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C. R. Physique 4 (2003) 347–354
COMPTES RENDUS PHYSIQUE

Extra dimensions in physics and astrophysics/Dimensions supplémentaires en physique et astrophysique

Large new dimensions and quantum gravity around the corner

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Abstract

The electroweak unification mass may be the only fundamental scale in nature. If so, the visible universe may lie on a membrane floating within a higher dimensional space; new dimensions, black holes, quantum gravity, and string theory may become experimentally accessible in this decade. The dark matter could reside on parallel universes inside the extra dimensions. ***To cite this article: N. Arkani-Hamed et al., C. R. Physique 4 (2003).***

Résumé

Grandes nouvelles dimensions et gravité quantique au coin. La masse d'unification électrofaible peut être la seule échelle fondamentale de la nature. Dans ce cas, l'univers visible peut se trouver sur une membrane flottant dans un espace de dimension plus élevée ; les nouvelles dimensions, les trous noirs, la gravité quantique, et la théorie de cordes peuvent devenir expérimentalement accessibles durant cette décennie. La matière noire peut résider sur des univers parallèles à l'intérieur des dimensions supplémentaires. ***Pour citer cet article : N. Arkani-Hamed et al., C. R. Physique 4 (2003).***

1. Why is gravity weak?

Over three centuries after Newton proposed his famous law of gravitation, physics is still unable to answer the simple question: why is gravity so much weaker than all the other forces? The feebleness of gravity compared to, say, the familiar electric and magnetic forces is dramatic. The gravitational pull of the entire mass of the earth is not strong enough to keep a refrigerator magnet from lifting a paper clip off the ground. More quantitatively, the gravitational attraction between an pair of electrons is 10^{43} times weaker than the repulsive electric force between them. Normally, gravity is only important at large distances, keeping us on the ground and keeping the earth orbiting around the sun. This is because the atoms we are made of are electrically neutral, so that the electrical force between large congregates of atoms is vanishingly small, leaving gravity, weak as it is, as the only force left over.

Why is gravity so weak? As we will see, the modern formulation of this question represents a crisis in our current understanding of fundamental laws, one which has been with us for over two decades since the formulation of the Standard

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1631-0705/03/$ – see front matter
doi:10.1016/S1631-0705(03)00035-5

Model of particle physics. In the last year, a radical new approach to answering this question has been proposed where the nature of space–time is modified by invoking the existence of large new spatial dimensions, perhaps as big as a millimeter in size. If correct, this picture has the dramatic implication that, contrary to long-held expectations, the study of quantum gravity and its unification with the other forces will be an experimental science in the near future. High energy accelerators, such as the Large Hadron Collider (LHC) under construction at CERN, could produce small black holes or the strings predicted by superstring theory. Table-top experiments may observe deviations from the inverse square law for gravity at short distances.

Before motivating and describing these ideas in more detail, let us first back up and better set the stage. Since the force of gravity grows with mass, one way of understanding the weakness of gravity relative to the electric force between electrons is to ask how heavy the electrons would have to be in order for the forces to be equal. This mass is gargantuan, 10^{22} times heaver than the actual electron mass. The amount of energy required to produce such a heavy particle, derived from $E = mc^2$, is 10^{19} Giga electron Volts (GeV), and is known as the 'Planck energy'. Because at these masses and energies gravity becomes comparable in strength with the other forces, it has traditionally been assumed that the a theory unifying gravity with the other interactions would only manifest itself at these energies. Such a high energy can probe the tiny distance of 10^{-33} cm, the 'Planck length'. To get an idea for these scales, it is useful to compare them to more familiar atomic dimensions. The mass of the hydrogen atom corresponds to an energy of 1 GeV, its size is about 10^{-8} cm and the size of its nucleus is about 10^{-14} cm. The Planck length is really incredibly small, even on atomic scales, the Planck energy enormously higher than atomic energies.

By the above arguments, gravity is expected to become comparable to the other forces only at these enormous energies or tiny distances, and therefore any unified description of all forces is only expected to manifest itself at these scales. The Planck energy is enormously far removed from what can presently be attained even at our most powerful accelerators, which attain energies of order 100 GeV probing distances of about 10^{-16} cm. In the traditional view, therefore, the nature of the ultimate unified theory is hopelessly out of reach of direct experimental investigation in the foreseeable future.

