Stars, Galaxies & the Universe

Announcements

• Quiz #5 today in class
• HW#5 due Friday (10/1) at 5 pm
• From now on, HWs due Friday!!
• No labs this week – back to regular schedule next week!
• Observing trip instead – TUESDAY AND THURSDAY
  – Weather looks good – please arrive at 7 pm EAST END VAN Hall
  – Dress warmly and appropriate shoes
  – Website will be updated if trip is canceled due to weather:
    http://astro.physics.uiowa.edu/~clang/sgu_fall10/observing_trip.html
• Exam #1 grades are posted in ICON and answer keys are also available (both Form A and B) on the course website
  – No extra credit on exams, but please come see me if you want to talk over
  – 27 Sept 2010 1SGU - Dr. C. C. Lang

The Sun – our Star

• Powering of the Sun & all stars
• Forms of energy released
• Neutrinos
• Layers of the sun & how energy escapes

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How does the Sun Shine?

• Sun has its own energy source
  - main difference between a star and planet
• Sun’s energy source not well understood until the 1900s!
• Main constraint: Lifetime of the Sun
  need a vast, constant generation of energy
  Sun’s age: at least 4.6 billion years old (fossils)
  most original ideas could not SUSTAIN energy rate
• Additional constraint: Luminosity (energy/s) of the Sun
  rate of energy generation: 3.9 x 10^{26} Joules/second

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Possible Solar Heating Mechanisms

1. GRAVITATIONAL COLLAPSE
   - pressure of Sun’s layers → contraction
   - gas temperature increases as gas contracts
   → Sun would have started as hundreds of times larger and could only be 25 million years old to produce energy rate!

2. COMBUSTION (burning/fire)
   - burning of the Sun’s fuel: hydrogen, helium
   - Sun would burn itself out in only 10,000 years!!

Need a more powerful, longer lasting energy source?!!

More clues from deep inside the Sun...
The very core of the Sun is close to 15 million K
→ reservoir of Hydrogen under extreme temperatures and pressures

The Basics of Nuclear Fusion
Nucleus: the positively charged concentration of matter at the center of an atom
  • protons (positive)
  • electrons (negative)
  • neutrons (neutral)
Nuclear Interactions
- occur when a nucleus is struck by another nucleus
- extremely rare (but usually there are many nuclei)
- need high density, high temperature (collisions!!)
- in nuclear reactions, ELEMENTS \(\rightarrow\) new ELEMENTS

NUCLEAR FUSION!
- 2 nuclei \(\rightarrow\) are converted \(\rightarrow\) into 1 new nucleus
- this process generates ENERGY
- NUCLEAR "ENERGY" is the conversion of mass to energy
  \[ E = mc^2 \]
  famous Einstein revelation – mass=energy

Nuclear Fusion via the Proton-Proton Chain
Very roughly: Hydrogen + Hydrogen = Helium + energy
- Hydrogen: a single proton
- Helium: 4 particles: 2 protons, 2 neutrons
- “Proton-Proton Chain”
  - like a multi-car pile up on the interstate
  - Hydrogen collide with additional Hydrogen
The proton-proton chain

Elementary particles

- Protons (orange) – found in nuclei, positive charge
- Neutrons (blue) – found in nuclei, no charge
- Electrons (e⁻) – orbit nuclei, negative charge
- Photons (γ) – particles of light (gamma-rays)
- Positrons (β⁺) – anti-matter electrons, positive charge (e⁺ in book); “beta”-particles
- Neutrinos (ν) – ‘ghost particles’, no charge, can easily pass through normal matter

Nuclear fusion: proton-proton chain

\[ 4(1\text{H}) \rightarrow \text{He}^4 + \text{energy} \]

\[ \Delta M = 4M_{1\text{H}} - M_{\text{He}^4} = 4.8 \times 10^{-29}\text{kg} \]

\[ E_F = \Delta M c^2 = 4.3 \times 10^{-12}\text{J} \]

where 1 MeV = 1.6 \times 10^{-13}\text{Joules}, and \( E_F = 26.7\text{ MeV} \)

Heating of the Sun: Nuclear Fusion

Eventually you get ENERGY released when Helium formed!

