PARTICLE DARK MATTER*

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Abstract

Several ideas for new physics beyond the standard model may provide particle candidates for the dark matter in the Galactic halo. The two leading candidates are an axion and a weakly-interacting massive particle (WIMP), such as the neutralino in supersymmetric extensions of the standard model. Several possibilities for detection of such particles are discussed. An assessment of the relative merits of various WIMP-detection techniques is given. I then review the prospects for improving our knowledge of the amount, distribution, and nature of the dark matter in the Universe from future maps of the cosmic microwave background.

I. INTRODUCTION

Almost all astronomers will agree that most of the mass in the Universe is nonluminous. The nature of this dark matter remains one of the great mysteries of science today. Dynamics of cluster of galaxies suggest a universal nonrelativistic-matter density of $\Omega_0 \simeq 0.1 - 0.3$. If the luminous matter were all there was, the duration of the epoch of structure formation would be very short, thereby requiring (in almost all theories of structure formation) fluctuations in the microwave background which would be larger than those observed. These considerations imply $\Omega_0 \gtrsim 0.3$ [1]. Second, if the current value of $\Omega_0$ is of order unity today, then at the Planck time it must have been $1 \pm 10^{-60}$ leading us to believe that $\Omega_0$ is precisely unity for aesthetic reasons. A related argument comes from inflationary cosmology, which provides the most satisfying explanation for the smoothness of the microwave background [2]. To account for this isotropy, inflation must set $\Omega$ (the total density, including a cosmological constant) to unity.

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FIG. 1. Rotation curve for the spiral galaxy NGC6503. The points are the measured circular rotation velocities as a function of distance from the center of the galaxy. The dashed and dotted curves are the contribution to the rotational velocity due to the observed disk and gas, respectively, and the dot-dash curve is the contribution from the dark halo.

However, the most robust observational evidence for the existence of dark matter involves galactic dynamics. There is simply not enough luminous matter ($\Omega_{\text{lum}} \lesssim 0.01$) observed in spiral galaxies to account for their observed rotation curves (for example, that for NGC6503 shown in Fig. 1). Newton’s laws imply a galactic dark halo of mass $3 \times 10^9$ times that of the luminous component. With the simple and plausible assumption that the halo of our galaxy is roughly spherical, one can determine that the local dark-matter density is roughly $\rho_0 \simeq 0.3$ GeV cm$^{-3}$. Furthermore, the velocity distribution of the halo dark matter should be roughly Maxwell-Boltzmann with a velocity dispersion $\simeq 270$ km s$^{-1}$.

On the other hand, big-bang nucleosynthesis suggests that the baryon density is $\Omega_b \lesssim 0.1$, too small to account for the dark matter in the Universe. Although a neutrino species of mass $\mathcal{O}(30$ eV$)$ could provide the right dark-matter density, N-body simulations of structure formation in a neutrino-dominated Universe do a poor job of reproducing the observed structure. Furthermore, it is difficult to see (essentially from the Pauli principle) how such a neutrino could make up the dark matter in the halos of galaxies. It appears likely then, that some nonbaryonic, nonrelativistic matter is required.

The two leading candidates from particle theory are the axion, which arises in the Peccei-Quinn solution to the strong-CP problem, and a weakly-interacting massive particle (WIMP), which may arise in supersymmetric (or other) extensions of the standard model.

Here, I review the axion solution to the strong-CP problem, the astrophysical constraints to the axion mass, and prospects for detection of an axion. I then review the WIMP solution to the dark-matter problem and avenues toward detection. Finally, I briefly discuss how
measurements of CMB anisotropies may in the future help determine more precisely the amount of exotic dark in the Universe.

II. AXIONS

Although supersymmetric particles seem to get more attention in the literature lately, we should not forget that the axion also provides a well-motivated and promising alternative dark-matter candidate [7]. The QCD Lagrangian may be written

\[ \mathcal{L}_{QCD} = \mathcal{L}_{\text{pert}} + \theta \frac{g^2}{32\pi^2} \tilde{G}G, \]

where the first term is the perturbative Lagrangian responsible for the numerous phenomenological successes of QCD. However, the second term (where \( G \) is the gluon field-strength tensor and \( \tilde{G} \) is its dual), which is a consequence of nonperturbative effects, violates \( CP \). However, we know experimentally that \( CP \) is not violated in the strong interactions, or if it is, the level of strong-\( CP \) violation is tiny. From constraints to the neutron electric-dipole moment, \( d_n \lesssim 10^{-25} \text{ e cm} \), it can be inferred that \( \theta \lesssim 10^{-10} \). But why is \( \theta \) so small? This is the strong-\( CP \) problem.

