The Universe is Filled with an Ancient Radiation

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Abstract

This article is an overview of the oldest electromagnetic radiation in the Universe, known as the Cosmic Microwave Background (CMB), representing a snapshot of the cosmos approximately 380,000 years after the Big Bang. I discuss how precise measurements from COBE, WMAP, and Planck telescopes have given us clues about when and how the CMB formed, and helped us refine our understanding of the Universe's composition, age, and geometry.

If you could see it or sense it, you would have known that the Universe today is bathed in *an all-pervasive radiation field reaching us from every direction in the sky*. Unfortunately, we, as humans, can not directly sense it because it is electromagnetic radiation (combination of electric and magnetic fields propagating through space) in the microwave range.[1] But we can detect it with a microwave antenna. In fact, it was detected rather accidentally by the radio astronomers Arno Penzias and Bob Wilson of Bell Laboratories in 1964 (Figure 1). I said accidentally, because they were

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[1] We are familiar with the microwaves we use to cook food in microwave ovens. These waves are 12.2 centimeters long. They are part of the family of electromagnetic radiations, the same family that contains radio waves (used in broadcast radio signals), infrared (used in various remote controllers), visible light (what we can detect with our eye), ultraviolet (used in sterilization and disinfection of water, air, and medical equipment), X-rays (used in bone imaging), and gamma rays (used in medicine to treat cancer). The only difference between all these different forms of electromagnetic radiation is the length of their wave, from very long radio waves (from millimeters to hundreds of kilometers) to extremely short gamma rays (less than one hundredth of a nanometer).

looking for microwave signals reflected from an orbiting communications satellite at a specific wavelength of 7.35 centimeters. When they turned their horn-reflector antenna toward the sky, they found a slightly stronger than expected signal no matter what direction they pointed the antenna. They thought it was some "noise" in their system. They did their best to reduce it. But despite all their efforts,[2] the excess signal remained. It was the same in every direction (isotropic) which meant it was not coming from any specific star or galaxy or galaxy cluster. The radiation was unpolarized (the plane in which the electric field oscillates was random) and constant in time ("free from seasonal variations" in Penzias and Wilson paper). Fortuitously, they got in touch with Robert Dicke at Princeton University who had theorized earlier that the Universe, if it began in a *hot and dense state and cooled over time*, should now be filled with microwave radiation.[3] In fact, Dicke and his research team were about to build a microwave antenna to detect it when they realized they had been scooped!

Because this radiation was in the microwave range, it was given a name — the *Cosmic Microwave Background*, or CMB[4] for short.

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[2] The story goes that, as part of the clean up, they had to evict some squatter pigeons roosting inside the antenna and clean up "the usual white dielectric" produced by pigeons (physics humour).

[3] Penzias and Wilson wrote a paper in The Astrophysical Journal (July 1965) describing their discovery. The Princeton team, Dicke, Peebles, Roll and Wilkinson, wrote a companion paper in the same issue outlining their theoretical explanation of the origin of CMB as a relic of an early hot, dense and opaque Universe (which later became known as the Hot Big Bang model of the Universe). Actually, Dicke and company were unaware of the fact that Ralph Adler and Robert Herman had predicted, in 1948, the existence of CMB at a temperature of about 5 Kelvin, but somehow their work went unnoticed. Even more strange, there had been a prior measurement of the cosmic background radiation (CMB) by Andrew McKellar in 1941 at an effective temperature of 2.3 Kelvin using stellar absorption lines, but both Adler-Herman and McKellar papers had fallen into obscurity. (Kelvin is a temperature used frequently in physics - it is defined as Celsius degree plus 273.15. The "absolute zero" temperature (lowest possible temperature in the Universe) is 0 K or -273.15 degree Celsius.)

[4] For an excellent introduction to CMB at the undergraduate level, read the book *Introduction to Cosmology* by Barbara Ryden (Addison Wesley). In fact, I strongly recommend this award winning book to all cosmology enthusiasts.

