COSMOLOGICAL-PARAMETER DETERMINATION WITH COSMIC MICROWAVE BACKGROUND TEMPERATURE ANISOTROPIES AND POLARIZATION

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Forthcoming cosmic microwave background experiments (CMB) will provide precise new tests of structure-formation theories. The geometry of the Universe may be determined robustly, and the classical cosmological parameters, such as the cosmological constant, baryon density, and Hubble constant, may be determined as well. In addition, the "inflationary observables," which parameterize the shapes and amplitudes of the primordial spectra of density perturbations and long-wavelength gravitational waves produced by inflation, may also be measured and thus provide several new tests of inflation. Although most attention has focussed on the more easily observed temperature anisotropies, recent work has shown that the CMB polarization provides a wealth of unique information that may be especially important for determination of the inflationary observables. Secondary anisotropies at small angular scales produced by re-scattering of photons from partial reionization may be used to constrain the ionization history of the Universe.

1 Introduction

Despite its major triumphs (the expansion, nucleosynthesis, and the cosmic microwave background), the big-bang theory for the origin of the Universe leaves several questions unanswered. Chief amongst these is the horizon problem: When cosmic microwave background (CMB) photons last scattered, the age of the Universe was roughly 100,000 years, much smaller than its current age of roughly 10 billion years. After taking into account the expansion of the Universe, one finds that the angle subtended by a causally connected region at the surface of last scatter is roughly 1°. However, there are 40,000 square degrees on the surface of the sky. Therefore, when we look at the CMB over the entire sky, we are looking at 40,000 causally disconnected regions of the Universe. But quite remarkably, each has the same temperature to roughly one part in $10^5$!
The most satisfying (only?) explanation for this is slow-roll inflation, a period of accelerated expansion in the early Universe driven by the vacuum energy most likely associated with a symmetric phase of a GUT Higgs field (or perhaps Planck-scale physics or Peccei-Quinn symmetry breaking). Although the physics responsible for inflation is still not well understood, inflation generically predicts (1) a flat Universe; (2) that primordial adiabatic (i.e., curvature) perturbations are responsible for the large-scale structure (LSS) in the Universe today; and (3) a stochastic gravity-wave background. More precisely, inflation predicts a spectrum $P_s = A_s k^{n_s}$ (with $n_s$ near unity) of primordial density (scalar metric) perturbations, and a stochastic gravity-wave background (tensor metric perturbations) with spectrum $P_t = A_t \propto k^{n_t}$ (with $n_t$ small compared with unity). (4) Inflation further uniquely predicts specific relations between the “inflationary observables,” the amplitudes $A_s$ and $A_t$ and spectral indices $n_s$ and $n_t$ of the scalar and tensor perturbations. The amplitude of the gravity-wave background is proportional to the height of the inflaton potential, and the spectral indices depend on the shape of the inflaton potential. Therefore, determination of these parameters would illuminate the physics responsible for inflation.

Until recently, none of these predictions could really be tested. Measured values for the density of the Universe span almost an order of magnitude. Furthermore, most do not probe the possible contribution of a cosmological constant (or some other diffuse matter component), so they do not address the geometry of the Universe. The only observable effects of a stochastic gravity-wave background are in the CMB. COBE observations do in fact provide an upper limit to the tensor amplitude, and therefore an inflaton-potential height near the GUT scale. However, there is no way to disentangle the scalar and tensor contributions to the COBE anisotropy.

In recent years, it has become increasingly likely that adiabatic perturbations are responsible for the origin of structure. Before COBE, there were numerous plausible models for structure formation: e.g., isocurvature perturbations both with and without cold dark matter, late-time or slow phase transitions, topological defects (cosmic strings or textures), superconducting cosmic strings, explosive or seed models, a “loitering” Universe, etc. However, after COBE, only primordial adiabatic perturbations and topological defects were still considered seriously. And in the past few months, some leading proponents of topological defects have conceded that these models have difficulty reproducing the observed large-scale structure.

We are now entering an exciting new era, driven by new theoretical ideas and developments in detector technology, in which the predictions of inflation will be tested with unprecedented precision. It is even conceivable that early in the next century, we will move from verification to direct investigation of the high-energy physics responsible for inflation.

