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Preface. Through a glass, darkly

The planet Uranus was discovered in 1781 by the British astronomer William Herschel. Not long after its discovery, astronomers charting the orbit of Uranus found small discrepancies between the predicted and observed positions of the planet. In September 1845, British astronomer John Adams proved mathematically that the deviations in Uranus' orbit could not result merely from the gravitational pull of the other known planets and he predicted the existence of another, previously undetected planet in the solar system. The eventual discovery of the planet Neptune in September 1846 by the German astronomer Johann Galle thus marked the first detection of astronomical "dark matter" whose presence was first deduced by its gravitational effects. However, in the history of physics, we also find a case in which the assumption about the existence of an unseen medium was later proven to be totally wrong. Until 1887, physicists assumed that *aether*—a substance that pervades all space—was a necessary medium for the propagation of light. A famous experiment by American researchers Albert Michelson and Howard Morley not only showed unambiguously that this medium does not exist, but the experimental results also set Einstein on the road to a new theory of space and time—special relativity.

Astrophysicists today are faced with a similar "Neptune vs. aether" dilemma. On the face of it, there are many indications that about 90% of the *matter* in our universe is in the form of "dark matter"—matter whose constituents do not emit electromagnetic radiation and that interact very weakly with ordinary matter. The luminous galaxies we see are just like the tiny minilights on a huge, dark, Christmas tree. The existence and amount of the "dark matter" is deduced, for example, from the speeds of galaxies in clusters of galaxies. In equilibrium, the gravitational force of all the matter in the cluster exactly balances the proneness of the galaxies to scatter in all directions. Careful determinations of the speeds thus "weigh" the cluster. Other observations, like *gravitational lensing*—the bending of light from distant sources by the cluster's gravity—also confirm that about 90% of the mass in clusters is dark.

The most likely candidates for the constituents of the dark matter are some exotic elementary particles that are relics of the very early, high-energy universe. Elementary particle theories that link fermions (that have a fractional quantum mechanical spin) and bosons (with integer spin) are known as supersymmetry (or, affectionately, SUSY) theories. Supersymmetry requires the existence of (yet undiscovered) fractional spin, neutral, massive partners to integer spin particles like the photon. The lightest members of this menagerie of SUSY particles are known as *neutralinos* and they are the leading candidates for dark matter.

However, there is another possibility, in principle, to explain the extra gravity usually attributed to dark matter. The idea behind this alternative is similar in spirit to the lesson learned from the aether. Instead of requiring the existence of an unseen medium, maybe the *theory* of gravity itself needs to be changed. One proposed modification suggests that our three-dimensional (plus time) universe with all of its elementary particles is stuck to a (three-dimensional) membrane that exists in a higher-dimensional space. Particles like protons and electrons cannot move in the extra dimensions and neither can the electromagnetic fields (a bit like electrons being confined to move along a copper wire). Gravity and its carrier—the graviton—can, on the other hand, extend and travel into the higher-dimensional space. In this model, the gravitational effects we attribute to dark matter could simply represent the gravity of matter that resides in a membrane/universe parallel to ours. Photons cannot travel throughout the extra dimension separating the

parallel universes and consequently the matter in the parallel universe is necessarily "dark" to our detectors.

Luckily, experiments planned for the coming decade will be able to distinguish between the "Neptune" and "Aether" options. The Large Hadron Collider (LHC), the world's most powerful particle accelerator which is being built in Geneva, is less than a decade away from achieving the energy range (proton beams with 7-on-7 TeV) needed to discover neutralinos. The LHC could also discover particles predicted to exist by the new theories of gravity. Furthermore, the new theory predicts deviations from Newton's inverse square law at submillimeter distances. No fewer than four experiments are expected to test gravity at these small distances during the coming few months to years.

As if the existence of dark matter was not puzzling enough, since 1998 there exists strong evidence that most of the universe's total energy density is in the form of an even more mysterious "dark energy." Observing a few dozen stellar explosions known as Type Ia supernovae at redshifts of order $z \sim 0.5$–1, two teams discovered that the expansion of the universe is accelerating!

Type Ia supernovae are extremely bright (occasionally outshining an entire galaxy) events representing the complete thermonuclear disruptions of white dwarf stars. Since Type Ia supernovae are nearly perfect "standard candles" (their small deviations from a constant luminosity are well calibrated), they can be used as superb distance indicators to distances spanning half the universe's age. The expectation prior to 1998 was that distant supernovae would reveal that the universe had been expanding in the past *faster* than predicted by a simple Hubble expansion, because of the deceleration caused by gravity. Instead, the two teams found (independently) that the distant supernovae were receding *slower* than the Hubble law, implying an accelerating cosmic expansion propelled by some "dark energy." The pressure associated with this dark energy is negative, resulting in gravity becoming a *repulsive* force. The observations, together with measurements of the anisotropy of the cosmic microwave background radiation, suggest that the energy density in the dark energy is about 73% that required for a geometrically flat universe.

The precise nature of the dark energy is probably the greatest mystery of today's physics. It is generally assumed that this dark energy represents the energy associated with the physical *vacuum*. However, the value of the observed energy density is some 55 orders of magnitude smaller than that expected from supersymmetry considerations. Currently, it is not even clear if the dark energy density is constant in time, as would be expected for Einstein's "Cosmological Constant" (introduced to produce a static universe), or evolving as some uniform scalar field (dubbed "quintessence"). It is also possible, in principle, that the accelerating universe and the deduced dark energy are also manifestations of the need for a new theory of gravity.

The Space Telescope Science Institute Symposium on "The Dark Universe: Matter, Energy, and Gravity" took place during 2–5 April 2001.

These proceedings represent a part of the invited talks that were presented at the symposium, in order of presentation. We thank the contributing authors for preparing their papers.

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