THE UNIVERSE IN THE CLASSROOM

No. 89 • Spring 2015 www.astrosociety.org/uitc

The Universe: Part III. Bringing Precision to the 2015 Model

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Two previous issues of *Universe in the Classroom* (Part 1 number 86 and Part 2 number 87) introduced many of the properties of the 2014 model Universe, including the cosmic microwave background (CMB), Dark Matter, Dark Energy and a very early, very brief moment of rapid expansion called Inflation. This cosmological model is complex, but well supported by observations, as I have tried to show. It is also very precisely determined. Much of that precision has been achieved through careful studies of the CMB, the heat left over from the Hot Big Bang (see Part 1 for an introduction).

In Part 3, I will bring our description of the Universe up to date ("the 2015 model") and explain some of the scientific riches that can be distilled from the CMB.

What Do We See when We "See" the CMB?

We "see" the CMB not with our eyes because the characteristic wavelengths of the cosmic background are several thousand times too long for our eyes to pick up. Instead we use specialized radio telescopes such as the Atacama Cosmology Telescope (Fig. 1). But what do they "see" when they are used to study the CMB?

There is an exact analogy to what we see when we look at a cumulus cloud in a clear sky. As suggested in Fig. 2, what we see is just the surface of the cloud. Inside the cloud light scatters from water droplets in the cloud; once light reaches the surface, however, it is free to travel unscattered and undeviated to our eyes. The same is true for the CMB. Our radio telescopes "see" back to a surface where the CMB photons last scattered. Once they leave that *surface of last scattering*, they are free to travel through transparent space to our waiting detectors. In the cosmic case, the scattering objects aren't water droplets but free electrons. A cloud of free electrons will scatter photons; if the free electrons suddenly disappear, the photons are free to travel.

So where do the free electrons come from, and

Fig. 1. The Atacama Cosmology Telescope, one of the many specialized instruments now being used to map the CMB. It is almost hidden behind the 12-sided shield placed to prevent radiation from the ground leaking into the telescope. (Image credit: ACT Team)

why do they suddenly disappear? Recall that early on the Universe was hot. When the temperature was above ~3000 K (the surface temperature of a cool star), all of the ordinary matter of the Universe was ionized. Since 90% of all atoms in the Universe

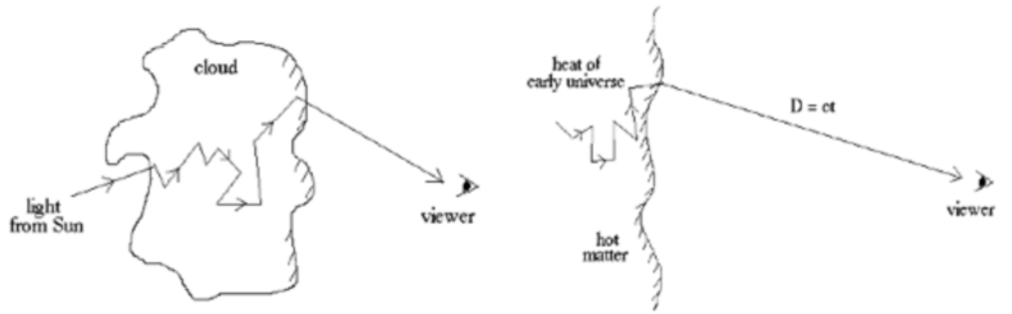

Fig. 2. The surface of a cumulus cloud serves as an analogy for the surface of last scattering: light is free to travel to us only when it stops scattering, when it no longer interacts with water droplets (in clouds) or free electrons (in the early Universe). (Drawing by Benjamin Walter)

are hydrogen, let's consider just hydrogen. When ionized, hydrogen is just a free proton and a free electron. These free electrons scatter the cosmic photons. About 380,000 years after the Big Bang, however, the temperature dropped below 3000 K, and the free protons and electrons combined to form neutral hydrogen — a far weaker scatterer of radiation. So the Universe suddenly became transparent. In analogy with the cumulus cloud, we thus "see" a surface at t = 380,000 yr. That surface is all around us so we expect the CMB to be roughly the same in all directions, or to use the specific term, isotropic. Indeed that was one of the tests of the cosmic origin of the CMB (see [Part 1](#)).

