Dark Matter: Its Nature

What is the stuff that makes up most of the mass in the universe? The answer to this simple-sounding question is far from obvious, and actually presents one of the greatest unsolved mysteries of astrophysics, cosmology, and elementary particle physics. With conventional astronomical methods one can only see the 'luminous matter', notably in the form of stars, which reveals its presence by the emission of light. On the other hand, one can determine the gravitating mass of various systems such as spiral galaxies or galaxy clusters from their dynamical properties, and one finds a huge discrepancy relative to luminous matter. Assuming the usual law of gravity, one is led to conclude that there are large amounts of 'dark matter', a term first introduced by FRITZ ZWICKY in his seminal paper of 1933 where he studied the dynamics of GALAXY CLUSTERS.

The physical properties of dark matter can be constrained by several powerful astrophysical and cosmological arguments which disfavor 'baryonic matter' as a main constituent. This term refers to hydrogen, helium, and the heavier elements which, besides electrons, consist of protons and neutrons, falling into the 'baryon' category of ELEMENTARY PARTICLES. But some new form of matter appears to hold galaxies and galaxy clusters gravitationally together! The most popular explanation is that of 'particle dark matter' which goes back to Cowsik and McClelland who speculated in 1973 that neutrinos could play this role. However, while recent experiments indicate that neutrinos do have mass—which has been an open question for decades—it looks impossible to attribute all of the dark matter to these weakly interacting particles.

One is thus led to postulate hitherto undetected elementary particles for the cosmological dark matter. On the other hand, there are already independent particle-theory motivations for certain new particles which could well play this role. The dark-matter problem thus provides one of several links between particle physics and cosmology; it is a key ingredient of 'astroparticle physics', or alternatively 'PARTICLE ASTROPHYSICS'. The laws of the microcosm of elementary particles and the macrocosm of the largest structures in the universe, inner space and outer space, are closely intertwined!

Perhaps the most remarkable development of the 1990s is that the physics of dark matter has turned into a truly experimental science. If any of the popular speculations about the nature of dark matter are correct, this mysterious stuff may well turn up in one of the current or near-future direct search experiments.

In the following, the astrophysical motivation for the reality of dark matter and the most important astrophysical constraints on its nature will be discussed. Well-motivated candidates, current search strategies and preliminary results will then be reviewed.

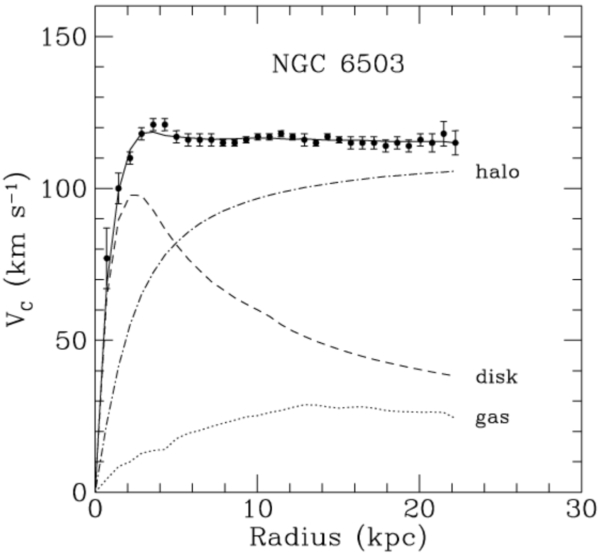

Figure 1. Rotation curve of the spiral galaxy NGC 6503 as established from radio observations of hydrogen gas in the disk (K Begeman *et al Mon. Not. R. Astron. Soc.* **249** 439 (1991)). The dashed curve shows the rotation curve expected from the disk material alone, the chain curve from the dark-matter halo alone.

Dynamical evidence

Rotation curves of spiral galaxies

Why are astronomers so sure that there are large amounts of dark matter lurking everywhere in the universe? The flat rotation curves of SPIRAL GALAXIES provide perhaps the most impressive evidence. These systems consist of a central bulge and a thin rotating disk. It is natural to measure its orbital velocity as a function of galactocentric radius by virtue of the Doppler shifts of spectral lines. Galaxy disks tend to contain neutral hydrogen which can be observed by its 21 cm line emission, allowing one to measure the rotation curves to much larger radii than with optical tracers.

