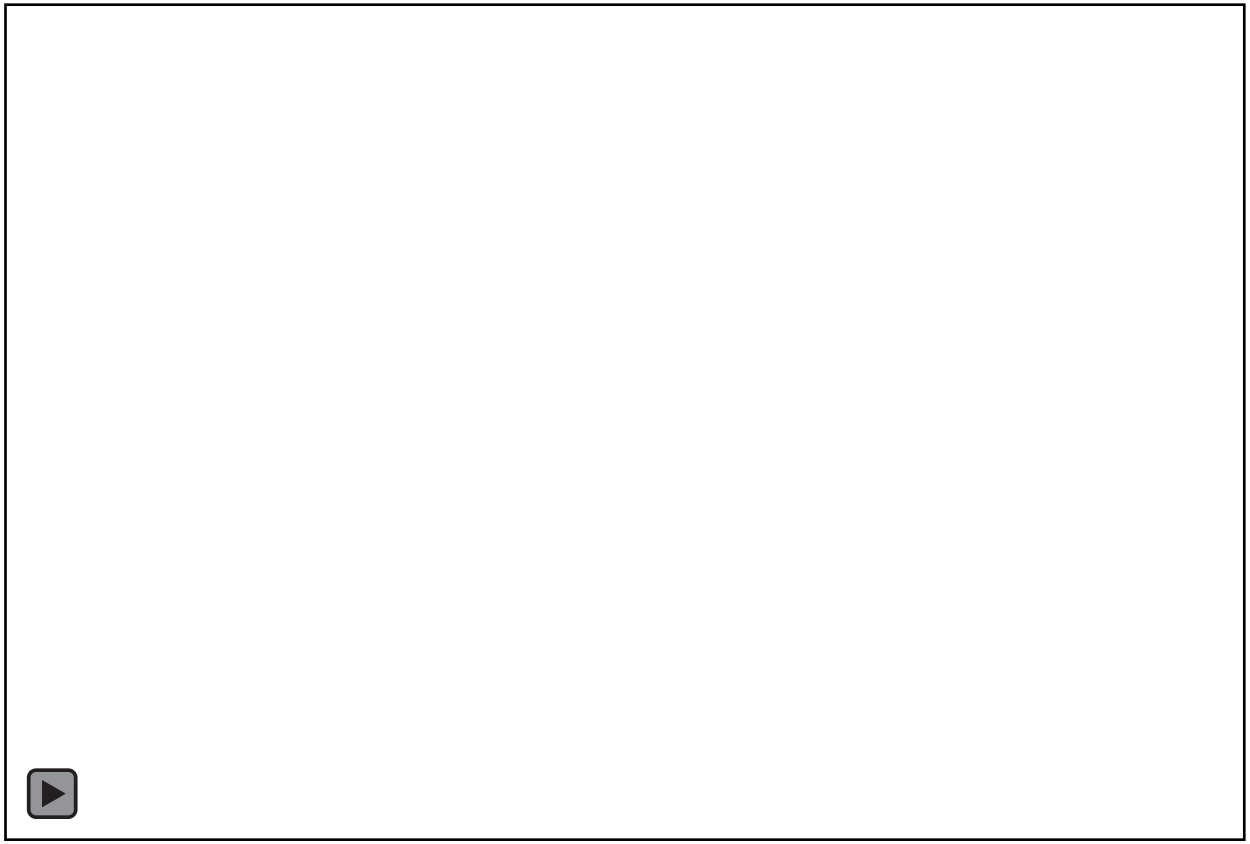
Radiative zone rotates as solid body, Tachocline has shear that varies with latitude, Differential rotation in convection zone, Near surface shear layer

Observed Internal Rotation



By measuring thousands of mode frequencies we can also infer the rotation speed inside the Sun. Red is faster (26 days) and blue is slower (35 days).

Variations from smooth differential rotation



Alternating fast and slow bands, migrate to equator over sunspot cycle. Known as “zonal flows” or “torsional oscillation”. Speeds of a few m/s on top of 2 km/s equatorial rotation.

From SOHO/MDI

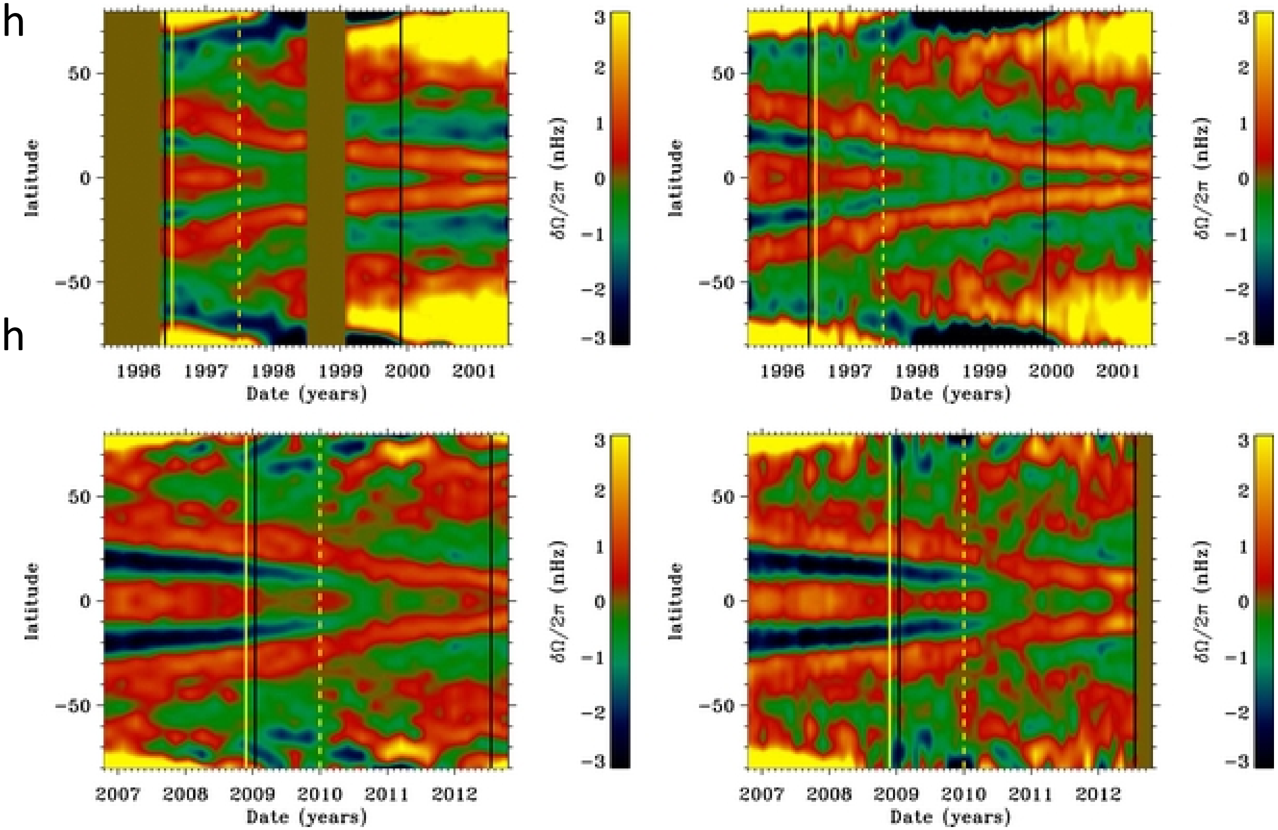
Zonal Flows aka Torsional Oscillation

North

1996-2001

South

2002-2012



Rotation rate residuals, MDI+HMI on left, GONG on right.

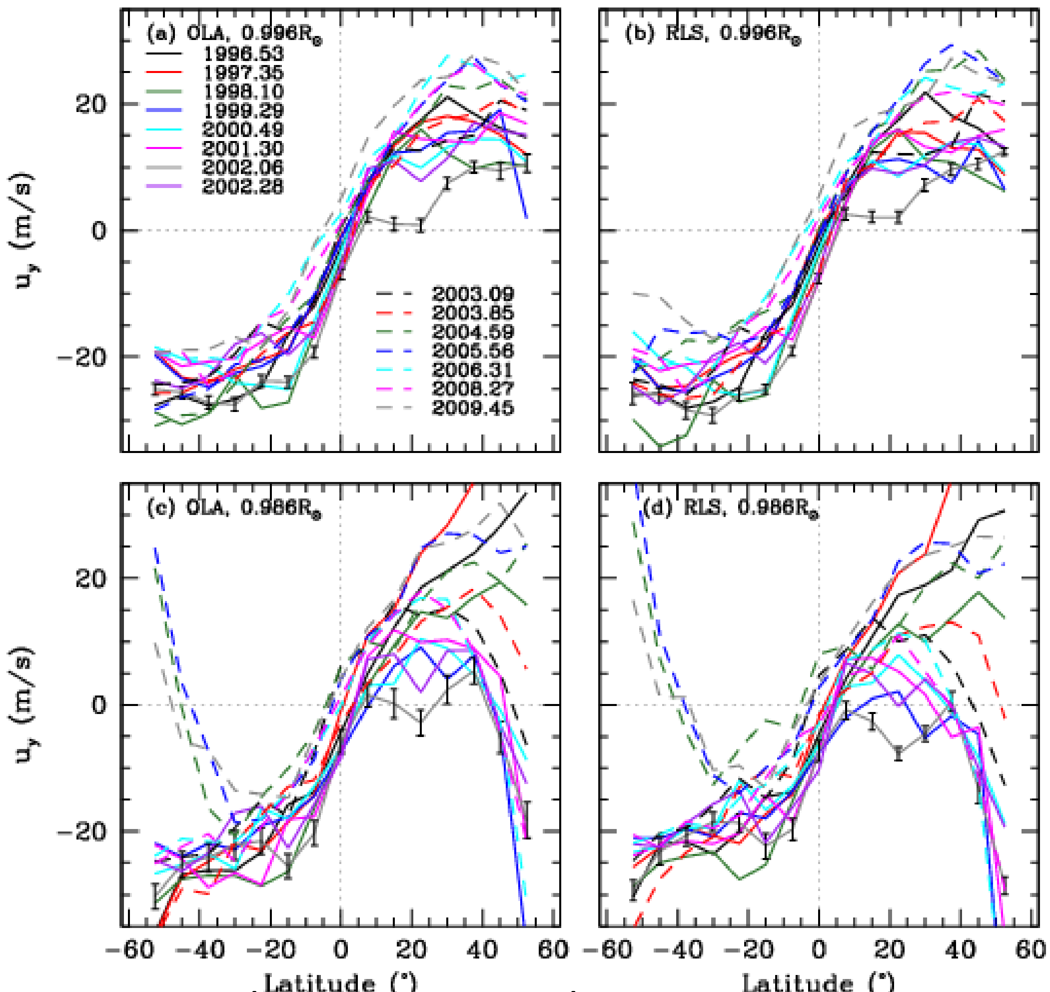
Depth of 0.99 Rsun.

Note difference in amplitude of high latitude branch in the present cycle.

May be related to weak polar field.

