Astronomy 102, Fall 2003

Homework Set 6 Solutions and Commentary

1. *In class, we discussed that about 2/3 of the energy density of the Universe is in dark energy. What makes up most of the energy density of our Galaxy? How do you know? Is this at odds with dark energy making up most of the energy density of the Universe? Why or why not?*

Most of the energy density of the Galaxy is made up of dark matter. For those of you worried about the difference between "energy density" and normal density (or "mass density"), remember that $E = mc^2$. Most of the energy density of the Galaxy is in the form of mass, specifically, the mass of dark matter. We know that dark matter must be there because stars farther out from the center of the galaxy orbit faster than they would given the gravity from the matter we see. Note that the gravity of this dark matter is attractive, like normal matter. It's what holds the galaxy together. Dark matter is very different from dark energy!

This is not at odds with most of the Universe being made up of dark energy, simply because dark energy is probably distributed throughout the Universe uniformly (or very close to that), while dark matter is clumped in galaxies and clusters. Dark matter in our galaxies is distributed more smoothly than the stars are, by a long shot, but there's no dark matter in the huge voids between galaxies. Dark energy, however, is everywhere; not only in the voids, but also in galaxies, and in the room you are in.

2. *When we look to distant redshifts, we sometimes say we are looking back to the "era of deceleration". Suppose that dark energy acts like Einstein's cosmological constant, i.e. its density is constant and does not change as the Universe expands. If the Universe's expansion is accelerating now, why would we say that the expansion is decelerating for galaxies with very high redshifts?*

There are a few points in here. First is to recognize that we are looking back in time when we look at very distant objects in the Universe. The way it is stated is a little non-obvious, however, unless you're an astronomer used to this terminology. Strictly speaking, cosmological redshifts don't have anything *directly* to do with distance; instead, they tell you how much the Universe has expanding. However, since the Universe has been expanding ever since the big bang (i.e. it's never been contracting), the more expansion you see, the further back in time you must be looking, and thus the greater the distance to which you must be looking.

When you look at a very high redshift, you are looking at the Universe when it was much smaller than it is today. That means that all of the mass (normal matter and dark matter) which is spread through the Universe now was compacted closer together, and thus there was a higher normal matter density. The gravitational attraction of all of that mass for each other would have been greater as it was at a higher density. However, if the dark energy *density* was the *same*, the effect of dark energy would be similar to what it is now. Thus, if you go back far enough in time, you'll reach a point where the matter was compressed enough that its attractive gravitational effect could overcome the repulsive gravitational effect of the dark energy. At this time, then, the expansion of the Universe would have been decelerating, in contrast to today, when dark energy overcomes matter and the Universe is accelerating.

Note 1: One very common misconception was that it is the wavelengths of light decelerating. The argument went that they were losing energy due to the redshift, and thus that was what was "slowing down". This is wrong. Yes, photons which are shifted to longer wavelengths are shifted to lower energies; however, they always move at the same speed, the *speed of light*. This question was talking about the acceleration or deceleration of the expansion of the Universe itself, not the light that we use to look at that Universe.

Note 2: Many of you tried to argue that seeing a deceleration was somehow an optical illusion. In fact, this is not the case. (There is something called "superluminal motion" in active galactic nuclei which *is* an optical illusion— nothing there is really going faster than the speed of light— but with respect to the expansion of the Universe, when we say we are seeing a deceleration, we've taken into account out all the effects that the expansion has had on the light itself.)

Note 3: A few of you used terms such as "the deceleration of the acceleration", which don't really make sense. An acceleration is a speeding up of the *rate* of expansion, and a deceleration is a slowing down of the *rate* of expansion.

Note 4: A few of you made the argument that the Universe is accelerating, but since we're looking back in time we see it decelerating. This also isn't correct. I moved from California to Tennessee a few years ago. Yet, looking back on that, I wouldn't say that I moved west, just because I'm looking back on it now. . . .

