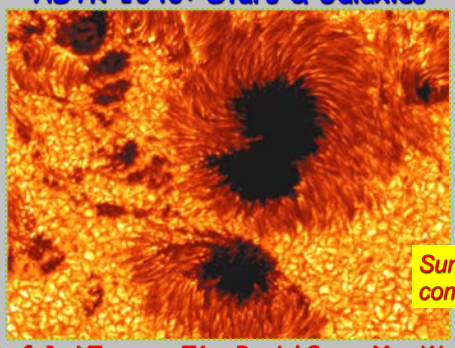
ASTR 1040: Stars & Galaxies



Prof. Juri Toomre TAs: Daniel Sega, Max Weiner

Lecture 8 Thur 6 Feb 2020

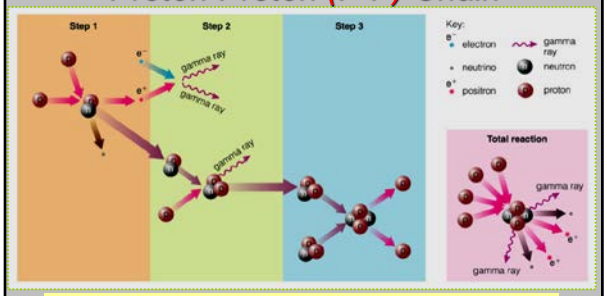
zeus.colorado.edu/astr1040-toomre

Topics for Today

- Solving the puzzle of solar neutrinos
- Helioseismology: acoustic waves excited by convection to probe interior
- Rich solar magnetism and its cycles
- Sunspots and the "butterfly diagram"
- Start reading Chap 15: Surveying the Stars
- New Homework #4 available; HW #3 due; HW #2 Graded; Observ #2 tonight ??
- Review Set for Mid-Term Exam 1 (next Thurs in class, review Wed eve 6pm)

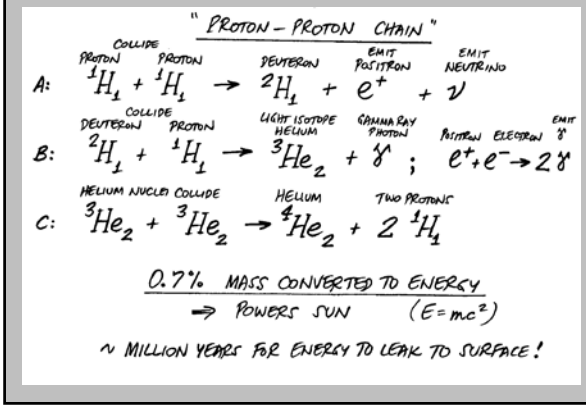
REMINDER

Proton-Proton (P-P) Chain



Burn 600 million tons of H every sec, making 596 million tons of He and `4 million tons goes into ENERGY'

Energy = Gamma-ray photons + electron neutrinos



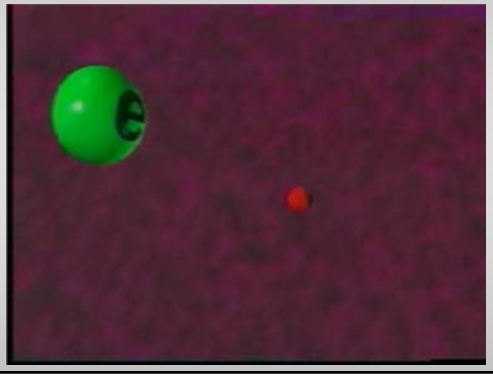
Proton-proton chain: summary

- Input: 6 protons
- Output: 1 helium
  2 protons
  2 positrons → gamma rays
  2 neutrinos
  + more gamma rays

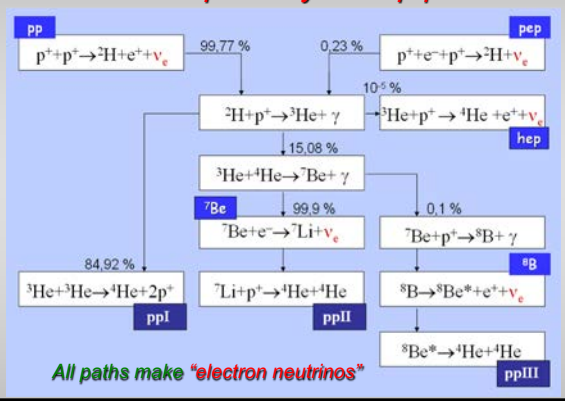
4 hydrogens → 1 helium + 2 neutrinos + gamma rays (energy)

DO WE SEE THE GAMMA-RAYS, NEUTRINOS ?

