IV. ASTRONOMY: THE SUN and the MOON
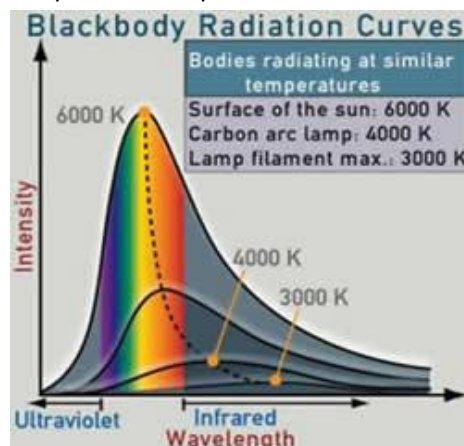
A. Stars are huge, opaque, luminous balls of gas held together by the mutual gravitational attraction of their constituent particles.
   1. There are about 400 billion stars in our Milky Way Galaxy. The Sun is typical in size, but much closer to us than any other star.
   2. The very hot, dense, ionized inner parts of a star emit continuous radiation (a "continuum"); many physical processes smear out the discrete emission lines that are characteristic of low-density gases.
   3. Cooler, less dense outer layers of gas absorb certain wavelengths in the manner discussed previously.
      a. The chemical composition can be determined by analysis of the absorption lines.
      b. This is how we know that stars consist of normal elements found on Earth.
   4. The outer atmosphere of a star is transparent, and the "surface"(photosphere) is simply the region beyond which the gases are opaque. This surface radiates light into space.
   5. The wavelength of the peak (brightest part of the star's spectrum, which determines the color of the star, is a measure of it's surface temperature, as explained below.
B. Ignoring absorption lines, which are generally weak, the spectrum of a star resembles that of a "black body".
   1. A black body absorbs all incident radiation; none is transmitted or reflected. It is a "perfect absorber".
   2. A black body has a certain **temperature**, which is a measure of the average speed with which constituent particles (atoms, molecules) jiggle around: the higher the temperature, the greater the average speed.
   3. The randomly moving particles, some of which are charged, emit electromagnetic radiation. This is called the **thermal radiation**.
   4. The shape of the spectrum emitted by a black body depends only on the object's temperature, not on it's chemical composition or other properties. It is a "perfect emitter".
   5. This spectral shape is called the Planck curve, in honor of the physicist Max Planck; it's derivation was a fundamental problem in quantum mechanics.

Blackbody Radiation Curves

Bodies radiating at similar temperatures
Surface of the sun: 6000 K
Carbon arc lamp: 4000 K
Lamp filament max.: 3000 K

6000 K
4000 K
3000 K

Intensity
Ultraviolet
Infrared
Wavelength

6. At all wavelengths, the spectrum (Planck curve) of a hot black body is higher (i.e. brighter) than that of a colder black body having the same surface area.
7. An important property is that the spectrum of a hot black body peaks at a shorter wavelength than the spectrum of a colder black body.
    a. Thus, if one heats an iron ball with a powerful torch, it first glows dull red, then orange, followed by white (a combination of colors, like sunlight), and eventually blue.
    b. Some quantitative examples: at temperatures of 4000K, 5000K, 6000K, and 7000K, the peak of the black body spectrum is at wavelengths of 7200Å, 5800Å, 4800Å, and 4100Å, respectively.
    c. The product of the temperature (T) and the peak wavelength (λ_{max}) is a constant: **$T\lambda_{max}= 2.9 \times 10^7$Å K**. This is known as **Wien's law**.
    d. Note that a human (which can be approximated as a black body with T = 300K) emits thermally at infrared wavelengths (approx. 10^5Å, or 10µm, according to Wien's law).
        i) Thus, we can be seen with infrared detectors even at night.
        ii) We are visible at optical wavelengths, however, only because of reflected light (e.g., sunlight, or light from indoor bulbs). This has nothing to do with our thermal emission.
8. Per unit of surface are, a hot black body emits much more energy per second than a cold black body.
    a. This is known as the **Stefan-Boltzmann** law.
    b. It can be expressed mathematically as **$E = \sigma T^4$**, where E is the energy emitted per unit area (e.g., cm^2) per second, T is the temperature, and σ is a constant (known as the Stefan-Boltzmann constant)
    c. For example, if two stars have the same surface area, but one is twice as hot as the other, the hotter star emits 2^4 = 16 times as much energy (per second) as the colder star.
    d. However, in the above example, if the hotter star's radius R is ¼ that of the colder star, then it's surface is $(1/4)^2$ = 1/16 as large as that of the colder star, because the surface area of a sphere is given by $4\pi R^2$. This exactly balances the greater emission per unit are, making the two stars equally luminous (i.e., equal power, or total energy emitted per second).
    e. In general, the **luminosity** (L) of a black body is given by it's surface area (S multiplied by the energy emitted per unit area per second (E): **L = SE**
        i) For a sphere of radius R and temperature T, we have L = $4\pi R^2 \sigma T^4$.
        ii) Thus, if we know the luminosity and surface temperature of a star, we can derive it's radius R.
C. The Sun, being only 1 AU (150 million km) away, can be studied in considerable detail.
    1. It's visible surface (photosphere) subtends about half a degree in the sky.
        a. At the sun's distance, this corresponds to a diameter of 1.4×10^6 km.
        b. Given that the Earth's diameter is about 1.3×10^4 km, about 110 Earths could fit across the diameter of the Sun.
        c. The Sun's volume is therefore over a million (110^3) times that of the Earth.

