Chapter 2

Toward Understanding Gravitation.

Andrew Jackson. ”Toward Understanding Gravitation”, *21st Century Physics FlexBook*.

2.1 Preface—A Note to the Teacher and Student Regarding Background Information and Pedagogy

Nearly every physics textbook has an adequate section regarding Newton’s universal gravitation, Cavendish’s work and an introduction of Kepler’s laws of planetary motion. Therefore, in this work I will not attempt to *teach* those topics, but will assume that students have a basic understanding of the physics involved as it pertains to an understanding of gravity. Many textbooks do not contain a treatment on current understanding and development of the ideas regarding gravitation. Those that do often place this material as footnotes to a chapter or as chapters late in the text that a typical class may never cover. This chapter of the 21^{st} *Century Physics FlexBook* will attempt to address our changing understanding of gravitation and in doing so also introduce the student to a few interesting areas of astronomy and cosmology. This chapter should be an appropriate extension to a study of Newton’s universal law of gravitation. The presentation deals with gravitation from a purely conceptual approach. The appropriate high school level mathematical treatment would pertain to Newton’s universal law of gravitation and it is assumed that the students will study from traditional text or with their teachers.

The chapter is set up in dialogue style. This technique has a wonderful heritage in physics going back to Galileo’s *Dialogue Concerning the Two Chief World Systems* published in 1632. **Bold Print** statements represent questions asked by a student with the appropriate answers following. It is my practice and suggestion that a treatment of universal gravitation in a high school physics class be approached in a historical manner starting with Aristotle and extending to as near the present understanding as possible.

2.2 Toward an Understanding of Gravitation (With a Few Interesting Side Trips)

What is Gravity?

If we begin our view of gravity from an Aristotelian view, you may find that it is not far from your own initial thoughts on gravity. Aristotle ($\sim$ 350 BCE) taught that the heavenly bodies moved in perfect circular

Figure 2.1: Aristotle Contemplating the Bust of Homer - painted by Rembrandt in 1653 at a time when scientists understood the planets to orbit the sun, but had no concept that a force called **gravity** caused their motion and were only beginning to abandon Aristotelian beliefs of motion. (13)

orbits around the Earth. The more mundane things here on Earth tended to move toward their natural place. For some objects, like rocks and people, that natural place was to be drawn toward the center of the Earth. For other objects like fire, smoke, and steam that natural place was to the heavens.

It was quite a long time after Aristotle that the English language included the word **gravity** in the sense that you think of it in your science class. The Latin word *gravis* means heavy, but it was not until the mid $1600s$ that the term **gravity** was used to describe a force that gives objects their weight. Here is a formal definition from the Online Etymology Dictionary, `http://www.etymonline.com/index.php?search=gravity`.

Common to Aristotle's and all earlier ”theories” of the motion of heavenly bodies is the belief [dogma] that the Earth is at the center of the center of the universe and that they orbit in the perfect geometric form, namely a circle.

Aristotle's description of how and why things fell or orbited was attacked often and by many. Many Arabic mathematicians and physicists tackled the issues in the middle ages, which lead to some of the same statements eventually made and published by Galileo and Newton. These ideas published by Newton and Galileo are the ideas you are likely to find in your physics text.

So Aristotle had it wrong, but now we know the truth about gravity—right?

Well, in a word—no. Physicists have answered many questions about gravity, but they have created many more questions, too.

What Do We Know About Gravity Now?

The modern era of astronomy begins with Copernicus. The Aristotelian astronomy [developed largely by Ptolemy] had use a hierarchy of circles to accurately describe the motion of heavenly body. Copernicus found that the description is simplified if the sun is placed at the center and the Earth and the other planets revolve around it; in particular, it leads to a simple explanation of retrograde motion.

Kepler's, Galileo's, and Newton's work with regard to gravity is well supported in your physics book, I am sure. This is the traditional material of introductory physics. I will just touch on a couple of important points to support ideas I wish to develop in this chapter. You will need to use other resources to pick up on the ”traditional details” like solving mathematics-based physics problems. In this chapter, I hope to help you understand how our current knowledge about gravity has developed. I hope you will understand how ideas were built on top of one another, how questions got answered, and how new questions came to be while some old questions still remain. I hope you will also get a sense for how technology and data collection played a roll in answering and developing important questions about gravity.

So, what we know about gravity starts with Kepler? What did he figure out?

Johannes Kepler ($\sim$ 1600) was a gifted mathematician. Around 1600 he began working with one of the world's most gifted astronomers, Tycho Brahe. It is important for you to know that at this time Kepler and his contemporary Galileo understood and believed Copernicus' theory of a sun-centered solar system. Kepler applied his gifts of geometry to more than three decades of precision data regarding the position of Mars in the sky. By 1619 Kepler had published his three laws of planetary motion.

1. All planets move in elliptical orbits with the Sun at one focus.
2. A line connecting a planet to the Sun sweeps out equal areas of space in equal amounts of time.
3. The period of a planet's orbit squared is directly proportional to the cube of its orbital radius.

It is so easy to state and learn these laws that it may lead you to think they were easy to figure out. If you would like to gain a little understanding of Kepler's accomplishments you should look over the details of how he came to these three conclusions at `http://www-groups.dcs.st-and.ac.uk/~history/Extras/Keplers_laws.html`

Figure 2.2: Johannes Kepler as painted in 1610 by an unknown artist. He would soon hear of a revolutionary new tool for astronomy—the telescope. (1)

It is also very useful for you to have a good understanding of these laws and the nature of ellipses, so here is a little project for you to do.

Elliptical Homework

Get a scrap piece of cardboard, two push-pins, a loop of string, and a pencil.

Push the two pins into the cardboard.

Place the loop of string on the cardboard with the two pins in the loop.

Use a pencil to pull the loop away from the pens to make the loop tight against the pencil and the two pins.

Move the pencil around in a circle (it's an ellipse) keeping the loop tight as you draw.

The shape you have is an ellipse. The two pin holes are the two foci. Mark one as "Sun." The drawn curve is the path of a planet around the Sun. See if you can sketch in the idea of Kepler's Second Law of Planetary Motion.

The eccentricity of an elliptical orbit is found by measuring the two distances shown and dividing the difference between them by the larger. Therefore, the eccentricity of a circle is equal to zero.

The eccentricity for Mars is about 0.09, which is much larger than Earth's. What does that tell you about how elliptical the orbits of the planets are? Can you use a string, pin, and pencil to create an ellipse with $e = 0.09$?

