THE UNIVERSE IN THE CLASSROOM

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The Universe: the 2014 Model. Part I. The Hot Big Bang and its Consequences

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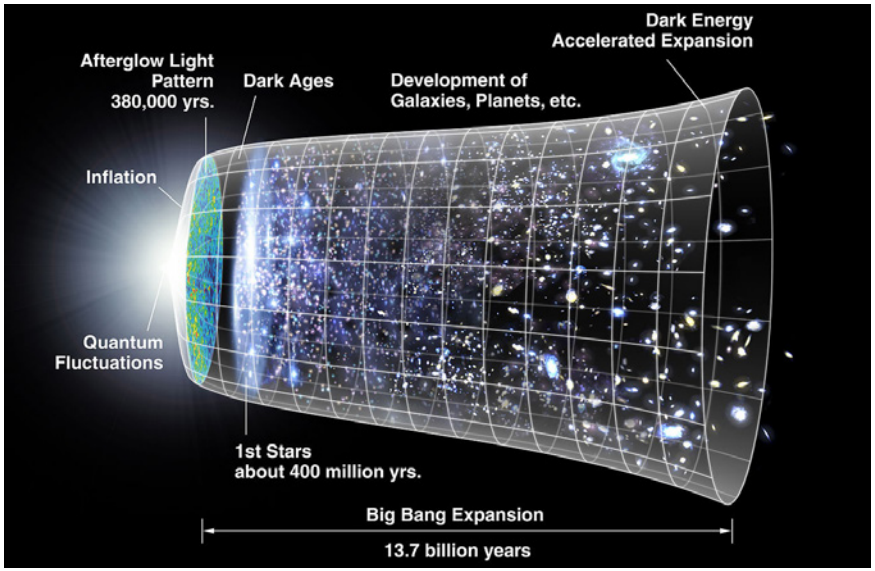
In the past few decades, we have made huge strides in understanding what the Universe is like, and how it evolved. In fact, this is a vast understatement! Fifty years ago, we knew the Universe was expanding, and had a rough idea of its age, somewhere between 7 and 20 billion years. There was a lively debate on whether the expansion was slowing down or not. There were hints — which most astronomers ignored — that some kind of matter was present in the Universe other than stars and galaxies. Very little else was agreed on, and a prominent physicist dismissed cosmology, the study of the properties and history of the Universe, as "a dream of zealots."

In 2013, we *know* the Universe began in a Hot Big Bang 13.8 billion years ago; it is expanding faster and faster; Dark Matter and Dark Energy control the destiny of the Universe; and ordinary matter (planets, stars and galaxies) makes up only 5% of the total. In this special three-part edition of The Universe in the Classroom, we lay out what is currently known about the properties and evolution of the Universe and of the large-scale structures within it. That is, we present the current, **2014, model of the Universe**. In the case of things we are now quite certain of, I will explain how we know what we know. In the case of things we believe to be true, I'll indicate how we might be able to confirm our hypotheses. Note that we have already introduced the notion of a scientific model and emphasized the importance of empirical evidence. A study of the properties and history of the Universe involves many other Science Practices and Crosscutting Concepts listed in the Next Generation Science Standards. We will point out some as we go along. All in all, both the self-consistency and strong empirical support for the 2014 model of the Universe make it a fine example of a successful explanation of one grand aspect of the natural world.



(Image credit: NASA/WMAP Science Team)

Properties of the Universe as a Whole

Expansion

In the 1920s, Edwin Hubble made the unexpected discovery the Universe is an expanding system. He also showed the expansion was *uniform*, that is, the speed with which any two objects (say galaxies) move apart depends only on their distance apart, d. Specifically, we write the speed v as

$v = H_o \times d$,

where H_o is a constant which specifies how fast the Universe is now expanding. Note two things about this simple equation. First, there is nothing about direction in it — the expansion is the same in all directions. Second, the connection between v and d is a direct proportion. If galaxy B is twice as far away from us as galaxy A, galaxy B will recede at twice the speed of galaxy A. These are the properties of uniform expansion. In the case of uniform expansion, there is a very useful simplification we can introduce, the so-called *scale factor*, a(t). It is a bit difficult to grasp at first, but once understood, it makes many properties of the Universe easier to follow. We start by recalling that the speed v represents a change of distance with time. Thus Hubble's results as given above tells us the change in any distance in the expanding Universe is proportional to the distance itself. Since all distances change by the same proportion, it is simpler to talk about a *change in scale*. As the Universe expands according to Hubble's Law, all distances are scaled up at the same rate. For any distance D between any two objects in the Universe, we can write

$D(t) = a(t) \times D_o$

Where D_o is the current distance, and D(t) is the distance at any time. As the Universe expands, a(t) changes. At times before the present ($t<t_o$), $a(t)<1$ (the Universe and all distance in it were smaller). In the future, a(t) will increase above unity.

