

Astronomy 101 - Test 3 Review

THE SUN

The Sun is a star, a hot glowing ball of gas powered by fusion. It is a fairly average star. The Sun is about halfway through its expected 10 billion year lifetime.

The basic regions of the Sun we discussed are the core, radiative zone, convective zone, photosphere and corona (others I didn't emphasize).

The core is the Sun's (and any star's) engine. The gas there is completely ionized, and it is so hot that fusion reactions can occur. In a fusion reaction, the nuclei of two atoms collide to make the nucleus of a new atom. Temperature is a measure of the random speeds of the ionized particles. You need high temperatures because you need to collide two nuclei at very high speeds for them to stick. This is because they both have a positive charge and so they repel each other. But if brought close enough together, an even stronger, attractive force called the strong nuclear force makes them stick together. But you need a high speed collision to get them close enough, hence the high temperature needed.

Fusion reactions make energy, which power all stars, and hold them up against their own gravity. This balance of gravity with the pressure from fusion is called "hydrostatic equilibrium." The main reaction going on in the Sun's core is the fusion of four protons (or hydrogen nuclei) into a helium nucleus, by a chain of reactions called the proton-proton chain. By such reactions, new elements are made. Energy is produced because the mass of the helium nucleus is slightly less than the mass of the four protons. That tiny mass difference gets converted to energy according to Einstein's famous equation $E=mc^2$. In the Sun, hydrogen fusion into helium takes about 10 billion years. Core hydrogen fusion is the main phase of any star's life and how fast it happens sets the lifetime of stars.

To be stable, a star must get rid of energy at its surface as fast as it makes it in its core. The energy produced by fusion initially gets to the surface of the star by radiation, which bounces its way off of particles, slowly inching its way out. Eventually, it reaches a cooler zone where it has trouble making any progress (because atoms and ions with bound electrons are present and absorb and re-emit photons in random directions), and then the energy is carried to the surface by convection, which is just rising pockets of hot gas and falling cooler gas. We can see this bubbling happening at the Sun's surface in photos, which show a mottled appearance.

The layer of the Sun we see is called the photosphere. Its yellow color is due to its 5800 K temperature, because its spectrum is roughly like a blackbody, where color relates to temperature. When we take a spectrum of the Sun, we see not only the blackbody spectrum but also thousands of absorption lines, each of which comes from a different atom or ion in a different state.

On the surface are sunspots, which vary in number on an 11 year cycle. They are dark, usually in pairs, about Earth-size, each lasting a couple of months. They are the way in which Solar rotation was first measured. They are darker because they are cooler than their surroundings (about 4500 K). The Solar surface radiates like a blackbody, and cooler

blackbodies are dimmer. Sunspots are places of unusually high magnetic field, where it has burst out of the surface of the Sun, creating a loop. The solar cycle has to do with the Sun's magnetic field completely reversing its direction every 11 years.

The corona is at about 1 million K but very low density. It's best seen in eclipses, and is very bright in X-rays. Its structure is always changing, probably as gas escapes from it episodically, leaving behind coronal holes. The Solar Wind is particles leaving the Sun from the corona. Prominences and flares are types of active regions on the Sun's surface.

PROPERTIES OF STARS

Useful things to know about stars are distance, luminosity, temperature, mass, size, age, lifetime, chemical composition, environment, speed. The most common distance unit is the parsec, which is a little over 3 light years. The parallax technique using Earth's orbit as a baseline can be used to measure distances of stars within a few parsecs of the Sun. We didn't talk about methods for more distant stars (except in clusters, see later). Once the distance is known, the luminosity of a star can be found from its distance and its apparent brightness. An accurate temperature can be found from the star's color, which we quantify by seeing how bright the star is when observed through two different color filters. Hotter stars are blue, cooler ones red (because they are roughly blackbodies), so hotter ones are relatively brighter seen through a blue filter than a red one, compared to cooler ones.

Spectra can tell you a lot about a star (from the pattern of absorption lines), but the main thing that governs how a spectrum looks is the surface temperature. The spectral classes OBAFGKM are a sequence of surface temperature, hotter to cooler. The Sun is a G star.

Stellar sizes are mostly measured from stars whose luminosity and surface temperatures are known: for blackbodies, luminosity depends on temperature to the fourth power times surface area. So you use this to get the surface area, which then tells you the radius. They range from one-hundredth to about 1000 times the Sun's radius.

Masses are determined from binary stars, whose orbital properties (period, their separation) depend on their masses. They're also determined from the theory of stellar structure, which has led to predictions of how a star's spectrum and color depends on its mass.

