

Dark Gravity – What is it?

*“Over, under, sideways, down, backwards, forwards, square and round” -
The Yardbirds*

Why Dark Gravity?

By dark gravity, I am referring to the limitations in our knowledge about gravity and space-time, rather than to a particle or energy field as in the case of dark matter and dark energy. Gravity is exceptionally weak in comparison to the other 3 forces, and gravitons remain undetected to date. Although Einstein’s theory of general relativity has been revolutionary in developing our understanding of gravity, and has been extremely successful observationally, it remains a *classical* theory. It appears to apply everywhere on large scales, but does not address the smallest physical scales or highest energies. That is, there is no proven quantum theory of gravity, although many attempts are underway to construct one. It is expected that there is a force carrier particle for gravity, known as the graviton. The graviton is expected to have zero mass and have a spin of 2 (the photon is also massless, but has a spin of 1.) But the graviton has not yet been observed.

Gravity is much, much weaker than the other 3 forces of nature (the electromagnetic force, the strong nuclear force, and the weak nuclear force.) This may seem counter-experiential, but it is true. The reason we experience gravity as significant is that the Earth’s mass is very large. But even a small magnet can overcome the force of gravity and pick up an object. Most matter is very close to neutral so the electromagnetic forces are shielded away. But whenever you pick something up you are overcoming gravity basically with electromagnetic forces that are the source of the chemical energy that moves your hand and allows you to grasp the object.

Dark matter and dark energy appear to be real and found throughout the universe and the relative amounts of these two quantities are measured. In contrast, dark gravity is a concept that reflects our incomplete knowledge at present of the underlying reality of space-time and gravity.

The Standard Model of Particle Physics

The Standard Model provides a framework for the known particles and the 3 known forces with quantum descriptions – electromagnetism, the strong force and the weak force.

Three Generations of Matter (Fermions)

	I	II	III	
mass →	2.4 MeV	1.27 GeV	171.2 GeV	0
charge →	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	0
spin →	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
name →	u up	c charm	t top	γ photon
Quarks	4.8 MeV	104 MeV	4.2 GeV	0
	$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$	0
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
	d down	s strange	b bottom	g gluon
Leptons	< 2.2 eV	< 0.17 MeV	< 15.5 MeV	91.2 GeV
	0	0	0	0
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	Z weak force
	0.511 MeV	105.7 MeV	1.777 GeV	80.4 GeV
	-1	-1	-1	± 1
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
	e electron	μ muon	τ tau	W[±] weak force
				Bosons (Forces)

Figure 1. The Standard Model for elementary particles. Quarks are in the upper part of the chart, leptons are in the lower part, and the force carrier particles are in the rightmost column. The graviton is not part of the Standard Model. Credits: Fermilab, Office of Science, United States Department of Energy, PBS Nova, MissMJ

All particles have certain fixed quantities, such as their rest masses, their charges, their spins etc. Charges are in units of the electron and proton charge that are -1 and +1, respectively. While the electron is seen as fundamental, protons and neutrons are known to consist of triplets of up quarks and down quarks, which have charges of $\frac{2}{3}$ or $-\frac{1}{3}$, respectively*. The proton, for example, is composed of two up quarks and a down quark, which equates to a charge of +1. The neutron is composed of one up quark and two down quarks, resulting in a charge of 0.

In addition to matter particles, there are several particles known as force carrier particles. For the electromagnetic force, the zero mass, spin +1 photon is the carrier. For the weak force, three particles are involved, the W^+ , the W^- and the Z. These particles have mass, unlike the force carrier

* This is of course an arbitrary human definition. Had we known about quarks before protons and electrons, we probably would have defined up quarks as having a charge of 2 units, down quarks as having charge equal to -1, and protons and electrons as +3 and -3 respectively. That is, the charge unit would have been defined by the quark rather than the proton and electron.

particles for the strong force. There are 8 particles that act as force carriers for the strong force; these are collectively known as gluons.

There is also expected to be a force carrier for gravity, known as the graviton, which is believed to be massless and have a spin of 2. It remains undetected, and is not part of the Standard Model.

The Standard Model has been extended with a theory known as supersymmetry that postulates additional particles which are partners to the known particles, but that have greater masses. For example, the spin $\frac{1}{2}$ electron would have a partner with spin 1, known as the selectron. None of these putative supersymmetric particles have been observed; but they may be detected at higher masses (energies) with the Large Hadron Collider particle accelerator. One of the most likely candidates for dark matter is the lightest supersymmetric particle. It is predicted to be highly stable and weakly interacting (interacting through only gravity and the weak force.)

