

# Astronomy 1143 Quiz 4 Review Answers

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## Cosmological Distance Ladder

1. What is the Distance Ladder?

- It is the list of methods of measuring distances to objects. Each method only works for a range of distances, so multiple methods are needed to obtain the full range of distances that we see in the universe.

2. List the “rungs,” or methods, of the Distance Ladder by increasing distance.

- Trigonometric parallax (works up to 1000 parsecs): Nearby objects (outside the Solar System) change position relative to background stars as the Earth moves around the Sun over the course of the year.  $d = 1/p$  where  $p$  is the angular change in relative position of the object in arcseconds and  $d$  is its distance in parsecs.
- Spectroscopic parallax (works up to 50–60 kiloparsecs): Measure the spectral type and brightness of a star, use the Hertzsprung-Russell diagram to figure out what luminosity a star of that spectral type must have. Since brightness of a star depends on luminosity and distance to the star, can use the measured brightness and the HR-diagram luminosity to find the distance (brightness = luminosity / ( $4\pi \times \text{distance}^2$ )).
- Cepheids and RR Lyrae (works up to 30 – 40 Megaparsecs): These types of stars pulsate with a regular period that’s easily measurable. The luminosity of these stars is correlated with the period of pulsations, so if you know the period and can measure the brightness, can find the distance through the luminosity-brightness-distance relation (brightness = luminosity / ( $4\pi \times \text{distance}^2$ )). This method requires a calibration to get the overall magnitude of the luminosity-period relation, so need another distance-measuring method to calibrate this one before it can be used.
- Tully-Fisher relation (works as far as you can measure rotation curves of galaxies): The total mass of a galaxy (including dark matter) gives the galaxy some rotation speed, which is just how fast it’s spinning. But the total mass is also related to the total luminosity of the galaxy, because galaxies with more stars have more mass and also emit more light. So even though we can’t directly measure the total mass of the galaxy (since most of it is dark), we can infer how much there is from how fast it’s spinning, which then lets us infer how much luminosity it must have. We measure how fast it’s spinning by measuring the width of the 21-cm hydrogen emission line, which will be wider (due to different parts of the galaxy being Doppler shifted differently) when the galaxy is spinning faster. Then we can measure its brightness and get the distance from the luminosity-brightness-distance relation (brightness = luminosity / ( $4\pi \times \text{distance}^2$ )).
- Supernovae Ia (works up to a few hundred Megaparsecs): Supernovae Ia are a different type of supernovae than core-collapse: they occur when a white dwarf is sucking up mass from a star that’s nearby. White dwarfs can’t be more massive than 1.4 times the mass of the Sun, because then they can’t support their own weight and collapse, which causes a Type Ia supernova. Since all white dwarfs collapse at the same mass, the resulting Type Ia supernova is always the same

luminosity (and it's really bright too, so this works well to large distances). So if you measure the brightness of a Type Ia supernova, you can get the distance to it from the luminosity-brightness-distance relation ( $\text{brightness} = \text{luminosity} / (4\pi \times \text{distance}^2)$ ) because they all have the same luminosity, and astronomers know from theoretical arguments what that luminosity is.

## The Big Bang Model

### 1. What is the Big Bang Model?

- It is the idea that the universe began in a hot, dense state that was the same everywhere. It was so dense that there was no way for the light to escape anywhere, so there were more photons than matter particles, which means the universe was “radiation dominated.”
- The only elements that were made at the beginning of the universe were mostly hydrogen and some helium. Every other element had to be made in the cores of stars, so the very first stars contained only hydrogen and helium.
- When the universe started expanding, it began to cool and became less dense. When it was about 300,000 years old, it was no longer so dense that photons couldn't escape from the hot gas, so it became “transparent,” which means that photons were able to travel through space instead of being trapped in the hot gas.
- The furthest back in the universe we can see is to the point where the universe became transparent and the photons were released to be able to travel to us. This is a background behind everything else in the universe, which is seen in all directions. The photons from this “wall” were initially very energetic because they came from very hot gas, but as the universe expanded they became redshifted so now we see them as microwaves. This is the Cosmic Microwave Background.
- Before recombination, stable atoms couldn't form because the photons would immediately ionize the atoms.
- The universe continues to expand, with gravity working on small scales to pull clumps of matter together in stars, galaxies, and clusters of galaxies.

