A1143: History of the Universe, Autumn 2012

11. Dark Matter and Exotic Energy

Reading: Re-read sections 7.4 and 7.5. We had them on a previous assignment, but you are now in a better position to understand them. Then read Chapter 11, and Chapter 12.3.

The rest of Chapter 12 is optional.

A Note on Terminology

I have so far used the term "exotic energy" to refer to a form of energy that has strong negative pressure and therefore produces repulsive gravity.

The book uses the term "dark energy," which has become the standard term in the cosmology community.

These are different terms for the same thing. For purposes of this course, I have used "exotic energy" to minimize confusion with "dark matter."

Dark matter is *not* the same thing as dark energy (or exotic energy).

Dark matter exerts *attractive* gravity, holding galaxies together.

Exotic/dark energy exerts *repulsive* gravity, causing the expansion of the universe to speed up instead of slowing down.

Evidence for the Big Bang Theory: Recap

We have the following key pieces of *empirical* evidence for the big bang theory (as defined in the previous section):

- GR is a very accurate description of gravity on solar system scales. [1915 - present]
- Hubble's law shows that the universe is expanding, in a pattern ($v = H_0 d$) that is consistent with a homogeneous universe ("the center is everywhere"). [1929]
- Large scale maps of the distribution of galaxies and quasars are also consistent with a universe that is homogeneous when averaged over large scales. [1960s - 1990s]
- The estimated ages of the oldest stars, about 13 billion years, are similar to the age $t_0 \approx 1/H_0$ inferred from the expansion rate. [1950s - 1990s]
- The 25% helium abundance found in old stars agrees well with the amount of helium that should be produced in the hot early universe (big bang nucleosynthesis). We have no good alternative explanation for this much helium in the oldest stars. [Mid-1960s]
- The 0.001% deuterium abundance found in old intergalactic gas clouds agrees well the amount of deuterium that should be left over from the hot early universe ("escapees" that didn't get fused into helium). We have no good alternative explanation for this deuterium. [1970s - 1990s]
- Space is filled with a cosmic microwave background (CMB), coming from all directions, with a blackbody spectrum of photon energies. This is exactly what we expect for the leftover radiation from the hot early universe. There is no good alternative explanation for the CMB. [1965]

Open Questions

We would like to know:

- What is the geometry of space?
- What forms of matter and energy does the universe contain?
- Why does the universe have structure (galaxies, clusters of galaxies, and so forth)?
- Why does a universe with the properties that we observe exist in the first place?

Geometry, Matter, and Energy: Recap

Here's what we have learned so far about geometry, matter, and energy.

1. The angular size of spots on the CMB implies that the geometry of space is very close to flat.

This requires that the total density of matter and energy in the universe is very close to the critical density: $\bar{\rho}_{\mathrm{tot}} = \rho_{\mathrm{crit}}$.

This evidence dates to 1999-2000, with balloon-based experiments that made maps of the CMB.

2. At the very least, the universe contains:

- atoms (made of protons, neutrons, and electrons)
- photons, in particular large numbers of CMB photons (discovered 1965)
- dark matter, detected by its gravitational effect in holding galaxies together in clusters and accounting for the flat rotation curves of disk galaxies. First evidence from the 1930s.

By adding up the mass of galaxies (which includes stars, gas, and dark matter) and dividing by the volume they are spread over, we find $\bar{\rho}_{\mathrm{matter}} \approx 0.25\rho_{\mathrm{crit}}$.

3. Observations of distant supernovae show that the expansion of the universe is speeding up, not slowing down.

This evidence dates to 1998-1999, with the first large surveys of distant supernovae.

The attractive gravity of matter should cause the expansion of the universe to decelerate.

Explaining accelerating expansion requires exotic energy, with strong negative pressure that causes repulsive gravity.

Reproducing the supernova observations requires $\bar{\rho}_{\mathrm{exotic}} \approx 0.75\rho_{\mathrm{crit}}$. More exotic energy than attractive matter $\Longrightarrow$ repulsion wins over attraction.

Adding the matter density and the exotic energy density gives $\bar{\rho}_{\mathrm{tot}} = \rho_{\mathrm{crit}}$, as required to explain the geometry inferred from the CMB.

The Formation of Structure

The CMB is extremely smooth — differences in temperature in different directions are less than 0.01%.