The axion arises in the Peccei-Quinn solution to the strong-\( CP \) problem [9], which close to twenty years after it was proposed still seems to be the most promising solution. The idea is to introduce a global \( U(1)_{PQ} \) symmetry broken at a scale \( f_{PQ} \), and \( \theta \) becomes a dynamical field which is the Nambu-Goldstone mode of this symmetry. At temperatures below the QCD phase transition, nonperturbative quantum effects break explicitly the symmetry and drive \( \theta \rightarrow 0 \). The axion is the pseudo-Nambu-Goldstone boson of this near-global symmetry. Its mass is \( m_a \simeq \text{eV} \left( 10^7 \text{ GeV}/f_a \right) \), and its coupling to ordinary matter is \( \propto f_a^{-1} \).

A priori, the Peccei-Quinn solution works equally well for any value of \( f_a \) (although one would generically expect it to be less than or of order the Planck scale). However, a variety of astrophysical observations and a few laboratory experiments constrain the axion mass to be \( m_a \sim 10^{-4} \text{ eV} \), to within a few orders of magnitude. Smaller masses would lead to an unacceptably large cosmological abundance. Larger masses are ruled out by a combination of constraints from supernova 1987A, globular clusters, laboratory experiments, and a search for two-photon decays of relic axions [10].

One conceivable theoretical difficulty with this axion mass comes from generic quantum-gravity arguments [11]. For \( m_a \sim 10^{-4} \text{ eV} \), the magnitude of the explicit symmetry breaking is incredibly tiny compared with the PQ scale, so the global symmetry, although broken, must be very close to exact. There are physical arguments involving, for example, the nonconservation of global charge in evaporation of a black hole produced by collapse of an initial state with nonzero global charge, which suggest that global symmetries should be violated to some extent in quantum gravity. When one writes down a reasonable ansatz for a term in a low-energy effective Lagrangian which might arise from global-symmetry violation at the Planck scale, the coupling of such a term is found to be extraordinarily small (e.g., \( \lesssim 10^{-55} \)). Of course, we have at this point no predictive theory of quantum gravity, and several mechanisms for forbidding these global-symmetry violating terms have been proposed [12]. Therefore, these arguments by no means “rule out” the axion solution.
In fact, discovery of an axion would provide much needed clues to the nature of Planck-scale physics.

Curiously enough, if the axion mass is in the relatively small viable range, the relic density is $\Omega_a \sim 1$ and may therefore account for the halo dark matter. Such axions would be produced with zero momentum by a misalignment mechanism in the early Universe and therefore act as cold dark matter. During the process of galaxy formation, these axions would fall into the Galactic potential well and would therefore be present in our halo with a velocity dispersion near 270 km s$^{-1}$.

Although the interaction of axions with ordinary matter is extraordinarily weak, Sikivie proposed a very clever method of detection of Galactic axions [13]. Just as the axion couples to gluons through the anomaly (i.e., the $G\tilde{G}$ term), there is a very weak coupling of an axion to photons through the anomaly. The axion can therefore decay to two photons, but the lifetime is $\tau_{a\to\gamma\gamma} \sim 10^{50} s (m_a/10^{-5} \text{eV})^{-5}$ which is huge compared to the lifetime of the Universe and therefore unobservable. However, the $a\gamma\gamma$ term in the Lagrangian is $L_{a\gamma\gamma} \propto a\vec{E}\cdot\vec{B}$ where $\vec{E}$ and $\vec{B}$ are the electric and magnetic field strengths. Therefore, if one immerses a resonant cavity in a strong magnetic field, Galactic axions which pass through the detector may be converted to fundamental excitations of the cavity, and these may be observable [13]. Such an experiment is currently underway and expects to probe the entire acceptable parameter space within the next five years [14]. A related experiment, which looks for excitations of Rydberg atoms, may also find dark-matter axions [15]. Although the sensitivity of this technique is supposed to be excellent, it can only cover a limited axion-mass range.

It should be kept in mind that there are no accelerator tests for axions in the acceptable mass range. Therefore, these dark-matter axion experiment are actually our only way to test the Peccei-Quinn solution.