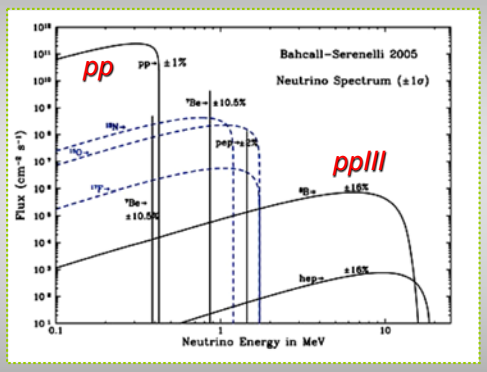
Collision of electron with positron (anti-matter): annihilate, two gamma-rays emitted



Three pathways for "p-p chain"



Solar neutrino energy spectrum



Clicker – Doppler shifts? A.

- *Star moving away from us at 0.01 the speed of light emits a spectral line with a wavelength of 600 nanometers (nm). What is the observed wavelength of that line?*
- A. 606 nm
- B. 600.6 nm
- C. 594 nm
- D. 596.4 nm
- E. 600 nm

$$\Delta\lambda / \lambda = v/c$$

Meanderings of outbound photons

P-P chain makes gamma-ray photons, which "random walk" outwards (getting absorbed, re-emitted), gradually cooling

Heading outward (slow & fast)

Gamma rays slowly work their way outwards, cool, and become sunlight (about million years)

Neutrinos don't interact with much, zoom right out of Sun and into space, carry 2% of the Sun's energy – even travel right through Earth!

Those Mysterious Neutrinos

MADE BY P-P BURNING IN CORE

- *Mass-less or with very small masses*, travel close to speed of light
- *Don't interact (almost) with other matter*: requires lead wall 1 light year thick to stop a neutrino!
- *Lots of them*: 10^{38} neutrinos/sec from the Sun, 65 billions/cm^2/sec coming through YOU !
- But we can still catch some, using massive underground "detectors": *BIG PUZZLE*

Big Puzzle: Catching Solar Neutrinos

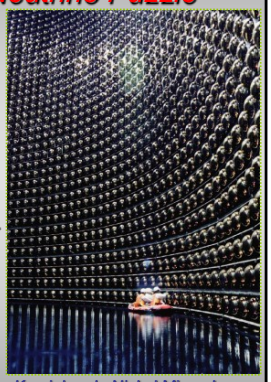
Visionary: Ray Davis

- **Located deep underground, rock blocking other particles**
- Huge underground vat of dry-cleaning fluid
- Chlorine captures neutrino, becomes radioactive argon
- **Only collects 1 neutrino about every 3 days** -- even with 100,000 gallons
- **Solar theory predicted THREE TIMES more!**
- Big hunt started, called ***SOLAR NEUTRINO PROBLEM***

Homestake Gold Mine SD

Resolving the Solar Neutrino Puzzle

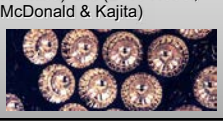
- ***Super-Kamiokande*** uses massive tank of water to capture neutrinos
- Each rare capture gives flash of light, detected by giant tubes
- **Captures lower energy neutrinos from p-p chain, so more sensitive test of fusion**
- Suggests some **electron neutrinos** may change into **muon and tau neutrinos** during course of flight to us (8 minutes)
- ***MSW Neutrino Oscillations*** require neutrinos to have some mass!