We can now replace our original question-why is gravity so weak? With an equivalent one-why are the particle masses we know so much lighter than the Planck mass? In order to be able to answer this new question, we have to understand how particles acquire their mass to begin with. In the Standard Model, the masses of all the particles originate from interactions with a hypothetical field-the Higgs field-permeating all of space. This Higgs field has an associated energy scale of about 175 GeV, called the electroweak scale, and this sets the overall mass scale for all the particles we know of. This energy is tantalizingly close to what is being probed at todays highest energy accelerators, and corresponds to short distances of about 10^{-16} cm.

We have finally arrived at the modern formulation of our original question. Instead of asking: why is gravity weak? We ask: why is the electroweak energy scale 10^{16} times smaller than the Planck energy? This brings us to the end of the line: the Standard Model is incapable of answering this question. The value of the electroweak scale cannot be predicted by the theory but is simply adjusted to fit experimental observation. The situation is even more desperate than this: due to certain quantum instabilities, these adjustments must be made to very fine accuracy of order one part in 10^{32}. If the adjustments are off by more than one part than this, the electroweak scale would land on top of the Planck scale, instead of being 10^{16} times smaller than it. This is clearly a major conundrum. To make an analogy, it is like walking into a room, and seeing a pencil standing on its tip in the middle of a table, balanced within 10^{-32} degrees of vertical! While this is not by itself impossible, it is highly unstable configuration, and one wonders how this peculiar situation came about.

The inability of the Standard Model to explain the huge difference between the electroweak and Planck scales, together with the quantum instability that further exacerbates the difficulty, is known as the 'Hierarchy Problem'. For twenty years, there has been a uniform theme in attempting to solve this problem. The Planck scale has been taken as fundamental, and the nature of particle physics has been altered near 10^{-16} cm in order to stabilize the electroweak scale. The most popular modification of the Standard Model which accomplishes this involves a new sort of symmetry in physics, called supersymmetry. Going back to our pencil analogy, supersymmetry acts like an invisible hand holding up the pencil, removing the instability which makes it want to fall to the table. While accelerators have not yet turned up any direct evidence for supersymmetry, the supersymmetric extension of the Standard Model is supported by a compelling bit of indirect evidence. When the measured strength of the strong, weak and electromagnetic forces are theoretically extrapolated to shorter distances using supersymmtric rules, they are found to very accurately meet at a common strength near 10^{-30} cm. This hints at some sort of supersymmetric unification of these three forces at a fundamental level.

2. The new picture

2.1. Making gravity weak with large spatial dimensions

For the last two decades, supersymmtery has provided the only viable framework for addressing the hierarchy problem. But in the last year we have proposed a new approach. Instead of changing particle physics near 10^{-16} cm, the nature of space–time and gravity itself are altered. The main observation is that the hierarchy problem in only a problem if one really believes that both the electroweak and Planck scales correspond to real, physically meaningful short-distance scales in nature where new phenomena occur. What evidence do we have for this assumption? The physical nature of the electroweak scale is an experimental fact, since we have probed the strong, weak and electromagnetic interactions to distances approaching 10^{-16} cm, and the unification of electromagnetic and weak forces has actually been aboserved to occur here. But what about the Planck scale? What experimental evidence do we have that gravity really becomes strong only at 10^{-33} cm? The answer is that there is absolutely no direct evidence for this supposition. Indeed, precisely because it is so weak, the inverse square law for gravity has only been tested down to distances of about a millimeter! The assumption that gravity only becomes important near 10^{-33} cm is then based on an enormous extrapolation of the inverse square law for over thirty orders of magnitude past where it has actually been checked experimentally. Given that the result of this extrapolation directly leads to the hierarchy problem, it is well worth challenging its validity.

We propose to solve the hierarchy problem by nullification, by declaring that the real, physical Planck scale, where gravity actually becomes strong, is very close to the electroweak scale. The ultimate unification of gravity with the other forces would then take place near 10^{-16} cm rather than 10^{-33} cm as traditionally assumed. Since this scenario entails a much stronger gravitational force at short distances, how do we understand the apparent weakness of gravity as measured at distances larger than a millimeter? This can be explained by invoking the presence of large new spatial dimensions. The idea that extra dimensions could be relevant to the unification of gravity with the other forces is very old, going back to the work of Kaluza and Klein in the twenties, and has been revived in modern string theories which seem to require a total of nine or ten spatial dimensions. However, it has always been assumed that the dimensions were invisible because they were curled up in a ball near the Planck length of 10^{-33} cm. By contrast, the extra dimensions we are talking about are huge, curled up on sizes perhaps as big as millimeter.

