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The Unbelievably Weird World of Modern Physics

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Assembly Room, A. K. Smiley Public Library

SUMMARY

According to our best and brightest scientists, the world is very different from what our common sense tells us it is. At the largest scale, 95% of all the mass energy in the universe is composed of something we cannot see, cannot measure, and do not understand. Dark matter is most certainly made up of material we have never encountered in our visible world, and dark energy is exerting a force we don't understand. We live in a universe started by an inconceivable Big Bang, out of which everything in our universe emerged, from a place we do not understand. Our universe is filled with black holes, whose properties are incomprehensible, and which might actually bridge to other dimensions or a parallel universe.

At the scale of the microscope and smaller, the world is even stranger. Our smallest objects are both particles and waves, and they exist in many places at once before we observe them. They can be coupled together such that they act like one particle even when they are separated. Our universe has a unique set of properties that are perfect for creating the conditions we see today. If they were even infinitesimally different, no stars would have formed. Theorists say this is impossible unless there were an infinite number of universes and we are the perfect one. And finally, the ultimate theory that will explain everything can only be formulated in a space of many dimensions.

ABOUT THE AUTHOR

Bill Jury was born in a suburb of Detroit, Michigan in 1946. He attended the University of Michigan and the University of Wisconsin, receiving a PhD in Physics at UW in 1973. He spent his entire career at the University of California, Riverside and retired in 2008 as a Distinguished Professor of Soil Physics in the Department of Environmental Sciences. Over his research career he published 225 papers and four books, and has been identified by the Institute for Scientific Information as one of the 100 most highly cited researchers in the world in both the fields of Engineering and Environmental Science. Among other awards and honors, he was given the US Department of Agriculture Secretary's Honor Award for Environmental Protection in Washington DC in 1999, and in 2000 was one of 72 scientists in all fields elected to the U. S. National Academy of Sciences. While at UCR he gave the Faculty Research Lecture, received both the Graduate Student Association and Faculty Senate Distinguished Teaching Awards, and served as the first chair of the Faculty Academy of Distinguished Teaching. During his career at UCR he served as Department Chair, Vice Provost for Academic Personnel, and Interim Executive Vice Chancellor and Provost before retiring in 2008.

This paper is an overview of the progress made by some of the most brilliant physicists on the planet in understanding the laws governing the very big and the very small objects in our universe. I'm going to talk about some very strange discoveries and some even stranger theories, and will do my best to explain them in a way that is understandable. Please interrupt with questions at any time or request a clarification if you are not following what I say. That will help me to stay on track.

I actually came from the world of physics, receiving my PhD in that subject from the University of Wisconsin in 1973. Although I left mainstream physics after graduation to pursue a career researching the physics of the environment, I kept following the latest developments in my private reading over the years. I want to share with you today a few of the more startling discoveries, all of which will shake the foundations of what we each would regard as reality.

How Large is the Universe?

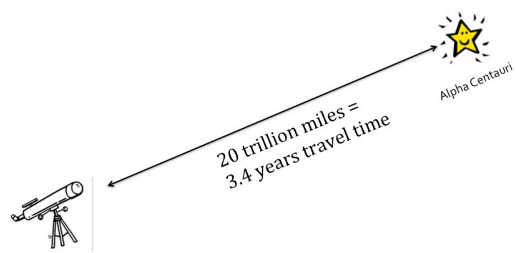
I want to begin by talking about the largest possible object, namely the universe, and describe what all scientists believe was its beginning in the biggest explosion of all time, called the Big Bang. First off, though, I want to characterize the visible universe as we see it today, which is primarily a collection of stars of varying sizes, ages, and energy content. Our sun is a medium-sized star, nothing special, but it has some very impressive credentials nonetheless. It is about 4.5 billion years old, and for its entire lifetime has been releasing enough energy each second to equal what 4 billion large power plants would produce in a year. Since it may be difficult to grasp the significance of a billion power plants, I have a simpler illustration. The sun releases enough energy in one second to melt a ball of ice 450 miles in diameter and boil it away to vapor. I have put this ball next to a map of California to help you grasp how much energy I'm talking about.

