Astronomy 100Lg Nick Warner, Spring 2004

NOTES ON STARS

1. FROM OBSERVATION TO THEORY

Fundamentally important:

1) Understand how distances to stars are measured.
2) The parsec and the light year as important units of distance (for once, it might be in order to learn their values).
3) The basic notion of proper motion (and the typical amount of motion), as well as that of stellar size.
4) The connection between apparent brightness, distance and luminosity: the inverse square law. The idea of apparent magnitude. The definition of absolute magnitude.

Color of stars and the relation to temperature. Learn the principal spectral types (the famous mnemonic). All this allows drawing the Hertzsprung-Russel (HR) diagram. Allow yourself to be amazed that observed stars do not form a random scatter diagram, but a very characteristic structure. Learn the principal features of the HR diagram (main sequence, red giants, white dwarfs). How the HR diagram encodes the radius of a star. Know the basic idea of spectral type, and how it reflects the temperature of the star's photosphere. Understand the reasons why absorption line strength depends upon temperature.

How does spectral type and the star's apparent color give information about the amount of interstellar absorption of light ("garbage")? Note how spectroscopy helps to resolve ambiguities about where a star of given color is in the HR diagram (Luminosity Class). This is crucial in order to use our knowledge of stars to determine stellar distances.

Finally, the mass of stars: Learn how it is determined. Note the mass-luminosity relation of main-sequence stars. Such strikingly simple relations do cry out for a simple explanation. Lifetimes of stars and how they depend upon mass.

Understand that, for a theorist, the mass determines essentially every bulk property of a star, and almost very aspect of a its evolution.

2. AN OVERVIEW OF THE THEORY OF STELLAR EVOLUTION

- Imagine an interstellar cloud, so big that it creates a gravitational force that prevents its hydrogen and helium (and some other...) atoms from flying away

- If gravity is big enough (and if it isn't, just imagine a yet bigger cloud, there must be a critical mass that can do it), the cloud begins to contract.

- Simple laws of gas physics (Kelvin-Helmholtz) heat the cloud up.

- At the surface, the cloud radiates away energy, like any black body. To compensate for the energy lost, the cloud must fall more into itself (it loses gravitational energy, turning it into heat).

- But by contracting more, it becomes hotter and hotter. The Stefan-Boltzmann law says that more and more energy will be radiated away (recall: for instance, 16 times more radiation energy at the double temperature.). This is a runaway process: the contraction becomes faster and faster.

Note for aficionados: When a substance loses energy and becomes thereby hotter, something very peculiar is going on. The physicist calls this "negative specific heat". In gravitating systems that follow Newton's laws this is always so. A famous example is the "satellite paradox", which consists in the fact that a satellite becomes faster and faster the more it is subject to the gentle braking by the Earth's atmosphere. Of course it is only a seeming paradox: if you tally kinetic energy plus potential energy of the satellite plus the heat taken by the atmosphere, then energy conservation plays beautifully. That's how it is in a contracting star. The analogy with the satellite example is: "kinetic energy of the satellite $\equiv$ kinetic energy of the gas particles in the star"; "potential energy of the satellite $\equiv$ potential energy of all gas particles in the star"; "heat absorbed by Earth atmosphere $\equiv$ radiation sent out by the star".

• Calculations (using the total gravitational energy) show that it takes some 10 million years for a cloud to become so small and hot as the Sun. *Please digest what you just read. By mere contraction, with no nuclear energy yet, you have explained the existence of a hot shining sphere such as the Sun, and thus all stars. Kelvin was mighty proud of this discovery.* **It does explain why the Sun and the stars shine - at least for a time.** *Only if you believe that the Earth and therefore the Sun must be much older than 20 million years you have a problem. Kelvin was so convinced of his idea that he thought the problem must be with those who think the Earth is older than 20 million years.* However, the evidence from geology, biology and paleontology showed that that the real age of the Earth and Sun must be *at least* a few hundred million years, and by the end of the 19th century this evidence was simply too compelling to ignore. Thus the physicists had a problem: What energy source could give the Sun an immense lifetime measured in billions of years?

• The solution was found in 20th-century physics, with nuclear energy. It was shown that a cloud that has reached the size of the Sun has attained a central temperature of a few million degrees. **At this temperature, hydrogen naturally begins to ignite and "burn" into helium by nuclear fusion**. The enormous energy thus released has two consequences: (i) it can make good for the energy loss at the surface (therefore the contraction stops, (ii) it extends the life of the Sun in essentially its present form until the energy supply is exhausted, which is after 10 billion years.

• Now, billions of years might be long, but that's nothing compared to eternity. Inevitably, the hydrogen fuel in the core will be completely exhausted.