The purpose of this talk is to review how forthcoming CMB experiments will test several of these predictions. I will first review the predictions of inflation for density perturbations and gravity waves. I will then discuss how CMB temperature anisotropies will test the inflationary predictions of a flat Universe and a primordial spectrum of density perturbations. I review how a CMB polarization map may be used to isolate the gravity waves and briefly review how detection of these tensor modes may be used to learn about the physics responsible for inflation. I then discuss some recent work on secondary anisotropies at smaller angular scales, and how these may be used to probe the epoch at which objects first underwent gravitational collapse in the Universe. I close with some brief remarks about further testable consequences of inflation.

2 Inflationary Observables

Inflation occurs when the energy density of the Universe is dominated by the vacuum energy $V(\phi)$ associated with some scalar field $\phi$ (the “inflaton”). During this time, the quantum fluctuations in $\phi$ produce classical scalar perturbations, and quantum fluctuations in the spacetime metric produce gravitational waves. If the inflaton potential $V(\phi)$ is given in units of $m_{Pl}^4$, and the
inflaton $\phi$ is in units of $m_{\text{Pl}}$, then the scalar and tensor spectral indices are

$$1 - n_s = (1/8\pi) (V'/V)^2 - (1/4\pi) (V'/V)' , \quad n_t = -(1/8\pi) (V'/V)^2 .$$  

The amplitudes can be fixed by their contribution to $C_{2}^{TT}$, the quadrupole moment of the CMB temperature, $S \equiv 6 C_{2}^{TT,\text{scalar}} = 33.2 [V^3/(V')^2]$, and $T \equiv 6 C_{2}^{TT,\text{tensor}} = 9.2 V$. For the slow-roll conditions to be satisfied, we must have $(1/16\pi)(V'/V) \ll 1$, and $(1/8\pi)(V''/V) \ll 1$, which guarantee that inflation lasts long enough to make the Universe flat and to solve the horizon problem.

When combined with COBE results, current degree-scale–anisotropy and large-scale-structure observations suggest that $T/S$ is less than order unity in inflationary models, which restricts $V \lesssim 5 \times 10^{-12}$. Barring strange coincidences, the COBE spectral index and relations above suggest that if slow-roll inflation is right, then scalar and tensor spectra must both be nearly scale invariant ($n_s \simeq 1$ and $n_t \simeq 0$).

3 Temperature Anisotropies

The primary goal of CMB experiments that map the temperature as a function of position on the sky 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 spherical harmonics,

$$\frac{\Delta T(\hat{n})}{T} = \sum_{lm} a_{lm}^T Y_{lm}(\hat{n}) , \quad \text{with} \quad a_{lm}^T = \int \hat{d}\hat{n} Y_{lm}^*(\hat{n}) \frac{\Delta T(\hat{n})}{T} .$$

Statistical isotropy and homogeneity of the Universe imply that these coefficients have expectation values $\langle (a_{lm}^T)^*(a_{l'm'}^T) \rangle = C_l^{TT} \delta_{ll'} \delta_{mm'}$ when averaged over the sky. Roughly speaking, the multipole moments $C_l^{TT}$ measure the mean-square temperature difference between two points separated by an angle $(\theta/1') \sim 200/l$.

Predictions for the $C_l$’s can be made given a theory for structure formation and the values of several cosmological parameters. Fig. 3 shows predictions for models with primordial adiabatic perturbations. The wriggles come from oscillations in the photon-baryon fluid at 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.

These small-angle CMB anisotropies can be used to determine the geometry of the Universe. The angle subtended by the horizon at the surface of last scatter is $\theta_H \sim \Omega^{1/2} 1^\circ$, and the peaks in the CMB spectrum are due to causal processes at the surface of last scatter. Therefore, the angles (or values of $l$) at which the peaks occur determine the geometry of the Universe. This is illustrated in Fig. 3(a) where the CMB spectra for several values of $\Omega$ are shown. As illustrated in the other panels, the angular position of the first peak is relatively insensitive to the values of other undetermined (or still imprecisely determined) cosmological parameters such as the baryon density, the Hubble constant, and the cosmological constant (as well as several others not shown such as the spectral indices and amplitudes of the scalar and tensor spectra and the ionization history of the Universe). Therefore, determination of the location of this first acoustic peak should provide a robust measure of the geometry of the Universe.

