Educator's Guide and Script For
Atom: The Key to the Cosmos

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INTRODUCTION

The goal of this program is to present an upper level high school or college introductory overview of the atom and show students how the vast variety and richness of everything we see around us is built up and how it fits together comes down to atoms and the mysterious laws they obey. This is the program, *Atom: The Key to the Cosmos,* Professor Jim Al-Khalili shows that in our quest to understand the tiny atom, we unraveled the mystery of how the entire universe was created. It's a story with dramatic twists and turns, taking in world-changing discoveries like radioactivity, the Atom Bomb and the Big Bang. All this forms part of an epic narrative in which the greatest brains of the 20th century competed to answer the biggest questions of all - why are we here and how were we made?

ADVANCED VOCABULARY DEFINITIONS

- **Aston, Francis -** (1 September 1877 - 20 November 1945) A British chemist and physicist who won the 1922 Nobel Prize in Chemistry for his discovery, by means of his mass spectrograph, of isotopes, in a large number of non-radioactive elements
- **Atom** - The atom is a basic unit of matter that consists of a dense, central nucleus surrounded by a cloud of negatively charged electrons. The atomic nucleus contains a mix of positively charged protons and electrically neutral neutrons
- **Atomic nucleus** - The very dense region at the center of an atom consisting of protons and neutrons
- **Baade, Walter -** (March 24, 1893 - June 25, 1960) A German astronomer who emigrated to the USA in 1931
- **Big Bang -** The Big Bang is a cosmological model of the universe that has become well supported by several independent observations
- **Chadwick, James -** (20 October 1891 - 24 July 1974) An English Nobel Laureate in physics, awarded for his discovery of the neutron.
- **Curie, Marie -** (7 November 1867 - 4 July 1934) A physicist and chemist who was a pioneer in the field of radioactivity and the first person honored with two Nobel Prizes, in physics and chemistry

- **Electric charge -** Electric charge is a physical property of matter which causes it to experience a force when near other electrically charged matter. Electric charge comes in two types, called positive and negative. Two positively charged substances, or objects, experience a mutual repulsive force, as do two negatively charged objects. Positively charged objects and negatively charged objects experience an attractive force
- **Electro-magnetic force -** In physics, the electromagnetic force is the force that the electromagnetic field exerts on electrically charged particles. It is the electromagnetic force that holds electrons and protons together in atoms, and which holds atoms together to make molecules
- **Electron -** A sub-atomic particle carrying a negative electric charge
- **Gamow, George -** (4 March 1904 –19 August 1968) A Russian-born theoretical physicist and cosmologist, he discovered alpha decay via quantum tunneling and worked on radioactive decay of the atomic nucleus, star formation, stellar nucleosynthesis, big bang nucleosynthesis, cosmic microwave background, nucleocosmogenesis and genetics
- **Helium -** A colorless, odorless, tasteless, non-toxic, inert monatomic chemical element that heads the noble gas series in the periodic table and whose atomic number is 2
- **Hoyle, Fred -** (24 June 1915 - 20 August 2001) An English astronomer noted primarily for his contribution to the theory of stellar nuclear fusion
- **Hydrogen -** The chemical element with atomic number 1
- **Iron -** A chemical element with the symbol Fe (Latin: ferrum) and atomic number 26
- **Neutron -** In physics, the neutron is a subatomic particle with no net electric charge and a mass slightly larger than that of a proton
- **Nuclear fusion -** In physics and nuclear chemistry, nuclear fusion is the process by which multiple atomic particles join together to form a heavier nucleus. It is accompanied by the release or absorption of energy
- **Nuclear physics -** Nuclear physics is the branch of physics concerned with the nucleus of the atom
- **Nucleus** - The very dense region at the center of an atom consisting of protons and neutrons
- **Oppenheimer, Robert -** (22 April 1904 - 18 February 1967) American physicist who headed the Manhattan Project, known as the "Father of the Atomic Bomb"
- **Penzias, Arno - (**6 April 1933 -) An American physicist and 1978 Nobel laureate in physics, who with Robert Wilson discovered in 1964 the cosmic microwave background radiation
- **Proton -** In physics, the proton is a subatomic particle with an electric charge of one positive fundamental unit
- **Radioactivity -** The emission of ionizing particles or radiation from an unstable atomic nucleus
- **Red Giant -** A luminous giant star of low or intermediate mass that is in a late phase of its evolution