        d. However, as we will derive later, the Sun's mass is only about 330,000 Earth masses, so it's average density is lower than that of the Earth.

2. The sun's spectrum peaks at about 5000 Å.

        a. According to Wien's law, the Sun's surface temperature is therefore about 5800 K.

        b. 5000 Å corresponds to green light. However, the overall blackbody spectrum of the Sun is perceived by the human eye as white light, not yellow as is usually taught.

                i) This can be very clearly seen during a total solar eclipse: seconds before totality, only a tiny part of the Sun's photosphere is uncovered, and it can be viewed safely with the unaided eye. It has a dazzling white color, if the Sun is high in the sky.

                ii) The Sun appears yellow, or even orange or red, when it is approaching the horizon and generally safer to examine; gas and dust in the thicker atmosphere preferentially scatter and absorb the blue-green wavelengths.

3. It is probably no accident that human eyes are most sensitive to electromagnetic radiation near the peak of the Sun's spectrum, and to which Earth's atmosphere is transparent.

D. Sunspots are dark blotches on the photospheres.

1. Some of them are visible to the unaided eye (through a filter), and hence are much larger than the Earth. the approximated rotation period of the Sun (1 month) can be measured by monitoring large, long-live sunspots.

2. Spectra show that sunspots are about 2000K cooler than the surrounding photosphere.

        a. According to the Stefan-Boltzmann law they are less luminous per unit area, and hence appear darker.

        b. However, if the gas in a sunspot were plucked from the Sun and viewed alone, it would glow brightly; many stars have surface temperatures of 3800K.

3. Sunspots are regions of strong, tangled magnetic fields.

        a. These fields inhibit the rise of hot, ionized gas from below the photosphere, so the regions cool down.

        b. Away from sunspots, the Sun's magnetic field is reasonably simple. Globally, it resembles that of a bar magnet.


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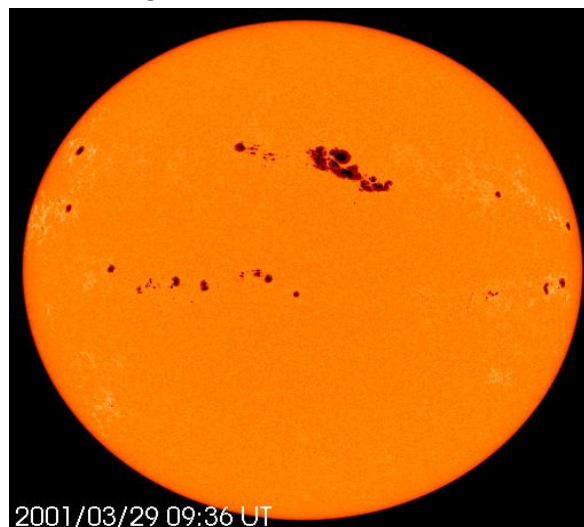
4. When observed in excellent viewing conditions, the Sun's photosphere appear somewhat grainy.
   a. The bright granules are hot, rising, convective cells (pockets of gas) that bring energy from the interior to the surface.
   b. This is analogous to blobs of water carrying energy from the bottom of a heated pot to the eggs floating on top.
   c. After releasing it's heat, the gas is denser, and it sinks back down. This cooler gas appears darker than it's surroundings because of the Stefan-Boltzmann law: less light is emitted per unit area.
E. Besides the photosphere, the main external components of the Sun are as follows:
   1. The Chromosphere is a thin layer (about 10^4km thick) immediately above the photoshere.
      a. It's temperature is about 10^4K, hotter than the photosphere.
      b. The heating is probably mechanical: rising pockets of gas deposit their energy of motion (kinetic energy) in the chromosphere.
      c. It glows with a red color because the electrons in many hydrogen atoms are jumping from the third to the second energy level.
   d. The chromosphere is most easily seen during a total solar eclipse.

