THE UNIVERSE IN THE CLASSROOM

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The Universe: the 2014 Model.
Part II. Cosmological Puzzles (and Ways to Resolve Them)

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In Part I, we presented evidence that (a) the Universe is expanding, isotropic and homogeneous; (b) it has nearly flat, Euclidean geometry; and (c) it is filled with the cooled-down remnants of a Hot Big Bang.

We also raised a puzzling issue centering on the average density of the Universe. If the curvature of space is small, the total density ought to be near the special value of 9 x 10^{-30} gm/cm^3. If we count up all the ordinary matter in atoms, planets, stars and galaxies, however, this observed density is much smaller. Are we missing something?

Dark Matter

Yes. One contributor to the density is Dark Matter, matter that, unlike ordinary matter, does not interact with light in any way. Here it is important to point out that Dark Matter is not the same as black matter (say a charcoal briquette). Charcoal does interact with light — by absorbing it. Dark Matter does nothing to light. That, of course, makes it difficult to detect: we can't "see" it. All cosmic Dark Matter does is to exert gravity. The notion there is a different (and "Dark") form of matter has a long history. Fritz Zwicky first posited it some 80 years ago. His studies of the motions of galaxies in clusters of galaxies, like the one shown in Figure 1, indicated they would fly away unless there was sufficient mass to hold them together gravitationally. The mass of all the galaxies alone was not enough — more was needed. But it doesn't show up in photos like Figure 1 — hence it must be "Dark."

Using a similar argument, Vera Rubin made the argument for Dark Matter both more quantitative and more convincing. She showed that the rotation of spiral galaxies (Figure 2) would rip them apart unless more matter was present in them than just the mass of their stars alone. Dark Matter was needed to hold in the rapidly moving stars in the outer reaches of the galaxies.

Figure 1. A cluster of galaxies (Abell S1077) held together gravitationally. (Image: ESA/Hubble & NASA. Acknowledgement: N. Rose)

You may have noticed by now what seems like a contradiction. I've written both that galaxies (and clusters) contain Dark Matter, and that the mass of all the galaxies is too small to bring the average density up to 9 x 10^{-30} gm/cm^3. Surely, you may be thinking, the Dark Matter must count when we

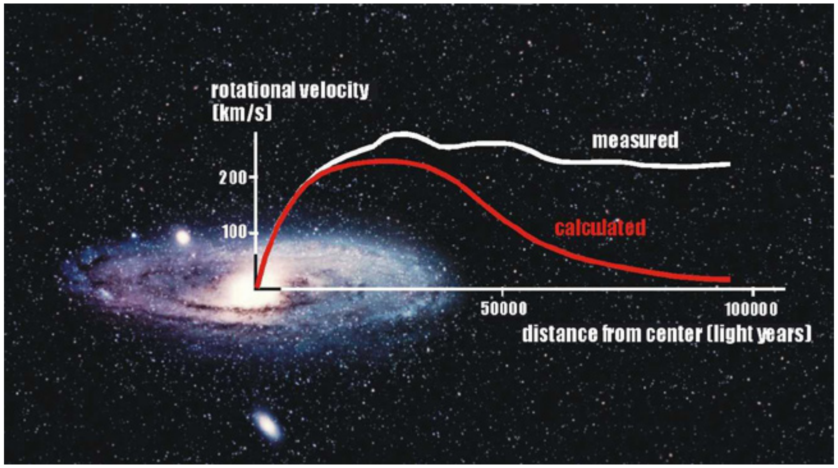

Figure 2. If only the mass of visible stars contributed to the gravitational force holding a galaxy together, we would expect a sharply decreasing rotational speed as the distance from the galactic center increases beyond a few thousands of light years (as shown in red). Instead, the measured velocities change little with distance from the center. Additional mass — Dark Matter — is required to hold the stars in. (Image from SuperCDMS at Queen's University)

add up the mass of galaxies. Even if we include it, however, the average density in any chunk of the Universe remains far too low to ensure a flat geometry. Something is still missing. Some of this missing mass, of course, could lie outside the galaxies: there is no reason there shouldn't be Dark Matter outside as well as inside the galaxies. If we can't see it, how can we know how much Dark Matter there is, and where it is?

It turns out there is a way to detect Dark Matter, a method that depends on its gravitational action alone; we will come back to that towards the end of this installment. For the moment we will stay with what we have learned so far: there is Dark Matter present (exactly how much there is, we will leave to Part III in this series) and the Universe has close to flat geometry.

But *Why* Is the Geometry Flat?

