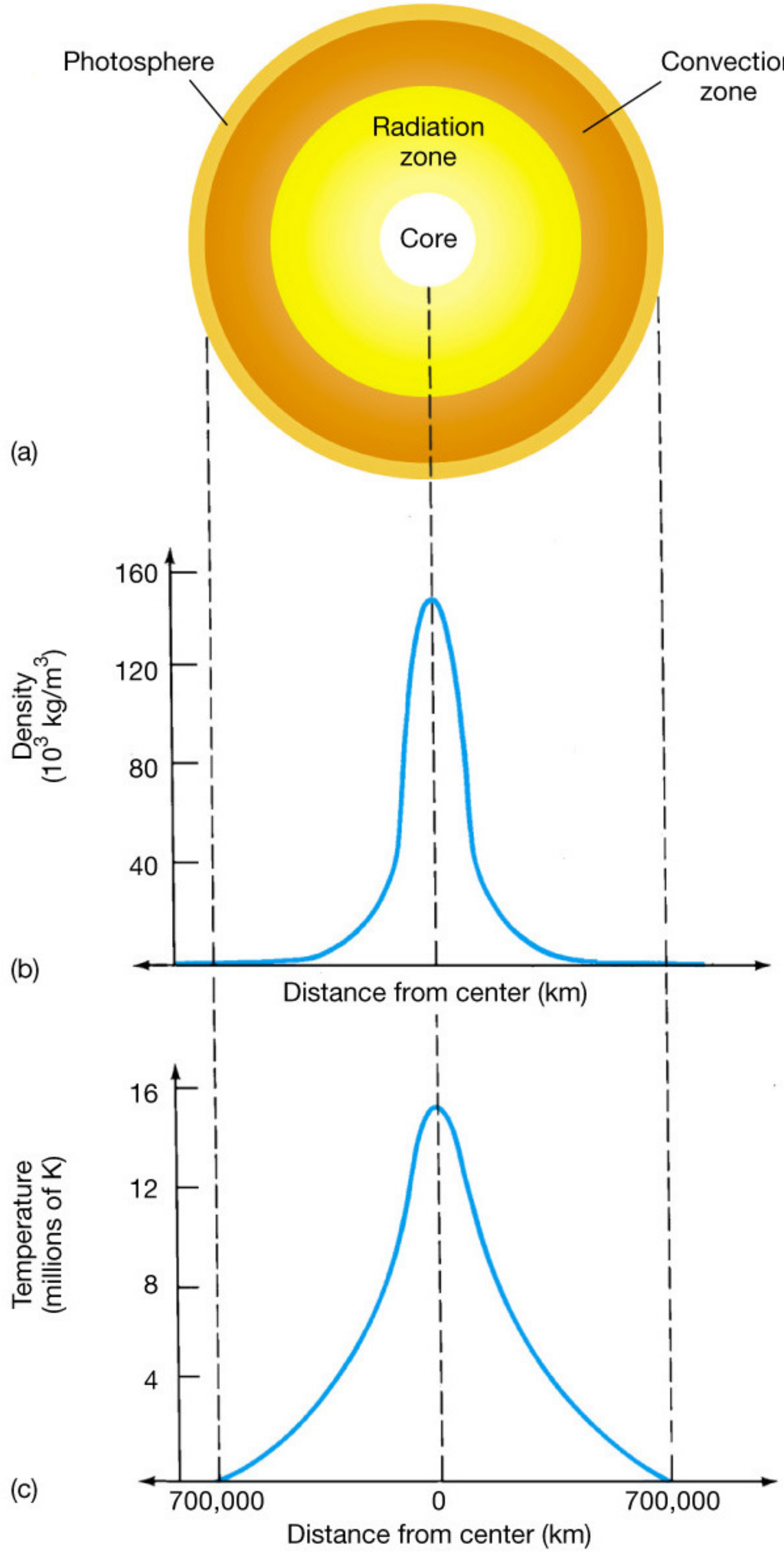
11/15/19
let's move on to stars now, using our sun as a prototype.