Adopting the scale factor allows us to plot the expansion of the Universe in a single, simple graph (Figure 1). We know a(t) is increasing now, that is, at time t_o. We show this with a solid line segment sloping upwards. Now we can ask what a(t) was like in the past — we know it was smaller. For the moment, let us assume no forces are acting to slow down or speed up the expansion. Then we can project a(t) back into the past, as shown by the dashed lines in Figure 1.

The Big Bang

There is an immediate and important consequence. Projecting the expansion back into the past, as shown by the dashed line, we find that a = 0 at some moment in the past. If the scale factor goes to zero, all distances in the Universe must also go to zero. If all distances were zero, the density must have been infinite. It is reasonable to associate this moment with the beginning of our expanding Universe — we call it the *Big Bang* — and start the clock of the Universe then by setting time t = 0. On this graph, we label the present time as t_o. If, as we have assumed, no forces act, it is easy to see from the graph that $t_o = 1/H_o$. Sadly, astronomers use odd units for H_o : in these units* $H_o = 70$, and the estimated age of the Universe is about 13-14 billion years.

The HOT Big Bang

We have seen that the expansion of the Universe implies a beginning when the distances between all

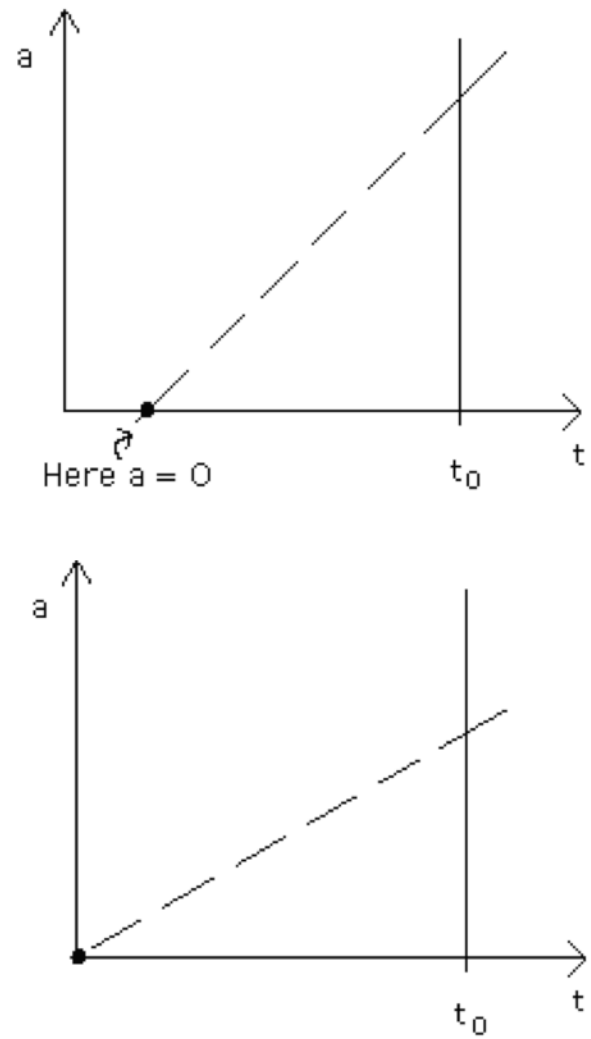


Figure 1. Top: We know the Universe is expanding now (at to); thus the scale factor is increasing as shown by the short solid line segment. We can then project back into the past — assuming no forces act — and see that a = 0. This moment of infinite density is what we call the Big Bang. In the lower figure, we start the clocks of the Universe at this moment, so to becomes the present age of the Universe. (Image courtesy of Bruce Partridge)

* These units are km/sec per Megaparsec of distance; a Megaparsec is = 3.08×10^{19} km. Thus the proportional change in distance each second is ~ $70/3.08 \times 10^{19}$ ~2.27×10^{-18} or about 7.2×10^{-11} per year; the Universe is expanding, but slowly, and its age = $1/H_o = (7.2 \times 10^{-11})^{-1}$ years ~ 14 billion years.