- **Rutherford, Ernest -** (30 August 1871–19 October 1937) A New Zealand chemist and physicist who became known as the father of nuclear physics
- **Stellar nuclear fusion -** Nuclear reactions taking place in stars to build the nuclei of the elements heavier than hydrogen
- **Strong nuclear force -** In particle physics, the strong nuclear force holds quarks and gluons together to form protons and neutrons
- **Super nova -** A stellar explosion
- **Wilson, Robert -** (10 January 1936) An American astronomer and 1978 Nobel laureate in physics, who with Arno Penzias discovered in 1964 the cosmic microwave background radiation

SCRIPT

ATOM: THE KEY TO THE COSMOS

Chapter 1: The Atom and the Creation of the Universe

As we gazed up at the heavens, we asked where we had come from; how all the stars were created; how the elements were made; even how the universe itself had begun? One of mankind's greatest achievements is that we have answered these questions. What is truly remarkable is that this understanding has come through the study of the smallest building blocks of matter, atoms. As we peered inwards, we realized we could explain what we saw when we peered outwards. The atom has helped us solve the greatest mysteries of existence.

Everything in the world we see is made out of tiny objects called atoms, and yet we only proved their existence at the beginning of the 20th Century. The first shock was to discover how small they were - less than millionth of a millimeter across. There are trillions in a single grain of sand.

Amazingly, we now have a pretty good idea of the number of atoms in the known universe. Now given the vastness of the universe and the minuteness of the atom, it’s not surprising that this is a mind-numbingly huge number. It's one followed by over 70 zeros. That’s a trillion, trillion, trillion, trillion, trillion, trillion, trillion atoms.

We don’t only know the raw number of atoms in the cosmos, we also know that they come in 92 different flavors. These are called elements, and you'll recognize many of them as familiar parts of the world around us. Oxygen, iron, carbon, tin, gold and so on. Everything in the universe, the stars, the planets, the mountains, the seas, the animals, you and me, we're all made of these atoms, or combinations of them.

It's an astonishing human achievement that we know not only how many atoms there are in the universe and how many different types there are, but why they exist at all. We can now explain how every one of those trillion trillion, trillion, trillion, trillion, trillion, trillion atoms was created. It turns out that the answer to the mystery of creation itself lies within the heart of each and every atom in the universe.

The story of how we came to understand creation itself, started over one hundred years ago, in a small laboratory in South East Paris. This piece of paper is a remarkable artifact. It's from the notebook of the woman who first studied radioactivity, the chemist Marie Curie. It's incredible. One hundred years later and this piece of paper is still spitting out radioactive particles. Still stuck to the paper are tiny but intensely radioactive particles of a substance that Marie Curie discovered in 1898 - a substance she called radium.

It was a sensational discovery, for one primary reason. Though radium looks like an unremarkable gray metal, it contradicted all the then known laws of science, because, radium pumps out invisible, yet powerful rays of energy, which could fog sealed photographic paper and burn human flesh. Also, radium appeared to contain within it an inexhaustible store of energy. Curie worked out that a gram of radium, a piece much smaller than a penny, contains more energy than a hundred tons of coal.

To the Scientific community radioactivity was just about the most exciting thing possible. The brightest minds of a generation clambered to study it and the price of radium, its most potent source, soared to thousands of pounds per ounce. And radioactivity didn't disappoint. In 1919 it produced its greatest revelation yet. A revelation that would ultimately lead to a fundamental understanding of the atomic world.

The revelation was that radioactivity allowed humanity to fulfill an age-old dream. To become alchemists.