III. WEAKLY-INTERACTING MASSIVE PARTICLES

Suppose that in addition to the known particles of the standard model, there exists a new, yet undiscovered, stable (or long-lived) weakly-interacting massive particle (WIMP), $\chi$. At temperatures greater than the mass of the particle, $T \gg m_\chi$, the equilibrium number density of such particles is $n_\chi \propto T^3$, but for lower temperatures, $T \ll m_\chi$, the equilibrium abundance is exponentially suppressed, $n_\chi \propto e^{-m_\chi/T}$. If the expansion of the Universe were so slow that thermal equilibrium was always maintained, the number of WIMPs today would be infinitesimal. However, the Universe is not static, so equilibrium thermodynamics is not the entire story.

At high temperatures ($T \gg m_\chi$), $\chi$’s are abundant and rapidly converting to lighter particles and vice versa ($\chi\overline{\chi} \leftrightarrow ll\overline{l}$, where $ll\overline{l}$ are quark-antiquark and lepton-antilepton pairs, and if $m_\chi$ is greater than the mass of the gauge and/or Higgs bosons, $ll\overline{l}$ could be gauge- and/or Higgs-boson pairs as well). Shortly after $T$ drops below $m_\chi$ the number density of $\chi$’s drops exponentially, and the rate for annihilation of $\chi$’s, $\Gamma = \langle \sigma v \rangle n_\chi$—where $\langle \sigma v \rangle$ is the thermally averaged total cross section for annihilation of $\chi\overline{\chi}$ into lighter particles times relative velocity $v$—drops below the expansion rate, $\Gamma \lesssim H$. At this point, the $\chi$’s cease to annihilate, they fall out of equilibrium, and a relic cosmological abundance remains.
FIG. 2. Comoving number density of a WIMP in the early Universe. The dashed curves are the actual abundance, and the solid curve is the equilibrium abundance.

FIG. 2 shows numerical solutions to the Boltzmann equation which determines the WIMP abundance. The equilibrium (solid line) and actual (dashed lines) abundances per comoving volume are plotted as a function of $x \equiv m_\chi/T$ (which increases with increasing time). As the annihilation cross section is increased the WIMPs stay in equilibrium longer, and we are left with a smaller relic abundance.

An approximate solution to the Boltzmann equation yields the following estimate for the current cosmological abundance of the WIMP:

$$\Omega_\chi h^2 = \frac{m_\chi n_\chi}{\rho_c} \simeq \left( \frac{3 \times 10^{-27} \text{cm}^3 \text{sec}^{-1}}{\sigma_A v} \right),$$

(2)

where $h$ is the Hubble constant in units of 100 km s$^{-1}$ Mpc$^{-1}$. The result is to a first approximation independent of the WIMP mass and is fixed primarily by its annihilation cross section.

The WIMP velocities at freeze out are typically some appreciable fraction of the speed of light. Therefore, from equation (2), the WIMP will have a cosmological abundance of order unity today if the annihilation cross section is roughly $10^{-9}$ GeV$^{-2}$. Curiously, this is the order of magnitude one would expect from a typical electroweak cross section,

$$\sigma_{\text{weak}} \simeq \frac{\alpha^2}{m_{\text{weak}}^2},$$

(3)

where $\alpha \simeq \mathcal{O}(0.01)$ and $m_{\text{weak}} \simeq \mathcal{O}(100 \text{ GeV})$. The value of the cross section in equation (2) needed to provide $\Omega_\chi \sim 1$ comes essentially from the age of the Universe. However, there is no a priori reason why this cross section should be of the same order of magnitude as the
cross section one would expect for new particles with masses and interactions characteristic of the electroweak scale. In other words, why should the age of the Universe have anything to do with electroweak physics? This “coincidence” suggests that if a new, yet undiscovered, massive particle with electroweak interactions exists, then it should have a relic density of order unity and therefore provides a natural dark-matter candidate. This argument has been the driving force behind a vast effort to detect WIMPs in the halo.