The example of figure 1 illustrates the general behavior of the rotation curves. The orbital velocity rises from the center outward until it reaches a value of the order of 100 km s^{-1}, where it stays constant out to the largest measured radii, a systematic trend already diagnosed by Freeman in 1970. This behavior is entirely unexpected because the surface luminosity of the disk falls off exponentially with radius, implying that the mass M of luminous matter, mostly stars, is concentrated around the galactic center. Thus one expects a Keplerian decline of the orbital speed, $v_{\rm rot} = (G_{\rm N}M/r)^{1/2}$ (Newton's constant $G_{\rm N}$, radius r), in analogy to the planetary motions in the solar system—see the dashed line in figure 1.

The difference between the expected and measured rotation curve is ascribed to the gravitational effect of

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dark matter. A number of arguments suggest that this material is not part of the galactic disk itself. First, in our galaxy the vertical distribution of stars together with their velocity dispersion reveals that there is no significant amount of disk dark matter. Second, a thin self-gravitating disk is dynamically unstable. Third, the hydrogen is vertically more extended than would be expected if all of the gravitating matter were in the disk, especially at large radii ('hydrogen flaring').

An overall picture of spiral galaxies emerges where the bulge and disk are dynamically subdominant components immersed in a huge dark-matter halo. It is not crucial that this halo be strictly spherical; it may well be somewhat oblate or even triaxial.

For the direct detection of dark matter, our own Milky Way is the most interesting galaxy. Its rotation curve conforms to the standard picture with an approximate plateau value for the rotation velocity of 220 km s^{-1}. The dark-matter density in the solar neighbourhood implied by models of the halo is 300MeVcm^{-3} within about a factor of two, i.e. roughly the mass equivalent of a hydrogen atom per 3 cm^3. (Note that the atomic mass unit corresponds to 931.5 MeV.)

Cosmic density contribution

The contribution ρ of a given matter component to the overall density of the universe is usually expressed in terms of the 'omega parameter' $\Omega=\rho/\rho_{crit}$. Here, ρ_{crit} = $3H^2_0/(8\pi G_N) = h^2$ 1.88Ã—10^{-29} g cm^{-3} is the critical density with H_0 the present-day cosmic expansion parameter ('Hubble constant'). It is usually written as $H_0 = h$ 100 km s^{-1} Mpc^{-1}; different measurements span the approximate range h = 0.5–0.8. In the framework of the usual Friedmann–Lemaître–Robertson–Walker cosmology the spatial geometry of the universe is Euclidean for $\Omega = 1$ ('flat universe'), the spatial curvature is negative for $\Omega<1$ ('open universe'), and positive for $\Omega>1$ ('closed universe').

The cosmic density contribution of galaxies is related to the measured luminosity density of the universe, (1.7±0.6)–10^8 $h\,L_{ô}$Mpc^{-3} in the visual spectral band (solar luminosity $L_{ô}$). Most of the light is produced by stars; thus multiplying with the mass-to-light ratio for a typical stellar population of a few $M_{ô}/L_{ô}$ gives us the luminous matter density. One finds

$$\Omega_{lum}h = 0.002 - 0.006$$

to be a consistent range. Therefore, luminous matter alone is far from the critical density.

Typical mass-to-light ratios of galaxy halos are at least around 30 h as far as the measured rotation curves reach, providing a cosmic density of $\Omega_{gal} \gtrsim 0.03$–0.05. The rotation curves tend to stay flat out to the largest measured radii and thus the true size of dark-matter halos is not known. Estimating their extent from galactic satellite dynamics yields $\Omega_{gal}h$ = 0.2–0.5.

Figure 2. Hubble Space Telescope image of the galaxy cluster Abell 2218, showing a number of arcs and arclets around the two centers of the cluster. They are distorted images of background galaxies, caused by the cluster's gravitational lens effect. (NASA HST Archive.)

Clusters of galaxies

Galaxy clusters are the largest gravitationally bound systems in the universe. Zwicky first noted in 1933 that the velocities of the member galaxies tend to be so large that huge amounts of dark matter are needed to bind them gravitationally. Taking a cluster mass-to-light ratio of around 300 $M_{ô}/L_{ô}$ as representative for the universe leads to a cosmic matter density of Ω_M = 0.1–0.4.