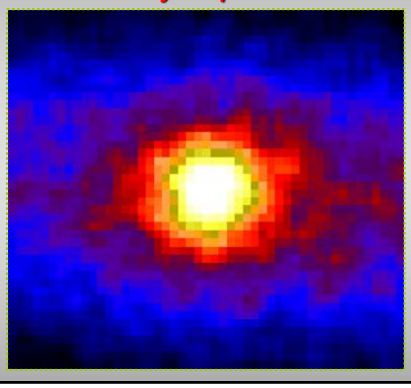
Kamiokande Nickel Mine, Japan

Sudbury Neutrino Observatory (SNO)

- Uses ***"heavy water"*** -- one H in H_20 replaced by its stable isotope deuterium (P+N)
- SNO is capturing **all three types of neutrinos** (electron, muon, tao)
- ***"Solar neutrino problem"*** leads to big physics advance (2002 Nobel Phys Prize; Davis & Koshiba) and (2015 Nobel; McDonald & Kajita)



Sun Viewed by Super-Kamiokande



500 day "exposure"

Solar Thermostat

- ***Why doesn't the Sun go into a runaway reaction?***

Fusion rate is *VERY sensitive to temperature,*
→ tight feedback loop

CRUCIAL

A. **If energy generation (fusion rate) speeds up:**

- 1. Pressure in core will increase, lifting the gas against gravity (core expands)
- 2. Gravitational energy is created from thermal energy → the gas cools
- 3. **Energy generation (fusion rate) slows down**

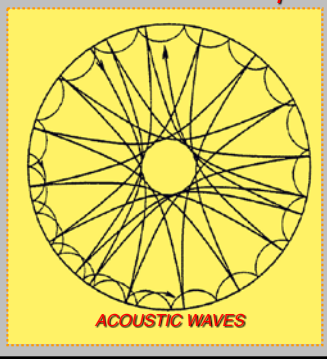
More on solar thermostat

B. **However, if energy generation drops:**

- 1. Core pressure drops
- 2. Solar core starts to shrink
- 3. Temperature rises
- 4. **Fusion rates go up again**

- ***Sun is remarkably stable,*** only small (30%?) increase in fusion rate over billions of years

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



Some waves noodle just below the surface

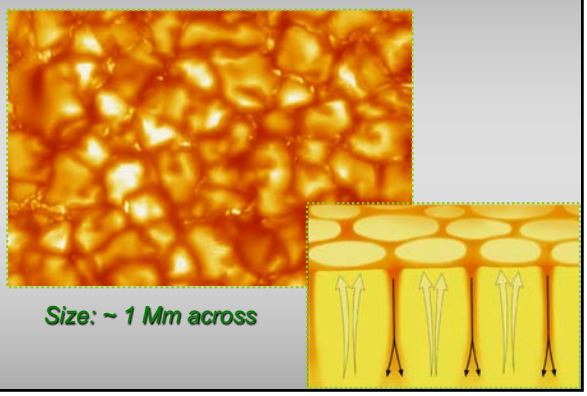
Others almost make it to the center

All excited by turbulent granulation visible in photosphere

How Sound Makes A Surface Bounce

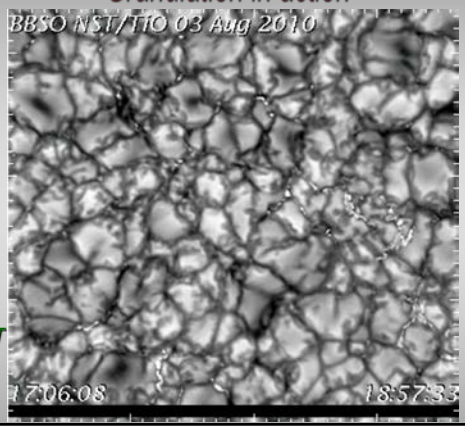
- Sound waves inside Sun cause the *photosphere to move up and down*, with *"five-minute oscillations"*
- Waves are excited and driven by the turbulent and fast granulation near surface
- Can detect these with Doppler imaging of gas at solar surface ("see" the sound)

