ASTR 1040: Stars & Galaxies

Pleiades Star Cluster

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Lecture 9 Tues 25 Sept 2018

zeus.colorado.edu/astr1040-toomre

Topics for Today and Thur+

- *Helioseismology: acoustic waves excited by convection to probe interior*
- *Revisit solar magnetism and its cycles*
- *Use of supercomputers to simulate dynamics within the Sun*
- *Effects of solar magnetism on Earth*

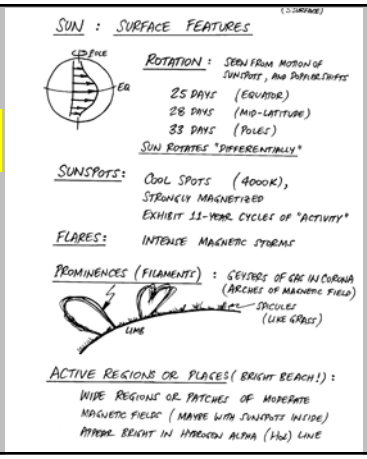
- *What can we measure in other stars?*
- *How do we begin to classify other stars?*
- Why *temperature and spectral lines* are *closely linked* in classifying stars *O B A…M*

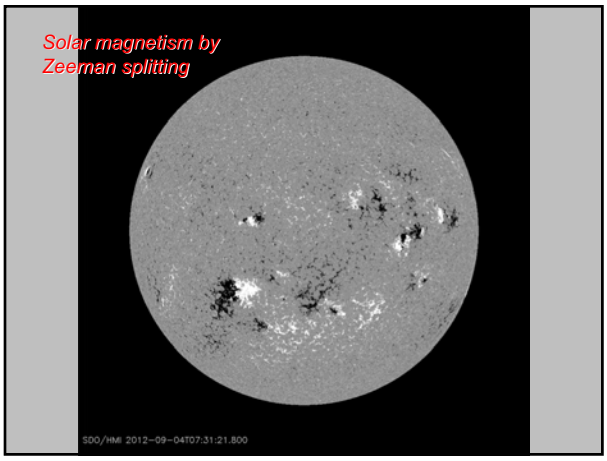
Logistics

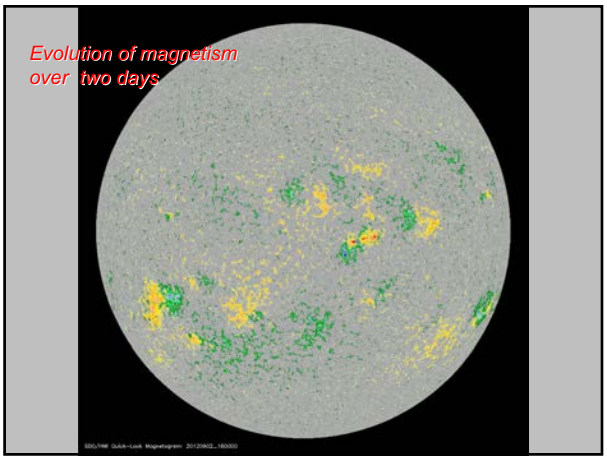
- *Overview read Chap 15: Surveying the Stars*
- *Review Session Wed (tomorrow) 5-7pm here (G125) –- Ryan Horton*
- *Mid-Term Exam 1 Thurs in class (see rules in Review Set #1, still available)*
- *Homework #3 (+answers) returned today*
- *Observ #4 (tonight) cancelled by weather and full moon*

