Astronomy 102, Spring 2003
Homework Set 5 Solutions

1. *Consider the following two facts: (1) Nearby elliptical galaxies have formed stars over a range of times (i.e. the stars weren't all formed right once, or right at the beginning of the Universe). However, they haven't formed any stars in the last 1-2 billion years. (2) The speed of light is not infinite. For instance, we are eight light minutes from the Sun, so when we look at light from the Sun, we're seeing it as it was eight minutes ago. Given these two facts, what might you expect to observe about the colors of elliptical galaxies observed billions of light-years away compared to the colors of nearby elliptical galaxies?*

When looking far away, we're looking back in time. If we enough billions of light years away, eventually we should be looking back to the time when elliptical galaxies were still forming stars. At that time, there would be hot, massive blue stars— which don't live very long, and hence are not seen in nearby elliptical galaxies (which haven't formed any new stars in the last couple of billion years). This will make those elliptical galaxies look bluer than the nearby ones, for the same reason that nearby spiral galaxies (which have star formation) look bluer than elliptical galaxies.

Many of you mentioned another effect: because of the cosmological redshift due to the expansion of the universe, the light that reaches us will be redder than it was emitted. As such, we might expect the distant elliptical galaxies (where light has had more time to travel and be redshifted by the expansion of the universe) to be redder than nearby galaxies. This is true– although when trying to figure out the "true" colors of a galaxy, we can easily enough correct for redshift. (Only one person mentioned both this effect and the star formation effect in the previous paragraph. Of course, if you put the two together, at the level of this course it's hard to figure out which effect is more important! (The redshift will make more difference for the most distance stars.)

Note: several of you were not clear that it is a younger *population* of stars that would make a galaxy forming stars bluer than a galaxy which hasn't formed stars recently. It is *not* the same stars which are now redder! Yes, stars do get redder at the end of their lives when they move to the red giant branch, but that's only the last 10% of their lives; on the main sequence, they don't change much in color. The cooler, red, low-mass stars we see in nearby elliptical galaxies were *never* hot and blue! Stars do not gradually get redder as they age; stellar *populations* do, because the higher mass (and, on the main sequence, bluer) stars die off sooner than the lower mass stars.

Note 2: To see star formation in elliptical galaxies, you really need to look back more than 2 billion years. They *are* a bit bluer, but that's only because stars a bit more massive than the Sun haven't died off yet (there are no very luminous hot blue stars, but those galaxies are still closer to the time when they were forming stars). Things are even more complicated than that, though. Galaxies in clusters merge with each other, so it's possible that some of the stars (probably not many) you see in an elliptical galaxy were actually formed in another galaxy (perhaps a small spiral or dwarf galaxy) which later merged with the elliptical. All of these are details beyond the scope of this problem, however.

2. Chapter 17, Question 15. *Assume the Sun is located 27,000 light-years* (2.6×10^{17} *km) away from the center of the Milky Way Galaxy, and is moving along a circular orbit at a speed of 220 km/s. How long does it take our Solar System to make one complete circuit around our Galaxy? Also answer: if the Galaxy is 14 billion years old, how many times has the Sun been around the Galaxy?*

If we're moving in a circle, the full distance to cover for one circuit is one circumference:

$$c \;=\; 2\,\pi\,r \;=\; 2\,\pi\,(2.6 \times 10^{17}\,\mathrm{km}) \;=\; 1.64 \times 10^{18}\,\mathrm{km}$$

The time it will take to go around is this distance divided by the speed:

$$t \;=\; fraccv \;=\; \frac{1.64 \times 10^{18}\,\mathrm{km}}{220\,\mathrm{km}s} \;=\; 7.4 \times 10^{15}\,\mathrm{s} = 240\text{ million years}$$

For some reason many of you were inspired to quote the number of years to way way WAY too many significant figures.