Meanwhile, some quizzical theorists were troubled by yet another puzzle — just why is the geometry of the Universe so flat? In principle, the Universe could have any old curvature, positive or negative, big or small. It is perfectly possible to imagine a Universe so strongly curved it never gets any bigger than a soccer ball, with a radius of curvature of roughly 12 cm. Indeed, "Why is the Universe so flat?" is equivalent to the question "Why is the Universe so big?"

Related to that question is one more: Why is the Universe so homogeneous (so closely the same everywhere)? How could two chunks of the Universe, located a long way apart, "know" to have the same density?

One answer to these questions — but not a very satisfactory one — is to say, "That's just the way it is." But scientists like to probe deeper and to minimize the number of explanations that come down to unspecified causes.

Inflation

In the early 1980s, two young theorists in the US and the (then) Soviet Union came up with a neat way of ensuring both homogeneity and flat geometry.

Alan Guth and Andrei Linde independently suggested the Universe went through a very early phase of very rapid expansion. That solves the problems, but the numbers involved are staggering. We now think this phase kicked in something like 10^{-32} sec after the Big Bang, and lasted something like 10^{-30} sec. In that sliver of time, the Universe expanded by a huge amount; again in rough figures, by about 10^{25} in size. This huge change of scale stretched out any curvature to make it essentially flat. A soccer ball with a radius of 12 cm has very evident curvature; but a soccer ball of radius 12 cm x 10^{25} would be so huge as to be imperceptibly curved. This huge expansion flattens the Universe. In addition, the expansion would stretch tiny regions that did have time to settle into homogeneity up to astronomical scales (as explored in the box below). Adding an early phase of explosive expansion thus solves both puzzles. This suggestion also solved some other pesky problems and, more importantly, it is consistent with all current cosmological observations. It has come to be called "Inflation."

Because it so successfully solves these puzzles, Inflation is now accepted as part of the standard picture of the history of the Universe. There are differences of opinion on when it started (but certainly very early) and how long it lasted. There are also *many* suggestions for what drives the rapid expansion (about the same number of ideas — if not more — than the number of theorists working on Inflation!).

It is slightly unsettling that we seem to have replaced a couple of large questions about the curvature and homogeneity of the Universe with another one about the physics behind Inflation. There is hope in the fact different theories of Inflation make different predictions about observable phenomena. In other words, these predictions are *testable*. They thus fit in the framework of normal science. Can we devise experiments or observations that can discriminate among the various ideas about Inflation? We will answer that question in the last installment of this three-part series.

A second reason to take seriously the idea the Universe once expanded explosively is that the Universe appears to have entered a second phase of

A requirement for any chunk of the Universe to be homogeneous is that all parts of it have had time to interact with each other. Otherwise, there is no way to ensure all parts of the chunk have the same density. Since physical interactions can't propagate faster than the speed of light, c, we need to start with chunks smaller than ct. Here, t is the time available for physics to act to make the chunk homogeneous. This is at most the time since the Universe began. So let's run the sums for a chunk that starts out a mere 10^{-23} cm in size at the beginning of Inflation. If Inflation begins at 10^{-32} sec, ct is equal to 3×10^{-22} cm, so our imagined chunk is indeed small enough to be homogeneous. Then that chunk, like all others in the Universe expands by a factor of 10^{25}. In a tiny fraction of a second it has grown to ~100 cm in size — not yet astronomically large, but the chunk still has 13 billion years to expand more slowly following Hubble's Law.

run-away expansion. This came as a huge surprise when it was discovered by two rival groups of astronomers in 1998. In Part I of this series, we explained that the presence of matter — ordinary or Dark Matter — in the Universe must, by the action of gravity, slow down the expansion. Instead groups led by Saul Perlmutter and by Adam Reiss and Brian Schmidt have established convincingly that the expansion of the Universe is accelerating, and has been for 5–10 billion years. Both the matter we see in the form of stars and galaxies and the Dark Matter are indeed trying to pull the Universe together, but something stronger is blowing it apart. Inflationary expansion is not just a property of a quick moment in the distant past; it is a property of our present Universe.

Dark Energy

So what drives this later phase of expansion? It appears to be a mysterious substance called Dark Energy. Like Dark Matter, Dark Energy does exert a gravitational pull, so it can be thought of as contributing to the overall density of "stuff" in the Universe. Indeed, Dark Energy contributes even more to the total density than Dark Matter, solving the puzzle we started with. It is not just Dark Matter that brings the density of the Universe up to of 9×10^{-30} gm/cm^3, but Dark Energy as well.

