Dark Matter and the Equivalence Principle

Joshua A. Frieman and Ben-Ami Gradwohl

The notion that there may be hidden matter in the universe has a long history. In the last century, the attribution of anomalies in the orbit of Uranus to the gravitational pull of an unseen planet led to the discovery of Neptune. More recently, analysis of the motions of stars and gas in the outer regions of galaxies and of galaxies within groups and clusters of galaxies has indicated the presence of nonluminous matter—dark matter—amounting perhaps to 90% of the total mass in these systems (*1*). A typical spiral galaxy like our own is thought to be embedded in a halo of dark matter that extends well beyond the visible disk (*2*).

Although it is usually assumed that dark matter acts through gravity alone, recent work (*3–5*), motivated in part by experimental tests of the equivalence principle (which states that inertial and gravitational mass are the same), shows that this assumption can be put to the test: dark matter, it turns out, must act on visible matter mainly by gravity, but the presence of an additional long-range interaction at the 10% level cannot be ruled out. The nongravitational interaction between dark matter particles is also tightly constrained by astrophysical observations, but its strength can still be of the same order as gravity.

Unseen forces? The nearby Andromeda galaxy: Is its dark halo tugging on the Milky Way with a force stronger than gravity?

Knowledge of the amount and spatial distribution of dark matter is limited and fragmentary. Cosmologists would like to know if the universe contains enough matter, dark plus visible, such that it will eventually recollapse. At present we can say for certain only that the total density is within a factor of 10 of this critical value.

Even less is known about the composition of the dark matter. Proposals for its identity run the gamut from supermassive black holes of as much as a million solar masses to hypothetical elementary particles weighing as little as a ten-billionth of an electron mass; theories of particle physics have provided a gallery of exotic dark matter candidates, including axions, massive neutrinos, and weakly interacting massive particles, known as WIMPs. Occupying a more prosaic middle ground among dark matter candidates are brown dwarfs, essentially large planets with less than a tenth of the mass of the sun. Brown dwarfs, recently dubbed MACHOs for "massive compact halo objects," are not hot enough to burn hydrogen and are therefore very faint. As if this were not complicated enough, there is no guarantee that the cosmic dark matter might not be a mixture of several quite different species.

Astrophysicists distinguish between two broad classes of dark matter candidates, baryonic (made primarily of protons and neutrons, or more fundamentally of quarks) and nonbaryonic. Prime examples from these two categories are MACHOs and WIMPs, respectively. Cosmological nucleosynthesis (the generation of helium, deuterium, and lithium in the first 3 min) seems to require more baryonic matter than astronomers see in the form of visible galaxies, suggesting that at least some of the dark matter is baryonic. In fact, the dark matter in galaxies could perhaps be made entirely from baryons. Beyond the scale of galaxies, however, a greater proportion of dark matter is indicated, which would likely be nonbaryonic in nature. Whether the dark matter in the universe is predominantly baryonic or of more exotic nonbaryonic composition must ultimately be decided by experiment and a number of observational searches to detect axions, WIMPs, and MACHOs in the halo of our own galaxy are now in progress.

The existence of dark matter is inferred from its acceleration of ordinary luminous matter, such as stars and gas, and its deflection of light in gravitational lenses. Normally one assumes that the interaction between dark and ordinary matter is purely gravitational; although this assumption is consistent with the observational evidence, it is open to question as long as the nature of the dark matter remains unknown. In particular, if the dark matter consists of nonbaryonic particles, then according to several models of particle physics, they could interact through a long-range force comparable with or even stronger than gravity. If this were the case, inferences from observations of stellar and galactic motions about the density of dark matter in the universe would be seriously compromised. Recently, several authors (*3–5*) have studied the experimental and astrophysical evidence to see what can be deduced about any long-range nongravitational interactions of dark matter.

Fundamental forces are usefully characterized by their range and strength relative to gravity. The range of a force is roughly the separation out to which an inverse-square law holds. Gravity and electromagnetism follow inverse-square laws at all distances and thus have infinite range, whereas the short-range weak force is strongly suppressed at distances larger than the nuclear scale. Range is inversely proportional to the mass of the exchanged boson which, in the language of particle physics, mediates the force: the electromagnetic interaction is mediated by the massless photon, but the W and Z bosons of the weak interaction are heavy. Any new long-range force pertaining to dark matter would have to be mediated by a massless or very light particle.

