Astronomy 1 – Introductory Astronomy
Spring 2014

Review of first six weeks – one page (or less) of notes for each class; main points, important equations, not a comprehensive list of topics discussed in each class

Here is the syllabus:

Week 1: angles, scale of the solar system
Reading etc: pp. 29-31; Powers of Ten

Week 2: light, inverse square law, thermal emission distance to Sirius, temperature of the Sun and Sirius
Reading etc.: Ch. 15 first few pages; Ch. 5, secs. 1 and 2

Week 3: spectra, incl. stellar spectra, Doppler shift
Reading etc.: Ch. 5, secs. 3, 4, and 5

Week 4: gravity and orbits, Kepler's third law
Reading etc.: Ch. 4

Week 5: masses of stars, structure of stars, energy sources of stars, spectral types, main sequence
Reading etc.: Ch. 15; Ch. 14, secs. 1 & 2

Week 6:, HR diagram, star clusters, evolution of stars
Reading etc.: Ch. 17

Class 1 (Jan 21)

Angle-size-distance relationship

$$\theta = \frac{57.3L}{d}$$

With that constant of proportionality, the angle subtended is in degrees as long as the physical size of the object (or the separation between two objects) L and the distance d are in the same units.

Even if two stars are not the same distance from us, we can talk about the angle between them (their "angular separation").

Fist at arm's length is roughly 10 degrees.

There are 360 degrees in a full circle, and degrees are divided into 60 arc minutes, which are each divided into 60 arc seconds.

If the distance to the Moon, say, is known, then the above equation can be used to compute the Moon's size (diameter) from its apparent angular size and the distance.

Class 2 (Jan 23)

For the distance to the Sun, the A.U., we bounce radar (a pulse of light; radio waves) off of Venus when it's at its maximum elongation (angular separation from the Sun). The round trip travel time gives us the distance to Venus via:

$$v = \frac{d}{t}$$

and a little trigonometry gives us, then, the length of the A.U.

And then the measurement of the angular size of the Sun (about 0.5 degrees, nearly identical to that of the Moon) gives the size (diameter or radius) of the Sun.

Class 3 (Jan 28)

The inverse square law of light comes from the dilution of light as it expands away from a point-source, filling a greater volume with increasing distance. By considering imaginary concentric spheres, centered on the source of light, we can see that the brightness, B, for an observer a distance, d, from the light source of luminosity, L, is given by:

$$B = \frac{L}{4\pi d^2}$$

The brightness is in units of Joules/s/m^2 or Watts/m^2, where a Watt is a J/s. And the luminosity is in units of Watts, W, while the distance is in units of m.

The luminosity of the Sun can be computed from its known distance and measured brightness of B = 1360 W/m^2. That's the brightness totaled over all wavelengths.

But this equation is more often used to compute the distance to a star or other object based on an estimate of the object's luminosity, often based on similarities between the spectrum of the object and spectra of other objects, of known luminosity. For example, a star that had a spectrum very similar to the Sun could be assumed to have the same luminosity as the Sun.

The bright star Sirius can be estimated to have a luminosity 26 times higher than the Sun's. This is based on its hotter temperature and bluer color, inferred from measuring its spectrum. Given that value: $L_{sirius} = 26L_{sun}$, we can compute the distance to Sirius using the inverse square law.

Class 4 (Jan 30)

Light is both a particle (a "photon") with energy given by:

$$E = hf$$

where h is Planck's constant, h = 6.63×10^{-34} Js and the photon's frequency, f, is given in Hertz or 1/s, and a wave, governed by the equation:

$$\lambda f = c$$

where λ is the wavelength of light (in meters, but commonly expressed in nanometers, nm, with 10^9 nm per m) and c is the speed of light (c = 3.0 X 10^8 m/s).

The wavelength of light is perceived by our eyes/brains as color. The shortest wavelength we can see is about 400 nm and is blue light, while red light around 700 nm is the longest wavelength we can see. This range is referred to as the *visible* range of light (or electromagnetic radiation). Shorter wavelengths are ultraviolet light, X-rays, and gamma rays. Longer wavelengths are infrared (IR) and radio.

Thermal emission is the light given off by all warm objects, according to their temperature. It has a characteristic spectral shape (the "blackbody" spectrum or Planck function). Fig. 5.19 gives an excellent summary.