The sun will produce energy at this rate for its entire lifetime, which is about 10 billion years. There are a lot of stars in the universe, some smaller than our sun, and some much bigger. To get a proper picture of how big the universe is, we need to expand our view beyond the sun and our solar system.

Seeing into the Past

Before we look at a bigger picture, however, I need to introduce a new measure of length: the light year, which is the distance that light travels in a year. Light moves at a speed of a little more than 186,000 miles per second, and thus travels about six trillion miles in a year. That distance is about 8,000 round trips to Jupiter and back from Earth. Since our sun is about 93 million miles from Earth, it only takes about 8½ minutes for light to reach us. But everything outside our solar system is a long way away. In fact, every time we look at stars, we are looking into the past. Even the closest star to us, Alpha Centauri, is sending us information that is 3½ years old. If the star blew up this instant, we wouldn't see the explosion in the night sky until September of 2020.

Telescopes See into the Past



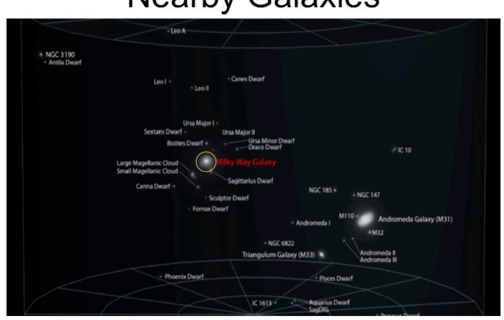
How Many Stars are in the Universe?

Over time, gravity has caused the stars that formed near each other to clump together into galaxies, with a large space between different ones. Let's take a look at the collection of stars we belong to called the Milky Way Galaxy. Our sun and solar system are just a small point at this scale, located in the lower right spiral. There are about 400 billion stars in our galaxy, which is about 100,000 light years wide. By comparison, you could put about 400 billion grains of sand in a cubic box 50 feet on a side. And since our sun is just an average star, the Milky Way contains about 400 billion times as much energy as our sun.

The Milky Way

If we step back and take a bigger look, we see the immediate neighborhood of our Milky Way galaxy, which at this scale is like a small hazy ball. Even though our sister galaxy Andromeda is relatively close to us, it is still more than 2.5 million light years away from our galaxy.

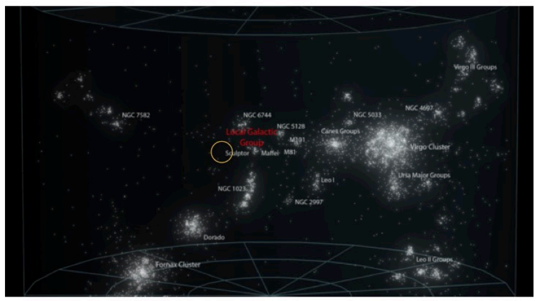
Nearby Galaxies



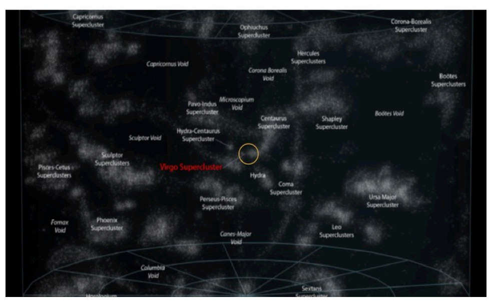
At an even larger scale we group galaxies into superclusters. The circle in each picture contains everything that was in the previous slide. We are part of the Virgo supercluster, which contains about 100 of the galactic groups like our own and is about 110 million light years across. If we blow up the scale once again to produce a snapshot of the region near us, we see that there are many superclusters like our own. In fact, there are millions of these superclusters in the universe. At the largest scale we finally see the entire universe, which is so large that even the superclusters just appear as points at this scale.

The visible universe is about 90 billion light years wide. There are at least 100 billion galaxies, each containing an average of about 400 billion stars. When you add up all the energy coming from these stars, you get quite a staggering total, which I again express in terms of the energy a power plant puts out in a year.