Fig. 4 shows data from current ground-based and balloon-borne experiments. By fitting the theoretical curves to these points, several groups find that the best fit to the data is found with a total density $\Omega \simeq 1.0$. However, visual inspection of the data points in Fig. 4 clearly indicate that this current determination of the geometry cannot be robust.
Figure 1: Theoretical predictions for CMB spectra as a function of multipole moment $l$ for models with primordial adiabatic perturbations. In each case, the heavy curve is that for the canonical 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), $\Omega + \Lambda = 1$. 
Figure 2: Current CMB data.
Figure 3: Simulated MAP and Planck data.
In the near future, the precision with which this determination can be made will be improved dramatically. NASA has recently approved the flight of a satellite mission, the Microwave Anisotropy Probe (MAP) in the year 2000 to carry out these measurements, and ESA has approved the flight of a subsequent more precise experiment, the Planck Surveyor. Fig. 3 shows simulated data from MAP and Planck. The heavier points with smaller error bars are those we might expect from Planck and the lighter points with larger error bars are those anticipated for MAP. Even without any sophisticated analysis, it is clear from Fig. 3 that data from either of these experiments will be able to locate the first acoustic peak sufficiently well to discriminate between a flat Universe ($\Omega = 1$) and an open Universe with $\Omega \approx 0.3 - 0.5$.

By doing what essentially boils down to a calculation of the covariance matrix for such simulated data, it can be shown that these satellite missions may potentially determine $\Omega$ to better than 10% after marginalizing over all other undetermined parameters (we considered 7 more parameters in addition to the 4 shown in Fig. 1), and better than 1% if the other parameters can be fixed by independent observations or assumption. This would be far more accurate than any traditional determinations of the geometry.

We also found that the CMB should provide values for the cosmological constant and baryon density far more precise than those from traditional observations. If there is more nonrelativistic matter in the Universe than baryons can account for—as suggested by current observations—it will become increasingly clear with future CMB measurements. Subsequent analyses have confirmed these estimates with more accurate numerical calculations.

Although these forecasts relied on the assumptions that adiabatic perturbations were responsible for structure formation and that reionization would not erase CMB anisotropies, these assumptions have become increasingly justifiable in the past few years. As discussed above, the leading alternative theories for structure formation now appear to be in trouble, and recent detections of CMB anisotropy at degree angular separations show that the effects of reionization are small.

The predictions of a nearly scale-free spectrum of primordial adiabatic perturbations will also be further tested with measurements of small-angle CMB anisotropies. The existence and structure of the acoustic peaks shown in Fig. 1 will provide an unmistakable signature of adiabatic perturbation and the spectral index $n_s$ can be determined from fitting the theoretical curves to the data in the same way that the density, cosmological constant, baryon density, and Hubble constant are also fit.

Temperature anisotropies produced by a stochastic gravity-wave background would affect the shape of the angular CMB spectrum, but there is no way to disentangle the scalar and tensor contributions to the CMB anisotropy in a model-independent way. Unless the tensor signal is large, the cosmic variance from the dominant scalar modes will provide an irreducible limit to the sensitivity of a temperature map to a tensor signal.

4 CMB Polarization and Gravitational Waves

Although a CMB temperature map cannot unambiguously distinguish between the density-perturbation and gravity-wave contributions to the CMB, the two can be decomposed in a model-independent fashion with a map of the CMB polarization. Suppose we measure the linear-polarization “vector” $\vec{P}(\hat{n})$ at every point $\hat{n}$ on the sky. Such a vector field can be written as the gradient of a scalar function $A$ plus the curl of a vector field $\vec{B}$: $\vec{P}(\hat{n}) = \nabla A + \nabla \times \vec{B}$. The gradient (i.e., curl-free) and curl components can be decomposed by taking the divergence or curl of $\vec{P}(\hat{n})$ respectively. Density perturbations are scalar metric perturbations, so they have no handedness. They can therefore produce no curl. On the other hand, gravitational waves do have a handedness so they can (and we have shown that they do) produce a curl. This therefore provides a way to detect the inflationary stochastic gravity-wave background and thereby test
the relations between the inflationary observables. It should also allow one to determine (or at least constrain in the case of a nondetection) the height of the inflaton potential.