Recently it has become possible to measure cluster masses from the image distortion of background galaxies caused by the cluster's gravitational light deflection ('weak gravitational lensing'); an example is shown in figure 2. One uses the statistical distribution of these 'arclets' to reconstruct the shear field of gravitational image distortions and from there one can derive cluster mass distributions. (see GRAVITATIONAL LENSISNG BY CLUSTERS OF GALAXIES). They confirm the large mass-to-light ratios inferred by Zwicky's method.

When X-RAY TELESCOPES became available in the mid-1960s, galaxy clusters were found to be the most powerful x-ray sources in the sky. The emission is extended over the entire cluster and thus reveals the presence of large amounts of hot gas ($T = 10^7$–10^8 K) where x-rays are produced by electron bremsstrahlung. The mass in this 'x-ray gas' is typically 10–20% of the total, i.e. clusters contain more mass in hot gas than in stars. Detailed studies reveal a cluster baryon fraction of typically $f_B h^{3/2}$ = 0.03–0.08.

Large-scale flows

On large scales the motion of galaxies is dominated by the overall cosmic expansion. Still, they exhibit 'peculiar velocities' relative to the overall cosmic flow; our group of galaxies moves at 627±22 km s^{-1} relative to the reference frame defined by the cosmic microwave background radiation. These motions are attributed to the action of gravity over the age of the universe, caused by the inhomogeneities of the matter density. The observed large-scale velocity fields, together with the observed galaxy distributions, are then translated into a measure for the matter density required to explain the large-scale flows. One finds

$$\Omega_M > 0.3$$

and even larger values by related methods which are more model-dependent.

Flat universe
The critical value $\Omega_{tot} = 1$ for the cosmic mass–energy density, corresponding to an overall Euclidean (flat) spatial geometry, is favored to avoid fine-tuning the cosmic initial conditions. In an expanding universe, Ω_{tot} quickly evolves away from 1 towards either 0 or ∞ so that the near-flatness of the present-day universe suggests $\Omega_{tot} = 1$ as an exact identity. Moreover, 'inflationary models' of the early universe generically produce a flat geometry even though one can construct specialized models which circumvent this outcome. The critical density exceeds the luminous mass by about two orders of magnitude so that the universe, if it is flat, contains more than 99% dark matter.

Astrophysical constraints

Big-bang nucleosynthesis
The first question about the nature of dark matter is whether it could not consist of ordinary material in some non-luminous form, perhaps stellar remnants such as neutron stars or molecular hydrogen clouds which are difficult to observe. However, the overall baryon abundance is severely constrained by big-bang NUCLEOSYNTHESIS.

When the universe was about three minutes old, the initial protons and neutrons formed helium at a mass fraction of about 22–25%, together with some traces of deuterium (D or ^{2}H), ^{3}He and ^{7}Li. Within the standard big-bang picture, these primordial light-element abundances depend only on the cosmic baryon density (see BARYOGENESIS).

The abundance most sensitive to $\Omega_B h^2$ is that of deuterium. Its measurement in intergalactic hydrogen clouds has recently become possible by observing quasar absorption lines. While this novel approach holds much promise toward a precision determination of the primordial deuterium abundance, one currently finds both high and low values of $D/H \doteq 2–10^{-4}$ and $2–10^{-5}$, respectively, which are mutually inconsistent unless the baryon distribution is vastly inhomogeneous on large scales. They span a range roughly corresponding to

$$\Omega_B h^2 = 0.005 - 0.024$$

which is consistent with the helium and lithium observations. The more favored low deuterium value corresponds to a high baryon content.

This range for Ω_B is depicted in figure 3 as a function of the Hubble expansion parameter together with the luminous mass density of (1) and the lower dynamical mass limit of (2). The currently favored range for H_0 is 50–80 km s^{-1} Mpc^{-1}, implying a gap between the cosmic baryon density and both the luminous and the dynamical matter density. Apparently there is a significant fraction of 'dark baryons' which never made their way into galaxies and stars, and more importantly, lots of unidentified non-baryonic dark matter. The apparent gap between the baryons and the dynamical mass density corresponds well to the baryon fraction implied by the x-ray gas in galaxy clusters discussed earlier.