SOLAR MAGNETISM

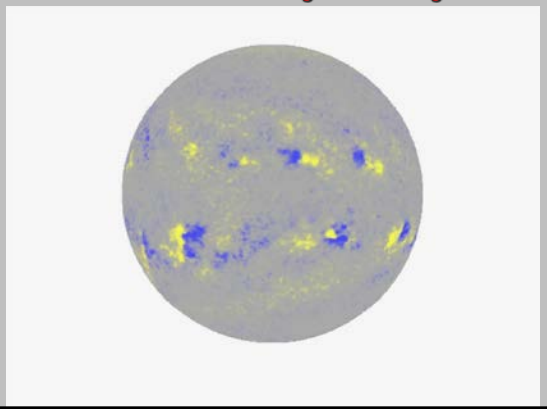
SURFACE FEATURES



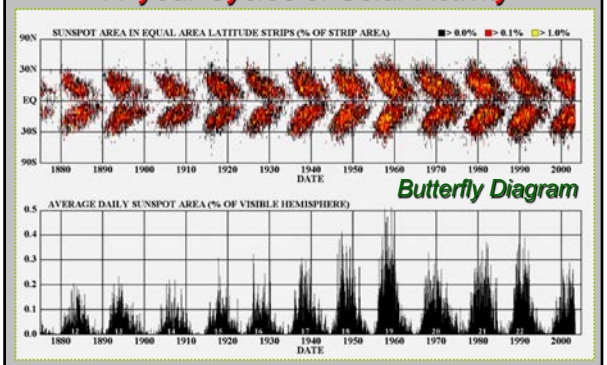




Global View of Evolving Solar Magnetism

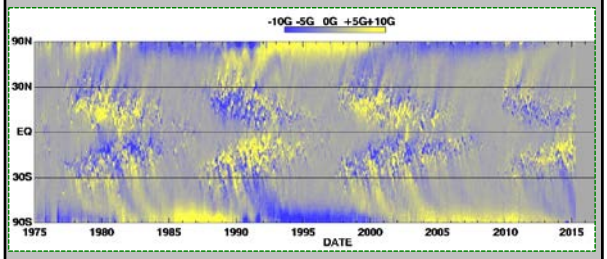


11-year Cycles of Solar Activity

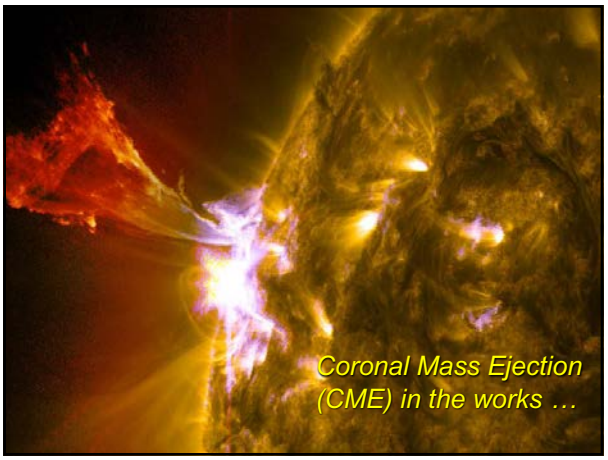


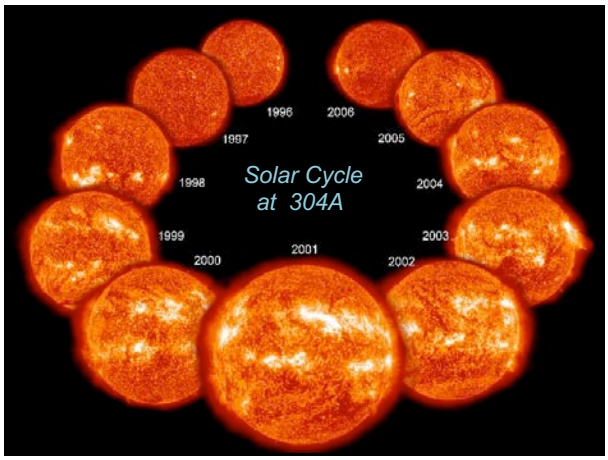
Butterfly Diagram

Emerging sunspot fields and their dispersal

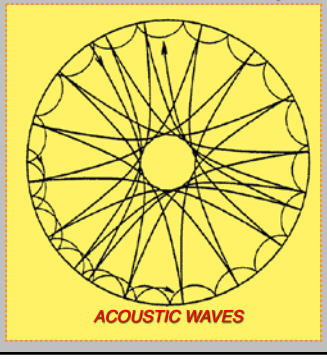


Hathaway





Helioseismology: *Millions of sound waves available to probe solar interior*



Some waves noodle just below the surface

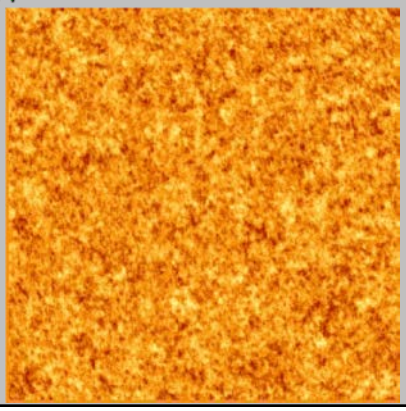
Others almost make it to the center

All excited by turbulent granulation visible in photosphere

How Sound Makes A Surface Bounce

- Sound waves inside Sun cause the *photosphere to move up and down*, with *"five-minute oscillations"*
- Waves are excited and driven by the turbulent and fast granulation near surface
- Can detect these with Doppler imaging of gas at solar surface ("see" the sound)

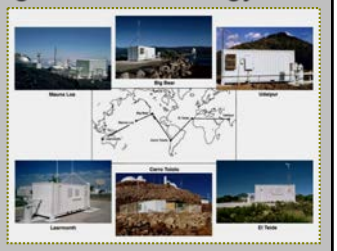
Doppler movie of solar surface from SOHO



