Astronomy 101 - Test 1 Review

FOUNDATIONS

Scientists use the metric system to measure things. It is based on powers ten, and is thus more logical than our everyday Imperial system. The kilogram (or gram), meter (or centimeter), and degree Celsius are the basic units. The Kelvin scale is also widely used for temperature. Density is how tightly packed the matter in an object is: higher density means more mass in a given volume. Angles are usually measured in degrees, arcminutes and arcseconds. We use scientific notation a lot in astronomy because very large and small numbers occur frequently.

The range of distances, masses, ages and times, and temperatures encountered in astronomy are enormous. The Astronomical Unit, the light year, the Earth Mass and the Solar Mass are some of the special units used in astronomy in addition to the metric system.

The Celestial Sphere is an ancient but still useful concept that allows us to navigate around the night sky, analogous to how we navigate the Earth with longitude and latitude. It is fixed to the stars so it does not rotate with Earth, but appears to rotate once a day as the Earth spins on its axis. It has an equator and poles. Polaris, or the Pole Star is a star located above (but a very long distance from!) Earth's North Pole, so that as the Earth rotates, the Celestial Sphere appears to rotate around this star.

The Solar Day is how long it takes for the Sun to return to a given position in the sky. The Sidereal Day is how long it takes the Earth to spin 360 degrees on its axis. These are not the same, because as the Earth spins, it also revolves around the Sun. Thus it must rotate a bit more than 360 degrees in order for the Sun to appear in the same position in the sky again. The Solar Day is therefore slightly (4 min) longer. Astronomers need to keep track of sidereal time because where an astronomical object appears in the night sky depends on where Earth is in its daily rotation. This allows astronomers to track, for instance, whether the object is moving in the sky.

Seasons exist because the Earth's rotation axis is tilted with respect to its orbit around the Sun. The summer solstice in the northern hemisphere occurs when the Earth's North Pole is at its most tilted towards the Sun, and so on.

The year we use is slightly shorter than the time it takes the Earth to complete exactly one orbit around the Sun. The difference is a matter of minutes. This is because the Earth's tilted rotation axis slowly precesses, or wobbles like a spinning top. It takes 26,000 years to do a complete wobble; in other words, while Polaris is the Pole Star now, over time it will slowly circle away from the North Celestial Pole, and return to it in 26,000 years. This means that if we used the Earth's orbital period around the Sun as our definition of a year, then in 13,000 years, July would be a winter month. We instead choose to define the year so that the summer solstice occurs at the same time every year, but this occurs at a slightly different position in the Earth's orbit every year due to precession. One consequence is that in 13,000 years Orion will be a summer constellation.

The Moon, because it orbits the Earth, undergoes a cycle of phases lasting 29.5 days, in which it goes from New Moon through First Quarter, Full Moon, Third Quarter and back to New Moon. During the cycle we see gradually changing fractions of the sunlit side, and the moon rises later each day. At New Moon, the Moon is close to the same direction as the Sun, so we see the mostly the nighttime side. At Full Moon, the Moon is in the opposite direction to the Sun, and we see the full daytime side. The cycle of phases is slightly longer than the Moon's orbital period of 27.3 days, for the same reason that the Solar Day is longer than the Sidereal Day.

Solar eclipses occur when the Moon passes in front of the Sun. Lunar eclipses occur when the Earth passes between the Moon and the Sun. We don't get Solar eclipses every month because of the Moon's complicated orbit around Earth. Its orbital plane is tilted, meaning that at most New Moons the Moon passes either above or below the Sun. Only at certain times of year, then, when the Moon's orbit crosses our sightline to the Sun, do we get eclipses. But the Moon's shadow creates a quite narrow track on the Earth's surface, so eclipses at a given place on the Earth's surface are quite rare. Furthermore, the direction of that tilt slowly changes with time, making eclipses even less regular. The Moon's orbit is also slightly elongated, meaning that some eclipses are annular if they occur when the Moon is at its furthest from Earth.

FROM ARISTOTLE TO NEWTON

The prevailing view in ancient Greek times was that the Earth was fixed, did not spin, and everything else rotated around the Earth. Aristotle argued for this. Aristarchus argued that everything goes around the Sun (heliocentric model), but his views did not prevail. Since what they could see in the sky was essentially their universe, the geocentric model was their cosmology, and this question was very important to the philosophy of their existence.

The biggest problem with the geocentric model was retrograde motion of the planets, which is naturally explained in the heliocentric model as a consequence of Earth going around the Sun. The geocentric model had to attribute it to complex spiraling motions of the planets themselves. The spiral loops are called epicycles.

