The Heat Death of the Universe

Nick Hood[1]

Abstract
This short talk, using the conclusions of generally accepted models of physics, traces the story of the birth and evolution of the universe from the Big Bang to today, and into the future: predicting its eventual long cold death in the Big Freeze.

Keywords
Universe — Physics — Model

[1] *Institute of Education, Teaching and Leadership, University of Edinburgh, Edinburgh, United Kingdom*
*__Corresponding author__: nick@cullaloe.com

Contents

Introduction

In the beginning God created the Heauen, and the Earth. And the earth was without forme, and voyd, and darkenesse was vpon the face of the deepe: and the Spirit of God mooued vpon the face of the waters. And God said, Let there be light: and there was light. And God saw the light, that it was good: and God diuided the light from the darkenesse [1].

In Asimov's novel Foundation [2], the mathematician Hari Seldon predicts the future evolution of human society in our galaxy, the Milky Way. Using the mathematics of the behaviour of large populations, he predicts two possible trajectories, one, involving 30,000 years of instability and war before the return to a stable civilisation and the other, where this interregnum lasts only a short thousand years.

Physicists have developed a model – no, several models – of our universe: how it came into being and how it will evolve and how it will, in some models, eventually die. These models are mathematical in nature but they are by no means abstract or solely theoretical. In this talk, I hope to share with you a little glimpse of our destiny.

1. Where did we come from?

Before we can consider the future, let's appreciate our past.

1.1 The Big Bang

The common misconception of the origins of the universe, often described as the "Big Bang", is that someplace, a long time ago, a huge explosion of matter occurred in which the stars and galaxies were made. The reality is weirder and much more wonderful than that. We came from nothing [3]. No matter, no time, no space, no energy: *nothing*. In an instant, all matter that ever existed, all energy and time itself (for time and space cannot be separated from each other, they are dimensions of the same thing) came into being: it was unimaginably, intolerably hot, dense and opaque and so immediately began expanding. §

1.2 Expansion into familiar forms

A period of rapid expansion saw equally rapid cooling, followed by further heating as exotic particles collided and reformed into new particles and anti-particles in a frenzy of change at relativistic speed. The fundamental forces of physics separated and converged. Energies were falling to the levels we can now re-create in particle colliders such as the Large Hadron Collider at CERN. It is through such experiments that we gain much of the verification of the theories that describe our understanding of how this universe came to be just exactly the way we see it. §

Continuing our story of the early universe, an imbalance in the number of quarks over their antimatter forms leads to protons and neutrons outnumbering anti-protons and anti-neutrons. The temperature had by now fallen to such a level that no more matter-anti-matter pairs could be made: mass annihilation leaves us with just one in 10 million of the original protons and neutrons from the early universe. The energy density of the universe is now dominated by photons and the universe is now less than twenty minutes old.

1.3 Synthesis

The temperature is a mere thousand million degrees. The pressure is about that of our atmosphere. Hydrogen nuclei, which consist of a single proton, dominate but a few neutrons and protons combine to make Helium and Deuterium. After about 400,000 years, the first atoms are made from electrons and these nuclei: Hydrogen dominates the universe and radiation decouples from matter. We can see the relic of this today: it is called Cosmic Microwave Background radiation. §

Over a long period of time, atoms in the universe are pulled together by gravitation: clumping together in increasingly larger clouds. The clouds become more massive and the pressure at the centre of these clouds increases so much that nuclear fusion begins: the first stars are born as the universe reaches its 100 millionth birthday. In a further 500 million years, these first stars will begin to swirl with others in a cosmic dance around a common centre of mass, forming the first galaxies. §

1.4 The cycle of star formation

Those early stars have never been visible to us, not least because they are long gone. Stars evolve as they consume their fuel, converting it into radiation and more complex elements. Hydrogen becomes Helium, then on up through the Periodic table of elements to Carbon, Nitrogen and as far as the size of star (and the amount of fuel it has) allows. Once the fuel is finished, the nuclear processes at the core cease and no longer support the weight of the outer material, which crashes into the centre unleashing a supernova explosion, scattering the material from inside the star into the surrounding vacuum of space. §

And so the cycle begins again: the scattered elements, over time, begin to attract each other through faint but not insignificant gravitational attraction. Clouds of dust begin to stick together, more attracting more strongly until once again, sometimes, enough is gathered to put such pressure on the core to ignite the fusion sequence again and a new star is born from the wreckage of an old supernova. Younger generation metal rich stars like our Sun began formation when the universe was 4 billion years old. Our star was formed 4.6 billion years ago, when the universe was 9.1 billion years old.

1.5 Planets and life

Sometimes, these clusters of material remain just that: balls of minerals and elements left stranded, often trapped in the gravitational field of a much more massive star. Metal-rich stars like our Sun are more likely to produce planetary systems. If the conditions are right - just right - then complex hydrocarbons self-organise into life forms. These life forms are made from elements formed in old, long dead stars. You are quite literally made of star dust. §

2. Good Times, Bad Times

In about 5 billion years, our star will eventually become a red giant, swallowing Mercury, Venus and probably us too, before rapidly collapsing to become a degenerate dwarf. But don't worry. The stelliferous era will continue for a while longer, ending when the continued expansion of the universe prevents star formation. Planets will be flung out of their orbits or consumed by larger bodies. The remnants of our Sun will have cooled so much that its glow will have faded like the clinkers in a cold fireplace. It is a Black Dwarf and the universe is a thousand million million years old. §

2.1 The Degenerate Era

Here begins the Degenerate Era, a time when the construction of complex atoms is undone and matter begins its long journey home. Galaxies disperse as stars are flung out of their elegant dance around the cosmic maypole. Some are consumed by Black Holes. Most material is locked up in dead stars such as black holes, or white dwarfs.

2.2 Black Holes

Black Holes are often presented as mysterious objects which suck in everything around them [4]. They exist today, the nearest one to us being many light years away. There is one at the heart of every Galaxy, and you can "see" ours in the the constellation Sagittarius. §

A Black Hole is an object so massive and its gravitational field so strong that anything that enters its event horizon cannot escape, including light. They were once stars - very large stars. The smallest star that can form a Black Hole is about three times the mass of our Sun. Sagittarius A* at the centre of our Galaxy is about 4.5 million solar masses.

Black Holes don't live forever, though. Through quantum effects near the event horizon, radiation energy can be emitted. This radiation is called Hawking radiation and is described as Black Hole evaporation. §

2.3 The Black Hole Era

At the end of the Degenerate Era, all protons have decayed into radiation and Black holes feast on material sucked in from nearby and grow larger. As the long years pass, these evaporate until the universe is 10^{100} years old and we enter the Dark Era. §

2.4 The Long Dark Night awaits

During the Dark Era, the universe will consist of a diffuse sea of electrons, positrons, neutrinos and radiation. It will continue expanding and cooling inexorably towards thermal equilibrium at Absolute Zero: the Big Freeze, or the Heat Death of the Universe at the ripe old age of 10^{1000} years old.

References

[1] unknown. *Genesis*. King James, 1611.

[2] Isaac Asimov. *Foundation*. Gnome Press, 1951.

[3] Janna Levin. Big bang briefly, August 2009.

[4] S. W. Hawking and R. Penrose. The Singularities of Gravitational Collapse and Cosmology. *Royal Society of London Proceedings Series A*, 314:529–548, January 1970.