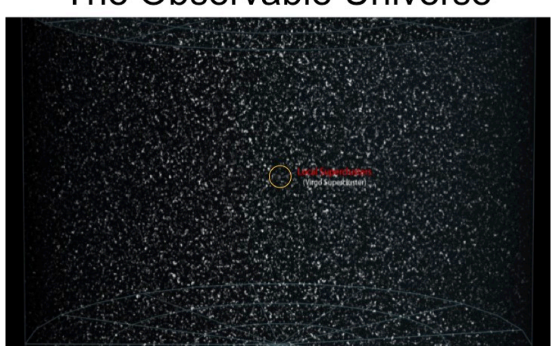
Virgo Supercluster



Local Superclusters



The Observable Universe



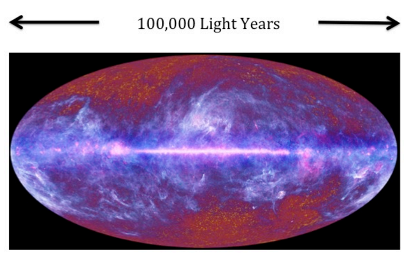
That number is 16 followed by 31 zeroes, called 160 nonillion. It isn't used very often so you probably haven't heard of it before. So now we know how much energy there is in the visible universe. Where did all this energy come from?

The Big Bang of Creation

If you believe the Big Bang theory, and virtually every scientist does, it all came from a single point in a massive explosion about 14.6 billion years ago. They know this because they have measured the speed and direction of motion of all the galaxies and can trace backward to their origin from a single point in the distant past. The Big Bang was so hot and so powerful that it had to cool down and expand for over 300,000 years before atoms could form.

How could such an incredible amount of energy ever be compressed to a point? Science doesn't know, and probably never will discover the answer. We actually have a picture of what the universe looked like when it was 300,000 years old. This first burst of light, when things cooled down enough for atoms to form and light to escape without being absorbed, can be detected today as faint microwave radiation. The universe was only 100,000 light years across then, about the size of the Milky Way galaxy today.

Space Telescope Photo of the Universe at 300,000 Years



Dark Matter and Dark Energy

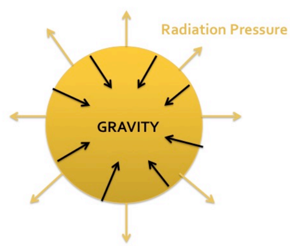
The stars and other space objects that show up on our telescopes constitute everything that we can see or measure in the universe. However, that turns out to be only a small fraction of the matter and energy in the universe, which is dominated by invisible dark matter and dark energy. Dark matter, even though invisible and undetectable, exerts a gravitational force on all the matter that we can see, and we can calculate the amount and location of the mass required to exert this extra force. It is unlike any other matter that we observe, and gravity is the only force it exerts. We have no idea why it is there or what it is made of, and none of our theories can explain its existence. Even though it is all around us, it passes harmlessly through everything visible without disturbing it. We estimate that it has about five times the mass of the visible universe.

But even dark matter and visible matter together contain only a small amount of the total energy of the universe between them. After we launched the Hubble telescope and began to track the most distant objects we realized that something invisible and undetectable called dark energy was pushing all of the galaxies farther apart by gravitational repulsion. Without this invisible force, the universe would eventually quit growing and slowly collapse back to a point. The energy required to produce this force is about 70% of the total mass energy in the universe. Strangely however, even though dark energy is present at every point in space, the force it exerts only operates at large scale, and doesn't affect stars within a galaxy. To summarize, 95% of the universe is made up of stuff we don't understand, can't see, and can't measure, exerting a force we don't understand.

Black Holes

Perhaps the strangest inhabitants of the universe are black holes, which are so dense that their gravity prevents light from escaping, so they can't be seen directly. Black holes are actually formed when a star dies, when the outward pressure exerted by its radiation weakens and gravity pulls it closer and closer together. As the star collapses inward, gravity keeps getting stronger and stronger, compressing the material to such an incredible density that it becomes a trap that lets nothing, not even light, escape it. Our best theories tell us that black holes are so dense that they actually rip a hole in space, and may connect at their other end with another parallel universe. Black holes come in all sizes, some as small as atoms but still weighing as much as a mountain, and others so massive they weigh millions of times more than our sun. These supermassive black holes are at the center of galaxies. We can't see black holes directly, but we can see their influence on nearby objects, some of which get too close to the black hole and get "eaten".