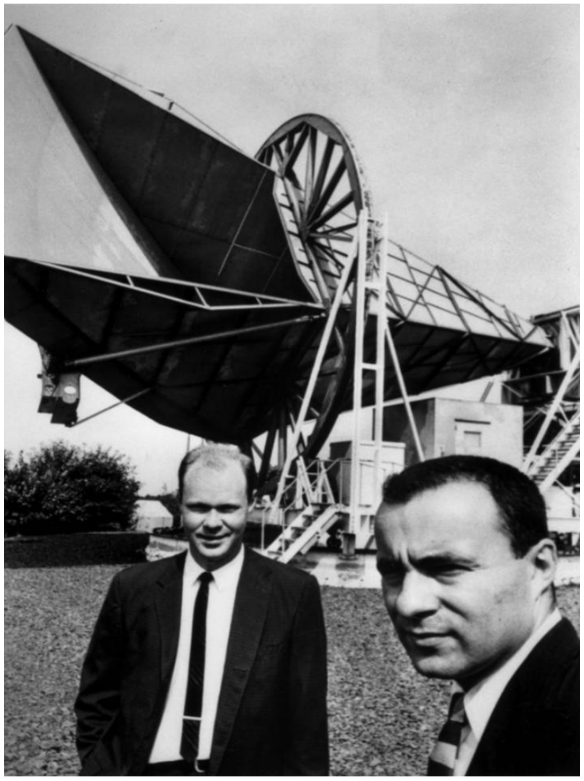

Figure 1: Penzias & Wilson in front of the Bell Labs horn antenna (1965). Image Credit: Nokia Bell Labs.

It is not at a fixed wavelength — the spectrum, how the energy density of the radiation varies at different wavelengths, of this radiation was thought to be emanated by an extremely cold blackbody.[5] But to confirm that CMB has indeed a blackbody spectrum, one had to measure it over a wide range of wavelengths. That was not an easy task. The CMB particle (called photons, the quantum particles associated with electromagnetic radiation) has, on the average, a tiny energy, not enough to split an atomic nucleus or even release an electron from an atom. So they can travel a very long distance through an intergalactic medium pretty unobstructed (meaning not interacting with any other particles)

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[5] In physics, a blackbody has a specific meaning — it is an idealized object that perfectly absorbs all electromagnetic radiation (including light) that hits it and, at any finite temperature, emits thermal radiation in a continuous spectrum. The intensity and peak wavelength of this thermal radiation depends only on its temperature, not its composition. For example, stars, incandescent light bulb filaments, electric heater coils are all good approximations to ideal blackbodies. Vantablack, a man-made material composed of carbon nano-tubes absorbs nearly 99.96% of incident light and acts as a near-perfect blackbody.

Figure 2: COBE satellite (NASA). Image Source: NASA.

but when they enter earth's atmosphere, they are quickly absorbed by water molecules (because the CMB photon's small energy is comparable to the energy of vibration or rotation of small molecules such as water). As a result, they are hard to detect at Earth's surface. Penzias and Wilson were lucky — they were measuring microwaves at a wavelength of 7.35 cm whereas microwaves of wavelengths shorter than 3 cm are strongly absorbed by water.

Shorter microwaves can indeed be measured from high altitude balloons (or at the south pole where the humidity is low and the altitude is relatively high), but the best way would be to measure it from a satellite above the atmosphere. Indeed, that was done by the COBE (**CO**smic **B**ackground **E**xplorer) satellite[6] launched

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[6] The COBE mission ran from 1989 through 1993. It was launched by a Delta-2 rocket directly into a circular, polar, and sun-synchronous orbit, 900 km above the Earth. The orbit plane was inclined at 99 degrees to the Earth's equator, and the time of launch was chosen