While symmetry is generally considered beautiful, it is in fact the breaking of symmetry that allows for our interesting universe. If everything were symmetric at all times then there would be perhaps only one force and only one particle type. Stars, planets and humans certainly wouldn't be around. Symmetry breaking is a very important principle in physics and is key to the inflationary phase of the Big Bang and many other important aspects of the evolution of the universe.

Supergravity

Supergravity was first proposed in 1976 by Freedman, Nieuwenhuizen and Ferrara. It is a unification of supersymmetry (on localized scales) and gravity (general relativity) formulated in 4-dimensional space-time. It is possible to formulate supergravity theories in higher dimensions as well. There are certain intriguing connections to string theory, such as an 11-dimensional supergravity which is the largest dimensionality that can have a single species of graviton. A space with 11 dimensions is favored by string theory as well, and it has been proven by Witten that 11 dimensions is the *minimum* number to contain the unification of the three non-gravitational forces. One major problem with supergravity is that it appears to require a very large cosmological constant (dark energy), in contrast with what is observed.

Modifications to General Relativity

Some physicists, including Bekenstein in particular, have proposed modifications to general relativity, which is a tensor theory in 4-dimensional space-time. The elements of the tensor define how the space-time metric is curved by the presence of mass and energy. Proposed

modifications include adding scalar and/or vector field terms to the equations that may modify the behavior of gravity at very large scales. Other theories modifying general relativity, such as those known as $f(R)$, predict a time-varying gravitational constant.

These modified gravitational theories attempt to explain the cosmological observations that have led to the requirements for dark matter and dark energy.

Observations such as galaxy clustering measures from the Sloan Digital Sky Survey provide rather strict limits on how large such departures from general relativity might be, and there is no apparent reason at this point to adopt any of these modifications. Such modifications do not address the question of how to unify gravity with quantum physics.

Loop Quantum Gravity

Loop quantum gravity starts with the realization that space and time cannot be continuous once one reaches a sufficiently small scale. The quantization of space occurs at about 10^{-33} cm, known as the Planck length. This is one billionth of one trillionth of one trillionth of a centimeter and is 20 orders of magnitude smaller than an atomic nucleus. Time is quantized at about 10^{-43} sec, which corresponds to the interval in which light can cross a Planck length.

There is a corresponding energy to this scale; it is known as the Planck energy and is around 10^{19} GeV, which is 10^{19} times greater than the rest mass energy of a proton. This is 10 billion billion times greater energy.

In loop quantum gravity (LQG) theories, space is quantized via a mathematical model known as spin networks, as outlined by Penrose. This method provides a way of building up space in chunks or tiles. Time and causality are implemented by enforcing sequencing rules in how tiles are laid down and connected. Loop quantum gravity is formulated in the normal 3 dimensions of space and one of time. Ashtekar, Rovelli and Smolin are key contributors to and proponents of LQG.

If LQG is true, then the universe may have experienced a Big Bounce from a compacted quantized state rather than a Big Bang from a singularity. LQG appears to be able to produce inflation of a type similar to the inflationary Big Bang model. There is also a way to exhibit a positive cosmological constant, playing the role of dark energy, from LQG.

LQG does not clearly explain the unification of forces such as in supersymmetry and string theories. It may be that aspects of both theories are true.

Strings and Branes

A major area of research is string theory, which seeks to unify the four forces of nature, including gravity, and to provide a quantum basis to gravity. It posits tiny one-dimensional strings as the ultimate source of matter, rather than point particles. String theory explores the nature of reality and matter all the way down to the Planck length. There is not one string theory; rather it is actually a branch of physics containing a collection of theories with a wide range of options. At energies below 10^{16} GeV, string theory can reproduce the Grand Unified Theory of the 3 quantum mechanical forces.

Different vibration modes of strings manifest themselves as various particles, just as different modes in a guitar string yield different notes. The theory has both open and closed strings (loops), and it has been extended to include sheets or membranes of 2 or more dimensions. These dimensions can be flat and rigid, or have vibration modes themselves. Typically open strings have their ends fixed to one or more membranes.

