18. DARK MATTER

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The total mass-energy of the Universe is composed of several constituents, each of which may be characterized by its energy density $\rho_i \equiv \Omega_i \rho_c$ and its pressure $p_i \equiv w_i \rho_i$. Here $\rho_c \equiv 3H_0^2/8\pi G_N$ is the critical density, and H_0 is the present value of the Hubble parameter. We will take $H_0 = 70\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ when a numerical value is needed; then $\rho_c = 5.2 \times 10^{-6}\,\mathrm{GeV/cm^3}$. We can express the total density as $\rho_0 = \Omega_0 \rho_c$, where $\Omega_0 = \sum_i \Omega_i$. The deceleration parameter $q_0 \equiv (\ddot{R}/R)_0/H_0^2$, where $R(t)$ is the scale factor and the subscript 0 denotes the present value, is then given by $q_0 = \frac{1}{2}\Omega_0 + \frac{3}{2}\sum_i \Omega_i w_i$.

In general, relativistic particles have an equation of state specified by $w = +\frac{1}{3}$, nonrelativistic particles have $w = 0$, and the cosmological constant (here treated as another form of matter) has $w = -1$. Spatially uniform scalar fields which are oscillating rapidly in time (that is, with a frequency much greater than the Hubble parameter H_0) also have $w = 0$. Spatially uniform scalar fields which are changing slowly in time have $-1 < w < 0$.

Certain contributions to the mass density are well determined. The photons of the cosmic microwave background radiation (CMB) have $\rho_\gamma = \frac{\pi^2}{15} T_0^4$, where $T_0 = 2.73\,\mathrm{K} = 2.35 \times 10^{-4}\,\mathrm{eV}$ is the present temperature of the CMB; this yields $\Omega_\gamma = 5.1 \times 10^{-5}$. Results from Big-Bang nucleosynthesis indicate that the total baryon density is in the range $0.008 < \Omega_b < 0.043$; of this, roughly 0.004 is accounted for by stars. A single species of neutrino with a Majorana mass m_ν would have $\Omega_\nu = 0.56\, G_N T_0^3 H_0^{-2} m_\nu = m_\nu/(45\,\mathrm{eV})$ and $w_\nu = 0$ if $m_\nu \gg T_0$, and $\Omega_\nu = 0.23\,\Omega_\gamma$ and $w_\nu = \frac{1}{3}$ if $m_\nu \ll T_0$.

There is strong evidence from a variety of different observations for a large amount of dark matter in the Universe [1,2,3,4]. The phrase "dark matter" signifies matter whose existence has been inferred only through its gravitational effects. Two categories should be distinguished: baryonic dark matter, composed of baryons which are not seen (including black holes formed by stellar collapse), and nonbaryonic dark matter, composed either of massive neutrinos, or of elementary particles or fields which are as yet undiscovered (including primordial black holes). The particles or fields which comprise nonbaryonic dark matter must have survived from the Big Bang, and therefore must either be stable or have lifetimes in excess of the current age of the Universe.

There are a number of different observations which indicate the presence of dark matter (baryonic or nonbaryonic). These observations include rotation curves of spiral galaxies [5], which indicate that individual galaxies have halos of dark matter whose density falls off as $1/r^2$ at large distances r from the galaxy's center. In our own Galaxy, estimates of the local density of dark matter typically give $\rho_{\mathrm{dm}} \simeq 0.3\,\mathrm{GeV/cm^3}$, but this result depends sensitively on how the dark-matter halo is modeled.

An estimate of the total pressureless matter density $\Omega_{\rm m}$ (that is, of all components, baryonic and nonbaryonic, with $w_i = 0$) can be made from studies of rich clusters of galaxies. The baryonic mass of a cluster can be inferred from X-ray emissions, and the total mass from galactic velocities (via the virial theorem) or gas dynamics [6]. Assuming that the ratio of these masses is typical of the Universe as a whole, we obtain the value of $\Omega_{\rm m}/\Omega_{\rm b}$. Using the nucleosynthesis value of $\Omega_{\rm b}$ then yields $\Omega_{\rm m} = 0.4 \pm 0.1$. This is at least roughly consistent with a number of other estimates of $\Omega_{\rm m}$, such as from mass-to-light ratios for clusters [7] and from large-scale velocity fields [8]. This value of $\Omega_{\rm m}$ would imply that 90% of the pressureless matter in the Universe is nonbaryonic.

An estimate of the total density Ω_0 can be made from fluctuations in the CMB (see Section 15 on "Big-Bang Cosmology" in this *Review*). The first acoustic peak in the power spectrum of these fluctuations is predicted to occur at a multipole $\ell \sim 220\,\Omega_0^{-1/2}$; current data yields $\Omega_0 \sim 0.8 \pm 0.2$ [9]. This is consistent with the generic prediction $\Omega_0 = 1$ of inflationary models.

Type Ia supernovae can be used as standard candles to get information on the relationship between redshift and distance [10]. If we assume that the dominant contributions to Ω_0 are from pressureless matter and an unknown component X, then the results require $w_X < -0.6$ (at the 95% CL, ignoring any systematic errors). Assuming $w_X = -1$ (a cosmological constant), the results constrain the combination $0.8\,\Omega_{\rm m} - 0.6\,\Omega_X$ to be -0.2 ± 0.1.