20^{o} across

Tools of Imaging Helioseismology

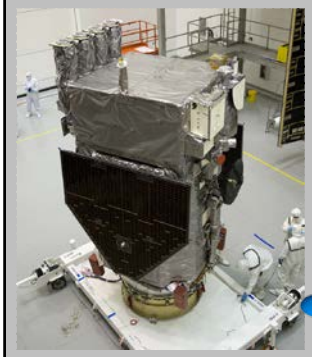
SOHO Spacecraft
Michelson Doppler Imager (MDI)

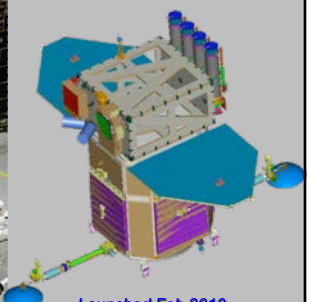


Global Oscillation Network Group (GONG)

Solar Dynamics Observatory (SDO)

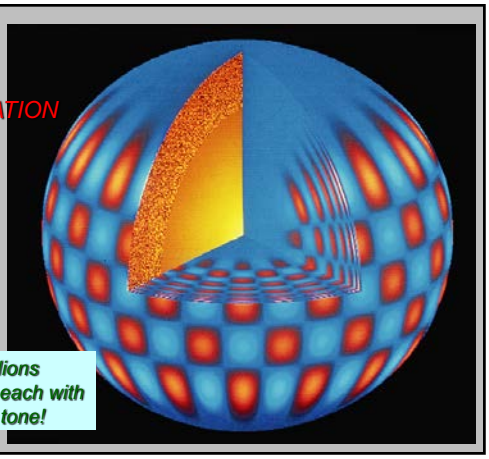
MDI offspring: Helioseismic & Magnetic Imager (HMI)





Launched Feb 2010
(4096x4096)

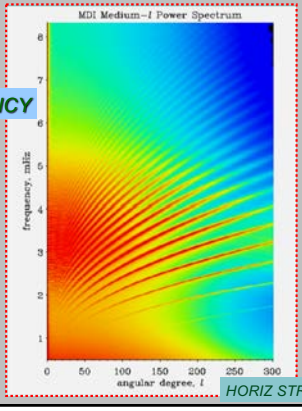
SOLAR OSCILLATION MODE



One of millions of modes, each with a different tone!

"Power Spectrum" of Solar Oscillations

FREQUENCY



HORIZ STRUCTURE

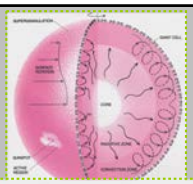
Each oscillation mode has a distinctive (measurable) tone

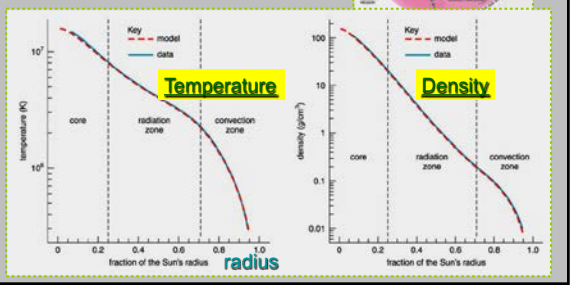
Sensitive to how sound speed varies with depth

Tests models of inside temperature

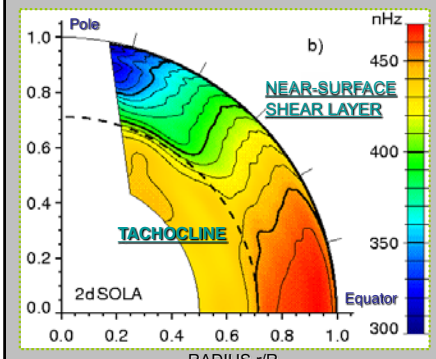
Observed from SOHO and GONG

Solar Interior Models
Theory vs Helioseismology





Interior Differential Rotation Profile



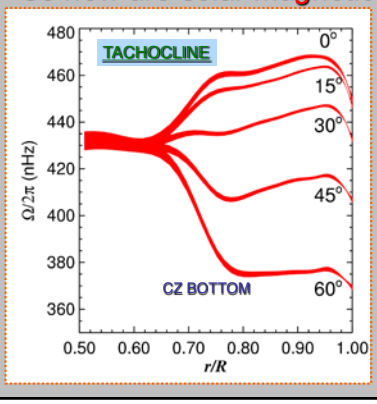
Big surprises:

Fast equator, slow pole -- over most of convection zone

Tacholine of strong shear at its base

Radiative zone rotates uniformly

So how are solar magnetic fields built?

