DARK MATTER

Written and compiled by Aurora G. Miller,
Chief Science Officer USS Odyssey

A note to the reader/user of this article: however this article is drawn from official sources and lecture, it may contain fictional contents or estimates which have not yet proven.

Should you have any questions concerning this article and the things in it feel free to ask or leave a message, however I cannot guarantee that I will know the answer to every question you might have, I will do my best to answer them.

Introduction

A great deal of effort has been made since 1687, the year of publication of Issac Newton's classic work "Philosophiae Naturalis Principia Mathematica", towards explaining the motion of astrophysical objects in terms of the laws of gravitation. Since then, the deviations of observed motions from expected trajectories have proved very effective in deepening our understanding of the Universe. Whenever anomalies were observed in the motion of planets in the Solar system, the question arose: should such anomalies be regarded as a refutation of the laws of gravitation or as an indication of the existence of unseen (today we would say "dark") objects?

The second approach proved to be correct in the case of the anomalous motion of Uranus, which led the French astronomer U. Le Verrier and the English astronomer John Couch Adams to conjecture the existence of Neptune, eventually discovered in 1846 by J.G. Galle. Conversely, the attempt to explain the anomalies in the motion of Mercury as due to the existence of a new planet, called Vulcan, failed, and the final solution had to wait for the advent of Einstein's theory of general relativity, i.e. the introduction of a more refined description of the laws of gravitation.

The modern problem of dark matter is conceptually very similar to the old problem of unseen planets. We observe in large astrophysical systems, with sizes ranging from galactic to cosmological scales, some "anomalies" that can only be explained either by assuming the existence of a large amount of unseen, dark, matter, or by assuming a deviation from the known laws of gravitation and the theory of general relativity.

There is compelling evidence for the existence of dark matter. Although our understanding of its nature and distribution is still incomplete, many independent observations suggest that about 30% of the total energy density of the Universe is made of some sort of non-baryonic dark matter. The dark matter problem is not only relevant to astrophysicists but also to the particle and high-energy physics community. In fact, some of the best dark matter candidates come from possible extensions of the Standard Model of particle physics. There is certainly no shortage of particle dark matter candidates found in such models.

Although many simple models of supersymmetry, extra dimensions or other scenarios are widely discussed by the particle and astro-particle communities, the phenomenology of the actual physical theory could be more rich and complex. Collider experiments are probing significant regions of the parameter space of these hypothetical particles. Conversely, a positive astrophysical detection of dark matter would provide invaluable information regarding the physics “beyond the Standard Model”.

Beyond the standard model of Physics

The concepts of dark energy and dark matter do not find an explanation in the framework of the Standard Model of particle physics. Nor are they understood in any quantitative sense in terms of astrophysics. It is interesting that also in the realm of particle physics, evidence is accumulating for the existence of physics beyond the Standard Model, based on theoretical and perhaps experimental arguments.

On the experimental side, there is strong evidence for oscillations of atmospheric neutrinos (originating from electromagnetic cascades initiated by cosmic rays in the upper atmosphere) and solar neutrinos. The oscillation mechanism can be explained under the hypothesis that neutrinos do have mass, in contrast to the zero mass neutrinos of the Standard Model.

On the theoretical side, many issues make the Standard Model unsatisfactory, for example the hierarchy problem, i.e. the enormous difference between the weak and Planck scales in the presence of the Higgs field, or the problem of unification addressing the question of whether there exists a unified description of all known forces, possibly including gravity, known as the String Theorem.

This is a typical example of the strong interplay between particle physics, theoretical physics, cosmology and astrophysics. From one side, theoretical particle physics stimulates the formulation of new theories predicting new particles that turn out to be excellent dark matter candidates. On the other side, cosmological and astrophysical observations constrain the properties of such particles and consequently the parameters of the new theories.

Terminology

But exactly is dark matter? Where does it come from and what role does it play in space? In the article I will try to shed some light on the concept of dark matter and its influences in the galaxy, no doubt I will leave certain things unsaid or ill explained but this article is meant to present a general overview, not a paper meant to be written for a scientific public.

In astronomy and cosmology, dark matter is a theoretical form of matter that is undetectable by its emitted radiation, but whose presence can be inferred from gravitational effects on visible matter. According to present observations of structures larger than galaxies, as well as Big Bang cosmology, dark matter and dark energy could account for the vast majority of the mass in the observable universe.