To about 0.1% the CMB is indeed isotropic — as shown in the rather bland first panel of Fig. 3. In whatever direction we look, we see the same temperature of 2.7255 K.* The maps shown in Figs. 3 and 4 show the entire sky, unwrapped and flattened into two dimensions. The projection chosen has the plane of the Galaxy running horizontally across the equator. And of course the CMB is not really orange; we use false color to indicate the observed temperature. What is important is that the temperature shown in the first panel is the same everywhere on the sky — or isotropic — as predicted.

Anisotropies, or Fluctuations, in the CMB

A closer examination of the CMB, however, shows small departures from isotropy. Those are also shown in Fig. 3. The second panel shows what happens if we subtract 2.7255 K from every point in the previous map, then bump up the color scale by ~1000. One part of the sky is clearly hotter than the opposite part by about 3 mK. This *dipole anisotropy* has a ready explanation, our old friend, the Doppler effect. If the Earth is in motion with speed v relative to the rest of the Universe, then we rush at the CMB photons in the direction we move, blueshifting them slightly and leading to a slightly higher temperature: $\Delta T/T = v/c$, where c is the speed of light. In the direction from which we are receding,

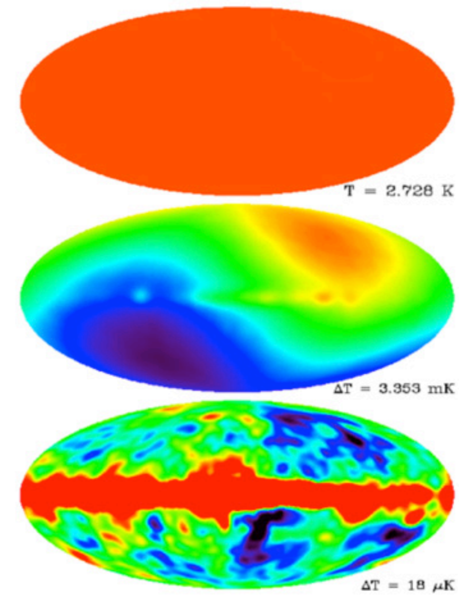

Fig. 3. Maps of the entire sky (in Galactic co-ordinates), with the temperature of the CMB indicated in false color. The upper panel shows how isotropic the CMB is. In the middle panel, we subtract the average temperature and bump up the color scale to see that there is some residual anisotropy, hotter in one direction than the opposite, caused by the motion of the Earth. Emission from the plane of the Milky Way Galaxy is also weakly visible in a band down the center. In the lower panel, we subtract out the large-scale anisotropy caused by the motion of the Earth, and again increase the color scale to reveal the fluctuations in the background CMB. Note that the numerical values for T_o and the dipole amplitude ΔT have been updated to 2.7255 K (a 0.1% change) and 3.3645 mK (a 0.3% change). (Image: COBE figure from http://lambda.gsfc.nasa.gov/product/cobe)

there is a redshift and slight cooling of the same magnitude. The *Planck* satellite has measured ΔT to be 3.3645 ± 0.002 mK, so we know the velocity of the Earth to sub-percent precision. We are moving towards a point lying between the constel-

* You may ask, why 2.7255 K and not 3000 K? The answer is that the surface of last scattering is a long way away, and hence strongly redshifted. Indeed, the redshift is ~1100, and the observed temperature is lowered by that factor.

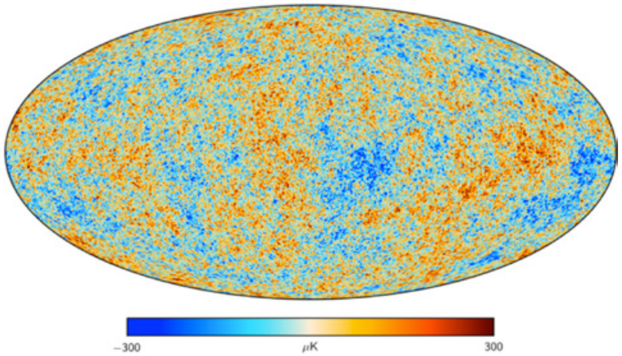

Fig. 4. *Planck*'s map of the CMB: a picture of the Universe as it was at age 380,000 years. Note the small range of temperature fluctuations, at most a few hundred microKelvin! (Image: *Planck* Team figure)

lations Leo and Crater with a speed of 370 Km/sec., the sum of the Sun and Earth's motion around the Galactic center and the motion of the whole Milky Way galaxy. Current measurements are good enough to pick up the smaller ΔT caused by the yearly motion of the Earth around the Sun (~30 Km/sec). Galileo was right!