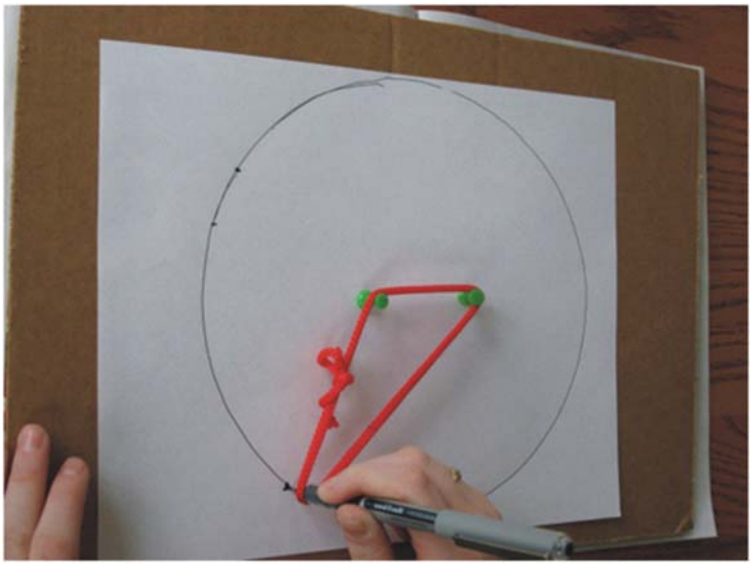


Figure 2.3: Creating an Ellipse (2)

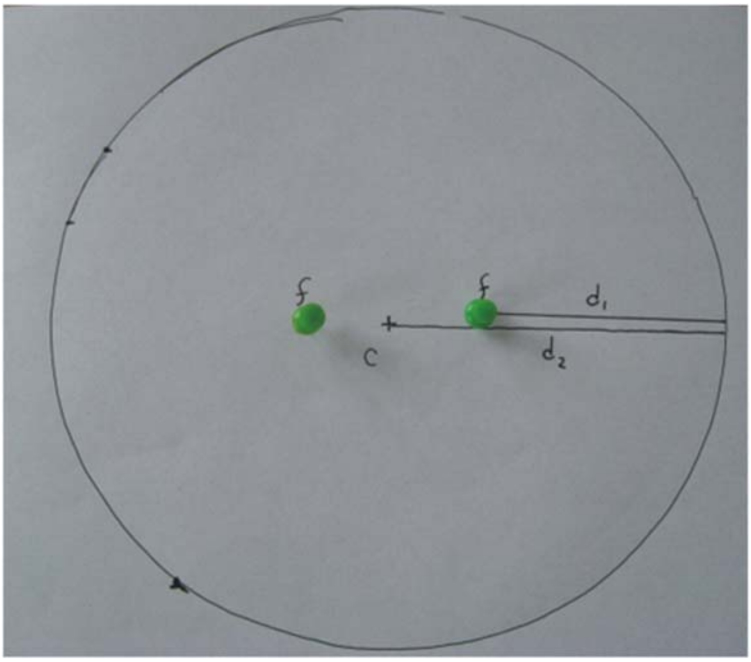


Figure 2.4: This ellipse has an eccentricity of 0.25. The sun would be at one focus. (8)

If you make the loop of string a bit shorter and draw another ellipse it will represent the path of another planet. See if you can apply an understanding of Kepler's third law of planetary motion to the two ellipses. This would be an excellent thing to talk through with another student or teacher once you have given it some thought on your own.

OK—I drew a couple of ellipses and I think I understand Kepler's laws of planetary motion. But if they are laws, he got it all figured out, right?

It is so important to understand the scientific meaning of the words: *law*, *theory*, and *hypothesis*. Before we go on with more physics about gravity, let's take an important aside.

An Important Aside

What is a scientific law? How does it differ from a hypothesis or a theory? How does a theory become a law? These are all great questions that you really need to be able to answer. The earlier in your science studies you understand these differences and relationships the better. A scientific hypothesis is not just a "best guess." It's an idea of how something works or an explanation based on the evidence available. It is a statement limited to a specific situation and must be testable. In other words, it should be something that could be proven wrong.

A scientific law is a statement of fact that is believed to be always true, but offers no explanation. The law of inertia is a wonderful example. It is understood that objects at rest will stay at rest unless a force causes them to move. Scientists do not have an explanation for WHY objects cannot begin moving from a state of rest without a force acting on them, but such a thing has never been observed and we believe it to be universally true. Kepler's laws of planetary motion fit the description of scientific laws well when they were initially stated. In the early $1600s$ we did not understand that the Sun and planets were exerting forces on each other through gravitation. Kepler put together decades of data and found that for the six known planets, all of them behaved as described by his three statements. His laws offer no explanation for WHY the planets behave this way, thus they are planetary laws. Newton's universal law of gravitation fits this description as well. It does not tell us HOW two different masses exert forces on each other, it simply describes it and names it. The question "How does a theory become a law?" is a trick question. The answer is—it cannot! Scientific theories EXPLAIN things. A theory in science provides a big picture understanding and view that helps to explain many different phenomena. For example, the atomic theory says that matter is made of discrete units of matter that maintain their "identity" through physical and chemical change. This atomic theory is very useful in understanding chemical reactions and much more.

Therefore, in science, the theory of evolution is not less certain than the law of universal gravitation. They do very different jobs. The theory of evolution EXPLAINS HOW speciation occurs through natural selection and Newton's law of universal gravitation states what we observe without explanation. We are still in search of a THEORY of gravitation. There are a few promising hypotheses, however.

Theories and laws. I'll try to remember the difference. What about this universal law of gravitation?

I will leave the majority of the teaching of Newton's universal law of gravitation to your traditional textbook or Internet sources. Go read up on it and do a few problems and come back. One place you can do this is the Physics Classroom at `http://www.physicsclassroom.com/Class/circles/u6l3a.cfm`

OK. I solved some problems and I'm back. Seems like Newton got it all figured out.

In Newton's life (1643-1727) he came to understand that all masses attracted each other with a force that was directly proportional to the product of the masses and inversely proportional to the distance between them squared. BUT, neither he nor his contemporaries were able to turn this proportionality into an equality. It is not terribly difficult to think up an experiment to try to measure the constant of proportionality in

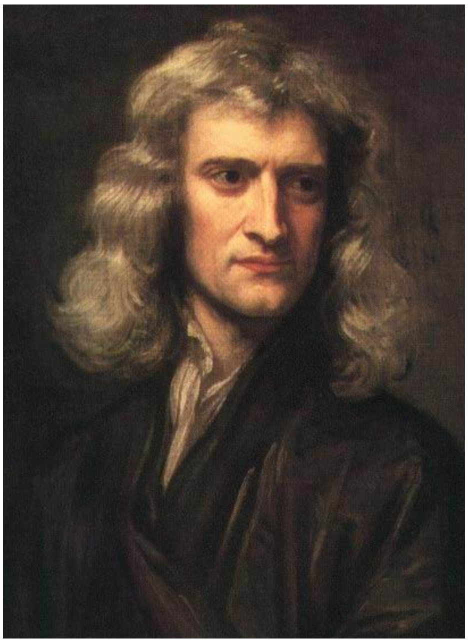


Figure 2.5: Sir Isaac Newton (1643–1727) as painted in 1689 by Godfrey Kneller. (4)

this equation $F = \frac{GMm}{d^2}$ where G is some constant that turns the mathematics from a proportionality to an equation. With equations you can solve problems.