The Hertzsprung-Russell (HR) diagram is a plot of luminosity vs. surface temperature for stars and is a powerful diagnostic. Most stars lie along the Main Sequence, running from high luminosities and temperatures to low. It is also a sequence of mass and radius, with the most massive and largest having the high luminosity and temperature (O stars). This is where a star sits on this diagram for most of its life, as the lumin. and temp. don't change. The lower the mass of a star, the more commonly it is found. High-mass stars are rare. For Main Sequence stars, the radius depends on the mass (so twice the mass means twice the radius), but the luminosity depends on the cube of the mass (so twice the mass means eight times the luminosity). Some stars are found in the upper right part of the diagram, called Red Giants, Horizontal Branch stars and Red Supergiants (also known as Asymptotic Giant Branch stars). These are all old-age stars, which are in the last 10% or so of their life. In the lower left part are white dwarfs. Star radius also increases from bottom left to top right in this diagram.

We observe two kinds of star clusters: "open clusters" and "globular clusters". The

Pleiades are an example of the former. There are 10's to 100's of stars, rather loosely associated with each other. Over time, they tend to disperse, so the ones we see are the younger ones, say 10's to 100's of millions of years old. The Orion Nebula and other emission nebulae have young clusters within them.

The globular clusters are very tightly packed assemblages of stars that are 12-14 billion years old. They were pretty much the first stars ever to form in the Milky Way. Each contains typically a million stars, in a size of about 50 pc across.

INTERSTELLAR GAS AND STAR FORMATION

There is gas between the stars, called the Interstellar Medium (ISM) with a wide range of densities and temperatures (10 K up to millions of K), but all much less dense than stars, typically 10^{24} times less dense. The gas is crucial because stars form out of such gas clouds when they collapse, and stars return some gas when they end their lives as planetary nebulae or supernovae. There is also dust mixed in with the gas. Although it's only about 2% of the mass of the gas, it is noticeable because it blocks starlight very well. What starlight does get through a dusty region is "reddened", so stars look redder than they actually are when viewed through the dust.

One type of ISM structure is called an Emission Nebula or an HII Region. These are glowing clouds of gas that are lit up by stars that have just formed, particularly the short-lived massive stars. Most of their light comes from emission lines, not blackbody radiation. Their red color is because a single red emission line of hydrogen accounts for most of their light. They are typically 1-20 pc in size. Examples include the famous Orion Nebula and the Eagle Nebula, whose central parts were beautifully imaged by the Hubble Space Telescope. Although important as signposts of star formation, they do not account for much of the interstellar mass.

A second important type of interstellar gas is the widespread atomic (or HI) gas. The H atoms give off radiation at a wavelength of 21 cm, in the radio range, which is well studied with the Very Large Array. The atomic gas accounts for about half the mass of all interstellar gas.

Molecular gas clouds are the coldest, densest kind of clouds and are the ones within which stars form by parts of the cloud collapsing. They are observed through the emission lines resulting from rotational transitions of the molecules. H_2 is the most common but is very hard to observe, it turns out, so other "trace" molecules like CO are observed instead. These are observed with specialized radio telescopes. They also account for about half the interstellar mass.

There is also million-degree gas that shines in X-rays. Also cosmic rays: nuclei and electrons traveling near the speed of light, probably accelerated in supernova explosions. There are also magnetic fields, typically a million times weaker than Earth's.

Most stars form as members of a cluster in clouds of molecular gas. Parts or all of a molecular gas cloud may be unstable to collapsing under its own gravity (the pressure of the gas is not enough to prevent collapse). As a cloud or part of one collapses, it is expected to fragment many times, so that a large number of individually collapsing fragments results. Each is destined to form a star or perhaps a binary star system. As they collapse, they

heat up, as the energy of collapse is converted into random motions (the speed of which is measured by temperature) through collisions of molecules. They also start to flatten out because they are rotating (something we observe through the Doppler shift). At the center of the disk is the growing protostar. If one can measure the temperature and luminosity of the protostar, one can place it on the H-R diagram and compare it with theoretical predictions of the path it takes as it contracts. These are called Hayashi tracks. The protostar basically moves down and to the left in the diagram, but different masses have different tracks, with higher mass stars also forming faster. Eventually the protostar's core gets hot enough for fusion to begin, and the immense resulting energy and pressure halts the collapse, and the star is stable.

Brown dwarfs are the lowest mass stars that can form. They have too little mass for fusion to begin, so they are "failed stars". They are hard to detect because they are so faint, but after they were predicted, many have been discovered since the first in 1994.

STELLAR EVOLUTION

Stars live from millions of years (for the most massive, O stars, say 50 times the Sun's mass) to trillions of years (for the least massive, M stars, say one-tenth the Sun's mass).