More precisely, the Stokes parameters \( Q(\hat{n}) \) and \( U(\hat{n}) \) (where \( Q \) and \( U \) are measured with respect to the polar \( \theta \) and azimuthal \( \phi \) axes) which specify the linear polarization in direction \( \hat{n} \) are components of a 2 \( \times \) 2 symmetric trace-free (STF) tensor,

\[
P_{ab}(\hat{n}) = \frac{1}{2} \begin{pmatrix} Q(\hat{n}) & -U(\hat{n}) \sin \theta \\ -U(\hat{n}) \sin \theta & -Q(\hat{n}) \sin^2 \theta \end{pmatrix},
\]

where the subscripts \( ab \) are tensor indices. Just as the temperature is expanded in terms of spherical harmonics, the polarization tensor can be expanded,

\[
\mathcal{P}_{ab}(\hat{n}) = \sum_{lm} \left[ a_{(lm)}^G Y_{(lm)ab}^G(\hat{n}) + a_{(lm)}^C Y_{(lm)ab}^C(\hat{n}) \right],
\]

in terms of the tensor spherical harmonics \( Y_{(lm)ab}^G \) and \( Y_{(lm)ab}^C \), which are a complete basis for the “gradient” (i.e., curl-free) and “curl” components of the tensor field, respectively. The mode amplitudes are given by

\[
a_{(lm)}^G = \frac{1}{T_0} \int d\hat{n} \mathcal{P}_{ab}(\hat{n}) Y_{(lm)}^{G*ab}(\hat{n}), \quad a_{(lm)}^C = \frac{1}{T_0} \int d\hat{n} \mathcal{P}_{ab}(\hat{n}) Y_{(lm)}^{C*ab}(\hat{n}).
\]

Here \( T_0 \) is the cosmological mean CMB temperature and \( Q \) and \( U \) are given in brightness temperature units rather than flux units. Scalar perturbations have no handedness. Therefore, they can produce no curl, so \( a_{(lm)}^C = 0 \) for scalar modes. On the other hand tensor modes do have a handedness, so they produce a non-zero curl, \( a_{(lm)}^C \neq 0 \).

A given inflationary model predicts that the \( a_{(lm)}^X \) are gaussian random variables with zero mean, \( \langle a_{(lm)}^X \rangle = 0 \) (for \( X, X' = \{T, G, C\} \)) and covariance \( \langle \left( a_{(l'm')}^{X'} \right)^* a_{(lm)}^X \rangle = C_{l'l'}^{XX'} \delta_{mm'} \).

Parity demands that \( C_{l}^{TC} = C_{l}^{GC} = 0 \). Therefore the statistics of the CMB temperature-polarization map are completely specified by the four sets of moments, \( C_l^{TT}, C_l^{TG}, C_l^{GG}, \) and \( C_l^{CC} \). Also, as stated above, only tensor modes will produce nonzero \( C_l^{CC} \).

To illustrate, Fig. 4 shows the four temperature-polarization power spectra. The dotted curves correspond to a COBE-normalized inflationary model with cold dark matter and no cosmological constant (\( \Lambda = 0 \)), Hubble constant (in units of 100 km sec\(^{-1}\) Mpc\(^{-1}\) ) \( h = 0.65 \), baryon density \( \Omega_b h^2 = 0.024 \), scalar spectral index \( n_s = 1 \), no reionization, and no gravitational waves. The solid curves show the spectra for a COBE-normalized stochastic gravity-wave background with a flat scale-invariant spectrum (\( h = 0.65 \), \( \Omega_b h^2 = 0.024 \), and \( \Lambda = 0 \)) in a critical-density Universe. Note that the panel for \( C_l^{CC} \) contains no dotted curve since scalar perturbations produce no C polarization component. The dashed curve in the CC panel shows the tensor spectrum for a reionized model with optical depth \( \tau = 0.1 \) to the surface of last scatter.

As with a temperature map, the sensitivity of a polarization map to gravity waves will be determined by the instrumental noise and fraction of sky covered, and by the angular resolution. Suppose the detector sensitivity is \( s \) and the experiment lasts for \( t_{yr} \) years with an angular resolution better than 1°. Suppose further that we consider only the CC component of the polarization in our analysis. Then the smallest tensor amplitude \( T_{min} \) to which the experiment will be sensitive at 1σ is

\[
\frac{T_{min}}{6 C_{l}^{TT}} \approx 5 \times 10^{-4} \left( \frac{s}{\mu K \text{sec}} \right)^2 t_{yr}^{-1}.
\]

Thus, the curl component of a full-sky polarization map is sensitive to inflaton potentials \( V \gtrsim 5 \times 10^{-13} t_{yr}^{-1} (s/\mu K \text{sec})^2 \). Improvement on current constraints with only the curl polarization component requires a detector sensitivity \( s \lesssim 40 t_{yr}^{1/2} \mu K \text{sec} \). For comparison, the
Figure 4: Theoretical predictions for the four nonzero CMB temperature-polarization spectra as a function of multipole moment $l$. The dashed line in the lower right panel shows a reionized model with optical depth $\tau = 0.1$ to the surface of last scatter.
detector sensitivity of MAP will be \( s = \mathcal{O}(100 \mu K \sqrt{\text{sec}}) \). However, Planck may conceivably get sensitivities around \( s = 25 \mu K \sqrt{\text{sec}} \).