Granulation: near-surface turbulent convection



Size: ~ 1 Mm across

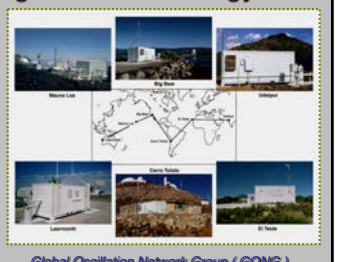
Granulation in action



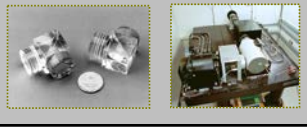
BBSO 1.6m NST adaptive optics

Tools of Imaging Helioseismology

SOHO Spacecraft Michelson Doppler Imager (MDI)

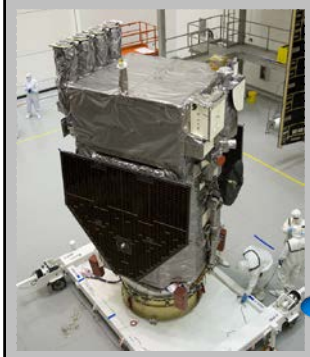


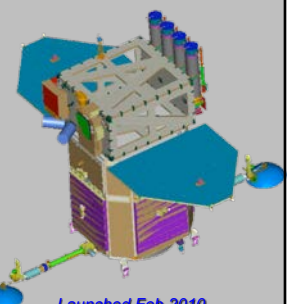
Global Oscillation Network Group (GONG)



Solar Dynamics Observatory (SDO)

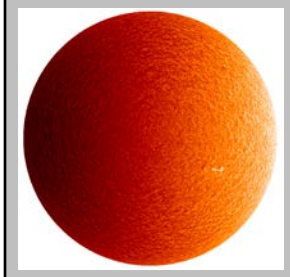
MDI offspring: Helioseismic & Magnetic Imager (HMI)



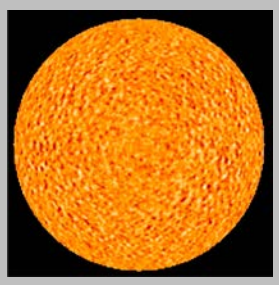


Launched Feb 2010
(4096x4096)

Dopplergrams

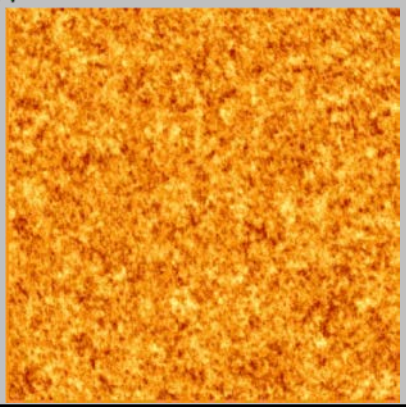


Dopplergram of the Sun



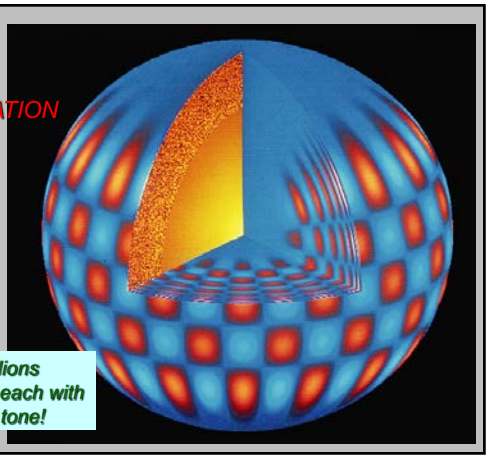
Dopplergram sequence with Rotation removed

Doppler movie of solar surface from SOHO



20° across

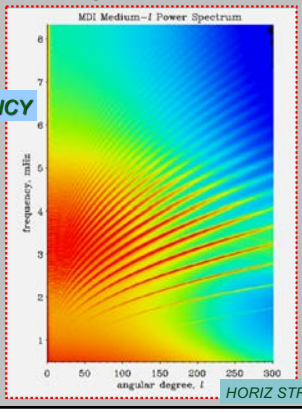
SOLAR OSCILLATION MODE



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

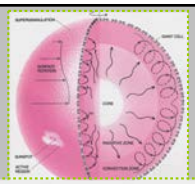
Sensitive to how sound speed varies with depth