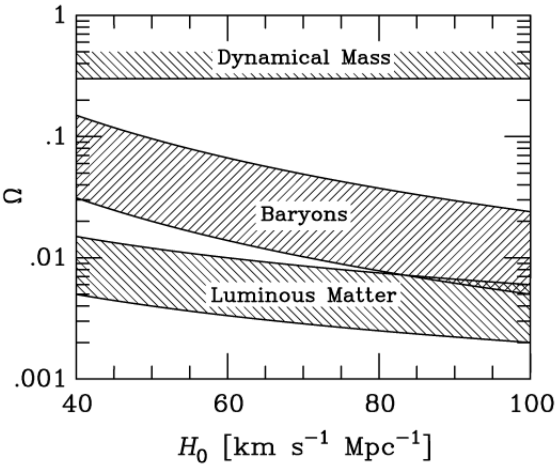

Figure 3. Cosmic matter components as a function of the assumed present-day Hubble expansion parameter.

Structure formation
The standard theory of cosmic structure formation holds that at some early time the universe was almost perfectly homogeneous, apart from tiny density modulations, which were enhanced by the action of gravity as time went on, leading to the formation of galaxies, clusters, and large-scale coherent structures. It is often argued that the primordial density variations came from quantum fluctuations in the very early universe which were boosted to macroscopic scales during a phase of exponential expansion ('INFLATIONARY UNIVERSE').

The amplitude of the density fluctuations at the epoch when the COSMIC MICROWAVE BACKGROUND radiation decoupled from the ambient plasma has now been inferred from several experiments, notably the COBE satellite, which measured the temperature fluctuations across the sky. An amplitude of the fluctuation spectrum consistent with these measurements is too small to allow the observed structures to form if the medium consists only of baryons and radiation. Weakly interacting particles fare better because they are not held up by photon pressure ('dark-matter boost'). This is a generic argument against baryonic dark matter even though there may be possibilities to circumvent it.

The matter which makes up the cosmic ‘fluid’ can diffuse, wiping out part of the initial density fluctuations. This effect is particularly important for weakly interacting particles which can diffuse far until their momentum has been sufficiently redshifted by the cosmic expansion; they erase the primordial fluctuation spectrum up to a scale which is larger for less massive particles. One speaks of ‘hot dark matter’ if the fluctuations are wiped out below scales which later correspond to galaxies, while ‘cold dark matter’ has this effect only on subgalactic scales. The dividing line (‘warm dark matter’) corresponds to a particle mass in the keV range.

The consensus is now almost universal that some variant of a cold dark matter scenario is probably how our universe works, where structure forms by the gravitational instability mechanism from a nearly scale-invariant spectrum of primordial density fluctuations. It strongly disfavors both baryons and low-mass particles such as massive neutrinos as the main ingredients of the cosmic matter cocktail.

Cosmic microwave background

The cosmic microwave background radiation holds a wealth of cosmological information. Its very presence and its uncannily precise black-body nature are the most striking proofs of the hot big-bang cosmogony. The COBE satellite and more recent ground-based experiments have measured tiny angular temperature variations with typically 10 μK amplitudes which already provide tight constraints on theories of structure formation and thus on the nature of dark matter.

The most important information is contained in the power spectrum of the temperature sky map. While there is still a lot of scatter in the data, they already seem to confirm the appearance of features known as ‘acoustic peaks’ or ‘Doppler peaks’. Their angular scale and amplitude provide invaluable information on the properties of the universe at radiation decoupling.

There are two approved satellite missions, NASA’s Microwave Anisotropy Probe (MAP), to be launched in 2001, and ESA’s PLANCK, to be launched around 2007, which will take full-sky temperature maps at fine angular resolutions. It is thought that these experiments will ultimately be able to determine the most important cosmological parameters on the 1% level, notably the baryon fraction and total dark matter content. There remain degeneracies between different combinations of parameters, however, which will need to be broken by other methods.

Candidates and searches

Neutrinos

The presence of large amounts of dark matter in the universe is almost uncontroversial, and the case against baryons as a main component is quite compelling, leaving us with particle dark matter (PDM) as one possible solution. The candidate particles would have to be relics from the early universe where they would have been produced thermally in the hot and dense plasma, or by some non-equilibrium process.

