UNIVERSITY OF KANSAS
Department of Physics and Astronomy
Physical Astronomy (ASTR 391) — Prof. Crossfield — Spring 2022

Problem Set 8
Due: Monday, May 2, 20222, 11am Kansas Time
This problem set is worth **60 points**.

As always, be sure to: type the solutions, show your work, circle your final answer, and use the appropriate number of significant figures.

1. **Active Galactic Nuclei [25 pts]**

   (a) [10 pts] Draw a rough sketch of the "Unified Torus Model" of an AGN. Label and describe the different components of the AGN.
   Solution: A search online can find dozens of AGN schematic diagrams. Go check them out!

   (b) [5 pts] A spectrum of a Seyfert-I AGN shows a very broad emission line of Hβ (hydrogen-beta, or H-beta) with a width of about 20 nm. Assuming that the line width is dominated by rapid rotation of material in the AGN's inner accretion disk, estimate the speed of the material.
   Solution: We can look up the Hβ line online and find that it has a central wavelength of 486 nm. Recal that the Doppler shift of light changes the wavelength λ_0 by an amount $\Delta lambda$, related to the speed by

$$\frac{\Delta\lambda}{\lambda_0} = \frac{v}{c}. \tag{1}$$

   Thus the speed of material orbiting around the center of this AGN must be something like

$$v \approx \frac{\Delta\lambda}{\lambda_0} c \approx \frac{20}{486} c \approx \boxed{0.04\,c \approx 12,000 \text{ km s}^{-1}}. \tag{2}$$

   (c) [5 pts] An astronomer takes a spectrum of a distant quasar and notes that the Hβ line has been shifted to a wavelength of roughly 680 nm. Estimate the redshift, z, of this quasar.
   Solution: Redshift is determined by the wavelength shift, $\Delta\lambda$, of a rest-wavelength λ_0 (which is related to the recessional velocity of the observed object):

$$z = \frac{\Delta\lambda}{\lambda_0} \tag{3}$$

   and the wavelength shift is just the difference between the intrinsic (rest) wavelength and the observed wavelength:

$$\Delta\lambda = \tag{4}$$

   So here, we have:

$$z = \frac{\Delta\lambda}{\lambda_0} = \frac{680 - 486}{486} = \boxed{0.4}. \tag{5}$$

   An object with a redshift of $z = 0.4$ would be at a distance of roughly 2 Gpc — two *billion* parsecs.

   (d) [5 pts] The elliptical galaxy M87 is 16 million pc (Mpc) from Earth. Its central supermassive black hole is 240 AU across; estimate the angular diameter of the black hole (in arc seconds) as observed from Earth.
   Solution: We can set this up as a standard (narrow!) astronomical triangle and use basic trigonometry, or alternatively we can remember that something 1 AU across and 1 pc away will be just 1" (1 arc-second) across. The physical size of the M87 black hole is 240 AU, so if it were at 1 pc it would appear 240" across on the sky (still just 4 arc-minutes, not so large). But actually it is 16 million times further away, so it will subtend an angle 16 million times smaller. In other words,

$$\theta_{BH} = 1'' \times \frac{240}{16 \times 10^6} = \boxed{1.5'' \times 10^{-5} = 15\,\mu\text{as (microarcsec)}}. \tag{6}$$

2. **Large-scale Structure. [10 pts]** Describe the various types of structure in the universe, from (relatively) small-scale individual galaxies on up to the largest scales.

   Solution:

   - **Individual galaxies**, such as the Milky Way or Andromeda (each of which have dozens of smaller, dwarf galaxy, satellites;
   - Groups, such as our Local Group, which have just a few "big" (Milky Way-scale) galaxies, plus their attendent satellites;
   - **Clusters**, such as the Virgo or Fornax cluster, which contain (at least) dozens of "big" galaxies. The Milky Way and Local Group are not considered to be part of any galaxy cluster, although they are part of ...
   - **Superclusters**, such as the Virgo Supercluster (which our Milky Way and Local group are members of), can contain hundreds to thousands of 'big' galaxies. Superclusters (like galaxy clusters) also tend to have the empty spaces around them filled with IGM (inter-galactic medium): hot, diffuse gas with a mass greater than that of all the stars in the galaxies making up the cluster!
   - **Filaments, walls, and voids**: Clusters and superclusters tend to be arranged in filamentary structures (a bit like the water that makes up a foamy lather of soap bubble). In between the densely-packed galaxy regions are cosmic 'voids' that are relatively empty, with few or no galaxies in them.
   - **The Universe.** Everything described above, as far as we can see!

3. **The expanding universe [25 pts]**

   (a) [10 pts] A classmate mentions to you that "Astronomers observe galaxies in all directions speeding away from us, so that means that we must be near the center of the Universe." Explain why this student's conclusion is incorrect, and what the proper interpretation is.

   Solution: While it's true that we observe almost all other galaxies (at least, those outside the Local Group) moving away from the Milky Way, it is not true that we are at or near the 'center of the universe.' Nor is it true that the universe necessarily has a 'center' at all. Instead, all galaxies are moving away from all other galaxies: so an observer in any part of the universe would still observe the same cosmic expansion of the universe (and they too might be briefly confused into thinking themselves the center of the cosmos!).

   (b) [5 pts] What is the approximate, currently-accepted value of the Hubble Constant? What is the significance of this quantity?

   Solution: The value of the Hubble constant is roughly

   $$\boxed{H_0 \approx 70 \text{ km s}^{-1} \text{ Mpc}^{-1}}. \tag{7}$$

   It is used in Hubble's Law to relate the distance and apparent recessional velocity of distant galaxies, as $d = v/H_0$.

   (c) [5 pts] A distant galaxy is observed to have a redshift of $z = 0.6$. Estimate the apparent velocity of this galaxy relative to the Milky Way, and use that (with Hubble's Law) to estimate its distance.

   Solution: The redshift just measures the Doppler shift of an object's spectrum:

   $$z = \frac{\Delta\lambda}{\lambda_0} = \frac{v}{c}. \tag{8}$$

   So if $z = 0.6$, the velocity is just

   $$\boxed{v \approx 0.6c \approx 180,000 \text{ km s}^{-1}}. \tag{9}$$

   This means that, with Hubble's law, the distance of the galaxy is roughly

   $$d = \frac{v}{H_0} \approx \frac{180,000 \text{ km s}^{-1}}{70 \text{ km s}^{-1} \text{ Mpc}^{-1}} \approx \boxed{2600 \text{ Mpc} = 2.6 \text{ Gpc}}. \tag{10}$$

   Over two billion parsecs away!

(d) [5 pts] A Type-Ia supernova is observed in a distant galaxy. Since this supernova can be used as a 'standard candle,' the distance to the galaxy is measured to be $\sim$700 Mpc (megaparsecs, or millions of parsecs). Use Hubble's law to estimate the relative velocity of this galaxy relative to the Milky Way, and its redshift z.

Solution: We use the same set of equations as above, but backwards. So for the galaxy's velocity we have

$$v = d \times H_0 \approx (700\ \mathrm{Mpc})(70\ \mathrm{km\ s^{-1}\ Mpc^{-1}}) \approx \boxed{49,000\ \mathrm{km\ s^{-1}}}. \tag{11}$$

This is roughly one-sixth of the speed of light, so we have a redshift of

$$z = \frac{v}{c} = \frac{49,000}{300,000} \approx \boxed{\frac{1}{6}}. \tag{12}$$