R. Howe et al. 2013 ApJ 767 L20

Meridional Flow
Cycle 23 and rising phase of cycle 24



3 Mm deep

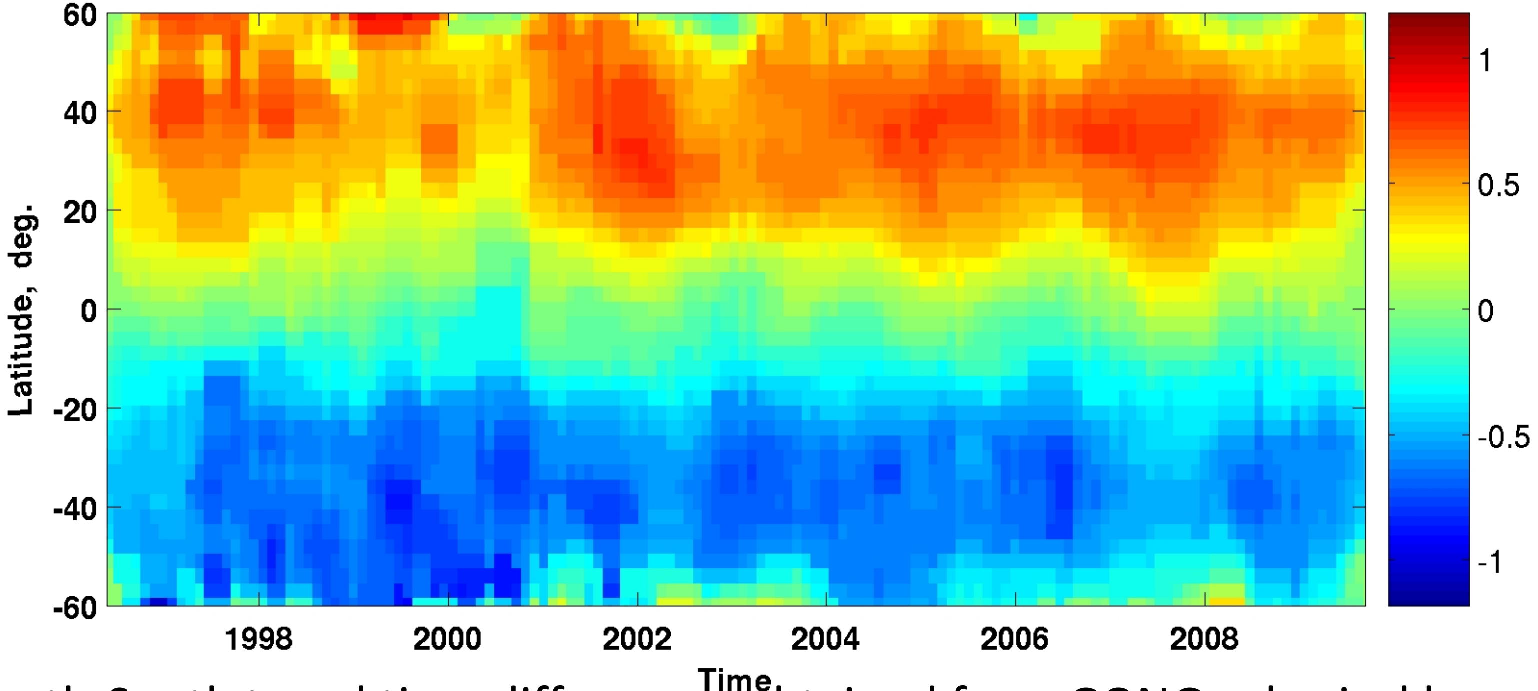
10 Mm deep

60 South

60 North

Results for Ring diagram analysis with OLA and RLS inversions.

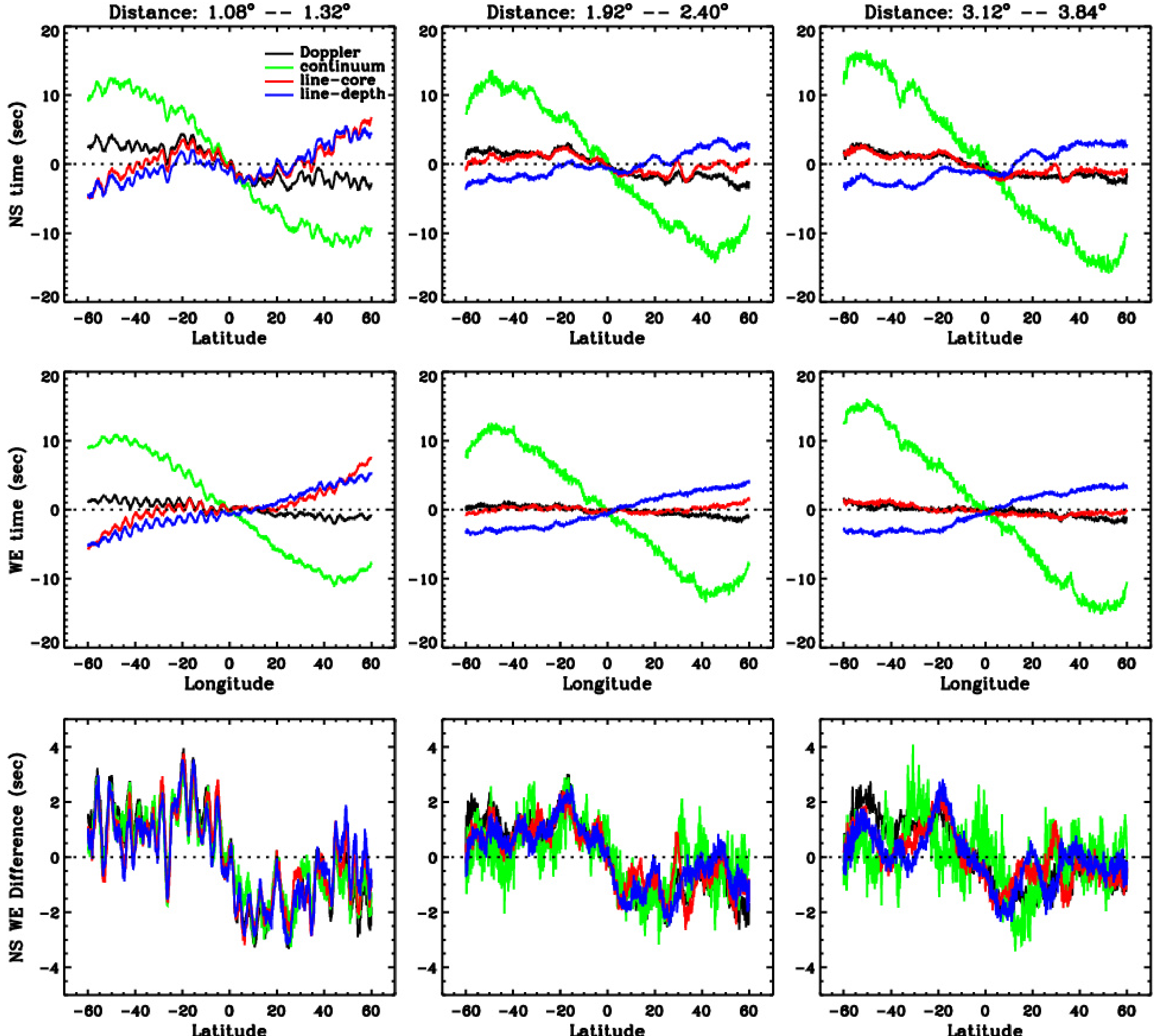
Meridional Flow vs Time, another method



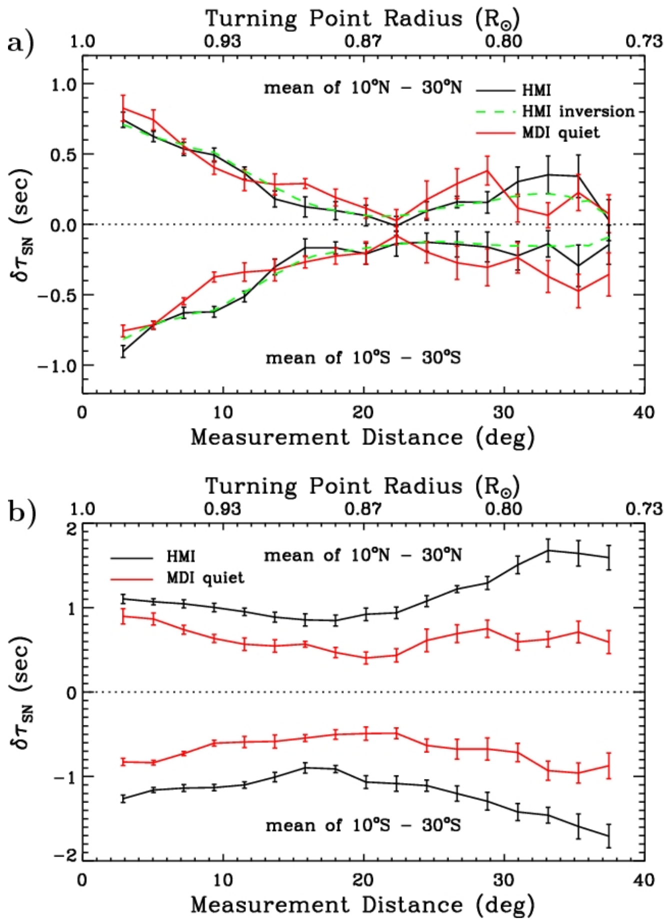
North-South travel time differences obtained from GONG spherical harmonic time series. Blue color corresponds to the flow propagating to the south and red one to the north. At high latitudes some B-angle related artifacts are visible. Approximately lower turning point of the waves is about 0.91R (Kholikov et al., in preparation)

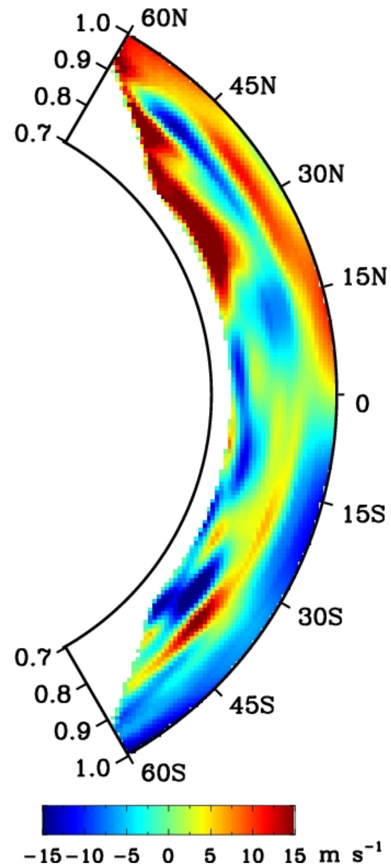
http://www.noao.edu/noao/staff/irenegh/meridional_web/meridional.html

Meridional flow, Now What?