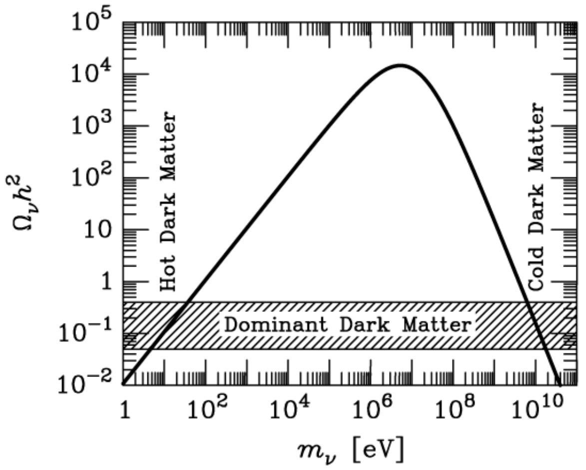

Figure 4. Cosmic mass density as a function of the assumed neutrino mass (‘Lee–Weinberg curve’). The hatched band indicates the required range for Ωh^2 of the dominant particle dark matter component.

The minimum required relic density is $\Omega_{\mathrm{PDM}} \gtrsim 0.2$ if we use (2) and allow for a significant baryon fraction. The observed age of the universe together with the measured expansion rate yields $\Omega h^2 \gtrsim 0.4$ so that

$$\Omega_{\mathrm{PDM}} h^2 = 0.05 - 0.4$$

where $h \gtrsim 0.5$ has been used.

Of the known particles, neutrinos are the only candidates. Their relic density as a function of the assumed mass is shown in figure 4. There are crudely as many background neutrinos in the universe as there are microwave photons. Multiplying this number by m_ν explains the increasing branch of figure 4 and gives $\Omega_\nu h^2 = \sum m_\nu / 93$ eV, whence the required neutrino mass is 4–40 eV. There is a second solution for a neutrino mass of a few GeV on the decreasing branch; the number of relic neutrinos is reduced by annihilations for $m_\nu \gtrsim 1$ MeV, where they are still in thermal equilibrium when the cosmic temperature falls below their mass.

The laboratory limit of about 20 MeV for ν_τ, and much less for ν_μ and ν_e, precludes the large-mass solution among the known neutrino families. The low-mass solution, however, is problematic from the perspective of structure formation because they represent ‘hot dark matter’. In addition, there is a problem with neutrinos filling the dark-matter halos of galaxies as they cannot be arbitrarily densely packed in phase space. This ‘Tremaine–Gunn argument’ requires $m_\nu \gtrsim 20$ eV for typical spiral galaxies, and a few 100 eV for dwarf galaxies so that neutrinos could not be the dark matter on all scales.

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Finally, the positive evidence for neutrino masses from recent oscillation experiments points to sub-eV mass differences between the three flavours so that their masses would have to be much larger than their differences ('degenerate masses') if they were to be dark matter. The largest cosmologically allowed mass of about 40 eV then distributes itself among the three families so that each of them must be lighter than about 13 eV, exacerbating the Tremaine–Gunn problem.

Weakly interacting massive particles (WIMPs)

Neutrinos on the decreasing branch in figure 4 would play the role of cold dark matter and are thus favored by cosmology, but in this mass range they do not exist. One thus postulates novel weakly interacting massive particles (WIMPs; see WIMPS AND MACHOS) to fill the gap. On the other hand, from a theoretical perspective one postulates a 'SUPERSYMMETRY' which predicts a new partner to every known particle. The lightest supersymmetric particle in the form of a 'neutralino' could well play the WIMP role. Independently of the dark-matter problem, the search for supersymmetry is one of the main goals of the most ambitious particle accelerator ever, the Large Hadron Collider (LHC) which is currently under construction in Geneva at the CERN Laboratory.

If the dark matter consists of some form of WIMPs, then our Milky Way galaxy should be filled with a 'gas' of these almost collisionless particles which would permeate everything, including our laboratories. The experimental search for galactic WIMPs has turned into an entire branch of non-accelerator particle physics, with numerous groups mounting more and more sensitive detectors. Usually one tries to measure the tiny energy depositions caused by a rare collision of a galactic WIMP with a nucleus in a crystal. In semiconductor crystals, especially germanium, one searches for the resulting electronic signal, in sodium iodide crystals for the scintillation light, or one may cool the crystal to very low temperatures and search for the minuscule heating caused by WIMP collisions; an example for such a cryogenic setup is shown in figure 5.