• If the star has a mass less than about 0.4 solar masses ($M_\odot$) then it is believed that the whole star (and not just the core) will become depleted in hydrogen all at once. The star will then contract, becoming hotter, but no further fusion will occur. So it becomes a rather weak "white dwarf," consisting of compressed helium. It then slowly cools to become a black dwarf. At present, this scenario is purely theoretical since such small stars take about 20 billion years to reach this stage, and the current age of the universe is about 14 billion years. The term "white dwarf" is a slight misnomer here, we usually reserve the term for the kind of star described below.

• For stars bigger than about 0.4 ($M_\odot$) it is only the core that becomes depleted in hydrogen. The star must contract again, because at the surface it continues to be hot and radiating away energy. Both the core and the outer part contract. Therefore, the envelope of the star is heating up. Note that prior to this it used to be too cold in the envelope (*i.e.* outside the core) for hydrogen to burn into helium, and so there is still plenty of unburnt hydrogen fuel outside the core. But now the renewed contraction ignites this shell hydrogen: so-called *shell burning* sets in. The shell burning blows up the outer envelope of the star by a tremendous amount: From a small star like the Sun to a giant, whose diameter can become as big as the *orbit* of the Earth. That is, the solar surface will lap at the Earth.

• Although the shell-burning giant easily attains a luminosity of say 10,000 solar luminosities, its temperature becomes cooler, that is, its color becomes *red*, because the surface is now so gigantic that even a low temperature suffices to radiate away the high luminosity (for those who like formulae recall that one has: $L = 4\pi\sigma R^2 T^4$). *For this reason, the star is called a red giant* (Famous example: Betelgeuse in the constellation of Orion).

• While the shell burning blows up the star (in the H-R diagram: to the right-top corner), the core still contract until it gets so hot that *helium* is ignited (for this you need some 100 million degrees). As a result of this "helium core burning", the first heavy element, carbon, is synthesized - along with some oxygen. For subtle physical reasons, in stars between 0.4 and about 2.5 solar masses, this new phenomenon happens first in a giant explosion (helium flash), then in a controlled way. For stars of more than about 2.5 solar masses, the onset of helium core burning is a more controlled process. Either way, the red giant evolves on the so-called *horizontal branch.* The star once again has an energy source in its core, and so it move back towards (but not onto) the main sequence. A star like the Sun can stay on the horizontal branch for a few hundred million years (typically about 5-10% of its main-sequence lifetime), while it burns all helium in the core into carbon, thereby producing a lot of energy.

• However, and by now you know it, again once the helium is converted into carbon and some oxygen, and once the shell is burned out, there is inevitable contraction. Stars between about 0.4 and 6 solar masses attempt to start helium shell burning, but the result is that the star sheds or blows off its outer envelope of hydrogen and helium leaving its core behind as a small but intense, white-hot ember. The ejected outer envelope becomes a *planetary nebula.*

• In higher mass stars (more than about 6 solar masses) all sorts of thermonuclear reactions take place, and a fascinating scenario happens on an accelerated rhythm. We will first classify the **final states** of stars, the stellar graveyard. Mass is the key parameter, but in view of the fact that stars can shed their outer envelopes or even explode (supernovae), one has to be careful to use *only the mass of the left over (the remnant)* after the explosion.

3. THE STELLAR GRAVEYARD

In the following paragraphs, the mass is that of of the remnant star, and not the original parent star.

I. Light stellar remanants (up to $1.4M_{\odot}$ ($M_{\odot}$=solar mass), thus including the Sun), shrink to a size of the planet Earth. They become *white dwarfs*. Inside, they look consist largely of carbon and oxygen nuclei floating in a sea of electrons (the core material of the original parent star). At the beginning, they are very hot due to residual heat from their past life. But since the white dwarfs have no energy source, they will eventually cool down and become invisible ("black dwarfs"...). The physical force that can withstand gravity is the pressure of electrons, piled up enormously by the so-called Pauli-exclusion principle (which forces most of the electrons to be very fast and exert a very high pressure). Note that for these light stars this force becomes active before carbon would burn into higher elements.

II. Intermediate stellar remnants (from $1.4M_{\odot}$ to $3M_{\odot}$) do not end as white dwarfs. The physical forces of the electrons are too weak to do the job in these heavier stars. So when such stars run down from the horizontal branch to the white-dwarf region, they are not stopped at the size of a white dwarf, but they shrink even further. There are again temporary reprieves while the star converts carbon into silicon and ultimately iron, but as one learns in nuclear physics, there is no drip of energy to be gained from iron. No reprieves anymore, the contraction goes to its ultimate destiny: it stops when the whole star becomes a single, giant atomic nucleus consisting of neutrons. Neutrons, under the influence of the Pauli-exclusion principle, deliver the pressure. Since atoms are to their greatest part empty, a star can indeed be squeezed down to a size of a few km diameter. (Imagine the whole stellar mass compressed to the size of a typical big city.) However, this remnant (that is, the single giant atomic nucleus) is now stable and will remain forever. It is called a *neutron star*.