String theory is mathematically consistent only when there are many more dimensions of space than 3; it is self-consistent in 10 or 11 or even 26 dimensions, depending on how it is formulated. One of those 10 or 11 or 26 dimensions is time; 3 are our familiar spatial dimensions; and the remaining 6 or 7 or 22 would be hidden (dark) spatial dimensions which are not visible to us. Typically it is because the dimensions are rolled up to be very small, much smaller than we can detect even with our best technology*.

The 11-dimensional versions of string theory models may be more general with the 10-dimensional models representing projections (or low energy limits). This is somewhat analogous to a movie being a projection of a 3-D world onto a 2-D screen.

Membranes normally go by the short name of branes. Brane confinement is not when one is sent to a mental hospital, but instead refers to the situation when a set of particles or forces are restricted to move only within a brane. The space between branes is called the bulk. So one might have forces that are felt throughout the bulk and on one or more branes and others that are felt only within a given brane.

Models with gravity in extra dimensions

A number of models have been built that are informed by the developments in string theory, but that do not require a complete string

* It is conceivable that one or more dimensions would be small but still detectable. Experiments are underway to look for deviations in the strength of gravity at relatively small scales, but still larger than the atomic scale.

theory treatment. These include models by Randall and others wherein branes are postulated to exist within a bulk, which has higher dimensions.

One illustrative model has 2 branes. The first brane could be our 4-dimensional universe, on which familiar matter and the 3 nongravitational forces would be confined. Gravity would be centered perhaps on a second brane and permeate throughout the bulk as well. In fact it would reach to the other brane – our world, but it would be much much weaker than on its home brane.

The strength of gravity on its home brane would be comparable to the strength of the other 3 forces on our brane. But it would fall off in strength very rapidly – exponentially – with distance from its home brane. Thus the strength on our brane could be the requisite 36 or so orders of magnitude lower.

2 Branes and the Bulk

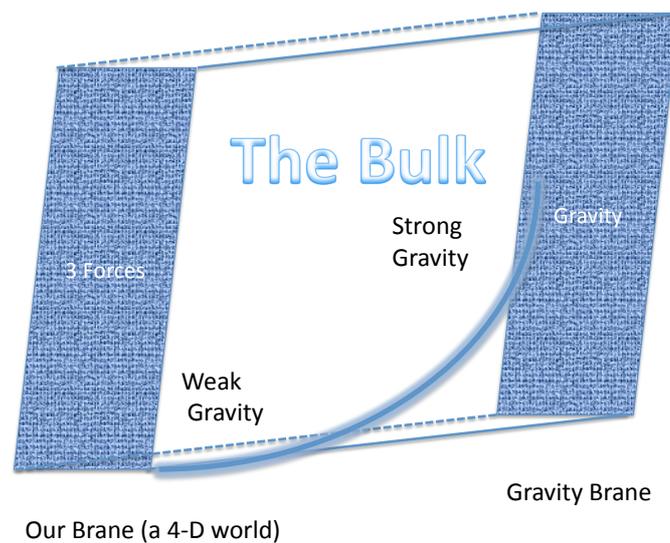


Figure 2 – Our brane, a gravity brane, and the bulk. Our brane, a 4-D world, is on the left, and a second brane, on the right, is separated from ours in an extra dimension (fifth dimension.) Gravity is very strong on the second brane, and its force extends through the bulk but weakens with distance in an exponential fashion. At our brane, it is much, much weaker.

Summary

There is much that we do not yet understand about gravity, despite the great success of general relativity. In order to unify physics between the 3 quantum forces and the *classical* theory of gravity, theories such as

supersymmetry, supergravity, quantum loop gravity and string theories are being developed. There is general support for the existence of a particle known as the graviton, the force carrier for gravity, that has spin 2, and zero mass. It is thought that if a massless, spin 2 particle is found, then it will be the graviton. The search for single gravitons with current technology is a hopeless endeavor, however.

In string theory, gravitons and gravity are not bound to branes, which may well be the explanation for why gravity is so much weaker than the 3 other forces, which are confined to the brane on which our observable universe lives.

Currently the experimental focus is on detecting new heavier particles with the LHC to probe supersymmetry and string theories. Also there are searches underway for gravity waves, which are coherent states of many gravitons. Gravity waves should be efficiently generated around black holes and neutron stars. One example is the LIGO gravity wave experiment that has detectors in both Washington state and Louisiana. In addition, LQG makes predictions about time delays in gamma ray propagation from very distant sources due to the 'quantum foam' structure of space. Observations have begun but are inconclusive to date.