None of these observations give us any direct indication of the nature of the dark matter. The halos of galaxies could have significant fractions of baryonic dark matter in the form of remnants (white dwarfs, neutron stars, black holes) of an early generation of massive stars, or smaller objects which never initiated nuclear burning (and would therefore have masses less than about $0.1\,M_\odot$). These massive compact halo objects are collectively called MACHOs. Results from searches via gravitational lensing effects [11] show that MACHOs with masses from $10^{-6}\,M_\odot$ to $0.1\,M_\odot$ each are not a significant component of our Galaxy's halo. However, the results also indicate that MACHOs with masses of approximately $0.5\,M_\odot$ each comprise roughly half the total mass of the halo. This situation is difficult to reconcile with models of star formation.

For purposes of galaxy formation models [12], nonbaryonic dark matter is classified as "hot" or "cold," depending on whether the dark matter particles were relativistic or nonrelativistic at the time when the horizon of the Universe enclosed enough matter to form a galaxy. If the dark matter particles are in thermal equilibrium with the baryons and radiation, then only the mass of a dark matter particle is relevant to knowing whether the dark matter is hot or cold, with the dividing line being $m_{\rm dm} \sim 1\,{\rm keV}$. In addition, specifying a model requires giving the power spectrum of initial density fluctuations. Inflationary models generically predict a power spectrum which is nearly scale invariant. With these inputs, galaxy formation models require primarily cold dark matter, with significantly less hot dark matter. However, either a negative-pressure component or some hot dark matter is needed in addition to cold dark matter. For example, a model with $\Omega_{\rm cdm} = 0.3$, $\Omega_{\rm hdm} = 0$, $\Omega_X = 0.7$ and $w_X = -0.6$ gives a good fit to all current data [13].

There is a constraint on neutrinos (or any light fermions) if they are to comprise the halos of dwarf galaxies: the Fermi–Dirac distribution in phase space restricts the number of neutrinos that can be put into a halo [14], and this implies a lower limit on the neutrino mass of roughly $m_\nu > 80\,\mathrm{eV}$.

There are no presently known particles which could be cold dark matter. However, many proposed extensions of the Standard Model predict a stable (or sufficiently long lived) particle. The key question then becomes the predicted value of Ω_{cdm}.

If the particle is its own antiparticle (or there are particles and antiparticles present in equal numbers), and these particles were in thermal equilibrium with radiation at least until they became nonrelativistic, then their relic abundance is determined by their annihilation cross section σ_{ann}: $\Omega_{\mathrm{cdm}} \sim G_{\mathrm{N}}^{3/2} T_0^3 H_0^{-2} \langle \sigma_{\mathrm{ann}} v_{\mathrm{rel}} \rangle^{-1}$. Here v_{rel} is the relative velocity of the two incoming dark matter particles, and the angle brackets denote an averaging over a thermal distribution of velocities for each at the freeze-out temperature T_{fr} when the dark matter particles go out of thermal equilibrium with radiation; typically $T_{\mathrm{fr}} \simeq \frac{1}{20} m_{\mathrm{dm}}$. One then finds (putting in appropriate numerical factors) that $\Omega_{\mathrm{cdm}} \simeq 7 \times 10^{-27}\,\mathrm{cm}^3\,\mathrm{s}^{-1} / \langle \sigma_{\mathrm{ann}} v_{\mathrm{rel}} \rangle$. The value of $\langle \sigma_{\mathrm{ann}} v_{\mathrm{rel}} \rangle$ needed for $\Omega_{\mathrm{cdm}} \simeq 1$ is remarkably close to what one would expect for a weakly interacting massive particle (WIMP) with a mass of $m_{\mathrm{dm}} = 100\,\mathrm{GeV}$: $\langle \sigma_{\mathrm{ann}} v_{\mathrm{rel}} \rangle \sim \alpha^2 / 8\pi m_{\mathrm{dm}}^2 \sim 3 \times 10^{-27}\,\mathrm{cm}^3\,\mathrm{s}^{-1}$.

If the dark matter particle is not its own antiparticle, and the number of particles minus antiparticles is conserved, then an initial asymmetry in the abundances of particles and antiparticles will be preserved, and can give relic abundances much larger than those predicted above.

If the dark matter particles were never in thermal equilibrium with radiation, then their abundance today must be calculated in some other way, and will in general depend on the precise initial conditions which are assumed.

The two best known and most studied cold dark matter candidates are the neutralino and the axion. The neutralino is predicted by the Minimal Supersymmetric extension of the Standard Model (MSSM) [15,16]. It qualifies as a WIMP, with a theoretically expected mass in the range of tens to hundreds of GeV. The axion is predicted by extensions of the Standard Model which resolve the strong CP problem [17]. Axions can occur in the early universe in the form of a Bose condensate which never comes into thermal equilibrium. The axions in this condensate are always nonrelativistic, and can be a significant component of the dark matter if the axion mass is approximately $10^{-5}\,\mathrm{eV}$. Axions can also arise from the decay of a network of axion strings and domain walls.

There are prospects for direct experimental detection of both these candidates (and other WIMP candidates as well). WIMPs will scatter off nuclei at a calculable rate, and produce observable nuclear recoils [2,16,19]; current data excludes certain regions of parameter space of the MSSM. Axions can be detected by axion to photon conversion in a microwave cavity in a strong magnetic field, and limits on the allowed axion-photon coupling have been set [18].

WIMP candidates can have indirect signatures as well, via present day annihilations into particles which can be detected as cosmic rays. The most promising possibility arises from the fact that WIMPs collect at the centers of the sun and the earth, thus greatly increasing their annihilation rate, and producing high energy neutrinos which can escape and arrive at the earth's surface in potentially observable numbers [16,20].

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