Stellar — The Sun (as an Example Star)
C+O Chapter 11

Basic Properties

We have discussed the Sun at some length, but let's review the basic properties here.

Mass: 1 $M_\odot \simeq 2 \times 10^{30}$ kg
Radius: 1 $R_\odot \simeq 7 \times 10^{8}$ m
Total Lifetime: $\sim 10^{10}$ years

Central Temperature (modeled): 1.57×10^{7} K
Photosphere Temperature: $\sim$ 5800 K
Luminosity: $L_\odot \simeq 3.4 \times 10^{26}$
Composition: 75% H, 24% He, 1% other; Z = 0.0122

Spectral classification: G2V
Apparent Visual Magnitude: 26.74
Absolute Visual Magnitude: 4.83
Color: (B-V) = 0.63

Mean distance from Earth: 1 AU$\simeq 1.5 \times 10^{11}$ m

Apparent rotational period at its equator: $\sim$28 days

From inside out....

Solar Interior

The interior of the Sun is composed of the "core," which supports nuclear reactions. Most stars then have radiative and convective zones, although as we know the placement of these zones depends on the stellar mass.

For the Sun, the radiative zone extends from the center of the core out to 0.714 $R_\odot$. The convective zone extends from 0.714 $R_\odot$ to 1.0 $R_\odot$.

99% of the Sun's energy is produced within 0.24 $R_\odot$, and 100% within 0.30 $R_\odot$. 91% of teh energy is generated via the proton-proton chain.

Solar radiation has a difficult time escaping from the core to the photosphere, due to the density of the Sun. On average, photons take 200,000 years to travel from the Sun's core to its surface because they are constantly being absorbed and reemitted in random directions.

Convection moves material from one Solar radius to another. In the absence of convection, the byproducts of fusion cannot be redistributed throughout the star. Your book states that in the core, the mass fraction of hydrogen has decreased from 0.71 to 0.34 and the mass fraction of helium has increased from 0.27 to 0.64. The convective zone in the Sun does not reach all the way down to the core, so the mass fractions have not changed much at the Solar photosphere.

Solar Neutrinos

One aspect of fusion we haven't discussed much is the production of neutrinos.

Your book goes into the long history of neutrino detections. Neutrinos do not like to interact with matter and are therefore very difficult to detect. The neutrinos from the Sun are passing right through you all the time! If, we could detect neutrinos, this would be a window into the fusion rate of the Sun, providing valuable information about how the Sun produces energy. I don't feel the need to reproduce this long history, but the upshot is that the detection of neutrinos confirmed the reaction rates, but neutrinos must switch "flavors" on their way to the Earth and therefore must have mass. Neutrinos were thought to make up significant "dark" matter in the Universe, but it turns out that they are not massive enough to be a major dark matter contributor.

Solar Atmosphere

Although the Sun is just one continuous and largely homogeneous ball of gas, stellar atmospheres can be separated into the corona, transition region, chromosphere, and photosphere. Below the photosphere is just the interior. Each of these regions has characteristic properties, and in the Sun we can also talk about the "heights".

Photosphere

The photosphere is the "surface" of the Sun. What does that mean? It means that this is where the visible light photons we receive originate, or in other words where $\tau = 1$.

There are a couple problems with this definition: first, τ is wavelength-dependent, and so is the location where $\tau = 1$. Second, the criterion $\tau = 1$ simply defines a hollow sphere, not a layer. To resolve these issues, we use 500 nm to evaluate τ and take 100 km below this surface as the base of the photosphere (at

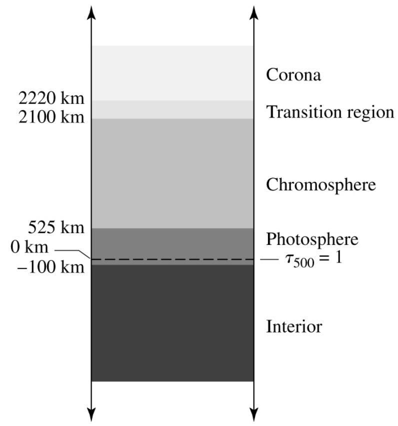

Figure 1: Stellar atmospheres. The y-scale values are unique to the Sun.

a temperature of 9400 K) and 525 km above as the top (at a temperature of 4400 K).