Chapter 2: Manipulating the Atom

Alchemy - the power to change base metals into gold, the quest for a so-called philosopher's stone, which has the magical ability to transmute one substance into another, has been an obsession for centuries. It conjures up wonderful tales of sorcery and wizardry as anyone who's read Harry Potter knows very well. The power and wealth that would surely come to anyone who mastered alchemy seduced many great scientists and thinkers like Isaac Newton, Robert Boyle and John Locke. All of them tried to change one element into another and all of them failed.

Then in 1919, the secret of alchemy, the mystery of the philosopher's stone, was finally revealed not in a wizard's den but in the physics department at Manchester University. The world's first true alchemist was Ernest Rutherford. A loud, straight-talking New Zealander, Rutherford had come to dominate the study of radioactivity. He had wonderful intuition, and was fearlessly prepared to challenge conventional wisdom.

And alchemy would require Ernest Rutherford to follow his intuition deep into the unknown. The discovery was almost accidental. It began when one of Rutherford's students noticed that when radioactive materials like radium were placed inside a sealed container of ordinary air, mysteriously, small amounts of the gas hydrogen begin to appear.

Now this was bizarre. Ordinary air contains virtually no hydrogen - yet in the presence of radioactivity, it was appearing out of nowhere. This was precisely the kind of problem that Rutherford, now at the height of his powers as an experimental physicist, loved. He flung himself at it.

He began by isolating all the gases that make up the air we breathe - oxygen, nitrogen, water vapor and carbon dioxide and studied how they each behaved in the presence of radioactivity. And then Eureka. Rutherford realized that in the presence of powerful radioactive rays, the gas nitrogen, which makes up about 80% of the air we breathe, changes into two new substances - the gases oxygen and hydrogen. Then and there Rutherford had transmuted one element into two others - he had become an alchemist and radium, with its powerful radioactivity, was the philosopher's stone.

The press hailed Rutherford as the first alchemist but in fact that was the least of it. What alchemy had shown him was the inside, not just of the atom, but of the strange object at its centre, its tiny beating heart - the nucleus.

To get a sense of his achievement, remember Rutherford and his contemporaries at Cambridge had only a pretty sketchy idea of what an atom was. But they did have an idea of its size. It's mind-numbingly tiny. One ten millionth of one millimeter across. Let me put it another way there are more atoms in a single glass of water than there are glasses of water in all the oceans of the world.

And Rutherford now also knew that the atom had structure, that within the atom, there was a sub-atomic world. He pictured each atom like a tiny solar system. At its centre was an object, which Rutherford called the atomic nucleus. Orbiting this, like planets, were the electrons. But what on earth was the nucleus?

Rutherford was convinced that alchemy had shown him the answer. To understand how Rutherford did this, we have get inside his head - to think like he did. Rutherford had fantastic intuition coupled with an intensely practical approach to science. So he hated ideas that relied on complicated mathematics. When it came to the atomic nucleus, Rutherford looked for the simplest idea that worked. And what worked was to imagine that the nucleus is made of tiny rigid spheres, like snooker balls. Using this incredibly simple image, Rutherford could construct all the elements in the universe. He could explain how the huge variety of atoms are made of the same basic components.

So here’s how it works: Hydrogen, which is the simplest atom, consists of just one sphere, which Rutherford called a proton, which is the Greek word for 'first'. All the other elements are made by adding more protons into the nucleus. It's as simple as that.

So helium, which is the second lightest element, comprises of two protons. Lithium has three. Carbon, which is the element that is the basis of all life, has 6 protons. The oxygen we breathe has 8. Uranium, which is the heaviest, naturally occurring element, has 92 protons.

This was Rutherford's inspirational idea - that each element is defined by the number of protons in its nucleus. It's a wonderfully elegant and simple idea. An idea that explains how so much of the universe we see around us is constructed. But, as scientists often find, nature is never quite as simple as it seems at first sight. Sure enough, a big problem emerged with Rutherford's proton. And it was to be one of Rutherford's own protégés who was the first to identify it.

Chapter 3: The Structure of the Atom

Francis Aston was an interesting character as a young man he enjoyed the adventurous outdoors and was into skiing and motor racing and apparently in about 1909 he discovered surfing in Waikiki Beach in Hawaii. But he soon realized that the call of the physics laboratory was greater than the call of the waves. And it was while at Cambridge that he invented an incredible piece of equipment that's now housed here in this rather austere and plain looking building, the Cavendish laboratory.

