GRAVITATIONAL SHIELDING AND THE RANGE OF GRAVITATIONAL FORCE

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ABSTRACT

Current ideas on the nature of gravitation are based mainly on the results of applying Newtonian theory to distributions of matter embedded in empty space. Application of Einstein's theory to a statistically uniform distribution of matter filling all space shows that these ideas need to be revised. In particular, gravitational shielding occurs and has important observable consequences; and gravitational forces have a finite range, essentially the radius of the theoretically visible universe. The last fact may explain the observation that the size of self-gravitating systems has a well-defined upper limit.

Gravitational Shielding and the Range of Gravitational Force

Two of the most widely accepted dogmas of modern science are the beliefs that gravitational shielding is impossible and that gravitation is a long-range force. This essay argues that neither of these beliefs is consistent with the simplest and most conservative picture we can form of the physical universe.

The argument will be greatly facilitated if we recognize at the outset that the theory we employ to describe gravitational phenomena -- in this essay Einstein's 1915 theory -- determines the phenomena only in part. To describe an actual physical system we must specify not only the laws governing the physical processes that occur in it, but also the "auxiliary conditions" that serve to distinguish the system in question from other systems to which the same laws might apply. In ordinary physics it is natural and convenient to separate the physical laws, which are given once and for all (or until a better theory comes along!), from the auxiliary conditions, which vary from system to system. This distinction becomes highly questionable, however, when it is applied not to ordinary bounded systems but to the universe as a whole. We could of course think of the actual universe as one among many possible universes, each defined by a different set of auxiliary conditions. But it seems out of keeping with the spirit of modern science to postulate the existence of unobservable phenomena -- especially on such a grand scale -- for the sake of preserving what is essentially a metaphysical distinction. Much more natural is the view that the universe we observe -- and hence the set of auxiliary conditions that defines it -- is unique. This view puts the auxiliary conditions on the same footing as the physical laws, and thus erases the time-honored metaphysical distinction between "inherent" and "accidental" properties of the physical universe.

The question we need to ask, then, is: What are the properties of gravitation in the actual universe? And the answer must depend on what we assume about the structure of the universe. The simplest assumption that is consistent with astronomical observations is expressed by the Strong Cosmological Principle (SCP), which may be described as the ultimate generalization of Copernicus' denial that the earth occupies a privileged position in the universe. The SCP asserts the possibility of finding a complete statistical description of the universe which, at any given instant of cosmic time, does not serve to define any preferred position or direction in space. (The ordinary, or weak, cosmological principle merely asserts that the mean distribution of matter and motion has this property; the perfect cosmological principle, that the universe is not only spatially homogeneous and isotropic but is also in a steady state.) The SCP is the strongest symmetry postulate that is consistent both with currently accepted physical theories and with astronomical observations.

The properties of gravitation in a universe satisfying the SCP may be studied within the framework of general relativity. The following results of such a study, which is still far from complete, show that some long-cherished ideas about the nature of gravitation, based on applications of Newtonian theory to bounded systems embedded in empty space, need to be drastically revised.

(1) In a Newtonian island universe every mass element contributes to the force experienced by a test particle. In a relativistic universe satisfying the SCP only the fluctuating component of the mass distribution gives rise to gravitational forces. For since the mean density field looks isotropic from every vantage point, it can nowhere define a preferred direction and hence cannot give rise to forces of any kind. Although the mean

distribution of matter and motion, or substratum, is force-free, the theory shows that it is in a state of accelerated expansion. This motion cannot be interpreted in terms of Newtonian physics. Not only are gravitational forces absent, but it is impossible to associate either gravitational potential energy or kinetic energy in any consistent way with the expanding substratum.

(2) In a Newtonian island universe the momentum of a test particle is constant in the absence of forces (Galileo's Law of Inertia). In a relativistic universe satisfying the SCP the momentum of a test particle varies inversely as the scale factor (defined as the radius of a sphere containing, on the average, a fixed number of baryons). This law applies to photons as well as to particles of finite rest mass, and is responsible for the phenomenon of the red shift.

