General relativity, 6

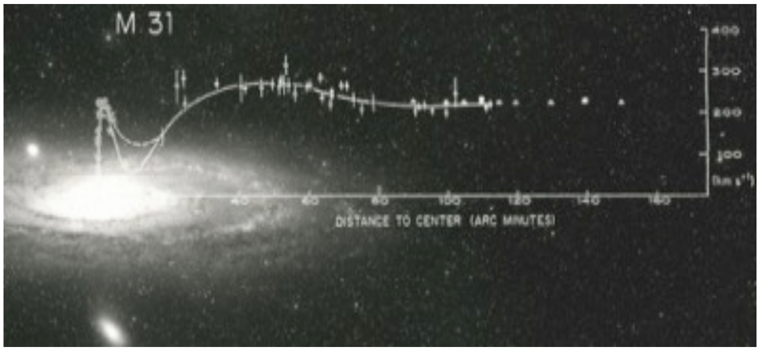
Modern cosmography

The “normal” matter in the universe—i.e., stuff made of protons, neutrons, and electrons—forms lumps floating in a dilute fog. The lumps are galaxies, clusters of 10^7 to **10^{11} stars** bound together by gravity. In the currently observable universe, it is estimated that there are roughly **10^{11} galaxies**. The dilute fog is **primarily neutral atomic hydrogen gas with some helium-4 mixed in** (making up a total of 98% or more of the fog); there are also very small fractions of ^2H (deuterium), ^3He, and ^7Li. The ratio of hydrogen to helium is about 3:1 in terms of mass and about 10:1 in number of atoms. The total mass in the gas clouds is much larger than in galaxies. On average the density of ordinary, visible mass in the observable universe is equivalent to about **one proton per cubic meter**. Thus, there is almost no ordinary matter (on average) in the universe.

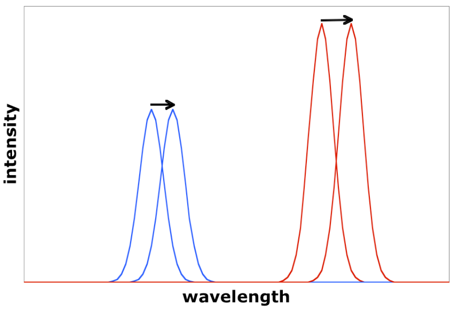
The universe is also filled with electromagnetic radiation, the vast majority of which is in the *microwave* region of the spectrum. The average energy density of **radiation** in the universe **is about 0.1% that of the visible mass** energy. So there is also almost no radiation (on average) in the universe, either. Galaxies are not uniformly spread out. They appear to form larger structures (clusters) that viewed at great distances remind one of irregular spider webs. On the other hand, the intensity of the cosmic microwave background (CMB) radiation falling on Earth *is extraordinarily uniform* in all directions; this lack of structure tells us that the source of the CMB must *not* be associated with the galaxies. Importantly (as we will see), there are **about 1 billion CMB photons for every proton in the universe**.

In our region of the “Milky Way” galaxy, stars are a few light years apart, so the stellar density near us is roughly 1 star/100 ly^3. (Recall: 1 ly = distance light can travel in one year $\approx 10^{16}$ m. By comparison, we are 8 light-minutes from Sun [a light year $\approx 5\text{x}10^5$ light-minutes], and the solar system is about 10 light-hours across [a light year $\approx 10^4$ light-hours]; the diameter of the solar system is a puny fraction of a ly.) This works out to about 10^7 protons/m^3, vastly higher than the overall average. Our galaxy (assuming it contains about 10^{11} stars) must spread out over 10^{13} ly^3 or so, implying a diameter of 10^4 to 10^5 ly. That’s probably a typical value for other galaxies.

In most galaxies the intensity of light falls off exponentially with increasing radius: $I(r) \propto \exp(-r/D)$. Given that light intensity is proportional to the mass emitting the light, one would expect that more-or-less all of the mass of a galaxy would be contained within a sphere of radius $r = 2D$ to $3D$. Galaxies rotate, so one would expect the orbital speed of a test mass at radius r to be given roughly by $v^2(r)/r = GM(r)/r^2$. In other words, at the edge of the galaxy, i.e., for $r > 3D$, the orbital speed should drop off like $1/r^{1/2}$. In fact, for almost all galaxies the orbital speed—as determined by Doppler shift of hydrogen emissions, such as the 21 cm radio waves—approaches a *constant value* for radii much larger than $3D$. See the figure to the right. (http://www.dtm.ciw.edu/content/view/122/168/) This implies that ***M*** **continues to *increase* as *r***



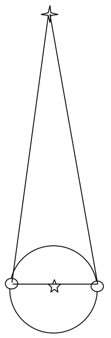
increases for distances much larger than where the visible light stops. This invisible mass is called "**dark matter**." Its existence was first suggested in the 1930s, but was only convincingly inferred from measurements made by **Vera Rubin** and her colleagues in the 1970s. We now know that there is about **five times more dark mass than electromagnetically radiating mass** in the universe. (See also GR 4. Note that Rubin's discovery preceded the corroborating observations of gravitational lensing. You might think that such an important discovery would have merited a Nobel Prize, but it didn't. Rubin received lots of other recognitions, including the US Medal of Science, but not the Big One. Unfortunately, she died on Christmas Day, 2016.) In addition to not emitting or reflecting electromagnetic radiation, this dark matter has another strange property. It seems to be spherically distributed around a galaxy. (Again, look at GR 4.) This is strange because rotation, gravity, and energy dissipation—typically in the form of electromagnetic radiation—tend to cause galaxies to flatten into disks. A galaxy's **dark mass doesn't radiate, so it can't settle into a flattened shape**!



