LECTURE 9: DO WE UNDERSTAND THE SUN?

## 9.1 THEORY OF THE SUN

We have now developed a theory of the sun (and similar main sequence stars). According to this theory, the sun:

- is a cloud of gas held together by gravity
- is 70% hydrogen, 28% helium, and 2% "metals" (heavier elements), by mass
- balances gravity with pressure $\Longrightarrow$ central temperature is very high (15 million degrees Kelvin)
- is luminous because photons carry energy out from the hot core, slowly, by random walks and convection
- fuses hydrogen to helium in its core, thereby maintaining its central temperature

Given the mass of the sun, fairly simple calculations show that this theory predicts the luminosity and radius of the sun roughly right, and that the nuclear energy supply is enough to let the sun survive for billions of years.

## 9.2 SOLAR MODEL

One can construct a detailed model of the sun by solving the equations of

hydrostatic equilibrium (pressure balances gravity)

energy transport ("leaking photons")

nuclear energy generation

at every point in the star. The solar model tells the density, temperature, and pressure of the gas at every point in the sun.

Given the mass, composition, and age of the sun, this model reproduces the observed luminosity and radius of the sun precisely.

This success is reassuring, but we would like more convincing evidence that our theory is correct.

## 9.3 SOLAR OSCILLATIONS

The sun "rings like a bell", with millions of tiny oscillations (pulsations) going on simultaneously.

The period of a typical oscillation is about 5 minutes.

Solar astronomers can measure these oscillations very precisely using Doppler shifts.

Theorists can predict the oscillation behavior from the solar model.

### 9.4 SOLAR OSCILLATIONS: RESULT

Comparison of theory and experiment reveals spectacular agreement.

The solar model correctly predicts the speed of sound at each radius in the sun to within 1%.

The precision is high enough to allow tests of fine details of solar theory, like rotation of the solar interior, or the slow settling of heavier elements towards the center of the sun over its lifetime.

This agreement is a great success of the theory, **BUT**

> it doesn't test what's happening in the very center of the sun
>
> it doesn't provide *direct* evidence for nuclear fusion

### 9.5 TESTING THE FUSION HYPOTHESIS WITH SOLAR NEUTRINOS

The sun is opaque to photons, so we don't see into the center.

Some fusion reactions (like the first step of the proton-proton chain) produce neutrinos.

Neutrinos don't feel the nuclear or electromagnetic interaction, only the weak interaction $\Longrightarrow$ a neutrino can pass through the sun or through the earth without noticing.

Typically, a block of lead about 1 light-year long is needed to stop a neutrino.

The sun is transparent to neutrinos, so we can "see" to the center. But neutrinos are hard to capture.

The sun produces lots of neutrinos, and occasionally one can "hit" an atomic nucleus and turn a neutron into a proton. A neutrino can also "scatter" an electron.

With a big detector, one can expect to see a few dozen reactions per month caused by solar neutrinos. Four solar neutrino experiments are now operating (one since the late 1960's).

### 9.6 SOLAR NEUTRINOS: RESULTS

(1) *Great success*

All four experiments detect neutrinos.

One experiment shows that the neutrinos come from the direction of the sun (the others can only tell how many neutrinos are captured, not what direction they come from).

Implication: there *is* fusion in the sun. A dramatic confirmation of our theory.

(2) *Puzzling failure*

The experiments detect fewer neutrinos than the solar model predicts.

They detect about 1/4 to 1/2 the expected rate, depending on the experiment.

## 9.7 WHAT'S WRONG?

There are many possible solutions to the solar neutrino problem. Solutions can be divided into four broad categories:

(1) The experiments are wrong.

The experiments are very difficult. It seems unlikely that all four are wrong, but one or two might be.

The theory of the sun is wrong

(2) in minor details (nuclear reaction rates, details of chemical composition, opacity of envelope).

(3) in a fundamental way (structure is different near center, core "turns on and off"). But it's hard to change the theory of the sun without spoiling the agreement with solar oscillation observations.

(4) The theory of neutrinos is wrong.

It is known that there are three types of neutrinos. The experiments only detect one kind. Maybe the detectable neutrinos are transformed into undetectable neutrinos as they pass out of the sun.

Particle physicists consider the last solution to be fairly plausible. If it turns out to be true, an astronomical puzzle will again have led us to new fundamental physics.

## 9.8 SUMMARY

The principles of stellar structure that we have discussed can be used to construct a detailed model of the sun, which can be tested against observations.

Given the mass, composition, and age of the sun, the model correctly predicts the radius and luminosity of the sun.

Solar oscillations can be measured precisely using Doppler shifts. Predictions of the solar model match these observations spectacularly well (1% accuracy).

Neutrinos can escape directly from the center of the sun, so solar neutrino experiments can "see" the core of the sun.

Four experiments detect solar neutrinos, providing *direct* evidence that nuclear fusion occurs in the sun.

Each experiment detects fewer neutrinos than predicted by the standard solar model. This disagreement is called the solar neutrino problem.

Possible solutions: (1) the experiments are wrong (2) the theory of the sun is wrong in minor details, (3) the theory of the sun is wrong in a fundamental way, (4) the theory of neutrinos is wrong.

Experiments in the next few years should reveal which of these solutions is correct.