First, you might think of taking two objects of mass M and m and placing them d apart. Now all you need to do is measure the force of attraction and solve for G. While this is simple to think of, it is far beyond the ability of simple force scales to measure the incredibly small force of attraction between the two masses, even if the masses are huge. The best scales of Newton's era were not up to the task. Another simple experiment you may think of is to take a known mass m and find out how much it weighs. This would be the force F of attraction to the mass of the Earth when separated by a distance equal to the Earth's radius. During Newton's time the radius of the Earth was well known, but the value of its mass was not known. One equation with two unknowns, the mass of the Earth and the value of G, makes for an unsolvable problem.

Newton died with two major aspects of universal gravitation left unexplained: the value of the universal gravitation constant G, and an explanation for HOW gravity reached out through space and exerted a force. After all, if you want to exert a force on a friend you have to physically touch him or throw something at him. For example, it wasn't obvious that the Earth and the Moon were doing either to each other. So how were the Earth and the Moon pulling on each other with gravity?

My physics textbook has a value for G, so somebody figured that part out. Cavendish, right?

Yes, that's correct. By the end of the $18th$ century, Henry Cavendish utilized a sophisticated piece of equipment to measure the gravitational attraction between massive lead balls. Comparing this amount of force of attraction to the sphere's weight (their attraction to the sphere Earth) he was able to determine the density of the Earth. This allowed others to then determine the mass of the Earth and ultimately (as far as understanding gravity at least) the value of G, the universal gravitation constant.

Today that value is known to be 6.67428×10^{-11} m^3 kg^{-1} s^{-2} with an uncertainty of about $\pm 0.00067 \times 10^{-11}$ m^3 kg^{-1} s^{-2}. Or put another way, about ±0.01%.

Wow. They know the value of G really well!

Figure 2.6: In 1798 Cavendish finds a way to measure the incredibly small forces that lead to a determination of the Universal Gravitation Constant. (6)

No, not very well at all in some respects. To put that in perspective, we know the mass of the electron with 2000 times more certainty, Planck's constant with 2000 times more certainty, and the electron's charge with 4000 times more certainty than we know the Universal Gravitation Constant! `http://physics.nist.gov/cuu/Constants/index.html`. Another interesting thing about the universal gravitation constant is that we don't have any strong evidence to believe it is necessarily universal or constant. In conjunction with Newton's law of gravitation it does work very well for examining the motions of the planets around the Sun and for getting spaceships to the Moon, Mars, and even the outer fringes of our solar system with great precision. But, there are still some pretty basic questions that can be asked for which we don't know the answers. Such as, has G always been this value from the big bang until now? Is G the same value near the super massive black hole in the center of our galaxy as it is here in a physics lab? What does the value of G really tell us about the fabric of our universe?

Um, I'll hold onto those for later. We have a universal law of gravitation, and we know the value of G—at least pretty well. Any luck on how gravity applies a force without touching?

Yes, and this question brings us into the $20th$ century and to the famous physicist Albert Einstein (1879 - 1955). In 1905 Albert Einstein had a rather remarkable year. Notice in the 1904 picture of Einstein that he is not the iconic old man with unruly hair. This is Albert Einstein at the age of 25, at his sharpest. In 1905 he published three amazing papers. These papers explained the photoelectric effect, explained Brownian motion, and introduced his special theory of relativity. All three are amazing and you may wish to do some studying on any or all of these topics. However, it is the third paper on the special theory of relativity that will forge a connection to gravity for us. In this paper he postulates that the speed of light is a constant in all inertial reference frames and that it is the ultimate speed limit in the universe. The paper postulates that the law of physics are the same (or are "invariant") for all observers moving with a constant velocity. Einstein's paper did away with a need for "luminous ether," changed concepts of time and space and the concept of simultaneity, but still did not deal with gravity.

In 1915 Einstein published his paper on general theory of relativity, in which he postulated that the laws of

Figure 2.7: Albert Einstein at the age of 25 at the time of his most amazing year of work that he published the next year in 1905. (12)

physics are the same for observers moving with constant acceleration (that's why it is more "general" than the "special" relativity). In this paper, Einstein introduces the concept that mass bends the fabric of space and time and that this warping of space and time IS gravity.

Bending space and time...science fiction? And, if I did believe it, how does it account for gravity exerting a force without touching?

Not fiction, way stranger than science fiction, because it really happens. This amazingly complex idea is easy and fun to model. Time for some more homework.

Warping the Fabric of Space

Materials: large metal coffee can, bubble solution, pipette or eye dropper, and mineral oil

The empty coffee can has one end that is open and one that is closed. Punch or drill a hole through the side of the can near the closed end. A couple of holes the size of a pencil would be good. Dip the open end of the can into the bubble solution. A film of bubble solution should cover the opening. Use the pipette to place a drop of oil in the center of the film of bubble solution. Place another drop on the film off center. Watch what happens. Why do the drops attract each other? Experiment with placing the drops in different ways. Can you create a drop that orbits another drop?

An alternative to this experiment can be done with a trash bag slit to make a single layer of plastic anchored between tables with various balls placed on its surface or if you have a trampoline it can serve nicely as a model universe.

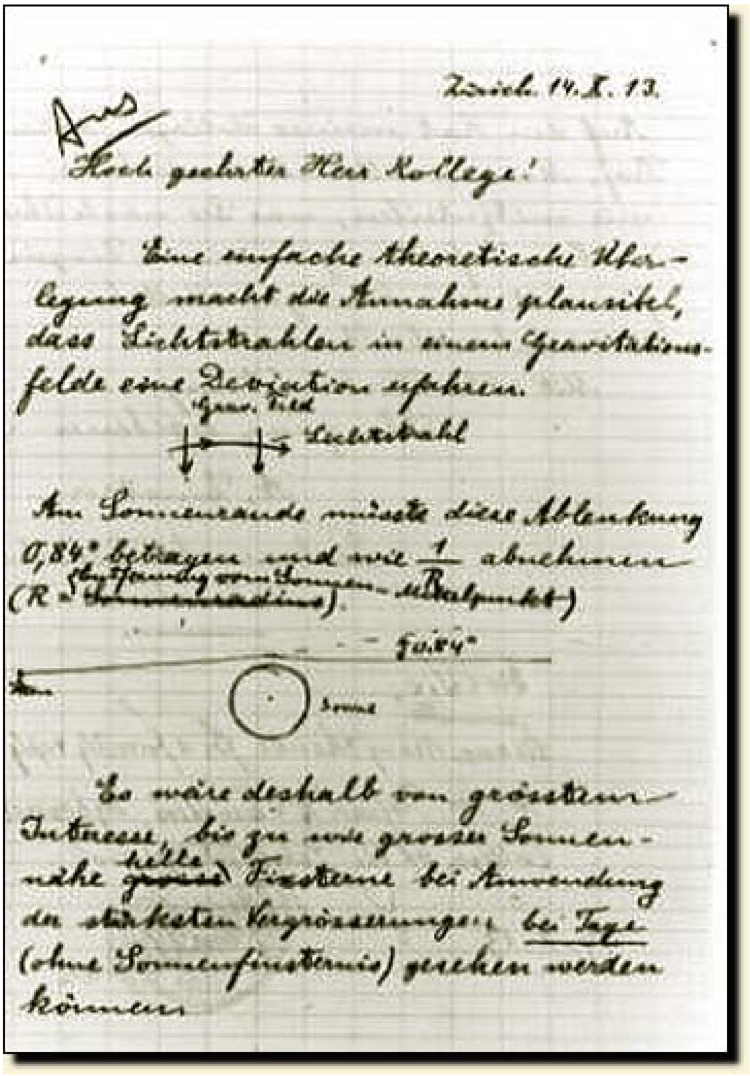
OK—I'm through playing with oil drops on a soap film. Remind me how that experiment models general relativity and the warping of space and time.