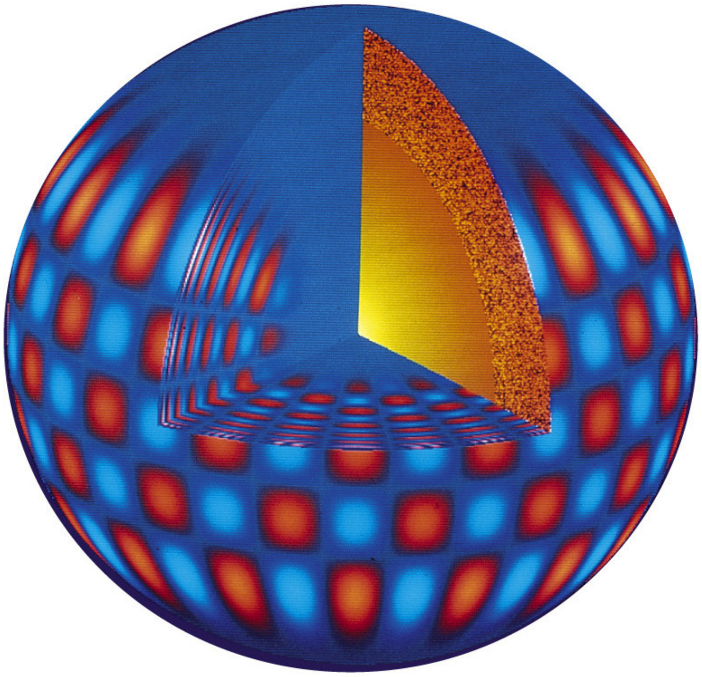
First question, is how do we even know that stars that we see in the sky are the same kinds of things as our sun? (Spectra!)

What do we know about our sun and how do we know it?
The total power emitted by the sun (if we measure the received flux from the sun at the earth and knowing how far away we are from the sun we can figure out the total power)
its diameter (small angle relationship)
it's mass (from Kepler's laws of orbital motion in Newton's form)
temperature (Wiens law)
composition (at least we can identify spectral lines and that tells us something-- in particular mostly hydrogen and helium—about 71% H and 28% He by mass)

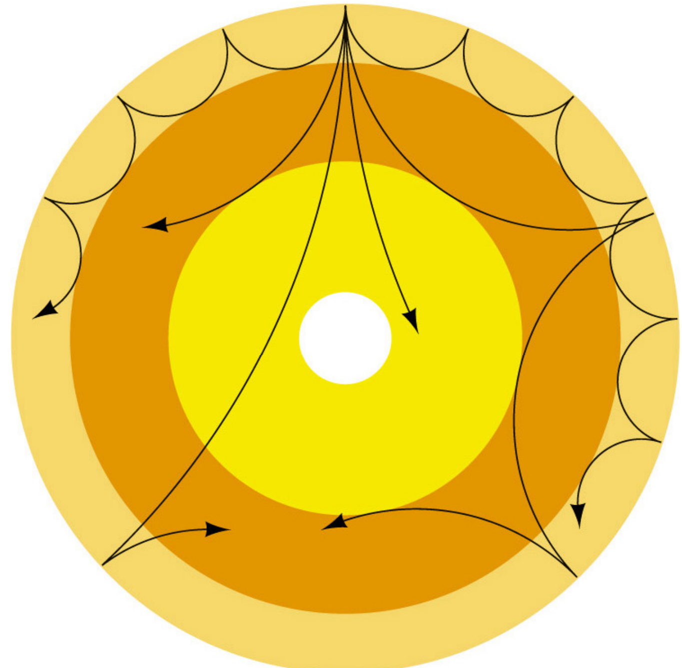
The next question after these properties, is what's the structure of the sun? In understanding the structure of the sun we need to understand the concept of hydrostatic equilibrium. Since the sun is hot and mostly gases, we can basically treated as a big blob of some sort of fluid. In order for it not to be collapsing or expanding (which we observe it is not), each little blob of matter it is made in must have (on average) a net force of zero on it. The primary forces on matter in the sun or the gravitational force pulling him towards the center, and pressure difference pushing outward—essentially the buoyant force on the blob. The balance of gravitational and pressure forces is what is referred to as hydrostatic equilibrium. Just as when we go deeper in the ocean the pressure is increasing with depth, the pressure in the sun is increasing as we move towards the center. To support a high pressure, gas such as the hydrogen and helium in the sun must have a high temperature (ideal gas law and similar for ionized gases). We can therefore make a model of the conditions inside the sun (temperature, pressure, density is a function of position).