This is Aston's original spectrograph. It's an amazing piece of equipment, because for the first time scientists were able to weigh individual atoms. It's incredible. It looks a bit like a gun. It's a very strange shape. Now they could weigh atoms accurately they discovered that there was a fundamental problem with Rutherford's model of the nucleus.

Basically the numbers didn't quite add up. All the atoms of the known elements apart from hydrogen were much heavier than they should be. For instance, helium with 2 protons should weigh twice as much as hydrogen with just one. In fact it's four times as heavy. Rutherford realized this could mean just one thing - apart from the proton, there's something else inside the atomic nucleus. But what? It took 12 years to find the answer.

Now as head of the prestigious Cavendish Laboratory in Cambridge Rutherford threw all his resources into the project. He bullied and cajoled his students and researchers until one, called James Chadwick, hit the nuclear physics equivalent of gold. Chadwick built this in 1932 and to think that with just this tiny piece of equipment he discovered the missing ingredient of the atom. For me as a practicing nuclear physicist this really is an amazing device, when I think of the huge accelerators, which are built today to conduct experiments to probe the nucleus of the atom. It's really awe inspiring in its simplicity.

He put a source of radioactivity at this end of the tube. The radioactivity then stuck a small target in the middle here, and then out of the target came new particles that sprayed out of this end here. It's a bit like an atomic gun shooting out Rutherford's missing particles.

What Chadwick discovered was that along with the protons, there's another kind of particle inside the nucleus. It weighs almost exactly the same as a proton but is much more elusive because it carries no electrical charge. Technically we say it's electrically neutral and hence its name - the neutron. It immediately solved the problem of the weight of atoms. So helium is four times as heavy as hydrogen because as well its 2 protons, it contains 2 neutrons. And oxygen has 8 neutrons along with its 8 protons making it sixteen times as heavy as hydrogen. So in 1932, the atomic family was complete. Scientists announced that every atom in the universe is made of just three basic components - electrons, tiny particles that orbited a nucleus, which in turn is made of protons and neutrons.

Over Christmas 1932, physicists at the other great centre of atomic physics, the Niels Bohr Institute in Copenhagen, celebrated the neutron's discovery and the completion of the nuclear trinity - by writing a musical about it. Some of the great names in physics took part in this musical. Their excitement was primarily due to one thing - they knew they stood at the threshold of an entirely new kind of science with entirely new rules - what we now call 'nuclear physics.'

Chapter 4: The Mysterious Proton and the Strong Nuclear Force

The first challenge for nuclear physics was this: although physicists now knew what the tiny nucleus was made of, they couldn't explain how it all held together. In fact it was worse than that - the existing laws of physics predicted that every atomic nucleus should self-destruct instantly. The main problem was this: all protons, the key ingredient of the atomic nucleus, have positive electric charge. And things with the same charge repel each other. Just like these magnets.

So, just like these magnets, if two protons get close together, they should then just fly apart. But weirdly inside the atomic nucleus they don't. Dozens of protons stick right next to each other. So what sticks them together? What stops the protons from flying apart? The answer was big news. It was nothing less than an entirely new force of nature. For centuries, humans had only ever encountered two natural forces, gravity, which pulls us down to the earth, and electromagnetism. Now hidden inside the atomic nucleus was something completely new. It was called the Strong Nuclear Force. And the easiest way to imagine it is with some Velcro.

If I put Velcro around these magnets they start to behave slightly differently. At first they repel each just as before. But when they get close enough, the Velcro kicks in and they stick. Its effect is very short range, but very, very strong. And this is exactly the same with protons. The Strong Nuclear Force explains what holds the nucleus together. The Strong Nuclear Force works between all protons and neutrons, but what is truly surprising about it is its strength. It's by far the most powerful force in the universe. More than a trillion, trillion, trillion times stronger than gravity.

