



Will the current rate of expansion of the universe result in a Big Freeze, Big Crunch or Big Rip?

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ABSTRACT

The eventual fate of the universe has been a question that has been around and tried to be answered for many millennia. Currently there are 5 main theories for the ultimate fate of the universe: Big Freeze, Big Rip, Big Crunch, Big Bounce and Big slurp. A lot of research has been conducted by satellites such as NASA's Wilkinson Microwave Anisotropy Probe (WMAP) satellite on the different variables that are important in deducing how the universe is going to end which I am going to go through in this research paper. By assessing these variables and what it means towards the momentum of expansion and the pull (or push) of gravity, we will see the most probable method of the demise of the universe. However, as with most concepts and theories in Astronomy and Astrophysics, our ideas are changing everyday so what we believe today may be different to what we think will happen tomorrow.

INTRODUCTION

Since the dawn of the earliest forms of humans, there has always been an innate sense of inquisition and curiosity. For example, the invention of the wheel and the ability to control fires were the result of trial and error and the 'survival of the fittest' mentality that has been ingrained in the human brain for millennia due to our brains taking its form from a long sequence of events through thousands and tens of thousands of years of evolution through natural selection. This interest gradually turned to space and the cosmos. Greek astronomers would draw the sky every day and examine the change in the positions of the stars and stars would be used to navigate oceans. The expanding universe has slowly become one of the main points of interest for scientists and humans. Along with the discovery and discussions over the universe expanding at an accelerating rate, scientists have wondered how the Universe is going to eventually end. Will it keep expanding forever or will it collapse in the same way stars collapse?

DISCUSSION

First Discovery of the Universe Expanding

It was first discovered in 1929 by Edwin Hubble through observations of the light from distant galaxies that the universe is expanding. Hubble analyzed the light that he recorded and measured the wavelength of the spectrum of light that was detected. Hubble discovered that the wavelength of light from distance galaxies are red shifted – the light is seen as shifted towards the red end of the light spectrum. Essentially what this means is that the wavelength of the light has become longer. Galaxies that are further away are red-shifted more meaning they are moving away from the Earth faster. Thus, it was established that the universe is in fact expanding and that galaxies are moving away from each other. In fact, from this observation of the fact that the universe is expanding, scientists established that the universe must've been extremely small at the origin of the universe. Thus, the Big Bang Theory of the universe was established from this fact additionally. This was the theory that the universe started as an extremely small hot dense ball and expanded and cooled into the universe that we know today forming stars, galaxies, galaxy clusters and many more astronomical bodies along the way.

The Accelerated Expansion of the Universe

It was thought after the discovery that the universe is expanding that it is doing so at a decelerating rate due to gravity. Due to the vast expanse of the universe, it seemed intuitive to scientists and theoretical physicists that the force of gravity must be bringing the universe together. However, in 1998, two projects found evidence that the opposite was in fact the case. The Supernova Cosmology Project and the High-Z Supernova Search Team both analyzed type Ia supernovae. A type Ia supernova is thought to result as a result of a white dwarf exploding outwards due to it going over the Chandrasekhar limit which is the threshold for white dwarfs before they cease to exist by exploding into a type Ia supernova. The Chandrasekhar limit is 1.4 solar masses. The luminosity of these Supernovae is all the same which makes them extremely useful for analyzing the structure for the universe. The researchers found that the light produced from these supernovae was dimmer than expected. Since light emitted from astronomical bodies are dimmer when they



are farther away, this shows that the universe expanded more than they thought it did thus showing that the universe is expanding at an accelerating rate.

Why the Universe is Expanding at an Accelerated Rate

There have been many propositions for why the universe is expanding at an accelerated rate. One of the most famous explanations has been dark energy. Dark energy is thought to make up 68% of the universe. Very little is actually known about what actually dark energy is but there have been different theories to what it could be.

One of these theories is that dark energy is a property of space. Einstein's field equation that contains a cosmological constant says that 'empty space' can actually possess its own energy. Since dark energy is a feature of space itself in this scenario, the abundance of it would not reduce. Thus, as the universe expands and more of space appears, there is more of this energy causing even more expansion creating a continuous loop of space being created at a faster rate.

Another explanation is that dark energy has properties that are opposite to that of normal matter and standard energy. This exotic energy and properties have been named quintessence. Dark energy could actually be pushing space in all directions causing it to expand.