   2. The corona is a large, low-density envelope of very hot gas.
      a. It's temperature can reach 2 million degrees.
         i) It emits X-rays.
         ii) Spectra show that many of the atoms are highly ionized, as would be the case if they were experiencing high-speed collisions.
         iii) The heating mechanism is probably a combination of mechanical heating (as with the chromosphere) and release of energy stored in magnetic fields.
         iv) Although the temperature is high, the total heat content is low because the gas is so tenuous.
      b. It has complex structure due to charged particles traveling along magnetic fields.
      c. Essentially the only time one can see it is during a total solar eclipse.

3. The solar wind is a stream of charged particles (mostly electrons and protons) streaming from the Sun at speeds of up to 500 km/s. It interacts with planetary magnetic fields and with comets.
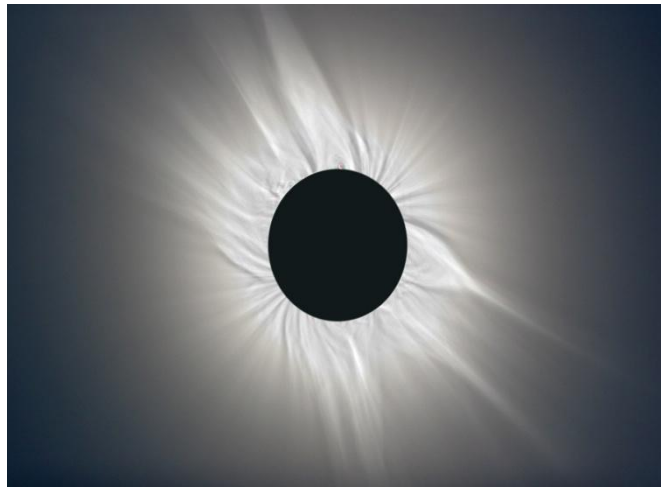

4. A solar flare is a violent release of energy from a localized region of the Sun's surface.
   a. Temperatures can reach 5 million degrees.
   b. Large numbers of emitted charged particles interact with Earth's atmosphere and produce disturbances in radio communications.
5. A prominence is a more gentle eruption from the Sun's surface.
   a. Gas tends to follow magnetic field lines, producing beautiful loops.
   b. The gas temperature is about 10^4 K.
   c. As in the chromosphere, the loops glow with a red color.


◉ ←— Approx. size of Earth
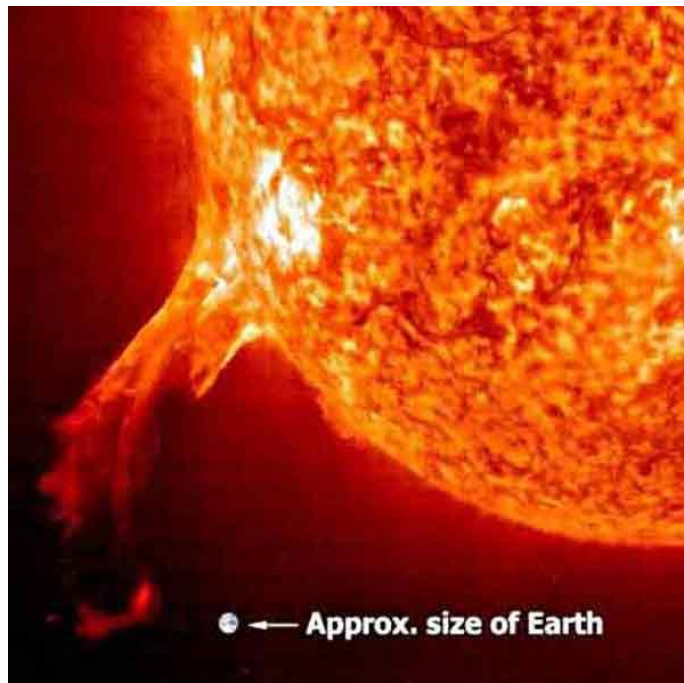
F. The Sun goes through an activity cycle.
   1. The number of visible sunspots varies over a period of about 11 years.

