

GRAVITATIONAL CONSEQUENCES OF MODERN FIELD THEORIES

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I would like to discuss some gravitational consequences of certain extensions of Einstein's general theory of relativity. These theories are not "alternative theories of gravity" in the usual sense. I will assume that general relativity is the appropriate description of all gravitational phenomena which have been observed to date.

Nevertheless, there are at least two reasons for considering extensions of general relativity. The first and most important is the fact that general relativity does not incorporate the observed quantum mechanical nature of matter and non-gravitational forces. The second is the common belief that at a fundamental level, gravity should be unified with the other forces of nature. In particular, this will require that gravity itself be described quantum mechanically. It is usually thought that since macroscopic amounts of matter are required for gravity to be detected and classical physics is a good approximation for macroscopic objects, these extensions of general relativity will not be observable. As I will try to explain, this is not necessarily the case.

The effects of combining gravity with quantum matter fields have been extensively studied. The most important consequence of this investigation is the following: *black holes are not really black.* This is Hawking's remarkable prediction that black holes emit thermal radiation at a temperature $T = 10^7 (M_{\odot}/M)^{\circ}K$ where M_{\odot} is the mass of the sun and M is the mass of the black hole. For solar mass black holes this is much less than the 3° cosmic background radiation. But if much smaller black holes were formed at the time of the Big Bang, they would radiate away their mass and eventually evaporate. In particular, a 10^{15} gm black hole would be in the final stages of evaporation today, having radiated most of its mass in gamma rays. This prediction indicates a deep theoretical connection between general relativity, quantum mechanics, and thermodynamics. The observation of evaporating black holes would surely represent a major advance in physics.

Another consequence of combining general relativity with more realistic theories of matter is *cosmic strings*. These are very thin (diameter approximately 10^{-26} cm) tubes of energy that were possibly formed in a phase transition in the early universe. If they exist, they would have a number of important gravitational effects. First they could act as seeds for galaxy formation. This would avoid the difficulty of reconciling the observed isotropy of the cosmic background radiation with the amplitude of perturbations needed at the time of decoupling to evolve to form galaxies. Second, cosmic strings could act as gravitational lenses. Light from a single quasar or distant galaxy, which passes above and below a cosmic string, could be focused so that an earth-based observer sees multiple images. In fact the most likely way of detecting cosmic strings is believed to be through the observation of a series of multiple images. Finally, cosmic strings will contribute to the gravitational radiation background, since this is their main source of energy loss. This aspect of cosmic strings has been discussed by Schutz and Matzner at this meeting.

Now let us turn to the idea of unification. This work began in the 1920's with Kaluza and Klein. They showed that the two forces known at that time — gravity and electromagnetism — could be unified by postulating that spacetime had five dimensions. They argued that we only observe four because one dimension is a circle of very small radius. With the discovery of the strong and weak nuclear forces, this idea has been extended and is now incorporated in the currently popular theory known as *superstrings*. (Despite the similarity in name, these strings are quite different from ones discussed above.) This new theory not only unifies gravity with the other known forces but also with the matter. The different elementary particles and forces all arise from different excitations of a single string. At the same time, this theory is probably the first in which gravity is consistently treated quantum mechanically.

The theory of superstrings predicts that the dimension of spacetime is 10. The six dimensions we do not see are curled up into a very small ball. The size of this ball, as well as the size of the fundamental strings, is determined from Newton's constant G , Planck's constant h , and the speed of light c . This scale is known as the Planck length and is $L_P = (Gh/c^3)^{1/2} = 10^{-33}$ cm. Clearly direct observation of these extra dimensions or the strings themselves will be difficult! However, there are some intriguing new effects which may be observable at much larger distances. These effects have not yet been thoroughly investigated. Preliminary studies have yielded qualitative rather than quantitative results due to the difficulty of extrapolating over so many orders of magnitude.

Possible gravitational consequences of superstring theory:

...*Short Distance Violations of the Weak Equivalence Principle (WEP)*. Recall that the WEP states that objects of different composition will accelerate at the same rate in a gravitational field. In the theory of superstrings, at large distances one recovers general relativity, but also an extra scalar field called the dilaton. The mass of the dilaton is known to be much less than the Planck mass ($M_P = (hc/G)^{1/2} = 10^{19}$ GeV), but has not yet been calculated reliably. If it is zero, then the dilaton couples gravitationally just like a Brans-Dicke scalar, but couples to matter in a way which violates the WEP. Since the relevant coupling constants are expected to be of order one, this is in serious conflict with the Etövös-type experiments. Furthermore, the theory predicts a unique value for the Brans-Dicke coupling constant of minus one which is also clearly ruled out by observation. For both of these reasons the dilaton must have a non-zero mass and hence a finite range. Current laboratory Etövös experiments can set lower limits on the mass of about 10^{-6} eV. However, at distances comparable to the Compton wavelength of the dilaton, one would expect violations of the equivalence principle.

More generally, one can show that theories with extra spacetime dimensions generically have scalar fields that violate the weak equivalence principle. Thus, this principle is **NOT** a fundamental building block of unified gravitational theories, but only an approximate result which is valid at large distances.

...*Time Variation of the Coupling Constants*. The low-energy coupling constants (gravitational, electromagnetic, etc.) depend on the dilaton and the size of the internal six dimensional space. In a general cosmological context, one expects these quantities to change with time. Thus, one expects the coupling constants to evolve. Once again the actual rate of change is difficult to calculate reliably.

Turning the argument around, current observational limits on their rate of change can also set limits on the masses of the appropriate particles.

DISCUSSION

PAIK: You said that the dilaton mass (M_P) is bigger than 10^{-5} eV, which corresponds to a range less than 1 cm. How do you set such a limit from the Eotvos experiment? Did you get the limit from the laboratory inverse square law? It depends on the strength of dilation coupling α . Is α of the order of unity?

HOROWITZ: Yes for both questions. The coupling for dilaton is expected to be of the order of unity. In principle, this can be calculated from the theory, but we need to better understand several non-perturbative effects (such as supersymmetry breaking) before such calculations can be made.

TALMADGE: It is my understanding that laboratory $1/r^2$ tests set limits on α only for the range from 0.1 cm to a few meters. Why then do you exclude the distance scales larger than a few meters? Does the theory predict a specific value for the relative strength of the new coupling to Newtonian gravity? Could it in principle?

HOROWITZ: There are, of course, other tests of the inverse square law for distances larger than a few meters. These experiments have set upper limits on the strength of new forces of about 1% that of gravity. Since the dilaton is expected to couple with the same strength as gravity, its range must be shorter.