Eq. 6 is the sensitivity obtained by using only the curl component of the polarization, which provides a model-independent probe of the tensor signal. However, if we are willing to consider specific models for the tensor and scalar spectra, the sensitivity to a tensor signal may be improved somewhat by considering the predictions for the full temperature/polarization auto- and cross-correlation power spectra.

For example, Fig. 5 shows the 1σ sensitivity \( \sigma_T \) to the amplitude \( T \) of a flat \( (n_t = 0) \) tensor spectrum as a function of detector sensitivity \( s \) for an experiment which maps the CMB temperature and polarization on the full sky for one year with an angular resolution of 0.5°. The dotted curve shows the results obtained by fitting only the TT moments; the dashed curve shows results obtained by fitting only the CC moments; and the solid curve shows results obtained by fitting all four nonzero sets of moments.

In Fig. 5, we have assumed that the spectra are fit only to \( S, T, \) and \( n_s \), and the parameters of the cosmological model are those used in Fig. 5. If one fits to more cosmological parameters (e.g., \( \Omega_b, h, \Lambda \), etc.) as well, the the sensitivity from the temperature moments, important for larger \( s \), is degraded. However, the sensitivity due to the CC component, which controls the total sensitivity for smaller \( s \), is essentially unchanged. Again, this is because the CC signal is very model-independent.

For detectors sensitivities \( s \gtrsim 20 \mu K \sqrt{\text{sec}} \), the tensor-mode detectability for the three-parameter fit shown in Fig. 5 comes primarily from the temperature map, although polarization does provides some incremental improvement. However, if the data are fit to more cosmological parameters (not shown), the polarization improves the tensor sensitivity even for \( s \gtrsim 20 \mu K \sqrt{\text{sec}} \). In any case, the sensitivity to tensor modes comes almost entirely from the curl of the polarization for detector sensitivities \( s \lesssim 10 \mu K \sqrt{\text{sec}} \). Since the value of \( s \) for Planck will be somewhat higher, it will likely require a more sensitive future experiment to truly capitalize on the model-independent curl signature of tensor modes.

Finally, it should be noted that even a small amount of reionization will significantly increase the polarization signal at low \( l \) as shown in the CC panel of Fig. 4 for \( \tau = 0.1 \). With such a level of reionization (which may be expected in CDM models, as discussed in the following Section), the sensitivity to the tensor amplitude is increased by more than a factor of 5 over that in Eq. (6). This level of reionization (if not more) is expected in cold dark matter models, so if anything, Eq. (6) and Fig. 5 provide conservative estimates.

5 The Ostriker-Vishniac Effect and the Epoch of Reionization

Although most of the matter in CDM models does not undergo gravitational collapse until relatively late in the history of the Universe, some small fraction of the mass is expected to collapse at early times. Ionizing radiation released by this early generation of star and/or galaxy formation will partially reionize the Universe, and these ionized electrons will re-scatter at least some cosmic microwave background (CMB) photons after recombination at a redshift of \( z \simeq 1100 \). Theoretical uncertainties in the process of star formation and the resulting ionization make precise predictions of the ionization history difficult. Constraints to the shape of the CMB blackbody spectrum and detection of CMB anisotropy at degree angular scales suggest that if reionization occurred, the fraction of CMB photons that re-scattered is small. Still, estimates show that even if small, at least some reionization is expected in CDM models; for example, the most careful recent calculations suggest a fraction \( \tau_r \sim 0.1 \) of CMB photons were re-scattered.

Scattering of CMB photons from ionized clouds will lead to anisotropies at arcminute separations below the Silk-damping scale (the Ostriker-Vishniac effect). These anisotropies arise
Figure 5: Results for the $1\sigma$ sensitivity $\sigma_T$ to the amplitude $T$ of a flat ($n_t = 0$) tensor spectrum as a function of detector sensitivity $s$ for an experiment which maps the CMB temperature and polarization on the full sky for one year with an angular resolution of 0.5$^\circ$. The vertical axis is in units of the temperature quadrupole. See text for more details.
at higher order in perturbation theory and are therefore not included in the usual Boltzmann calculations of CMB anisotropy spectra. The level of anisotropy is expected to be small and it has so far eluded detection. However, these anisotropies may be observable with forthcoming CMB interferometry experiments\(^\text{23}\) that probe the CMB power spectrum at arcminute scales.