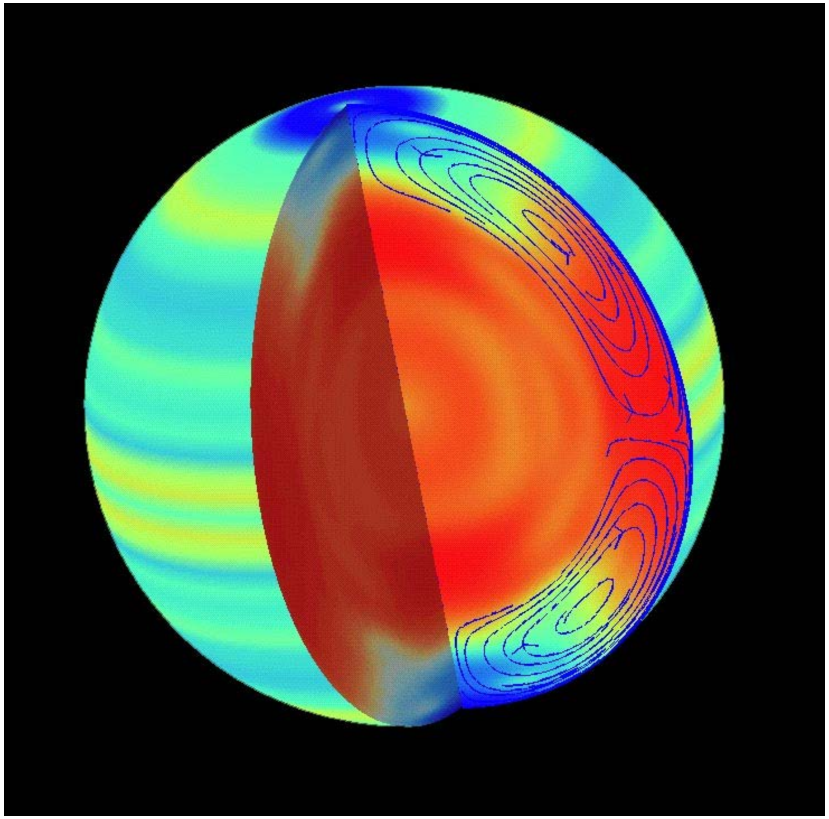


Meridional flow, …

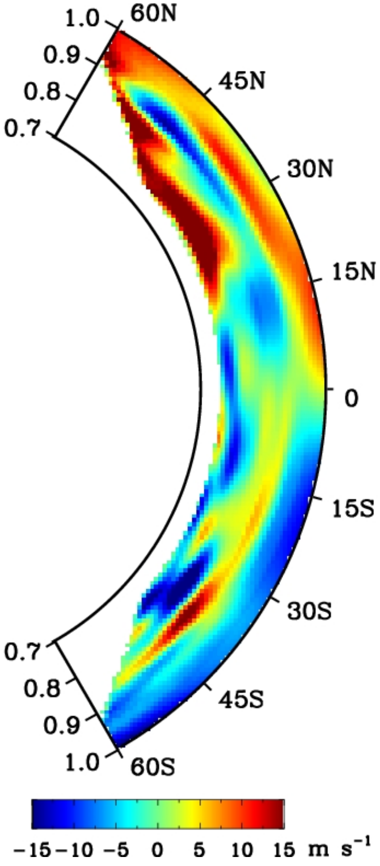




Meridional flow, Maybe.

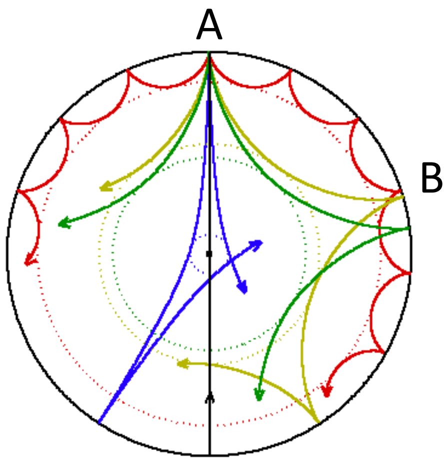


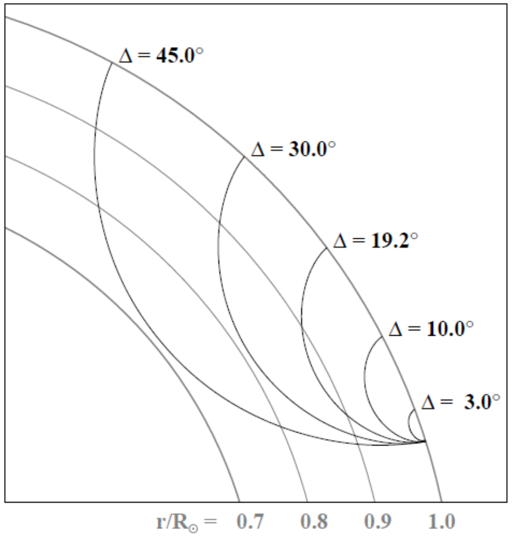
Old idea



New Data

Time-Distance Helioseismology Example





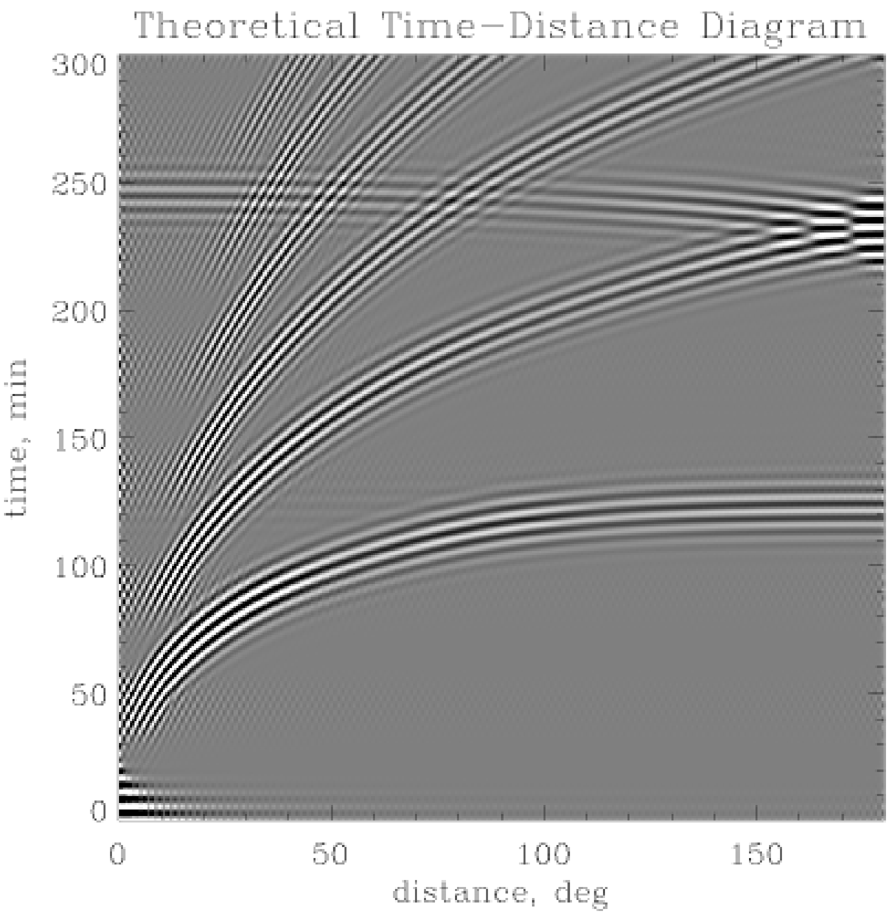
Waves going in all directions are reflected at each point on the surface.

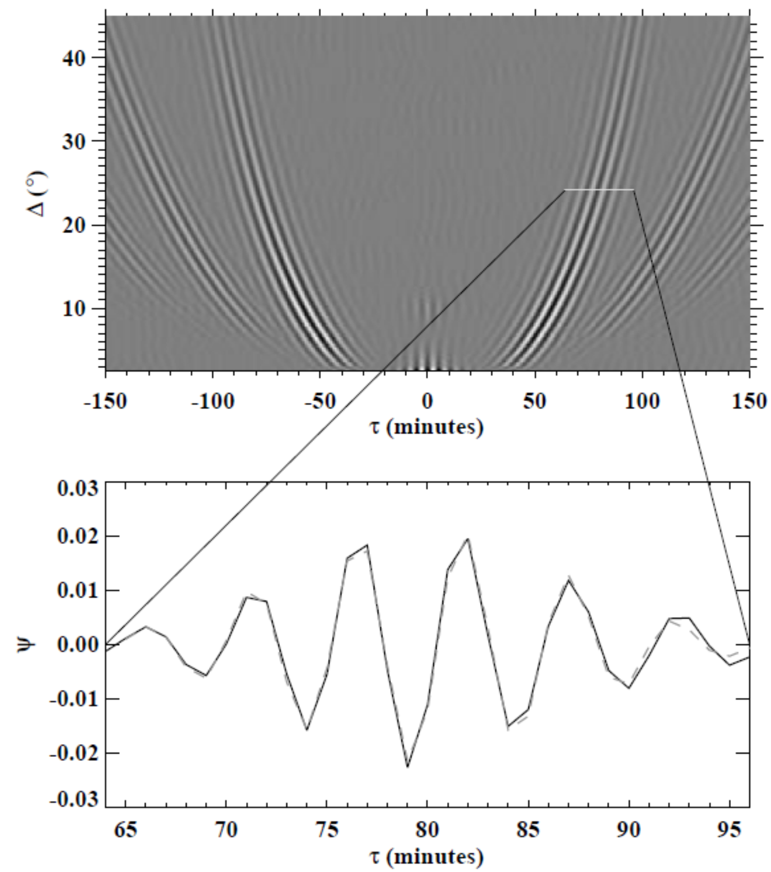
Cross-correlations of the time series observed at pairs of points (A,B) reveal the integrated travel-time along the interior path that "connects" A with B.

Differences between the A→B and B→A directions arise from bulk motion along the path.

Analyses of travel-time maps provide maps of flows and temperatures beneath the surface.

