# The Expanding Universe
# Transcript

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The discovery of the expansion of the universe was one of the outstanding discoveries of the twentieth century. Prior to the 1920s, no scientist imagined that space could be expanding. The universe was simply assumed to be static.

The first cracks in the static universe edifice appeared with the work of Willem de Sitter. He was aware of the redshifts of some galaxies being measured by Arizona astronomer Vesto de Slipher. A redshift of the spectrum indicates a velocity away from us, a blue shift towards us. Most of the nearby galaxies that Slipher measured had redshifts, not blueshifts.

American astronomer Edwin Hubble became famous overnight when he announced in 1929 that the redshifts of the galaxies increased systematically with their distance from the earth. For most astronomers this meant that the universe of galaxies was expanding. In reality it is the space in which the galaxies are embedded that is expanding.

Remarkably, while Hubble's name was soon assigned to the law that asserted that the redshift of a galaxy is proportional, on the average, to its distance from us, this very law was independently discovered two years earlier by Georges Lemaitre, a Belgian cosmologist and Jesuit priest. Unfortunately, Lemaitre published his pioneering work in French, in an obscure journal that was overlooked at the time. Lemaitre's original work was published in English in 1931, but his modesty led him to omit a key section on the expansion law, on the grounds that Hubble had already published this.

There is another key contributor to the expansion saga, in this case to its theoretical interpretation in terms of a cosmological model. Russian mathematiciam Alexander Friedmann published in 1922 solutions to the Einstein equations of general relativity that showed the possibility of a non-static universe.

Einstein refused to accept that the universe could be expanding, until Hubble's results were published. We now call the mathematical description that describes the expansion of the universe, and in particular its past and future evolution, the Friedmann-Lemaitre equation.

Little new happened in cosmology in the 1930s. The large measured value of Hubble's constant maintained a lively debate between advocates of the expanding universe and those suspicious of the interpretation of redshifts in terms of the expansion of space. How could the age of the universe be less than the age of the earth?

Hubble used Cepheid variable stars, distinguishable at great distances from their regular brightness variations, as distance scale indicators. This was how he established the distances to the nearest galaxies, and thereby set the distance scale for venturing deeper into the universe.

The age discrepancy was largely resolved by Walter Baade in the 1940s. He benefited from the dark-outs in Los Angeles during the second world war to observe the Andromeda galaxy with unprecedented precision. He showed that there were two types of Cepheid variable stars. The distances to nearby galaxies increased by a factor of two once this was taken into account in the calibration procedure. Now the age of the universe inferred from its expansion agreed with that inferred from isotopic measurements. The stage was set for the expanding universe and its many consequences.

Russian-American physicist George Gamow made the next break-through that established a hot and dense origin for the expanding universe. What he pioneered was the notion that in the first few minutes, when the universe passed through a phase that was as dense and hot as the centre of the sun, protons could fuse together to form helium nuclei. These thermonuclear reactions occur in the core of the sun, indeed they power the sun. He and collaborators calculated that as much ten percent of the particles in the universe could be helium nuclei. Modern calculations confirmed his estimates. Modern observations find that there is a substantial amount of helium that was produced before any stars had formed, much as Gamow had argued.

British astronomer Fred Hoyle could not accept the idea of a singular origin to the universe, as implied by Friedmann's theory of the expanding universe. Lemaitre had one solution, something he dubbed the primeval atom, in which a repulsive force, denoted by what we call the cosmological constant, effectively an energy density, countered the force of gravity. This allowed a static solution for the beginning of the universe, avoiding the singularity. However Lemaitre's explanation was largely abandoned because the primeval atom was found to be unstable.

Hoyle's solution was more radical. He postulated, along with Bondi and Gold, that the universe was in a steady state. As space expanded, matter was created out of the vacuum to form new galaxies. Hence the density of galaxies remained constant; there was no need to postulate a moment of creation. He called the rival theory the Big Bang, a term that remained long after the Steady State theory had collapsed. The Steady State universe did not endure for two reasons. One was that studies of radio galaxies led by UK astronomer Martin Ryle found that the number greatly increased in the past.

Hoyle’s response was to postulate that we lived in a large hole. But the crushing blow to the steady state theory came from the discovery of the cosmic diffuse background microwave radiation, a direct testament of a fiery and dense past..

Perhaps the greatest legacy from Gamow’s studies of the first minutes of the universe was the realization that there should be a pervasive but very cold relic radiation field. He did not consider the observational implications, and the model was forgotten. A decade later however, a group of astronomers led by Robert Dicke in Princeton New Jersey rediscovered Gamow’s model, without ever being aware of Gamow’s prediction, and added one crucial new ingredient. The fossil radiation would have cooled to a few degrees Kelvin and should be visible in microwaves as blackbody radiation. Gamow’s collaborators Alpher and Herman predicted the temperature, itself a remarkable accomplishment, in 1951 but failed to make the connection with microwave astronomy.