It is easy to understand how extra dimensions can make gravity appear weak at large distances. Imagine a mass placed somewhere in the a given number n extra dimensions curled up at some size R. If we place another mass at distances much closer than R to the first one, we cannot tell that the extra dimensions are curled up to a finite size. The force between the masses would be that of gravity not in three spatial dimensions but in $3 + n$ dimensions. In order to see what kind of force this entails, recall that the usual inverse square law can be understood by the dilution of the gravity field lines piercing a sphere surrounding the mass, falling off as the area of the sphere grows. Since the area of the sphere grows as the square of the radius, the force falls off as the square of the radius. By the same logic, the force law in $3+n$ dimensions should fall off as the area of a hypersphere, giving an inverse cube law for four dimensions, an inverse fourth power law in five dimensions, and in general an inverse $2+n$ power law for n extra space dimensions. The force between our two masses would follow this inverse $2+n$ power law at distances much smaller than the size of the extra dimensions. What happens if we now place the masses at distances much larger than R away from each other? It is easy to see that the force law cannot continue to drop off as quickly as before: because the extra dimensions have a finite size, the field lines cannot continue to spread in them indefinitely, and are eventually allowed to spread only in our usual three dimensions. This means that at distances larger than R, the force between the masses obeys the usual inverse square law for gravity. This is to be expected, since at these long distances the extra dimensions should essentially be invisible.

Summarizing then: given n extra dimensions of size R, at distances much larger than R gravity obeys the usual inverse square law appropriate to three spatial dimensions, while at distances smaller than R, the inverse $2 + n$ power law appropriate to $3+n$ spatial dimensions is found. If these dimensions are slightly smaller than a millimeter, where we have measured gravity, we would be oblivious to their existence. However, their presence invalidates the extrapolation used to conclude that gravity only becomes strong at 10^{-33} cm. Indeed, at distances smaller than R, gravity grows in strength much more rapidly than indicated by the inverse square law, and the physical scale where gravity really becomes strong can be far larger than 10^{-33} cm. From this point of view, the old Planck length of 10^{-33} cm is a completely fake scale, resulting from a linear extrapolation of the inverse square law as measured at long distances over thirty orders of magnitude to shorter distances.

In order to solve the hierarchy problem, we want the actual scale where gravity catches up to the other interactions to be close to 10^{-16} cm. For a given number n of extra dimensions, this requirement fixes their size R. For $n = 1$ extra dimension, R ends up being close to the earth–sun distance, far too large for comfort! This case is then already excluded by observation. However, already for $n = 2$ extra dimensions, this size drops to about a millimeter, which as we have been emphasizing is precisely where our direct knowledge of gravity ends, and is therefore not immediately excluded! Going to the maximum of $n = 7$ dimensions allowed by string theory corresponds to a size of about 10^{-12} cm, about the size of the nucleus of the Uranium atom. This is tiny by normal standards but still huge by the yardstick of particle physics.

What we have accomplished is a rephrasing of the hierarchy problem in new, geometrical terms. The question of why gravity is weak is replaced by a new one: why are the extra dimensions large compared to the fundamental Planck length near 10^{-16} cm?

2.2. The universe on a wall

If these dimensions are so enormous, why have we not seen them yet? While we have not measured gravity beneath about a millimeter, we have a wealth of experimental knowledge about the behavior of all the other forces and interactions at distances far smaller than a millimeter, all the way down to near 10^{-16} cm. Surely, if light could propagate in extra dimensions a millimeter big we would literally 'see' the extra dimensions even with the human eye. So why have not we seen them? The answer is at once simple and peculiar: we have not noticed the extra dimensions because all of the matter and forces we know of – with the sole exception of gravity – are stuck to a 'wall' in the space of the extra dimensions. Electrons and protons and photons and all the other particles in the Standard Model cannot move in the extra dimensions, electric and magnetic field lines cannot spread into the higher dimensional space. As far as these particles are concerned, the universe might as well be three-dimensional. On the other hand, gravitational field lines can extend into the higher dimensional space, and the particle which carries transmits the gravitational force, the graviton, can travel freely into the extra dimensions. It is then only through gravity that the presence of the extra dimensions can be felt.

