Today +

- Revisit: neutrino puzzle -- test of deep interior
- Probing inside of sun with sound: helioseismology
- Solar magnetism and operation of dynamo

- Read S.4: Building blocks of universe -- discuss in recitation on Mon (basis of new Homework Set # 4)
- Overview read Chap 16: Properties of stars
- Review guide for Mid-Term Exam 1 (Mon 20 Feb)
- Next discussion response: What are effects of solar activity on our technological society?
- Go directly to Fiske Planetarium for next Tues class: Birth of Stars (read 17.2 and handout)

Proton-Proton (P-P) Chain

Thermonuclear FUSION

Two "electron" neutrinos produced

Big Puzzle: Catching Solar Neutrinos

REMINDER: 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

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!

Sun Viewed by Super-Kamiokande

500 day "exposure"
Sudbury Neutrino Observatory (SNO)

- Uses "heavy water" -- some H in $\text{H}_2\text{O}$ replaced by its stable isotope deuterium ($\text{P+N}$)
- SNO is capturing all three types of neutrinos (electron, muon, tau)
- "Solar neutrino problem" leads to big physics advance (2002 Nobel Phys Prize; Davis & Koshiba)

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!

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

Granulation: turbulent convection

Size: ~ 1 Mm across

Complex Interplay of Convection and Magnetism

SUNSPOTS amid field of GRANULES

1 Mm spacing on ticks
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”
- Can detect these with Doppler imaging of gas at solar surface (“see” the sound)
One of millions of modes, each with a different tone!

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 Helioseimology

Temperature
Density

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 in TACHOCLINE
Small-scale fields built in near-surface shear layer

Helioseismic Probing of Flows Below Surface

Global Patterns of SOLAR SUBSURFACE WEATHER
Meandering flows like jet streams, interact with active regions
SSW in Global View, Apr 2002

SSW Flows Changing as Cycle Progresses

Discussion
- How do we really know what is happening deep within the Sun?
- What is interplay between theory and observation?

Far-Side Imaging
Helioseismology

Reading Clicker – Solar Maximum?
- What observed features characterize the Sun at “solar maximum”?
- 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

Now back to SOLAR MAGNETISM
**View during solar eclipse**

**Diverse Scales of Solar Magnetism**

**Magnetic fields are built in convection zone**

**How differential rotation can stretch and change global magnetic fields**

**UV view of solar magnetism**

**Sunspot in White Light**
Zoom-in on evolving sunspot

11-year Cycles of Solar Activity

Butterfly Diagram

Sunspots show “Zeeman splitting”

1000+ Gauss magnetic fields in sunspots

But what really is a “magnetic field”?

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

Complex “magnetic carpet” in low corona

Huge prominence is big magnetic loop
Many Faces of the Sun: Composite

Coronal Mass Ejections (CMEs)

Combo: CME and UV disk

Theoretical Solar Cycle

Ben will discuss in recitation Mon