Einstein's equivalence principle asserts that local measurements cannot distinguish a system at rest in a gravitational field from one which is in uniform acceleration in empty space. It implies that two electrically neutral bodies of different composition will be accelerated equally toward a third body (the "source"). Following pioneering work by Dicke and co-workers in 1964 and Braginsky and co-workers in the early 1970s, the most

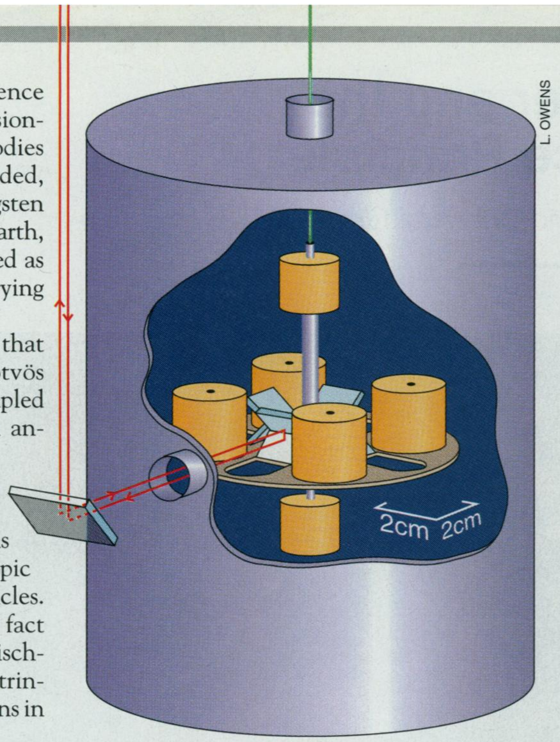
J. A. Frieman is at the NASA/Fermilab Astrophysics Center, Fermi National Accelerator Laboratory, Batavia, IL 60510. B.-A. Gradwohl is in the Department of Physics, University of California, Los Angeles, CA 90024.

sensitive modern tests of the equivalence principle have been achieved with torsion-balance experiments, in which two bodies of different compositions are suspended, like a dumbbell, from a quartz or tungsten fiber. In these experiments, the sun, the Earth, and various man-made objects were used as the sources to probe for forces of varying ranges (*6*).

In 1986, Fischbach *et al.* (*7*) claimed that reanalysis of the classic 1922 von Eötvös test of the equivalence principle, coupled with geophysical data on gravitational anomalies in mines, showed evidence for a new composition-dependent force of nature (the "fifth force"). Subsequently, a large experimental effort was undertaken to search for new macroscopic forces between ordinary (baryonic) particles. The spate of experiments has not in fact borne out the original suggestion of Fischbach *et al.* and has instead placed very stringent limits on new long-range interactions in ordinary matter (*8*).

Stubbs (*4*) and the Eöt-Wash group (*5*) have now shown how the same experimental method can be used to test for composition-dependent long-range forces between dark matter (baryonic or nonbaryonic) and ordinary matter (*9*). They consider the differential acceleration of the test bodies toward the center of our galaxy rather than toward the sun or the Earth. Stubbs (*4*) reinterprets the torsion-balance data by noting that, according to galactic halo models, the dark matter accounts for 25 to 50% of the acceleration of a body at the Earth's position toward the galactic center. From the viewpoint of a laboratory on Earth, the center of the galaxy makes a circuit across the sky once per sidereal day, so Stubbs' method is to search for differential accelerations in the torsion-balance results with a period of a sidereal day. In the same vein, the Eöt-Wash group (*5*) finds that the difference in acceleration toward the galactic center between beryllium and copper test bodies is $0.1 \pm 5.8 \times 10^{-12}$ cm s^{-2}, whereas the gravitational galactocentric acceleration attributable to the dark matter is estimated to be 6×10^{-9} cm s^{-2} (by comparison, the gravitational acceleration toward the Earth at its surface is 980 cm s^{-2}). The relative differential acceleration toward the dark matter is less than a tenth of 1%.

Once the composition dependence of the force is specified, this result gives a limit on the strength of any nongravitational force between ordinary and dark matter. For almost the entire range of parameters, the strength of any such new force must be less than a tenth that of gravity. Gravity is therefore the dominant long-range force between ordinary and dark matter (*10*). This conclusion puts on a firmer footing dynamical measurements of the dark mass within galaxies which rely on baryonic tracers (stars or gas) of the gravitational potential.