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Glossary

Bulk – The higher dimensional space in which branes and strings are embedded.

Brane – A membrane in 2 or more dimensions; these are objects from string theory. Open strings must end on a membrane. The vibrational modes of branes, like those of strings, will give rise to fundamental particles.

c – The speed of light in a vacuum.

Dimensions – We perceive that we live in a world with 3 spatial dimensions and 1 dimension of time. Dimensions are mathematically orthogonal or independent from one another and may have a flat or curved topology. Extra dimensions may be present and yet be too small or too warped for us to observe.

GeV – A giga-electron Volt, or one billion electron Volts. A single electron Volt is the energy required to move a single electron through a potential of one Volt. As a convention, particle rest masses are typically stated in GeV units (the energy equivalent of their rest mass $\times c^2$). The proton has a rest mass of .938 GeV (really .938 GeV/c²).

General Relativity – The theory of gravity, due to Einstein, that states that the presence of mass causes space to curve, and the curvature of space determines the way in which masses move.

Grand Unified Theory (GUT) – The theory which unifies the 3 quantum mechanical forces including electromagnetism and the strong and weak forces. GUT is part of the Standard Model. Gravity is not included in GUT.

Graviton – A massless spin 2 particle that mediates the gravitational force. Gravitons remain undetected but have a very strong theoretical basis.

Gravity – The weakest of the 4 forces by far, gravity is felt between all objects with either mass or energy, according to general relativity.

Large Hadron Collider (LHC) – The world's most powerful particle accelerator, located at CERN outside of Geneva, and recently entered into production.

LIGO – The Laser Interferometer Gravity wave Observatory, operated by Caltech and MIT, has two sites in Washington State and one in Louisiana.

With multiple sites false signals (e.g. due to earthquakes) can be rejected. Each site has two 'arms' perpendicular to each other, and each arm of substantial length has mirrors at both ends between which laser light is reflected repeatedly in order to measure the distance very precisely. If a gravity wave passes through the detectors then the distance between the mirrors will change slightly.

Membrane – See Brane.

Order of magnitude – A factor of 10. One hundred is two orders of magnitude larger than one. One million is six orders of magnitude larger than one.

Particle – In physics a fundamental particle is indivisible and assumed to be point-like. It has certain defined properties such as charge and rest mass and interacts with other particles through one or more of the physical forces.

Quantum theory – A theory in which particles have defined discrete values for charge, spin, etc. and they also have given rest masses (either zero or positive.) There are also rules governing how they interact and transition between different energy states or decay into other particles.

String – A very tiny open or closed loop whose vibration modes manifest themselves as different fundamental particles.

Symmetry breaking – A phase change from a symmetric state to a non-symmetric state. Liquid water is more symmetrical than ice. As the liquid cools it changes state and forms a crystalline structure. The same concept can be applied to particles and forces. At the very earliest time there may have been a single unified force that broke symmetry (possibly multiple times) as the universe cooled and expanded to unveil the current 4 known forces.

Problems

1. Is gravity weak or strong relative to other forces such as the electromagnetic force?
2. Is general relativity a classical theory, or a quantum theory?
3. The graviton is a particle with (a) zero mass, no charge and spin 1, (b) zero mass, no charge and spin 2, (c) positive mass, positive charge and spin 1, (d) positive mass, no charge and spin 2.
4. Are space and time continuous, or discrete?
5. What is a string, in string theory?
6. If there are extra dimensions of space would they be visible to us?
7. What are gravity waves; are they detected?

Answers

1. Gravity is much weaker than electromagnetism and the nuclear forces.
2. A classical theory
3. (b)
4. In general relativity they are continuous, but it is believed that at very small scales – around the Planck length - continuity will break down.
5. Strings are extremely tiny 1-dimensional objects whose vibrational modes result in the different “fundamental” particles that we detect.
6. Any possible extra dimensions beyond the 3 of space and one of time are expected to be curled up in a very tiny space or be so warped as to be extremely hard to detect.
7. Gravity waves are collections of many gravitons, similar to light waves being a collection of photons. Because gravity is so weak, gravity waves have not yet been directly detected, but experimental searches are underway.

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