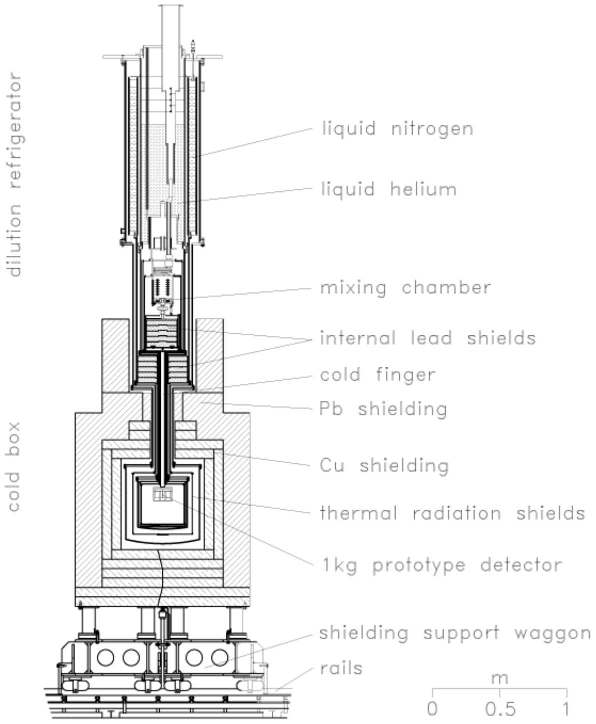

Figure 5. Schematic view of the experimental setup of CRESST, located in the Gran Sasso underground laboratory near Rome (Italy), as an example for a cryogenic dark-matter experiment.

The main experimental problem is the extremely small expected signal rate. In detail, it depends on the assumed WIMP properties and target material, but a typical number is below 1 event kg^{-1} d^{-1}. To reduce natural radioactive contaminations one must use extremely pure substances, and the cosmic-ray background requires locations deeply underground, for example in deep mines.

There exist other 'indirect' search methods. For example, WIMPs traversing the Sun or Earth will occasionally collide with a nucleus there, lose enough energy to get trapped, and ultimately annihilate with other trapped WIMPs. The resulting high-energy neutrinos from the Sun and the center of the Earth may well show up in existing and future neutrino telescopes.

While supersymmetric models are quite flexible in their predictions, the current round of experiments has reached the sensitivity where one can begin hoping to find these elusive dark-matter candidates.

Axions

A cold dark matter candidate *sui generis* is provided by axions, low-mass bosons which are postulated in the framework of quantum chromodynamics, the theory of the strong interaction among quarks. Other than neutrinos and WIMPs, these particles would arise from a nonthermal process in the early universe, producing essentially a Bose condensate, i.e. highly occupied, quasi-classical oscillations of the axion field. The axion mass would lie in the 10^{-5} eV regime, corresponding to GHz oscillation frequencies of the axion field.

Axions would have tiny electromagnetic interactions, implying that galactic dark-matter axions would drive a microwave cavity, provided it is placed in a strong magnetic field. Two such experiments are now in operation, one in Livermore, California (US Axion Search), the other in Kyoto, Japan (CARRACK). Their sensitivity is enough to detect the feeble output of a microwave cavity, induced by galactic dark-matter axions. Again, within the next few years one has a realistic chance to detect dark matter if the underlying hypothesis of the existence of axions is correct.

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Dim stars (MACHOs)

As long as particle dark matter has not been found, one may continue to speculate that the arguments against baryons are wrong and that galactic halos consist of ordinary matter in some non-luminous form. Obvious candidates are dim stars which have been termed massive astrophysical compact halo objects (MACHOs) as a deliberate pun on the WIMP hypothesis.

The physical nature of MACHOs could be stars which are too small to shine brightly (brown dwarfs or M dwarfs) or burnt-out stellar remnants (WHITE DWARFS, NEUTRON STARS, BLACK HOLES). Of course, stellar remnants seem implausible, among other reasons because they would have to arise from a large population of normal stars, of which there is no trace in the halo.

