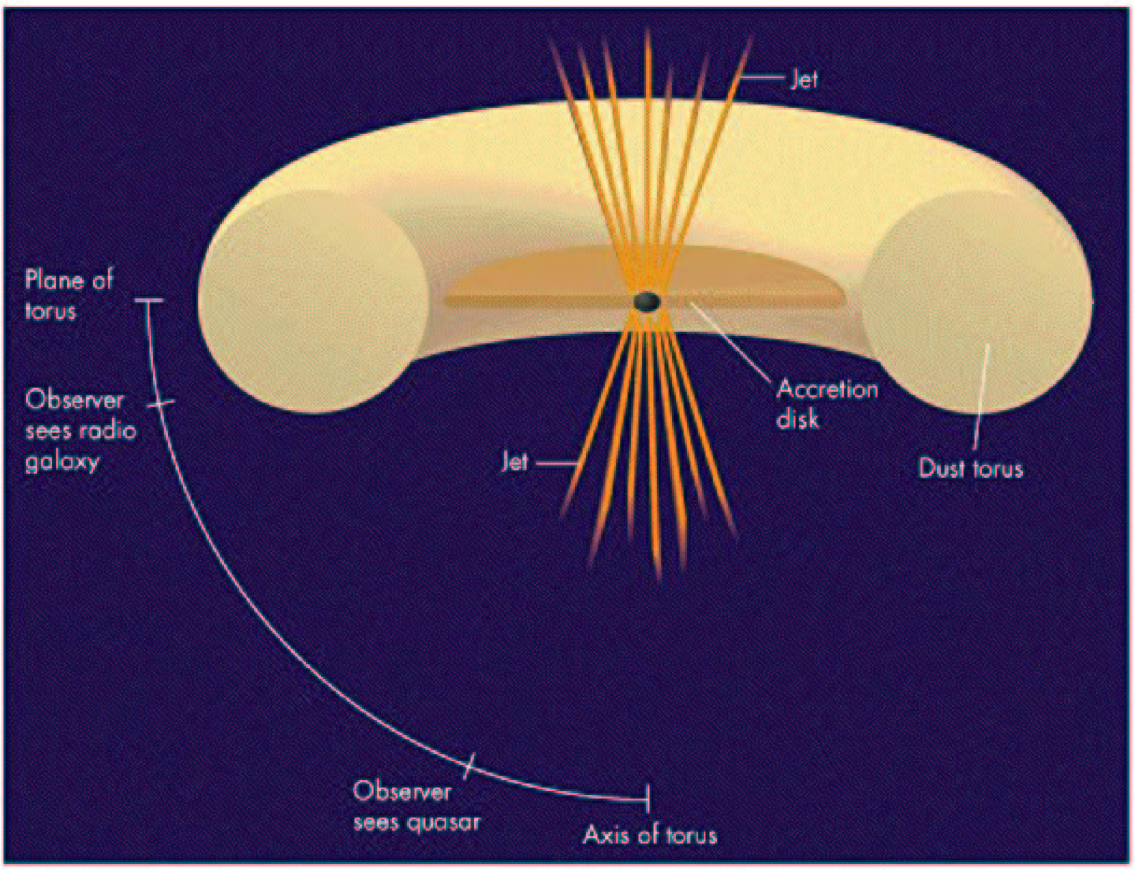
ASTR 220 Homework #9 Solutions
Spring 2005

1. *Active Galactic Nuclei.*

   (a) *Sketch a diagram of an AGN, clearly labeling its major parts: the supermassive black hole, accretion disk, molecular torus, and jets.*

   (b) *Indicate on your diagram where you would have to be to view the AGN as a* ***quasar AND*** *as a* ***radio galaxy****.*

   The following figure shows approximately what you should have drawn. As indicated on the figure, you would see a quasar if you were looking along a jet at the accretion disk. You would see a radio galaxy if you looked perpendicular to the jets. (In the figure, the molecular torus is labeled as the dust torus.)



2. *Ch. 15, Review Questions, #21.*

   The length of time it takes for an object to change in brightness tells us its maximum size. Let's imagine that the accretion disk around a supermassive black hole suddenly got brighter because some gas fell into it. When the disk gets brighter, the light that leaves the disk on the side closest to the Earth will get to the Earth sooner than the light that left the far side of the disk. All of the light travels at the same speed – the light from the far side of the disk just has farther to go. Here on Earth, we receive the brighter light from the near side of the disk, so the AGN looks a little brighter to us. Then we receive the brighter light from the part of the disk just beyond the near side of the disk, so the AGN looks even brighter; then we receive the brighter light from the part of the disk beyond that, and so on, until finally we receive the brighter light from the far side of the disk and the AGN looks as bright as it's going to get to us. The time it took for the AGN to increase in brightness is how long it took for light from the far side of the disk to travel the length of the accretion disk. Consequently, if it took 6 hours for the AGN to completely increase in brightness, the light took 6 hours to cross the disk. The accretion disk can only be at most 6 light-hours across. (A light-hour is how far light travels in an hour.)