Now let's look even more closely. We subtract the big dipole signal, then bump up the scale by yet another factor of 100 (panel 3 of Fig. 3). In this panel, microwave emission from the plane of the Galaxy paints a broad band down the middle of the plot. It too can be subtracted (as was done for Fig. 4) — and in any case is not what we are interested in. Instead we look at regions far from the Galactic plane, and we see that the map of the CMB looks mottled. There are small temperature anisotropies, of order 0.1 mK, everywhere we look. Again, there is a simple explanation: the surface of last scattering, like the surface of most cumulus clouds, is not absolutely smooth. There are small fluctuations in the density of matter from place to place on the surface — and these show up as small temperature variations.

Finally, we show the newest map of the CMB, made by the European Space Agency's *Planck* satellite, in Fig. 4. That map is in effect a "baby picture" of how matter was distributed in the Universe when the Universe was only 380,000 years old.

It is the careful study of these weak temperature fluctuations in the CMB that has revolutionized the study of the Universe, turning it into a precision science.

What Do We Learn from the Study of Fluctuations in the CMB?

A glance at Fig. 4 (our best current map of the surface of last scattering) shows that there are fluctuations in temperature on all scales. A discerning eye may see that the mottling is particularly pronounced on a certain scale (which turns out to be ~1°). Wouldn't it be nice to be able to plot "how much fluctuation there is" as a function of scale? There is such a plot, called a power spectrum, which conventionally plots the square of the amplitude (i.e. ΔT^2) against a quantity called the spatial frequency, ℓ, which is inversely proportional to angle in the sky. We use ℓ rather than the angular scale itself because so much of the interesting detail appears at small angles. To a good approximation, $\ell = 180°/\theta$, where θ is the angular scale. The power spectrum, it turns out, represents all the rich detail of the CMB map in a single detailed curve (Fig 5).

The dots are the measured power spectrum derived from the *Planck* map shown in Fig. 4. The red line that fits them so spectacularly well is the 2015 cosmological model! We really do understand the properties and history of the Universe with gratifying precision. To obtain this beautiful fit, we must of course have the *right* cosmological model. For instance, if there were no Dark Matter in the

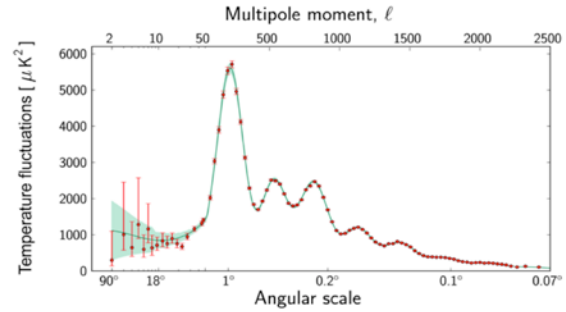

Fig. 5. The power spectrum shown here is a way of representing the amplitude of observed fluctuations in the CMB (dots) as a function of their angular scale. This graph contains the same information as the map of Fig. 4. The red line is the predicted power spectrum based on the 2015 model of the Universe; the agreement is excellent! (Image: *Planck* Team)

Universe, the amplitude of the fluctuations would be much greater (and the curve would be higher). To fit the observations, the density of Dark Matter must be 0.267 ± 0.014 times the critical density (as defined in Part 1).

What else can we learn from the measured power spectrum? One thing that strikes the eye in Fig. 5 is a peak in the power at an angular scale of just under 1°, or ℓ = 200-220. There are also subsidiary peaks that appear at multiples of ℓ = 200-220 (i.e. around 400-450 and 600-650…). All these features have a common origin. Recall that the surface of last scattering is a snapshot of the distribution of matter at a particular moment in the history of the expanding Universe — when the Universe was 380,000 years old. The visible and physically connected Universe at that time was thus only 380,000 Light Years across. At that special length, the amplitude of fluctuations was particularly pronounced (see the fine *Scientific American* article by Hu and White for details). We know what that special length was, and how far away the surface of last scattering is, so we can predict how large an angle θ that length would appear to cover. If we use Euclidean geometry, the answer is 0.9° . If the large-scale geometry of space were curved however, we would get a different answer (for instance > 0.9° if the curvature is positive). The angular scale of the observed peak serves as a measure of geometry (as we mentioned in Part 1). The 2015 results from Planck tell us that any curvature in the cosmos must be < 0.5%. The geometry of the Universe is indeed flat just as Inflation predicts (see Part 2).