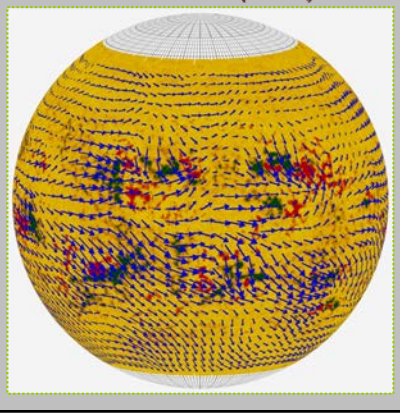


TWO MAGNETIC DYNAMOS:

Global magnetic fields built within CZ, likely near TACHOCLINE

Small-scale fields built in near-surface shear layer

Solar Subsurface Weather (SSW) Global View



April 2002

Reasoning Clicker Q

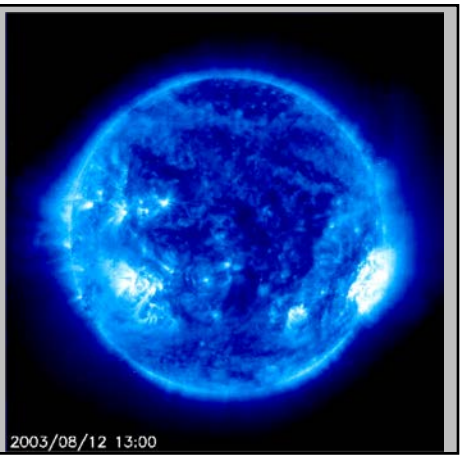
B.

- *If the Sun's core went out of balance and shrank a little, what would happen there?*
- **A.** Density would decrease and fusion would slow down, releasing less energy
- **B.** Density and temperature would increase and fusion would speed up, releasing more energy
- **C.** The whole Sun would eventually shrink and thus core would come back into balance
- **D.** Not much would really change, so nothing to worry about

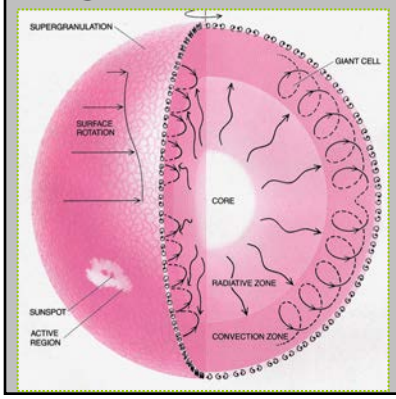
RETURN TO MAGNETISM

UV view of solar magnetism

chromosphere & low corona



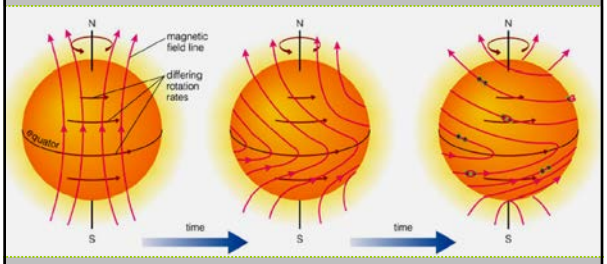
Magnetic fields are built in convection zone



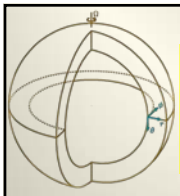
Convection Zone:
ROTATING SHELL OF TURBULENT PLASMA

Differential Rotation
and
Magnetic Dynamo
.....
go HAND-IN-HAND

How differential rotation can stretch and change global magnetic fields

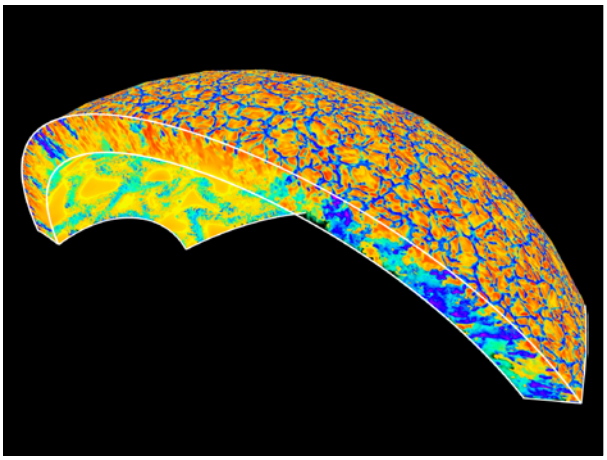


BUT THIS IS TOO SIMPLISTIC ....