Dark Energy, however, has a second property — it drives accelerated expansion. Interestingly, Einstein had incorporated something very like Dark Energy into cosmology many years before 1998. When he first applied his new theory of General Relativity to the cosmos, Einstein, like all his predecessors and contemporaries, naturally assumed the Universe was static. Hubble's discovery of uniform expansion lay some years in the future (see Part I). So Einstein was faced with a problem. How can the Universe be static if gravity acts always to pull matter together? Einstein's answer was to introduce into the equations of General Relativity something called the cosmological constant. It is akin to a new "force," to speak loosely, which serves to balance gravity. In his formalism, this new "force" depends only on distance, not mass or density. In this sense, it is a "constant." Adding this term allowed a precarious balance with the inward pull of gravity, and hence static equilibrium. (We will explore the physical properties of the cosmological constant below, and then drop the potentially misleading description of it as a kind of "force.")

Once the expansion of the Universe was discovered, however, the cosmological constant was no longer thought to be static. Thus Einstein abandoned the cosmological constant, and it faded from discussion. The statement that the cosmological constant was "the biggest blunder of my life" is attributed — probably erroneously — to Einstein. In any case, it may be that declaring the cosmological constant a blunder was in fact a bigger blunder. Since it acts to counter gravity, the cosmological constant can produce the run-away expansion we see in the Universe today.

Introducing the cosmological constant, however, undermines several of the conclusions drawn earlier in Part I. Since the cosmological constant is independent of mass, its magnitude is unaffected by density. Thus density alone no longer determines the expansion of the Universe. Instead, density and the cosmological constant take turns in determining the expansion rate of the Universe. Early in the history of the Universe, when the density was high, deceleration due to gravity dominated. Only later did the density of ordinary and Dark Matter fall enough so that the cosmological constant became the dominant effect. The result is to produce a far more complicated graph of the scale factor, a(t), as shown schematically in Figure 3. At early times, the expansion of the Universe was indeed slowed down by the action of gravity (so initially a(t) behaves as shown in the earlier Figure 2 in Part I). The Universe was nevertheless still expanding, so the density was dropping. Thus the relative strength of gravity decreased compared to the (constant) cosmological constant. At a certain moment in time, the two "forces" became equal, but the expansion continued, reducing still further the density and hence the effect of gravity. Once the expansion of the Universe began to accelerate, of course, the density dropped so rapidly that the matter no longer mattered. The expansion runs away, and the Universe continues to expand at an accelerating rate. In the limit as the density approaches 0, the increase is exponential with time. Also, once the expansion enters an accelerating phase, our future becomes clear — we live in a Universe that expands forever, no matter what the density is. The crossover to a phase of run-away expansion is thought to have occurred when the Universe was several billion years old (well before the Solar System formed).

Let us return to the fundamental question: what produces this run-away expansion? The cosmological constant was introduced as an extra term in the equations of General Relativity, without any real physical explanation. But there is a more fundamental way to look at the cosmological constant, and that is in terms of a new constituent of the Universe, *Dark Energy*. This is emphatically different from Dark Matter, which "gravitates" or attracts like ordinary matter. Dark Energy instead has very different properties. First, if the cosmological constant is indeed constant, the amount of Dark Energy must remain constant even as the Universe expands. This is in flat contradiction to the behavior of matter (whether Dark or ordinary): for these, the density drops as the Universe expands. This apparently paradoxical behavior of Dark Energy is allowed if we treat Dark Energy as a special kind of vacuum. If you start with a small container of vacuum, and expand the container, you just end up with more vacuum. Hence the term "false vacuum" often applied to Dark Energy. As the Universe expands, and its volume increases, so does the amount of Dark Energy, in just such a way as to keep the amount of Dark Energy per cubic cm constant. Yes, this is perplexing, but it appears to agree with the observations, as we will see in Part III.

There are still more oddities of Dark Energy to explore. We have just argued the amount of Dark Energy or false vacuum in each cubic cm of the Universe remains constant. Now we make use of Einstein's best-known equation, $E = mc^2$. If there is a certain amount of energy in each cm^3, there must be an equivalent amount of mass, $m = E/c^2$. This mass, like any other, must gravitate. As a consequence, the Dark Energy does contribute to the deceleration of the Universe. Indeed, since we have argued that Dark Energy appears to be causing the run-away expansion of the Universe today, the amount of Dark Energy per cm^3 must exceed the density of both Dark Matter and ordinary matter. It does, as we'll show in Part III.