The film represented space (or at least two dimensions of it). The oil drop was modeling a massive star. The drop's mass bent the space (bubble film) around it. When another drop was placed nearby, it felt "attracted" to the first one because it just slid downhill to it. The first drop didn't reach out and grab the second drop, instead it created a bend in space that affected the motion of the second drop. With a little practice you can easily create two small drops orbiting a larger drop similar to planets orbiting the Sun.

And what about time?

It doesn't really model that part. But it should help you see how mass can bend the space around it. It turns out time is just another dimension. There are three dimensions of space and one of time in our normal everyday world. When you are in class you are separated from the people to either side, in front and behind you, and in the classroom above you (assuming there's a floor above you) by three dimensions of space. You are separated from the person who uses your desk next by a period by time. In his work on general relativity, Einstein's mathematics led him to believe mass distorted space and time.

I'm a science student. I want some evidence. Does this really happen?



Zürich. 14. X. 13.

Ans

Hoch geehrter Herr Kollege!

Eine einfache theoretische Überlegung macht die Annahme plausibel, dass Lichtstrahlen in einem Gravitationsfelde eine Deviation erfahren.

Grav. Feld

Lichtstrahl

Am Sonnenrande müsste diese Ablenkung 0,84" betragen und wie $\frac{1}{R}$ abnehmen (R = ~~Sonnenradius~~ Entfernung vom Sonnen-Mittelpunkt).

0,84"

Sonne

Es wäre deshalb von grösstem Interesse, bis zu wie grosser Sonnennähe ~~grosse~~ helle Fixsterne bei Anwendung der stärksten Vergrösserungen bei Tage (ohne Sonnenfinsternis) gesehen werden können.

Figure 2.8: Einstein's letter shows how to look for mass bending light during a solar eclipse. (3)

Remarkable claims demand remarkable evidence. Einstein knew that others would be skeptical—it is the nature of science! He even offered a few ways for others to test his ideas. One test he suggested was to look at Mercury's orbit. It is so close to the Sun that the way the Sun warps space around it should affect Mercury's orbit. General relativity correctly accounted for some motions of Mercury that were known and could not be explained by Newtonian gravitation. He also suggested utilizing a total eclipse of the Sun to see if the positions of stars located behind the Sun would appear to be shifted because their light had to pass so close to our massive Sun.

In 1919 the first attempts were made at making these measurements. These results were inconclusive but subsequent measurements during an eclipse in 1922 matched wonderfully with Einstein's predictions. This science was newsworthy in 1919.

Cool. Did general relativity predict any other interesting astronomical occurrences?

Boy, it certainly did. It was so amazing that Einstein didn't believe it himself! His mathematics indicated that something was totally wrong according to what was held to be true at that time. It was so remarkable that Einstein introduced a "constant" to get rid of it and to make the mathematics fit the "known" reality.

What was it? What did it indicate?

General relativity showed that the universe should either be expanding or contracting—that it could not simply "be." It could not exist in a static manner.

But I thought that the universe is expanding—at least I think I've heard that.

Right. But in the first half of the 20*th* century that is NOT what scientists held to be true. Many religions have a moment of creation as part of their theology. The scientific community of the early 1900s did not share that paradigm. The widely held scientific view of the universe was very different from what it is today in many ways. One substantial way it was different was that most scientists believed that the universe was and always had been very much the way it was seen to be at that time.

And how was it "seen to be" at that time?

All the stars that you can see with the naked eye in the clearest, darkest night sky are part of our Milky Way galaxy. In fact, the terms *Milky Way* and *galaxy* represented the same celestial bodies in the late 1800s. In fact, even if you have a really nice backyard telescope, all of the stars you can see belong to the Milky Way galaxy. In the mid-1800s that was the extent of our knowledge. Astronomers of the time would have referred to "the galaxy" and the faint glow of it in our sky as "the Milky Way." What we now call our galaxy was considered to be the entire universe. There were a few interesting non-star things in the sky known as nebulae (cloudy spots). You can see a lovely nebula in the constellation Orion in the three stars that make his sword. You can also see a much smaller (smaller in appearance from Earth that is) nebula in the constellation Andromeda known then as the Andromeda nebula.

I thought that was called the Andromeda galaxy.

It is now. In the late 1800s some very large telescopes were created. When astronomers looked at some nebulae like the Andromeda nebula and the Whirlpool nebula, they were able to observe individual stars. Because such large telescopes were needed to resolve these into individual stars, it meant that these stars were VERY far away. Examining other nebula like the Orion nebula showed they were truly wisps of glowing and reflecting gas. We also made observations of our own galaxy that led us to understand that we actually exist in a flattened out collection of stars. At this point, we then realized that the universe was MUCH larger than our own cluster of stars and actually contained many far-flung collections of stars. The term *galaxy* was eventually re-tooled to describe the isolated large clusters of stars and the word *universe* came to mean all of the known space including these island galaxies.

The term *Milky Way* came to be the name of our galaxy. So three terms—*Milky Way*, *galaxy*, and *universe*, which were originally synonymous, came to mean three different things as our understanding of the structures