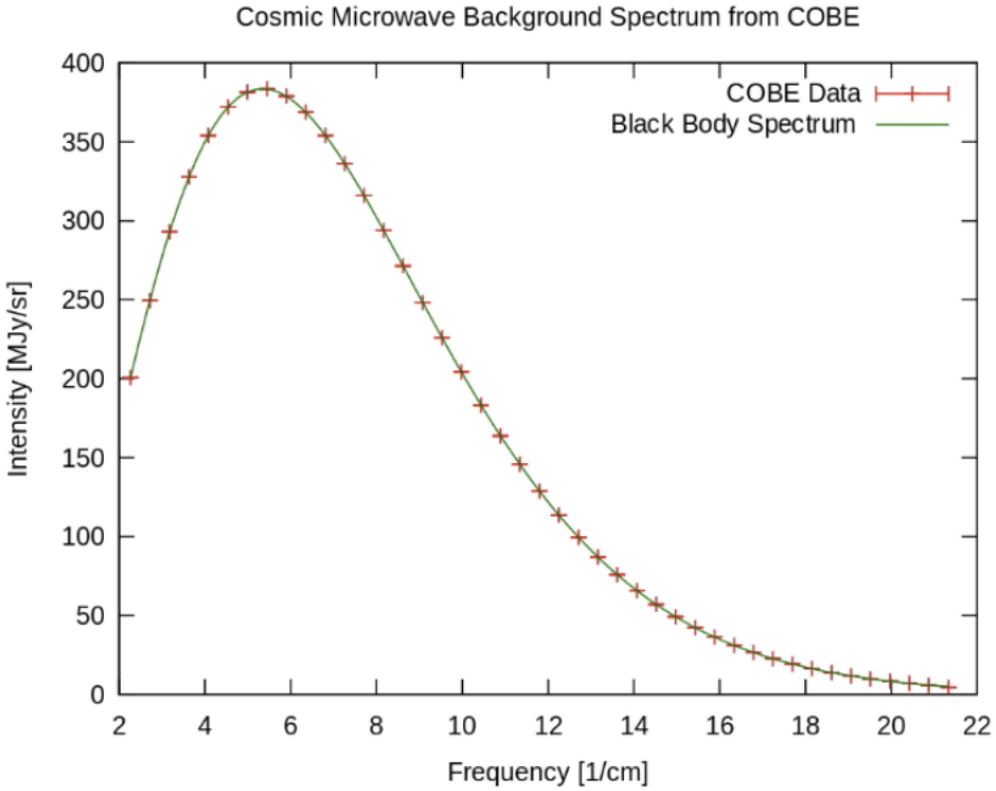

Figure 3: CMB spectrum detected by COBE. Image Source: Wikipedia.

in 1989 (see Figure 2).

Originally planned for a 6 month operation, COBE's CMB measurement mission lasted till 1993. The results are shown in Figure 3 above — the spectrum is a black-body spectrum at temperature 2.725 Kelvin (-270.4 degree Celsius) to a very high precision. The horizontal axis is plotted in frequency (inverse of wavelength) and the vertical axis shows how much power is carried by CMB at different wavelengths. The error bars in the data are smaller than the width of the theoretical blue line (known as Planck's Law). What a perfect fit!

Other than this stunning discovery that the whole Universe (the mostly empty space away from light emitting objects like stars, etc.) is emitting a very cold blackbody spectrum at -270.4 de-

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so that the orbit plane was nearly perpendicular to the line to the Sun. In this orbit, the spacecraft can be oriented to always point away from the Earth and approximately perpendicular to the Sun, so that the Sun never illuminates the instruments — you can think of Sun's radiation as a contamination on CMB which ought to be avoided.

gree Celsius, what else did we learn from the COBE mission? For one thing, the infrared spectrophotometer (a scientific instrument that quantitatively measures how much light is incident on it) called FIRAS[7] in the COBE satellite was sensitive enough that it could have detected deviations from the theoretical model[8] as small as one part in 10,000 — no such deviations were found!

The second finding was a bit more subtle. In one half of the sky, the spectrum was seen to be slightly blue-shifted (meaning the wavelengths were a little shorter than expected) while the CMB from the other half of the sky was red-shifted (wavelengths longer than expected). It was quickly realized that this deviation (technically known as a **dipole distortion**) is a simple Doppler shift;[9] it just meant that the observer (the COBE satellite itself) has a net motion relative to a reference frame in which CMB is isotropic. But what does that really mean? Think of all the motions that contribute to the actual motion of COBE in space. First, the orbital motion of COBE around the Earth (speed about 8 km per sec); second, the orbital motion of Earth around the Sun (speed about 30 km per sec); third, the orbital motion of Sun around the galactic center of Milky Way (speed about 220 km per sec); and fourth, the orbital motion of our galaxy around the center of mass of the Local Group[10] of galaxies (speed about 80 km per sec).