Cosmological Principle

Cosmological equations can actually help us with modelling the expansion of the universe. For example, the Friedmann equations describe how the universe will expand or contract in the future. The Friedmann equations are built on two essential assumptions (Cosmological Principle) which are that the universe is homogeneous and isotropic. But what does that actually mean?

Homogeneity

The universe is described as homogenous which means that it is translation invariant. The universe is the same everywhere and that there is no special or unique part. This fact came to be through N-body simulations which model and simulate the behavior and movement of particles in systems. Therefore, it was established that for distances of 260/h Mpc or more, the universe is homogenous.

Isotropy

When we describe the universe as isotropic, we are saying that it looks the same in all directions and that there is no preferred direction in the universe. Again, this is the case mainly on very large scales. This is very similar to homogeneity, but homogeneity is more to do with how uniform the universe is whereas isotropy is how the universe looks the same from one point.

It is also important to realize that homogeneity and isotropy are different and one thing being homogenous does not imply or necessarily mean that it is also isotropic.

Robertson-Walker Metric

Before deriving and explaining the Robertson-Walker metric, it is important to define what a metric actually is. In mathematics, a metric is a system or function that gives the distance between two points in a set of points in n-dimensional space. In the simplest sense, length is a metric and is measured in meters. There are metrics present for 2 dimensional and 3-dimensional space. However, once it gets to 4th dimensional space, metrics become slightly difficult to conceptualize. For very large cosmological distances, Einstein's general relativity needs to be taken into account as well as general relativity links the third dimensional space and 1 dimensional time together to give 4th dimensional space and time. The name of the metric that links two distances in 4th dimensional space time is called the Minkowski metric, the equation of which is: $ds^2 = -c^2 dt^2 + dr^2 + r^2 d\Omega^2$.

However, the Minkowski metric does not take into account the assumptions we have established below which are that the universe is homogeneous and isotropic at extremely large scales. Thus, Howard Robertson and Arthur Walker independently (Arthur Walker built on the work produced by Howard Robertson) introduced a new metric that satisfied the cosmological principles and axioms. This is named as the Robertson-Walker metric and the equation of this metric is: $ds^2 = -c^2 dt^2 + a(t)^2 \left[\frac{dx^2}{1-kx^2/R_0^2} + x^2 d\Omega^2 \right]$. There are two very important terms that appear in this equation which is $a(t)$ and k which appear in the Friedmann equation as well which I will describe later in the research paper.

The Friedmann Equation

The Robertson-Walker Metric can further be evolved using the Einstein Field Equations to finally get the Friedmann equation. This can be done using the equation $G_{\alpha\beta} = \frac{8\pi G}{c^4} T_{\alpha\beta}$.

Here, $G_{\alpha\beta}$ is the curvature of space and $T_{\alpha\beta}$ is the stress-energy tensor. It describes the distribution of mass/energy. Additionally, we have $G_{\alpha\beta} = R_{\alpha\beta} - \frac{1}{2}g_{\alpha\beta}R$ which is another one of the Einstein Field Equations. $R_{\alpha\beta}$ here is the Ricci tensor and R is the Ricci scalar. The Ricci tensor measures the curvature and how the shape of an object changes and deforms as it moves along the geodesics of space-time. Through careful manipulation of the terms, we obtain the Friedmann Equation which is:

$$H^2 = \frac{8\pi G}{3c^2} \varepsilon(t) - \frac{kc^2}{R_0^2} \frac{1}{a(t)^2}$$

Terms

$a(t)$ is the scale factor of expansion of the universe in the equation and is a function of time. The Hubble constant and scale factor are linked. $H = \frac{\dot{a}}{a}$. Thus, the above equation is the same as replacing H^2 with $(\frac{\dot{a}}{a})^2$. $a(t)$ can be defined as how much a volume of space expands in a certain amount of time.

$\varepsilon(t)$ is the energy density.

k is an extremely important term and is the curvature parameter. It is a constant of the Robertson-Walker metric and represents the geometry of the universe.

R_0 is the scaling parameter

The curvature of the universe depends on whether the average density of the universe is above, or below the critical density threshold which is $10^{-29} \text{ gcm}^{-3}$.

In the equation, H is the Hubble parameter describing how fast a galaxy moves away from another galaxy. H_0 is its value *today* and is measured to be roughly $70 \text{ km s}^{-1} \text{ Mpc}^{-1}$.

Another form of the Friedmann Equation which we are going to use for modelling the expansion is:

$$\frac{H^2}{H_0^2} = \frac{\Omega_r}{a^4} + \frac{\Omega_m}{a^3} + \frac{1 - \Omega_m - \Omega_\Lambda}{a^2} + \Omega_\Lambda$$

In this case, ω is the cosmic density parameter.