III. If the mass of the stellar remnant (*i.e.* what remains of it after a supernova explosion, see below) is bigger than $3M_{\odot}$, even a neutron star is too weak to prevent the ultimate collapse into some very strange new thing. This thing is called a *black hole*, whose gravity is so strong that not even light can escape from it. More precisely, light cannot escape from within a sphere that surrounds whatever the matter has become. The radius of this sphere around the remnant is called the Schwarzschild radius (typically a few km), and the surface of this sphere is called the *event horizon*.

4. STELLAR DEATH THROES

In the cores of heavy stars everything is burnt up to the inert element iron. The iron cannot be "burnt" and so the energy source is extinguished. The core is very dense, and it and the surrounding layers undergo rapid collapse under their own gravity. The iron core runs through the white-dwarf and neutron star phases. The contraction from white-dwarf size (about that of the Earth) to neutron star size (about 20 km) happens in about one second. Temporarily, the neutron-star size core will be compressed by the inertia of the imploding motion. This is analogous to dropping a very elastic ball. For a very short time, the whole energy of the ball is elastic potential energy of the deformed ball; here the compressed core contains lots of potential energy. The collapse is brought to a sudden halt by the neutron star core, and the enormous amount of energy and hence heat liberated in the contraction. The imploding core "bounces," and this bounce is extremely violent, moving back out through the star, and a few *hours* later it emerges from the stellar surface as a *supernova explosion.* What in the case of the ball is a harmless popping up, is for the star an explosion and shockwave that can splatter up to 80% of the star into space. To understand the energetics properly, one should note that in the **single second of contraction** (from white-dwarf to neutron-star size) as much energy is produced as in the whole previous life of the star. Within a few days, this energy becomes visible at the surface of the exploding star. For a few days, such a star can outshine a whole galaxy. A supernova within our galaxy could be seen even in daylight. Notice that there is nothing wrong with energy conservation. The star started in a cloud and becomes a cloud again. However, lots of energy was radiated out which was "paid" by *(1) the remnant with lots of negative gravitational energy, and (2) the fraction (say 1%) of the original mass that was converted into energy.*

For us here on Earth, very importantly, the energy of a supernova also causes

(1) the **synthesis of elements** heavier than iron. Supernovae are the only phenomena in the universe that can create them. Essentially, that one-second explosion produces a shower of neutrons, that bombard all the nuclei contained in the layers above. Since there is a vast abundance of excess energy in the explosion, all nuclear reactions, even those that by themselves would not happen, are now driven forwards by the energy release. Among the newly created elements, the stable nuclei will stay, while the unstable will decay. Incidentally, the observed lifetime of a supernova is very strongly connected to the half life of certain isotopes (*e.g.* nickel-58; cobalt-56), which is a good observational confirmation of this rather fantastic theory.

(2) the **ejection** of a sizeable fraction of the star, including the newly synthesized elements, into deep space, where the matter can become part of a *new cloud from which a new star can be born.* Second- and later-generation stars thus contain heavy elements (needed for us on Earth, for instance.).

Whether at the end of a supernova explosion the remnant becomes a neutron star or a black hole depends on how much mass the explosion ejects. If the leftover is less than $3M_\odot$, a neutron star remains, otherwise a black hole.

5. THE MAIN RESULTS OF THE THEORY OF STELLAR EVOLUTION

- We have seen a striking relation between mass, luminosity, and color of stars. This cries out for an explanation, and indeed, the application of the ordinary laws of physics shows that any (stellar-sized) gas cloud undergoes a very similar history - the one outlined above.

- Stars are the "interface" between the Big Bang and us. There were no elements except hydrogen and helium at the beginning. Previous generations of stars were the "furnaces" that cooked together the heavier elements. And they were nice enough to spread them around during their final stages (supernovae.).

- Massive stars are born hot, blue, and luminous, and their higher luminosity even wins over the larger amount of nuclear fuel. (To understand *why* massive stars are more luminous is not so elementary...) The net result is that massive stars die young, while tiny stars, which are cool, red, and faint, grow very old. The smallest ones can easily live to be several times the present age of the universe.

- Observationally, stellar evolution is tested by looking at the population of all stars. Like with people, we can then simultaneously see young and old stars, without being forced to wait the millions and billions of years to see the things happen in a single object.

- Open star clusters are relatively young, which is revealed by the fact that their stars still lie on the main sequence. Globular clusters are very old, which is revealed by the fact that their HR diagram is filled with all possible states of stellar evolution. Since we believe we know our theory quite well, we are convinced that the oldest globular clusters must be some 10-15 billion years old. Some models of the universe claimed an age of the universe significantly lower than that (about 8-10 billion years). These models were based upon superb observational data from the Hubble Space Telescope. On the other hand, our confidence in our understanding of stellar physics is (justifiably) very high. So it seemed that there was a contradiction between two very robust branches of astrophysics. As we will see, the resolution of these apparently conflicting pieces of data came from yet more observational data and caused us to re-think our ideas about the dominant form of energy in the universe .....

This will be discussed in the next part of the course.