Dark matter is believed to play a central role in structure formation and galaxy evolution, and has measurable effects on the anisotropy of the cosmic microwave background. All these lines of evidence suggest that galaxies, clusters of galaxies, and the universe as a whole contain far more matter than that which interacts with electromagnetic radiation: the remainder is frequently called the "dark matter component," even though there is a small amount of baryonic dark matter. The largest part of dark matter, which does not interact with electromagnetic radiation, is not only "dark" but also, by definition, utterly transparent.

The vast majority of the dark matter in the universe is believed to be nonbaryonic, which means that it contains no atoms and that it does not interact with ordinary matter via electromagnetic forces. The nonbaryonic dark matter includes neutrinos, and possibly hypothetical entities such as axions, or supersymmetric particles. Unlike baryonic dark matter, nonbaryonic dark matter does not contribute to the formation of the elements in the early universe ("big bang nucleosynthesis") and so its presence is revealed only via its gravitational attraction. In addition, if the particles of which it is composed are supersymmetric, they can undergo annihilation interactions with themselves resulting in observable by-products such as photons and neutrinos ("indirect detection").

Nonbaryonic dark matter is classified in terms of the mass of the particle(s) that is assumed to make it up, and/or the typical velocity dispersion of those particles (since more massive particles move more slowly). There are three prominent hypotheses on nonbaryonic dark matter, called Hot Dark Matter (HDM), Warm Dark Matter (WDM), and Cold Dark Matter (CDM); some combination of these is also possible. The most widely discussed models for nonbaryonic dark matter are based on the Cold Dark Matter hypothesis, and the corresponding particle is most commonly assumed to be a neutralino. Hot dark matter might consist of (massive) neutrinos. Cold dark matter would lead to a "bottom-up" formation of structure in the universe while hot dark matter would result in a "top-down" formation scenario.

Observations and evidence for dark matter

The first person to provide evidence and infer the presence of *dark matter* was Swiss astrophysicist Fritz Zwicky, of the California Institute of Technology in 1933. He applied the virial theorem to the Coma cluster of galaxies and obtained evidence of unseen mass. Zwicky estimated the cluster's total mass based on the motions of galaxies near its edge and compared that estimate to one based on the number of galaxies and total brightness of the cluster. He found that there was about 400 times more estimated mass than was visually observable. The gravity of the visible galaxies in the cluster would be far too small for such fast orbits, so something extra was required. This is known as the "missing mass problem". Based on these conclusions, Zwicky inferred that there must be some non-visible form of matter which would provide enough of the mass and gravity to hold the cluster together.

Much of the evidence for dark matter comes from the study of the motions of galaxies. Many of these appear to be fairly uniform, so by the virial theorem the total kinetic energy should be half the total gravitational binding energy of the galaxies. Experimentally, however, the total kinetic energy is found to be much greater: in particular, assuming the gravitational mass is due to only the visible matter of the galaxy, stars far from the center of galaxies have much higher velocities than predicted by the virial theorem. Galactic rotation curves, which illustrate the velocity of rotation versus the distance from the galactic center, cannot be explained by only the visible matter. Assuming that the visible material makes up only a small part of the cluster is the most straightforward way of accounting for this.

Galaxies show signs of being composed largely of a roughly spherically symmetric, centrally concentrated halo of dark matter with the visible matter concentrated in a disc at the center. Low surface brightness dwarf galaxies are important sources of information for studying dark matter, as they have an uncommonly low ratio of visible matter to dark matter, and have few bright stars at the center which would otherwise impair observations of the rotation curve of outlying stars.

For 40 years after Zwicky's initial observations, no other corroborating observations indicated that the mass to light ratio was anything other than unity (a high mass-to-light ratio indicates the presence of dark matter). Then, in the late 1960s and early 1970s, Vera Rubin, a young astronomer at the Department of Terrestrial Magnetism at the Carnegie Institution of Washington presented findings based on a new sensitive spectrograph that could measure the velocity curve of edge-on spiral galaxies to a greater degree of accuracy than had ever before been achieved.