The first WIMPs considered were massive Dirac or Majorana neutrinos with masses in the range of a few GeV to a few TeV. (Due to the Yukawa coupling which gives a neutrino its mass, the neutrino interactions become strong above a few TeV, and it no longer remains a suitable WIMP candidate. LEP ruled out neutrino masses below half the Z⁰ mass. Furthermore, heavier Dirac neutrinos have been ruled out as the primary component of the Galactic halo by direct-detection experiments (described below) and heavier Majorana neutrinos have been ruled out by indirect-detection experiments (also described below) over much of their mass range. Therefore, Dirac neutrinos cannot comprise the halo dark matter; Majorana neutrinos can, but only over a small range of fairly large masses. This was a major triumph for experimental particle astrophysicists: the first falsification of a dark-matter candidate. However, theorists were not too disappointed: The stability of a fourth generation neutrino had to be postulated ad hoc—it was not guaranteed by some new symmetry. So although heavy neutrinos were plausible, they certainly were not very well-motivated from the perspective of particle theory.

A much more promising WIMP candidate comes from supersymmetry (SUSY). SUSY was hypothesized in particle physics to cure the naturalness problem with fundamental Higgs bosons at the electroweak scale. Coupling-constant unification at the GUT scale seems to be improved with SUSY, and it seems to be an essential ingredient in theories which unify gravity with the other three fundamental forces.

As another consequence, the existence of a new symmetry, R-parity, in SUSY theories guarantees that the lightest supersymmetric particle (LSP) is stable. In the minimal supersymmetric extension of the standard model (MSSM), the LSP is usually the neutralino, a linear combination of the supersymmetric partners of the photon, Z⁰, and Higgs bosons. (Another possibility is the sneutrino, but these particles interact like neutrinos and have been ruled out over most of the available mass range.) Given a SUSY model, the cross section for neutralino annihilation to lighter particles is straightforward, so one can obtain the cosmological mass density. The mass scale of supersymmetry must be of order the weak scale to cure the naturalness problem, and the neutralino will have only electroweak interactions. Therefore, it is to be expected that the cosmological neutralino abundance is of order unity. In fact, with detailed calculations, one finds that the neutralino abundance in a very broad class of supersymmetric extensions of the standard model is near unity and can therefore account for the dark matter in our halo.

If neutralinos reside in the halo, there are several avenues for detection. One of the most promising techniques currently being pursued involves searches for the O(keV) recoils produced by elastic scattering of neutralinos from nuclei in low-background detectors. Another strategy is observation of energetic neutrinos produced by annihilation of neutralinos in the Sun and Earth in converted proton-decay and astrophysical-neutrino detectors (such as MACRO, Kamiokande, IMB, AMANDA, and NESTOR). There are also searches for anomalous cosmic rays which would be produced by annihilation of WIMPs.
in the halo. Of course, SUSY particles should also show up in accelerator searches if their mass falls within the experimentally accessible range.

Although supersymmetry provides perhaps the most promising dark-matter candidate (and solves numerous problems in particle physics), a practical difficulty with supersymmetry is that we have little detailed predictive power. In SUSY models, the standard-model particle spectrum is more than doubled, and we really have no idea what the masses of all these superpartners should be. There are also couplings, mixing angles, etc. Therefore, what theorists generally do is survey a huge set of models with masses and couplings within a plausible range, and present results for relic abundances and direct- and indirect-detection rates, usually as scatter plots versus neutralino mass.

Energetic neutrinos from WIMP annihilation in the Sun or Earth would be inferred by observation of neutrino-induced upward muons coming from the direction of the Sun or the core of the Earth. Predictions for the fluxes of such muons in SUSY models seem to fall for the most part between $10^{-6}$ and 1 event m$^{-2}$ s$^{-1}$ [8], although the numbers may be a bit higher or lower in some models. Presently, IMB and Kamiokande constrain the flux of energetic neutrinos from the Sun to be less than about 0.02 m$^{-2}$ s$^{-1}$ [18,26]. MACRO expects to be able to improve on this sensitivity by perhaps an order of magnitude. Future detectors may be able to improve on this limit further. For example, AMANDA expects to have an area of roughly $10^4$ m$^2$, and a $10^6$-m$^2$ detector is being discussed. However, it should be kept in mind that without muon energy resolution, the sensitivity of these detectors will not approach the inverse exposure; it will be limited by the atmospheric-neutrino background. If a detector has good angular resolution, the signal-to-noise ratio can be improved, and even moreso with energy resolution, so sensitivities approaching the inverse exposure could be achieved [27]. Furthermore, ideas for neutrino detectors with energy resolution are being discussed [28], although at this point these appear likely to be in the somewhat-distant future.