a. There should be a maximum around the year 2012.

b. During solar maximum there can be over 100 spots at any given time, while at solar minimum the number drops to only a few.

c. Solar maximum is also characterized by a large number of eqhemeral phenomena such as prominences and flares.

d. Since the magnetic polarity of sunspots changes every 11 years (i.e., north-south pairs, followed by south-north), the period of the solar activity cycle can be thought of as 22 years instead of 11 years.

2. The solar activity cycle is the manifestation of a complex dynamo; details are not yet understood.

a. The Sun's rotation period is shorter at the equator (approx. 25 days) than near the poles (approx.. 33 days), so it doesn't behave like a solid body.

b. This "differential rotation" stretches and tangles magnetic field lines, giving rise to sunspots.

G. Solar eclipses occur when the Moon is exactly, between the Earth and the Sun.

1. The Moon casts a shadow in space, but this shadow can intersect earth only if the alignment is very good.

a. Because of the 5° tilt between the Moon's orbital plane around the Earth, and the Earth's orbital plane around the Sun, the new moon's shadow generally misses the Earth

b. These two inclined planes intersect in a line; the Sun, Moon, and Earth can therefore be roughly collinear during two intervals per year, separated by six months.

c. These "eclipse seasons" do not always yield an eclipse, however, since the Moon must be in the right part of it's orbit when the potential for alignment exists.
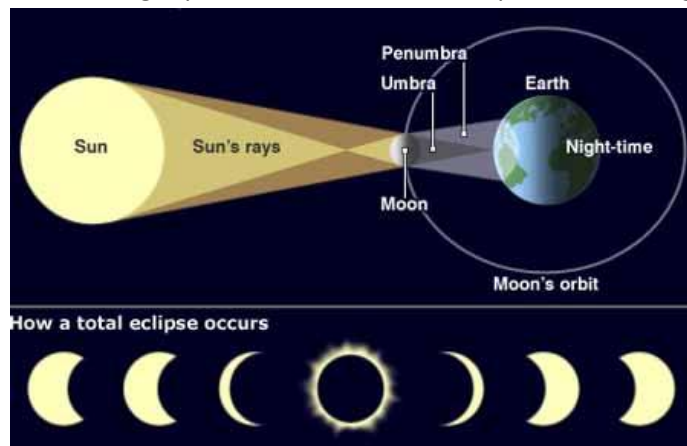
2. Although the Sun's physical diameter is about 390 times the Moon's diameter, the Sun is also about 390 times farther from Earth than the Moon is.

a. Thus, the Sun and the Moon subtend (cover) roughly the same angle in the sky: ½°.

b. This cosmic coincidence allows us to see total solar eclipses: the Moon's shadow reaches the Earth.

c. The solar chromosphere and photosphere are visible only during complete (or very nearly complete) totality because they are much fainter than the sunlit sky.

d. As the Moon orbits the Earth, the location at which totality is seen sweeps across the Earth from west to east along a narrow path (typically 100 to 200 km wide).

e. At locations adjacent to this path, a partially eclipsed Sun is observed, part of the Moon blocks part of the Sun's photosphere. The fraction covered decreases with increasing distance from the path of totality.

f. Although the partial phases span 2-3 hours, totality at a given location lasts only a few minutes; very rarely it lasts over 5 minutes, but never in excess of 7.3 minutes.

    i)   The duration depends primarily on the relative angular sizes of the Sun and Moon. These vary form one eclipse to another because both the Earth's orbit and the Moon's orbit are elliptical.

    ii)   A long eclipse occurs when the Moon is closer to Earth than average, because it looks large relative to the Sun. It also helps if the Sun is farther from Earth than average, so that it looks smaller.

g. A total solar eclipse occurs somewhere on Earth every 1.5 years, on average.

h. At a given location, totality is seen roughly every 360 years, on average. Thus, one must travel to have a good chance of experiencing totality. The next total solar eclipse visible from parts of North America will occur on August 21st, 2017.