\[ \text{Hydrogen} + \text{Hydrogen} + \text{Hydrogen} + \text{Hydrogen} = \text{Helium} + \text{energy} \]

Two types of energy:

1. gamma rays - highly energetic photons, carry energy out get trapped in Sun’s gaseous layers
2. neutrinos – particles which carry energy with little mass do not get trapped in the Sun’s gas layers

Test of fusion hypothesis: LOOK for neutrinos!
Neutrinos

- Properties of Neutrinos
  - Elementary particles
  - Travel at/near the speed of light
  - Perhaps massless (perhaps not)
  - Neutrinos can come in a variety of “flavors”: electron, muon, and tau

- 50 trillion solar electron neutrinos pass through the human body every second

Detection of neutrinos would be proof of nuclear fusion in the core of the Sun

- Conversion of H → He produces $10^{38}$ neutrinos/sec
- Each second, $10^{14}$ neutrinos pass through each m² on Earth...

...however, in certain reactions (neutrinos with $^{37}$Cl) neutrinos generate radioactive Argon ($^{37}$Ar)

$\rightarrow$ Make “neutrino telescopes” using large vats of dry cleaning fluids: perchlorethylene $C_2Cl_4$

Neutrino Detectors across the World

Homestake Experiment in Lead, SD

Sudbury Observatory in Sudbury, Ontario, Canada
Super Kamiokande is a large volume of water surrounded by phototubes that watch for the Cherenkov radiation emitted when an incoming neutrino creates an electron or muon in the water.

Receiving Nobel Prizes – Fall 2002

Dr. Masatoshi Koshiba
Dr. Ray Davis

Neutrino Detectors across the World

Neutrinos do not interact with matter in the way photons do… but occasionally they generate a detectable radioactive product.
The “NEUTRINO PROBLEM” – the ‘neutrino flux’ measured by detectors is only 1/3 of theory value!

Balance of gravity & pressure in the Sun
stability of the Sun:

- OUTWARD gas pressure
  balanced by
- INWARD gravity of Sun’s incredible mass

Convection zone
Radiative zone

Nuclear burning core

Energy produced in the core is carried outward by photons.
Nuclear reactions produce energy in the Sun’s core.
The interior layers of the Sun

1. The Core
- innermost 25%
- \( T \sim 15 \) million K
- the density here is compressed by *entire* weight of Sun
  \( \rightarrow 150x \) density of water!
- region where energy is generated by fusion

2. Radiative Layer
- solar "midsection"
- \( T \sim 1-10 \) million K
- energetic photons carry energy out of core
- energy lost to gas layers
- eventually, these photons get stuck in the gas layers

Transport of energy through the radiative zone
Photons produced via fusion scatter many times in the Sun’s dense interior - a "random walk".
Random Walk
The same formula holds in 2 and 3 dimensions.
For the Sun, the average distance between collisions is about
\( l = 1 \text{ mm} \). Photons travel at the speed of light, so the time
between collisions is
\[ t = \frac{l}{c} = \frac{1 \times 10^{-3} \text{ m}}{3 \times 10^8 \text{ m/s}} = 3 \times 10^{-12} \text{ s} \]
The radius of the Sun is \( L = 7 \times 10^8 \text{ m} \). The average number of
collisions before a photon escapes is
\[ n = \left( \frac{L}{l} \right)^2 = \left( \frac{7 \times 10^8 \text{ m}}{10^{-3} \text{ m}} \right)^2 = 5 \times 10^{23} \]
The average photon stays in the Sun for a time
\[ T = tn = (3 \times 10^{-12} \text{ s})(5 \times 10^{23}) = 1.5 \times 10^{12} \text{ s} = 50,000 \text{ years} \]
A more accurate estimate gives \( 120,000 \text{ years} \)

The interior layers of the Sun

3. Convection region
- outermost 30%
- \( T \sim 10,000-1 \text{ million K} \)
- rising, sinking of gas transports energy
  HOT gas rises up
  COOL gas sinks down

Convective zone
Evidence for Convection: Solar Granules

- on the solar surface
- 1000’s miles across
- dark = cooler gas
- light = hotter gas
- speed of motion up & down measured by DOPPLER EFFECT!

Solar Granules: courtesy of the Swedish Solar Telescope