The post Main Sequence evolution of stars less than about 8 solar masses is as follows. When hydrogen is exhausted in the core, it shrinks because it's not yet hot enough to fuse helium. A shell around the core shrinks too, becoming hot enough to fuse hydrogen vigorously. The star expands and grows more luminous, becoming a Red Giant, for about 1 billion years (times given are for a 1 solar mass star). Diameter about 1 AU. Eventually, the core gets hot enough to fuse helium into carbon, which first happens in a flash (in the core, no change seen at surface). It is now a Horizontal Branch star, with core helium fusion and a shell of hydrogen fusion around it. The star shrinks somewhat. This lasts about 100 million years. Eventually, the helium is exhausted, and the core is not hot enough to fuse carbon into heavier elements, so it shrinks. The rest of the star shrinks around the core, and a shell around the core get hot enough for helium to fuse into carbon. Outside that is a shell of hydrogen fusion into helium. The star is now an Asymptotic Giant Branch star or a Red Supergiant. The energetic shell fusion causes the star to expand again and become very luminous. The helium fusion becomes unstable, increasing and decreasing, causing the whole star to repeatedly expand and contract. Eventually, the envelope of the star is ejected into space altogether, eventually becoming visible as a Planetary Nebula. The left over carbon core of the star is called a White Dwarf. It never gets hot enough for fusion, and the light we see from it is just a result of it cooling down, over billions of years. It has about half the mass of the Sun, but is only Earth-sized, so the density is high, about a million grams per cubic centimeter!

Note the positions of these stages on the HR diagram.

Stars with masses more than roughly eight times the Sun's have a different evolution. They do get hot enough for carbon fusion, and many other elements. the core-and-shell structure continues for these stars through many more phases, leading to an onion-skin like structure, with various shells of fusion, with each more interior shell fusing a heavier element than the previous one. At the center is an iron core at about 10 billion K temperature. What

happens next is catastrophic (see below).

Remember the following general concepts about stellar evolution: 1) temperature increases with depth in a star. 2) the larger the atomic nucleus, the higher its positive charge, the higher the repulsive force when colliding with another nucleus, and thus the higher the energy of a collision needed for the two nuclei to stick, and thus the higher temperature needed for fusion (temperature measures the energy in random motions). 3) Fusion supplies energy and pressure to support the core and the star. If no fusion is occurring in the core because it isn't hot enough, the core shrinks. When something shrinks under its own gravity, the energy of the inward motion goes into causing the temperature to rise. Eventually it may get hot enough for fusion to start again. 4) When a core shrinks, the surrounding material shrinks (and heats up) too because the core is not supporting its weight. A shell around the core may get hot enough for fusion. So, for example, while a helium core is shrinking and not yet hot enough for helium fusion, a shell of hydrogen around it does get hot enough for hydrogen fusion. 5) Shell fusion tends to be very vigorous, causing the surrounding envelope to expand greatly and the luminosity to increase dramatically.

Clusters are excellent testbeds of stellar evolution theory as discussed above because all the stars in a cluster formed at the same time, they're all at the same distance, and they all have about the same mix of elements. It is pretty easy to make an HR diagram for an entire cluster. The pattern of stars in the diagram is strongly related to the cluster's age, and so it is easy to get the age of a cluster

The distance to a globular cluster is also easy to get by observing how bright the Horizontal Branch stars appear to be. Our theory says they are all about 100 times the Sun's brightness, so knowing this and measuring their apparent brightness gives you the distance.

STELLAR EXPLOSIONS

A nova (I asked you to read about these) is an explosion due to fusion on the surface of a white dwarf in a binary system with a small separation of the stars. If the other star is a main sequence (or giant or supergiant) star, the tidal force can stretch its envelope so much that matter spills onto the white dwarf. Due to its strong gravity, this matter gets severely condensed and heated. Eventually, enough can pile up to start a burst of hydrogen fusion. The white dwarf brightens tremendously, and some of the gas is ejected from the white dwarf - the ejected gas may be observed as a small nebula. If this whole process repeats, it's called a "recurrent nova".

Once they have an iron core, massive stars soon end their lives in an explosion. Any fusion of iron to a heavier element requires energy, instead of producing energy, so fusion of iron cannot make energy to make pressure to support the core. So it collapses catastrophically. The high temperature means the photons are energetic enough to hit the iron nuclei and break them back apart into protons and neutrons. The protons then react with the electrons to make more neutrons, so the collapse results in a big ball of neutrons. They get compressed until essentially touching, at which point the core rebounds like a rubber ball, causing the rest of the star to explode at thousands of km/sec. This is a Core Collapse or Type II Supernova. They happen in the Milky Way every 30 years or so. They are

bright enough to compete with the rest of the light from their parent galaxy, for a few days. The Crab Nebula is a famous example of a “Supernova remnant”: the debris from a star observed to explode in 1054. An important supernova was observed to explode in 1987 in the Large Magellanic Cloud, a companion galaxy to our own. It is the best studied supernova ever, and has confirmed much of our theory of such explosions.