Think about this way, if I was pulled down to the earth, not by gravity, but by the Strong Nuclear Force, then I’d weigh trillions of times more than I actually do. In fact I’d weigh more than the entire galaxy. The reason I don’t weigh that much is because the strong nuclear force is only felt down at a distance of a trillionth of a millimeter.

With the Strong Nuclear Force, humans finally began to get a glimpse what was actually going on inside the atomic nucleus. Roughly speaking all nuclear behavior is down to a balance between the strong nuclear force squashing the protons and neutrons together and the electric charge on the protons forcing them apart.

Physicists realized that picturing the nucleus as a battlefield between different elemental forces solved one of the oldest mysteries of all time. It's this, a question humans have asked ever since the dawn of time is ‘How does the sun shine?’ Now sunlight is the source of all life on earth but how is it made? It's all to do with the forces inside the atoms that make up most of the sun - hydrogen

This is how it works: the nucleus of a single atom of hydrogen consists of just a proton. And every now and again inside the high pressure high temperature cauldron of the sun this proton can get squeezed up close to another and bang, the strong nuclear force kicked in and fuses them together. Now this is a process that eventually leads to the creation of a helium atom and it’s accompanied by the release of energy as a burst of light and heat, it’s a bit like slamming two symbols together and releasing a burst of sound.

Hydrogen fusing into helium and the energy released are what we see and feel as sunshine. This process of two hydrogen nuclei slamming together and releasing energy became known as nuclear fusion. The turmoil between strong nuclear and electro-magnetic forces as they strive to dominate the nucleus, does more than just power the sun. It's at the heart of everything.

But in the late 1930s, before people figured out that story, nuclear physics did something much closer to home. In no uncertain terms, it redefined the history of mankind, right here on earth.

Chapter 5: The Atomic Bomb

The Atom bomb changed everything. The excitement of pre-war scientific research, the days when physicists sang songs about their discoveries were over. Robert Oppenheimer summed up the grim mood with these words, “The physicists have known sin; and this is a knowledge which they cannot lose."

The terrible irony of the atomic bomb is that because of the ‘scientist's sin,’ because of that ‘knowledge that cannot be lost,’ something of great significance did emerge, something that would ultimately reveal the full story of the 14 billion years of the entire universe.

The war had caused a massive 2 billion dollars to be poured into nuclear research. People now knew an astonishing amount about the atom and its nucleus. Specifically, scientists had detailed measurements of how stable or unstable different atomic nuclei were. That stability was a direct result of the battle between the strong nuclear force holding the nucleus together and the electromagnetic force pushing it apart.

In some atoms the balance tipped towards the strong force, making them very stable, but when the electromagnetic force had the upper hand they were inherently unstable. By the late 40's scientists began to investigate the implications of the way the nuclear stability of atoms varies. They noticed one very strange fact about the nuclear stability of one particular atom. Of all the 92 different elements, of the 92 different types of atoms that make up the universe around us gases like hydrogen and oxygen solids like carbon and silicon, metals like gold and silver. One is special. Iron.

So what makes iron so special. Its stems from the unique structure of its nucleus. The 26 protons along with its neutrons combine in a very special way to make iron incredibly stable. For some reason nature has decreed this as the number that allows the strong force and the electromagnetic force to balance each other perfectly. It makes iron the most stable element in the universe.

Now we can understand why fusion occurs. Lighter atoms can combine together to become more iron like. And fission is the opposite process. Atoms heavier than iron can split into lighter ones more iron like pieces so all the elements seek the stability of iron. And that fact underpins the whole history of the cosmos.

The best way to understand this is to imagine the relative stability of atoms as a couple of graphs. Here's what they show. The very lightest elements, hydrogen and helium, are, not quite as stable as they could be. They'd like to be something else. Something even more stable. Similarly the heaviest elements like Uranium and Polonium are actually unstable. In fact they're so unstable that they even fall to pieces naturally through radioactivity. And here in the middle are the most stable atoms of all - nickel, cobalt, and iron.

So far so good. Now here's the amazing bit. This nuclear stability graph turned out to be uncannily similar to a different graph altogether, but it was a similarity that no one had ever suspected. That's because data for this other graph came not from the tiny nucleus, but from as different an arena as you can imagine - the vast expanses of space.

