Astronomy 101 Test 1 Review

FOUNDATIONS

Scientists use the metric system to measure things. It is based on powers of 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.

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. At New Moon, the Moon is close to the same direction as the Sun, so we see 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, might we get eclipses, but only if a New Moon occurs at that time. Furthermore, the angle 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 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 discovered sunspots and thus solar rotation. 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 fixed in space. 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. These waves refract, or bend, when they 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, \( c = 300 \text{ million meters per second} \). 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. For light, for example, 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 blackbody 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, may have their peak in the infrared, but would appear red to us. Also for objects with a blackbody 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. So for instance, if traveling fast enough towards a red light, it might appear green. It is very powerful for determining the motions of objects in astronomy. The bigger the relative motion, the bigger the change in wavelength.

Spectroscopy teaches us an enormous amount about astronomical objects. Kirchoff’s Laws describe 3 types of spectra that we see. A “Continuous” spectrum is radiation over a broad range of wavelengths, and is produced by a hot opaque solid, liquid or dense gas. An “Emission line” spectrum is bright at specific wavelengths only, and is produced by a transparent hot gas. A continuous spectrum with “absorption lines” is bright over a broad range of wavelengths, with some dark lines. It is produced by a transparent gas absorbing light from a continuous spectrum source. The pattern of lines is a fingerprint of an element in a gas, and for each element, the emission and absorption lines occur at the same frequencies.

But what causes spectral lines? For this we need to understand a bit about atomic structure, and the particle nature of radiation. On large scales, light acts as a wave. But on small scales, light travels as individual packets of energy, called photons. Photon energy is proportional to radiation frequency. Atoms are made up of positively charged nuclei, containing protons and perhaps neutrons (which have no charge), and electrons which orbit the nucleus. The simplest atom is hydrogen, which is usefully described by the Bohr model. The atom has a lowest energy state, called the ground state, which has the electron in the lowest level. An atom must gain energy to move to an excited state. To do this, it must absorb a photon, or collide with another atom. Only certain energies (or orbits) are allowed. The atom can only absorb photons of exactly the right energy to boost the electron to one of the higher levels. When an atom absorbs a photon, it moves to a higher energy state briefly. When it jumps back to lower energy state, it emits a photon in a random direction. This is true of all elements, not just hydrogen. Each element has its own allowed energy levels, and thus its own spectrum. The number of protons defines the element, and isotopes of elements have different numbers of neutrons. If an atom loses one or more electrons because of absorbing an energetic photon, or a collision with another atom, it is called an “ion”.

Now we can understand Kirchoff’s laws. A continuous spectrum is a blackbody spectrum, from a hot, opaque object. We get an absorption line spectrum, say, the spectrum of a star, when a relatively cool, transparent gas absorbs certain wavelengths in a continuous spectrum going through it. We get an emission line spectrum from a hot, transparent gas cloud, where atoms are in excited states, and then photons are given off at specific wavelengths as the electron cascades down energy levels.

We can also study the spectra of molecules, which are very complex.

Telescopes will not be on Exam #1.