Geometry of the Universe

By Avi Loeb on July 8, 2020

At ancient times, wise people like Aristotle thought that heavy objects fall faster than lightweight objects under the influence of gravity. About four and a half centuries ago, Galileo Galilei decided to test this assumption experimentally. He dropped objects of different masses from the Leaning Tower of Pisa and found that they all fall the same way under the influence of Earth's gravity. Three-and-a-quarter centuries later, Albert Einstein was struck by Galileo's finding and realized that if all objects follow the same trajectory under gravity, then gravity might not be a force but rather a property of spacetime, the fabric which all objects share the same way (establishing the so-called "equivalence principle"). More importantly, Einstein recognized that when spacetime is curved objects do not follow straight lines. He reckoned that the Earth moves around the Sun because the Sun curves spacetime in its vicinity. The Earth's orbit follows a circle, similarly to a ball on the rubber surface of a trampoline whose center is pulled down by the weight of a person.

In November 1915, Einstein formulated his insight through mathematical equations that established the foundation for his General Theory of Relativity. One side of Einstein's equations includes all masses that source gravity (like the person standing on the trampoline) and the other side quantifies the curvature of spacetime. In the words of John Wheeler: "Spacetime tells matter how to move and matter tells spacetime how to curve".

The first solution of Einstein's equations was derived by Karl Schwarzschild a few months later, while serving on the German front during World War II. This solution describes the curved spacetime around a point of mass, labeled a "black hole" by Wheeler half a century later. In Schwarzschild's solution, the curvature of spacetime diverges at the central point, called the "singularity" because that is the singular point where Einstein's theory breaks down. This breakdown is for an obvious reason: Einstein's theory of gravity did not incorporate quantum mechanics. However, quantum corrections must be important when the curvature is large and most physicists expect the singularity to disappear in a quantum theory of gravity. Despite many attempts to unify General Relativity with Quantum Mechanics (such as versions of string theory or loop quantum gravity), we do not have an experimentally-verified version of the theory as of yet. But gladly, the rest of spacetime is protected from the uncertain description of the singularity. The solution admits a spherical event horizon that surrounds the singularity at the so-called Schwarzschild radius. No information can escape from inside this event horizon.

Einstein's equations also describe the evolution of the Universe at large. We know several facts from observing the Universe over the past century. First, the Universe expands. Second, on very large scales the expanding Universe is nearly homogeneous (same density of matter and radiation) and isotropic (same expansion rate in all directions). Under these circumstances, Einstein's equations admit a simply spherically symmetric solution, derived by Alexander Friedman, Georges Lemaitre, Howard Robertson and Arthur Walker. The curvature of spacetime in this solution can be positive (like the surface of a ball), negative (like the surface of a saddle) or zero (like a flat surface). In the spirit of Galileo, can we measure the actual cosmic geometry experimentally?

The simplest experimental approach is to draw a large triangle through the universe and measure the sum of its angles. For a negative or positive curvature, the sum would be larger or smaller than 180 degrees, respectively, whereas for a flat geometry it would be exactly 180 degrees. Mother Nature has been very kind to us in providing the base of this triangle in the Cosmic Microwave Background (CMB) sky. Let me explain.

Early on, the Universe was hot and dense. Four hundred thousand years after the Big Bang, the cosmic soup of particles cooled to a temperature below 4,000 degrees Kelvin, at which electrons and protons recombined to make hydrogen atoms. When the dense fog of free electrons disappeared, the universe became transparent to the CMB. Therefore, observations of the CMB allow us to witness the Universe at the epoch of recombination.

The CMB brightness is not perfectly uniform across the sky. After removing the effect of the Earth's motion relative to the cosmic frame, one finds that the CMB varies by roughly one part in a hundred thousand on a wide range of angular scales. But there is one special lscale that we can calculate from first principles at that time. It is the distance that sound (acoustic) waves traversed during the age of the Universe at the epoch of recombination. This "acoustic" scale can serve as the known base of our triangle. It signifies the spatial separation of parcels of the cosmic gas that could have been in acoustic contact with each other. By measuring this special correlation scale for CMB brightness fluctuations on the sky, we can draw an isosceles triangle with us at the corner opposite to this base of the triangle. Knowing the height and base lengths of the triangle as well as measuring the angle spanned by the acoustic scale on the sky would inform us whether the sum of the angles in this triangle deviates from 180 degrees, and hence the curvature of the Universe.

This experiment was done in 2000 and the characteristic hot and cold spots were measured to be a few times wider than the diameter of the Moon. This measurement was refined since then to a high level of precision by the latest data from the Planck satellite. It revealed that the geometry of the Universe is the simplest one we can imagine: flat!

Why is the universe so simple? Obviously, nature is under no obligation to represent the simplest solution to Einstein's equations.

One possible explanation is provided the theory of cosmic inflation. If the universe went through an early period during which it inflated exponentially (due to the dominance of the vacuum energy density), then all traces of its initial curvature would be flattened out. Inflation serves as the cosmic iron in erasing all pre-existing wrinkles from spacetime. How far beyond the observable volume of the Universe should we expect to find the "cliff" where the geometry be different? We have no clue. It depends on how long inflation lasted.

Interestingly, our expanding universe is now entering a new phase of exponential expansion due to the so-called cosmological constant. Here again, we have no idea how long this inflationary phase will last. If it continues for more than ten times the current age of the Universe, our galaxy will be left alone, surrounded by vacuum with no other source of light in sight. This would be the most dramatic incarnation of social distancing from extragalactic civilizations that we can imagine following the era of COVID-19.

Quantum fluctuations of the vacuum during inflation might have led to the slight brightness fluctuations of the CMB that seeded the formation of galaxies like the Milky Way. If our cosmic roots were formed then, we owe our existence to quantum. Keep that in mind next time you celebrate Mother's Day or Father's Day. In the spirit of full disclosure, perhaps we should also establish "Quantum Mechanics Day".

ABOUT THE AUTHOR

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(Credit: Nick Higgins)