3. *Ch. 15, Problems, #33.* We can figure out the luminosity of each Cepheid variable by looking at Fig. 15.12. One thing to notice about the graph is that the numbers on the axes do not increase evenly, but go up rapidly, so you need to include that in your estimate.

   The first Cepheid has a period of 8 days. On the graph in Fig. 15.12, we can find where the solid line cross 8 days and look over on the y-axis at the luminosity: approximately 2500 times the luminosity of the Sun. The second Cepheid has a period of 35 days. On the graph, the line crosses 35 days at a luminosity of approximately 11,000 times the luminosity of the Sun.

4. *By measuring the redshift of a galaxy's absorption lines, we find that the galaxy has a velocity of* $1.5 \times 10^3 km/s$. *According to the Hubble law, how far away is it? Assume that the Hubble constant is* $71 km/s/Mpc$.

   The Hubble law says $v = H_\circ d$: v is the velocity of the galaxy, $H_\circ$ is the Hubble constant, and d is the distance to the galaxy. We're told that the Hubble constant is $71 km/s/Mpc$. We know the velocity, so we want to find the distance. We can rearrange the equation to:

$$d = \frac{v}{H_\circ} = \frac{1.5 \times 10^3 km/s}{71 km/s/Mpc} = 21.1 Mpc$$

   The galaxy is 21.1 Mpc away. A note about units: since the Hubble constant has km/s in its units, I left my velocity in units of km/s. That way the units would cancel out nicely and the distance would be left in Mpc. Remember that 1 Mpc is 1 million parsecs. A parsec is 3.3 lyr, so 1 Mpc is 3.3 million light-years.

5. *The Distance Chain.*

   (a) *Which method for finding distance in the distance chain is the most accurate? Explain how it works.*

   The most accurate method we have for measuring distances is radar ranging, where we bounce light off an object and time how long it takes the reflection to return. We know the speed of light very accurately, so once we know how long it took for the light to travel to the object and back, we can calculate the distance.

   (b) *If this method is the most accurate, why don't we just use it to find the distance to all the objects we are interested in knowing the distance of?*

   Objects outside of our solar system are light-years away. The nearest star is 4.4 lyr away. Galaxies are millions of light-years away. If we tried to send a light signal out to bounce off an object that far away, it would take years for the signal to return. That's not very practical! Since radar ranging is impractical over larger distances, we must resort to other methods of finding the distance to object.s

6. *The luminosity of a white dwarf supernova is approximately* 10^{10} *times the Sun's luminosity, or* $3.8 \times 10^{36} W$. *We observe a white dwarf supernova in a distant galaxy that has an apparent brightness of* $2 \times 10^{-13} W/m^2$. *What is the distance of the galaxy? Give your answer in both* ***meters*** *and* ***light-years***. *(*$1lyr = 9.46 \times 10^{15} m$.*)*

We know that luminosity, apparent brightness, and distance are related by the inverse-square law for light:

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

In this case, we know the apparent brightness of the supernova as well as its luminosity, so we can calculate the distance. First, re-arrange the equation:

$$d = \sqrt{\frac{L}{4\pi B}}$$

Now put in our values.

$$d = \sqrt{\frac{3.8 \times 10^{36} W}{4\pi(2 \times 10^{-13} W/m^2)}} = \sqrt{\frac{3.8 \times 10^{36} W}{2.5 \times 10^{-12} W/m^2}} = \sqrt{1.5 \times 10^{48} m^2} = 1.2 \times 10^{24} m$$

What is this distance in light-years? We can use our conversion to find out.

$$d = \frac{1.2 \times 10^{24} m}{9.46 \times 10^{15} m/lyr} = 1.3 \times 10^{8} lyr$$

The galaxy is 130 million light-years away!

7. *Dark Matter in the Milky Way.*

   (a) *What is the approximate* ***radius*** *of the disk of the Milky Way galaxy? State the source of your information.*

   From Figure 14.1b of the textbook, we can see that the radius of the Milky Way is about 50,000 lyr.