To make an analogy, imagine that all the particles in the standard model, like electrons and protons, are billiard balls moving on the surface of a pool table. As far as they are concerned the universe looks two-dimensional. But there is a world outside the pool table. How could the two dimensional inhabitants find out about this world? When two billiard balls hit each other sufficiently hard, they can produce sound waves which travel in all three dimensions, carrying some energy away from the table surface. The sound waves are the analog of the gravitons which can travel in the full higher dimensional space, and energetic collisions of particles can indeed boil off gravitons escaping into extra dimensions, which are detected as some missing energy to the wall observers. We will have much more to say about this process below.

While it may seem strange that some particles should be confined to a wall in higher dimensions while others are free to travel everywhere, such occurrences are quite familiar from everyday life. For instance, electrons in a copper wire are only free to move around in the one-dimensional space of the wire, and do not travel into the bigger three-dimensional space. Similarly, water waves travel primarily on the surface of the ocean, not throughout its depth. The specific scenario we are describing, with all particles except gravity stuck to a wall, can also naturally arise in string theory. In fact, one of the major insights triggering the recent breakthroughs in string theory is that precisely such 'walls' exist in string theory. They are known as D-branes, and precisely have the needed property that particles like electrons and photons must be stuck to them while gravity can wander into all the dimensions.

3. Laboratory, astrophysical and cosmological constraints

This picture represents a drastic departure from our usual conceptions of the universe, changing physics both at sub-millimeter distances as well as at energies above a few TeV. A pressing question is then: is it alive? Can this picture be consistent with everything we already know experimentally about nature? Remarkably, the answer to this question is: Yes, despite its radical departure from our usual picture of the universe, this theory does not contradict any known experimental results. A few examples of the sorts of checks which are passed best illustrates how surprising this conclusion is.

A preliminary worry one might have is that changing gravity may affect the dynamics of objects held together by gravity such as stars and galaxies. This is no correct, however: we are only changing the structure of gravity at distances shorter than a millimeter. On the other hand, the gravity responsible for holding a star together must stretch out over thousands of kilometers between distant parts of the star; any change in gravity at distances as small as a millimeter is irrelevant. The general point is that, even though gravity gets strong much more quickly than usual, it still only catches up with the other forces near 10^{-16} cm; at all larger distances it is still very feeble compared to other forces.

There is a much more serious concern, however. In the old picture, the force of gravity is communicated from one particle to another by a massless particle called the graviton. So it is in the new picture with two important differences: the graviton interacts much more strongly with matter (reflecting that gravity is much stronger) and it can propagate in all the dimensions. Since the graviton is so much more strongly interacting than before and couples to energy, it can be copiously produced in highly energetic collisions. Once produce, the gravitons escape into the extra dimensions, leaking away energy from the wall where we live.

A particularly dangerous process occurs in the catastrophic collapse of Supernovae, where the temperature becomes so high that gravitons can readily be boiled off into the extra dimensions. Since the observation of the famous Supernova 1987A, however, we know that most of the energy in the Supernovae explosion gets emitted in the form of neutrinos, leaving little room for any energy to be leaked away by our gravitons. This limits how strongly gravitons couple to matter; the bigger the coupling the greater the undesired energy leakage. This constraint could have excluded the ideas we are talking about. If it turns out that the avoiding too much supernova cooling only allows gravity to get strong at energies a million times higher than a TeV, we could not solve the hierarchy problem in the way we are suggesting. However, detailed calculations show this not be the case.

The strongest limit is on the case with two extra dimensions, where gravity can only become strong about a factor of 50 above the TeV scale. For more than two dimensions, the constraints are weaker and gravity can consistently get strong near a TeV.

A large number of other possible constraints have been examined, ranging from unacceptable modifications of the successful big-bang picture of the early universe to collisions of ultra-high energy cosmic rays. None of the constraints are more severe than the supernova constraint just discussed, and therefore the theory passes all experimental checks. It is remarkable that this radically different picture for the universe can nevertheless be completely consistent with all known experimental results. Perhaps surprisingly, the theory is less severely constrained by experiments for more and more dimensions! We saw this right at the beginning: the case of one extra dimensions was excluded immediately since gravity was altered at solar-system distances. This points to why more dimensions are safer: the dramatic strengthening of gravity begins at shorter and shorter distances for more dimensions, and therefore has a smaller impact on larger distance processes which are constrained by experiment.