Time Distance Diagram

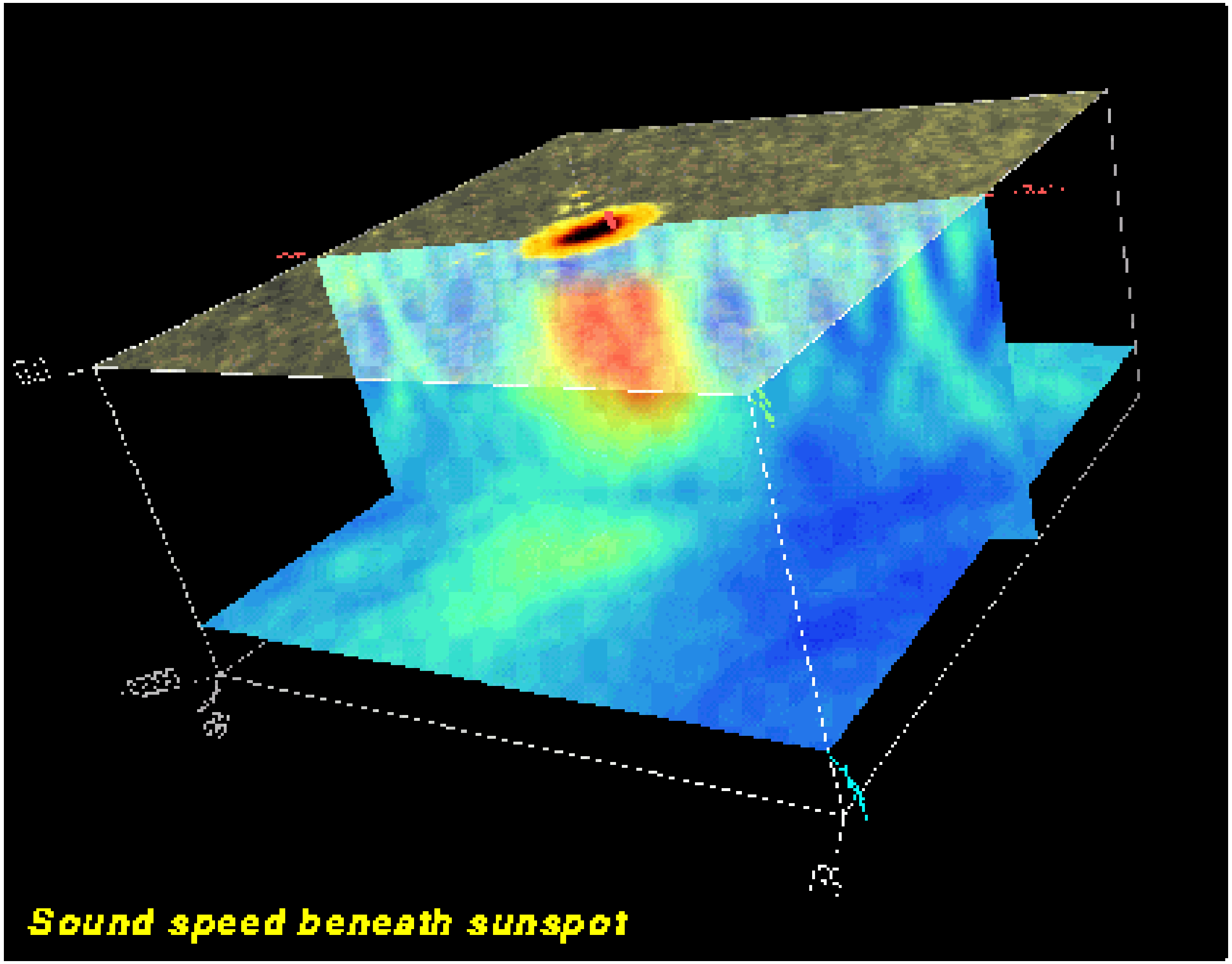




http://solarphysics.livingreviews.org/open?pubNo=lrsp-2005-6&page=articlesu12.html

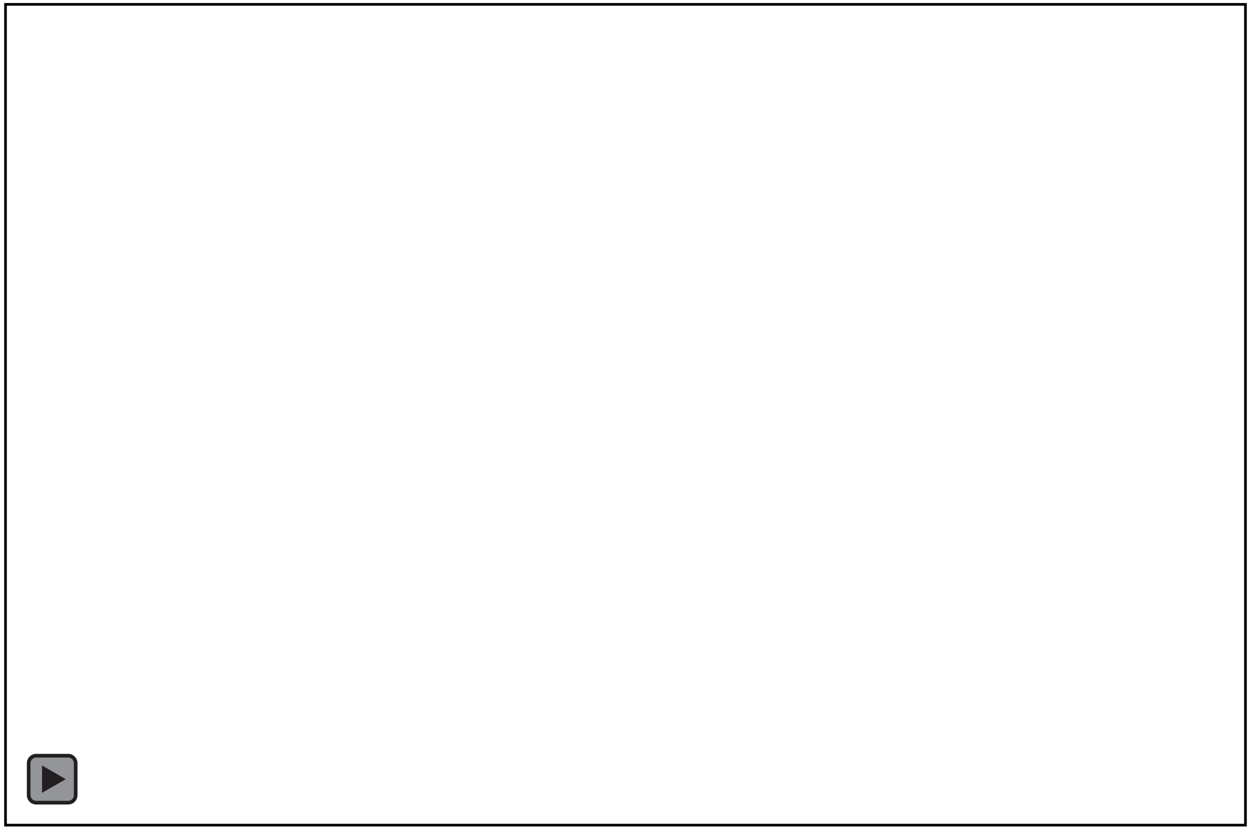
Giles, P. Dissertation, 1999

View of a Sunspot's Internal Structure

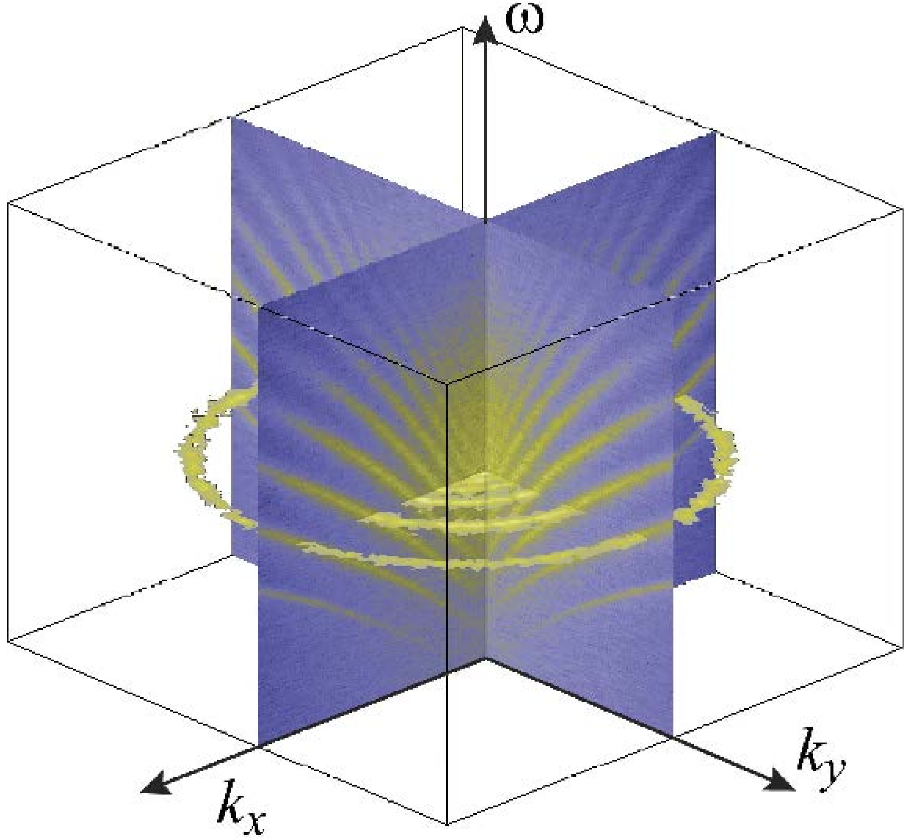


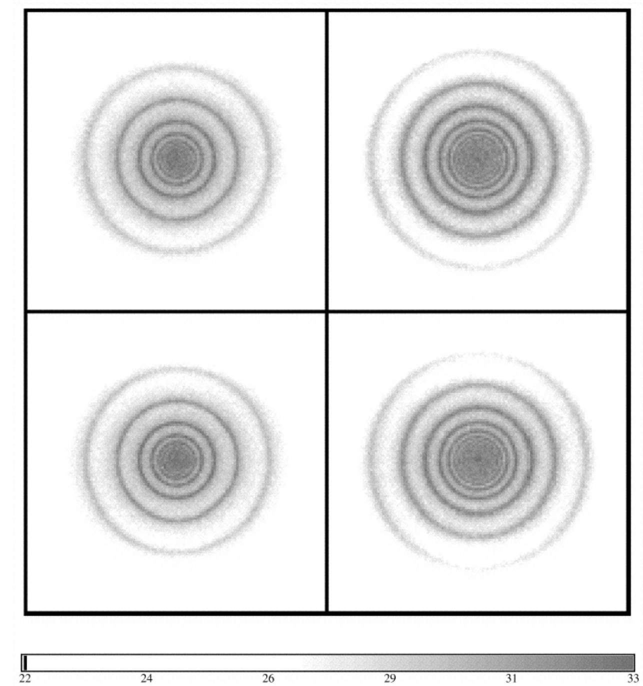
Sunspot data from MDI High Resolution, 18 June 1998

Animation showing the flows we found.
These motions probably hold the spot together.