The geocentric model was accepted for almost 2000 years, until the Renaissance, when Copernicus rediscovered Aristarchus' work. He also knew of some more recent, similar ideas from the Islamic world. He realized that the heliocentric model was more simple and elegant, and almost got rid of the strange epicycles. He suggested that everything orbited around the Sun in circular orbits, and was able to arrange the known planets in their correct order, and realized that the stars must be more distant because they didn't show retrograde motion. His arguments were not generally accepted.

Galileo used a telescope to discover that there were four moons orbiting Jupiter, and that Venus has a cycle of phases consistent with an orbit around the Sun rather than Earth. Thus the Earth was shown not to be the center of all things. He also co-discovered sunspots and concluded the Sun rotates. His findings were also not accepted by the Church but sewed the seeds for the acceptance of the heliocentric model.

Kepler used Brahe's precise data on the positions and relative distances of the planets to come up with three laws that described their motion. First, their orbits are ellipses, not circles, getting rid of the remaining epicycle problem, with the Sun at one focus of the ellipse. Second, planets move faster when closer to the Sun. Third, the square of a planet's orbital period is proportional to the cube of the semi-major axis of its elliptical orbit, showing how planets further from the Sun take longer to orbit.

Distances to planets, and thus the scale of the Solar System, were determined after Kepler by the technique of Earth-baseline parallax.

Newton considered experiments of how all objects, not just in space, interact with each other to derive his three laws of motion and law of gravity. Kepler, on the other hand, had just been trying different mathematical forms and equations to see what worked, without thinking much about the physical basis of his results. Newton's first law states that an object at rest or in straight-line motion at constant speed stays that way unless acted on by a force. The second law, F=ma, relates the force applied to an object to its mass and the resulting acceleration. Acceleration is a change in speed or in direction of a moving object. The third law says that every force or action is balanced by an opposite one. The law of gravity relates the strength of the gravitational force to the masses of the two bodies involved and their separation. The force increases in direct proportion to the masses, and in inverse proportion to the square of their separation. A consequence of these laws is that the Sun feels the gravitational force between it and the planets, just like the planets do, but responds very little to it because of its enormous mass. But the Sun is therefore not quite fixed in space. However, Newton showed why the Sun should be at the center of the Solar System for the first time. Newton showed that two objects orbit in ellipses around their common center of mass, which is at one focus of the ellipse.

RADIATION

Light, infrared, ultraviolet, X-rays, microwaves, and radio waves are all examples of the same phenomenon: electromagnetic radiation. Radiation travels as waves. Basic properties of waves are the amplitude, wavelength, period, frequency and speed. The speed is also the wavelength times the frequency. Waves refract, or bend, when the pass through materials of different densities, such as light going from air into glass or water. Radiation travels as electromagnetic waves, that is, traveling waves of changing electric and magnetic fields. All electromagnetic radiation, be it radio or X-rays, travels at the same speed, the speed of light, c = 300 million meters per second. Because speed equals wavelength times frequency, the bigger the wavelength the smaller the frequency. Once you specify the frequency, you know the wavelength, and vice versa.

The difference between light, ultraviolet, X-rays, radio waves, etc. is their wavelength or frequency, and together these types of electromagnetic radiation are what we call the electromagnetic spectrum. By a spectrum we mean spreading out waves according to their wavelength or frequency. Radio waves have the longest wavelengths, and gamma rays the shortest. For light, the different colors correspond to different wavelengths. The range of wavelengths and frequencies is huge, covering more than 25 powers of ten. The chemistry of the atmosphere allows some parts of the spectrum to be transmitted, such as light and radio waves, but causes some to be absorbed, like most ultraviolet and X-rays. To observe these, therefore, we must go above the atmosphere with satellites.

When you bend or refract light (or any radiation or wave), the bending angle depends on the wavelength, so for light, you can spread white light into the colors of the rainbow by sending it through a glass prism. Spreading out radiation according to its wavelength in some way is an incredibly powerful tool scientists use to study the nature of objects.

Radiation and all waves follow an “inverse-square law”, like gravity: the apparent brightness of an object decreases as the square of its distance from us increases. So a light bulb twice as far away looks four times as dim.