A Carbon-detonation or Type I Supernova again involves a white dwarf accreting matter from a binary companion. Despite the novae, accreting matter can gradually build up, eventually making the star so massive that it starts to contract and heat up (the so-called Chandrasekhar mass limit of 1.4 solar masses) so that the carbon undergoes catastrophic fusion. The whole star explodes with no remnant. Two merging white dwarfs in a binary may also cause such a supernova.

NEUTRON STARS, PULSARS

A neutron star is the remnant of a Core Collapse Supernova. It is a ball of neutrons, with a mass of roughly 1.5 times the Sun’s, yet packed into a size of only about 10 kilometers. A cubic centimeter of neutron star material on Earth would weigh about 100 million tons. Their magnetic fields are about a trillion times Earth’s. They spin on their axes a few times each second. They are visible as pulsars, sources of radio waves that give off a pulse a few times a second. The radio waves come from the magnetic poles of a spinning neutron star, and are beamed outwards in a narrow cone. The magnetic poles are generally not aligned with the rotation axis, like on Earth. So the whole picture is a bit like a lighthouse. If the Earth happens to be in the path of this beam from a pulsar pole, we’ll see a pulse of radio waves every time the pulsar rotates. Pulsars are incredibly accurate clocks, and their rotation periods are measured with amazing accuracy, as is the rate at which they are slowing down. The orbits of pulsars in binary systems have been extremely accurately determined, allowing confirmation of Einstein’s prediction that orbits should “decay” (the two objects should slowly spiral in towards each other). Unexpectedly, planets were found around a pulsar in 1992. It is unclear how or when the planets formed, given the violent supernova event that produced the pulsar.

BLACK HOLES

Before black holes, background on Einstein’s Theory of General Relativity, which predicts that light should follow a curved path near regions of strong gravity, not travel in familiar straight lines. It also predicts that light trying to leave a source of strong gravity will be “redshifted”, or its wavelength will get longer as it tries to leave. These effects have actually been observed in experiments: the Sun has been shown to bend starlight, and the redshift has been observed in light using tall towers on Earth.

Now imagine shrinking the Earth to 1 cm. Then the escape velocity (speed needed to escape Earth’s gravity, actually 11 km/sec) would be equal to the speed of light. Since this is the fastest speed believed possible, then nothing, not even light, could escape from the Earth. The Earth would then appear dark, and be a black hole. The radius that you would have to shrink an object of a certain mass for this to happen is called the Schwarzschild Radius. A black hole is then any object that has a radius smaller than the Schwarzschild radius for its mass. We don’t know of any process which would lead to

tiny Earth-mass black holes, but in the most massive stars, it is possible that when they collapse, their gravity overcomes the resistance of the neutrons mentioned above. Then, nothing we know of can stop the collapse proceeding, and a black hole is formed. They are probably at least three times the Sun's mass. The Schwarzschild Radius for such a mass is 9 km, so once the core shrinks to less than this size, it is a black hole. The Event Horizon is an imaginary sphere around the black hole with radius equal to the Schwarzschild Radius. Anything crossing the Event Horizon cannot get back out because it can't travel any faster than light. Once inside the Event Horizon, light and everything else is constrained to follow curved trajectories that never cross back outside. So it is a very strong version of the slight curvature of light paths caused by the Sun's gravity. We say that space is warped or curved by gravity.

Effects around black holes include: 1) Huge tidal forces. As you fall into a black hole feet first, your feet feel a stronger gravity than your head does because they're always closer to the black hole. So you get stretched out. This is called the tidal force. 2) Gravitational redshift. This was mentioned above. Any light reaching us from near the Event Horizon is redshifted greatly. At the Event Horizon itself, it is redshifted to infinite wavelength. 3) Time dilation: to a distant observer, a clock near the Event Horizon appears to be running slow. At the Event Horizon, it appears to stop altogether. A consequence of time apparently stopping is that the distant observer can never see an object entering the black hole. It seems to be poised at the Event Horizon forever. This is relative, if you were with the clock, you would see time proceeding normally and cross the Event Horizon "normally".

There is excellent evidence for black holes, but nothing is proven. Our best black hole candidates are binary stars in which one star is invisible but measured to be very massive (at least 3 Sun masses). They are also sources of X-rays, which are believed to be due to matter being pulled off the visible star onto the black hole. Before it goes in, it gets accelerated and heated tremendously, and so X-rays are expected from the gas just about to spiral into the black hole. A source called Cygnus X-1 is a very good candidate.