Ring Diagram Analysis for Local Helioseismology





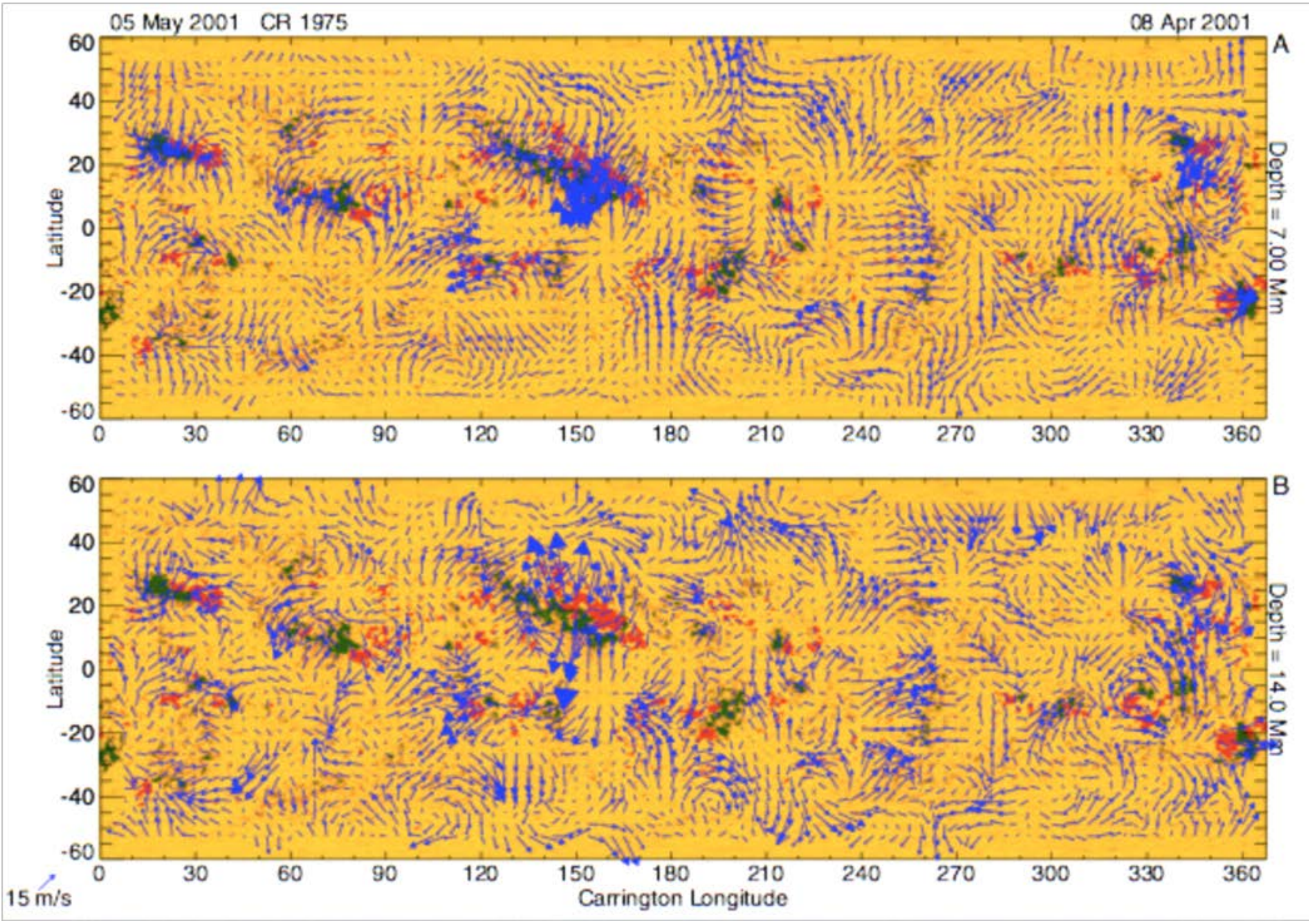
Slices at constant ω

Typically 5, 15, 30 degree regions are used, tiling entire disk each 8 hours

Basu, Antia, and Tripathy

THE ASTROPHYSICAL JOURNAL, 512:458–470, 1999 February 10

Solar Sub-Surface Weather – From Ring Diagrams

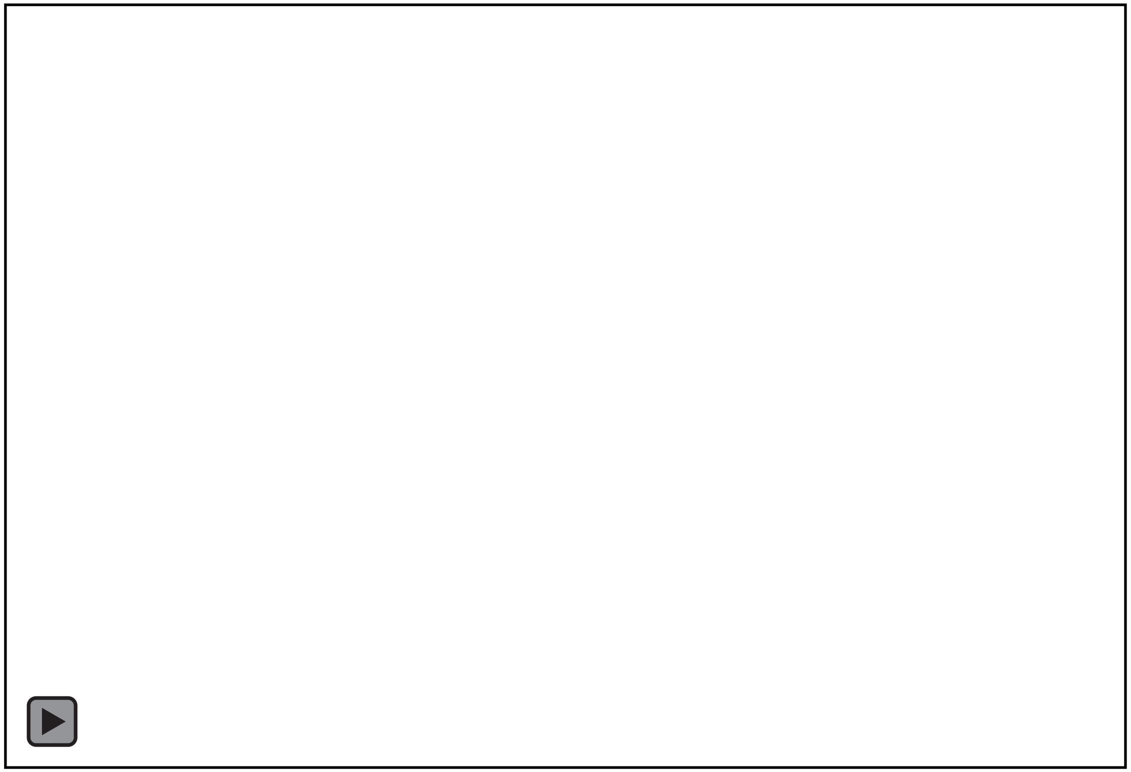


Synoptic maps of fluctuating flows for depth 7Mm and 14Mm for Carrington Rotation 1975. The magnetic field intensity and polarity are indicated by red and green in the underlaying synoptic magnetogram.

Inflows at superficial layers, outflows at deeper depth

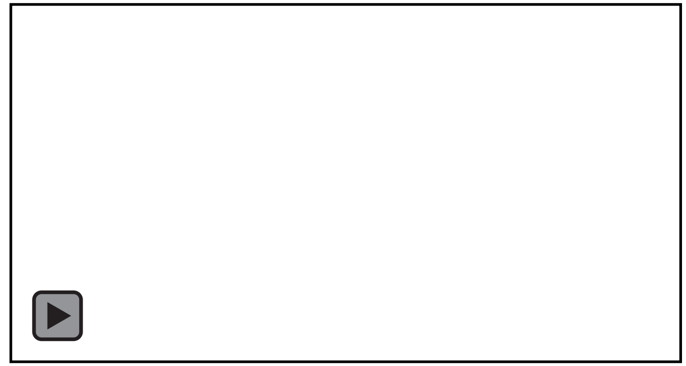
Haber, D. A., Hindman, B. W., Toomre, J. and Thompson M. J., 2004, Solar Physics

Local H-S Extends to the Backside

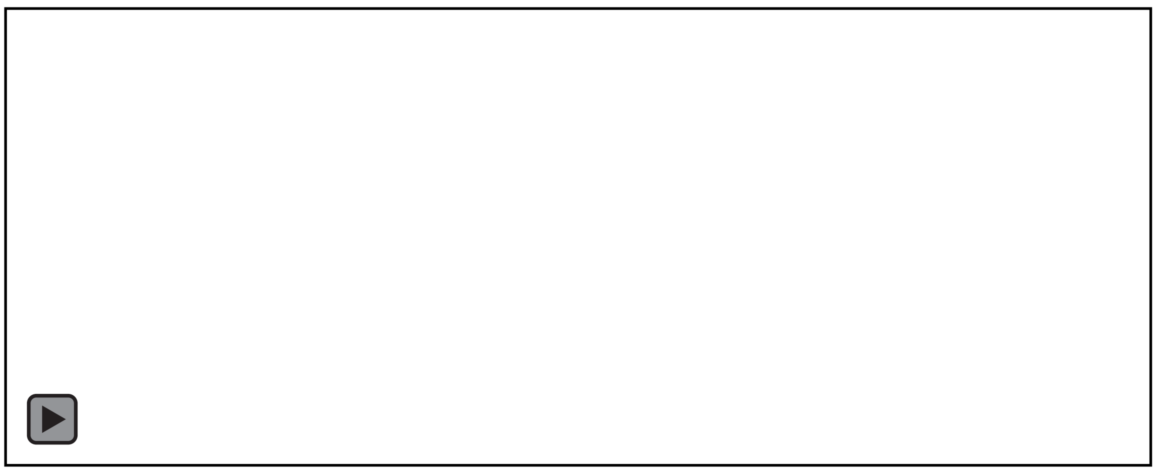


Farside sunspot detection with holographic local helioseismic method. The average phase of waves coming from a point are compared to that of waves leaving the front side, all shifted for average travel time.