One interesting aspect of the photosphere is that we will see down to different depths at the wavelength of an absorption line compared to the wavelength of adjacent continuum. We reach an optical depth of unity at a higher altitude at the wavelength of an absorption line.

The chromosphere is the next highest layer after the photosphere. Your book says it extends 1600 km above the photosphere. Compared to the photosphere, the density is decreased by a factor of 10^4 and the temperature is about 10^4 K.

The high temperature of the phosophere means that there are more ionizations (see Saha equation) and also more atoms in excited states (see Boltzmann equation). This, plus Kirchoff's law saying that we see hot diffuse gas in emission leads to emission lines arising from the chromosphere. Due to the low density, these lines are weak – they are only seen at the edge of the Sun during an eclipse.

Above the chromosphere is a "transition region," where the temperature rises even further, up to 10^6 K. Above the chromosphere is the corona, which is composed of a tenuous gas at extremely high temperarues. The number density is 10^6 times less than that of the photosphere. Remember, it is collisions that force a gas into LTE, and without a high density, collisions are infrequent in the corona and the gas is not in LTE. There is therefore no temperature that well-characterizes the gas, but we can still say that a characteristic temperature is $\gtrsim 2 \times 10^6$ K.

The corona can be observed at radio wavelengths, and also in the X-ray regime. The radio comes in part from free-free emission, and also synchrotron. The X-ray emission arises from ions, which can have a large number of transitions.

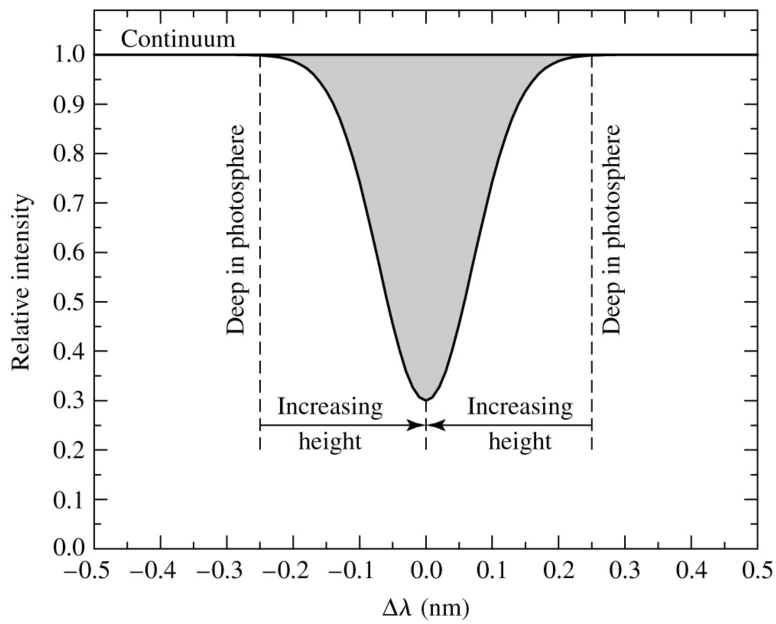

Figure 2: Due to optical depth effects, absorption lines originate from different zones from the continuum. Spectral lines seen in absorption come from the highest layer (largest radius), whereas the continuum comes from deeper in the Sun.

The Solar Wind

The Sun is to first order a magnetic dipole, with north and south magnetic poles. We will discuss the origin of this magnetic field later. For now, let's take it as a given. Ionized particles interact with magnetic fields by spiraling around them. If the field lines are closed, the particles are trapped. They will oscillate back and forth (this is largely what we see on the Earth, and is what gives rise to the auroras). If the field lines are open, however, the particles can freely escape.