This tells us that the early universe (at $t = 400,000$ years) was filled with smoothly distributed hot gas: no galaxies, stars, etc.

A region that starts out *slightly* above the average density has stronger gravity, so it will expand more slowly than its surroundings.

The excess density builds up over time, and eventually this region can collapse under its own gravity.

A region that starts out *slightly* below the average density has weaker gravity, so it will expand faster than its surroundings, and eventually lose its material to the surrounding regions.

Bottom line: If the early universe is smooth but not perfectly smooth, gravity can amplify the primordial bumps and wiggles into high contrast structure.

Over time, larger and larger structures can form.

Computer simulations of this process show that it produces filamentary structures, rounded tunnels and voids, and dark matter halos similar to those shown by astronomical observations.

Fluctuations in the CMB

For this gravitational explanation of structure to work, there must have been small bumps and wiggles in the early universe for gravity to act on.

These should produce small fluctuations in the temperature of the CMB in different directions, at a level of 0.001%.

After decades of steadily improving measurements, these fluctuations were finally detected in 1992, by the Cosmic Background Explorer (COBE) satellite.

They have been mapped with much higher resolution and precision by (many) subsequent experiments, such as the Boomerang balloon experiment and the WMAP satellite.

There are CMB fluctuations on all scales, but they are strongest at a particular scale determined by the speed of pressure waves in the early universe.

This preferred scale of CMB spots is what we use to measure the geometry of space.

The fluctuations in the CMB have the right properties to grow into the galaxies and clusters of galaxies that we observe today, *if* the universe is about 20% dark matter, 5% atoms, and 75% exotic energy.

If you go far away from these values, it no longer works — you don't predict the right structure today.

Dark Matter: What is it?

First a bit of technical terminology.

Protons and neutrons are collectively referred to as baryons.

(There are other baryons as well, but they are unstable particles that live only for a very short time. Bary comes from the Greek word for heavy.)

If dark matter is made principally of protons and neutrons (and their accompanying electrons, which have much less mass), we would say it is *baryonic.*

Could dark matter be baryonic?

The first challenge is to hide the baryons in some non-luminous form. Some ideas and problems:

- Black holes: Black holes would indeed be dark, but they would have to outnumber present day stars, and we should see (in distant galaxies) the light from the early stars that formed them.
- Snowballs: Frozen "snowballs" of hydrogen, held together by chemical forces, would be dark, but they would melt in the glow of the CMB.
- Gas clouds: Depending on their temperature, gas clouds are normally detectable in either visible light, or radio waves, or X-rays. It's very hard to make them totally dark.
- "Jupiters": Balls of hydrogen and helium, held together by gravity, but not massive enough to ignite fusion and shine as stars. These would be OK, if there is a way to form them in sufficient numbers.

But there is a *general problem* facing any form of baryonic dark matter.

The abundance of deuterium allows us to infer the average density of baryons in the universe: if the density were higher, then a smaller fraction of deuterium nuclei could have "escaped" being fused into helium in the early universe.

The measured deuterium abundance in old intergalactic gas clouds implies that the average density of baryons in the universe is 5% of the critical density.

The intensity of spots on the CMB gives (by a convoluted path that I won't try to explain) an independent estimate of the baryon density, which agrees with the one from deuterium.

But measurements of dark matter imply that it is 25% of the critical density.

Therefore *there are not enough baryons to account for the observed amount of dark matter*, falling short by a factor of five.

Most of the dark matter must be something else.

WIMPS

Our leading idea at present is that dark matter consists of a weakly interacting massive particle (WIMP), not yet discovered in laboratory experiments.

Here "massive" means roughly 10-1000 times the mass of the proton.

Weakly interacting means not affected by electromagnetism or the strong nuclear force.
WIMPs would still be affected by gravity and by the weak nuclear force.

The best known weakly interacting particle is the neutrino — hypothesized in the 1930s and discovered directly in the 1950s.
There are lots of neutrinos created in the hot early universe (similar to the number of CMB photons), but a typical neutrino can pass through the earth without noticing.
If neutrinos have a small mass, about 10^{-8} of the proton mass, then they could account for dark matter.
Neutrinos would still be moving rapidly at the time that galaxies formed, so they are referred to as "hot" dark matter.
However, theoretical studies in the 1980s showed that hot dark matter does not explain galaxy formation well, and current measurements indicate that the neutrino mass is less than 10^{-9} of the proton mass, not enough for them to be the dark matter.