Whole Earth
Sunny-side and far side

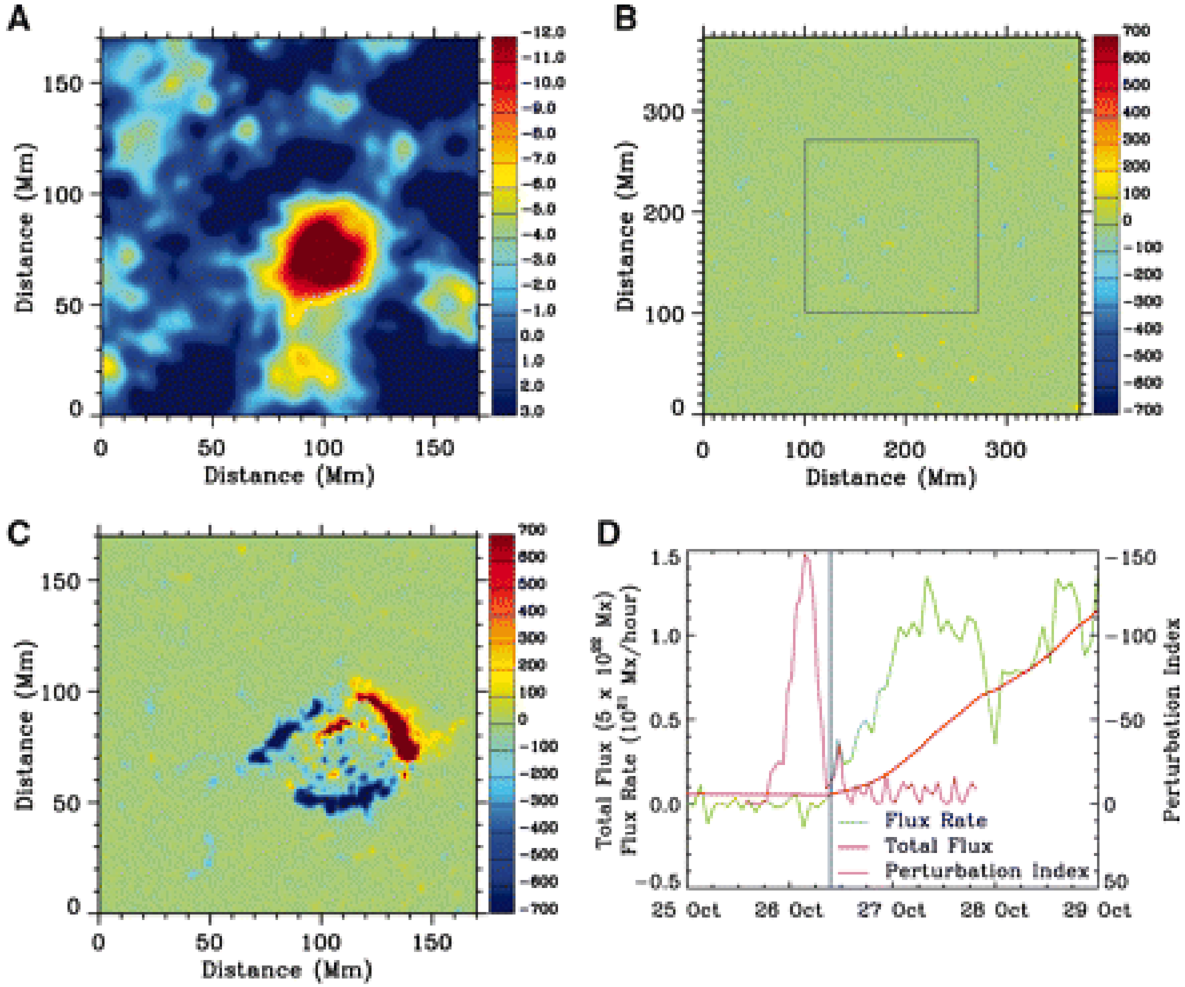


Whole Sun
Earth-side and far side



With helioseismology we can "see" the back side of the Sun

Deep detection of emerging active regions

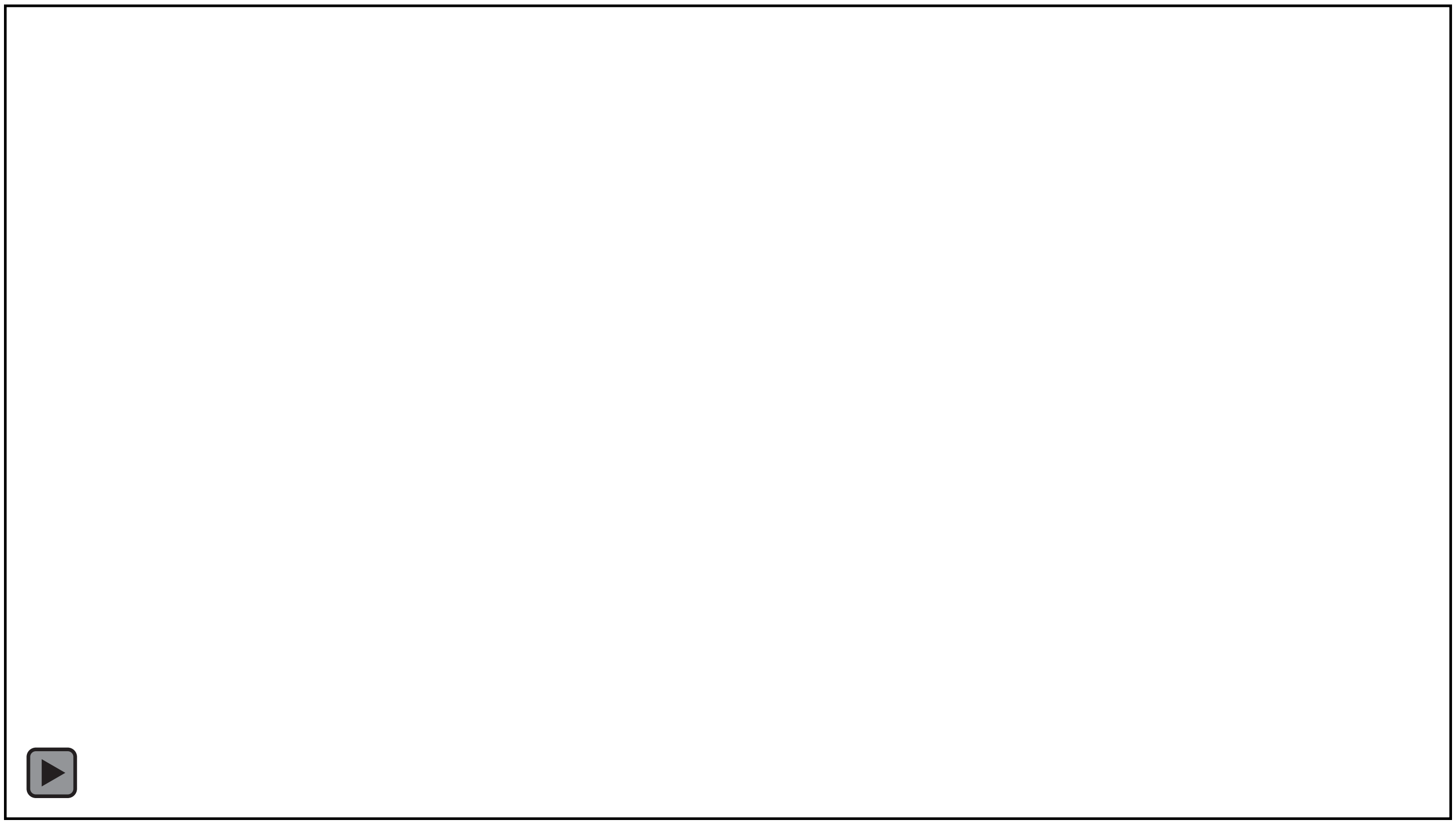


A. 60Mm deep phase perturbation, B. Surface magnetic field at time of A.
C. Magnetic field after 2 days. D. Perturbation index and magnetic field vs time

Movie of event from 2003

Result from Stathis Ilonidis et al. ,Science, 19 August 2011
Data from SOHO/MDI

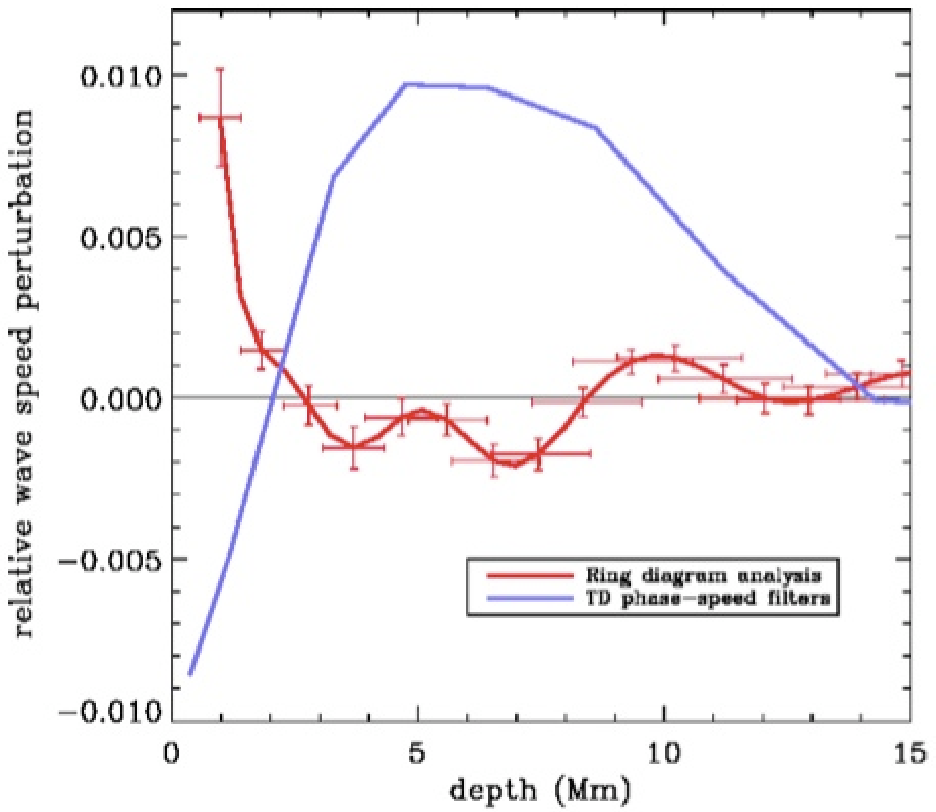
Another example from Feb 2011 event seen with SDO/HMI



Local HS - Successes and Prospects

- Quiet Sun seems to give robust results with all 3 methods giving similar results for near surface features.
  - Holography seems to see only features very near surface.
  - Rings limited depth
  - Time-distance can probe entire interior
  - Supergranulation, zonal flows, meridional flows in reasonable agreement.
- Active Sun – So far all measurements made in or near magnetic fields are suspect.
  - We need to learn how to do inversions in magnetic regions and near them.
  - Center-limb time-distance bias effect not understood
  - Deep detection not understood.
  - There are research opportunities!!!

Comparison between results from different techniques

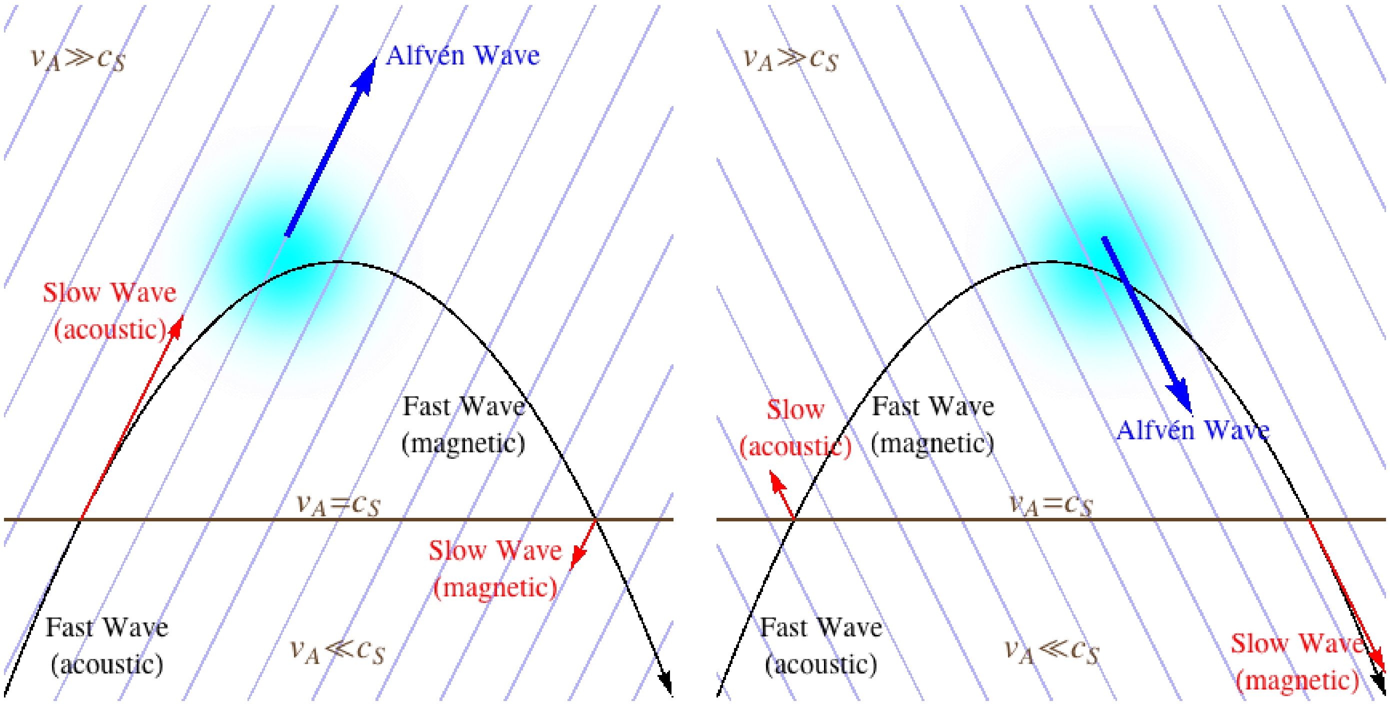


Comparison of two different local helioseismic methods used to infer wave speed perturbations below AR 9787. The red curve shows the averaged ring-diagram results, the solid blue curve shows the time-distance result, after averaging over the same area used for ring-diagram analysis.