Chapter 6: The Ever Changing Atom

This other graph came from astronomers who study the blazing light from stars and it shows the abundances of the different types of atoms in the universe. By far the most common atom of all is hydrogen. Followed closely by helium but not a great deal of anything else. Now look at this. It really is of cosmic significance. Both graphs, the stability graph and the abundance graph, show the strange but very noticeable peak in exactly the same place. The first scientists who spotted this were blown away. One graph from the tiny nucleus, the other from the vastness of space, point to the same magical atom. The atom that provided the key to unlocking the secrets of the entire universe. Iron, the atom which was the key to understanding the atomic nucleus, also turned out to be one of the most abundant atoms in the entire universe.

Amazingly the properties of its nucleus seem to lead directly to how much of it there is. And it's not just true of iron. Radium, which is very unstable, turns out to be incredibly rare. Aluminum, which is relatively stable turned out to be relatively common. It's a pattern, which appears right across the list of elements. The signature of their nuclei is written in the skies above us. And deciphering the meaning of this connection would require the greatest minds of a generation.

The first of these was a rebel and a maverick, called Fred Hoyle. He loved walking the hills and dales of his native Yorkshire. Hoyle always spoke his mind even though it brought him into conflict with his peers. He became something of a scientific pariah. More than almost any other scientist he explored the strange overlap between the science of the atom and the science of the cosmos. Hoyle realized what graphs revealed is that the underlying theme of the universe was ultimately change.

Everything in the universe is in a state of flux, the atoms trying to gain or lose protons in an attempt to become more stable. What Hoyle and his colleagues did was to ask how and where in the cosmos all this atomic transformation, all this alchemy, takes place. Hoyle knew that in stars like our sun hydrogen turns into helium by a process called nuclear fusion, but could nuclear fusion also be the way all the atoms in the universe are made.

Fred Hoyle's great insight was to work out precisely how the heaviest elements are created through nuclear fusion. Hoyle worked out that this process can only take place at unimaginably high pressures and temperatures of millions of degrees centigrade. In our universe, there's only one place where such conditions exist. In stars.

Fred Hoyle’s problem was with the details. To explain how fusion could create atoms heavier than helium was tricky and complicated. Hoyle had to explain precisely how in the fierce heat inside stars light atoms might fuse to become heavier ones. In the forties Hoyle worked out that our sun is hot enough to fuse atoms, like oxygen, carbon and nitrogen.

But what about heavier atoms, like copper, zinc or iron? His calculations showed that they could be made inside stars but these would have to be much hotter than our sun. And he knew exactly where to find them. These huge bloated stars near the end of their lives were called Red Giants. Astronomers had discovered that there were hundreds of millions of these monsters throughout the universe. Fred Hoyle reasoned that they were hot enough to allow weightier atoms to be fused.

But there was still a problem. Even the mighty Red Giants weren't hot enough to make the really heavy stuff, atoms like gold and uranium. To make these heavier than irons atoms would mean forcing them to fuse together becoming more and more unstable. It would require unimaginable temperatures and pressures. His only hope was that somewhere out there in the vastness of space were things so big and so hot, they made our sun look like birthday candle. And towards the end of the second world war, during a research trip to Southern California, Fred Hoyle found them.

This is the 100-inch telescope at the Mount Wilson observatory outside Los Angeles. When it was first built in 1917, it was without doubt the largest telescope in the world.

And it was while he was here he met up with the great astronomer Walter Baade who told him about supernovae. Now these are processes when massive stars explode with an incredible intensity and in a flash of inspiration Hoyle realized that here at last were the extreme conditions necessary to produce all the heavy elements.

What Baade was referring to was an explosion of simply cosmic scale. When the largest stars run out of hydrogen to fuse into helium, they come to the end of their lives and they collapse under the weight their own gravity. And then explode outwards.

In a blinding flash of inspiration Hoyle and his colleague William Fowler realized that supernova might be the hottest places in the universe. Hot enough to fuse together even the heaviest of atoms. Hoyle and Fowler had found the furnaces in which everything was made.