We can combine these two results to obtain a third. We have found that the geometry of the Universe is flat, so the total density must be equal to the critical density. We also found that Dark Matter makes up only 0.267 of the critical density (and that ordinary matter adds very little). There must be something else. There is: Dark Energy. To obtain agreement between the observations and the model, we need 2–3 times as much Dark Energy as Dark Matter: *Planck*'s 2015 value is 0.68 times the critical density, or 2.5 times the Dark Matter.

Much, much more can be "read" off the curve of Fig. 5. The relative heights of the main and subsidiary peaks tell us how much ordinary matter (protons, neutrons and electrons) must be present (~0.049 of the critical density). We also get an independent value for Hubble's constant, which tells us how fast the Universe is expanding. At 67.3 Km/sec per Mpc, it is a few percent lower than the values coming from observations of distant galaxies (a slightly worrying tension).

Polarized Fluctuations in the CMB

The CMB has one more trick up its sleeve. The microwave "light" that makes up the CMB is slightly polarized (like light reflected off a metallic surface) around the hot spots and cold spots in the CMB. We can represent the direction of polarization with a little rod or line, as done in Fig. 6. That figure shows that there are two "flavors" or modes of polarization. The so-called E-modes have radial symmetry. This mode of polarization is imprinted in the CMB by fluctuations in the density of matter. In contrast, the B-modes are not symmetric, but have a pinwheel like pattern. They can come only from an entirely different source, fluctuations in the fabric of space-time itself. These fluctuations are gravitational waves. In most theories of Inflation, gravitational waves are expected, purely on quantum mechanical grounds. We thus have a direct test of Inflation: B-mode polarization in the CMB, if detected, implies gravitational waves in the early Universe, and the presence of such fluctuations in space-time is a prediction of Inflation. Furthermore, the strength of the fluctuations in space-time (and hence the amplitude of the B-modes) varies from one model of Inflation to another. Measuring the B-modes would thus allow us to discriminate between models for the earliest moments of the Universe. Needless to say, the search for the B-modes has been intense.

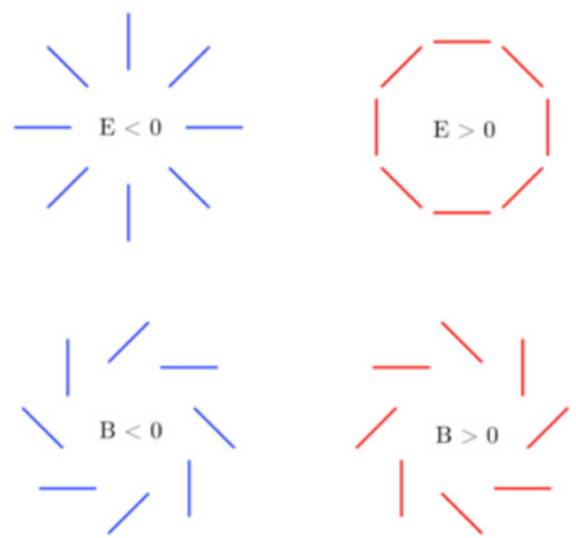

Fig. 6. Two modes of CMB polarization. The E-modes (top) are radially symmetric; the B-modes associated with Inflation have an asymmetric "pinwheel" pattern.

The much stronger E-modes were the first to be detected, however (by the DASI experiment in 2008). The amplitude of the E-modes has now been measured with precision (by *Planck* among other experiments), and agrees precisely with the 2015 model of the Universe. Thus the detection of the E-modes *confirms* the 2015 model, but does not offer *new* evidence. For that, we need the B-modes. Until March of 2014, no one had claimed a detection of the B-modes. A number of experiments had set limits on the amplitude of the B-modes ("they can't be any larger than…."), and these upper limits were good enough to rule out some theories of Inflation, so we were making some progress.

Then, in March 2014, a bombshell: the BICEP2 Team announced the detection of B-modes, based on observations made by a specially designed radio telescope located at the South Pole. Their B-mode measurements are shown in Fig. 7. You can see by eye the characteristic pinwheel pattern of B-modes around the prominent red blob in the upper center of the figure (red in this false color represents a CMB fluctuation of higher than average temperature). Around two less distinct blue (low temperature) blobs, the pinwheel runs in the opposite sense, as expected.