Spreading out the light from astronomical objects into a spectrum, we find that many (especially stars) have a so-called black-body spectrum. They radiate over a large range of frequencies or wavelengths. There is always wavelength where their radiation peaks. That wavelength depends on the object’s surface temperature: the hotter it is, the shorter the wavelength. This is Wien’s Law. The Sun, 5800 K at its surface, has the most radiation in the middle of the visible spectrum, at the wavelength corresponding to the color yellow. A hotter star would have its peak at a blue or even ultraviolet wavelength, but would appear blue to us because our eyes can’t see ultraviolet. Cooler stars, only 100’s of degrees, may have their peak in the infrared, but would appear red to us. Also for objects with a black-body spectrum, the intrinsic brightness, or how much radiation is coming off every square cm of its surface, depends on the surface temperature to the fourth power. So a star twice as hot as the Sun gives off 16 times as much radiation from every square cm. This is Stefan’s Law.

The Doppler effect is familiar from sound waves as the change in pitch depending on whether the thing making the sound is approaching us or receding (or if we are approaching or receding from it, it doesn’t matter). But it holds for all waves, including electromagnetic radiation. Any relative motion between the source and receiver in the direction that the wave is traveling causes a Doppler shift. Motion perpendicular to that direction causes no shift. So for instance, if traveling fast enough towards a red light, it might appear green (don’t try this, your car isn’t fast enough). It is very powerful for determining the motions of objects in astronomy. The bigger the relative motion, the bigger the change in wavelength.

SPECTROSCOPY AND ATOMS

Spectroscopy is the technique by which radiation is spread out into a spectrum. For light, you can do this with a prism or a diffraction grating. Kirchhoff’s Laws describe what kind of spectrum you get for light under various conditions. A luminous solid or dense gas produces a continuous spectrum. We now know this to be the black-body spectrum described above. A low-density hot gas produces an emission line spectrum, which is bright at a few specific wavelengths only. A low density cool gas absorbs light at specific wavelengths from something producing a continuous spectrum, to make a continuous spectrum with absorption lines. The absorption and emission line spectra of a gas have their lines at the same wavelengths, and are a fingerprint of the element(s) in the gas. These laws awaited the microscopic description of atoms to be explained.

On microscopic scales, light behaves like particles, traveling in individual packets of energy called photons. The packets still have a frequency, and the energy of the photon is proportional to its frequency.

Niels Bohr created a model of the atom based on experiments: the Hydrogen atom consists of a proton, a positively charged particle, orbited by an electron, which has an equal and opposite negative charge. The proton's mass is about 10^{-24} of a gram, and about 2000 times the electron's mass. They are held together because opposite charges attract, just like the attractive force gravity holds the Solar System together. The atom has a ground state, which is its lowest energy state, and excited states of higher energy. The energy to move into an excited state comes from the atom absorbing a photon or colliding with another atom. The higher the energy of the excited state, the further the orbiting electron is from the proton: you have to put energy into the atom to push the electron into an orbit further from the proton, to which it is attracted. However, only certain energies, or orbit radii, are allowed, and the atom can only absorb photons with exactly the right energy (and therefore frequency) to boost the electron to one of these levels. Otherwise, the photon passes through without interacting. The electron moves to the higher energy state only briefly, before returning to the ground state, possibly stopping at intermediate states along the way. Whenever it moves to a lower state, it emits a photon in a random direction. The loss in energy of the electron is exactly made up by the photon's energy. Thus the frequency of photons that can be absorbed or emitted by a hydrogen gas depend on the allowed energy levels of the electrons in the H atom.

Other elements differ by having more protons and also neutrons in their nucleus. A neutron is about as massive as a proton but has no charge. The nucleus is held together by a short range force called the strong nuclear force, which overwhelms the repulsion of the protons, which are all positively charged and would otherwise repel each other. In an atom, there are as many electrons orbiting the nucleus as there are protons in the nucleus, so there is no net charge. Each element has its own set of allowed energy levels for its electrons, and thus absorbs and emits a particular allowed set of photon frequencies. An element is uniquely identified by the number of protons in the nucleus, rather than anything to do with the number of neutrons or electrons.

So absorption lines are produced when light from a continuous source is viewed through a cold cloud of gas. Light of all frequencies passes through the cloud, but the photons with just the right energies (and thus frequencies) to boost electrons into higher energy levels are absorbed by the gas. When the electrons return to the ground state, the photons emitted go off in random directions. Very few go in the original direction. So the spectrum looks like it has dark bands at specific frequencies removed from it. Emission lines come from a hot gas because the collisions between atoms are energetic enough to raise electrons to higher energy levels. The electrons then drop back to lower levels, emitting a photon at a specific energy (frequency) every time. So a spectrum of the gas is dark except at specific frequencies corresponding to energies of the various downward jumps made by the electrons.

Ionization is the process by which one or more electrons are removed from an atom, to make an ion. The attraction between electron and nucleus must be completely overcome. This can be done with a sufficiently energetic photon or collision with another atom. A hydrogen ion is just a proton.