In 1964, two radio astronomers at the Bell Laboratories in Holmdel, New Jersey discovered the cosmic microwave background. They had beaten Dicke’s group in the race to discovery, although for them, it was a purely serendipitous result.

It took another 16 years before the COBE satellite demonstrated that the cosmic microwave background radiation had a perfect blackbody spectrum.

This provides the ultimate proof that the visible universe expanded from an extremely hot and dense past, with the blackbody spectrum of the relic radiation testifying that it originated in a perfect furnace

There was one more consequence from Gamow’s prediction of the light element abundances. The baryon, or ordinary matter, content of the universe had to be exceedingly small. If not, one would have produced excessive amounts of helium in the first few minutes. Essentially no deuterium.would be produced. From the success of nucleosynthesis, one inferred that baryons constituted at most ten percent of the critical density needed fot the simplest cosmology, the Einstein-de Sitter universe. In this model, there was a balance between kinetic energy of expansion and gravity, and the universe was at a critical density.

For decades, astronomers assumed that the “missing” matter was baryonic.

Perhaps it consisted of faint stars such as white dwarfs, or brown dwarfs.

In fact the case for missing matter, i.e. matter that is present but dark, only became firmly established with two key observational developments.

One was the advent of galaxy redshift surveys. These mapped out the distances and peculiar velocities of galaxies in the local universe. If the universe was at critical density, the velocities would be excessive. If the dark matter however weighed in at a tenth of the critical density one could nicely explain the large-scale structure of the universe. Since baryons, from the work of Gamow and collaborators could not exceed a few percent or so of the critical density, the case for dark matter was strengthened.

A key step was the measurement of the fluctuations in the cosmic microwave background. Half a century after Gamow’s insights, cosmologists measured the curvature of space. They did this by finding a standard ruler in the sky.

The early fluctuations, eventually the source of the galaxies, were like sound waves when the universe was mostly radiation. Only when the matter cooled and became atomic did the radiation no longer scatter against the radiation. From then onwards, the inhomogeneities in density could grow by gravity and form galaxies.

It was at this moment, 380000 years after the beginning that the first sound waves left their imprint on the relic radiation, the cosmic microwave background. The crests of the wave are separated by a length that is the distance light travelled through the universe at that instant. We measure this scale in the temperature fluctuations. If space is curved like a sphere this scale shifts to smaller values: distances become smaller. If space is curved like a hyperboloid, the opposite happens. We measure that space is exactltly in between, it is not curved but flat. From this we infer that the universe must have exactly a critical density of mass-energy to balance the expansion.

The space of the universe was shown to be Euclidean. Space was flat. Far more dark matter than baryons was needed. It becomes more complicated, as we will see in a future lecture. The universe also contains dark energy, a uniform energy field that acts like antigravity. Einstein called it the cosmological constant. and it amounts to two-thirds of the critical density.

All adds up to give a flat space for the universe.

One third of the critical density of the universe is dark matter, and about 15 percent of the dark matter is baryonic. We know that most of the mass in the universe must be nonbaryonic. It must also be dark, as it is not observed directly in the luminous regions of galaxies.

The flatness of the universe was not unexpected. It was a prediction of the theory of inflation. This development was the first major advance in cosmology since the establishment of the theory of the expanding universe by Friedmann and Lemaitre. It was to take half a century, and the entry of particle physicists into the field.

The high energy theorists realized that the early universe was a unique laboratory for exploring the implications of particle physics. One of their gifts to cosmology was the weakly interacting elementary particle as a candidate for dark matter. It relied on the breaking of symmetry between fermions and bosons believed to exist in the first nanoseconds of the universe at energies of order hundreds of GeV. We have not yet discovered dark matter, but there are many ongoing searches.

Inflation was a beautiful prediction that stemmed from the belief that at much higher energies all fundamental forces were unified. This grand unification occurred at much higher energies, at around $10^{-36}$ second after the Big Bang. US physicist Alan Guth and Russian physicist Andrei Linde independently proposed that as grand unification of the forces broke down as the universe expanded and cooled, a phase transition occurred in the state of matter that led to a brief injection of energy. A common analogy is a frozen lake, where the latent heat of the ice releases energy that allows liquid water to remain under the ice and fish to survive.

The energy release was briefly enormous as the state of matter transited from one in which all forces were equal to one in which the weak nuclear and electromagnetic forces were much less than the strong force, as is the case in nature. The result was a dramatic expansion of space. One could now understand why the present universe is so large. Another prediction was that any deviations from the flatness of space would be smoothed out as a consequence of the inflation, much like the surface of an expanding balloon. A final prediction was that the tiny irregularities present at the quantum level were boosted in scale. After inflation terminated, there were infinitesimal density fluctuations on all scales.

Hundreds of thousands of years later, these primordial fluctuations generate tiny ripples in the cosmic microwave background radiation. They have been detected and mapped out on the sky, most recently by the Planck satellite.

After billions of years elapsed, gravity eventually took over, and these primordial fluctuations gave rise to the formation of the galaxies.