Black Hole Formation



Why Are We So Perfect?

Another feature of our universe that has baffled the world's greatest physicists is that it is too perfect. It has a unique set of properties such as the strength of gravity that are balanced so precisely that if any of them had been slightly different, the universe never would have formed into stars, planets, and life. They like to think of the Big Bang as a random event, and there is just no way that something random could have created such a perfect balance. There are only two ways out of this dilemma: either something unknown (perhaps God?) caused it to turn out this way, or there are actually an infinite number of different universes that have been created, and we just happen to be the perfect one.

Infinite Parallel Universes

Since many physicists think the notion of God is too unscientific to be considered responsible for the universe, a number of different theories have been proposed that include an infinite number of universes out there where we can't see them or ever reach them. Perhaps the most interesting of these theories is the Many Worlds hypothesis, that says we live in a universe—or more accurately a *multiverse*—where timelines are constantly branching off and creating distinct and coherent worlds, each experienced by a different version of you. In fact, every time you make a decision, you split into two universes, each one a consequence of a different decision. It sounds like bad science fiction, but it is actually a rigorous theory. If you would like to see a good science fiction rendition of a parallel universe, watch *The Man in the High Castle* on Amazon.

The Origin of Quantum Mechanics

As we can see, there are a lot of mysteries and weirdness in the very large universe. It turns out that the very smallest objects we can perceive have even stranger behavior. In the early part of the 20th century we developed instruments that allowed us to determine the structure of atoms, consisting of protons and neutrons surrounded by orbiting electrons. The problem was that our physics theories of that time all said that atoms couldn't be stable, and would collapse immediately. This situation lasted for many years until finally a new theory, called quantum mechanics, was developed that showed how the atoms could be stable. Over the years this theory has been successful at explaining everything that was observed and every scientist in the world believes that it is correct. The problem is that it makes no sense at all.

Nobody Understands the Quantum World

The quotes shown in the next slide are all from Nobel Prize-winning physicists who were leaders in the development of quantum mechanics. Neils Bohr said: *Everything we think of as real is made up of things that cannot be regarded as real.* Richard Feynman, one of the most brilliant minds of all time, is quick to say that quantum mechanics cannot be understood. Erwin Schrödinger derived the mathematics of the theory that is so successful, and it nearly drove him crazy. And poor Einstein, who said quantum mechanics couldn't possibly be correct, spent the last 40 years of his life trying to derive a more logical theory, and he failed.

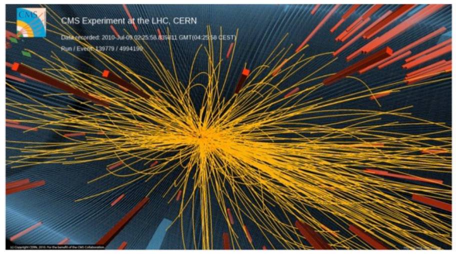
Foundations of Quantum Mechanics

Let's have a closer look at this strange theory by listing its assumptions. First, it says that matter and energy are the same thing and one can be turned into the other. This is the famous $E=mc^2$ postulate of Einstein. I illustrate it with a picture from the CERN supercollider in Switzerland showing the aftermath of a head-on collision of two protons traveling almost at the speed of light. Their collision produces over one hundred particles, with hundreds of times the mass of the protons that collided. These particles were created out of the energy carried by the moving protons. The reverse reaction, when mass is turned into energy, is partly responsible for the enormous energy of a hydrogen bomb.

Wave-Particle Duality

The second assumption of quantum mechanics is that all objects are both particles and waves, even though these are two very different things. We think of a particle as a solid object that would bounce off anything it hit, and that a wave would be something oscillating between limits and that when it hits another wave might either amplify or contract depending on whether the waves are in phase or not.