Fig. \(\text{22}\) shows the predicted temperature-anisotropy spectrum from the Ostriker-Vishniac effect for a number of ionization histories. The ionization histories are parameterized by an ionization fraction \(x_e\) and a redshift \(z_r\) at which the Universe becomes reionized. The optical depth \(\tau\) to the standard-recombination surface of last scatter can be obtained from these two parameters.

Reionization damps the acoustic peaks in the primary-anisotropy spectrum by \(e^{-2\tau}\), as shown in Fig. \(\text{1}\), but this damping is essentially independent of the details of the ionization history. That is, any combination of \(x_e\) and \(z_r\) that gives the same \(\tau\) has the same effect on the primary anisotropies. So although MAP and Planck will be able to determine \(\tau\) from this damping, they will not constrain the epoch of reionization. On the other hand, the secondary anisotropies (the Ostriker-Vishniac anisotropies) produced at smaller angular scales in reionized models do depend on the ionization history. For example, although the top and bottom dashed curves in Fig. \(\text{6}\) both have the same optical depth, they have different reionization redshifts \((z_r = 20\) and \(z_r = 57)\). Therefore, if MAP and Planck determine \(\tau\), the amplitude of the Ostriker-Vishniac anisotropy determines the reionization epoch.\(^\text{22}\)

In a flat Universe, CDM models normalized to cluster abundances produce rms temperature anisotropies of 0.8–2.4 \(\mu\)K on arcminute angular scales for a constant ionization fraction of unity, whereas an ionization fraction of 0.2 yields rms anisotropies of 0.3–0.8 \(\mu\)K.\(^\text{22}\) In an open and/or high-baryon-density Universe, the level of anisotropy is somewhat higher. The signal in some of these models may be detectable with planned interferometry experiments.\(^\text{22}\)

6 Discussion

If MAP and Planck find a CMB temperature-anisotropy spectrum consistent with a flat Universe and nearly-scale-free primordial adiabatic perturbations, then the next step will be to isolate the gravity waves with the polarization of the CMB. If inflation has something to do with grand unification, then it is possible that Planck’s polarization sensitivity will be sufficient to see the polarization signature of gravity waves. However, it is also quite plausible that the height of the inflaton potential may be low enough to elude detection by Planck. If so, then a subsequent experiment with better sensitivity to polarization will need to be done.

Inflation also predicts that the distribution of primordial density perturbations is gaussian, and this can be tested with CMB temperature maps and with the study of the large-scale distribution of galaxies. Since big-bang nucleosynthesis predicts that the baryon density is \(\Omega_b \lesssim 0.1\) and inflation predicts \(\Omega = 1\), another prediction of inflation is a significant component of nonbaryonic dark matter. This can be either in the form of vacuum energy (i.e., a cosmological constant), and/or some new elementary particle. Therefore, discovery of particle dark matter could be interpreted as evidence for inflation.

Large-scale galaxy surveys will soon map the distribution of mass in the Universe today, and CMB experiments will shortly determine the mass distribution in the early Universe. The next step will be to fill in the precise history of structure formation in the “dark ages” after recombination but before redshifts of a few. Reconstruction of this epoch of cosmic history will likely require amalgamation of the complementary information provided by a number observations in several wavebands. Detection of the secondary CMB anisotropies at arcminute scales produced by scattering from reionized clouds will provide an indication of the epoch of reionization, and therefore the epoch at which structures first undergo gravitational collapse in the Universe.\(^\text{22}\)
Figure 6: Multipole moments for the Ostriker-Vishniac effect for the COBE-normalized canonical standard-CDM model ($\Omega = 1$, $h = 0.5$, $n = 1$, $\Omega_b h^2 = 0.0125$), for a variety of ionization histories, as listed. We also show predictions for several open high-baryon-density models with the same $x_e$ and $\tau_r$, normalized to the cluster abundance, with dashed curves. The dotted curves show the primary anisotropy for this model for $\tau_r = 0.0, 0.1, 0.5, 1, \text{ and } 2$, from top to bottom.
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