The other possibility is direct detection of a WIMP via observation of the nuclear recoil induced by WIMP-nucleus elastic scattering in a low-background detector. The predicted rates depend on the target nucleus adopted. For example, in a broad range of SUSY models, the predicted scattering rates in a germanium detector seem to fall for the most part between $10^{-4}$ to 10 events kg$^{-1}$ day$^{-1}$ [8], although again, there may be models with higher or lower rates. Current experimental sensitivities in germanium detectors are around 10 events kg$^{-1}$ day$^{-1}$ [17]. To illustrate future prospects, consider the CDMS experiment [29] which expects to soon have a kg germanium detector with a background rate of 1 event day$^{-1}$. After a one-year exposure, their sensitivity would therefore be $O(0.1$ event kg$^{-1}$ day$^{-1}$); this could be improved with better background rejection. Future detectors will achieve better sensitivities, and it should be kept in mind that numerous other target nuclei are being considered by other groups. However, it also seems clear that it will be quite a while until a good fraction of the available SUSY parameter space is probed.

Generally, most theorists have just plugged in SUSY parameters into the machinery which produces detection rates and plotted results for direct and indirect detection. However, another approach is to compare, in a somewhat model-independent although approximate fashion, the rates for direct and indirect detection [8,30,31]. The underlying observation is that the rates for the two types of detection are both controlled primarily by the WIMP-nucleon coupling. One must then note that WIMPs generally undergo one of two types of
interaction with the nucleon: an axial-vector interaction in which the WIMP couples to the nuclear spin (which, for nuclei with nonzero angular momentum is roughly 1/2 and not the total angular momentum), and a scalar interaction in which the WIMP couples to the total mass of the nucleus. The direct-detection rate depends on the WIMP-nucleon interaction strength and on the WIMP mass. On the other hand, indirect-detection rates will have an additional dependence on the energy spectrum of neutrinos from WIMP annihilation. By surveying the various possible neutrino energy spectra, one finds that for a given neutralino mass and annihilation rate in the Sun, the largest upward-muon flux is roughly three times as large as the smallest [31]. So even if we assume the neutralino-nucleus interaction is purely scalar or purely axial-vector, there will still be a residual model-dependence of a factor of three when comparing direct- and indirect-detection rates.

For example, for scalar-coupled WIMPs, the event rate in a kg germanium detector will be equivalent to the event rate in a $(2-6) \times 10^6$ m$^2$ neutrino detector for 10-GeV WIMPs and $(3-5) \times 10^4$ m$^2$ for TeV WIMPs [31]. Therefore, the relative sensitivity of indirect detection when compared with the direct-detection sensitivity increases with mass. The bottom line of such an analysis seems to be that direct-detection experiments will be more sensitive to neutralinos with scalar interactions with nuclei, although very-large neutrino telescopes may achieve comparable sensitivities at larger WIMP masses. This should come as no surprise given the fact that direct-detection experiments rule out Dirac neutrinos [17], which have scalar-like interactions, far more effectively than do indirect-detection experiments [31].

Generically, the sensitivity of indirect searches (relative to direct searches) should be better for WIMPs with axial-vector interactions, since the Sun is composed primarily of nuclei with spin (i.e., protons). However, a comparison of direct- and indirect-detection rates is a bit more difficult for axially-coupled WIMPs, since the nuclear-physics uncertainties in the neutralino-nuclear cross section are much greater, and the spin distribution of each target nucleus must be modeled. Still, in a careful analysis, Rich and Tao found that in 1994, the existing sensitivity of energetic-neutrino searches to axially-coupled WIMPs greatly exceeded the sensitivities of direct-detection experiments [30].

To see how the situation may change with future detectors, let us consider a specific axially-coupled dark-matter candidate, the light Higgsino recently put forward by Kane and Wells [32]. In order to explain the anomalous CDF $ee\gamma\gamma + E_T$ [33], the $Z \rightarrow b\bar{b}$ anomaly, and the dark matter, this Higgsino must have a mass between 30–40 GeV. Furthermore, the coupling of this Higgsino to quarks and leptons is due primarily to $Z^0$ exchange with a coupling proportional to $\cos 2\beta$, where $\tan \beta$ is the usual ratio of Higgs vacuum expectation values in supersymmetric models. Therefore, the usually messy cross sections one deals with in a general MSSM simplify for this candidate, and the cross sections needed for the cosmology of this Higgsino depend only on the two parameters $m_\chi$ and $\cos 2\beta$. Furthermore, since the neutralino-quark interaction is due only to $Z^0$ exchange, this Higgsino will have only axial-vector interactions with nuclei.