Spectroscopy is extremely useful in astronomy. Because the spectra of different elements are unique, identifying frequencies of spectral lines can tell you which elements are present in an object and how much of each. They are also very sensitive to temperature. For instance, hotter stars have more energetic photons capable of ionizing elements, so for instance, the hottest stars show lines of ionized helium.

Because spectral lines occur at such specific frequencies, they are very useful for using the Doppler Shift. For instance, the slight motion produced in stars by orbiting planets leads to a periodic Doppler Shift in the star's spectrum as it cycles around the center of mass, sometimes coming towards us, sometimes going away. In this way, we have now found over 300 planets around other stars.

Molecules are two or more atoms joined together. Apart from the energy levels of the electrons, they also have specific energy levels associated with their vibration and rotation, leading to more complicated spectra. They form in cooler situations where atoms can collide slow enough to stick (remember, temperature is a measure of the random speeds of the particles in a gas) and there is little radiation energetic enough to break them apart. So cool clouds of interstellar gas and cooler stars have molecules.

TELESCOPES

First we must realize that astronomical objects are so far away that any light emitted from them, destined to hit our tiny telescope, travel in essentially parallel lines. All parallel light rays come together at a single point, the focus, after bouncing off our telescope mirror. If we are observing two stars, the light rays from the second star also travel in parallel lines, but all hit the telescope at a different angle. Those rays are also brought together at a focus, but shifted from the focus of the first star. The light from all the objects in our field of view are brought together at different points in a plane, the focal plane, which is parallel to the mirror. By putting a detector, like a CCD or photographic plate, in the focal plane, we make an image. A camera works pretty much the same way.

Refracting telescopes use a lens to focus light, rather than a mirror. These have many disadvantages compared to mirrors. They can only be supported around the edges, they absorb some light, especially ultraviolet and infrared, and air bubbles can affect the image quality. They are also subject to chromatic aberration. Because they focus light by bending (refracting) it, and different wavelengths are bent by different angles, they are not brought together at the same focus. These problems are all avoided with mirrors, and all large, modern telescopes use mirrors, which reflect light rather than refract it.

Larger mirrors capture more light from objects, and thus allowed fainter emission to be seen in the same exposure time.

The two main ways of observing an object are to make an image or a spectrum of it. Both generally employ a CCD (Charge Coupled Device, an electronic device as in a digital camera; photographic plates were once used), to record the image or spectrum. The CCD image can be recorded directly into a computer (like downloading digital camera images), and a CCD is more sensitive than a plate. Plates can be made bigger however, but CCDs are catching up.

Resolving power is how much detail you can see in an image. Angular resolution is the smallest angle by which two objects can be separated and still be distinguished. For the eye, this is about one arcminute. In general, it depends on the wavelength of the radiation divided by the mirror diameter. A 2.5 m mirror is capable of an angular resolution of 0.05 arcseconds, but blurring by the atmosphere ("seeing") limits the resolution of all ground-based optical telescopes to about one arcsecond. The blurring occurs because small scale density variations in the atmosphere cause parallel light rays to bend a tiny amount, so they are no longer quite parallel. This means that they are not brought to focus as well as they otherwise would be, and the otherwise sharp image is blurred. The great advantage of the Hubble Space Telescope is that it is above the atmosphere and thus can make much sharper images, at about 0.05 arcsecond resolution.

Optical telescopes are generally placed in high, dry, desert sites, remote from big cities (whose light makes it harder to see faint objects) such as the southwestern USA or the Andes mountains in Chile.

Radio telescopes are large reflecting metal dishes that focus radio waves just as mirrors focus light. Their angular resolution is generally poorer than optical telescopes because, although they are larger, radio wavelengths are much longer than optical ones. So typically their resolution is many arcseconds to a few arcminutes. However, interferometry is a (complicated) technique through which many radio telescopes, spread out over a large area, can act as one radio telescope of that area, as far as resolution is concerned. This is the principle behind the Very Large Array. However, not as many radio waves hit the dishes as would hit one huge telescope covering the same area, so although an interferometer has the same angular resolution as the equivalent single dish, it does not have the same sensitivity to faint radio sources.

Infrared, UV, X-ray and gamma-ray astronomy are typically done from satellites above Earth's atmosphere, because these frequencies are easily absorbed by the atmosphere. The infrared emission from Earth's warm atmosphere is also very strong, overwhelming the infrared radiation from space to a large extent. We are biased to optical telescopes because we are largely visual beings, but astronomical objects emit radiation across the electromagnetic spectrum, and we must study all of it to understand their physics.