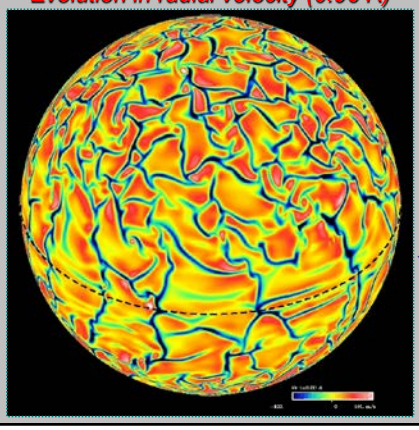


Supercomputer simulations:
Global convection & dynamo building of magnetic fields

- Study turbulent convection interacting with rotation in bulk of solar CZ: 0.72 R - 0.97 R
- Realistic solar mean stratification
- Simplified physics: perfect gas, radiative diffusivity, compressible, subgrid transport
- Correct global spherical geometry



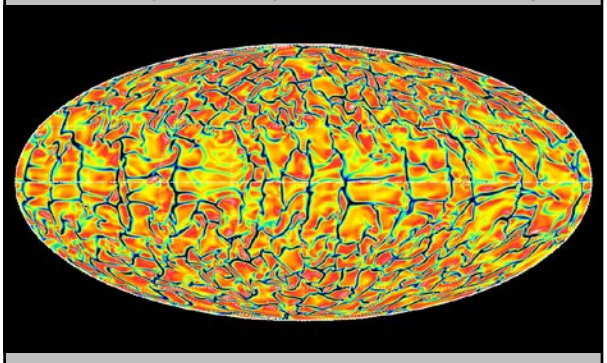
Evolution in radial velocity (0.96 R)



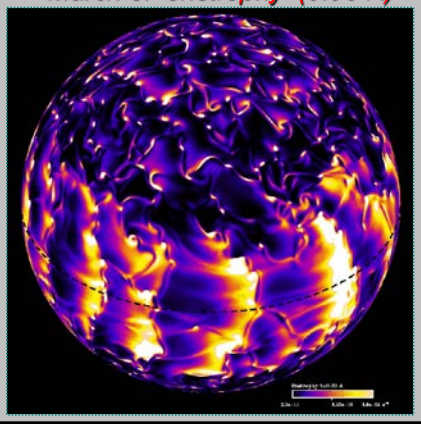
NEAR TOP OF LAYER

VIEWED IN CARRINGTON FRAME

Global (Mollweide) view of radial velocity



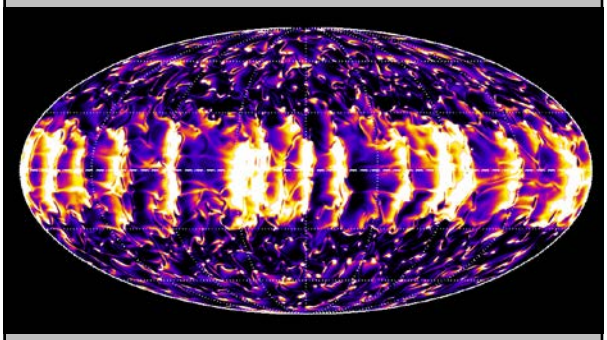
March of enstrophy (0.96 R)