Can we check this? Obviously we can't dig into the sun and find out what it's like inside. However, being a compressible fluid the material in the sun supports oscillations/waves much like seismic waves in the earth. Instead of earthquakes, we have continuous driving of these waves by flows of energy and matter in the sun. This is much like sticking a musical instrument in the wind and hearing the tones generated. We can see these oscillations and waves in the sun by looking at the Doppler shift of the surface of the sun. This study of the sun by oscillations is called helioseismology. Here's a sort of pattern we might see from the earth (figure 9.5 ABGU). Since the pattern of oscillations depends on the density and composition and temperature and pressure of the stuff making up the sun, we can use this to check our model and improve it. (Figure 9.6 ABGU or above).



(a)



(b)

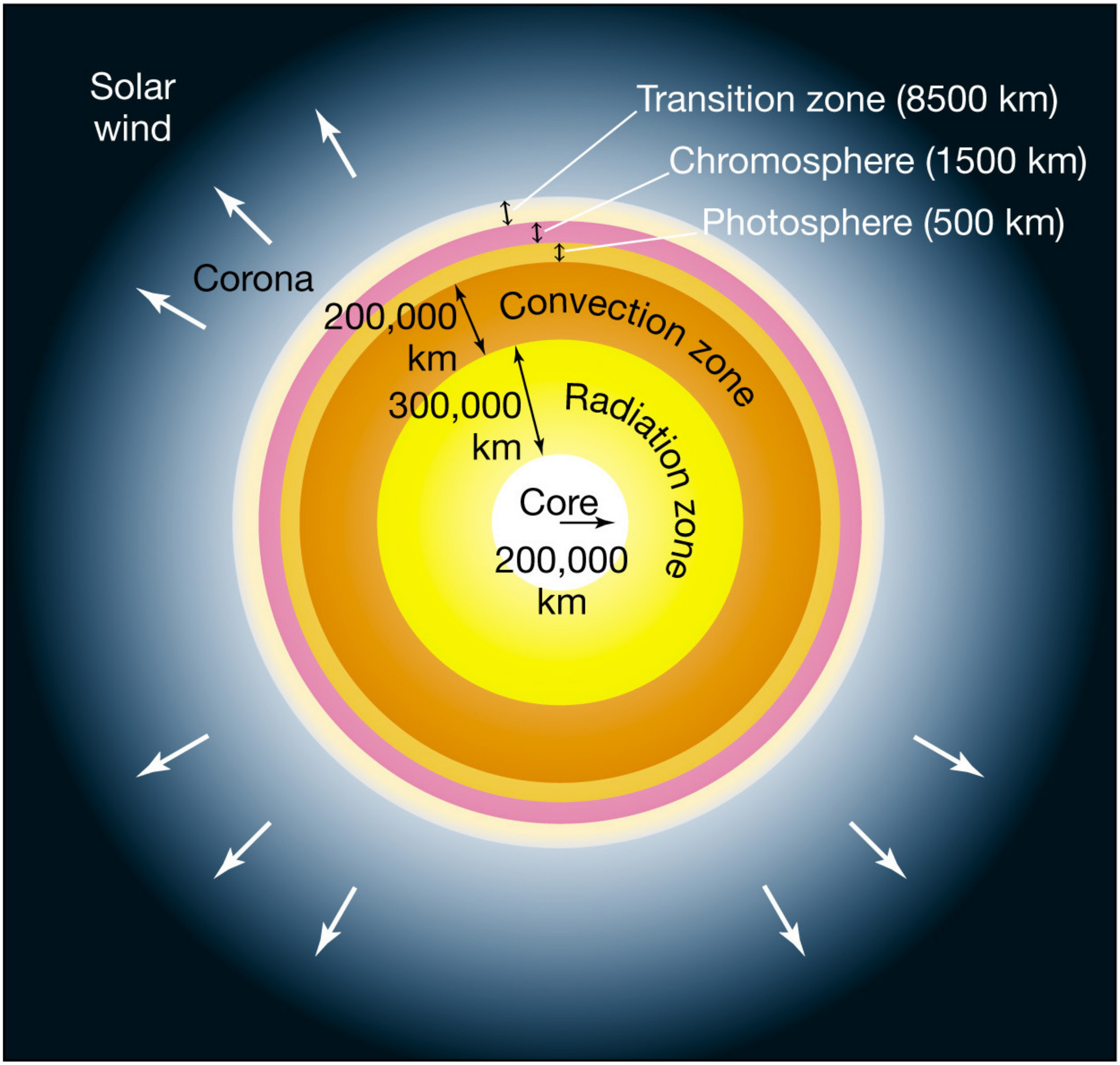
Where does all the energy pouring out of the sun come from?