3. During a total solar eclipse, the following phenomena are seen:

a. First contact: the moment the Moon begins to cover the Sun's photosphere.

b. Partial phases: progressively more of the Sun is covered. The sky doesn't darken appreciably until well over half of the photosphere is blocked.

c. "Shadow bands": when only a thin sliver of the photosphere is uncovered, low-contrast bands of light are sometimes seen shimmering across the ground. They are produced by inhomogeneities in Earth's atmosphere. A useful analogy is the bands seen at the bottom of a swimming pool, which are produced by surface ripples.

d. The shadow of the Moon looms in the west, approaching quickly.

e. "Baily's beads": only a small part of the photosphere is uncovered, and small bits can shine through valleys at the Moon's edge, creating a few short-lived beads of sunlight. The sky darkens rapidly, and the air temperature drops.
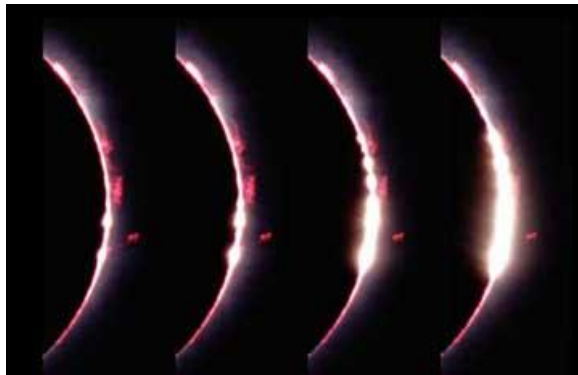
f. "Diamond ring": can be considered the last Baily's bead. Only a tiny fraction of the photosphere is uncovered. The chromosphere and inner corona become visible, and form a ring around the dark Moon. The much brighter photosphere looks like a

glistening white diamond for a few seconds. Often prominences are visible as well. The final darkening of the sky is very rapid and dramatic.

g. Totality: all of the Sun's photosphere is covered. The sky is relatively dark (though somewhat brighter than on a night of full moon), and the full corona appears, usually with beautiful and complex structure. Large prominences can be seen, as well as the chromosphere near the beginning and end of totality. Bright stars and planets are visible.

h. After totality ends, the above sequence is seen in reverse; there is another diamond ring, perhaps some Baily's heads, the receding shadow of the Moon, shadow band, and the full set of partial phases.

i. The entire phenomenon of a total solar eclipse is indescribably beautiful. Most people who have seen one found it to be a very moving experience. Photographs and words simply do not convey the drama, beauty, and thrill of a total solar eclipse: it must be witnessed in person!

4. The partially eclipsed Sun must not be viewed directly; a special dark filter should be used.

a. An indirect way of viewing the partial phases is with a "pinhole camera": punch a small hole in some hole in some cardboard, and project an image of the Sun onto the ground, in the shadow of the cardboard.

b. Holes between leaves in trees can form natural pinhole cameras many crescent suns are seen on the ground.

5. Contrary to popular belief, the totally eclipsed Sun is perfectly view directly with the unaided eye, binoculars, or a telescope.
   a. However, if even a tiny part of the photosphere is uncovered, binoculars or telescopes should not be used: they collect enough light to quickly damage the retina.
   b. The diamond ring is safe to observe for a few seconds with the unaided eye, but not with binoculars or telescopes.

6. If the Moon is farther from Earth than average, and the Sun is closer than average (e.g., in January), the Moon's angular diameter is somewhat smaller than that of the photosphere.
   a. The Sun is not completely eclipsed. Instead, an annulus of the photosphere surrounds the dark Moon.
   b. Such an annular eclipse is only a special case of a partial solar eclipse, but a memorable one.