A practical search method involves the gravitational light deflection caused by a galactic MACHO which happens to pass near the line of sight to a background star. While the effect is too weak to produce several resolved images of the target star, its apparent brightness will temporarily increase because the MACHO's gravitational field effectively focuses more light into the telescope ('gravitational microlensing'). Such events are rare so that one must monitor millions of stars simultaneously to obtain a reasonable event rate. The Large and Small Magellanic Clouds as target regions have enough bright stars at a suitable distance and have been used since the early 1990s by the MACHO and EROS Collaborations in an attempt to find non-luminous stars making up the Milky Way halo.

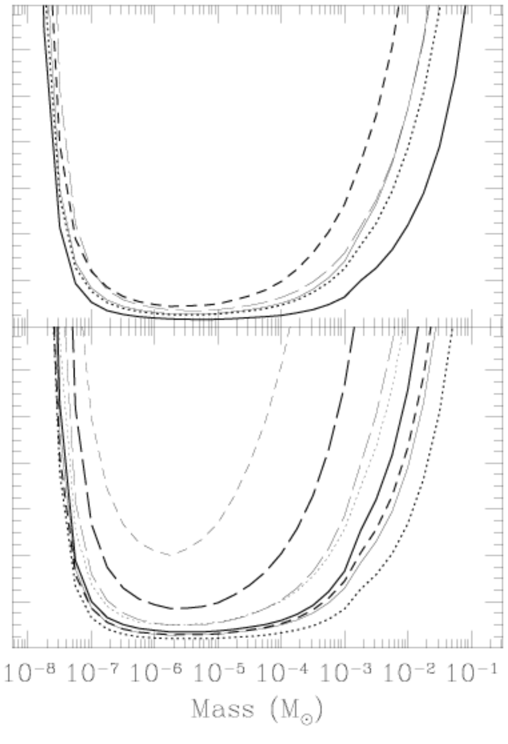

Figure 6. Upper limit to the Milky Way halo fraction that can be attributed to MACHOs as a function of their assumed mass from a combined analysis of the MACHO and EROS data. The different line styles correspond to different halo models; the upper panel shows those used by the EROS Collaboration, while the lower panel the ones of the MACHO Collaboration. In each case the solid curve represents a 'standard halo'. (C Alcock *et al Astrophys. J.* **499** L9 (1998).)

The duration of the temporary brightness excursion of a lensed star depends on the relative distances between observer, lens and target star, and on the lens mass. The non-observation of short-time events has allowed these experiments to exclude MACHOs over a wide mass range as a dominant halo component (figure 6), but does not yet exclude brown dwarfs as a possibility.

On the other hand, about a dozen positive events have turned up which, if attributed to MACHOs, would point to a mass around 0.5 $M_\odot$. However, the early excitement about the apparent discovery of some or all of the galactic dark matter has given way to a more sceptical assessment—the apparent mass range of the observed events simply does not seem to make sense. Perhaps the least troubling interpretation is that one is not seeing MACHOs but normal stars as lenses, which is possible if there is an unrecognized population of stars between us and the Large Magellanic Cloud, or even by stars within the Magellanic Clouds themselves if their distribution is different from what had been thought. Thus, while the observed MICROLENSING events are no doubt real, the question of where and what the lenses are remains for now wide open. (See also DARK MATTER IN GALAXIES.)

Primordial black holes

While stellar remnants seem implausible, black holes which formed in the early universe cannot be excluded as dark-matter candidates. From a structure-formation perspective, they represent cold dark matter; from a search perspective, they could be MACHOs. The main objection is the lack of a plausible production mechanism in the early universe. Surely, as long as particle dark matter remains undiscovered, and as long as the observed microlensing events remain unexplained, primordial black holes should not be brushed aside.

Cosmological constant (vacuum energy)

It is possible, and indeed implied by particle physics theory, that gravitating energy is associated with the ground state of quantum fields, i.e. with the vacuum. In the equations of general relativity it would play the role of a 'COSMOLOGICAL CONSTANT', an optional term which is permitted by the symmetries of the equations, but which is not motivated by the Newtonian limit. Vacuum energy would form a perfectly homogeneous background and thus cannot explain galactic rotation curves or dark matter in galaxy clusters. On the other hand, it could well explain the gap between dynamical measures of dark matter and the critical density (figure 3). We could have a Euclidean universe even if 'real matter' contributes only a sub-critical mass density.