### 2. What is some observational evidence for the Big Bang?

- The universe is still expanding
- Very old (metal-poor) stars have the correct amount of helium predicted by Big Bang Model nucleosynthesis (fancy word for making elements)
- The Cosmic Microwave Background exists

### 3. What is the Cosmic Microwave Background? Why does it exist?

- A very uniform radiation background across the sky.
- It exists because in the early universe, photons were bouncing around, trapped by the hot gas. Once the universe cooled more, however, the gas became neutral (as opposed to hot and ionized) and less opaque to photons and they were allowed to fly freely out in space. The CMB are photons escaping at the time in the past when the universe became neutral. These photons cool as they reach the Earth because of the expansion of the universe.
- CMB photons now are observed at 2.7K, with small fluctuations (on the order of  $10^{-4}$ ). These seemingly tiny over and underdensities eventually evolve into the galaxy clusters and voids.

### 4. How old do we think the universe is? How about the Sun? The Earth?

- The universe is about 14 billion years old (roughly  $1/H_0$ ).
- The Sun is about 10 billion years old.
- The Earth is about 4 billion years old.

# Expansion, Mass, and Density of the Universe

1. How do we know the universe is expanding?
  - The Hubble Law: We observe galaxies that are far away are moving away from us faster than galaxies that are close by (distance-redshift relation). It measures the expansion of the galaxy.
  - The Hubble Law states  $zc = H_0d$ , where  $z$  is the redshift,  $c$  is the speed of light,  $d$  is the distance, and  $H_0$  is the Hubble Constant.
  - The Hubble Constant,  $H_0$  is the slope of this relationship and is determined by measuring the distance other galaxies. As it is difficult to measure distance to far away galaxies, it is hard to measure  $H_0$ . Presently, we measure  $H_0 = 70$  km/s/Mpc.
  - We know how fast they're moving because of the Doppler shift of the light coming from them.
2. What makes up the mass-energy of the universe?
  - Most of it is dark energy, 67%
  - Next is dark matter, 29 %
  - Then the matter we can actually see, called baryons, that makes up stars, planets, galaxies, etc., 4%
  - Neutrinos and photons make up the last tiny little bit, about 0.1%
3. What is dark energy?
  - We don't really know... but if it wasn't there, the expansion started by the Big Bang would slow down due to gravity.
  - Therefore we can infer that it is some energy that causes the universe to continue to expand, kind of like the opposite of gravity. It pushes things apart instead of pulling them together.
  - Dark energy is also sometimes referred to as the "cosmological constant."
4. What drives the expansion of the universe?
  - Dark energy, also called the Cosmological Constant.
5. What slows down the expansion of the universe?
  - Gravity caused by matter in the universe, both dark matter and conventional matter like atoms and stars.
6. What is the critical density?
  - The critical density is the density of matter and energy (both light and dark matter and dark energy) in the universe that would perfectly balance expansion and gravitational collapse.
  - If the density of the universe is greater than the critical density ( $\rho > \rho_c$ ), there is no vacuum energy and universe would collapse in on itself as a "Big Crunch."
  - If the density of the universe is less than the critical density ( $\rho < \rho_c$ ), the universe would expand forever.
  - For our universe, the density (of matter AND dark energy) is roughly equal to the critical density, which means the universe will continue to expand at a decreasing rate until eventually it slows down to stop. The amount of dark matter and vacuum energy (dark energy) determine whether or not the universe will expand forever. (Side note: recent observations of very distant Type Ia supernovae suggest the expansion is speeding up instead of slowing down, so perhaps the density of our universe is a tiny bit smaller than the critical density).