First, however, we'd better sort out an apparent contradiction. Dark Energy was introduced to explain the observed *acceleration* of the expansion of the Universe. But we have just argued the Dark Energy contributes an equivalent mass that instead acts to slow the expansion. In fact Dark Energy does both. The reasons are technical (see "C5", listed in the "Resources" section). The paradoxical result that Dark Energy contributes to the density of the Universe and yet drives accelerated expansion arises from the role of pressure in General Relativity. In the case of Dark Energy (the "false vacuum"), the pressure is not only large but also *negative*. The negative pressure overwhelms the gravitational effect of Dark Energy.

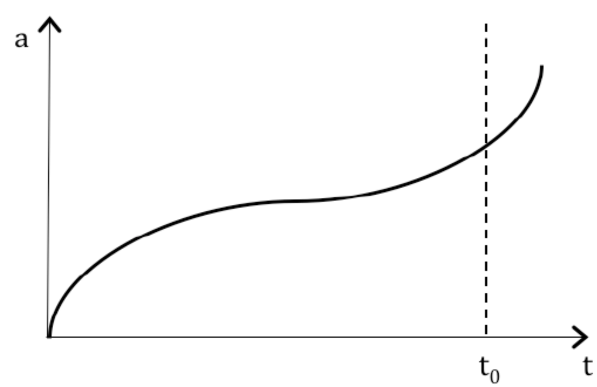

Figure 3. Our current understanding of the expansion history of the Universe. Early on, gravity dominates, and the curve a(t) is concave downwards (the expansion is slowed, as was the case shown in Figure 2 in Part I). At later times, but well before the present moment t_0, the cosmological constant takes over, expansion accelerates and the curve arcs upwards.

Given all these paradoxes, it is appropriate to look carefully at the astronomical evidence supporting Dark Energy as well as Dark Matter.

Another Pause to Consider the Evidence

We started Part II with a puzzle involving density, then considered another puzzle — the "flatness" of the geometry of the Universe. As responses to these puzzles, cosmologists have introduced Dark Matter and Inflation. For good measure, we threw in Dark Energy. What is the observational evidence for each of these new features of the 2014 model of the Universe?

(More) Evidence for Dark Matter.

Earlier, the evidence that Dark Matter resides in (and contributes to the gravitational mass of) both galaxies and clusters of galaxies was sketched. Some form of matter — matter that is not visible — is needed to hold both galaxies and clusters together. A neat feature of General Relativity allows us to confirm the existence of large amounts of Dark Matter in clusters. First, we have known since 1919 that General Relativity correctly predicts that mass bends light. The mass of the Sun, for instance, deflects the apparent positions of radio

Figure 4. The massive cluster of galaxies (the fuzzy yellow objects) Abell 1689. Its visible and Dark Matter gravitationally lens faint background galaxies, forming the faint blue arcs most clearly seen to the upper right of the cluster.
Image: NASA, ESA, Hubble Heritage Team (STScI/AURA)

sources behind it by a few arcseconds. The much larger mass in clusters of galaxies does the same; it deflects the light of background objects. In effect, a cluster becomes a sort of gravitational lens. Like an ordinary lens, say one in your glasses, it can magnify, distort or amplify a background source of light. Figure 4 shows the characteristic arcs of gravitational lensed galaxies seen in the vicinity of the massive cluster of galaxies called Abell 1689. The strength of the lens, and the degree of distortion or magnification, depend only on how close the light passes to the cluster and the mass of the cluster. The former can easily be measured, so the amount of lensing provides a direct measure of the total mass of clusters like Abell 1689. In every case where such total masses have been measured, the total is much greater than the sum of the masses of all the galaxies in the cluster. Much more matter is needed — Dark Matter.*

Evidence for Inflation.

Until March of this year, all the evidence in favor of Inflation was, in a sense, either circumstantial or based on the very observations that suggested the idea of Inflation in the first place. The Universe's geometry is flat, for instance: consistent with Inflation. So are some properties of small fluctuations in the temperature of the heat left over from the Big Bang (introduced in Part I of this series). What was needed was a "smoking gun" proof the Universe went through an early and dramatic period of exponential expansion. Just such proof was reported by the BICEP2 Team on the 17th of March, 2014. That proof will be discussed in detail in Part III.

Evidence for Dark Energy.

I have already mentioned the observed acceleration of the expansion of the Universe, which appears to require Dark Energy to explain it. But how was the accelerated expansion itself detected in 1998?

Purely by accident! Two rival groups were working on a way to measure the overall density of matter in the Universe (in effect, trying to resolve the puzzle with which we started). They both employed the same feature of General Relativity we have just discussed: mass bends light. In this case, the more-or-less uniform matter filling the Universe also lenses the light from distant objects. For a source of light at a given distance from us, there is stronger lensing and more magnification or amplification if the density of the Universe is high. So a source at a given distance appears brighter in a high density Universe than in a low density one.