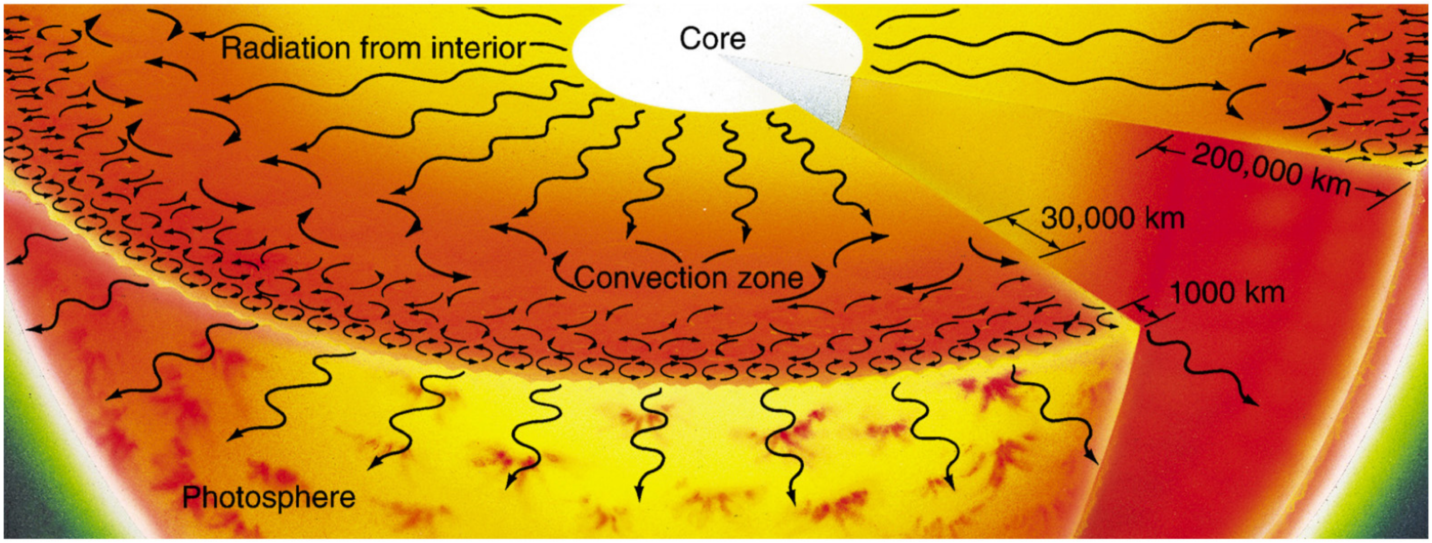
Well, we can tell that it's not just leftover energy from the sun's formation or some chemical reaction because there's no way either of those could continue to put out the sort of energy the sun is putting out for as long as the solar system has been around.