The Earth is composed primarily of spinless nuclei, so WIMPs with axial-vector interactions will not be captured in the Earth, and we expect no neutrinos from WIMP annihilation therein. However, most of the mass in the Sun is composed of nuclei with spin (i.e., protons). The flux of upward muons induced by neutrinos from annihilation of these light Higgsinos would be $\Gamma_{\text{det}} \simeq 2.7 \times 10^{-2} \text{ m}^{-2} \text{ yr}^{-1} \cos^2 2\beta$ [34]. On the other hand, the rate for scattering from $^{73}$Ge is $R \simeq 300 \cos^2 2\beta \text{ kg}^{-1} \text{ yr}^{-1}$ [32,34]. For illustration, in addition to their kg of
natural germanium, the CDMS experiment also plans to run with 0.5 kg of (almost) purified $^{73}\text{Ge}$. With a background event rate of roughly one event kg$^{-1}$ day$^{-1}$, after one year, the 3σ sensitivity of the experiment will be roughly 80 kg$^{-1}$ yr$^{-1}$. Comparing the predictions for direct and indirect detection of this axially-coupled WIMP, we see that the enriched-$^{73}\text{Ge}$ sensitivity should improve on the current limit to the upward-muon flux (0.02 m$^{-2}$ yr$^{-1}$) roughly by a factor of 4. When we compare this with the forecasted factor-of-ten improvement expected in MACRO, it appears that the sensitivity of indirect-detection experiments looks more promising. Before drawing any conclusions, however, it should be noted that the sensitivity in detectors with other nuclei with spin may be significantly better. On the other hand, the sensitivity of neutrino searches increases relative to direct-detection experiments for larger WIMP masses. It therefore seems at this point that the two schemes will be competitive for detection of light axially-coupled WIMPs, but the neutrino telescopes may have an advantage in probing larger masses.

A common question is whether theoretical considerations favor a WIMP which has predominantly scalar or axial-vector couplings. Unfortunately, there is no simple answer. When detection of supersymmetric dark matter was initially considered, it seemed that the neutralino in most models would have predominantly axial-vector interactions. It was then noted that in some fraction of models where the neutralino was a mixture of Higgsino and gaugino, there could be some significant scalar coupling as well [35]. As it became evident that the top quark had to be quite heavy, it was realized that nondegenerate squark masses would give rise to scalar couplings in most models [36]. However, there are still large regions of supersymmetric parameter space where the neutralino has primarily axial-vector interactions, and in fact, the Kane-Wells Higgsino candidate has primarily axial-vector interactions. The bottom line is that theory cannot currently reliably say which type of interaction the WIMP is likely to have, so experiments should continue to try to target both.

IV. DARK MATTER AND THE COSMIC MICROWAVE BACKGROUND

The key argument for nonbaryonic dark matter relies on the evidence that the total nonrelativistic-matter density $\Omega_0 \gtrsim 0.1$, outweighs the baryon density $\Omega_b \lesssim 0.1$ allowed by big-bang nucleosynthesis. With the advent of a new generation of long-duration balloon-borne and ground-based interferometry experiments and NASA’s MAP [37] and ESA’s COBRAS/SAMBA [38] missions, CMB measurements will usher in a new era in cosmology. In forthcoming years, the cosmic microwave background (CMB) may provide a precise inventory of the matter content in the Universe and confirm the discrepancy between the baryon density and the total nonrelativistic-matter density, if it indeed exists.

The primary goal of these experiments is recovery of the temperature autocorrelation function or angular power spectrum of the CMB. The fractional temperature perturbation $\Delta T(\hat{n})/T$ in a given direction $\hat{n}$ can be expanded in terms of spherical harmonics,

$$\frac{\Delta T(\hat{n})}{T} = \sum_{lm} a_{(lm)} Y_{(lm)}(\hat{n}), \quad \text{(4)}$$

where the multipole coefficients are given by
\[ a_{(lm)} = \int d\hat{n} Y^*_{(lm)}(\hat{n}) \frac{\Delta T(\hat{n})}{T}. \]  

(5)

Cosmological theories predict that these multipole coefficients are statistically independent and are distributed with variance \( \langle a^*_{(lm)} a_{(l'm')} \rangle = C_l \delta_{ll'} \delta_{mm'} \). Roughly speaking, each \( C_l \) measures the square of the mean temperature difference between two points separated by an angle \( \theta \sim \pi/l \).