Higher temperature thermal emission sources are bluer and brighter. These two laws are given as:

$$\lambda_{max} = \frac{2.9X10^6 nmK}{T}$$

and

$$B_{surf} = \sigma T^4$$

Thermal spectra are one type of continuous spectrum. There are two other types of spectra: absorption line and emission line spectra. The criteria are: continuous = hot, opaque source; emission line = hot, transparent source; absorption line = cool transparent gas in front of a hot, opaque source.

Note that room- and body- temperature objects emit mostly infrared light. The light we see emanating from most objects around us is reflected sunlight or artificial light.

Class 5 (Feb 4)

The spectral lines are due to electrons moving between orbits – or energy levels – in atoms. Each element has its own energy level structure and thus its own unique set of emission and absorption lines.

When a source of light is moving with respect to an observer, the spectral lines are seen to shift – to shorter (bluer) wavelengths if the source is moving toward the observer and (redder) longer wavelengths if it's moving away. This Doppler effect is given by:

$$\frac{v_r}{c} = \frac{\lambda_{shift} - \lambda_{rest}}{\lambda_{rest}}$$

Only the component of the velocity directly toward or away from the observer, v_r, affects the Doppler shift. Sideways motion has no effect.

Class 6 (Feb 6)

Atoms are made of neutrons and protons, which weigh about the same, in the nucleus, at the atom's center, orbited by lighter (by a factor of about 2000) electrons. The neutrons are neutral, in terms of electric charge, while the protons are positively charged and the electrons are negatively charged.

Like charges repel while opposite charges attract.

Electrons are attracted to the positively charged nucleus, so it takes energy to move them to higher orbits (or levels). These orbits are discrete – quantized – they exist only at certain energies.

Kinetic energy and potential energy are two forms of energy. There are many kinds of potential energy – all of which have to do with the position of something (a charged particle or a massive object) with respect to the source of some force (electromagnetism, gravity, the nuclear binding force).

Other types of energy include thermal energy (which is really the kinetic energy of all the random motions associated with heat) and radiant energy (light; photons).

Class 7 (Feb 11)

Forces (pushing or pulling, either physically or with electricity, magnetism, gravity) accelerate masses, make them move faster, giving them energy. Force times the distance over which the force is applied equals energy.

The acceleration due to a force is inversely proportional to the mass of the object that's being moved:

$$a = \frac{F}{m}$$

$$F = ma$$

For gravity, the force between two masses is directed toward the other mass, and for both objects is equal to:

$$F_g = \frac{GMm}{r^2}$$

Note how these two equations taken together lead to the result that the acceleration due to gravity is independent of the mass of the object.

Circular motion involves acceleration toward the center. This centripetal acceleration is given by:

$$a_{cent} = \frac{v^2}{r}$$

and there is a centripetal force associated with this acceleration that's just given by F = ma; so it's the expression above for centripetal acceleration multiplied by the mass of the object moving in a circle.

Class 8 (Feb 13)

An orbit (a circular one, at least) is simply circular motion where the central force associated with the centripetal acceleration is due to gravity. Equating them gives:

$$v^2 = \frac{GM}{r}$$

which can be recast as Kepler's third law:

$$p^2 = \frac{4\pi^2 a^3}{GM}$$

or

$$p^2 = \frac{4\pi^2 a^3}{G(M + m)}$$

if the mass of the second object is significant.

Two orbiting objects orbit from their common center of mass, given by:

$$M_1 r_1 = m_2 r_2$$

We can weigh the Sun simply from the Earth's orbital period (one year) and size (one A.U.). We can weigh the components of a binary star system by using Kepler's third law to get the combined mass and then using the center of mass equation to get the mass of each star separately.

Class 9 (Feb 18)

Pressure holds up stars against the force of their own gravity.

For most stars, this is gas pressure, given by the ideal gas law:

$$P = nkT$$

where n is the number density (particles per m^3) and k is Boltzmann's constant, $k = 1.38 \times 10^{-23}$ J/K, and T is the temperature.

The number density is related to the mass density (kg/m^3) by:

$$\rho = mn$$

where m is the average particle mass.

Pressure is a force per unit area (Newton per square meter, N/m^2), but only pressure differences – or gradients – lead to net forces. A wall or window with strong but equal air pressure on both sides won't feel a force, but if there is a pressure difference between the two sides, there will be an associated force pushing from the high pressure side to the low pressure side.

Similarly, the high pressure deep inside a star and the much lower pressure at its surface causes an outward force of gas pressure that balances the inward force of gravity.

High pressure at the center of a star is due to both high density and high temperature.