H. Measurements during solar eclipses provided the first observational confirmation of a prediction made by Albert Einstein with his general theory of relativity.
   1. This theory, published in 1916, postulates that mass warps space and time, producing the phenomenon we call gravity.
      a. Particles follow their natural paths through curved space-time; indeed, this is why planets orbit the Sun.
      b. The theory predicts that light should also follow a curved path.

2. Light passing close to the edge of the Sun should bend, but only a little because the Sun's mass is small. The deflection decreases with increasing angular distance from the Sun.
   a. This effect seems impossible to measure, since stars are invisible when the Sun is up.
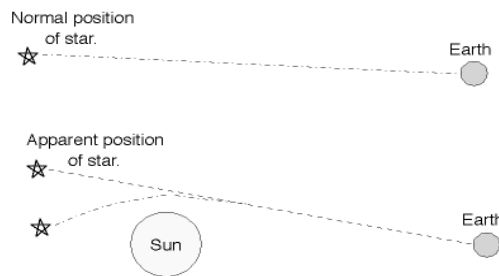
   b. During a total solar eclipse, however, bright stars are visible, and their apparent positions can be measured.
   c. These apparent positions can be compared with the "true" positions, as measured in a photograph obtained during a time of year when those stars up at night.
   d. The observations are difficult; only stars adjacent to the edge of the Sun undergo the full deflection, but bright stars are rare, and the inner corona overwhelms faint stars.
   e. Success was first achieved by Arthur Eddington during a total solar eclipse in 1919; the shift of stars at the edge of the Sun was 1.7 seconds of arc, as predicted by the stars.
   f. New of the confirmation made Einstein an instant celebrity; before this he was still obscure, at least to the lay public.
   g. Measurements during subsequent eclipses were used to confirm the predicted bending.
I. Lunar eclipses occur when the Earth is exactly between the Sun and the Moon.
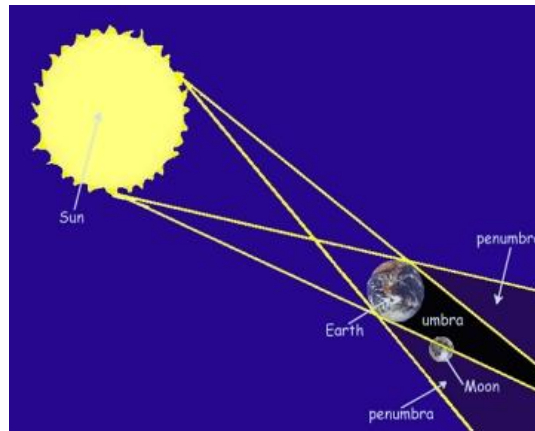
   1. Earth casts a shadow in space, but this shadow intersects the Moon only if the alignment is very good. This can happen during two "eclipse seasons" per year, as for solar eclipses.
      a. When part (or all) of the Moon is immersed in the Earth's shadow we have a partial (or total) lunar eclipse.
      b. From the Moon's perspective, the Earth blocks all of the Sun's photosphere during a total lunar eclipse.

   c.   Since the earth's shadow is nearly three times the size of the Moon at the Moon's distance from Earth, a total lunar eclipse lasts about an hour.

   d.   Note that a total lunar eclipse is visible from the entire dark hemisphere of Earth. From any given location of Earth, total lunar eclipses are therefore much more common than total solar eclipses, even though they occur with about the same intrinsic frequency.

2. The Moon is not completely dark during a total lunar eclipse.

   a.   The Earth's atmosphere refracts (bends) some of the sunlight toward the Moon

   b.   Blue and green photons are preferentially absorbed and scattered, leaving predominantly orange and red light to pass through. This is the same effect that we see during sunset.

   c.   Thus, the fully eclipsed Moon generally looks reddish-orange.

   d.   If the Moon goes through the central part of the Earth's shadow, or if there is a large amount of dust or smoke in the atmosphere, the eclipse looks darker than usual.