objects were equal to 0. Thus the early Universe was very dense. But we know when we squeeze matter together (for instance by squeezing air into a bike tire) the matter heats up. This observation led George Gamow and his colleagues to suggest, some 70 years ago, that the Big Bang *would have been* **hot** as well as dense. If the Universe started off hot as well as dense, some residual heat should be left in the Universe (where else would it go?). This left-over heat was discovered in 1964; we now know the present temperature of the Universe is a few degrees above absolute zero, specifically $T_o = 2.725$ K, or about -455 F. Other properties of this left-over heat (and their contribution to our understanding of the Universe) are discussed later. We also know to high precision the heat looks the same in all directions. This is consistent with uniform expansion, but has a further consequence. If we modestly assume we are not at the center of the Universe, and hence any other observer in the Universe would see the same temperature in all directions, we can infer the Universe is the same everywhere. In other words, the Universe is *homogeneous*.

Adding Gravity, and the Future of the Universe

Let's add one more, obvious, observation to the mix. The Universe is full of stars and galaxies, that is, of matter. Matter gravitates, so there *are* forces acting in the Universe. Thus Figure 1 does not represent the actual Universe as we know it. Since gravity is always an attractive force, the result of taking account of the matter in the Universe is to slow the expansion, as reflected in Fig. 2. Note that adding gravity to the picture does not change the conclusion there was a Big Bang as a = 0.

Is gravity strong enough to slow the expansion to a halt, allowing the Universe to re-collapse, as shown in Fig, 2A? Or, in contrast, will the Universe continue to expand forever, even though the expansion is slower and slower? Put more dramatically, what is our remote future? Will the Universe eventually collapse back to a state of high density (the "Big Crunch"), squashing us all, as a(t) = 0? That depends on how much matter there is in the Universe. More matter implies stronger gravitational forces and more slowing down. Here is a beautiful example of how scientists rely on empirical evidence to answer deep questions. Since the Universe is homogeneous, what we really need to know is the average density of the Universe. It turns out the density required to stop the expansion is extremely low (a mere 9×10^{-30} gm/cm^3 would suffice). When we start adding up all the galaxies in a given chunk of the Universe to find the actual density, however, we find an even smaller density, way below the magic number of 9×10^{-30} gm/cm^3. Does this mean we have our answer—the Universe will not recollapse, but instead expand forever? Unfortunately no. As we will see later there are other forms of matter that add to the overall density. We need to revise our understanding and to find another method to answer the question.

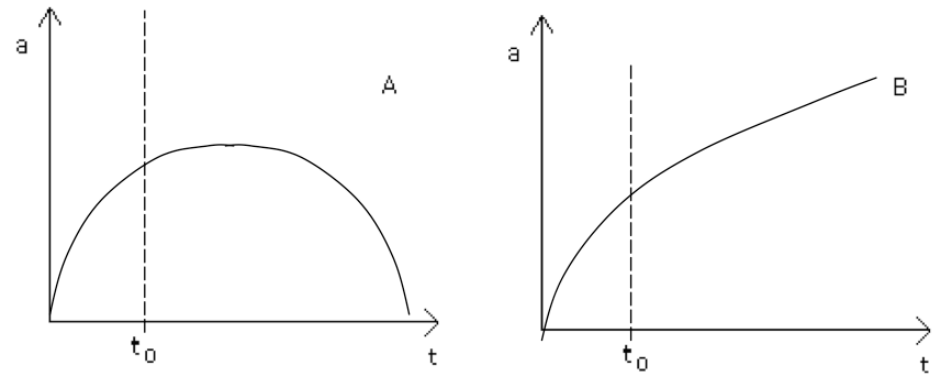


Fig. 2. Two possible histories of the Universe, as traced by the evolution of the scale factor a as a function of time. A shows a recollapsing Universe and B a lower-density Universe that expands forever. (Image courtesy of Bruce Partridge)

The Curvature of Space and the Future of the Universe

Fortunately, there is another approach. It is also a method that gives a precise answer. It hinges on Einstein's demonstration that matter bends or warps space. Since the Universe on a large scale is observed to be both homogeneous and the same in all directions, any warping of space must also be homogeneous or uniform. A succession of eminent mathematicians, including Gauss and Riemann, showed 150 years ago there are only three kinds of uniformly warped space. The simplest is space with no warping — ordinary Euclidean or "flat" space — with all the properties we are familiar with from plane geometry. But space can also be (uniformly) positively curved. Envisioning curved three-dimensional space is difficult, so we consider instead two-dimensional space. Flat 2-D space is a uniform plane; if it is the same everywhere, it cannot have edges so it must be an infinite plane. Uniformly *positively* curved space is instead like the curved surface of a balloon (the 2-D space is the rubber membrane of the balloon, curved everywhere by the same amount if the balloon is a nice sphere). Even more difficult to envision is uniformly *nega-*

tively curved space. A Pringles potato chip (or a saddle) can serve as an illustration of a chunk of negatively curved space.