3. *A typical Cosmic Microwave Background (CMB) photon observed today has a wavelength of 1 mm (=10-3 m). The CMB was emitted more than 13 billion years ago, when the Universe was about 1/1100th its current size. What was the wavelength of a typical CMB photon when it was emitted? Is this in the visible range of the electromagnetic spectrum? If so, what color would it be? If not, in what range of the electromagnetic spectrum is it?*

The cosmological redshift is:

$$1 + z = \frac{\text{Size Now}}{\text{Size Then}}$$

so we have

$$1 + z = 1100$$

Redshift affects measured wavelengths of light according to:

$$z = \frac{\lambda_{\text{obs}} - \lambda_{\text{em}}}{\lambda_{\text{em}}}$$

two lines of algebra can change this to:

$$1 + z = \frac{\lambda_{\text{obs}}}{\lambda_{\text{em}}}$$

The observed wavelength (λ_{obs}) is the wavelength now, so we can figure out the emitted wavelength with another two steps of algebra:

$$\lambda_{\text{em}} = \frac{\lambda_{\text{obs}}}{1 + z}$$

$$\lambda_{\text{em}} = \frac{10^{-3}\,\text{m}}{1100}$$

$$\lambda_{\text{em}} = 9 \times 10^{-7}\,\text{m} = 0.9\,\mu\text{m}$$

Light at $0.9\,\mu$m ($= 9000\,$Å) is at a slightly *longer* (larger) wavelength than the edge of the visible spectrum, which puts it in the near-infrared region of the spectrum.

4. *Recall your results on last week's homework for the age of the Universe assuming that the expansion rate hadn't changed. In the absence of dark energy, the Universe's expansion rate would have been slowing down since the big bang. Before the discovery of dark energy, there was a cosmological age crisis, in that the oldest stars in (found in globular clusters around our Galaxy) are known to be about 13 billion years old, whereas many cosmologists thought the Universe had a mass density equal to the critical density and was less aged! Without dark energy, and given a current expansion rate, would you need a Universe that is very low density or very high density to accommodate these old globular clusters? Why? Would cosmologists led to conclude this value of the mass density believe that the Universe would recollapse in a Big Crunch, or expand forever into a Big Chill?*

In the absence of dark energy, it is the matter density that governs the rate of change of the expansion of the Universe. In a high matter density Universe, the gravitational attraction between all of that matter would be higher, which would tend to really put the breaks on the Universe's expansion. If it's slowed down a lot, then it must have been a lot faster in the past. In contrast, if the mass density is very low, then it hasn't slowed down as much, and the expansion rate in the past is more similar to today's.

What does this have to do with the age of the Universe? Instead of the expansion of the Universe, think about the motion of a car. A car is going 10mph. Suppose that one mile back, it was going a lot faster, say 60mph, and it's been slowing down since. Compare this to another car, also going 10mph, but which was only going 20mph a mile back. Which car covered that mile in less time? Obviously, the one which as slowed down more, because it's average speed was higher.

Similarly, a dark-energy-free high-mass Universe, which has decelerated *more* than a low-mass Universe, will have needed *less time* to get from the Big Bang to where we are now than the low-mass Universe would need. If your globular cluster ages tell you you need a Universe absolutely as close to the no-deceleration limit (analogous to how long it would have taken that car to go a mile if it was going 10mph the whole time) of 13 billion years as you can push it, then they would tend to suggest that we must be living in a very low mass Universe.

(Meanwhile, cosmological theorists believed we were in a critical mass Universe, because that solved various other problems. It was only with the introduction of dark energy that we were able to solve all the problems at once. In an accelerating Universe, you can have a Universe which is even older than a dark-energy-free low-mass Universe, but which has critical energy density— much of that density now being made up of dark energy rather than dark matter and normal matter.)

5. *Nucleosynthesis in the Big Bang created only Hydrogen, Helium, and a little Lithium, and almost nothing else. However, observations of interstellar gas clouds show a measurable concentration of Carbon, Oxygen, Iron, and other elements. What can you conclude about the gas in these interstellar clouds? (You may not know the answer to this question, but you should recognize at least that there is a problem! In a couple of weeks, we will have discussed everything you need to know to understand the answer to this question.)*

The gas produced by the Big Bang only had the lightest elements. However, interstellar gas shows heavier elements. This means that the interstellar gas can't have come directly from the Big Bang without other things having happened to it.

It turns out that the Universe's forges are stars. Stars are powered by nuclear fusion— the combining of lighter elements to make heavier elements. This means that much of the interstellar gas we see, which has heavier elements, must have at one point been *inside a star*, and been somehow thrown back out into the interstellar medium. Otherwise, there would have been no way to build up the heavy elements that are seen.