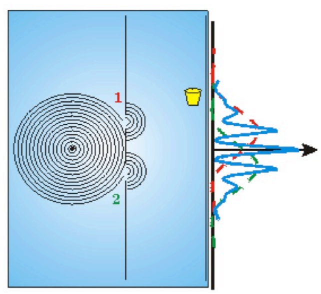
E=mc^2



A high-energy collision of two protons creating over 100 particles

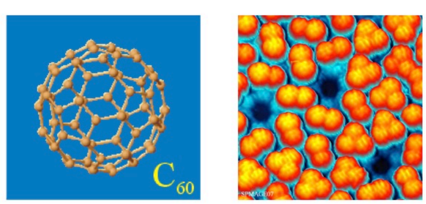
As the diagram shows, if two waves are in phase their amplitudes add together and strengthen into a bigger version of the separate waves. However, if they are out of phase they cancel each other out. This is how noise-cancelling headphones work. The two-slot diffraction experiment is a good way of illustrating this. As the wave reaches the slots it spreads radially out so that when it reaches the screen some of the waves are in phase and some are not, producing so-called diffraction lines. The short movie is an illustration of this principle.

Wave Interference

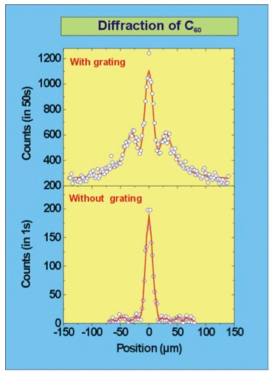


Amazingly, we get the same result when we send a beam of electrons through the slits. If we cover one slit, the electron acts like a particle and all of the electrons that go through the open slit land close together on the detector screen. However, when both slits are open, the detector screen has diffraction lines with spaces between them where no electrons were recorded. Recently, this experiment was repeated using huge molecules called Buckminsterfullerene or Bucky balls, consisting of 60 carbon atoms. They are actually big enough to be seen with a special microscope called a scanning tunneling microscope, as shown in the photo at the right. Here they clearly appear to be particles.

Buckminsterfullerene



However, when a beam of Buckyballs was shot through a diffraction grid, the screen detected interference lines, just like it was a wave.

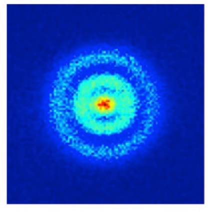


Another feature of quantum mechanics is the so-called uncertainty principle. It is impossible to know both exactly where a particle is and how fast it is moving. The more precisely you measure one, the less you know about the other. For example, the only way to see something is to shine light or some other form of radiation on the object. The light "particles" bounce off the object and show you where it is, but in the process they change the object's velocity.

Observation and Existence

The mathematics that describes particles in quantum mechanics theory only represents particles using probability distributions. For example, an electron orbiting around a proton in a hydrogen atom has a certain probability of being at many different locations around the proton. However, when the electron is observed, it comes into existence at the place where it is detected. Prior to that, in a sense it is many places at once. This was recently proven in a very clever experiment where hydrogen atoms were repeatedly treated in an identical manner and then observed. When all of the different observations were put together, it reproduced the probability distribution predicted by quantum mechanics, as shown in the photo. Here the electron is like a cloud orbiting the proton rather than a particle.

Hydrogen Atom Photo



There is a very famous paradox that uses this principle called Schrodinger's cat. In this thought experiment a cat is placed in a closed box where there is a deadly gas in a capped vessel that will be released when a hammer drops on it and smashes it. The hammer is held in place by a device that will drop the hammer when it is hit by a particle released from the random decay of a radioactive atom next to it. If we use quantum mechanics to describe the behavior of the radioactive atom at a particular time, it will have a certain probability of having released a decay particle and smashed the vessel, and a certain probability that it hasn't done so yet. Thus, it has both decayed and not decayed before we observe it and our observation forces it to become one or the other. However, the cat will be dead if the gas has been released and will be alive if it has not, so as part of this description prior to observation, the cat is both alive and dead. No wonder Schrodinger hated quantum mechanics!

Lest you think this is all silly and hypothetical, let me remind you that all these assumptions are required by quantum mechanics, and that this theory has never been proven wrong. In a sense, nothing is real until we observe it. That is why many physicists admit that we really don't understand reality.