The BICEP2 Team did its best to ensure that these signals were truly cosmic, and not due to some sort of foreground, such as microwave emission from warm dust in the Milky Way. Since the BICEP2 instrument operated at only one frequency,

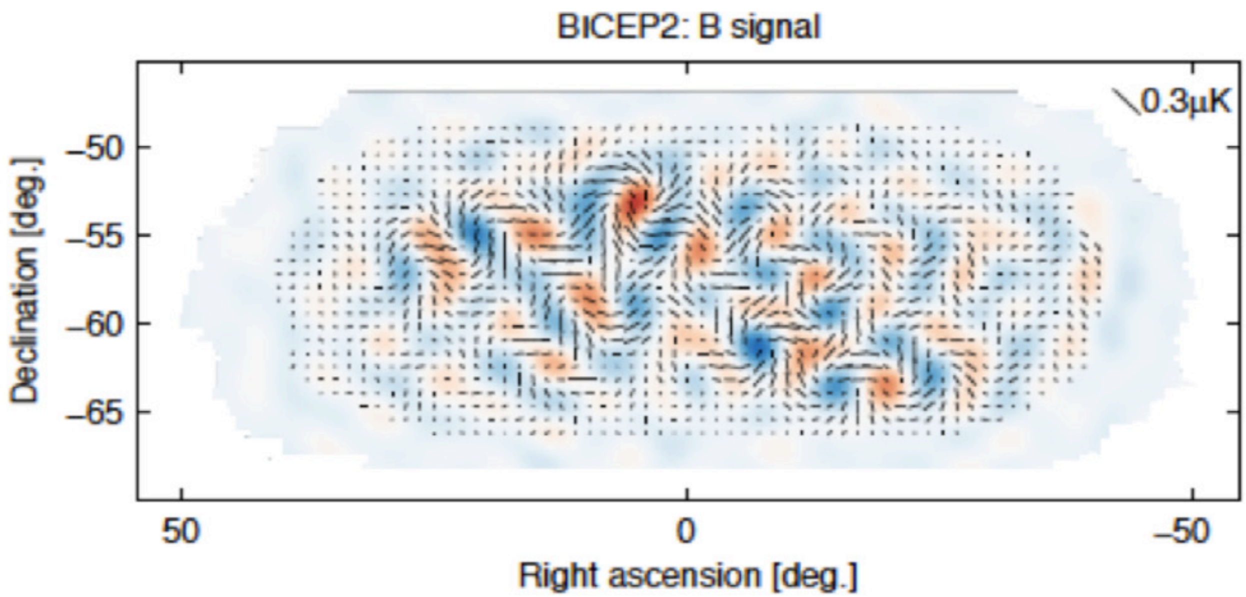

Fig. 7. The BICEP2 map of B-mode polarization. Notice how tiny the measured signal is – less than or about 0.0000003 K! (Image: BICEP2 Team)

the team's ability to map and eliminate foregrounds was limited. *Planck*, on the other hand, had both reasonable sensitivity and multi-frequency coverage; however, the *Planck* data weren't quite ready for publication in March 2014. Once published, the *Planck* data suggested that about ½ the claimed BICEP2 signal was produced by polarized emission coming from messy tendrils of dust in our Milky Way galaxy. The two teams then joined together to publish a thorough account of the B-modes: we have a firm and secure upper limit on the strength of the B-modes. What we await, eagerly, is an actual *detection*!

The hunt for the B-modes is just one example of gaps in the 2015 model of the Universe. Another gap is the slight tension between the CMB value for the Hubble constant and the one derived from supernova observations. A third is the puzzling difference between two hemispheres of Fig. 4. It is easy to see that the lower right half of the *Planck* map looks lumpier than the upper left. Why? We don't know. So the 2015 model Universe is still missing some hubcaps and a hood ornament. Even deeper questions remain open: what *is* Dark Matter? To a scientist, unanswered questions are a delight and a promise. One day, someone will answer these questions and fill in these gaps. Perhaps you, or one of your students….

Resources

W. Hu and M. White, *Scientific American* (2004) explains why fluctuations of a certain size on the surface of last scattering are favored.

Wayne Hu's fine website "An Introduction to the CMB:" http://background.uchicago.edu/~whu/beginners/introduction.html.

A more detailed presentation of the CMB and what we learn from it: B. Partridge and N. Vechik "Cosmology for Community Colleges: A Curricular Companion" www.haverford.edu/C5.

A website with more about the *Planck* mission and its results: http://www.esa.int/Our_Activities/Space_Science/Planck/Planck_at_a_glance.

BICEP2 press release announcing the discovery of B-modes:
https://www.cfa.harvard.edu/news/2014-05.

Using Google to search for either "Planck" or "BICEP2" will bring you to sites explaining the apparatus and methods of these two CMB experiments.