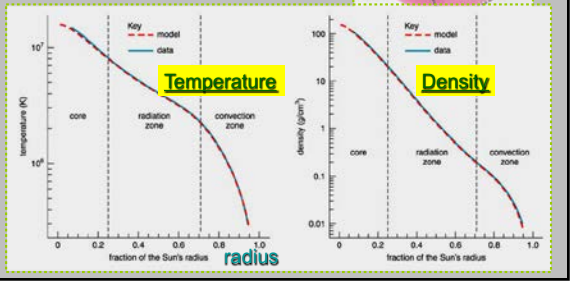
Tests models of inside temperature

Observed from SOHO and GONG

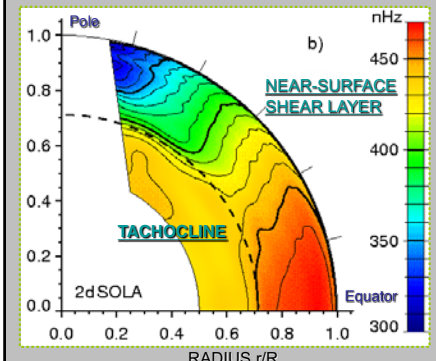
Solar Interior Models

Theory vs Helioseismology





Interior Differential Rotation Profile



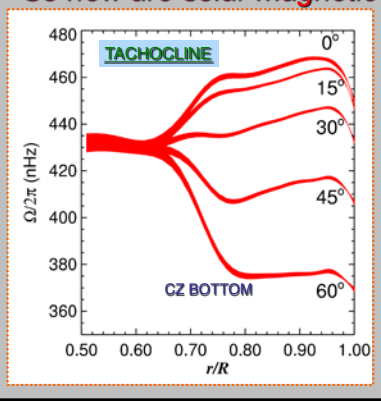
Big surprises:

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?

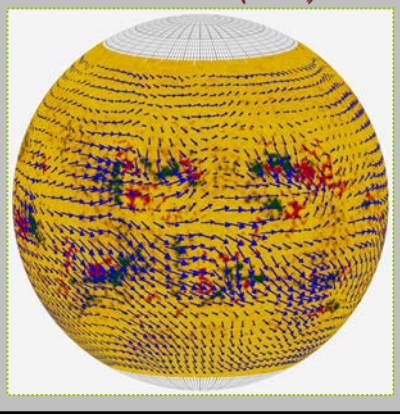


TWO MAGNETIC DYNAMOS:

Global magnetic fields built within CZ, likely near TACHOCLINE

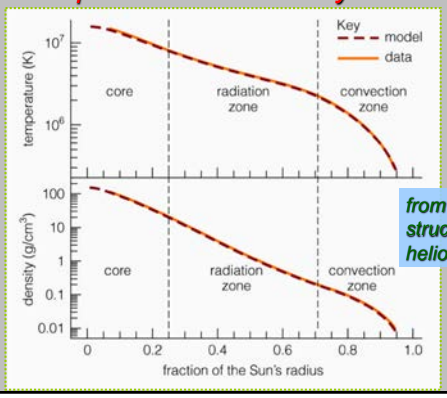
Small-scale fields built in near-surface shear layer

Solar Subsurface Weather (SSW) Global View



April 2002

Temperature and density with radius



from "stellar structure" theory, helioseismology

Can high central pressure really hold up a star?

Demo of STEEL DRUM and its fate from pressure force

55 gallon drum: 23" diameter, 34.5" high

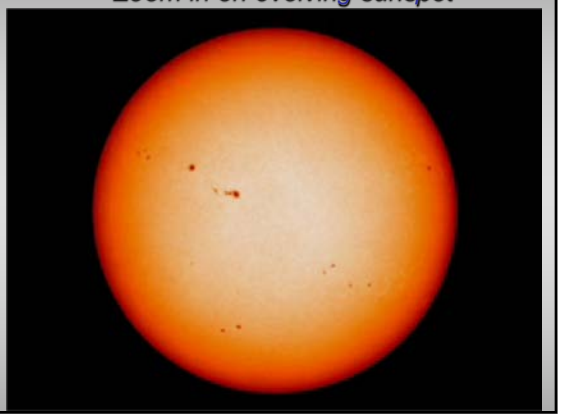
Reading Clicker – Solar Maximum ?