4. Experimental predictions

4.1. Quantum gravity at accelerators

Having been convinced that the framework is experimentally viable, we turn to discussing a number of dramatic experimental predictions that could provide positive evidence for the existence of large extra dimensions and strong quantum gravity effects. Since the whole point of the scenario is to lower the fundamental scale of gravity near the TeV scale to solve the hierarchy problem, the next generation of particle accelerators, which will come on line in under a decade and are designed to thoroughly probe physics at TeV energies, should uncover the nature of quantum gravity.

Suppose for instance that the underlying theory of quantum gravity is indeed string theory. Recall in this picture that what we have so far observed as the fundamental particles are merely the lowest energy vibrations of loops of string, much as the lowest note played on a violin string. While these strings have usually been thought of as only 10^{-33} cm long, in our picture they are much larger, near 10^{-17} cm. They can therefore be excited into higher vibrational states at planned accelerators, appearing as exotic new particles beyond those we know of with very specific characteristic properties. Producing these particles at accelerators would be like discovering all the higher pitched notes that can be played on a violin string, and would provide striking evidence for an underlying stringy structure of matter.

Furthermore, at sufficiently high energies, the strong gravity induced by particle collisions can produce small black holes about 10^{-16} cm in size. Once created, these black holes will begin to evaporate as predicted by Hawking. Now, black holes of astronomical size take billions of years to evaporate, but our small black holes will evaporate in less than 10^{-26} seconds. The observation of such phenomena would give a direct probe of quantum black hole physics.

Even before any of these more exotic aspects of quantum gravity are seen, evidence for strong gravity and extra dimensions can turn up from collisions in which gravitons are boiled off into the extra dimensions, much as what happens in the collapse of the Supernova. The difference is that at accelerators, the available energies are much higher and gravitons should be produced more readily. Since the gravitons escape away from the wall where we live, we have no way of directly detecting them. Therefore, processes where gravitons are copiously emitted will look like apparent violations of conservation of energy from our point of view. The exact properties of this ‘missing’ energy can be accurately predicted on theoretical grounds, and provide a smoking gun for the observations of extra dimensions and strong gravity at accelerators. The data currently available from the highest energy accelerators presently available at CERN and at Fermilab can already be used to set some (mild) constraints on our scenario. However, all of these signals should be easily accessible to the Large Hadron Collider being built at CERN, which will begin running in 2005.

4.2. Looking for extra dimensions in table-top experiments

It is also possible that new table-top experiments designed to measure gravity at distances shorter than a millimeter will uncover signals for extra dimensions. Recall that for the case of two extra dimensions that these dimensions could be as large as a millimeter in size. Therefore, Newtons law for gravity would change from an inverse square to an inverse fourth power law at distances somewhat beneath a millimeter! This is an unmistakable and dramatic prediction for these experiments. Extensions of our basic framework lead to a whole host of other possible signatures for these experiments, the most interesting of which is perhaps the possibility of *repulsive* forces more than a million times gravitational strength at sub-millimeter distances.

It is exciting that table-top experiments can potentially uncover such dramatic new physics. Two such experiments are currently being performed, one by John Price and collaborators at the University of Colorado and one by Aharon Kapitulnik and collaborators at Stanford University. Quite apart from the motivation from extra dimensions, however, these are extremely interesting experiments, as they will extend our direct knowledge of gravity to distances well beneath a millimeter, down to tens of microns. It is easy to understand many of the challenges involved in performing such experiments. In order to probe the gravitational force between two masses at at distances smaller than a millimeter, the sizes of the objects used must themselves be smaller than a millimeter. Even using very dense materials, this means that the masses themselves are very small. The gravity force to be measured in then so tiny that it is necessary to very accurately screen all other residual electromagnetic effects that might mask or fake the gravitational attraction being looked for. These experiments are clearly difficult and subtle, but they are equally clearly enormously important and exciting. Preliminary results are expected to be announced within the next couple of years.

5. New particles and parallel universes

One of the most interesting features of the picture we are imagining is that our entire 3-dimensional universe occupies a single point in the space of the extra dimensions. This is the natural continuation of the Copernican tradition in the understanding of our place in the world: not only is the earth not the center of the solar system, the sun not the center of our galaxy, our galaxy just one of billions of other galaxies in the universe, but our entire universe is a small speck in the much larger space of the extra dimensions.

