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On the Breakdown of Newton's Law of Gravitation at Great Distances.

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Observations on the motions of terrestrial bodies, the planets and the components of double stars and the analysis of the velocity dispersion and the distribution of galaxies in clusters of galaxies show that Newton's law of gravitation adequately describes the interactions between bodies separated by distances of from about 1 cm to a million light years (10^{24} cm). The nonexistence of clusters of clusters of galaxies and the smallness of the velocity dispersion among neighboring clusters of galaxies prove, however, that Newton's law is not universal but breaks down for bodies separated by more than a few million light years.

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In our endeavour to extend the frontiers of science it is important to check on the range of validity of the laws of physics and to search for new laws in the realms of experimentally established new phenomena. In the following we report on findings obtained through the observational analysis of the gravitational interactions between bodies which are separated by ever increasing distances.

Extended observations on galaxies and on clusters of galaxies at the Palomar Observatory led to the conclusion that in all probability Newton's universal law of gravitational attraction ceases to be valid when distances of the order of ten million light years or greater are considered. The analysis of the interactions of massive bodies which are separated by distances of the mentioned order indicates that, either there is no force acting at all between such bodies, or this force is much smaller than would be expected on the basis of Newton's $1/r^2$ law. Actually, according to the observations available at the present time, the force of attraction for very widely separated bodies might even have to be replaced by a force of repulsion.

Newton's law of gravitational attraction was originally derived from observations of the motions of the moon and of the planets; Newton postulated that "every particle of matter in the universe attracts every other particle with a force varying inversely as the square of their mutual distances and directly as the mass of the attracting particles." Newton, combining his law of gravitation with his famous laws of motion, successfully accounted for all of the observations available to him on the motions of planets, their satellites and the motions of comets.

With the construction of exceedingly sensitive recording instruments it also became possible to verify Newton's law in the interaction between bodies on or near the earth's surface as well as in their interactions with the earth itself.

The only strict proof of the validity of Newton's law in the spaces beyond the boundaries of the planetary system was given in connection with the motions of the components of <u>double stars</u>. A great many of these systems have been studied since Savary first showed in 1830 that the motions of the components of certain double stars observed by Sir William Herschel and F.W.G. Struve could be interpreted on the basis of Newton's law of gravitation and his laws of motion.

Kepler's laws of motion were checked for many double stars which lie at distances nearer than 700 light years. The components of double stars were proved to interact according to Newton's law. This proof is restricted to separations between the component stars not exceeding the dimensions of the solar system. From observations on double stars we therefore only know that Newton's law of gravitation, within the limited observational accuracy, describes the interactions between stars separated by distances not greater than one thousandth of a light year and that these interactions are the same for double stars within a sphere of 700 light years radius.

Beyond these proofs for the validity of Newton's universal law of gravitation, however, no further fundamental progress was made during almost one hundred years. For instance, no one succeeded in proving decisively that the billinos of stars within the Milky Way system or within any other galaxy interact accurately in accordance with Newton's law, although it is of course quite apparent that forces of attraction operate between these stars. They indeed show an obvious tendency for clustering, and the rotation of the Milky Way does not make them fly apart and disperse into interstellar space, as they would if the "centrifugal forces" were not held in check by forces of attraction directed toward the center of our galaxy.

Quite recently, however, and peculiarly enough, the study of the internal structure of clusters of galaxies led to a new proof for the near universality of Newton's law of gravitation. Zwicky[1] showed about twenty years ago that the distribution of bright and faint galaxies within globular clusters of galaxies, as well as their velocity distribution, can only be explained if it is assumed that Newton's inverse square law regulates the interactions between galaxies in clusters of galaxies. Zwicky's study of the physical conditions within clusters of galaxies led thus to a proof that Newton's law governs the interactions among galaxies separated by distances as large as several million light years, although it had not been possible to demonstrate decisively that the law really holds good for the interaction of stars separated by intermediate distances of only a few thousand light years.

Extending his reasoning and his observations, Zwicky[2] during the past ten years attempted to extend his analysis from the clusters of galaxies to larger units, that is clusters of clusters of galaxies, which were expected to measure ten millions of light years in diameter or more. The surprising fact, however, realized right at the start, was that the fifty or one hundred nearest clusters of galaxies are distributed quite uniformly and randomly in cosmic space and that there are neither any double nor multiple clusters of galaxies among them. A more extended analysis of about ten thousand of the nearest rich clusters of galaxies in cosmic space led to the same result. In contradistinction to the behaviour of galaxies and in violation of the expectations to be derived from Newton's law of gravitation there are no real clusters of clusters.(3) (It could be definitely shown that some slight apparent clustering was actually due to properties of optical projection and to effects of intervening clouds of interstellar and intergalactic dust.) In addition, from Newton's law we should expect a large velocity dispersion among the peculiar velocities of the centers of clusters of galaxies. This velocity dispersion was likewise found to be completely absent or much too small. These combined facts can easily be explained only on the assumption that the inverse square law of Newton ceases to be valid at distances greater than about ten million light years.

The proof for the non-validity of Newton's law at very great distances will have grave consequences for all cosmological theories, as well as for the theory of the expanding universe. Although some of the theories, such as Einstein's theory of general relativity, envisaged possible deviations from Newton's law of gravitation at distances greater than about one billion light years (as well as quantitatively insignifi- deviation at very small distances) the conclusion here drawn, that Newton's law needs a most radical modification at the relatively small distance of ten million light years, is in contradiction with all cosmological theories so far proposed.

Summarizing, we may say that, in contradistinction to expectations, neither clustering of clusters of galaxies, nor a large dispersion of peculiar velocities of the centers of clusters of galaxies exist. These observational results are complementary and interrelated. As I have suggested elsewhere,[3] some possible explanations of these results are as follows:

"1. Both results could be explained by assuming that gravitation ceases to act over distances greater than about 5 to 10 million light years (on Hubble's old distance scale), or, at least, that the mutual gravitational energy of two masses separated by such distances is smaller than about one-tenth of the energy computed from Newton's law of gravitation. If we assume this interpretation of the observations, the general theory of relativity in its present form will have to be abandoned, since the adjustment of the Einstein field equations to Newton's law for the limiting case of weak fields would not be correct.

"2. Modifications of Einstein's field equations might be caused by the following effects:

a) The gravitational field of a mass might be subject to shielding by matter surrounding this mass, the shielding being of a kind not so far considered.

b) A term of the type of the cosmological constant in the present field equations might be more important than presently assumed.

c) Contraterrene matter (now called anti-matter), might be the main constituent of, say, one-half of the clusters of galaxies, a situation in line with a suggestion made by the writer more than 20 years ago.[4] If anti-matter has negative gravitational mass, then clusters and anti-clusters would repel each other and our observations can be explained. In this case, as suggested in the original paper on the subject, hard γ rays, with energies up to 10^{18} ev, should be found in the primary cosmic rays.

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d) Attention must be called to the fact that, whatever hypothesis is finally found to be correct, the finiteness of the speed of propagation of gravitational interactions may be expected to limit the size of individual globular clusters of galaxies in some decisive manner, as we have pointed out previously.(5) This effect alone, however, cannot be responsible for both the non-existence of clusters of clusters of galaxies and for the low velocity dispersion among clusters of galaxies.

"The writer suggests that the assumption of the complete breakdown of Newton's law of gravitation for bodies separated by distances of 10 or more million light years be adopted for the present as a heuristic hypothesis, from which further conclusions should be derived and observationally tested."

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