A "wind" of particles emanates from the Sun, known as the Solar Wind. This stream of particles is launched from the corona at speeds of hundreds of miles per hour. Because of the high temperatures in the corona, the particles are ionized. A Solar wind is required, given that the Solar corona is so hot. This ionized wind has pressure $P = 2nkT$, assuming it is singly ionized. As your book shows, the pressure going outward from the Sun does not decrease to zero. Instead, it is some value higher than that of the material outside (the interstellar medium). As a result, particles are drawn from the Sun toward the lower pressure region. At the termination of the Solar wind, there is a "heliopause." Voyager I and II passed through this.

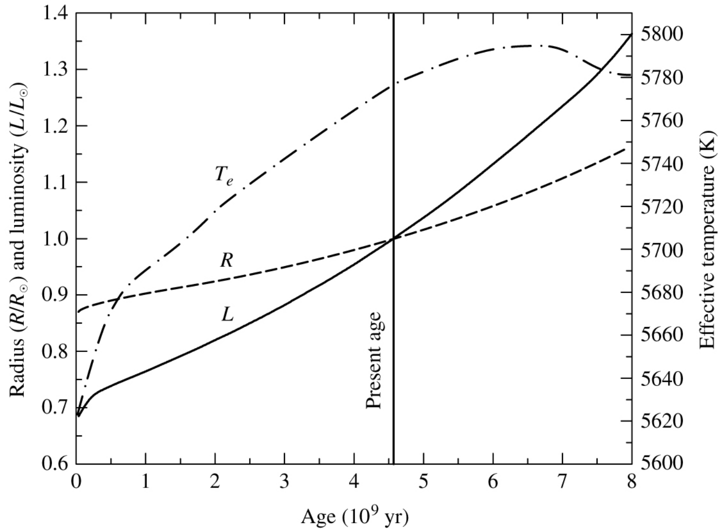

Figure 3: Solar evolution.

Time-variability of the Sun

The Sun's energy output is relatively stable over its lfietime, although not completely so. Over the course of its lifetime, the sun's luminosity, radius, and temperature will increase. The luminosity will roughly double, the radius will increase by $\sim 25\%$, and the temperature increase is small.

Magnetic fields, and their effects

The topic doesn't really fit in anywhere, but the Sun rotates "differentially," which means that different latitude rotate at different rates. The poles rotates slower than the equator. Furthermore, the rotation rate is different at different radii, with differential rotation only happening interior to about 0.70 $R_\odot$ (which just so happens to be approximately the boundary between the radiative and convective zones). This region is known as the "tacholine", and there is strong radial shear. We'll return to this point.

The long-term variability of the Sun is not the focus of our lecture today, however. There is more interesting physics at work in the outer layers of the Sun's atmosphere. Nearly all these processes have to do with the Sun's magnetic field.

Sunspots

Sunspots are regions of the photosphere with *relatively* lower temperatures compared to their surroundings. The darkest portion of a sunspot, its "umbra," has a temperature of about 3900 K. Taken together sunspots decrease the