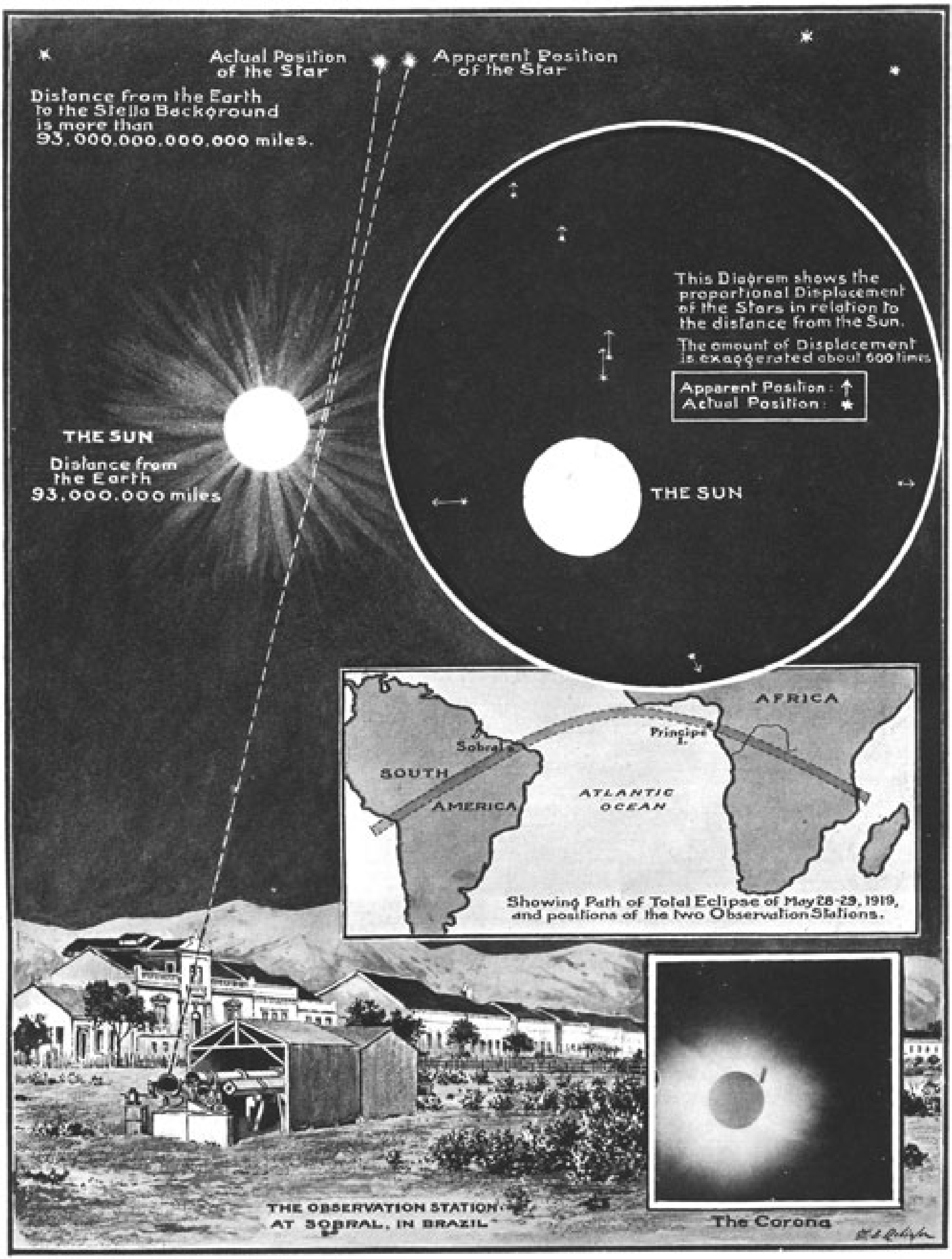


Figure 2.9: The 1919 Illustrated *London News* explains the science of the day—verification of aspects of Einstein's general theory of relativity by British astronomer Arthur Eddington. (7)

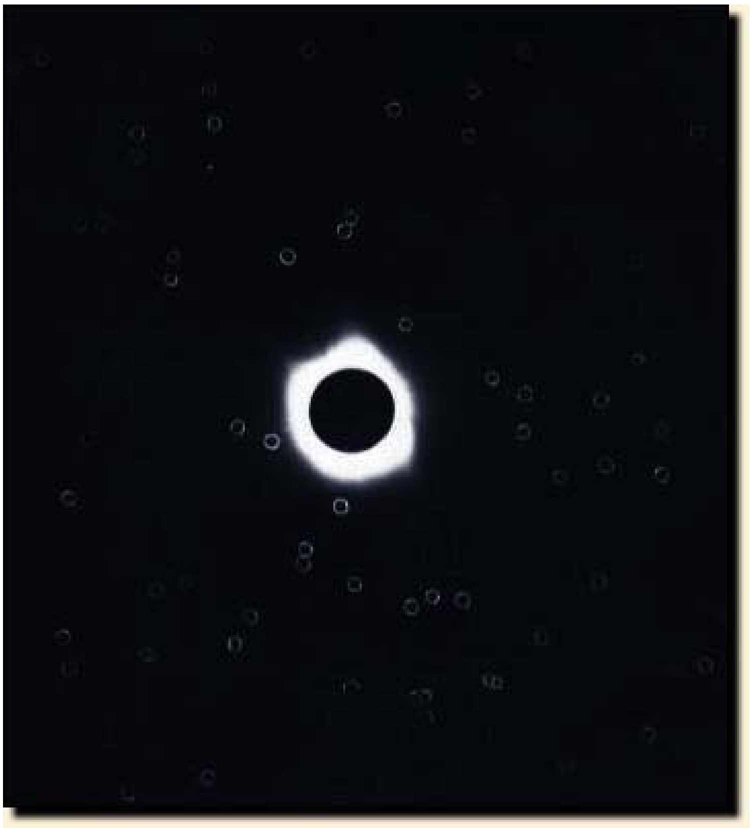


Figure 2.10: The 1919 Solar eclipse. The small white circles were drawn around stars visible during this 1919 solar eclipse. (10)