- *What observed features characterize the Sun at "solar maximum"?*

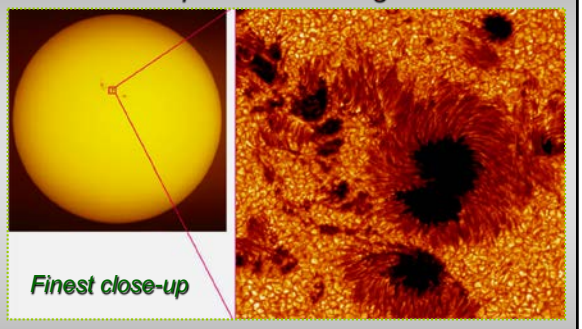
D.

- *A.* Sun becomes much brighter
- *B.* Sun emits light of longer wavelengths
- *C.* Sun rotates faster at the equator
- *D.* Many sunspots are visible on surface
- *E.* All of the above

Zoom-in on evolving sunspot

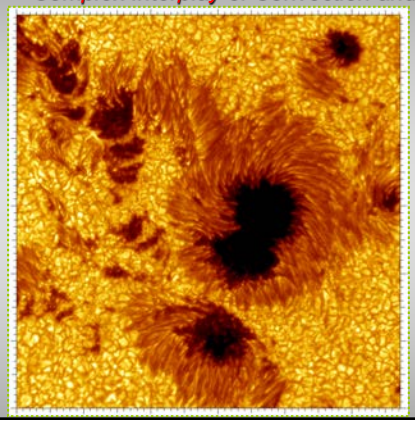


Sunspot in White Light



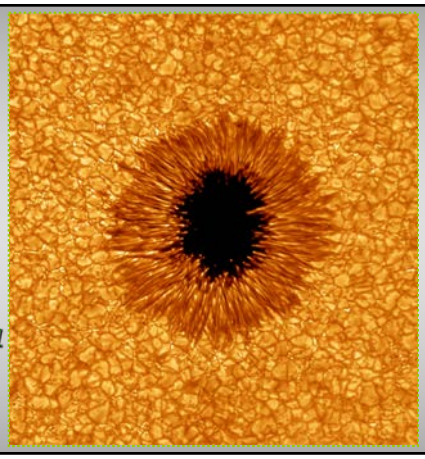
Finest close-up

Complex Interplay of Convection and Magnetism



SUNSPOTS amid field of GRANULES

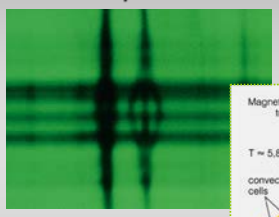
1 Mm spacing on ticks



Sunspot (2 July 2010) surrounded by GRANULATION

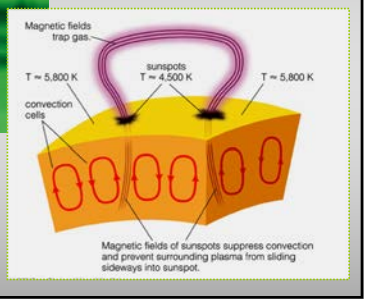
BBSO NST AO

Sunspots show "Zeeman splitting"



wavelength →

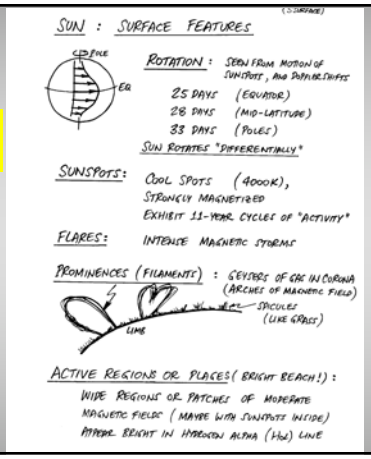
1000+ Gauss magnetic fields in sunspots



B loop demo

SOLAR MAGNETISM

SURFACE FEATURES



Solar magnetism by Zeeman splitting