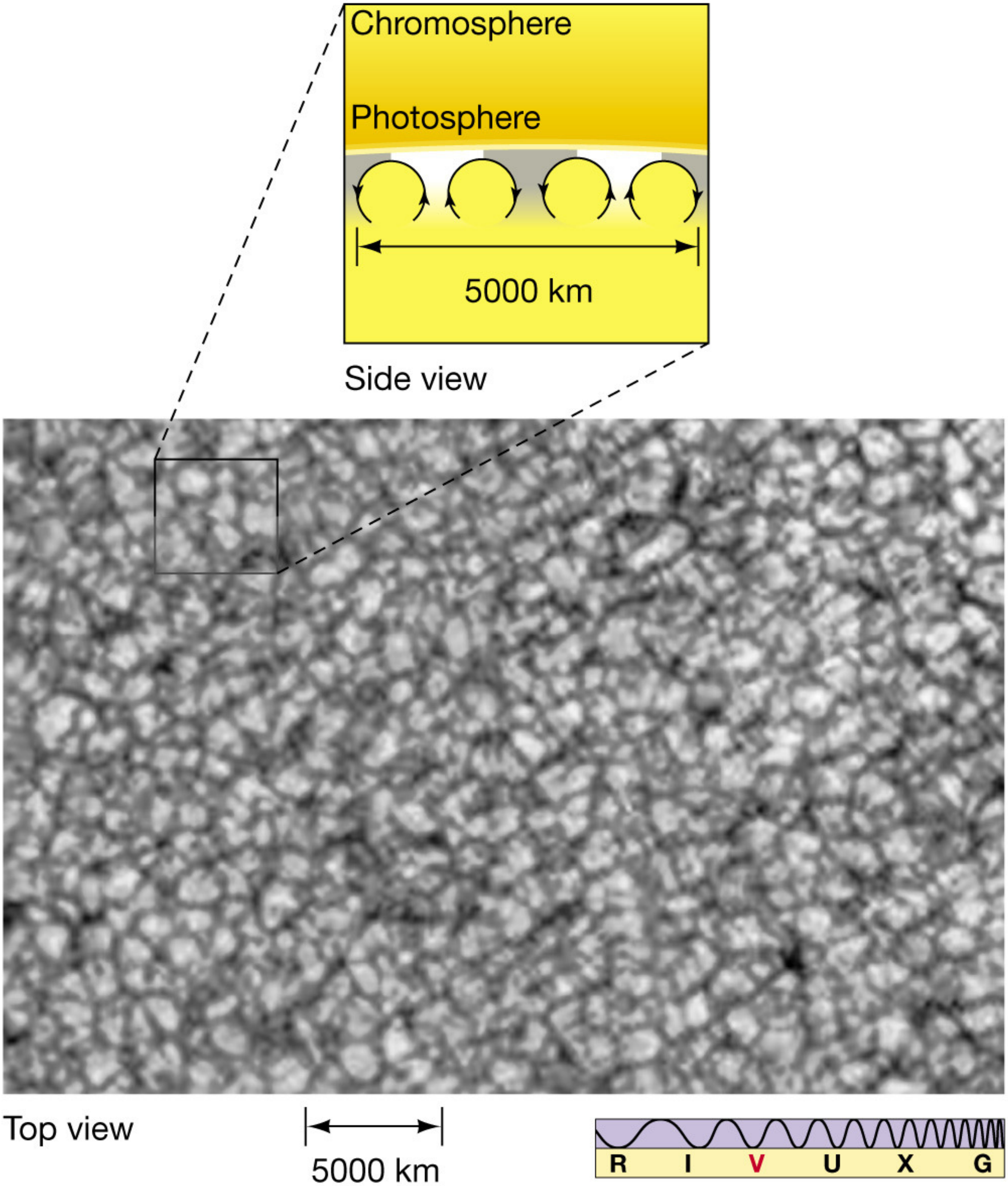
The force between the neutrons and protons of the nucleus is very strong. In the early part of the 1900s it was realized that energy could be released by combining the nuclei of light elements.
However, 2 hydrogen nuclei (that is, two protons) have positive electric charge. Would that make it easier or harder to get them together?
Because of this we need a high temperature and high density to bang them together hard enough and often enough for enough fusion reactions to take place to provide the power output of the sun.
There are many steps in the nuclear reactions that take place in the sun, but the net effect of all of them is to take 4 protons, combine them and make one helium nucleus and release energy and neutrinos (an extremely low mass subatomic particle).

Since this requires high temperatures and densities, this takes place in the innermost core of the sun within about 1/10 or 1/20 of the outer radius of the sun. The energy must be transported from there to the surface. There are two primary processes responsible: just outside of the core where the fusion is taking place, the temperature is so high that hydrogen and helium have no electrons stuck on them. This means they cannot absorb water magnetic radiation because there are no electrons to go to excited states. In this area, energy from the inner part of the sun is transported primarily by electromagnetic radiation.
Once the temperature has gotten low enough (at further distances from the center) that some of the nuclei can hang onto electrons, the gas absorbs energy flowing outward from the core and heats up, becomes less dense as it expands, and starts rising-- this is the process of convection which we are now familiar with. (See figure 9.2 or 9.7 ABGU (below)). The convection zone extends up to what's called the photosphere, which is the layer of