7. What is the parameter  $\Omega$  (called “omega”)?
- $\Omega$  is the ratio of the actual density (matter + dark energy) of the universe to the critical density, which determines the curvature of the universe.  $\Omega = \rho/\rho_c$
  - Saying that  $\Omega < 1$  means the universe is hyperbolic, or negatively curved (kind of like a saddle).
  - $\Omega > 1$  means the universe is spherical, or positively curved, like a globe.
  - For our universe, it turns out  $\Omega = 1$ , which means the universe is flat, or zero curvature, which means space appears the way you would think and geometry works normally.
8. How do the different mass-energies of the universe contribute to the value of  $\Omega$ ?
- Since dark energy takes up roughly 70% of the universe, it has a value of  $\Omega_\Lambda$  (the  $\Lambda$  is for dark energy) = 0.7, which means the ratio of dark energy density to the critical density is 0.7.
  - Matter (both visible, like atoms, and dark) makes up roughly the other 30%, so it has a value of  $\Omega_m = 0.3$ , which means the ratio of matter density to critical density is 0.3. Observing the abundance of deuterium, helium-3, helium-4, and lithium-7 checks our understanding of Big Bang Nucleosynthesis as each determines  $\Omega_m$ , also called the baryon density.
  - Since the total matter + energy density of our universe is roughly equal to the critical density, the total  $\Omega = \Omega_\Lambda + \Omega_m = 1$ . This, in fact, works, because  $0.3 + 0.7 = 1.0$ . Yay!
9. If the density of matter (dark and light) divided by the critical density is 0.3 (currently measured to be true), what would happen if there was no dark energy to make up the other 0.7 to get  $\Omega = 1$ ?
- $\Omega$  would not be 1, since there’s no dark energy, it would only be  $\Omega = 0.3$  from the matter. This means that since  $\Omega < 1$ , the universe would be hyperbolic (saddle shaped), and since  $\rho < \rho_c$ , it would also expand forever. Since there’s no dark energy to drive the expansion, the expansion would slow down.
10. What happens to the photons in the universe as the universe expands, and how does this impact the amounts of matter and radiation in the universe?
- Photons redshift to lower energies.
  - Since the amount of energy in photons decreases over time but the amount of energy in matter stays the same (matter doesn’t lose energy as it expands), the relative amount of energy in radiation decreases while the energy in mass stays the same, and the universe shifts from being radiation-dominated to being matter-dominated.
11. How do we measure the expansion of the universe and how it changes over the age of the universe?
- We look at the Doppler shifts of distant galaxies to determine how quickly they are moving away from us. If this speed is higher than expected, then the universe was expanding faster in the past (slower now). If the speed is slower than expected, the universe was expanding slower in the past (faster now).
  - This requires us to know the distance to these galaxies by some method other than Doppler shifts so that we can determine the redshift-distance relation. Usually we can use things like Type Ia supernovae, which is the distance measurement that works best at very large distances (see above section on the Distance Ladder).

## Large Scale Structure

1. What is large scale structure?
  - It is the clustering of galaxies and clusters of galaxies due to mutual gravitational attractions.
2. Does structure in the universe increase or decrease as the universe grows older?
  - The amount of structure increases over time, because matter pulls together into denser regions due to gravitational attraction. It takes a long time for galaxies and galaxy clusters to traverse the large distances necessary for this to occur, so structure only increases with time.
3. Why doesn't the expansion of the universe due to dark energy destroy large scale structure?
  - Dark energy causes expansion on much larger scales than gravity works. Gravity is quite strong on small distances, ("small" here meaning on the size of galaxy clusters), strong enough to overcome the expansion of dark energy and contract into galaxy clusters instead.

## Miscellaneous Cosmology

1. What does a flat rotation curve of galaxies tell us?
  - Flat rotation curve means that galaxies have matter distributions that are roughly spherical, but we only see stars in a disk. Therefore, there must be dark matter making up the sphere in addition to the stars and gas in the disk.
  - If dark matter is cold it forms more structure on small scales because it moves slower and forms clumps easily.
  - Brown dwarfs are another dark matter candidate because they are difficult to find and are composed of H and He.
2. What do we mean when we say the universe is "expanding?"
  - Space between objects like galaxies is expanding, pushing the galaxies apart from each other. The galaxies themselves are not moving apart, it's just space getting bigger between them.
3. What is Olbers' Paradox? What is the resolution?
  - If the universe is infinitely old and big, then the entire sky should be filled with stars.
  - It's not, so either the universe isn't infinitely old or isn't infinitely big.
  - The resolution is that the universe is not infinitely old. It began about 14 billion years ago with the Big Bang.
4. What is the 21-cm line and why is it useful for cosmology?
  - This is a spectral line of hydrogen that occurs when the hydrogen's electron spontaneously changes its spin from up to down.
  - It is useful for cosmology because all hydrogen emit this line, so we can use it to map where hydrogen is in the universe. Since hydrogen will cluster with other matter (like dark matter), we can then use it to figure out where dark matter is.
5. What is the Cosmological Principle?
  - The idea that the universe is homogeneous and isotropic. In other words, that no place in the universe is unique, and that it looks the same in all directions.

- This seems to hold on very large scales (many megaparsecs) even if it's not true for small scales

6. What is the Lyman-alpha Forest?

- The Lyman-alpha line comes from Hydrogen's transition from the ground state to the first excited state.
- In high redshift quasars (galaxies with an active black hole at the center), we see lots of absorption near the Lyman-alpha line. Hydrogen clouds between the quasar and us cause this absorption.
- By studying the Lyman-alpha Forest we can learn about the distribution of Hydrogen in the universe.