(3) In a Newtonian island universe the rate of change of a particle's momentum, reckoned in a fixed inertial frame of reference, is equal to the force exerted on the particle (Newton's Law of Motion). In a relativistic universe satisfying the SCP the rate of change of the momentum, <u>reckoned in the instantaneous rest frame of the particle</u>, is equal to the force exerted on the particle.

(4) In a Newtonian island universe the gravitational force field is conservative and its source density is proportional to the density of matter (Newton's Law of Gravitation). In a relativistic universe satisfying the SCP the gravitational force field is conservative and its source density is proportional to the <u>fluctuating component</u> of the matter density -- provided that the scale of the density fluctuations satisfies a certain inequality discussed below.

The last result means that in a universe satisfying the SCP gravitational forces are shielded, because the fluctuating component of the density represents a macroscopically neutral distribution in the same sense that a fully ionized plasma with equal numbers of protons and electrons is macroscopically neutral. Just as in a plasma, shielding limits the gravitational influence of fluctuations to a radius somewhat larger than the scale of the largest density fluctuations. Although gravitational shielding may seem at first sight to be a paradoxical idea, a moment's reflection will show that it is precisely this property of gravitation that enables us to treat the Galaxy, or the local group of galaxies, as an isolated system embedded in empty space -- an idealization that leads straight to the Newtonian concept of unshieldable gravitational forces. <u>Thus if it were not</u>

for gravitational shielding we could never have formed the notion that gravitational shielding is impossible!

(5) The final property of gravitation in a universe satisfying the SCP is perhaps the most surprising of all. It has an important bearing on the central problem of cosmogony: the formation of self-gravitating condensations in an expanding universe. Property (4) implies that gravitational forces in a universe satisfying the SCP, though shielded, have infinite range, like Coulomb forces in a plasma. The derivation of this result rests on two assumptions: that the fields are weak; and that the scale of the density fluctuations is much smaller than the radius of the visible universe (approximately ct, where c is the speed of light and t is the epoch, reckoned from the beginning of the expansion). The first assumption is always satisfied in practice, except in certain special regions such as the interiors of highly collapsed stars and superstars, which can be dealt with separately. But there is no physical reason why we should not consider density fluctuations whose scale is comparable to or greater than the radius of the visible universe. When we do, the mathematical description of the gravitational field becomes considerably more complicated. For example, the scalar gravitational potential must be replaced by a

tensor. Although the analysis is not yet complete, an important semi-quantitative result has emerged from a preliminary, simplified treatment: the gravitational force decays exponentially at distances from the source greater than the radius of the visible universe.

Thus in a universe satisfying the SCP gravitational forces have a finite range of the order of ct. The present radius of the visible universe is about 10 billion light years and its mean density is between 10^{-30} and 10^{-29} gm/cc. Relativistic cosmology tells us that the radius and the mass of the visible universe are each proportional to the epoch t, and hence have a constant ratio. An easy calculation now shows that the mass of the visible universe was comparable to the mass of a typical present-day galaxy (about 10^{42} gm) when the mean cosmic density was of the order of, or somewhat smaller than, 1 gm/cc (or approximately 1 atom per cubic Bohr radius). Certain theoretical arguments suggest that just at this point in the cosmic expansion the universe became unstable against gravitational condensation, in much the same way that a vapor becomes unstable against condensation when its temperature falls below the critical temperature.

These considerations offer a possible explanation of the remarkable observation that self-gravitating systems are limited in size. They also offer a way of testing some unfamiliar consequences of gravitational theory as applied to a universe satisfying the Strong Cosmological Principle.

REFERENCES

The reader who wishes to follow up some of the questions touched upon in this essay may find the following references to the technical literature helpful.

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