The pull of dark matter. The torsion balance used by the Eöt-Wash group to test the equivalence principle for dark matter: The instrument compared the acceleration of different test bodies toward the galactic center. A light beam directed onto one of the mirrors on the pendulum monitored its torsion oscillation. [Adapted from (*8*)]

So much for long-range forces between dark matter and ordinary matter. What can we say about the long-range interaction between two dark matter particles? Laboratory tests are of no use here, because experimentalists only have ordinary matter at their disposal, but some astrophysical tests are relevant (*3*). For example, since there exist gravitationally bound systems, such as galaxies and clusters, that are composed predominantly of dark matter, any long-range repulsive force must be weaker than gravity so that it does not unbind these systems.

In systems such as binary galaxies, groups, and clusters, individual galaxies are used as test particles to trace the gravitational potential and thus to determine the mass of the system. But if the galaxy mass is dominated by nonbaryonic dark matter interacting in part through a new long-range force, such dynamical mass estimates will be wrong. A repulsive force would delude us into believing that the system's mass, and therefore the density of the universe inferred from it, is smaller than it actually is; for example, a universe with greater than the critical density for recollapse could masquerade as a low-density universe that expands forever.

The Milky Way and the Andromeda galaxy, our nearest large neighbor, form a binary system with a separation of 2 million light-years. From the speed at which the two galaxies are known to be approaching, Kepler's law permits an estimate of their combined mass. The combined mass, which is sensitive to the dark matter interaction, must obviously be larger than the estimated mass of our own galaxy alone, which is insensitive to the dark matter–dark matter force because it is inferred from the motion of baryonic tracers, such as stars and gas, in the galactic disk. For the Andromeda–Milky Way system, any additional force must be less than roughly four times the strength of gravity.

Tighter constraints are obtained by considering the distribution of hot, x-ray–emitting gas in galaxy clusters, recently observed in unprecedented detail by the ROSAT satellite. These cluster observations indicate that the force between dark matter particles can, in fact, be no stronger than gravity. A similar constraint comes from the gravitational lensing of distant galaxies by foreground clusters.

Cosmology is the largest arena in which the effects of an additional dark matter interaction would be played out. A new force would dramatically affect the growth of the density inhomogeneities that are believed to have been the seeds of galaxies. Density perturbations grow more rapidly for an attractive interaction, or more slowly for a repulsive force, compared with their behavior with gravity alone. If gravity is the sole interaction, the equivalence principle forces the amplitude of the baryonic density fluctuations to track that of the dark matter. An additional force acting on the dark matter breaks this constraint and generates a scale-dependent "bias" between the dark matter and the baryons: on small scales, the dark matter clumps together more or less strongly than the baryons if there is an attractive or a repulsive force. In the view of many cosmologists, such a bias, with baryons more clustered than the dark matter, plays an important role in the observed clustering of galaxies. More generally, a long-range dark matter force has important implications for large-scale structure formation and the microwave background anisotropy detected in 1992 by the COBE satellite.

References and Notes

1. S. Tremaine, *Phys. Today* **45**, 29 (February 1992); A. Tyson, *ibid.*, p. 24 (June 1992).
2. J. Primack, D. Seckel, B. Sadoulet, *Annu. Rev. Nucl. Part. Sci.* **38**, 751 (1988).
3. J. A. Frieman and B. Gradwohl, *Phys. Rev. Lett.* **67**, 2926 (1991); B. Gradwohl and J. A. Frieman, *Astrophys. J.* **398**, 407 (1992).
4. C. W. Stubbs, *Phys. Rev. Lett.* **70**, 119 (1993).
5. G. Smith, E. G. Adelberger, B. R. Heckel, Y. Su, *ibid.*, p. 123.
6. C. M. Will, *Theory and Experiment in Gravitational Physics* (Cambridge Univ. Press, New York, 1985).
7. E. Fischbach *et al.*, *Phys. Rev. Lett.* **56**, 3 (1986).
8. E. G. Adelberger, B. R. Heckel, C. W. Stubbs, W. F. Rogers, *Annu. Rev. Nucl. Part. Sci.* **41**, 269 (1991).
9. For technical reasons, they used three different test materials.
10. This bound applies for a force range comparable with or larger than the distance of the Earth from the center of the galaxy, roughly 8.5 kpc (about 28,000 light-years).