   (b) *Calculate the mass of the Milky Way galaxy enclosed by a radius of 50,000 lyr (*$4.7 \times 10^{20} m$*). Use Figure 16.1c to find the approximate orbital velocity of stars at that distance.*

   The equation to calculate the enclosed mass is:

   $$M_r = \frac{rv^2}{G}$$

   r is the radius within which you want to find the mass. v is the orbital velocity of the stars at that radius. G is the gravitational constant, $6.67 \times 10^{-11} m^3/s^2/kg$. In this case our radius is $4.7 \times 10^{20} m$. From Fig. 16.1c, we can estimate the orbital velocity of the stars to be about 240 km/s. Let's convert that to m/s:

   $$v = (240 km/s)(1000 m/km) = 2.4 \times 10^{5} m/s$$

   Now we can calculate the mass inside that radius.

   $$M_r = \frac{(4.7 \times 10^{20} m)(2.4 \times 10^{5} m/s)}{6.67 \times 10^{-11} m^3/s^2/kg} = \frac{2.7 \times 10^{31} m^3/s^2}{6.67 \times 10^{-11} m^3/s^2/kg} = 4.0 \times 10^{41} kg$$

   (c) *Calculate the mass of the Milky Way galaxy enclosed by a radius of 80,000 lyr (*$7.6 \times 10^{20} m$*).*

   We can calculate this mass the same way. First, we estimate the velocity from Fig. 16.1c to be about 250 km/s, which is $2.5 \times 10^{5} m/s$. Now calculate the mass:

   $$M_r = \frac{(7.6 \times 10^{20} m)(2.5 \times 10^{5} m/s)^2}{6.67 \times 10^{-11} m^3/s^2/kg} = 7.1 \times 10^{41} kg$$

(d) *Given your answer to part a, would you expect your answers in parts b and c to be **approximately equal**? Why aren't they?*

According to part a, the radius of the Milky Way is 50,000 lyr. So if we measure the mass within a radius of 50,000 lyr (like in part b), that should measure the entire mass of the Milky Way. However, when we measure the mass within a radius of 80,000 lyr (in part c), we find that the mass has almost doubled!

The radius of the Milky Way that we stated in part a is based on the stars that we can see making up the disk. However, since the mass of the Milky Way increased when we measured outside the edge of the disk, that must mean that there is more mass there that we can't see. Some of that mass is in clouds of gas, which we can observe at radio wavelengths. However, there are not enough gas clouds to make up that missing mass – there must be other mass that we can't see: dark matter!

8. *Discuss the two major possible types of dark matter that astronomers think might exist. Which type is believed to make up most of the dark matter in the universe?*

The two major types of dark matter are called MACHOs and WIMPS. MACHOs stands for MAssive Compact Halo Objects. These objects are composed of baryons, which are normal sub-atomic particles like protons, electrons, and neutrons. That means that MACHOs could be any objects that don't emit a lot of light, such as brown dwarfs, lost planets, or faint stars.

WIMPs stands for Weakly Interacting Massive Particles. These objects are made up of some type of sub-atomic particle we haven't yet discovered yet, but must not interact with matter much and must have a lot of mass (for a sub-atomic particle).

Astronomers have been searching for both MACHOs and WIMPs. A number of MACHOs have been found: many faint stars and brown dwarfs. However, not enough MACHOs have been found for them to possibly make up all the dark matter we know must exist. Consequently, most astronomers believe the WIMPs make up most of the dark matter, even though we don't even know what these particles are yet.

9. *Ch. 17, Review Questions, #10.*

The cosmic microwave background was produced at the end of the era of nuclei. This is when the temperature of the universe got low enough that nuclei and electrons could join together and form stable atoms: for example, protons and electrons attracted each other by their opposite charges and made hydrogen atoms. When that happened, waves of light stopped bouncing around from electron to electron and could travel long distances through the universe. When this happened, the universe was about 380,000 years old. That means that the light from the cosmic microwave background has been traveling through space for 13.7 billion years less 380,000 years, or $1.37 \times 10^{10} yr - 3.8 \times 10^{5} yr = 1.3699962 \times 10^{10} yr$. In other words, for most of the time the universe has existed!

10. *The Big Bang is often described as an "explosion", which makes people think that matter was blown outward into a huge, empty universe. Explain why this description is incorrect.*

At the beginning of the universe, all matter as well as all spacetime was compressed to an infinitely small size. In other words, the universe itself was infinitely small. When the Big Bang happened, spacetime itself began to expand outward in all directions. Since matter exists in spacetime, all matter was carried outward in all directions as spacetime expanded.

The idea that matter was exploded outward into empty space is incorrect because there was no empty space – empty space would be spacetime, but all spacetime was compressed down into an infinitely small space. Matter and spacetime have expanded together since the Big Bang.