Among the most profoundly important characteristics of the observed universe is **galactic red shift**. Here's what's involved. Suppose you are at rest with respect to the center-of-mass of a cloud of glowing gas. The light emitted by each atom will have certain characteristic "colors" or frequencies (that can include IR and UV). If you pass this light through a spectral analyzer you'll see a spread of frequencies around each characteristic color due to the Doppler shift caused by atoms moving toward and away from you. Now, if you are moving relative to the center-of-mass of the cloud or if the cloud is at a different gravitational potential from you, *all* characteristic colors will be shifted by the same *fractional* amount, as in the figure to the right, either to the red or to the blue. *All* is important: other mechanisms can cause reddening of light, such as scattering by dust particles—you see that in sunsets on Earth. But, different frequencies are scattered differently, meaning that the fractional shift is *not* the same for every color. What is observed about galaxies is that essentially all show a consistent spectral shift across all frequencies. We'll call that "the galactic spectral shift." Though some galactic spectral shifts are blue, the *overwhelming* majority (of the hundreds of thousands measured) is red. The amount of galactic spectral shift is usually reported as a z-value, where $z = \left(\lambda_d - \lambda_e\right)/\lambda_e$, and where the λs are the "detected" and "emitted" wavelengths of the light coming from the galaxy. The highest confirmed galactic z to date is around 10. If the shift were due to the speed of the emitter relative to us, such a value would correspond to a recessional speed of about 98% the speed of light! Of course, gravity can cause a red shift also. If this z value were due to the gravity of the galaxy, the radius of the galaxy would only be (1+1/121) times its Schwarzschild radius. As we'll see below, there's a very well established correlation between a galaxy's red shift and its distance from us. It's hard to see why more distant galaxies should be systematically more condensed and, in any case, gravity doesn't explain blue shifts.

Galactic red shift and distance

Modern cosmography is founded in large part on the work of **Henrietta Leavitt**, an American astronomer who is only recently receiving the recognition she deserved. Leavitt had to struggle against gender prejudice in science. (Rubin experienced that, as well.) Though she was widely regarded as the smartest person working in the early 1900s in astronomy at the Harvard Observatory—where after seven years of unpaid volunteering she finally became employed at a wage of 30 cents/hour (!)—she could not pursue her own interests in theoretical astrophysics and instead had to labor endlessly analyzing innumerable photographic plates. That was serendipitous, though. She accidentally discovered (in 1912) that the absolute brightness of a special kind of variable star—a “**Cepheid variable**”—is a very specific function of the period of variation.



It’s not easy to measure distances to remote stars and galaxies: you don’t know *a priori* how big and bright the objects are. Distances to stars close to us can be measured by the phenomenon of **parallax**. Close-by stars appear to shift position relative to very distant stars because of Earth’s annual motion about the Sun. Knowing the diameter of Earth’s orbit and measuring the maximum angular shift in stellar position permits one to calculate the distance the star is from Earth. See the figure to the right. Unfortunately, this only works for stars that are within about 300 ly from us, well inside the Milky Way. Now, *some Cepheids* have measurable parallaxes. By measuring their maximum apparent brightness and determining their distance by parallax, it is possible to infer their absolute brightness. From this, an empirical rule (now known as Leavitt’s Law) can be deduced for connecting absolute brightness to period. Knowing this relation, one can tell how far away any Cepheid variable is (since apparent brightness falls off from its absolute value with distance squared). In other words, Leavitt’s discovery provided us with the first “standard candle” to measure distances where parallax fails. Using it demonstrates that some stars in the Milky Way were staggeringly farther away (tens of thousands of ly) than had previously been imagined.

As important as Leavitt’s discovery was for rescaling our own galactic environment, its true importance was demonstrated in 1923 by **Edwin Hubble** (after whom the Hubble Space Telescope is named). Before Hubble’s work, it was commonly held that the Milky Way was the *whole* universe. As larger optical telescopes became available, it also became clear that in addition to point-like stars the sky was also filled with little fuzzy blobs. These so-called “nebulas” were interpreted as clouds of some kind, but residing inside the Milky Way. In 1923, Hubble discovered a very bright Cepheid in the Andromeda Nebula. Knowing its period and measuring its brightness allowed him to conclude that this Cepheid was almost one million ly away! Andromeda was not a cloud in the Milky Way but a huge body of stars far outside the Milky Way. Using Leavitt’s Cepheid standard candle, Hubble discovered that the universe was filled with other Milky Ways—other galaxies. When this result was made public in 1924 it had a shocking effect. Not only was Earth *not* the hub of the Milky Way (as had been demonstrated by others earlier) but also, now, the Milky Way was *not* a particularly central part of the universe.

Hubble didn’t rest on his laurels. He and co-workers began to identify lots of other galaxies. They noticed that the light from galaxies often was shifted. The Cepheid meter stick could measure distances to some of the newly identified galaxies. The galactic spectral shifts of the closest galaxies didn’t seem to obey any rule, but **the more distant the galaxy, the redder the shift**. Other standard candles soon became available, and in short order it was apparent that z was really a measure of galactic distance.

Both Leavitt and Hubble should have been awarded the Nobel Prize (and Rubin, too). In fact, nominations were prepared for both, Leavitt in 1924 and Hubble on several occasions. Leavitt’s nomination was withdrawn after it became known to the nominator that she had died three years earlier (Nobels are not awarded posthumously). She was so quiet and unassuming, few people knew of her great achievement. Hubble, on the other hand, was very self-confident and a strong self-promoter. In the late 1940s, he actually hired a publicist to run a Nobel election campaign. That probably didn’t go over well with the staid Swedish Nobel Committee. In any event, Hubble died in 1953, apparently just as the Committee was finally preparing to honor him.