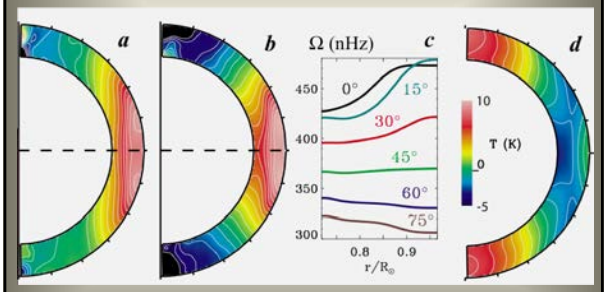
VORTICITY SQUARED

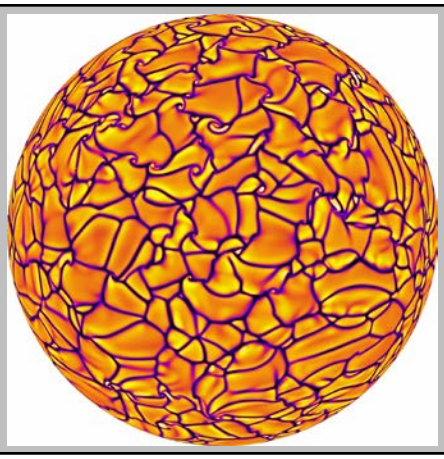
NEAR TOP OF SHELL

Global view of enstrophy



Resulting differential rotation built by convection: fast equator, slower poles





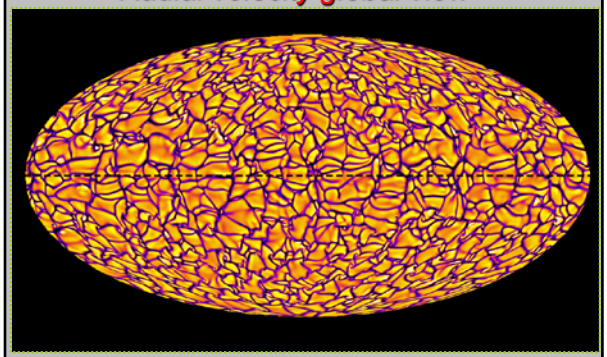
At highest resolution

Radial velocity

Case F

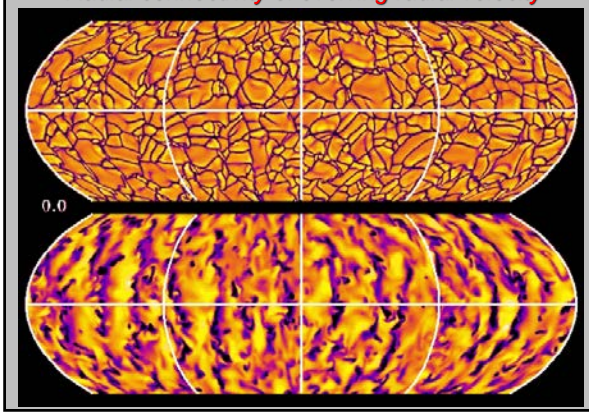
Miesch et al 2008, 2011

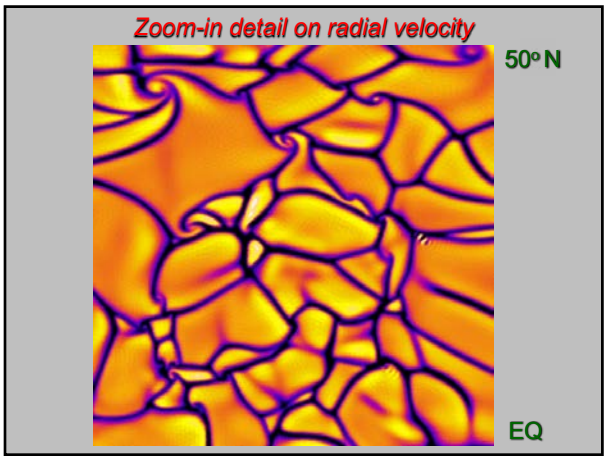
Radial velocity global view

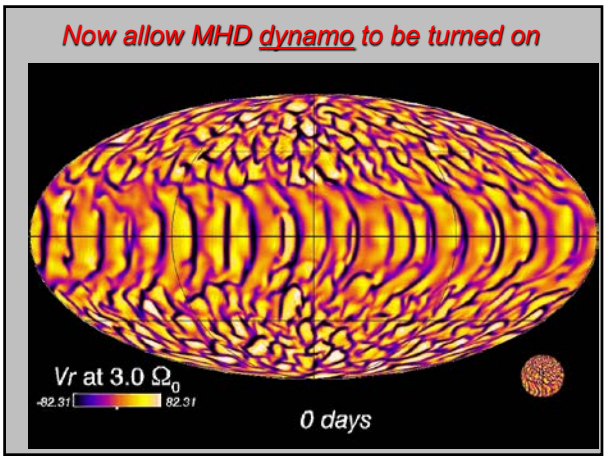


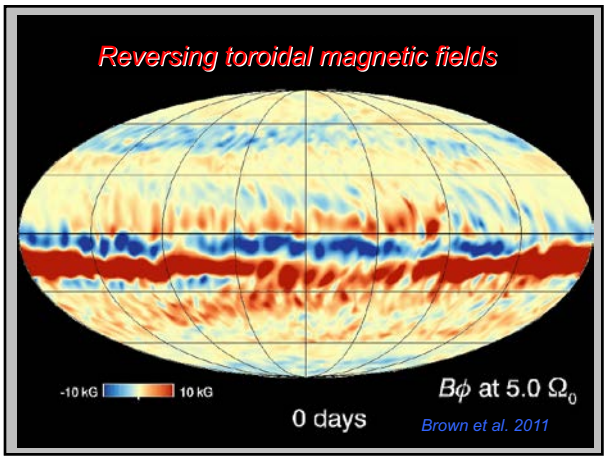
Case F

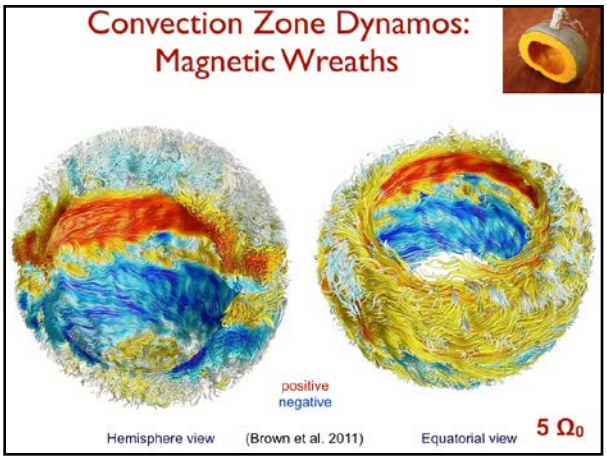
Radial connectivity of evolving radial velocity