The discovery of how atoms are made in stars is surely one of humanity's greatest achievements. Except for one glaring problem, one that Hoyle could never explain away. And it was this: Stellar nuclear fusion can explain how all the elements in the universe are made. Except for two. Two very important ones. The two simplest elements. hydrogen and helium.

Chapter 7: The Big Bang

In the 1940s, using increasingly accurate equipment scientists found that a quarter of the sun was in fact helium. Which was considerably more than they thought. They realized that to fuse that amount of helium would mean the sun would have to be burning at billions of degrees. But the truth was, the sun only burns at 15 million degrees. The sun just wasn't hot enough to have made all that helium. In fact it turns out that per cubic meter, the sun actually generates less heat than a human being. So I produce more heat than a piece of the sun the same size as me. This means that the sun is just not hot enough to make all the helium we know that it contains.

If the helium wasn't made in the sun, then where did it come from? And even more crucial was the question Hoyle was in denial about. If all the atoms in the universe stared off as hydrogen, where did that come from? All that hydrogen and all that helium needed an explanation.

This problem catalyzed one of the most vicious fights in post-war science. That's because it turned into a much bigger question - in fact the ultimate question - 'Was the entire universe created in a single instant or has it always been here?'

Nearly every post-war physicist was sucked into this controversy but two men were at its centre. One was Fred Hoyle. The other was an eccentric Ukrainian called George Gamow. Six feet four, a practical joker and a refugee from Stalin's Russia, another physicist said of Gamow, "Even when he's wrong, he's interesting."

Both men would stake their careers on this mother of all physics battles. It all began innocently enough. Gamow had recently been appointed a professor at George Washington University and thought the hydrogen and helium riddle might be worth exploring.

This was George Gamow's office at the GWU it's really pokey. It was here that Gamow worked on the problem of why there seemed to be too much helium gas in the sun than could be accounted for in the fusion of hydrogen. Gamov came up with a crazy idea that maybe most of this helium had been around before the sun was even formed. This is the moment it gets controversial and leads us inexorably into a row over creation.

For Gamow to assert that helium existed in the universe before the sun and the stars were formed, he had to come up with another place that was capable of making helium. Gamow knew wherever this process was, it needed to be staggeringly hot - a searing billion degrees centigrade - millions of times hotter than the sun. At this temperature, matter as we know it is ripped apart, hydrogen nuclei move about manically, constantly colliding, making helium at prodigious rate. But what cosmic event was a capable of reaching such an epic, terrifying temperature?

To explain this Gamow used a speculative theory which was doing the round as at the time that suggested that the whole universe had been created in a single cataclysmic explosion billions of years ago a theory that today we call the Big Bang.

For decades astronomers have known that the galaxies are flying away from each other at astonishing speeds. The universe is getting bigger. This means that in the past the universe must have been much smaller. And in the very, very distant past the entire universe must have been a tiny, almost infinitesimally minute dot. And the implication of this is a single moment of creation. An instant at which all matter, even time and space came into being.

In 1945 most scientists were uncomfortable with this idea, but not Gamow. He spotted it might solve the mystery of the excess helium in the sun and stars. Gamow worked out that if the entire cosmos was squeezed down to a tiny dot would make it immensely hot. In the first few minutes after the creation the universe would have been hot enough for hydrogen nuclei to squeeze together to create all the excess helium in the sun and the stars.

Now after the first few minutes the universe would have expanded, it would have been too cool. But a few minutes were all Gamov needed. In that time all the hydrogen and almost all the helium was made. That's about 98% of all the atoms in the universe. As Gamow put it, our universe was cooked in less time than it takes to cook a dish of duck and roast potatoes.

But by arguing that the big bang, a deeply controversial idea, had created most of the hydrogen and helium in the universe, Gamow ignited an enormous row over creation. Fred Hoyle soon became the most vocal of Gamow's critics.

Fred Hoyle hated the idea of the Big Bang with every fiber of his being. A committed atheist, he objected to the theory, because a single moment of creation, to him, smacked of a divine creator. Gamov hit back saying that without the big bang Hoyle couldn't properly explain why there was so much hydrogen and helium in the universe.

