Dark matter universe

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Most of the mass in the universe is in the form of dark matter—a new type of nonbaryonic particle not yet detected in the laboratory or in other detection experiments. The evidence for the existence of dark matter through its gravitational impact is clear in astronomical observations—from the early observations of the large motions of galaxies in clusters and the motions of stars and gas in galaxies, to observations of the large-scale structure in the universe, gravitational lensing, and the cosmic microwave background. The extensive data consistently show the dominance of dark matter and quantify its amount and distribution, assuming general relativity is valid. The data inform us that the dark matter is nonbaryonic, is "cold" (i.e., moves nonrelativistically in the early universe), and interacts only weakly with matter other than by gravity. The current Lambda cold dark matter cosmology—a simple (but strange) flat cold dark matter model dominated by a cosmological constant Lambda, with only six basic parameters (including the density of matter and of baryons, the initial mass fluctuations amplitude and its scale dependence, and the age of the universe and of the first stars)—fits remarkably well all the accumulated data. However, what is the dark matter? This is one of the most fundamental open questions in cosmology and particle physics. Its existence requires an extension of our current understanding of particle physics or otherwise point to a modification of gravity on cosmological scales. The exploration and ultimate detection of dark matter are led by experiments for direct and indirect detection of this yet mysterious particle.

Astronomical Evidence for Dark Matter

The evidence for the existence of dark matter has been known from astronomical observations for over eight decades. It has been tested and reinforced since then by a broad range of astronomical data. From the early pioneering observations by Fritz Zwicky in 1933 (1), who showed that the velocities of galaxies in the Coma cluster greatly exceeded the expectations based solely on the sum of the individual galaxy masses, thus requiring significant additional "dark matter," to observations in the 1970s of the motion of gas and stars in the outskirts of galaxies (refs. 2–4 and references therein), to theoretical arguments that showed that the local group and disk galaxies require significant dark matter halos for their dynamical stability (5–7), all established the early recognition of the existence of dark matter. More detailed observations of clusters of galaxies and large-scale structure further revealed the amount and distribution of the dark matter on large scales, showing that the total mass density of the universe is ~25% of the critical density (refs. 8–12 and references therein). Gravitational lensing observations by galaxies, clusters of galaxies, and large-scale structure provided important results that directly confirmed the existence of dark matter and measured its distribution on both small and large scales (e.g., refs. 13–15 and references therein). The accumulated data showed that the total amount of matter in the universe is approximately five times greater than the amount of baryonic matter (e.g., refs. 16 and 17), and it showed that the dark matter is mainly concentrated in large halos of galaxies and in clusters of galaxies (9, 12). These data provide a clear observational indication that the dark matter is nonbaryonic: the baryons in the universe constitute only $\Omega_b \sim 0.045$ of the critical density, based on observations of the deuterium and other light element abundances (18, 19), as well as on the precise observations of the cosmic microwave background (CMB) spectrum of density fluctuations and its baryon acoustic oscillations (16, 17). Thus, because the total mass density of the universe greatly exceeds the baryonic mass, with $\Omega_m \sim 0.25$ versus $\Omega_b \sim 0.045$, the dark matter has to be nonbaryonic (with $\Omega_{dm} \sim 0.2$). [Not all of the baryons in the universe shine; some baryons are "dark," such as stellar remnants, planets, rocks, etc.; these "dark baryons" are part of the $\Omega_b = 0.045$ baryonic budget, not the dark matter.] The recent observations of the CMB (16, 17) beautifully support all of the above findings and provide considerably more precise determination of the mass density of both the dark and baryonic matter. All of the data—from galaxies, to clusters, to large-scale structure, to the CMB—further constrain some of the main properties of the dark matter: it has only weak interactions, if any, with matter other than by gravity; it has to be "cold" (i.e., moving nonrelativistically in the early universe) because it clusters on small scales of galaxies and clusters; and it has to be nonbaryonic because the total mass greatly exceeds the amount of baryons in the universe. The cosmic baryon fraction in the universe is observed to be only $\Omega_b/\Omega_m \sim 0.17$ (16, 17).

Clusters of galaxies, the largest gravitationally stable systems in the universe, have served as important tools in the study of dark matter, helping reveal its nature and properties—from the original discovery of dark matter by Zwicky to numerous following studies in the optical, X-rays, lensing, and more. In the 1980s and 1990s, Bahcall and collaborators (refs. 8–11 and references therein) used clusters to show that, although they contain a large amount of dark matter, the total mass density of the universe inferred from clusters is low, $\Omega_m \sim 0.2$–0.3. They further showed that, although the mass distribution on galactic scale is considerably more extended than the distribution of light, reflecting the large dark matter halos around galaxies, this changes on the larger scales of clusters and large-scale structure where the mass follows light on all scales with a nearly constant mass-to-light ratio (9, 12). In 1993, White et al. (20) showed that the baryon fraction in clusters, which are expected to be representative of the universe, is greater than ~15%, nicely consistent with the recent CMB observations of the cosmic baryon fraction; this provided an additional early indication that the mass density of the universe is low (subcritical). Gravitational lensing observations of clusters directly measure the more detailed mass distribution in these systems and enable an improved understanding of the nature and clustering of dark matter.

This paper serves as an introduction to the PNAS Colloquium articles, which resulted from the Arthur M. Sackler Colloquium of the National Academy of Sciences, "Dark Matter Universe: On the Threshold of Discovery," held October 18–20, 2012, at the Arnold and Mabel Beckman Center of the National Academies of Sciences and Engineering in Irvine, CA. The complete program and audio files of most presentations are available on the NAS website at www.nasonline.org/programs/sackler-colloquia/completed_colloquia/dark-matter.html.