Just as we are not the only planet in the solar system, and the Milky way is not the only galaxy in the universe, we are lead to suspect that we are not alone in the large extra dimensions. There may be several other three-dimensional universes, parallel to our own, living only a millimeter removed from us in the extra dimensions. Similarly, while all the particles of the Standard Model are necessarily stuck to our own universe, there is no reason for the graviton to be the only particle feeling the extra dimensions. Far from being empty, the extra dimensions could have a multitude of interesting structures. Since photons are trapped to our own wall, there is no way we can 'see' any of these other universes. The only way the different universes can talk to each other is through particles such as the graviton (and perhaps others as well) that can freely move in all the dimensions.

The presence of extra particles and new universe in the extra dimensions can have important and observable consequences on our own universe. In fact, many of the outstanding mysteries of particle physics and cosmology can be addressed inside the extra dimensions. To take one example, there is impressive new evidence from the SuperKamiokande experiment in Japan, that neutrinos, ghostly elementary particles with no electric charge which are involved in radioactivity, carry a miniscule but non-zero mass. Our picture provides a natural explanation for this if the neutrino gains it mass by interacting with a partner living in the extra dimensions. Since the partner lives in the extra dimensions, it spreads itself throughout the large space available to it and hardly ever interacts with our neutrino living on our tiny speck of a universe – thus the mass resulting from this interaction is miniscule. The neutrinos are light for the same reason that gravity is weak: the large volume in the extra dimensions. As another example, a famous mystery in cosmology is what constitutes the 'dark matter', the invisible gravitating substance that is thought to make up over 90% of the mass of the universe. The dark matter have a natural home in our picture, they can reside on parallel universes! Since photons are stuck to our universe, any matter stuck to a parallel universe seems cannot shine our photons and is necessarily 'dark'. On the other hand, the effects of matter on the other universes are certainly felt gravitationally.

While the parallel worlds are static today, very much earlier in the history of our universe they may have been displaced from their present day positions and have been moving relative to us. Some of them have even repeatedly collided with our universe, much as comets are thought to have collided with the earth. This dynamics could trigger the superluminal expansion or 'inflation' of the universe which is thought to solve many of the thorniest problems of cosmology. Another cosmological puzzle concerns the apparent excess of matter over anti-matter in the observable universe. Such an excess could have been produced when parallel worlds collide and pass through each other, leaving equal magnitude but opposite sign excesses of matter over anti-matter on each world. These examples illustrate that once the space in extra dimensions is populated with new particles and universes, a rich new spectrum of theoretical possibilities are available to attack a multitude of unsolved mysteries at the frontiers of physical knowledge.

6. Folded universe

We have concentrated on how parallel universes can affect us, but what are they like themselves? What sort of particles and interactions reside there? In principle, they could be very different from our own universe, but there is an intriguing possibility where they have identical properties to our own world. This can be motivated if we imagine that the wall where we live is actually folded a number in the extra dimensions. Physical properties on each of the folds are identical to our own. However, since photons are restricted to moving along the wall, objects on the other side of a fold, less than a millimeter removed from us in the extra dimensions, can appear very distant. This is because the light they emit must travel over the tip and back along our side of the fold to reach us! If the tip of the fold is located far enough away, none of the light from the other side could have reached us within the current age of the universe. The different folds then effectively appear as distinct parallel universes, with the interesting property of having identical particles and physical laws as our own universe!

This suggests the fascinating possibility that the dark matter could actually be composed of ordinary matter-perhaps even ordinary stars-on the other folds. Thus, the dark matter could actually be shining brightly on its own fold, it is only because the light it emits has not yet traveled over the tip of the fold and made it to us that dark matter is 'dark'!

There are a number of important constraints on this picture for dark matter when it is examined in detail. For instance, all of the required dark matter cannot reside on just a single fold. The reason is that, since matter on the other folds have identical properties our own, they would have clumped densely into stars and galaxies just as our matter has. However, the dark matter is known to be more dilutely spread out in Halos about our galaxies. These (and other) potential difficulties are circumvented if the required amount of dark matter is matter is spread dilutely over a large number of folds rather than concentrated on just one fold.