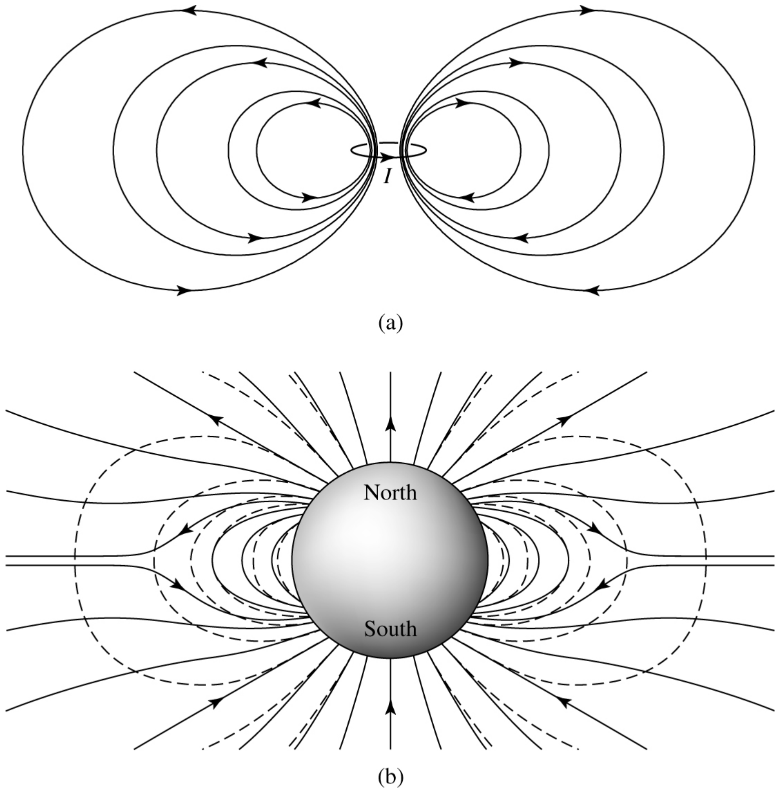

Figure 4: The Solar magnetic field is approximately bipolar.

Solar luminosity by ∼ 0.1%. Individual sunspots live for a few datys to a few months. They have diameters from 16 to 160,000 km.

Sunspots are cyclical, with maxima occurring every 11 years. We are right now (2023) near a maximum. Throughout this cycle, sunspots are found predominantly at intermediate latitudes, progressing toward the equator; individual sunspots do not migrate appreciably.

Sunspots originate at locations where the Sun’s magnetic field passes through its surface. This magnetic field inhibits convection, leading to cooler gas at the surface. This also explains why sunspots appear in pairs, with one pair having magnetic north and the other south. Throughout the 11-year cycle, sunspots will have the same parity as their hemisphere, magnetic north in the northern hemisphere and magnetic source in the southerm hemisphere.

But if the sunspots are variable, this implies that the Solar magnetic field is also variable – it is! The Sun rotates differentially, which means that if the magnetic field is tied to the Solar gas, it must experience shear as the Sun rotates. This twists the magnetic field lines, leading to the sunspot variation. Thus, the entire Sun has a 22-year cycle, with its magnetic north and south poles flipping every 11 years.