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All of the astronomical evidence for dark matter and its properties discussed above assume that general relativity is valid on large scales. Modifying this basic assumption will naturally affect the conclusions regarding dark matter. Models such as modified Newtonian dynamics (21) or other modification of gravity, change the basic physics of gravitation to eliminate the need for dark matter. Such phenomenological models, although not completely ruled out, have serious difficulties in fitting the precise observations available to date, especially those of clusters of galaxies (e.g., the Bullet cluster) and the CMB. [See discussion by Peebles (22) in this colloquium.] The amazing success of the current Lambda cold dark matter (LCDM) model to provide a remarkably consistent agreement with all of the accumulated observations on large scales—from the CMB, to large-scale structure, clusters and galaxies, gravitational lensing, baryon acoustic oscillations, and supernovae observations of the cosmic accelerated expansion—illustrate a triumph for cosmology and physics, even though the full interpretation of the meaning of "LCDM" (e.g., cosmological constant, cold dark matter, etc.) may not yet be the final word.

Although the LCDM model has been remarkably successful in explaining the observed cosmological data on large scales and over a huge range of redshifts, from ∼1,000 to ∼0, it has some potential challenges on small scales: in the innermost regions of dark matter halos and in the number of small dwarf satellite galaxies around normal galaxies. Weinberg discusses these "small-scale controversies" in this colloquium (23). They mostly represent a difference between cosmological dark matter simulations—which predict a cuspy distribution of dark matter in the centers of halos, and a large number of dwarf subhalo satellites around central galaxies—versus the observations that reveal a flatter dark matter distribution in the center of galaxies, and find only a small number of dwarf satellite galaxies around normal galaxies. These differences may likely be caused by complicated baryonic physics that is not yet fully accounted for in the simulations nor yet precisely understood. Efficient supernovae explosion feedback can likely flatten the cuspy centers of halos, and feedback combined with low star formation efficiency could explain the paucity of observed faint satellite dwarf subhalos galaxies around the Milky Way and other galaxies.

What Is the Dark Matter?

The dark matter, as discussed above, has to be nonbaryonic, cold, and does not interact much with matter other than by gravity. The existence of such matter requires new particles beyond the current standard model of particle physics. Many possibilities have been suggested, but so far none has been detected (see discussion in this colloquium by Peskin (24), Funk (25), and references therein). Models for the possible dark matter particle spread over a vast range of masses, from a small fraction of an electronvolt to larger than a solar mass. The most discussed possibility is that of weakly interacting massive particles (WIMPs). These are neutral, stable particles that were in thermal equilibrium in the early universe; they may be the lightest supersymmetric particles in the proposed supersymmetry extension of the standard model of particle physics. Within this class, special attention has been given to "neutralinos," the lightest supersymmetric partner of photos, the Z boson, and the Higgs bosons. The typical expected mass for WIMPs is in the range of approximately hundreds of gigaelectronvolts. The Large Hadron Collider (LHC) has been searching directly for these possible supersymmetric particles at the high energies available at the LHC. So far, none has been found. However, the parameter space of supersymmetry is large and the mass spectrum of the model may have a range that has so far evaded the LHC. The constraints from the LHC will improve in the near future and may hopefully find the dark matter particle(s) or otherwise place further tight constraints that will restrict these possible candidates. [A comprehensive discussion of the status of possible supersymmetric dark matter particles in the light of the LHC is given by Peskin (24) in this colloquium.]

In addition to possible dark matter detection with the LHC, WIMP dark matter could be detected via "direct detection" experiments in deep underground facilities, many of which have been operating for a while; and via "indirect detection" experiments, based mostly on astronomical observations searching for excess gamma-ray signals due to dark matter annihilation from regions of high dark matter density (such as the center of our galaxy, dwarf galaxies, or clusters of galaxies). Although a few positive claims have been made, such as an annual modulation signal detected in the event rate at the Gran Sasso Dark Matter (DAMA) underground experiment, the interpretation of the results have been controversial and in contradiction with other experiments. Witherell summarized the status of direct detection WIMP experiments in this colloquium.* Inconclusive claims have also been made from indirect detection methods such as the excess gamma-ray signals observed by the Fermi satellite originating from our Galactic center, a complex astrophysical environment. For a summary of indirect detection of dark matter with gamma-rays in this colloquium, see Funk (25) and Siegal-Gaskins (26).

Other frequently discussed possibilities for dark matter candidates include the axion, discussed by Rosenberg (27) in this colloquium. Ideas for more complex possibilities include a mixture of cold and warm dark matter components (the neutrinos are already one known hot dark matter but constitute a minor component), self-interacting dark matter, decaying or annihilating dark matter, primordial black holes, and more. Clear evidence from direct and indirect dark matter detection experiments would of course be needed to look for and confirm any type of dark matter possibility. In addition, the possibility of modified gravity has not yet been fully excluded.

Conclusions

Cosmology has revealed an amazing universe, filled with a "dark sector" that composes 95% of the energy density of our cosmos: only ∼5% of our universe is the normal baryonic matter we are familiar with; ∼20% of the universe is made up of the yet mysterious nonbaryonic dark matter, and ∼75% is the even more mysterious dark energy. Understanding the nature and properties of these dark sector components comprise the most fundamental open questions in cosmology and physics today. The exploration and ultimate detection of the dark matter is currently underway, with direct and indirect detection experiments as well as high-energy accelerators such as LHC, and with more precise astronomical observations. A clearer understanding of the dark matter is hopefully in sight.

*Witherell M, Summary of Direct Detection WIMP Experiments, Talk presented at Dark Matter Universe: On the Threshold of Discovery, October 18–20, 2012, Irvine, CA.

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