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[7] In fact, the COBE satellite had 3 different instruments: DIRBE to measure radiation with wavelengths between 0.001 mm and 0.24 mm (primarily to detect stars and dust within our own galaxy); FIRAS, mentioned above, for wavelengths between 0.1 mm to 10 mm; and DMR that would map variations (or anisotropies) in CMB at 3.3 mm, 5.7 mm and 9.6 mm. As you can see, the instruments overlapped in wavelength coverage, providing consistency checks on measurements in the regions of overlap — it also helped in discriminating signals from our galaxy, the solar system and CMB.

[8] The theoretical blackbody spectrum (shown as a blue line in Figure 3) is known as Planck's Law, one of the earliest triumphs of Quantum Mechanics.

[9] A simple example of Doppler shift is when an ambulance siren seems to be of higher pitch when approaching us and the pitch gets lower when it recedes from us. This is true for any wave we can detect in our surroundings — sound waves, light, radio waves, etc. The same is true for CMB which is nothing but microwaves.

[10] The Local Group is a collection of over 50 galaxies, including our own Milky Way, in our galactic neighborhood, bound together by gravity. It is dominated by the massive Andromeda

Figure 4: The dipole distortion in CMB as measured by WMAP, a more sensitive successor mission to COBE. Image Source: NASA.

Even after taking into account the effective Doppler shift due to all these motions, the data shows a remnant Doppler shift indicating the Local Group is speeding toward the Hydra-Centaurus galaxy supercluster at a speed of approximately 600 kilometers per second!

So, knowing that the dipole distortion has nothing to do with the CMB spectrum, it is possible to subtract it away. But we are not out of the woods yet. Look at Figure 4 above (results from WMAP,[11] a more technologically advanced successor mission to COBE).

Figure 4 shows the dipole distortion (the lighter and darker gray regions) due WMAP's proper motion. The contrast in this picture is set high to bring out the horizontal band across the middle which is due to the emission from the disk of our own galaxy — this foreground emission contaminates the CMB spectrum. To

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and Milky Way galaxies, with the Triangulum Galaxy as the third largest, and contains numerous smaller dwarf galaxies like the Magellanic Clouds.

[11] WMAP was a NASA spacecraft operating from 2001 to 2010 which measured temperature differences across the sky in the CMB — the radiant heat remaining from the Big Bang. The WMAP mission succeeded the COBE space mission and was part of the NASA Explorer program. After nine years of operations, WMAP was switched off in 2010, following the launch of the more advanced Planck spacecraft by the European Space Agency (ESA) in 2009. Planck was operational from 2009 to 2013. At the end of its mission, Planck was put into a heliocentric graveyard orbit and passivated to prevent it from endangering any future missions. The final deactivation command was sent to Planck in October 2013.

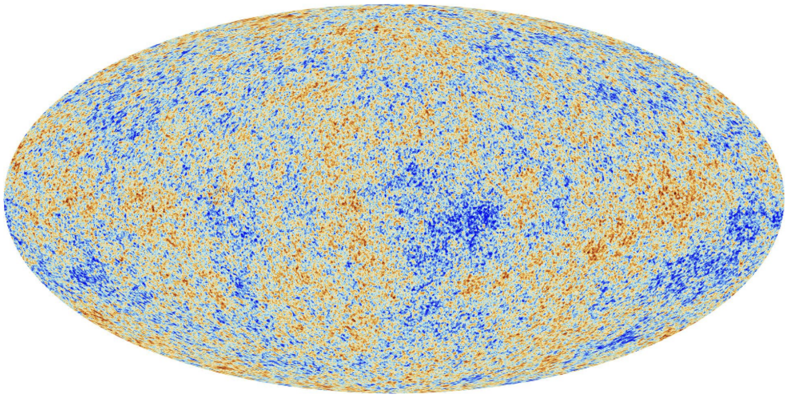

Figure 5: Temperature variations in CMB spectrum after the dipole distortion and the galactic emission band is removed (Planck/ESA data). Image Source: Planck/ESA.

get the pure CMB spectrum, we have to remove this too — the result is shown in Figure 5.