The heat at the star's center is generated by nuclear fusion – the combining of four hydrogen nuclei into one helium nucleus with the associated release of energy. The source of that energy is nuclear potential energy, like the source of the energy released in an exothermic chemical reaction is electric potential energy. One way to characterize the production of energy by nuclear fusion is by the amount of mass that's converted to energy – the difference between the helium mass and the four hydrogen masses. Using Einstein's $E = mc^2$, we can equate that mass to an energy.

Because a star uses its own mass for fuel – using up the hydrogen it's born with – the star will eventually run out of fuel.

Class 10 (Feb 20)

Types of binary stars – can use Doppler shift if two stars are too close together in angle. Such binary systems are called spectroscopic binaries. Visual binaries are binary systems where you can see the light from both stars and over time, you can see them orbiting their common center of mass. For both types of binaries, the angle at which we see the system can affect our measurements.

Distances to stars can be reliably measured using parallax – the apparent angular shift in the location of a star as viewed from the Earth at two different points in its orbit. If we define the half-angle of that apparent parallax shift as the parallax angle, p, then it is related to the distance between us and the star very simply:

$$p = \frac{1}{d}$$

where the distance, d, is expressed in parsecs (pc) where 1 pc = 3.09×10^{16} m = 3.26 light years.

The surface temperatures of stars are measured most accurately by the relative strengths of the absorption lines present in their spectra. Stars are categorized into spectral types, in decrease temperature order: OBAFGKM.

When the spectral types of stars are plotted vs. their luminosities a correlation among a majority of stars is seen – more luminous stars are also hotter. The stars that follow this trend are called main sequence stars, and the luminosity vs. spectral type plot is called a Hertzprung-Russell diagram.

Class 11 (Feb 25)

The HR diagram is the way we organize the trends (caused by the physics of stars) among the observable properties of stars. Stars' luminosities and temperatures are plotted directly on the HR diagram, but their radii can be directly computed from these two other quantities.

Most stars are on the main sequence, a narrow strip on the HR diagram that goes from low temperature and luminosity, diagonally up to high temperature and luminosity. Bigger and more massive stars are at the top and smaller and less massive stars are at the bottom.

Mass is the determining factor for the other properties – high mass stars (up to about 100 Msun have high luminosities (and temperatures and radii) because their large gravity demands a large pressure gradient. High pressure in their cores requires high temperatures which enable high fusion rates and thus the production of a lot of energy. That energy eventually makes its way to the star's surface where it is radiated into space as luminosity.

These main sequence stars are all fusing H to He in their cores.

Binary stars and orbits: all orbits are elliptical, where a circle is a special case of an ellipse. In the solar system, the Sun is at one of the foci of each planet's elliptical orbit. The planet (or other orbiting object) moves faster when it's near the Sun (or whatever it's orbiting) and slower when farther away. An ellipse is defined by its semi-major axis, which is akin to its radius, measured the long-way across the ellipse. It's that semi-major axis, a, that appears in Kepler's third law.

Class 12 (Feb 27)

The HR diagram is the "parameter space" in which we plot and try to understand stellar evolution – how stars change as they age.

Stars have to change because they use up their fuel (turning H into He), so they eventually run out of H in their cores. This leads the star to tap into a series of different energy sources and each one leads to a different configuration (radius, luminosity, temperature) for the star. So, the star moves around in the HR diagram.

For a low-mass star like the Sun, H to He fusion not in the core but in a shell above the core, is the next fusion source, and the star is a red giant at this stage. Eventually He starts fusing to C in the core, and then the He in the core runs out and He starts fusing in a shell above the core. But that releases so much energy that the outer layers of the star are ejected into space. The star dies, leaving behind a small, dense, hot (but not generating any new energy) core – a white dwarf.

For massive stars, the process of fusing heavier and heavier elements continues up to the point that the core is composed of iron. As these later stages of fusion occur, the star moves horizontally across the HR diagram (becoming a red supergiant and then back to a blue supergiant), before it explodes as a supernova, leaving behind not a white dwarf but a neutron star or black hole.

Star clusters: all the stars in a cluster are the same age (more or less). So clusters are a good place to study stellar evolution. The key concept is the main-sequence lifetime. Stars live their main sequence lives only so long as they have H left in their cores. Massive stars start with more, but use it up faster, so they live short lives. Low mass stars live much longer lives (because they are so much less luminous). By seeing what the most massive star left on the main sequence of a cluster is, we can estimate the age of the cluster.