If the Galaxy is 14 billion years old, then the sun has been around:

$$\frac{14 \times 10^{9}\,\text{years}}{240 \times 10^{6}\,\text{years}} \;=\; 59\,\text{times}$$

Many of you pointed out a flaw in this question: the Sun is only 4.5 billion years old! As such, it hasn't been around orbiting for all 14 billion years of the Galaxy's life, and has only been around:

$$\frac{4.5 \times 10^{9}\,\text{years}}{240 \times 10^{6}\,\text{years}} \;=\; 19\,\text{times}$$

3. Chapter 17, Question 16. *A solar-type star (mass=*2×10^{30} *km), accompanied by its retinue of planets, approaches a super-massive black hole. As it crosses the event horizon, half of its mass falls into the black hole, while the other half is completely converted to luminous energy.*

(a) As it signals its demise in a burst of electromagnetic radiation, how much energy (in units of joules) does the dying solar system send out to the rest of the Universe?

(b) This is likely how quasars emit energy. If a luminous quasar has a luminosity of 2×10^{41} *joules/second, how many solar masses per year does this quasar consume to maintain its average energy output?*

(a) If half of the mass gets converted to energy, that means that we can use $E = mc^2$ with $m = M_\odot/2 = 1 \times 10^{30}\,\mathrm{kg}$.

$$E \;=\; (1 \times 10^{30}\,\mathrm{kg})(3.0 \times 10^{8}\,\mathrm{m/s})^2 \;=\; 9 \times 10^{46}\,\text{joules}$$

(b) There are two ways to do this. The easier way is to use the results of part (a): we know we get 9×10^{46} joules for dumping in one solar mass. Thus, we can figure out the mass rate needed to maintain a quasar's luminosity:

$$\left(\frac{1\,M_\odot}{9 \times 10^{46}\,J}\right)\left(\frac{2 \times 10^{41}\,J}{s}\right) \;=\; 2.2 \times 10^{-6}\,\frac{M_\odot}{s}$$

To convert this to years:

$$\left(2.2 \times 10^{-6}\,\frac{M_\odot}{s}\right)\left(\frac{3.15 \times 10^{7}\,s}{\text{year}}\right) \;=\; 70\,\frac{M_\odot}{\text{year}}$$

The other way to do this is to start with 2×10^{41} J and use $E = mc^2$ to convert that into a mass per year. However, here you have to be careful! For each quantity of energy you want to get out, you have to dump in *twice* that much energy in the form of mass. Many of you who solved the problem this way left out this factor of two, and just used $E = mc^2$ to do a conversion of the energy value you ere given to a mass value. (Unit conversions can get you a long way, but you have to be careful to make sure you know what you're doing; otherwise, it's very easy to leave out things like this.)

4. Chapter 18, Question 6: *How do we know that the stars in globular clusters are the oldest stars in our Galaxy?*

Two pieces of evidence. First, by looking at all the stars in a globular cluster and plotting them on the H-R diagram, we see a well defined main sequence turn-off. (This "turn-off" is a visual feature on the H-R diagram, not something that any individual star does, or that you could use to find the age of an individual star.) Dating the globular clusters from that, we see that they are almost as old as the whole Universe, and we've seen no other stars.

There is another important piece of evidence: globular clusters have the *lowest* heavy element abundance of any star seen in the galaxy. (It's not just that they have *low* heavy element abundances, but that no other star is seen with lower abundances.) Heavy element abundances tell you how many generations of stars the gas from which the star under observation has been through before the star under observation formed. If you have fewer heavy elements, you've been through fewer generations. Thus, the globular cluster stars must come from the earliest generation of all the stars we've seen.

Several of you made the mistake of equating "older star = lower heavy element abundance". This *correlation* exists, but there are certainly exceptions. The Sun, for instance, even though it's 5 billion years old, has more heavy elements than some stars in the galaxy that are forming right now. Gas at different places in the galaxy goes through generations of star formation at different rates, so while *generally* stars that form later will have more heavy elements than stars that form earlier, it's more complicated than just that.

5. Chapter 19, Question 6. *As astronomers extend their distance ladder beyond 100 Mly, they change their standard candle from Cepheid variables stars to Type Ia supernovae. Explain why this is necessary.*

Simply because Type Ia supernovae are so much more luminous than Cepheid variables. Cepheid variables are giant stars, and are luminous for stars... but a Type Ia supernova can be as luminous as an entire galaxy. Objects of a given luminosity look dimmer and dimmer as they are farther and farther away. Beyond some point, the distance will be too great to be able to get a good measurement of Cepheid variables, simply because they will be too dim. SNe Ia, on the other hand, are so much more luminous that they can be seen to much greater distances.