And this brings us to the third important finding from the CMB mission. Looking at a specific direction in the sky, one can figure out the temperature of CMB observed along that direction. When averaged over all angular locations, COBE CMB data provides an average temperature of the sky, $T_{\text{avg}} = 2.725$ K ($-270.425°$ C). A spectacular result indeed. Most of the Universe, away from actively radiation emitting objects like stars, interstellar and intergalactic gases, is a very very cold place!

But as the annoying infomercial guy says, “That’s not all folks! You get more!” Knowing the average CMB temperature of 2.725 K, one can estimate the fractional deviation from the average along any direction in the sky, i.e., the fluctuations. Some directions will be above the average of 2.725 K and some will be below. To get a sense of how big these deviations are, we calculate the fractional deviation from the mean for any location and use standard statistical methods to find the standard deviation over the entire sky.[12] It turns out to be about 11 parts per million which means “the

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[12] Of course, the analyses of T_{avg} and the standard deviation excludes the regions of the sky contaminated by electromagnetic emission from our own galaxy.

temperature of the CMB varies by only 30 microKelvin across the entire sky". This strongly reinforces our assumption that "CMB is very close to being isotropic."

So what should we conclude from the analyses of these fantastic observational data from COBE, WMAP and Planck/ESA? The fact that the CMB *is nearly isotropic (once the dipole distortion is removed) and that it has an almost perfect blackbody spectrum strongly supports the Hot Big Bang model of the Universe — this kind of all-pervasive isotropic radiation field is only natural if the Universe was once hot, dense, opaque and nearly homogeneous.*[13] Any other explanation of the CMB with the observed properties would be difficult (or highly contrived) if the Universe did not once go through an early hot and dense phase (for example, look up the once proposed Steady State Model[14] by Bondi, Gold and Hoyle).

An astute reader may have noticed that I have used two key phrases rather cavalierly: one regarding the temperature fluctuations in CMB ("very close to being isotropic") and the second one regarding the Universe as a whole ("nearly homogeneous"). What do these really imply? Here is a short explanation. The temper-

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[13] According to the Big Bang model, the Universe started in a very dense and hot phase that expanded and cooled itself. For several hundreds of thousands of years the temperature was so high that neutral atoms could not form. Matter consisted mostly of photons and charged particles (protons and electrons). Electrons (and to some degree, the protons) interacted closely with the light particles (photons), and therefore light and matter were tightly coupled at that time (that is, light could not travel for a long distance without being scattered by charged particles). Light, therefore, could not propagate for long distances and the Universe was opaque. It took about 380,000 years for the Universe to cool down to a temperature at which atoms can form (about 3000 K). Matter then became neutral, and allowed the light to travel freely: the Universe became transparent. The relic of that 'first light' is the CMB. Since the time when radiation was released, the Universe has expanded (by a factor of about 1100), becoming cooler and cooler at the same time. The CMB has been affected by the same process: it has expanded and cooled down. Space has 'stretched' itself, and with it all length scales (such as the wavelengths of CMB photons). Today, we detect the CMB at microwave wavelengths that correspond to a temperature of 2.725 K, which are much longer than visible light.