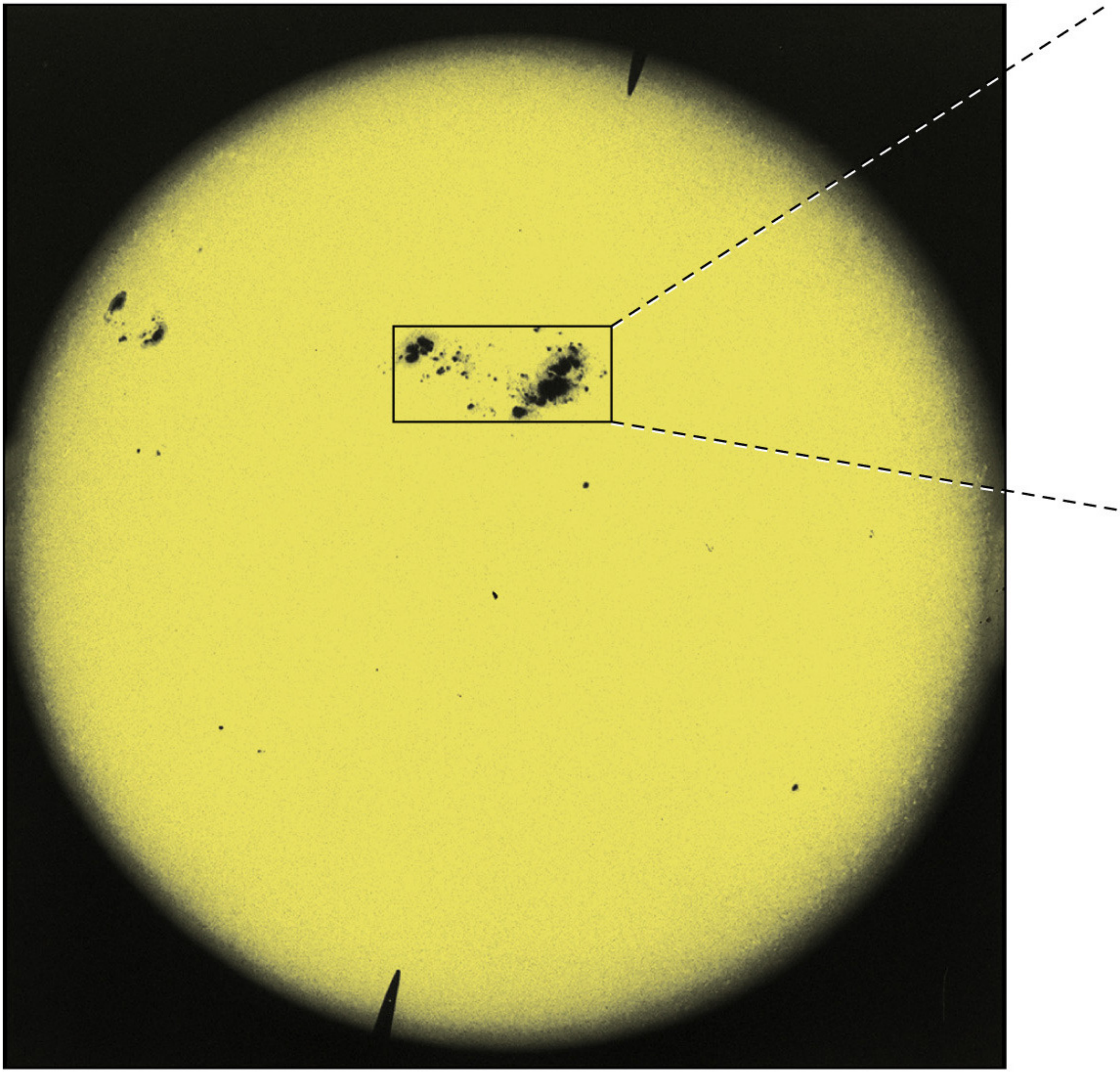
the sun we see. Close-up views of the sun show was called granulation which, based on measured Doppler shifts seem to be a pattern of small scale convection cells. (Figure 9.8 ABGU (further below)).