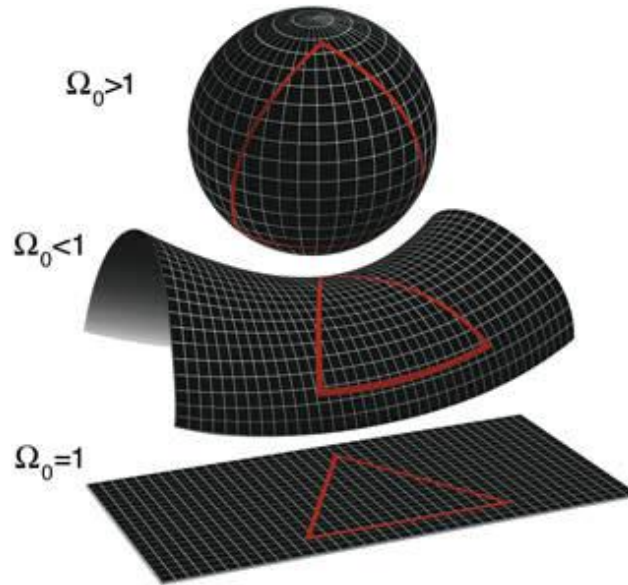
Curvature

If the Universe was flat, its geometry would correspond to that of a flat sheet as can be seen in the diagram below. In a flat universe, the value of ω_0 is 1. k , the curvature parameter, is 0.

If the Universe was "closed", its geometry would correspond to that of the surface of a ball as can be seen in the diagram below. In a closed universe, the value of ω_0 is greater than 1. k , the curvature parameter, is greater than 0.

If the universe was "open", its geometry would correspond to that of the surface of a saddle as can also be seen in the diagram. In an open universe, the value of ω_0 is less than 1. k , the curvature parameter, is less than 0.

It has been discovered that the curvature of the universe is in fact flat. In order to prove the flatness of the universe, astronomers have used cosmic microwave background radiation (CMBR). The cosmic microwave background radiation is the result of the explosion of the Big Bang, visible in all directions as red-shifted energy when the universe came into existence. When this radiation was released, the entire universe was 2,700 Celsius. At this instant, photons moved around and slowly over time, they got stretched out shifting them down from radiation into the microwave spectrum. By detecting the variations in the temperatures of CMBR across the sky, we have found that the universe is flat. If the universe was curved, the temperature variations would be different to what we detect today. The flat universe theory corresponds to the measurements that have been recorded.



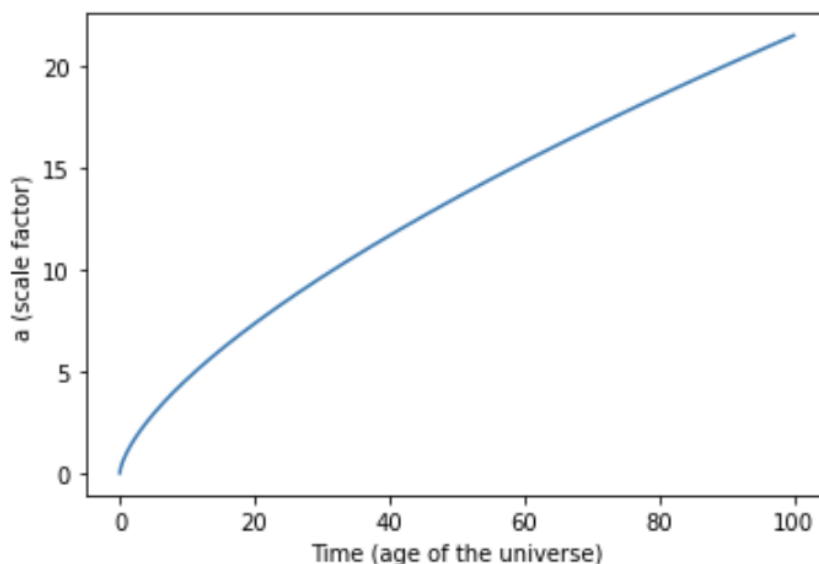
From ‘What is the Shape of the Universe?’ By Cody Cottier. Published: Tuesday, February 23, 2021.
<https://astronomy.com/news/2021/02/what-shape-is-the-universe>.