Now the beauty of introducing space curvature to our model. It turns out if the Universe has a high density, enough to cause recollapse, its space curvature will be positive. If the density is low, which we have seen implies expansion forever, its space curvature is negative. Flat space corresponds to the magic value of 9×10^{-30} gm/cm^3. Thus we do not have to measure density to determine the future of the Universe: we can measure space curvature instead. Again, we appeal to empirical evidence, but a different piece of evidence: the large-scale curvature of space.

The result, described a little more fully below and in more detail in a web site on cosmology called C5 (see bibliography), is quite clear: the Universe is very close to flat. This result comes from careful studies (see below) of the left-over heat. The best current result, from the European Space Agency's Planck mission, is the Universe is flat to within ~1%.

If the space curvature is very small, the density of matter must be very close to the magic value of 9×10^{-30} gm/cm^3. Yet we have seen that ordinary matter — the atoms that make up stars, planets, galaxies and even us — is a tiny fraction of this value. So there must be some *other* kind of matter present. This is one strong hint of the existence of Dark Matter, which we discuss in the next installment of *The Universe in the Classroom*.

Let's recap.

On large scales, the Universe is:

- expanding uniformly
- the same in all directions
- homogeneous
- very close to flat geometrically
- and full of the cooled-down remnant of the Hot Big Bang.

A Pause to Consider the Evidence

A skeptic might ask, how do we know all this? In particular, is there tangible evidence for a Hot Big Bang, a long-past moment when the properties of the Universe were hugely different from its current cool and empty conditions? That tangible evidence

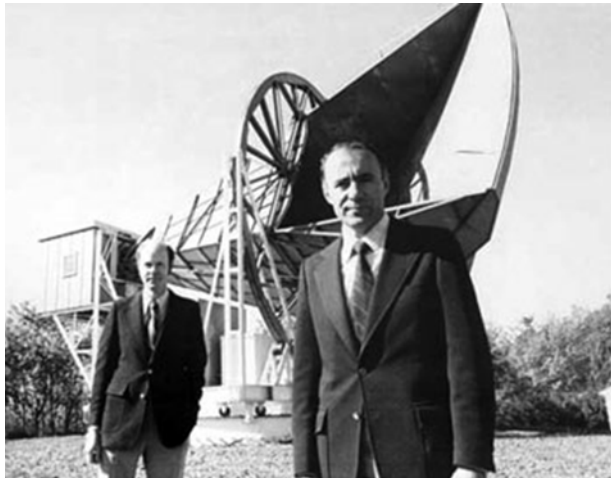


Fig. 3. Penzias and Wilson and the apparatus that first detected the heat left over from the Big Bang. (Image credit: National Park Service)

was supplied in 1964 by the discovery of what we call the cosmic microwave background (CMB) by Arno Penzias and Bob Wilson.

The evidence became far firmer over the next decades. Penzias and Wilson determined the temperature of the Universe today is not zero, but closer to 3 K. Later observations quickly showed this left-over heat has exactly the spectral properties you would expect from heat emerging from hot *and dense* matter, just the conditions we expect at the Hot Big Bang beginning of the Universe. The heat emitted by hot dense matter has a special dependence of intensity with wavelength called a blackbody spectrum. This dependence (or spectrum) has a peak intensity at a wavelength of roughly 3 mm/T, where T is the temperature. A blackbody spectrum for a temperature of 2.725 K is plotted in Figure 5. Superimposed on it are the Nobel Prize winning observations of the CMB made by John Mather and his colleagues using FIRAS, one of the instruments on NASA's COBE satellite (Fig. 4).

The error bars in the FIRAS measurement look large, but each represents 400 times the expected uncertainty of each measurement! The CMB has the right spectrum, and is the same in all directions, just as expected if it is a remnant of a Hot Big Bang.