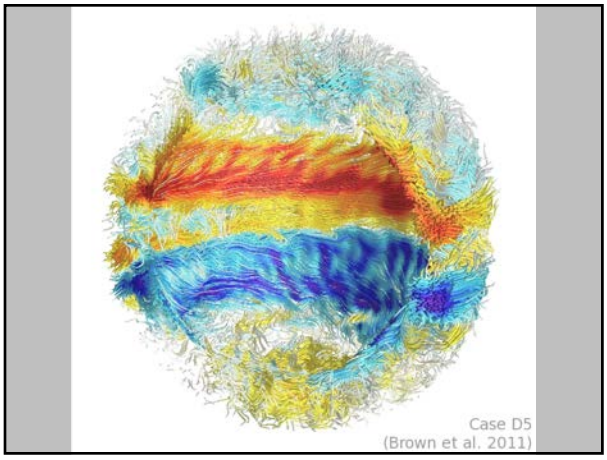


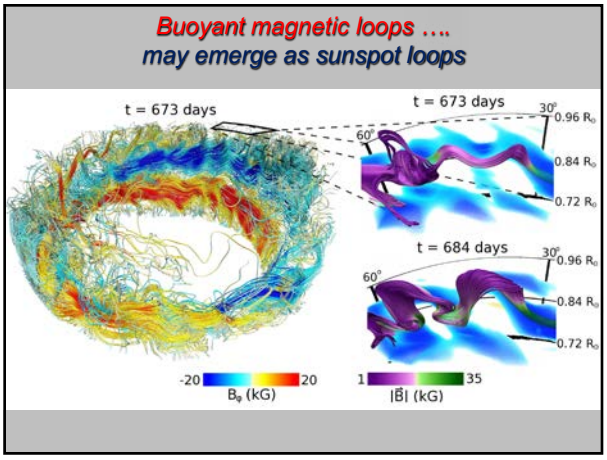

Zoom-in detail on radial velocity
50° N
EQ

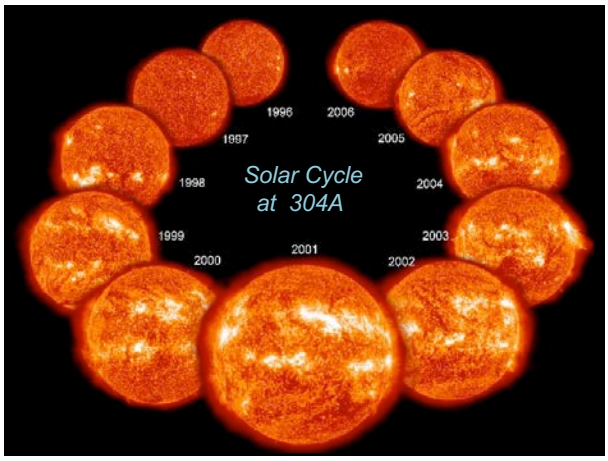

Now allow MHD dynamo to be turned on
Vr at 3.0 Ω0
-82.31
82.31
0 days


Reversing toroidal magnetic fields
-10 kG
10 kG
Bϕ at 5.0 Ω0
0 days
Brown et al. 2011

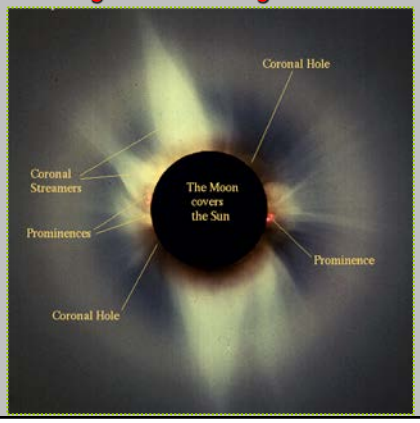

Convection Zone Dynamos:
Magnetic Wreaths
positive
negative
Hemisphere view
(Brown et al. 2011)
Equatorial view
5 Ω0


Case D5
(Brown et al. 2011)


Buoyant magnetic loops ….
may emerge as sunspot loops
t = 673 days
t = 673 days
t = 684 days
0.96 R⊙
0.84 R⊙
0.72 R⊙
-20
20
Bφ (kG)
1
35
|B| (kG)

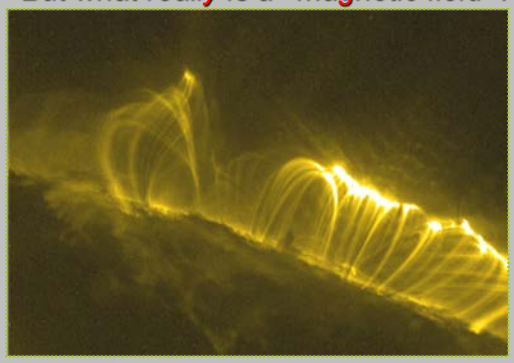


Largest-scale magnetic fields



Sunspots at surface yields huge magnetic structures in corona

But what really is a "magnetic field"?