Modelling the expansion of the Universe Using the Friedmann Equations

Results Obtained From Python modelling

Flat Universe

An Einstein-de Sitter Universe is one in which the universe is matter dominated and has only matter. In this model, the curvature k of the universe is 0 and omega is 1.0. In the model I have created below, I made use of omega being 1.1. The graph of this universe is:



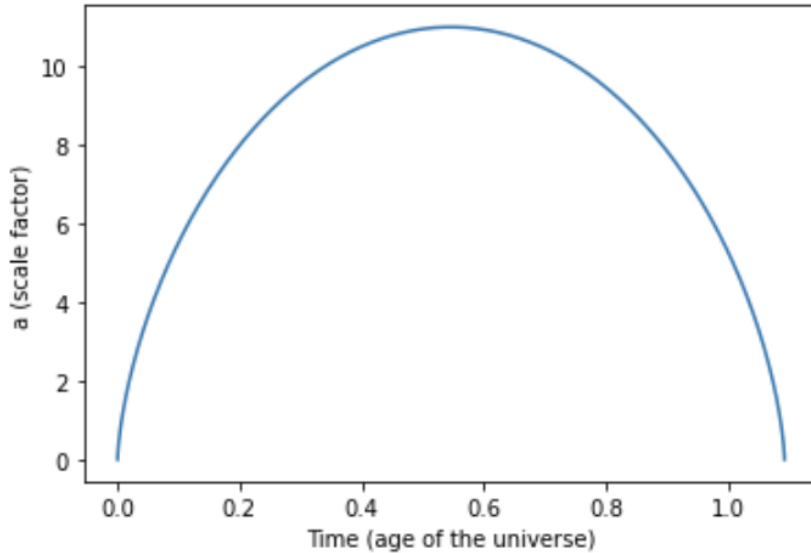
Modelled on python by solving the Friedmann equation and returning the scale factor (a) against time.

It is clear to see that for an Einstein-de Sitter universe, the universe is going to keep expanding forever. This is because the density of the universe in this model is less than the critical density (the hypothetical average density of the universe which will result in the universe halting its expansion after an infinite amount of time). There is not enough

gravitational pull to collapse the expansion meaning it will keep expanding forever. Therefore, in this scenario, the universe will end in a big freeze. According to the second law of thermodynamics, entropy increases in a system. Thus, according to this, the universe will slowly cool as it expands and matter and energy will start to become uniform and evenly spread until the temperature starts to cool until it gets to absolutely zero which is -273.15 degrees Celsius.

Closed Universe

A closed universe, or gravitationally bound universe, has a value of $k > 0$. A closed universe has a spherical shape and its omega value is greater than 1.

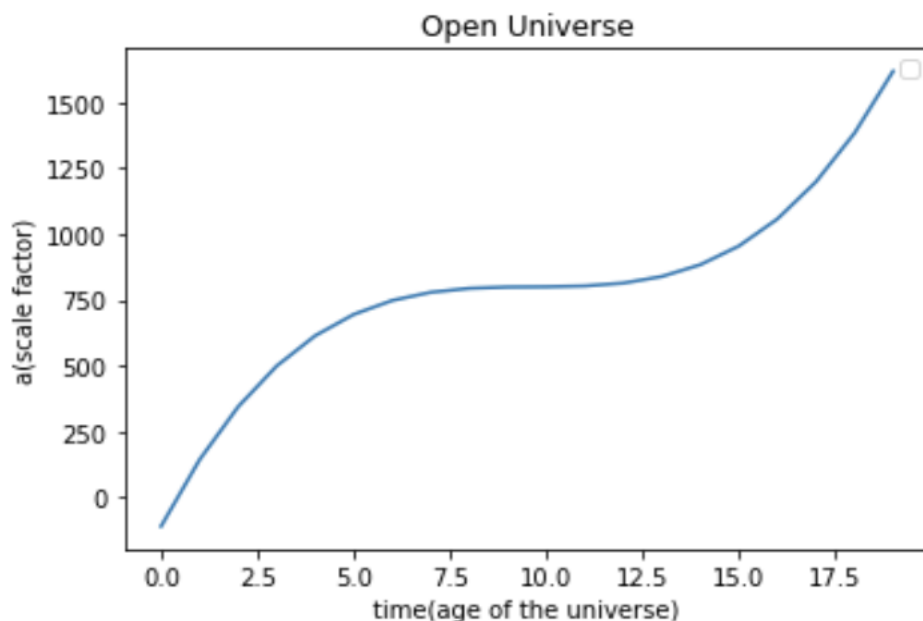


Modelled on python by solving the Friedmann equation and returning the scale factor (a) against time.