The most counterintuitive property of vacuum energy is that it is not diluted by the cosmic expansion but rather becomes more and more dominant relative to normal matter as time goes on. It cannot be measured locally; a modification of the cosmological redshift–distance relationship is the main observable consequence.

Type Ia SUPERNOVAE as standard candles at cosmological distances have recently provided some exciting evidence for a cosmological constant. While being far from definitive, it suggests that the universe could be Euclidean with something like 70% of the critical density in vacuum energy and 30% in matter. This scenario accommodates effortlessly the absolute and relative amounts of baryonic and non-baryonic matter implied by big-bang nucleosynthesis, the x-ray gas in galaxy clusters, dynamical indicators for dark matter, and a flat geometry of the universe.

Modified gravity

The hypothesis of particle dark matter requires non-trivial and perhaps bewildering extensions of the standard model of particle physics. As long as the nature of dark matter has not been positively identified it may seem no more radical to modify general relativity such that there is no need for dark matter. It has sometimes been argued that the hypothesis of dark matter is just a parameterization of our ignorance of the physical laws which apply on large astrophysical scales where no independent tests of the validity of general relativity exist.

In one phenomenological approach known as modified Newtonian dynamics (MOND), gravitational accelerations a below a certain limit a_0 are given by $a^2/a_0 = G_N M/r^2$ (Newton's constant G_N). With $a_0 \approx 10^{-10}$ m s^{-2} this approach is surprisingly successful at explaining a broad range of dark-matter phenomena related to dwarf galaxies, spiral galaxies and galaxy clusters. Unfortunately, MOND lacks a relativistic formulation so that it cannot be applied in a truly cosmological sense.

Before modifications of general relativity can be taken seriously they must pass relativistic tests. An important case are galaxy clusters where large amounts of dark matter are indicated by non-relativistic methods *à la* Zwicky (virial theorem) as well as by relativistic indicators (gravitational lensing). As virial and lensing masses seem to agree well in several cases, scalar–tensor extensions of general relativity are in big trouble, if not ruled out entirely.

No serious attempt has been made to discuss truly cosmological phenomena such as structure formation and microwave background temperature fluctuations in the framework of alternative theories of gravity. At present no covariant theory of gravity is known that can explain the dark-matter problems on all scales.

Conclusion

Over the past decade, the idea has become almost commonplace that most of the stuff in the universe consists of non-baryonic matter, perhaps in the form of neutralinos or axions which are motivated in particle physics for independent reasons. Yet this remains a radical conjecture which has often been likened to the Copernican revolution when Earth and with it Man was moved from the center of creation to some unspectacular average position. Probably the next big step in this second Copernican revolution will be precise measurements of the angular temperature fluctuations of the cosmic microwave background, which are expected to confirm or refute the apparent discrepancy between the baryon content of the universe and its dynamical mass density. Even then, however, the second revolution will not be complete without a direct and positive identification of the dark-matter particles or objects. Until that happens, perhaps by one of the ongoing experimental searches, one should keep an open mind. The true solution of the dark-matter problem may not have been thought up yet.

Web update (31 July 2002)

A team of 27 astronomers led by Professor George Efstathiou of the University of Cambridge has published strong evidence for the existence of dark energy using the clustering pattern of 250 000 galaxies in a large volume of the universe surveyed with the Anglo–Australian Telescope at Siding Spring in New South Wales, Australia. By comparing the structure in the universe now, some 15 billion years after the Big Bang, with structure observed in the cosmic microwave background radiation, which preserved information about what the universe was like when it was only 300 000 years old, the Anglo–Australian team could apply a simple geometrical test to elucidate the composition of the universe. Their results show that the universe is full of vacuum energy, completely consistent with the earlier supernovae results.

Christopher Kochanek of the Harvard–Smithsonian Centre for Astrophysics in Cambridge, Massachusetts and Neal Dalal of the University of California, San Diego have used radio telescopes and gravitational lensing to search for cold dark matter. They have studied seven galaxies, each magnified by four nearer ones. Because each lensing galaxy is in a slightly different position, the researchers got four different images of each of the seven distant galaxies. The four images should have been identical. But each is actually slightly different. The difference was enough to have been caused by the kind of clumps of dark matter around lensing galaxies that mathematical models predict.

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