Together with fellow staff-member Kent Ford, Rubin announced at a 1975 meeting of the American Astronomical Society the astonishing discovery that most stars in spiral galaxies orbit at roughly the same speed, which implied that their mass densities were uniform well beyond the locations with most of the stars (the galactic bulge). An influential paper presented these results in 1980. These results suggest that either Newtonian gravity does not apply universally or that, conservatively, upwards of 50% of the mass of galaxies was contained in the relatively dark galactic halo. Met with skepticism, Rubin insisted that the observations were correct. Eventually other astronomers began to corroborate her work and it soon became well-established that most galaxies were in fact dominated by "dark matter".

Structure formation

Dark matter is crucial to the Big Bang model of cosmology as a component which corresponds directly to measurements of the parameters associated with Friedmann cosmology solutions to general relativity. In particular, measurements of the cosmic microwave background anisotropies correspond to a cosmology where much of the matter interacts with photons more weakly than the known forces that couple light interactions to baryonic matter. Likewise, a significant amount of non-baryonic, cold matter is necessary to explain the large-scale structure of the universe.

Observations suggest that structure formation in the universe proceeds hierarchically, with the smallest structures collapsing first and followed by galaxies and then clusters of galaxies. As the structures collapse in the evolving universe, they begin to "light up" as the baryonic matter heats up through gravitational contraction and the object approaches hydrostatic pressure balance. Ordinary baryonic matter had too high a temperature, and too much pressure left over from the Big Bang to collapse and form smaller structures, such as stars, via the Jeans instability. Dark matter acts as a compactor of structure. This model not only corresponds with statistical surveying of the visible structure in the universe but also corresponds precisely to the dark matter predictions of the cosmic microwave background.

This *bottom up* model of structure formation requires something like cold dark matter to succeed. Large computer simulations of billions of dark matter particles have been used to confirm that the cold dark matter model of structure formation is consistent with the structures observed in the universe through galaxy surveys.

Composition of Dark Matter

That we can observe it doesn't mean that we can now understand what dark matter is, where it comes from, in fact many aspects of it remain speculative. It has been noted that the names "dark matter" and "dark energy" serve mainly as expressions of human ignorance, much like the marking of early maps with "terra incognita."

At present, the most common view is that dark matter is primarily non-baryonic, made of one or more elementary particles other than the usual electrons, protons, neutrons, and known neutrinos. The most commonly proposed particles are axions, sterile neutrinos, and WIMPs (Weakly Interacting Massive Particles, including neutralinos).

None of these are part of the standard model of particle physics, but they can arise in extensions to the standard model. Dark matter and dark energy represent the most popular theory among physicists and cosmologists to explain the various anomalies that Zwicky and subsequent researchers have observed. However, direct observational evidence of dark matter has remained elusive.

Other views on the 'dark matter problem'

A minority of scientists have suggested that the existence of a vast amount of undetected matter is less likely than the possibility that current theories of gravitation are simply incomplete (much like the now discredited theory of ether, once thought to be the medium through which light travels, but overturned in the early 20th century, or the chemical substance phlogiston). None of these alternatives, however, have garnered equally widespread support in the scientific community.

A proposed alternative to physical dark matter particles has been to suppose that the observed inconsistencies are due to an incomplete understanding of gravitation. To explain the observations, the gravitational force has to become stronger than the Newtonian approximation at great distances or in weak fields. One of the proposed models is Modified Newtonian Dynamics (MOND), which adjusts Newton's laws at small acceleration. However, constructing a relativistic MOND theory has been troublesome, and it is not clear how the theory can be reconciled with gravitational lensing measurements of the deflection of light around galaxies.

The leading relativistic MOND theory, proposed by Jacob Bekenstein in 2004 is called TeVeS for Tensor-Vector-Scalar and solves many of the problems of earlier attempts. However, a study in August 2006 reported an observation of a pair of colliding galaxy clusters whose behavior, it was claimed, was not compatible with any current modified gravity theories. In 2007, John W. Moffat proposed a theory of modified gravity (MOG) based on the Nonsymmetric Gravitational Theory (NGT) that claims to account for the behavior of colliding galaxies. This theory still requires the presence of non-relativistic neutrinos (another candidate for (cold) dark matter) to work: modified gravity alone is not sufficient.