Both men had their supporters and the arguments between the rival camps became quite shrill and personal. Hoyle was deemed an old-fashioned, crusty old Brit by Big Bang supporters and Gamow was condemned as a closet creationist by Hoyle's supporters.

The argument raged in scientific conferences and in the popular press. Secretly each side knew that though they both had compelling argument, but both lacked the killer piece of evidence that would settle things decisively. The conflict seemed destined to remain unresolved. Then, south of New York, close to the mean streets of New Jersey, an unlikely piece of equipment was to make one of the most important discoveries of the century and settle the argument once and for all.

This giant piece of sadly rusting machinery is the Bell Labs Horn Antennae in New Jersey. It's in fact a radio telescope but rather that look like the more traditional satellite dish it has this huge horn like structure which can be rotated around to face the sky and pick up radio signals from space. It's a bit like a giant hearing aid. But it could pin point very weak signals extremely accurately. It was originally built for research into satellite communication but instead it was used in the mid 60s to make one of the most important discoveries in the history of science.

Two researchers Arno Penzias and Robert Wilson had got hold of this antenna in 1963 from Bell Laboratories with the intention of doing research into the faint halo of hydrogen around the Milky Way. Before Penzias and Wilson could perform their experiment they had to get rid of all the background noise the antennae was picking up. It's a bit like the hiss on radio between stations. The spent the best part of a year checking all the equipment and electronics. The even got down on their hands and knees inside the dish to scrub it clean of what they called white dialectic material, which is basically pigeon crap. But even after all this there was still a faint persistent hiss that they couldn't get rid of. And it was there whichever direction the antennas pointed.

There was only one viable explanation. The noise was the sound of radiation, the after glow of the Gamow's Big Bang. Here at last was final proof that Gamow was right. The big bang had to have happened.

You see soon after the universe was created about 300,000 years after the big bang it had expanded and cooled enough for the atoms of the lightest elements to form, leaving the whole universe awash with light. Now George Gamow had earlier predicted that this afterglow of creation would today be in the form of weak microwave radiation. You can actually hear this radiation as a tiny fraction of the hiss on your radio or TV in between channels.

The detection of this cosmic background radiation by Penzias and Wilson showed that the Gamov big bang theory was correct and that he was right about how H and He were formed in the early universe. So this together with Hoyle's and Fowlers theory about how all the heavier elements were cooked inside stars gave us the complete picture. We finally understand how the atoms of all the elements in the universe were made.

In less than one hundred years science has performed a miracle. It had truly explained where we come from and was able to describe the entire 14 billion year history of the cosmos. In the beginning was the big bang - an explosion of unimaginable power. In the following ten minutes, in searing heat, the nuclei of just two types of atoms emerged, hydrogen and helium. For the next three hundred thousand years the universe expanded.

At that point another cosmic chapter began. Individual atoms separated out from each other. As they did this, they released light. It's the remnants of this light that Penzias and Wilson picked up with their horn antenna. Then millions of years after this, massive clouds of hydrogen coalesced into the first stars. In here they began to fuse, producing starlight and eventually all the other types of atoms that exist in the universe today.

Our earth and everything on it including our own bodies was forged long ago in the crucibles of space. For instance my body is almost 3/4 water, which we know is made up of oxygen and hydrogen atoms. We now understand that hydrogen was formed 13 billion years ago soon after the big bang itself. whereas oxygen had to wait to be cooked in stars like our sun. The same is true of another element on my body, carbon, the element on which all life forms on earth are based. But my body also contains other elements in smaller amounts, like iron. This element was formed in the dying embers of gigantic stars as they ground towards the end of their lives. There are also trace elements like zinc. There are only grams of zinc in my body but this element had to be created during a supernova, the explosion of a giant star with cosmic violence during which lighter atoms are fused together to form heavier elements. Same is true of all naturally occurring elements. There were all cooked in cosmic cauldrons. Romantically you could say that we are all made of stardust. But the truth is also that we’re all just nuclear waste.

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