The evidence the Universe did start in a hot and dense state convinced even those astronomers who had doubted the Big Bang. There were, however, some remaining puzzles. Some of the observed properties of the Universe we have just listed were

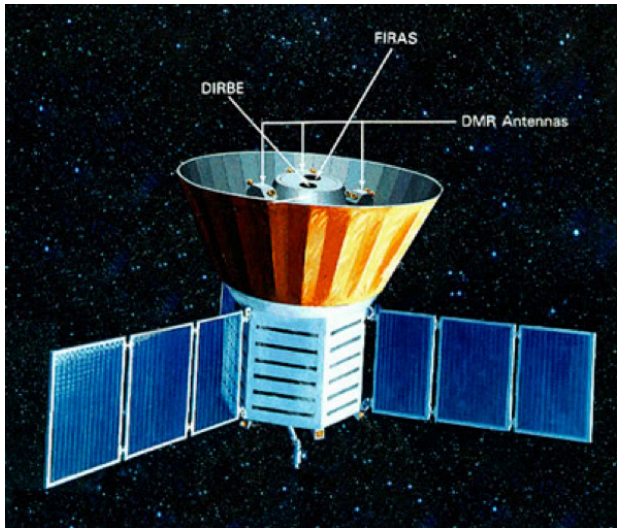


Fig. 4. NASA's COBE satellite. The FIRAS instrument aboard COBE was used by John Mather and his team to measure the spectrum of the CMB with high precision – showing it is indeed the remnant of a Hot Big Bang (see Fig. 5 next page). (Image credit: NASA)

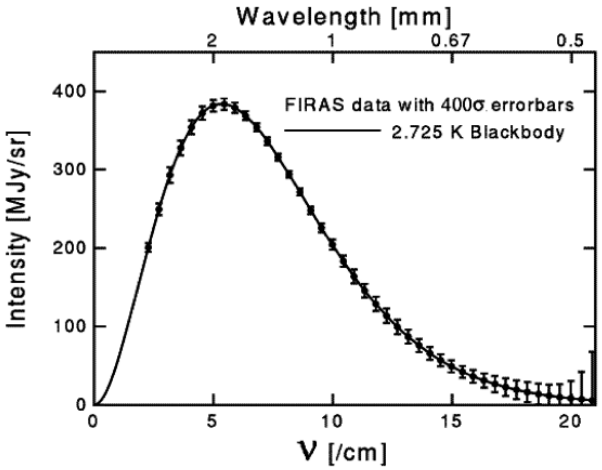


Fig. 5. The solid curve shows the spectrum (how intensity varies with wavelength) for the predicted blackbody spectrum of the CMB. Superimposed on it are the measurements from the FIRAS instrument aboard the COBE Satellite – with error bars 400 times the size of the expected uncertainty. The CMB is left from a Hot Big Bang! (Image credit: NASA)

hard to explain. We will explore these puzzles — and the elegant explanation that resolved them — in the next in this series of *The Universe in the Classroom*.

Resources

E. P. Hubble, *The Realm of the Nebulae*, Yale Univ. Press, 1936, on his discovery of expansion.

M. Bartusiak, *The Day We Found the Universe*, Pantheon Books New York, 2009, a revealing life of Edwin Hubble.

http://en.wikipedia.org/wiki/Scale_factor_(cosmology)
a pretty technical introduction to the scale factor (see also C5 listed below).

M. Rowan-Robinson, *The Cosmological Distance Ladder*, W.H. Freeman, San Francisco, 1985, on older methods to determine the expansion rate of the Universe.

COBE (and FIRAS)

http://en.wikipedia.org/wiki/Cosmic_Background_Explorer
a good summary of the findings of this mission.

Space Curvature

B. Partridge and N. Vechik, *Cosmology for Community Colleges: A Curricular Companion* ("C5"), covers material in this TNL in more detail. Soon to be up at
http://www.haverford.edu/faculty/bpartrid

http://www.esa.int/Our_Activities/Space_Science/Planck/Planck_reveals_an_almost_perfect_Universe
the 2013 press release of the first findings from ESA's Planck mission — including strong constraints on curvature of space.

http://www.nobelprize.org/nobel_prizes/physics/laureates/1978/wilson-lecture.pdf
Bob Wilson's Nobel Prize speech on the CMB.

P.J.E.Peebles, L.A. Page and R.B. Partridge, *Finding the Big Bang,* Cambridge Univ. Press, 2009, a history of the discovery of the Hot Big Bang.

Classroom Resources

Cosmic Times on NASA's Imagine the Universe website: http://cosmictimes.gsfc.nasa.gov is a site with many activities related to the history of cosmology.

Featured Activity

From *The Universe at Your Fingertips 2.0*:
Activity H9: Modeling the Expanding Universe
This is a sequence of activities to help students understand the expansion of the universe. It involves activities to help them picture the expansion and others to help them understand how Hubble discovered the pattern of galaxy Doppler shifts that provide evidence for the expansion.