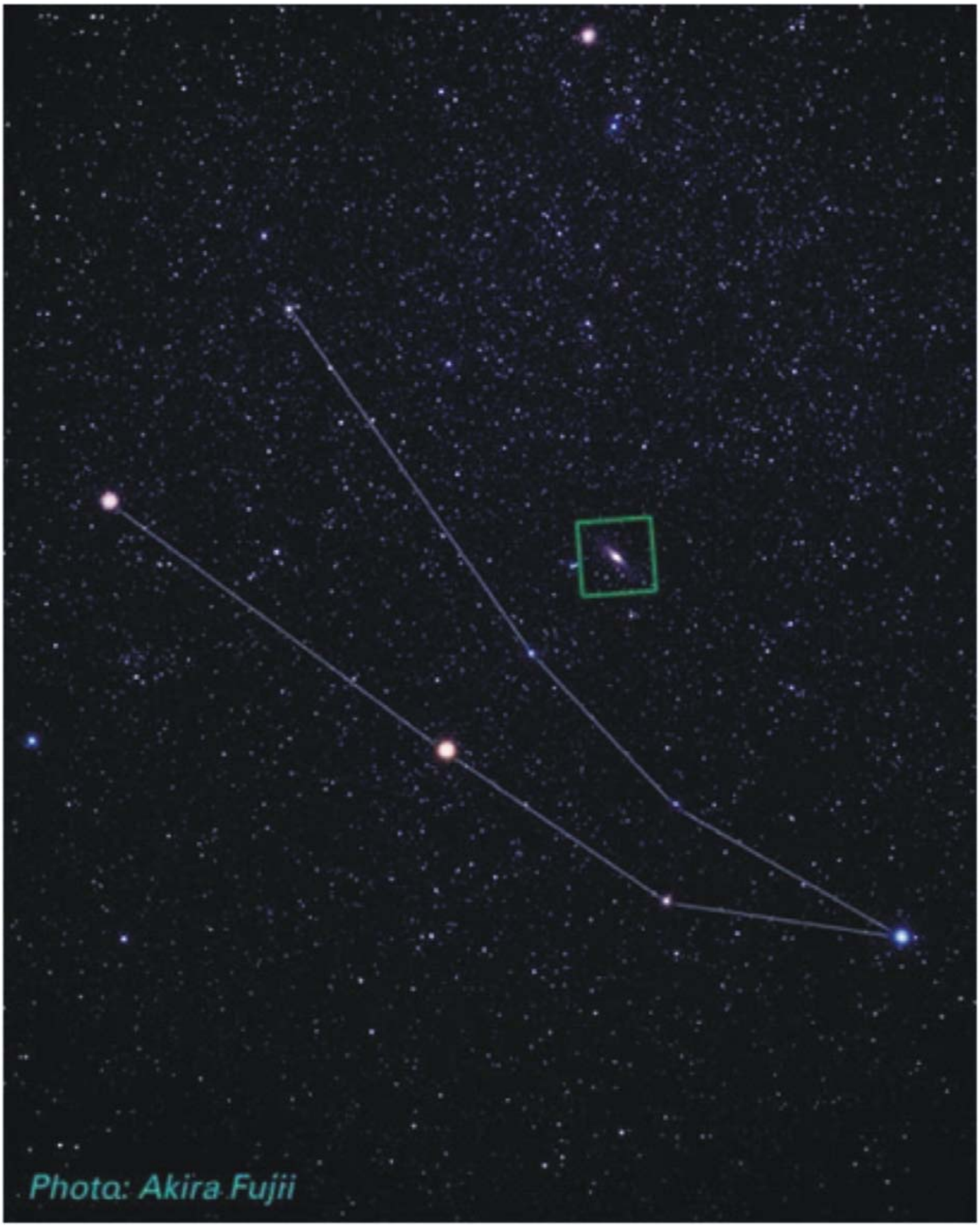


Figure 2.11: On a very dark night the Andromeda galaxy (in green box) is barely visible to the naked eye in the constellation Andromeda. It is the only object visible with the naked eye in the northern hemisphere that is not within the Milky Way galaxy. (5)

in space evolved from the late 1800s into the 1920s. A galaxy is a collection of billions of stars held together by mutual gravitation, the Milky Way is our galaxy, and the universe is ALL of it with some 100 billion individual galaxies each containing billions of stars.

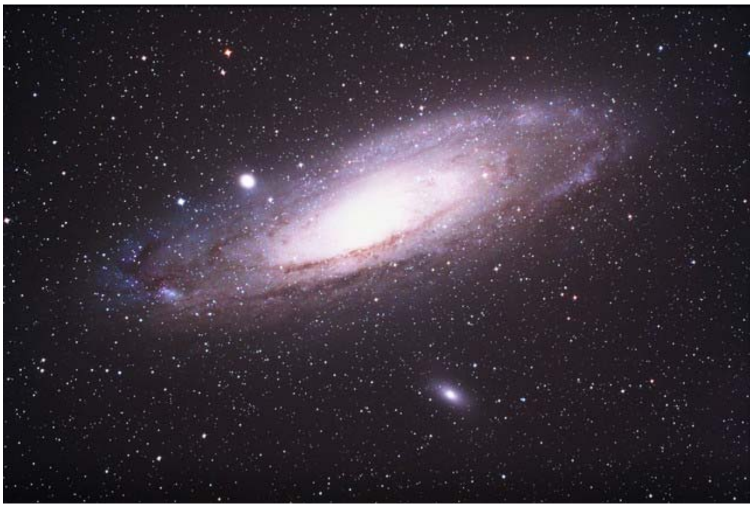


Figure 2.12: Photographed through a large telescope using a long exposure the spiral structure of the Andromeda galaxy becomes apparent. (11)

So the universe is a lot bigger than we thought, and it contains lots of galaxies. But what does this have to do with gravity?

In the early to mid–1900s, astronomers turned their attention to these very distant galaxies to try to determine how big the universe was. There is some very interesting history of astronomy that I'm going to have to leave out. These amazing details are provided at `http://cosmictimes.gsfc.nasa.gov/1929/guide/andromeda_farther.html`. The full story involves some fascinating discoveries and early contributions of women in astronomy. The end result is often attributed to Edwin Hubble. One major physics concept that played a key role in Hubble's discovery, as well as later work regarding our universe and galaxies, is the Doppler effect.

I think I've heard of that, but can you review for me?

Sure. The standard example is what you observe when a train is coming toward you blowing its horn. As the train approaches, the frequency of the sound you hear is transformed to a higher pitch by the train's motion. As the train passes you, the sound of the horn will drop to a lower pitch as it travels away from you. If you don't have a speeding train nearby, just tune your TV to a NASCAR race. When the coverage cuts to the camera stationed right down along the track you will hear a change. The sound that the engines make shifts frequency as the engines pass the camera. The sound shifts from a high-pitched whine to a deep roar. As the cars race toward you (the camera) the pitch is shifted to a higher frequency. When the car then moves away from you it is shifted to a lower frequency. A microphone riding alongside the car would hear a frequency in between the two. This is a noticeable effect because the speed of the observer is a significant fraction of the the speed of the sound. As the car rushes toward you, the vibrations causing the roar of the engine are occurring closer and closer to you and thus taking less time to travel to you. Therefore, they arrive at your ears with less time between them, which makes the pitch higher. Of course, the similar argument applies to the car moving away from you. A more detailed explanation can be found at the Physics Classroom, `http://www.glenbrook.k12.il.us/GBSSCI/PHYS/Class/waves/u10l3d.html`. This is known as the "Doppler effect," and applies to all waves, including electromagnetic waves such as light. We do not observe the Doppler effect with light in every day life because the speeds of the observer and source are a very small fraction of the speed of light.

And a much more detailed explanation with history and mathematics can be found at `http://www.phy6.org/stargaze/Sun4Adop2.htm`.

What Hubble concluded from his work and the work of others was that the light arriving from distant galaxies had been *Doppler shifted*. It had been shifted toward the red end of the spectrum, which meant the galaxies were moving away from us (or vice versa) at speeds that are significant compared to the speed of the wave—which in this case is the speed of light! Note, though, that this does not mean that the Earth is at the center of the universe. Imagine the universe as a bread pudding with the raisins representing the galaxies, and pick any raisin to represent our galaxy. As the pudding expands, the distance between the raisin you picked and any other raisin increases just as distant galaxies move away from us. This shows that the observed expansion of the universe does not imply that the milky way is at its center.

What he determined was the more distant the galaxy was, the faster it was moving away from us. Every direction he pointed the giant Mount Wilson telescope, every distant galaxy was moving away from us. The conclusion: The universe is expanding!

Figure 2.13: Edwin Hubble's research showed the Milky Way was one of billions of galaxies and that the universe is expanding. (9)

That's what Einstein's general theory of relativity predicted!

Good, I see that you've been paying attention. But, at that time it was such a radical departure from what was "known" to be true, that even Einstein couldn't believe what his own work was telling him. In hindsight, it makes perfect sense. Here on Earth you can throw a ball up in the air. Because it's under the influence of gravity it can either be moving upward and slowing down or it can be moving downward and speeding up. The one thing it can't do is just sit in the air without accelerating. The same thing is true of the universe. Since all the galaxies are pulling on each other with gravity it makes sense that it could either be collapsing in on itself and speeding up as it does so, or expanding outward but slowing its rate of expansion due to gravity trying to pull it all together. Once Hubble's data and conclusions were presented, Einstein proclaimed the addition of the stabilizing constant his biggest mistake.