We do not know how to do inversions where magnetic fields have perturbed the atmospheric structure.

Gizon, L., et al. 2009, Space Science Reviews, 144

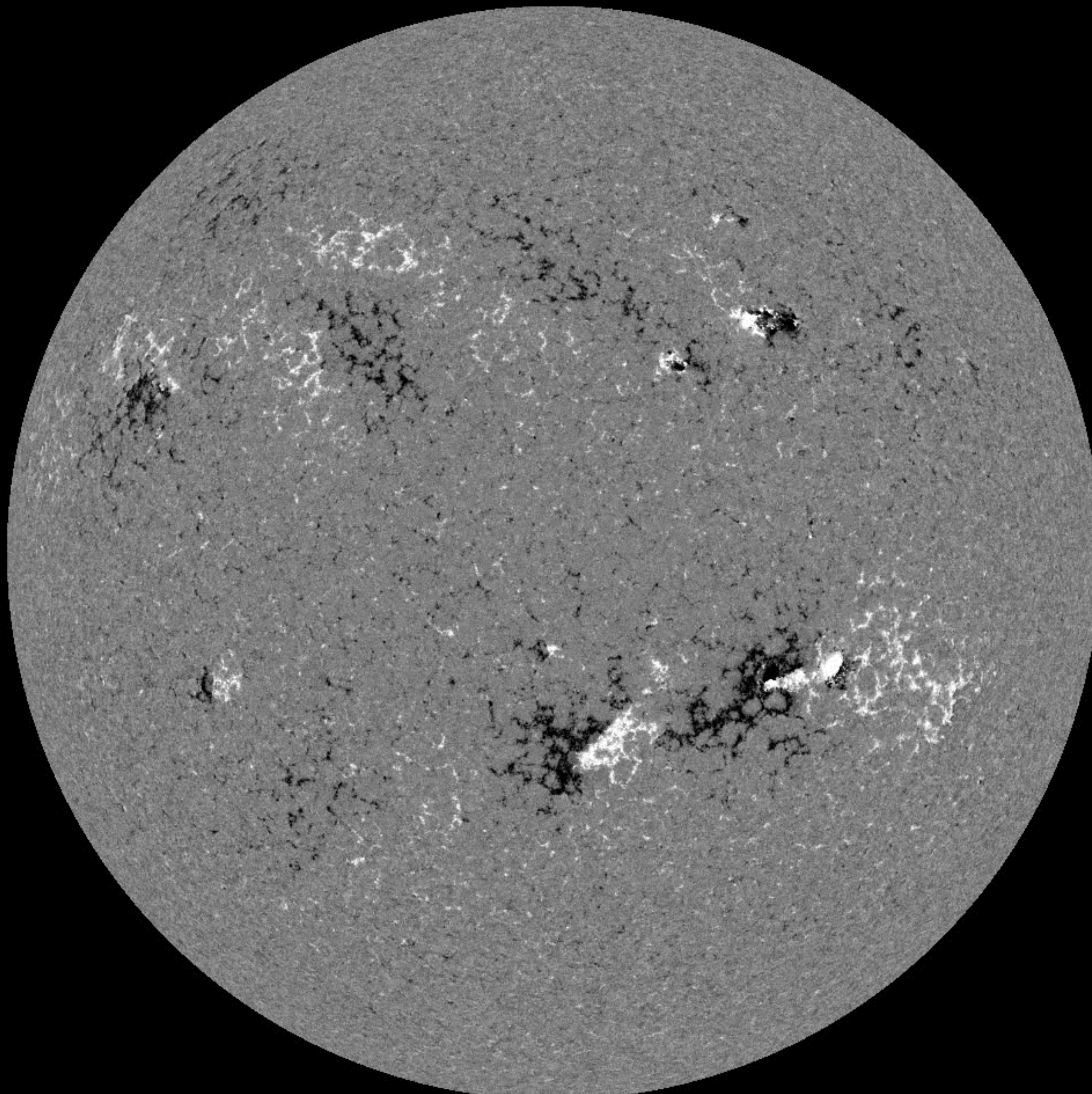
Problem for seismology – acoustic waves rising into magnetic regions will be converted to MHD waves. The phase of reflected acoustic waves will be altered.



Numerical simulations of conversion to Alfven waves in sunspots
Elena Khomenko, Paul Cally

The future for helioseismology as a tool to study the solar interior is bright.

Wait for it, or better, join the effort!