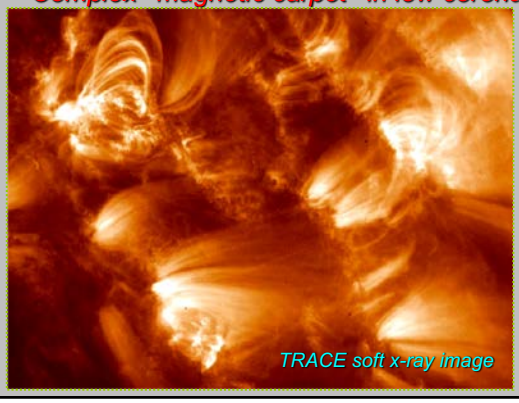
TRACE soft x-ray image: Arcade of magnetic loops on solar limb

Reading Clicker Question

Which is the most likely cause of the extreme heating in the chromosphere and corona?

A. Energy deposited by magnetic fields
B. Heat rising from the surface of the Sun
C. Photons created at the photosphere interacting with the solar atmosphere
D. Neutrino interactions with the solar wind
E. Ionization of hydrogen just above the surface

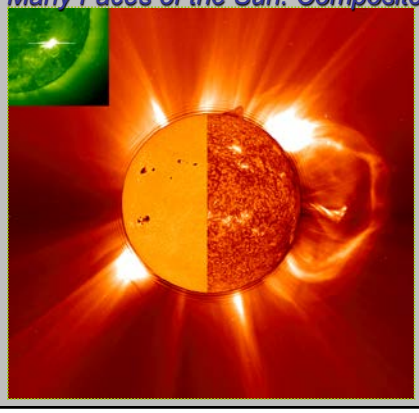
Complex "magnetic carpet" in low corona



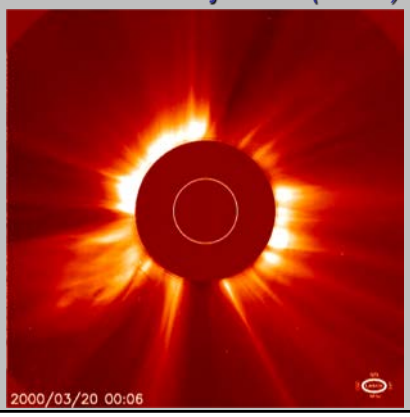
Magnetic Reconnection and Splendid Loops from SDO

Huge prominence is big magnetic loop

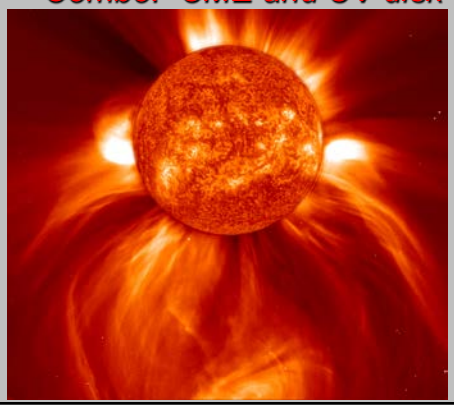
Many Faces of the Sun: Composite



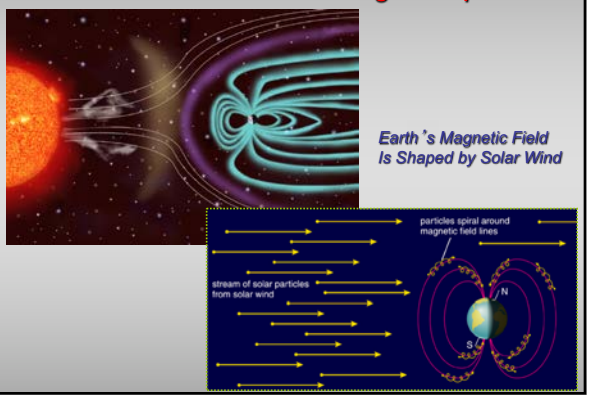
Coronal Mass Ejections (CMEs)



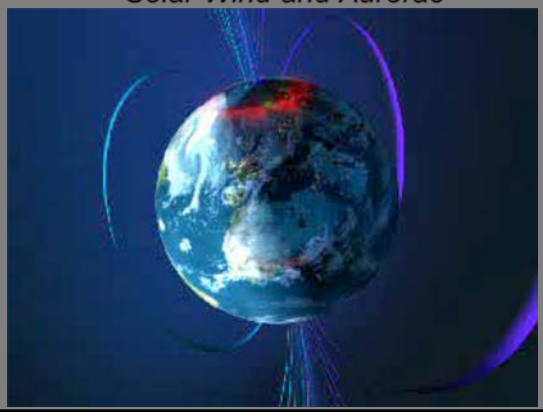
Combo: CME and UV disk



Solar Wind and Earth's Magnetosphere



Solar Wind and Aurorae



Northern Lights
(Aurora Borealis)