This is the big bang, right?

Correct again. If the universe is expanding today, it had to be a bit smaller yesterday. Play the film backwards in your mind, and eventually the universe had a beginning and took up no space at all. Run it forward in time and you have the Big Bang—the creation of the universe. You'll understand, of course, that such a major shift in the understanding of the universe doesn't happen easily or overnight. There were many very bright scientists who tried very hard to argue that the universe wasn't truly expanding. One prominent astronomer, Fred Hoyle, was still arguing against the possibility in the 1950s when he used the term "big bang" to ridicule the concept that the universe had a beginning and was presently expanding. The name stuck, but unfortunately it is somewhat misleading.

How so?

A "big bang" sounds like a loud explosion. Of course, in space there is no sound. Also, an explosion, like a stick of dynamite in a rock quarry, throws energy and matter out into space. The big bang did not throw energy and matter out into space. It is the creation OF space and time and eventually matter condensed out of the energy (but that is "matter" for another chapter!).

So if the universe is expanding, what's it expanding into?

Nothing. It is creating more space and time. It's no more or less confusing than to ask where does the time for tomorrow come from. It doesn't exist today, but by the end of tomorrow there will have been one more day in the life of the universe. The dimension of time expanded.

Is there other evidence for the big bang besides Hubble's receding galaxies?

Lots of evidence. Because the idea of the big bang assumes the universe started very small it also started off with immense heat and energy. Because it has not been expanding for an infinite amount of time, there should be some remnants of that energy left over in empty space. In the mid-1960s Arno Penzias and Robert Wilson were working for Bell Laboratories with microwave communication. While doing this work they accidentally discovered that no matter where they aimed their microwave receiver they received a constant background static. It was determined that this signal came from the leftover energy from the big bang and is called *background cosmic radiation.* This cosmic microwave background radiation (CMBR) tells us the temperature of space is about 2.7 Kelvin. This level of background radiation had been predicted earlier by George Gamow. It is always a great test of theory to PREDICT something and then later find out that it really exists! Another case of this occurred in the findings of the Cosmic Background Explorer (COBE) satellite. It was launched in 1989 to look for variations in the background radiation. Earlier examinations from Earth showed the CMBR to be very constant in every direction. This fit the theory, but it couldn't be perfectly constant or there wouldn't be clumps of matter (galaxies and stars) like we have now. COBE mapped the entire sky looking for minute variations in the CMBR and found exactly what theories predicted should be there—variations of about one part in $100,000$.

Another piece of evidence that should be mentioned is that the general theory of relativity indicates there should be expansion.

OR Contraction.

Correct. If the ball can be thrown up, it can fall back down. Does this analogy extend to the universe? This is a question still being debated. If the universe could contract then we already have a name for it—the big crunch. There are those that believe this is a possibility and if it is then the universe would be right back where it started and could perhaps have a big bang again. Others believe the mathematics shows the big bang to be a singular event. However, recent findings make the notion of a big crunch even less likely.

What findings?

In 1998 it was discovered that not only is the universe expanding but the rate of expansion is accelerating. That is very exciting and odd. If we return to the analogy of throwing the ball upward, the ball is not only moving upward but it is picking up speed! For the ball to do this, there must be some force continuing to push it upward. The same idea applies to the universe. This force is known as dark energy or Einstein's cosmological constant and it must be pushing "outward" to cause the universe to accelerate its expansion.

So Einstein was wrong when he thought he made a mistake?

Maybe. But you should recognize he didn't add the constant to address acceleration of expansion. He added the constant to push out against gravity to create a static universe—a form of the universe that clearly doesn't exist.

So, does dark energy exist?

It's an idea with lots of support. But it does have its problems. It's not supported or predicted by any bigger theory. It has not been detected in any direct way and it has to make up the majority of the energy in our universe! On the other hand, something has to be causing the accelerated expansion of the universe. So until something better comes along, dark energy is a favorite.

We've come a long way. Can you summarize things up to this point?

I'll try. Gravity is a force of attraction between masses. We can describe it very well mathematically with Newton's universal law of gravitation. The universal gravitation constant, G, in the equation is one of the fundamental constants in physics and one of the least well known. Einstein's general theory of relativity explains how gravity is a warping of the fabric of space–time and also predicts an expanding or contracting universe. The outwardly pushing cosmological constant he added to maintain a static universe may indeed be real and an expression of dark energy, which is causing the universe to accelerate its expansion. There is experimental support for the general theory of relativity and the big bang but currently there is no independent evidence for dark energy.

Universal gravitation and general theory of relativity can explain planets orbiting, an expanding universe, spiral galaxies, rocks falling to the ground, my weight, and lots of other things, not just the accelerating expansion of the universe.

Well, there is a problem with the spiral galaxies. They don't behave quite the way universal gravitation predicts they should and it doesn't seem to be explained by Einstein's work either.

Maybe it's dark energy again.

Good guess, but probably not. The most accepted answer is Dark Matter, but let me explain the problem first before we jump to an answer. Here is a picture of the Whirlpool galaxy. It was one of the first galaxies in which scientists resolved individual stars and led us to realize how vast our universe was. Newton's laws and Kepler's laws of planetary motion should apply to stars in the galaxy orbiting around the massive center (the bright core in the middle) of the galaxy. Remember Kepler's laws of planetary motion tell us that planets far from the center should take longer to go around the core than planets near the center. This is his third law: The period squared is directly proportional to the radius cubed. This means that stars far from the center take longer to go around in their orbit AND they are moving more slowly. Note, they take more time to go around because they are going a longer distance, but it's not just that. Kepler's law says they will be moving more slowly, not just take longer to go around.

In 1975 Vera Rubin determined that the vast majority of stars in several spiral galaxies were all traveling the

Figure 2.14: The Whirlpool galaxy beautifully displays its spiral nature while mysteriously hiding exactly how it spins the way it does. (15)

Figure 2.15: Vera Rubin's work in the mid–1970s provided solid observational evidence that galaxies are not moving in accordance with Kepler's laws OR possess large quantities of dark matter. (14)

SAME speed regardless of their distance from the galactic core. This observation means one of two things: Either the stars are not obeying Newton's laws or there is a great deal of matter fairly evenly dispersed between all the stars that we cannot see or detect other than through its gravitational interaction with the visible stars. This matter is not just dust and planets (often referred to as dim matter). Calculations show that in many cases that matter needs to be $50 - 75$ percent of the total mass of the spiral galaxies to account for their orbital mechanics. Interestingly, not all galaxies seem to have the same mix of dark matter to normal matter. Some have hardly any dark matter while some may be made of nearly entirely dark matter.

So dark matter really exists?