Furthermore, the difference increases with distance to the source. (I provide more detail in "C5" listed in the "Resources"). To use this approach, they needed a set of sources at different distances, but all of the same luminosity or energy output. These, somewhat quaintly in this age of LEDs, are called "standard candles." Both groups adopted as their "standard candles" a certain kind of exploding star, the Type Ia supernovae (see "Resources"). Both teams independently came up with the same, startling (indeed, Nobel Prize winning) results: Distant supernovae were fainter than they should be, even if the Universe had no matter in it! What was up? One possibility, soon dismissed, was a faint fog of intergalactic matter that absorbed some light. Another had been around since General Relativity was first applied to the Universe: a cosmological constant is present in the Universe, and is causing accelerated expansion. Distant galaxies and the supernovae they host are flying away from us faster than expected, thrust apart by Dark Energy. The

* There is some ordinary matter lying outside the galaxies in clusters — mainly very hot gas — but we can separately show that its mass is but a small fraction of the total mass needed to explain gravitational lensing like that shown in the figure.

supernova observations of the teams led by Saul Perlmutter, and by Brian Schmidt and Adam Reiss, are nicely consistent with the existence of Dark Energy, Dark Energy whose density stays constant as the Universe expands.

Observations of fluctuations in the temperature of the heat left over from the Big Bang, as we will see in Part III, fully support the supernova results. There must be Dark Energy, it must stay constant in time even as the Universe expands, and it must dominate the census of "stuff" filling each cubic centimeter of the Universe today. These observations tell us how the Dark Energy acts (it speeds up the expansion of the Universe), and how much of it there is. What they don't do is to provide a real handle on exactly what the Dark Energy is. I suspect, by now, you or your students will be asking that question. What exactly *is* this cosmological constant = Dark Energy = false vacuum? There is a crisp and definitive answer to this question: we have no idea. There are some speculative ideas, but no convincing and agreed upon explanation as yet. Dark Energy provides a fine example of how science often operates. First we find a puzzling property of Nature, then we characterize it, then we model it quantitatively, then we explain it physically. So it was with gravity. In the case of Dark Energy, we have not yet taken the fourth of these steps. For scientists, that is fortunate: there is still work to do!

Resources

General

B. Partridge and N. Vechik, 2013 "C5" — "Cosmology for Community Colleges: A Curricular Companion," http://www.haverford.edu/C5

On Dark Matter

Rubin, Vera. Dark Matter in the Universe. *Scientific American Presents: Magnificent Cosmos*. 1998.

M. White: http://astro.berkeley.edu/~mwhite/darkmatter/dm.html. Provides a nice review and additional references.

http://www.stsci.edu/~postman/CLASH/For_the_Public.html is a nice site on measuring mass using gravitational lensing.

On Inflation

A good description of Inflation by pioneers of the field:
Guth, Alan and Steinhardt, Paul. The Inflationary Universe. *Scientific American*. May 1984.

The website http://www.ctc.cam.ac.uk/outreach/origins/inflation_zero.php also treats inflation (and some other topics we have presented, albeit in a quite different way). The Wikipedia article on cosmic inflation is very rich — but also very technical.

A description of some of the *many* variants of inflation theory:
Nadis, Steve. Sizing Up Inflation. *Sky and Telescope*. November 2005.

On Dark Energy

The Wikipedia entry on "Dark Energy" is pretty good.

A review of the cosmological constant:
Krauss, Lawrence and Turner, Michael. A Cosmic Conundrum. *Scientific American*. September 2004.

See also a NASA site
http://science.nasa.gov/astrophysics/focus-areas/what-is-dark-energy/ and a somewhat spooky video: http://hubblesite.org/hubble_discoveries/dark_energy/

Finally, some different explanations for Dark Energy are given in
Ostriker, Jeremiah, P and Steinhardt, Paul. The Quintessential Universe. *Scientific American*. January 2001.

On the Supernova Observations and the Discovery of Dark Energy

Perlmutter, Saul. Supernovae, Dark Energy, and the Accelerating Universe. *Physics Today*. April 2003. (more technical than the following article).

Reiss, Adam and Turner, Michael. From Slowdown to Speedup. *Scientific American*. February 2004.

Both Perlmutter and Reiss won the 2011 Nobel Prize. See
http://www.nobelprize.org/nobel_prizes/physics/laureates/2011/advanced-physicsprize2011.pdf

Classroom Resource

Cosmic Times Teachers' Guide (http://cosmictimes.gsfc.nasa.gov/) has many activities related to cosmology, presented in a historical context.