Total Lunar Eclipse
December 20 - 21, 2010

North

West

East

South

UMBRA

PENUMBRA

Moon's path
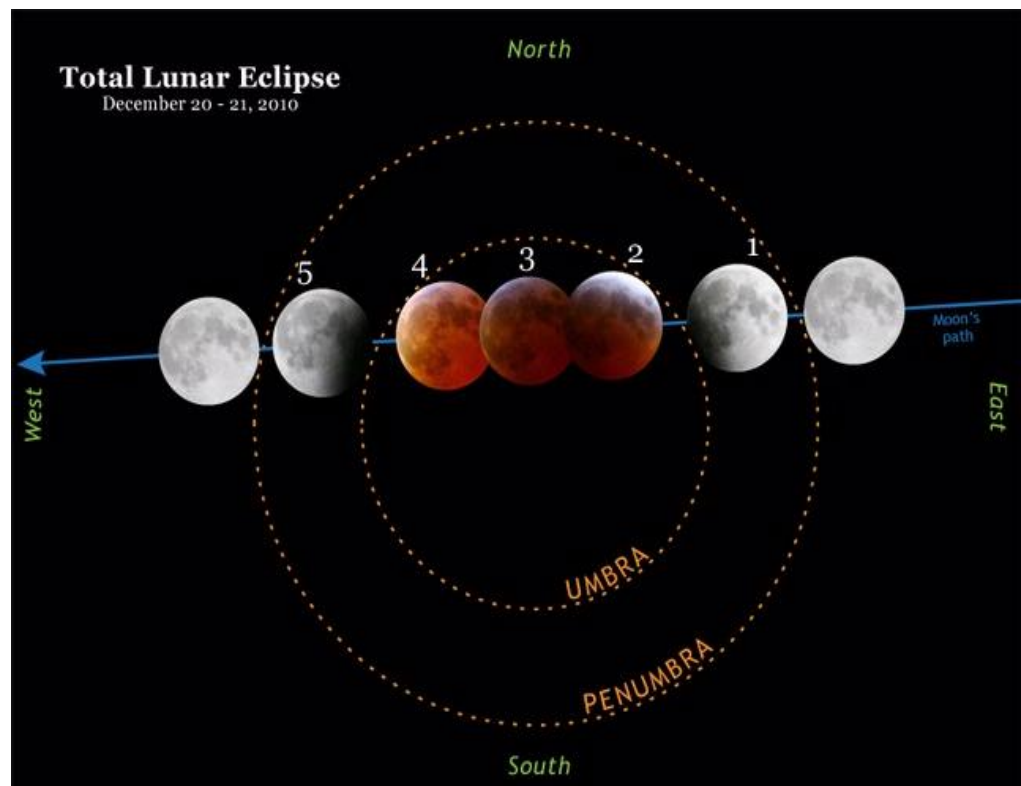
J. Questions:

1. Describe briefly what the Sun is, and how it is related to stars.

2. Define what is meant by the surface (photosphere) of a star.

3. Explain what physicists mean by the term "black body".

4. Discuss qualitatively the spectra of black bodies with different temperatures but the same surface area.

5. Calculate the wavelength at which the spectrum of a black body peaks, given it's temperature as 10,000 K.

6. Explain why a sunspot looks dark.

7. Summarize the different parts of the Sun above the photosphere, including ephemeral phenomena.

8. In what way are humans not a good approximation to black bodies?

9. Why do astronomers and physicists use the concept of a black body, when theoretically such objects are almost nonexistent?

10. Try to put yourself in the position of the ancients. What would you think if someone suggested that the stars are simply very distant suns?

11. Consider a sunspot viewed through a dark filter or reasonably thick fog. If the sunspot is barely visible to the unaided eye (which has a resolution of about 1 or 2 arc minutes), and the Sun's diameter is 30 arc minutes. Physically how large is the sunspot relative to the Earth?

12. State the reason that lunar and solar eclipses don't occur each month.

13. Summarize what phenomena can be seen during the course of a total solar eclipse.

14. Explain how measurements during a total solar eclipse helped confirm Einstein's general theory of relativity.

15. Compare and contrast total solar and lunar eclipse.

16. Discuss why a fully eclipsed Moon is not completely dark, and appears orange/red.

17. During a total lunar eclipse, what would someone on the Moon see when looking toward the Sun?

18. How is it possible that a given solar eclipse can sometimes be both total and annular? (that is, along part of the central eclipse path the photosphere is entirely hidden, but along other parts a thin annulus is visible).