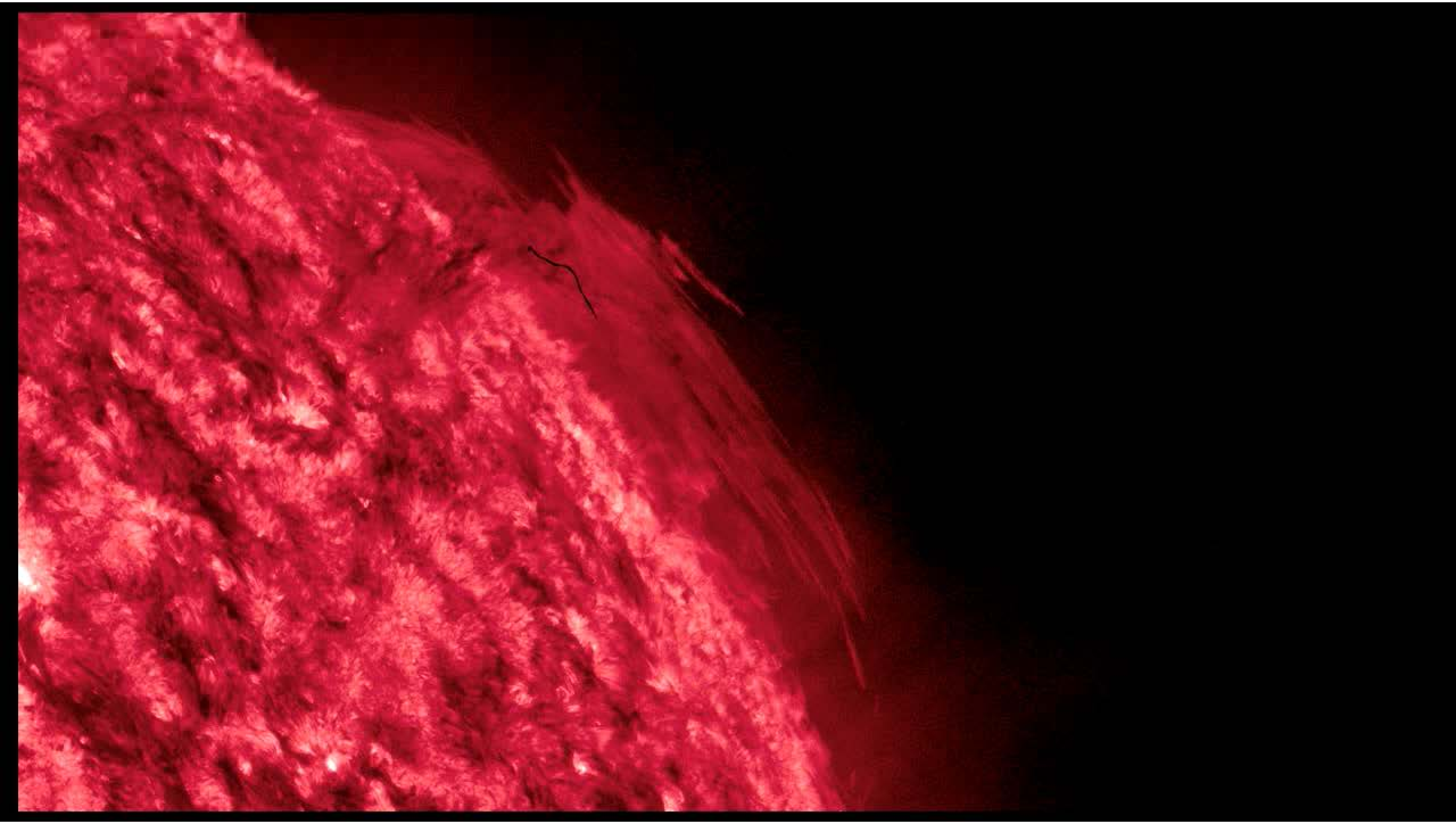


SDO/HMI Quick-Look Magnetogram: 20110427_060000

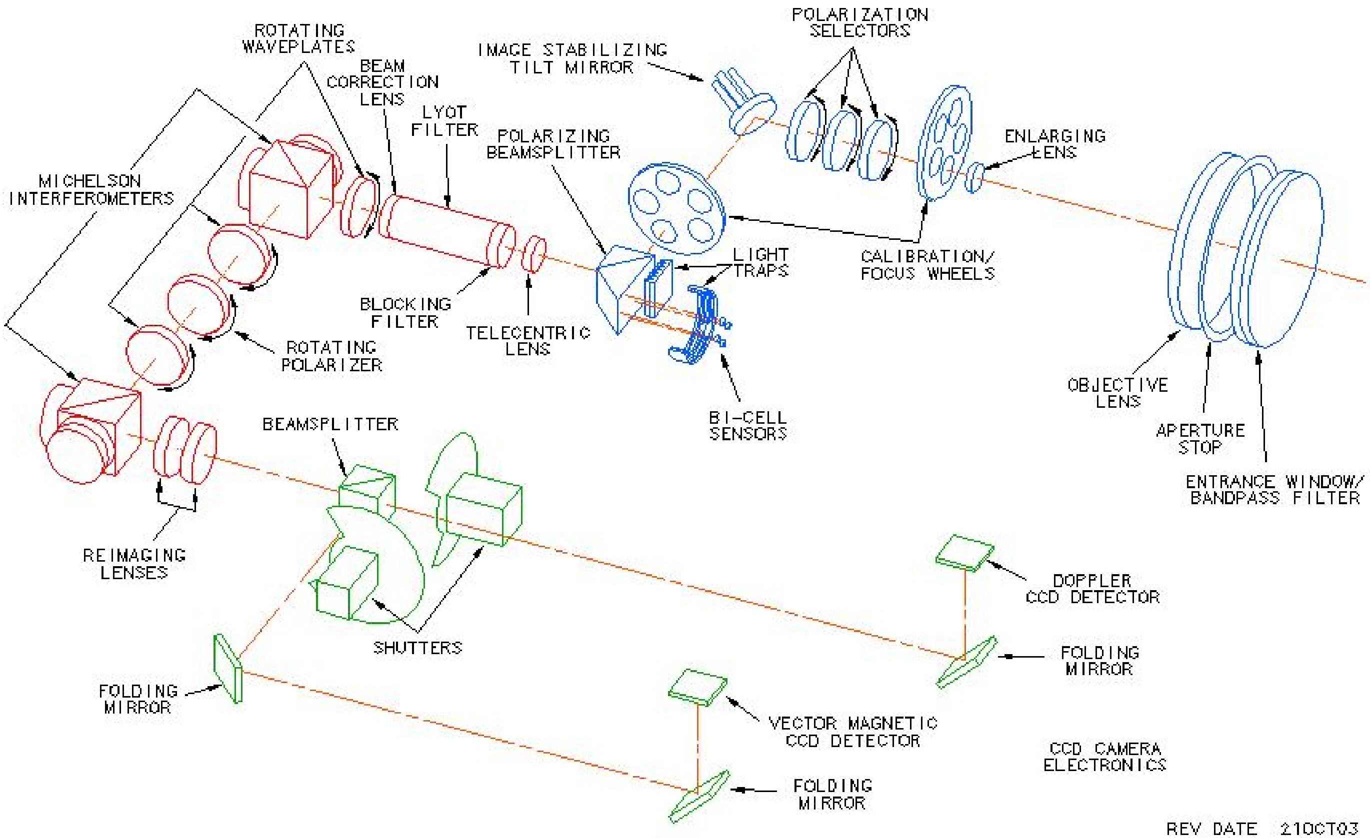
Disk passage of Feb 2011 Active Region

Feb 2011 Region, Vector Magnetic Fields

Filament Eruption



HMI Instrument Overview – Optical Path

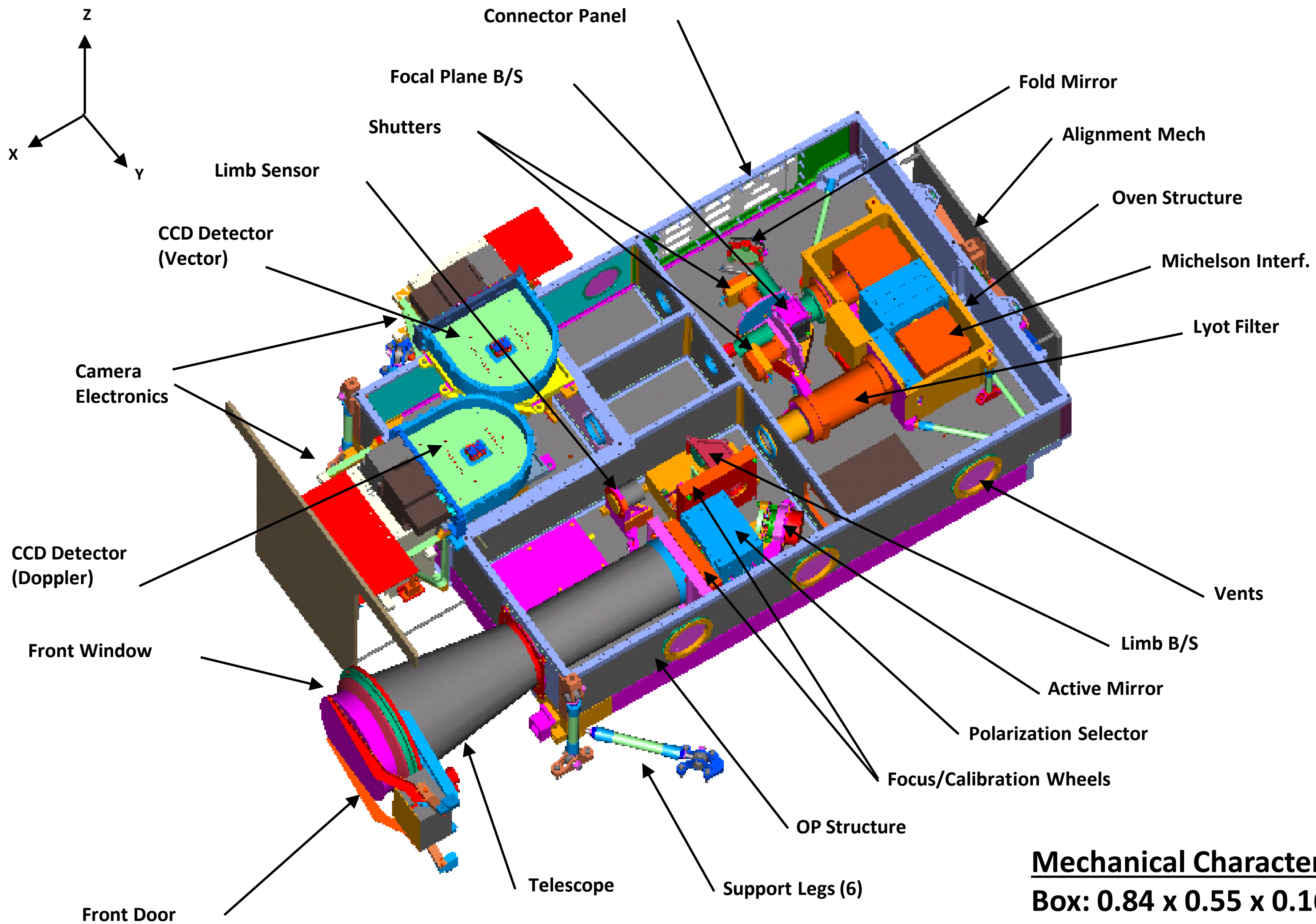


Optical Characteristics:
Focal Length: 495 cm
Focal Ration: f/35.2
Final Image Scale: 24µm/arc-sec

Camera Characteristics:
Format: 4096x4096 pixels
Pixels: 12µ
Exposure: 150ms
Read time: 2-sec

Filter Characteristics:
Central Wave Length: 613.7 nm
Bandwidth: 0.0076 nm
Tunable Range: 0.05 nm
Free Spectral Range: 0.0688 nm

HMI Optics Package



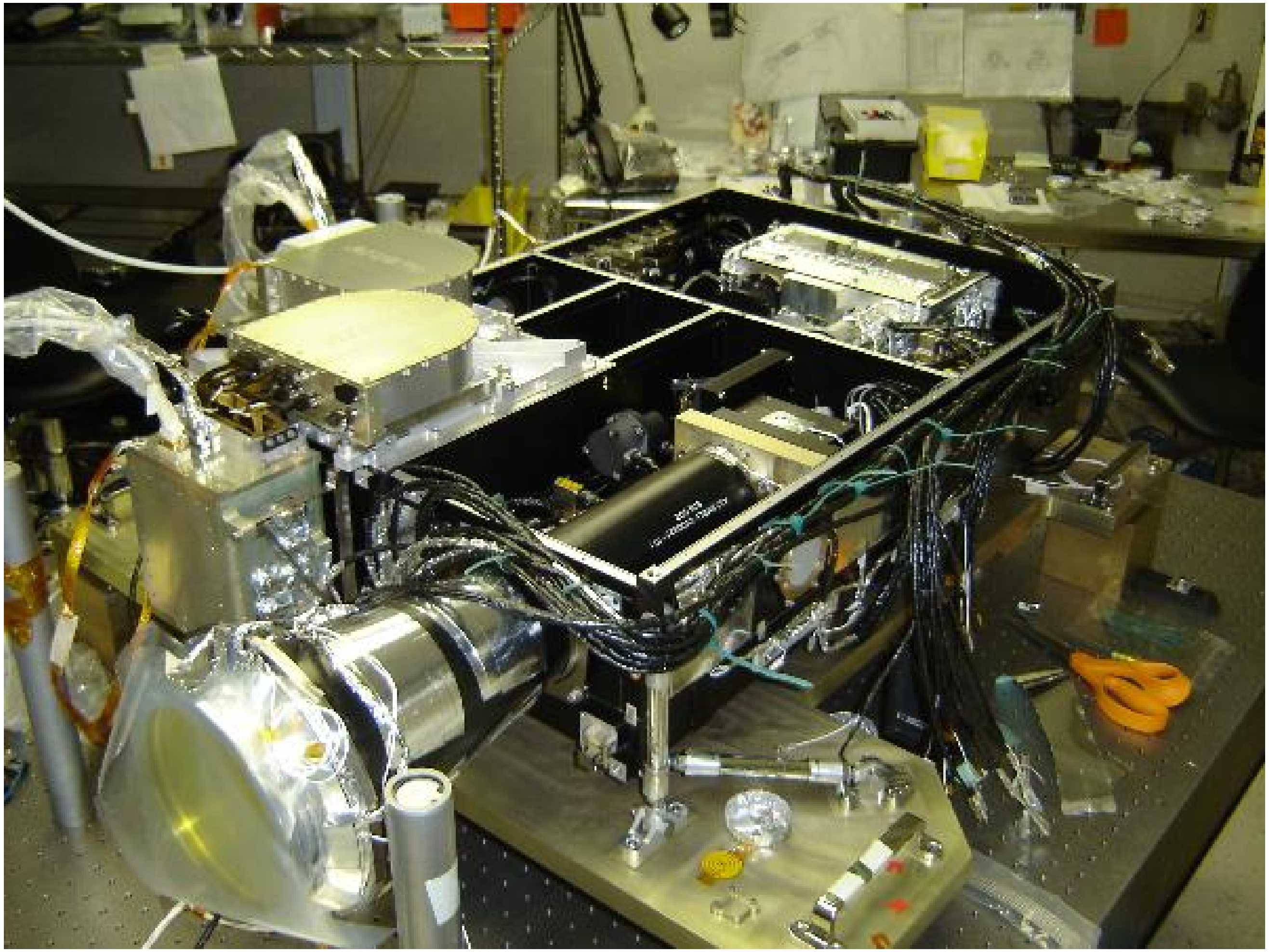
Mechanical Characteristics:

Box: 0.84 x 0.55 x 0.16 m

Over All: 1.19 x 0.83 x 0.29 m

Mass: 39.25 kg

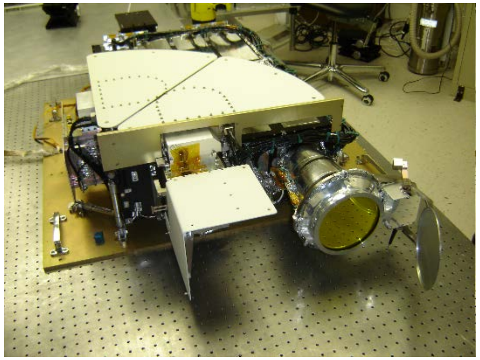
SDO/HMI – Inside the Box

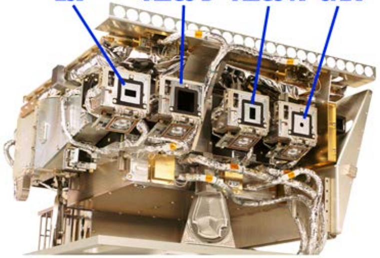


HMI obtains 32 16-megapixel images each minute

SDO

HMI





EVE

AIA

SDO

A few days before launch

SDO launch

10 Feb 2010