[14] The Hot Big Bang model and the Steady State model are described in most cosmology textbooks. See, for example, *Introduction to Cosmology* by Barbara Ryden [1]. Short summaries are also available in the Wikipedia articles [2] and [3].

ature fluctuations (also referred to as anisotropies) observed in CMB are real, not a measurement issue. We have to go back to a time before the formation of CMB to understand how these tiny fluctuations came about. At the very beginning, the Universe underwent a rapid inflation that lasted only until one hundred-nonillionth second (10^{-32} second). After inflation was over, the size of the Universe had increased by a factor of about 10^{30} (1 followed by 30 zeroes). Minute random *quantum fluctuations* in the structure of the Universe that were present at the moment when inflation started, were amplified up to cosmologically large scales during inflation — the Universe now consisted of significantly large regions with slightly different properties from place to place; in particular, the density of matter was slightly larger in some regions of the Universe than it was in others. These slightly denser regions eventually grew increasingly denser, as gravity caused them to draw more and more matter from the surroundings. For the same reason, the density of the less-than-average-density regions got even rarer — you might say "the rich gets richer at the poor's expense." These primordial fluctuations in the density of matter in the early Universe are the seeds of the rich cosmic structure — stars, galaxies, galaxy clusters — that we observe today. So the density fluctuations are a result of the brief period of inflation.

And this brings us to the next question: assuming the density fluctuations were created during inflation, how are they related to the temperature fluctuations we see in CMB? Before the CMB was released (approximately 380,000 years after the Big Bang), photons and ordinary particles were tightly coupled together, forming a single 'fluid' of matter and radiation. As the temperature cooled down to about 3000 K, electrons and protons were able to combine into neutral atoms and the two species decoupled from one another. The photons started to propagate freely across the

Universe, eventually reaching our telescopes. But the photons carried a memory of how matter and radiation were distributed at the time of this decoupling. If, at the time of decoupling, a photon was in a slightly denser region of space, it had to spend some of its energy against the gravitational attraction of the denser region to move away from it (sometimes referred to as "climbing out of the potential well"), thus becoming slightly colder than the average temperature of photons. Oppositely, photons that were located in a slightly less dense region of space, lost less energy upon leaving it than other photons, thus appearing slightly hotter than average. So the temperature fluctuations in the CMB reflect the pattern of structure in the matter right when the CMB was released. You might say the CMB is the ultimate snapshot of our Universe at the time atoms formed.

A note about post-COBE missions: The COBE mission ran from 1989 through 1993. Since then, there has been much more progress in our understanding of the Universe, particularly the CMB. Succeeding COBE, the WMAP, launched by NASA, started operation in 2001. Unlike COBE which orbited Earth, WMAP was stationed at Lagrange point L2,[15] 1.5 million kilometers from Earth. Its nine-year data release in 2012 gave us a trove of information, such as the Universe is 13.7–13.8 billion years old, 95% of the early Universe is composed of dark matter and dark energy, the curvature of space is less than 0.4% of "flat" and the Universe emerged from the Cosmic Dark Ages "about 400 million years" after the Big Bang.

Eventually the WMAP satellite was switched off in 2010 following the launch of the more advanced Planck[16] spacecraft by the Euro-

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[15] L2, the second Lagrange point, is a gravitationally balanced location about 1.5 kilometers behind Earth (opposite the Sun) where the gravitational forces of the Sun and Earth, plus the centrifugal force, balance. This allows spacecrafts like WMAP, Planck, and James Webb Telescope to orbit with minimal fuel and provides an unobstructed view of deep space.