It's very similar to dark energy in that respect. The vast majority of astronomers and physicists accept that it is probable but are really anxious to see some more supporting data, unification with other theories, and explanations of its nature.

Dark matter to keep the galaxies spinning right, and dark energy to account for the acceleration of expansion of the universe. Sounds like they're just making this stuff up to account for what they can't explain with "normal" physics.

Precisely! This is the way physics often works. First, observe a phenomenon you can't explain. Second, come up with an explanation. Sometimes the explanation involves things that are already understood and when things get really exciting it involves things no one has ever thought of! Then physicists around the world try to make observations, do experiments, or deal with the mathematics to either lend independent support to or tear down the new idea. Since dark energy is only going into its second decade and dark matter is only working on its fourth, these ideas are in the stage where people are looking for evidence to prove them wrong or for evidence to support them.

Oh, now I have lots of questions. You said often.

Right. The other way physics often works is now that we have these two relatively new ideas, physicists and astronomers are actively looking for things these theories *predict.* Sure these two phenomena were made up to describe things we already saw and couldn't explain. But does the presence of dark matter and dark energy predict things we haven't seen that we can go look for?

Like the general theory of relativity predicted light would be bent by the curvature of space near our Sun!

Right again. Finding this prediction to be true provided support for other claims of the theory.

What will it take to prove that dark matter and dark energy are correct?

It will never be proven correct. Bending of light didn't "prove" General Relativity correct, it just provided support for the theory. No amount of data, observations and calculations will prove a scientific theory or law to be true. The more data, observations and supporting calculations we have, the more trust we may have in a particular idea and the more we may build upon it. However, it only takes ONE observation of a fact that DOESN'T support the law or theory to send physicists scurrying for a new idea or adjustment to the old one.

Didn't Vera Rubin's observation of the way galaxies were spinning and the 1998 observation of the acceleration of the expansion of the universe show that the physics we were using was wrong?

That would be one view. If you go back to the page with the picture of Dr. Rubin, you will see that I said *"Either the stars are not obeying Newton's laws or there is a great deal of matter fairly evenly dispersed between all the stars that we cannot see or detect other than through its gravitational interaction with the visible stars."* You see there are really two choices—come up with a new idea or make adjustments to the old one. In the case of dark matter you either need a lot of rather mysterious matter that doesn't glow with any type of electromagnetic wave (radio, $x-$ray, visible light) or block any type of electromagnetic wave, OR you need to adjust other accepted laws of physics. The vast majority of astronomers and physicists have chosen to opt for the mysterious dark matter.

The majority. So there are those out there who don't?

Correct. There is ongoing scientific debate on whether string theory does or does not predict dark matter, but I won't attempt to (nor am I capable of) explain string theory. However, there are at least two alternate views regarding issues related to gravitation that have received some support and are, at the very least, interesting to examine. MOND is a concept that illustrates a minority view in a very interesting and understandable manner. MOND stands for modification of newtonian dynamics. Developed by Mordehai Milgrom, this theory adjusts Newton's laws of motion to match observation of the way galaxies spin. This is in contrast to assuming there is an abundance of Dark Matter so the dynamics match Newton's laws. An excellent article by Dr. Milgrom explaining the idea of MOND may be found at `http://www.astro.umd.edu/~ssm/mond/sad0802Milg6p.pdf`.

I'll go read the article, but what does MOND actually say?

Do go read the article, but essentially what MOND does is claim that when acceleration is less than some minimum value then the force on an object is no longer equal to mass times acceleration (Newton's second law) but equal to mass times acceleration *squared*. Making this assumption allows many things (not all, mind you) to work correctly without the need for dark matter.

And you said "at least two alternate views"?

John Moffat of the University of Toronto has proposed a "Non-Symmetric Gravitational Theory." Here Newtonian dynamics is left unchanged, but general relativity is altered from the way Einstein had it. If non-symmetrical gravitation theory is true it also avoids dark matter and accounts for the galactic rotation curves. Dr. Moffat's book *Reinventing Gravity* explains this at a popular level that you might find interesting to read.

All right then. We either need dark matter, MOND, non-symmetric gravitation, or something else for explaining certain phenomenon, like the mechanics of spiral galaxies and dark energy or something else to explain the accelerating expansion of the universe. I'll wait and see which idea(s) come out on top.

Wonderful, me too. And remember, it won't be that one gets proven correct, it will simply be that one theory is capable of explaining more phenomena and is supported by more observations.

I hesitate to ask this, but what else is being searched for related to gravitation?

Well, since you asked....In 1918 Einstein predicted that when massive objects (neutron stars, quark stars, black holes, supernova) explode, spin, or collide they should create ripples through the space-time fabric. These ripples are dubbed "gravity waves." As of yet, physicists have had no luck in finding them. Once we do find them (if they exist) it is reasonable to assume they would carry information with them about the object that generated them. NASA will soon (hopefully!) be launching LISA to search for these gravity waves. You can check out `http://lisa.nasa.gov/` for all the details of how LISA will accomplish this and what it hopes to discover. Meanwhile, here on Earth, LIGO is looking for the same phenomenon. Details regarding LIGO can be found at `http://www.ligo.caltech.edu/`.

The other holy grail related to gravitation is the graviton. The graviton is the hypothetical particle that may "carry" the force of gravity. This is in the same sense that the photon is the particle that transmits electromagnetic radiation. In many sources you will see the word "mediate"—the graviton would *mediate* the force of gravity. It seems that actually detecting a graviton will be far in our future if indeed it is ever possible. Detection and analysis of gravity waves may eventually allow more concrete knowledge of whether gravitons actually exist or not.

Now I'd like to suggest some activities or assignments for you to do to assess your understand-

ing of portions of the content of this chapter.

1. Create two ellipses in the manner described at the beginning of this chapter and use them to describe and explain Kepler's laws of planetary motion.
2. Explain why Newton's universal law of gravitation is a law and not a theory or hypothesis.
3. Go to `http://imagine.gsfc.nasa.gov/docs/science/know_l1/dark_matter.html` and read about dark matter. Read the article regarding MOND linked earlier in this chapter. Write an essay explaining which theory you believe is most likely to be found valid.
4. Create the coffee-can-and-soap-film universe explained in this chapter. Describe the experiments you were able to conduct and explain how this models aspects of the general theory of relativity. Explain in what ways this is NOT a good model of Einstein's notion of gravitation.
5. Go to `http://cosmictimes.gsfc.nasa.gov/1929/guide/andromeda_farther.html` and read the details of what preceded Hubble's determination that distant galaxies are receding from us. Click on the link at the bottom regarding Harvard's Computers and read the four biographies. Create a timeline showing the discoveries in these five different articles that lead to an understanding of an expanding universe. In your own words, explain the role that women played in uncovering the big bang.

2.3 Virginia Physics Standards of Learning

This chapter fulfills sections PH.1, PH.3, PH.4, PH.12 of the Virginia Physics Curriculum. (16)

Sources

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(14) Unknown. *Vera Rubin*. Public Domain.

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(16) `http://www.doe.virginia.gov/VDOE/Instruction/Science/ScienceCF-PH.pdf`