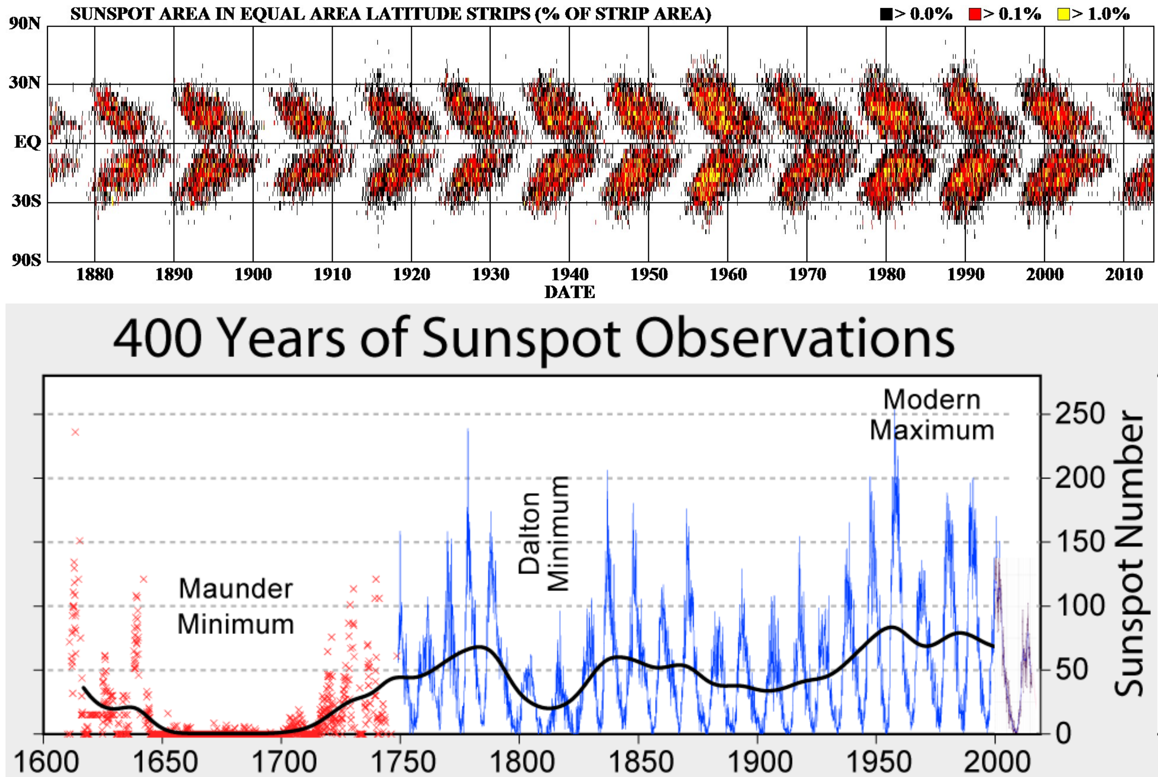

Figure 5: Sunspot number count and butterfly diagram.

This flipping is called the “magnetic dynamo” model. While it can reproduce many of the features of the Sun, it has trouble with others. Furthermore, the larger time-scales (> 22 years) are not explained by this theory.

Plages, CMEs, Solar flares, etc.

The surface of the Sun is quite active, as a result of the magnetic field. Plasma will follow magnetic field lines, leading to surface features called plages. When field lines cross and reconfigure, we can get more explosive events called coronal mass ejections and Solar flares. Basically, all time variable Solar phenomina such as these are strongly influenced or even generated by the Sun’s magnetic field.

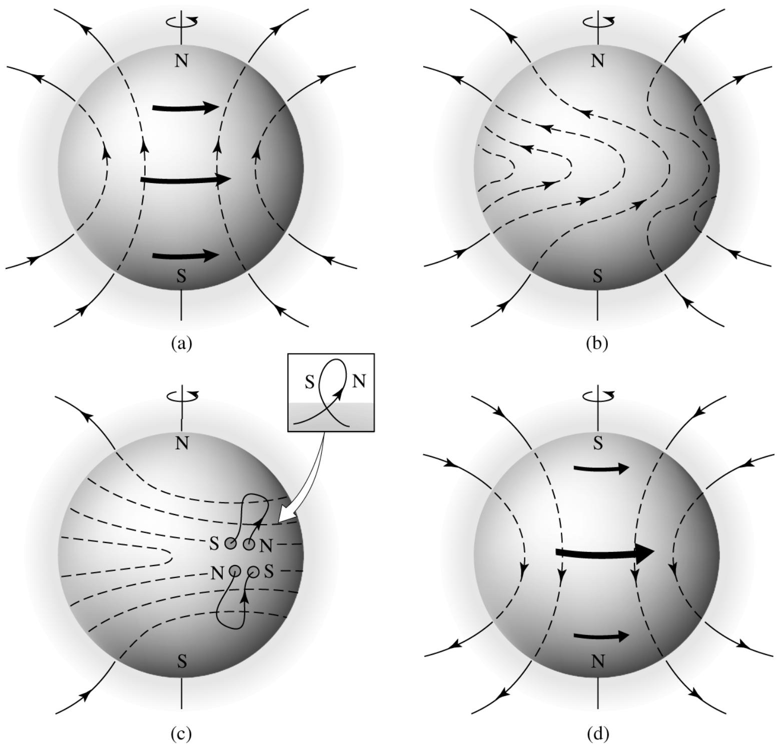

Figure 6: Magnetic dynamo.