[16] See Footnote # 11

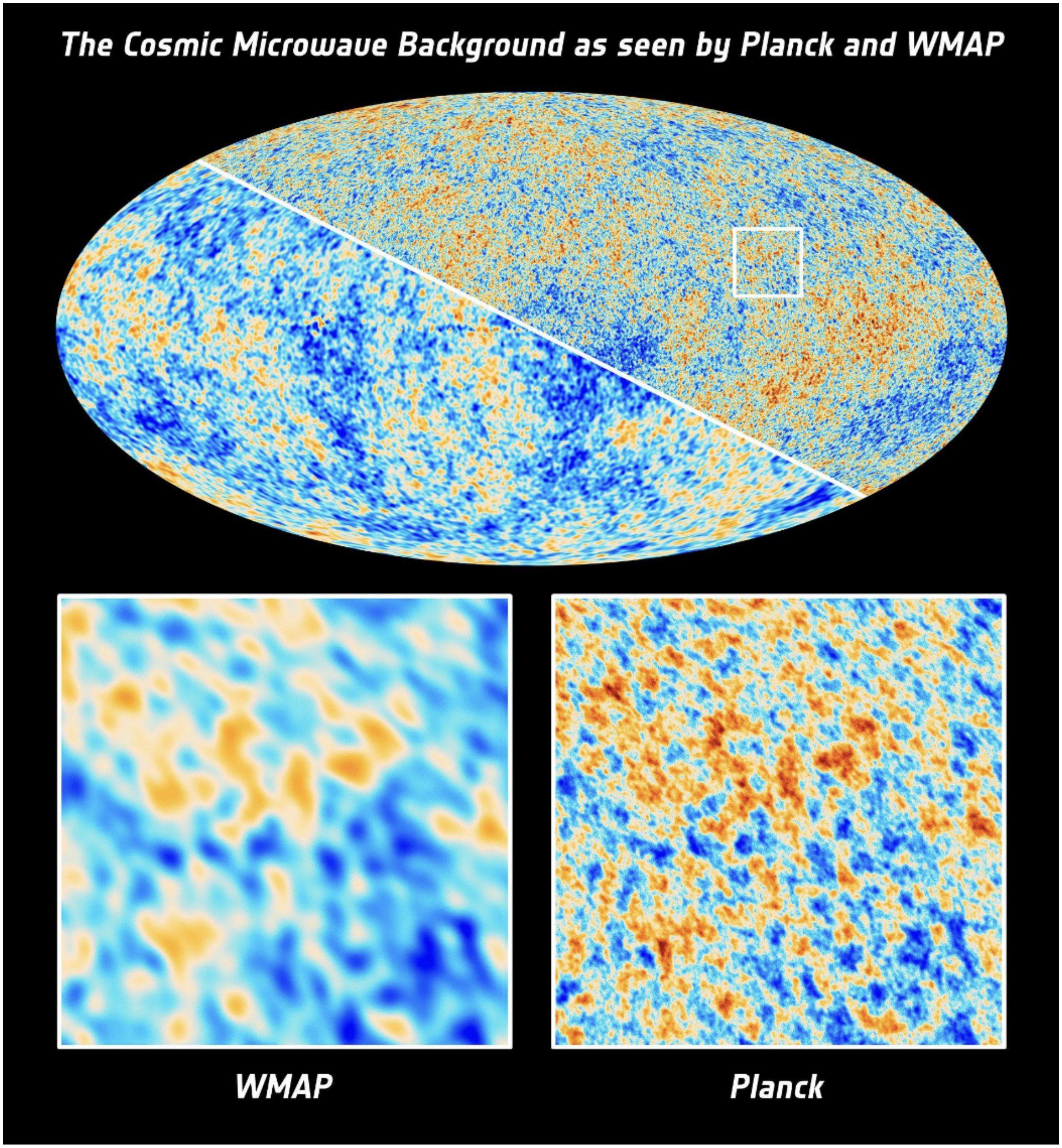

Figure 6: A comparison of resolutions in WMAP and Planck sky maps. The lower left of the upper panel is data from WMAP showing somewhat lesser resolving power than the upper right which is from Planck. The lower panel is a small square section of the sky seen by WMAP and Planck/ESA. Image Source: Planck/ESA.

pean Space Agency (ESA) in 2009. Planck/ESA had a higher resolution and sensitivity than WMAP, allowing it to probe the power spectrum of the CMB to much smaller scales (see a comparison of their sensitivities in Figure 6). According to the Planck/ESA team, the Universe contains about 4.82% ordinary matter, 26.8% dark matter and 69% dark energy. Maybe, in a future column, we can discuss the fascinating history of the Universe, its age and contents, and its possible evolutions with time.

It is worth pausing to appreciate how strange and intimate this all is. The same kind of microwaves we casually use to heat last night's leftovers are also quietly filling up the space around us, arriving at Earth from every direction after a multi billion year journey. Trillions and trillions of ancient photons are bathing our bodies, the walls, and our telescopes, carrying with them a snapshot of the Universe. We are not merely observers of the cosmic past; we are immersed in it. This is all a reminder that the Universe remembers its own beginning, and that memory may be floating all around us.

References

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