The Sun

(Chapter 16, Sections 16.1-16.3, *and* 16.6 and 16.7.)
[Remember, we're skipping 16.4, 16.5 on "Solar Magnetism" and "The Active Sun." But I think it would be foolish not to at least look through it to see how complex our star really is, and the sun-Earth connections. Just don't forget that you need to read section 16.6 and 16.7!]

◆ We can only observe light coming from the "surface" of the sun, called the **photosphere**—this is *not* a solid surface, like on the earth, but just the layer of the sun at which the density is low enough to allow the photons to escape. (We can also see light from the layers above the photosphere, called the chromosphere and corona, but they are of interest for different reasons—they don't lead to any understanding of the properties and evolution of the sun.)

◆ From observations of this light from the photosphere, along with knowing the distance to the sun, we learn the sun's size (about 100 earths), mass (300,000 earths), and luminosity (how much energy per second is emitted, its brightness, like the wattage of a light bulb—over 10^{26} Watts for the sun!), and its spectrum (from which we can get the abundances of elements (see sec. 16.3), as well as the amazing surface activity (which we won't cover for the exam—see 16.4, 16.5).

◆ We'll see later that the sun is more or less an average star, in just about all these quantities, including its composition (abundances of elements)

How do we learn about the *interior* of the sun, if we can't see in? Three techniques:

1. **Theoretical modeling**—e.g. hydrostatic equilibrium (pressure balances gravity), energy conservation through each layer… This gives the values of temperature, pressure, density, luminosity as a function of radius, from the center to the photosphere. This is the ***only*** way to get detailed predictions about the sun's (and other stars') interiors, *and* how the sun has and will evolve in time.

The huge temperatures at the center obtained in these models (many millions of degrees) is why we think that the source of the sun's energy is nuclear fusion by the proton-proton cycle (discussed below and in class) in its core. This is sec.16.6.

No one has ever thought of any other way that the sun could shine at its present enormous luminosity using any other kind of power source.

These models lead us to a theoretical picture of the structure of the sun consisting of several major regions (from center to surface):

Core (can only see by neutrinos—see below)—temperature about 10 million degrees! Understand why, and the implications.

Radiation zone—energy transport by huge number of absorptions and scatterings and reemissions.

Convection zone—can see the upper part of this layer as granulation.

Photosphere—where the density becomes low enough for photons to escape the sun. Interior to the photosphere the sun is *opaque* to its own photons.

[Still listing three methods that teach us something about the interior of the sun.]

2. **Helioseismology**—Vibrations visible at the surface give information about how waves propagate through the stellar interior, and so info about the density and rotation, especially the upper layers. (See Fig. 16.5)

3. **Solar Neutrinos** (sec. 16.7)—neutrinos are the products of nuclear reactions in the solar core. But unlike photons (light), neutrinos essentially *don't interact with matter (except certain materials) and so pass directly through the whole sun*.

◆ Most of these pass right through the earth too, but if we can collect a few of them using some kind of "neutrino telescope", we would have a way of "seeing" directly into the center of the sun!

◆ 1960s-1990s: Ray Davis' Homestead Mine neutrino experiment: number observed much smaller than predicted⇒ **solar neutrino problem.** But experiment is outrageously difficult, so many thought problem was with experiment.

Subsequent more recent experiments (SAGE, GALLEX, SuperKamiokande) confirmed Homestead result ⇒ **something wrong!** Has the sun "turned off"???

The neutrinos are generated in the first step of the proton-proton cycle that generates the sun's energy. So maybe the sun has temporarily "turned off" by some instability; it would take 10 million years to us to find out using light. Or maybe we don't understand something at some other fundamental level.

⇒ One way out: **maybe neutrinos *do* have mass** (unlike photons), in which case they can spontaneously transform into other types of neutrinos, along their path from the earth to the sun, which would not be detected by the experiments. These possible transormation among neutrinos are called *"neutrino oscillations."*

1998: Kamioka group reports evidence of neutrino oscillations. (See figure 16.29, p. 444)

2001: Ontario Sudbury Neutrino Observatory confirms, at just the level to explain the "missing" solar neutrinos. (Also p. 444)

So after over 40 years, the mystery is solved, and theoretical models for the solar interior are confirmed. This is extremely important because:

◆ Soon you will see that almost everything we think we know about the evolution of stars is based on theoretical models (we can't see into other stars either!)

◆ In addition, this is our first indication of the intimate connection between knowledge of particle physics and astronomy. No physicist any longer believes that neutrinos are massless, like photons.

[Later we'll see how the Kamioka neutrino experiment surprisingly detected the predicted neutrinos from a supernova explosion in 1987.