The great thing about WIMPs is that if you calculate how many should be left over from the hot early universe, you find that they naturally give the observed amount of dark matter.
Massive particles would move slowly at the time of galaxy formation, making them "cold dark matter," which turns out to explain observed galaxy properties much better.
Because they are weakly interacting, they do not produce light, and they can orbit in galaxy halos without colliding with each other and sinking to the middle.
Computer simulations that have cold dark matter, baryons, exotic energy, and the initial conditions implied by observed CMB fluctuations agree very well with the observed clustering of galaxies.

Dark Matter: Where is it? How much is there?
We detect dark matter by its gravitational effect on matter that we can see.
We know that there is dark matter in extended halos around galaxies and groups of galaxies.
Roughly speaking, for a typical galaxy like the Milky Way, the dark matter extends about 10 times further than the stars, and the total mass of dark matter is about 10 times the mass of the stars.
(Example numbers for the Milky Way: Stars go out to about 20 kpc. Dark matter halo extends to about 200 kpc. Total mass of stars is about $10^{11} M_\odot$. Total mass of dark matter is about $10^{12} M_\odot$.)
If, as in Homework 3, Part III, you multiply the typical mass per galaxy by the number of galaxies per volume, you find an average density $\bar{\rho}_{\rm matter} \approx 0.25\rho_{\rm crit}$.

We see large, nearly empty voids in the distribution of galaxies (e.g., the "bubbles" in the SDSS map of the universe on the main course web page).
Perhaps the voids could still have dark matter, even though they don't have galaxies. Maybe the voids could hold enough dark matter to allow $\bar{\rho}_{\rm matter} = \rho_{\rm crit}$.
This was a matter of major debate in the 1980s and early 1990s, since the theory of inflation predicted a flat universe.
Now the combination of acceleration measurements from supernovae and geometry measurements from the CMB tells us that space *is* flat but not because $\bar{\rho}_{\rm matter} = \rho_{\rm crit}$.
Instead $\bar{\rho}_{\rm matter} = 0.25\rho_{\rm crit}$ and there is exotic energy, producing repulsive gravity, with $\bar{\rho}_{\rm exotic} = 0.75\rho_{\rm crit}$.
Thus, most of the dark matter *is* in the extended halos around galaxies.

Exotic Energy: What is it?
We have a good idea of what dark matter *might* be.
We have several ideas of what exotic energy might be, but they all seem rather implausible.
We do know, from atomic and sub-atomic experiments, that "empty" space is filled with "virtual" particles, which briefly pop into existence and then disappear.

These are an inevitable consequence of the uncertainty principle of quantum mechanics.

The simplest explanation of accelerating cosmic expansion is that it arises from the gravitational effect of these virtual particles, i.e., the repulsive gravity of "vacuum energy."

However, it is difficult to understand why repulsive gravity of the vacuum would not be much, much stronger (making the universe double in size every trillionth-of-a-trillionth of a second).

At present, we have no good explanation of how the acceleration caused by the quantum vacuum could be as low as the acceleration we actually see.

Searching for the dark

Two of the major goals of contemporary cosmology are to discover what dark matter is and to learn more about exotic energy.

If the WIMP idea is right, then we might discover dark matter by

(a) creating dark matter particles in an accelerator experiment, like the one that discovered the Higgs boson

(b) detecting the rare events when a dark matter particle "hits" an atomic nucleus and produces a recoil, in a sensitive experiment buried deep underground to avoid radioactivity.

(c) detecting gamma rays produced by the occasional annihilations between dark matter particles and their anti-particles.

Lots of effort is going into all three of these directions.

If the vacuum energy idea is right, then the density of exotic energy (energy per unit volume) is always the same, throughout time and space.

The density of *matter* drops as the universe expands, so the expansion of the universe was once driven by the decelerating effect of matter but is now driven by the accelerating effect of exotic energy.

The vacuum energy idea is consistent with current measurements.

With better studies of supernovae and galaxy clustering and gravitational lensing, using large surveys from the ground and from space, we aim to test these predictions much more precisely, and maybe find some discrepancy that gives us a more direct clue to why the universe is speeding up.