Quantum Entanglement

As I said earlier, Einstein never accepted quantum mechanics. And one of the main reasons was because it allowed nonlocality. Under certain conditions, two particles can be created in such a way that they must always have the same values of certain properties. They are said to be entangled. In a famous paper Einstein created his own paradox by showing that quantum mechanics predicted something that violated physical law. In his paper he said that it was possible in principle to create two entangled particles with the same value of a property and send them off in opposite directions. When they got far apart, we could then change the value of the property in one of them, and quickly measure that property in the other, in a time faster than the speed of light could communicate between them. According to quantum mechanics, that second particle has to have changed its property value instantly, which Einstein said was impossible because they could not communicate in a time shorter than the time it would take light to travel between them. According to the theory of relativity, which everyone believes is correct, the speed of light is the fastest anything could travel, including communications, so there is no way the second particle could know that the first had changed. No one could figure a way out of this dilemma.

The next slide helps to illustrate Einstein's point. In the beginning particles A and B are created so that they must always be the same color, which is initially red. They now travel some distance apart, and A changes to blue. As quickly as the observers on the right try to look at B it will also have changed from red to blue, even if they are separated by the length of the universe. Einstein died in 1955, still probably chuckling over the dilemma his paradox had created for quantum mechanics. Unfortunately for him, however, a recent experiment in 2015 actually proved that nonlocality is real. In a sense, these two particles are only one particle, whether they are separated or not. This property is now accepted and will play a central role in the design of quantum computers, which could be billions of times faster than today's models because they can transmit information instantly.

Quest for the Unified Field Theory

For very sound reasons, theoretical physicists believe that a single theory should be able to explain the behavior of objects from the size of the universe all the way down to the smallest conceivable size. One basic requirement of this theory is that it must show that the four different forces in nature: gravity, electromagnetism, and the strong and weak nuclear forces, merge into one single force when conditions become sufficiently extreme, such as they would have been in the first instants after the Big Bang occurred.

The theory that would explain all these forces and offer a single description of the large and small objects of the universe has come to be known as the Unified Field Theory, and Einstein struggled in vain over the last 40 years of his life trying to derive it. It has remained the Holy Grail of physics for the better part of a century. However, a lot of progress has been made. In the 1960's, physicists proposed a theory that connected the electromagnetic and weak forces, and ten years later they connected those two to the strong nuclear force. This theory has been thoroughly tested and has proven correct wherever it has been used. The last unverified prediction of this model was finally consummated in 2013 when the Higgs boson, popularly known as the "God particle", was discovered at the CERN lab in Geneva. Thus, some 40 years ago theoretical physicists were ¾ of the way towards unifying the four forces and deriving a theory that could explain everything.

But connecting these three forces to gravity has proved to be incredibly difficult. And when a candidate for the unified field theory was proposed that could couple gravity to the other forces, it turned out to require a universe very different from the one we think we live in. This model is called string theory, and it has caused chaos within the previously staid world of the physics community.

In string theory the fundamental entity that forms the basis of the building blocks of matter is a one-dimensional vibrating string. It is so small as to be almost beyond comprehension, with a length scale of 10^{-33} cm, that is a 1 preceded by 32 zeros after the decimal point. To give you a feeling of how small that is, consider a reference particle, a single particle within the dust of talcum powder. It is typically about .001 cm, or about 1 thousand billion, billion, billion times larger than a string particle. By comparison, the width of the universe is about that much bigger than a flea. So how do we observe a string? The answer is we can't and we never will. The fundamental particle of this theory must be accepted on faith.

Are there any other strange things about this theory? Well, for one, the string is one-dimensional, but vibrates in 10 dimensions. As a consequence, the theory can only make predictions in a 10-dimensional universe, which presumably is more fundamental than the one we live in. It makes great predictions, but it turns out to be extremely difficult to describe what they mean in our three dimensional universe. Although it is not yet clear whether string theory is the correct formulation or not, everyone agrees that the only way to unify gravity with the other forces is with a higher-dimensional theory. Unfortunately, it is quite likely that any theory involving higher dimensions, and the incredibly small sizes of the fundamental particles making up a unified theory, will not be testable.

Now you understand the title of my talk. We really do live in an unbelievably weird world.