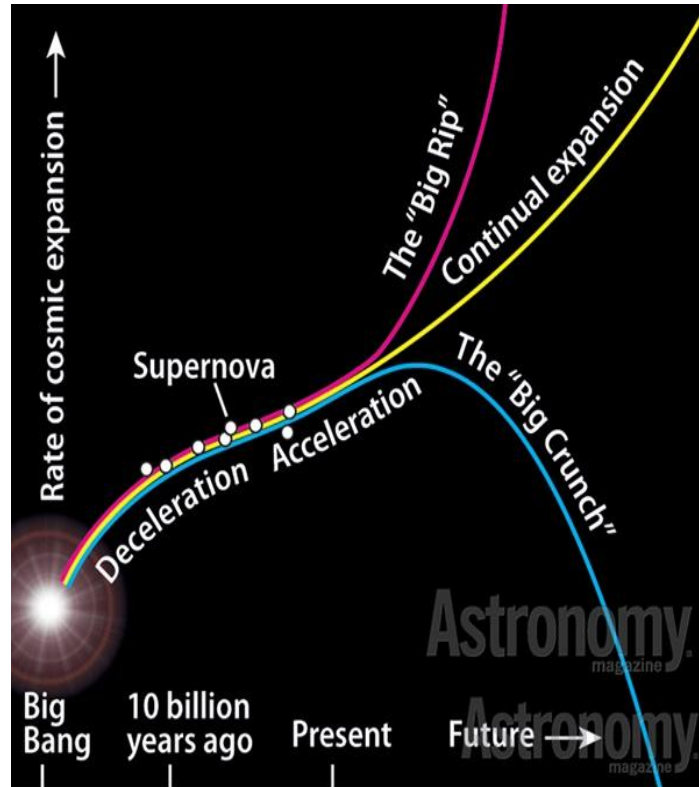
As can be seen in the model, the universe expands but at a decelerating rate. The scale factor increases until the peak after which the expansion reverses and the scale factor starts reducing after this. In this scenario, the average density of the universe is greater than the critical density resulting in gravitational attraction overcoming the expansion caused by dark energy and the universe collapses backwards.

Open Universe

An open universe has a value of $k < 0$. It has an omega value less than 1. In the model I have created below, I have taken omega to be 0.9.



In an open universe, the universe is shaped like a saddle and open outwards which is the exact opposite to a closed universe. If the universe was open with value of k less than 0, the universe will end in a big rip. In this scenario, additionally, dark energy keeps getting stronger and more abundant as more matter and space is created. The expansion of the universe is going to keep increasing until the end of time and the force of gravity will not slow down this expansion caused by dark energy at all so much so that subatomic particles will start getting torn apart. This fate would occur approximately 22 billion years from now. Galaxies, solar systems will disintegrate due to the expansion. The expansion will asymptote and will become infinite.



From ‘What is the Fate of the Universe?’ By David J. Eicher. Published: Monday, July 1, 2019.
<https://astronomy.com/magazine/greatest-mysteries/2019/07/9-what-is-the-fate-of-the-universe>

CONCLUSION

Many observations have been made in the last few decades that indicate that the universe is likely to end in a big Freeze. The biggest factor that tells us that this theory is more probable than other theories such as a big crunch is the theorized existence of dark energy. Even with the large force of gravity acting on the universe due to it being so expansive, it will likely not cause the universe to collapse onto itself because it is not strong enough to overcome the inflating effect of dark energy. Estimates say that the hubble rate is likely to drop but will asymptote to around 45km/s/Mpc and it will never go to 0 because of the inflating universe and the presence of dark energy behind the inflation. As the universe expands, the densities of the different matter constituents may get diluted and reduce, but as described above, dark energy is a feature of space itself and thus it’s average density will remain the same and it will not decrease.

The fate of the universe is extremely dependent on this dark energy. In fact, if dark energy starts to get stronger over time, the universe might instead of ending in a big freeze, end in a big rip which will ‘rip’ the fabric of space apart causing all astronomical bodies to get unbounded from each other. Alternatively, it is possible that dark energy actually reverses sign and instead of causing the universe to expand, causes it to collapse onto itself which is called the big crunch fate of the universe as modelled above for a closed universe. It is even possible that a big bounce occurs where a big crunch causes the universe to collapse and cease to exist and another universe being created in a loop of destruction and creation.

Although it is difficult to predict what may happen in the future, with current understanding of the universe and measurements of different variables, I believe that the universe will in fact end in a big freeze.



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