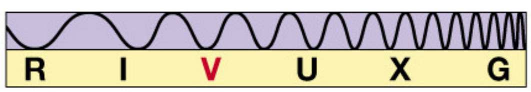



Core
Radiation from interior
200,000 km
30,000 km
Convection zone
1000 km
Photosphere

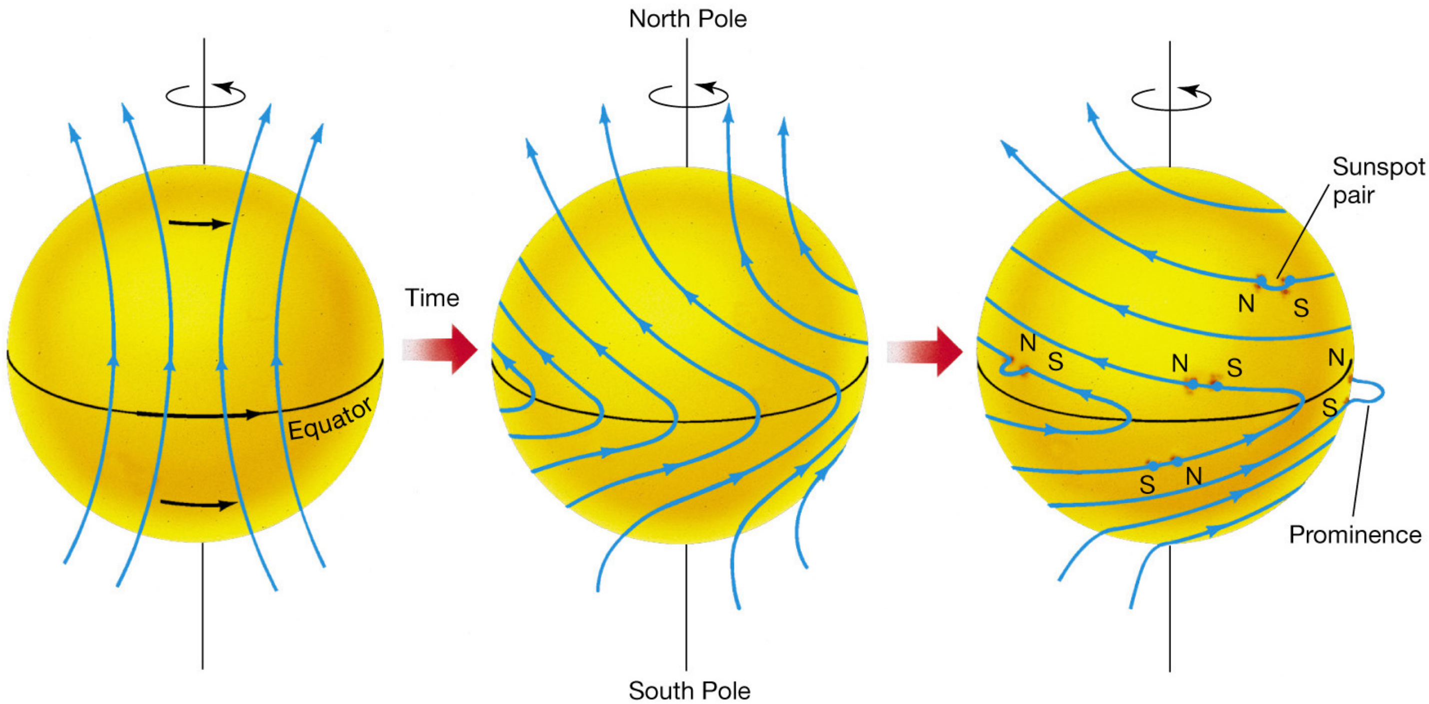


Another interesting feature of the sun which has been observed since Galileo first unadvisedly turned his telescope to look at the sun is its pattern of sunspots.





Sunspots we now know are regions of the sun or the temperatures slightly lower due to some effects of the sun's magnetic field. The basic idea is that strong convection and the electrically conducting ionized gas and rotation of the sun generates a magnetic field according to the usual dynamo model we have discussed in the context of planets. The different feature of the sun is that it does not rotate at a uniform rate all the way through--it rotates faster at the equator than the poles.



This tends to slowly twist up the magnetic field which eventually develops kinks which are regions of strong magnetic fields which suppress convection in localized areas of the sun's surface and lead to slightly cooler regions-- these are the sunspots we see. The twisting/kinking takes energy and eventually the field get so twisted up that it costs less energy to do something different and the field reverses itself. This happens every 11 years on average, and a complete cycle would then be 22 years. (Figure 9.18 ABGU)