![Theoretical predictions for CMB spectra as a function of multipole moment \( \ell \) for models with primordial adiabatic perturbations. In each case, the heavy curve is that for the standard-CDM values, a total density \( \Omega = 1 \), cosmological constant \( \Lambda = 0 \), baryon density \( \Omega_b = 0.06 \), and Hubble parameter \( h = 0.5 \). Each graph shows the effect of variation of one of these parameters. In (d), \( \Omega = \Omega_0 + \Lambda = 1 \).](image)

Theoretical predictions for the \( C_l \)'s can be made given a theory for structure formation and the values of several cosmological parameters. For example, Fig. 3 shows predictions for multipole moments in models with primordial adiabatic perturbations. The peaks in the spectra come from oscillations in the photon-baryon fluid at the surface of last scatter, and the damping at small angles is due to the finite thickness of the surface of last scatter. Each panel shows the effect of independent variation of one of the cosmological parameters. As illustrated, the height, width, and spacing of the acoustic peaks in the angular spectrum depend on these (and other) cosmological parameters. The CMB spectrum also depends on the model (e.g., inflation or topological defects) for structure formation, the ionization history of the Universe, and the presence of gravity waves. However, no two of the classical cosmological parameters affects the CMB spectrum in precisely the same way. For example, the angular position of the first peak depends primarily on the geometry (\( \Omega = \Omega_0 + \Lambda \) where \( \Lambda \) is the contribution of the cosmological constant) of the Universe [39], but is relatively...
insensitive to variations in the other parameters. Assuming that the primordial perturbations were adiabatic, we could fit for all of these parameters if the angular spectrum could be measured precisely.

COBE normalizes the amplitude and slope of the CMB spectrum to \( \sim 10\% \). However, the angular resolution was not fine enough to probe the detailed shape of the acoustic peaks in the power spectrum, so COBE was unable to capitalize on this wealth of information. Nor can it discriminate between scalar and tensor modes. A collection of recent ground-based and balloon-borne experiments seem to confirm a first acoustic peak, but they still cannot determine its precise height, width, or location. In the next few years, long-duration balloon flights (e.g., BOOMERANG and TOPHAT) and ground-based interferometry experiments (e.g., CAT and CBI) will begin to discern the first and higher few peaks. Subsequently, future satellite experiments, such as NASA’s MAP mission \[37\] and then ESA’s COBRAS/SAMBA \[38\] will accurately map the CMB temperature over most of the sky with good angular resolution and will therefore be able to recover the CMB power spectrum with precision.

Of course, the precision attainable is ultimately limited by cosmic variance and practically by a finite angular resolution, instrumental noise, and partial sky coverage in a realistic CMB mapping experiment. Assuming that primordial perturbations are adiabatic, one finds that with future satellite missions, \( \Omega \) may potentially be determined to better than 10\% after marginalizing over all other undetermined parameters, and better than 1\% if the other parameters can be fixed by independent observations or assumption \[40\]. This would be far more accurate than any traditional determinations of the geometry. (Of course, if primordial perturbations turn out to be isocurvature or due to topological defects, this may not be the case.) The cosmological constant \( \Lambda \) will be determined with a similar accuracy, so the nonrelativistic-matter density \( \Omega_0 \) will also be accurately determined \[41\]. Small variations in the baryon density have a dramatic effect on the CMB spectrum, so \( \Omega_b \) will be determined with even greater precision. Therefore, if there is more nonrelativistic matter in the Universe than the baryons can account for, as current evidence suggests, it should become clear with these future CMB experiments.

The CMB will also measure the Hubble constant and perhaps be sensitive to a small neutrino mass \[42\]. Temperature maps will also begin to disentangle the scalar and tensor (i.e., long-wavelength gravity-wave) contributions to the CMB and determine their primordial spectra, and this could be used to test inflation \[41\]. CMB polarization maps may also help isolate the tensor contribution \[43\]. Therefore, the CMB will become an increasingly powerful probe of the early Universe.

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