18. DARK MATTER

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There is strong evidence from a variety of different observations for a large amount of dark matter in the universe [1]. The phrase "dark matter" means matter whose existence has been inferred only through its gravitational effects. There is also extensive circumstantial evidence that at least some of this dark matter is nonbaryonic: that is, composed of elementary particles other than protons, neutrons, and electrons. These particles 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.

The abundance of dark matter is usually quoted in terms of its mass density $\rho_{\rm dm}$ in units of the critical density, $\Omega_{\rm dm} = \rho_{\rm dm}/\rho_{\rm c}$; the critical density $\rho_{\rm c}$ is defined in Eq. (15.5) (in Section 15 on "Big-Bang Cosmology" in this *Review*). The total amount of visible matter (that is, matter whose existence is inferred from its emission or absorption of photons) is roughly $\Omega_{\rm vis} \simeq 0.005$, with an uncertainty of at least a factor of two.

The strongest evidence for dark matter is from the rotation curves of spiral galaxies [1,2]. In these observations, the circular velocity $v_{\rm c}$ of hydrogen clouds surrounding the galaxy is measured (via Doppler shift) as a function of radius r. If there were no dark matter, at large r we would find $v_{\rm c}^2 \simeq G_N M_{\rm vis}/r$, since the visible mass $M_{\rm vis}$ of a spiral galaxy is concentrated at its center. However, observations of many spiral galaxies instead find a velocity $v_{\rm c}$ which is independent of r at large r, with a typical value $v_{\rm c} \sim 200\,{\rm km~s}^{-1}$. Such a "flat rotation curve" implies that the total mass within radius r grows linearly with r, $M_{\rm tot}(r) \simeq G_N^{-1} v_{\rm c}^2 r$. A self-gravitating ball of ideal gas at a uniform temperature of $kT = \frac{1}{2} m_{\rm dm} v_{\rm c}^2$ would have this mass profile; here $m_{\rm dm}$ is the mass of one dark matter particle. The rotation curves are measured out to some tens of kiloparsecs, implying a total mass within this radius which is typically about ten times the visible mass. This would imply $\Omega_{\rm dm} \gtrsim 10\,\Omega_{\rm vis} \simeq 0.05$. In our own galaxy, estimates of the local density of dark matter typically give $\rho_{\rm dm} \simeq 0.3\,{\rm GeV~cm}^{-3}$, but this result depends sensitively on how the halo of dark matter is modeled.

Other indications of the presence of dark matter come from observations of the motion of galaxies and hot gas in clusters of galaxies [3]. The overall result is that $\Omega_{\rm dm} \sim 0.2$. Studies of large-scale velocity fields result in $\Omega_{\rm dm} \gtrsim 0.3$ [4]. However, these methods of determining $\Omega_{\rm dm}$ require some astrophysical assumptions about how galaxies form.

None of these observations give us any direct indication of the nature of the dark matter. If it is baryonic, the forms it can take are severely restricted, since most forms of ordinary matter readily emit and absorb photons in at least one observable frequency band [5]. Possible exceptions include 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 one of the ongoing searches for machos via gravitational lensing effects [6] indicate that a significant fraction (roughly 20% to 60%, depending on the details of the model of the galaxy which is assumed) of the mass of our galaxy's halo is composed of machos.

There are, also, several indirect arguments which argue for a substantial amount of nonbaryonic dark matter. First, nucleosynthesis gives the limits $0.010 \leq \Omega_{\rm b} h_0^2 \leq 0.016$ for the total mass of baryons; h_0 is defined in Eq. (15.6) (in Section 15 on "Big-Bang Cosmology" in this *Review*). The upper limit on $\Omega_{\rm b}$ is substantially below the value $\Omega_{\rm dm} \gtrsim 0.3$ given by large scale measurements, even if h_0 is near the lower end of its optimistically allowed range, $0.4 \leq h_0 \leq 1.0$. A second, purely theoretical argument is that inflationary models (widely regarded as providing explanations of a number of otherwise puzzling paradoxes) generically predict $\Omega_{\rm total} = 1$. Finally, it is difficult to construct a model of galaxy formation without nonbaryonic dark matter that predicts sufficiently small fluctuations in the cosmic microwave background radiation [7].

For purposes of galaxy formation models, 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. Given this, models with only cold dark matter are much more successful than models with only hot dark matter at reproducing the observed structure of our universe, but there are still serious discrepancies [8]. Some of the suggestions proposed to alleviate these include a nonzero value of the cosmological constant Λ [9], significant deviations from scale invariance in the spectrum of initial fluctuations [10], and a mixture of both hot and cold dark matter [11]. Another class of models uses mass fluctuations due to topological defects [12].

The best candidate for hot dark matter is one of the three neutrinos, endowed with a Majorana mass m_ν. Such a neutrino would contribute $\Omega_\nu = 0.56\, G_N\, T_0^3\, H_0^{-2} m_\nu = m_\nu/(92\, h_0^2\,{\rm eV})$, where T_0 is the present temperature of the cosmic microwave background radiation. There is another 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 [13], and this implies a lower limit on the neutrino mass of $m_\nu \gtrsim 80\,{\rm eV}$.

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 $\Omega_{\rm dm}$.

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 $\sigma_{\rm ann}$: $\Omega_{\rm dm} \sim G_N^{3/2} T_0^3 H_0^{-2} \langle \sigma_{\rm ann} v_{\rm rel} \rangle^{-1}$. Here $v_{\rm rel}$ 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 freezeout temperature $T_{\rm fr}$ when the dark matter particles go out of thermal equilibrium with radiation; typically $T_{\rm fr} \simeq \frac{1}{20} m_{\rm dm}$. One then finds (putting in appropriate numerical factors) that

$\Omega_{\rm dm}h_0^2 \simeq 3\times10^{-27}\,{\rm cm}^3\,{\rm s}^{-1}/\langle\sigma_{\rm ann}v_{\rm rel}\rangle$. The value of $\langle\sigma_{\rm ann}v_{\rm rel}\rangle$ needed for $\Omega_{\rm dm}\simeq 1$ is remarkably close to what one would expect for a weakly interacting massive particle (wimp) with a mass of $m_{\rm dm} = 100\,{\rm GeV}$: $\langle\sigma_{\rm ann}v_{\rm rel}\rangle \sim \alpha^2/8\pi m_{\rm dm}^2 \sim 3\times10^{-27}\,{\rm cm}^3\,{\rm s}^{-1}$.

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 supersymmetric extensions of the Standard Model [14,15]. 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 [16]. Its mass must be approximately $10^{-5}\,{\rm eV}$ if it is to be a significant component of the dark matter. Axions can occur in the early universe 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 $10^{-5}\,{\rm eV}$.

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 [15,17]. This technique has been used to show that all the dark matter cannot consist of massive Dirac neutrinos or scalar neutrinos (predicted by supersymmetric models) with masses in the range of $10\,{\rm GeV} \lesssim m_{\rm dm} \lesssim 4\,{\rm TeV}$ [18]. The neutralino is harder to detect because its scattering cross section with nuclei is considerably smaller. Condensed axions can be detected by axion to photon conversion in an inhomogeneous magnetic field, and limits on the allowed axion-photon coupling (for certain ranges of the axion mass) have been set [16]. Both types of detection experiments are continuing.

Wimp candidates can have indirect signatures as well, via present-day annihilations into particles which can be detected as cosmic rays [15]. 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.

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