The presence of ordinary stars on the other folds lead to interesting experimental signatures. For instance, violent astrophysical processes on a distant fold could give produce gravitational waves which can be detected by gravity wave detectors such as LIGO. Normal sources of gravity waves, such as stars orbiting pulsars, can also be seen visually, but that is not the case here. LIGO could then provide evidence for the presence of folds by observing of gravitational radiation not be accountable for by luminous matter!

7. Other attempts

Our framework is not the first to propose extra dimensions larger than 10^{-33} cm. In 1990, Ignatios Antoniadis of École Polytechnique, in France, suggested that some of the dimensions of string theory might be as large as 10^{-16} cm in size. This size is enormous compared to the usual expectation that all the dimensions are curled up near 10^{-33} cm, but still miniscule compared to the sub-millimeter sized dimensions we have been discussing. In 1996, Petr Horava and Edward Witten suggested using a single extra about 10^{-28} cm big, in order to allow gravity to catch up with the other interactions near 10^{-30} cm rather than 10^{-33} cm. This made for a neat picture when combined with the supersymmetric unification of the strong, electromagnetic and weak forces also at 10^{-30} cm. Following this idea, Joe Lykken of Fermilab attempted to lower the scale of string physics near 10^{-16} cm. His specific proposal did not invoke large extra dimensions, but instead used a small parameter of about 10^{-16} in the theory to make gravity weak. In 1998, Keith Dienes, Emilan Dudas and Tony Ghergetta of CERN argued that extra dimensions smaller than 10^{-17} cm could allow the gauge forces to unify at distances much larger than 10^{-30} cm.

Since our proposal of large extra dimensions to solve the hierarhcy problem, a number of interesting variations have appeared, using the same basic ingredients of extra dimensions and our universe-on-a-wall, in order to address the hierarchy problem. A particularly interesting suggestion was made by Lisa Randall of Princeton and Raman Sundrum of Stanford. Their idea is that the strength of gravity itself may be changing rapidly in an extra dimension, peaking on a distant parallel universe and dropping to its weakest on our own world.

8. Outlook: observation of extra dimensions and quantum gravity by 2010?

For twenty years, the conventional approach to tackling the hierarchy problem – and therefore ultimately understanding why gravity is so weak – has been to assume that the Planck scale near 10^{-33} cm is fundamental and therefore the nature of particle physics near 10^{-16} cm must be altered. In this picture, the nature of quantum gravity is hopelessly out of the reach of experiment, and is left in the realm of theoretical speculation. We have shown that an alternate view is possible, where the apparent weakness of gravity is understood as the consequence of large new spatial dimensions perhaps as big as a millimeter where gravity propagates, while all the other particles we know of are confined to a wall floating in the extra dimensions. Remarkably, such a dramatic departure from our old picture of the universe is nevertheless completely consistent with experiment, illustrating how little we know about the universe beyond what we have directly measured! In this new scheme, the effects of strong quantum gravity, such as black holes and string theory, may be experimentally studied in the next decade at the Large Hadron Collider being built at CERN. On an even shorter time scale, table-top experiments at Colorado, Washington and Stanford may turn up the first evidence for extra dimensions by measuring deviations from Newton's law at sub-millimeter distances. The ideas we have been discussing provide a framework in which to tackle many other open problems of particle physics and cosmology through new particles and parallel worlds in the extra dimensions for instance, dark matter can reside on parallel universes or even be ordinary matter on our own 'folded' universe.

This new framework presents a completely different picture of physics beyond the Standard Model than the one which has been afforded by supersymmetry for two decades. Which scenario is more likely to be true? We feel that the new framework is very nearly as good as the old one in describing nature, and has very nearly the same chance to be true. There is only one success of supersymmetry which is not automatically reproduced in the new picture: the apparent unification of the strong, weak and electromagnetic forces in a grand unified theory. Even here, a number of ideas have been put forth on how to retain this success in the new framework, all taking advantage of the large space in the extra dimensions. What now needs to be done is to combine these ideas into a single complete theory. Progress in this area has been rapid in the last year, and such complete models may be just around the corner.

What we find most exciting, however, is that these new ideas make definite experimental predictions that will be checked within the next decade. It will be remarkable if deviations from Newton's law are found near, say, sixty microns, and stringy vibrations are produced at the LHC. This would turn quantum gravity, perhaps string theory, into testable science. Whatever happens, in the next ten years, experiment will finally point the way to answering a question unanswered since the time of Newton: by 2010 we will surely understand why gravity is so weak.