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The cosmic microwave background

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The interpretation of the redshifts of distant galaxies as due to a cosmological expansion led to the postulate of the Hot Big Bang cosmology as the descriptor of the structure and evolution of the Universe on large scales. Subsequently, the hypothesis that the light elements were synthesized in an early hot and dense epoch led to the prediction that the temperature of relict radiation in the present-day universe is close to 3 K. The discovery of the 3 K cosmic microwave background radiation (CMBR) by Penzias & Wilson (1965) was a confirmation of the Hot Big Bang cosmology. The origin of this observable relict in the radiation era of the early universe and its propagation through recombination and during the epochs of structure formation has made the CMBR a unique probe of the astrophysical and dynamical evolution in the universe.

At redshifts $z \geq 3 \times 10^6$, the high temperatures and densities ensured strong interaction between radiation and the fully ionized baryonic matter via free-free and double-Compton processes: these mechanisms change photon numbers and consequently the radiation was thermalized; matter and radiation were in thermodynamic equilibrium, and the radiation had a black-body Planck spectral form. During epochs $10^5 < z < 3 \times 10^6$, the decreased densities and temperatures resulted in the photon production / absorption process timescales exceeding the cosmological expansion timescales; however, Compton scattering continued to be effective in changing the photon energies significantly. Consequently, we expect the radiation content of the universe to have relaxed to a Bose-Einstein form if any astrophysical process resulted in the addition of photons to the background, or else to have simply maintained its primordial Planckian form throughout this period. Due to the absence of energy changing interactions with baryons during $z < 10^5$, the spectral form of the radiation — Planckian or Bose-Einstein form — will survive unchanged to the present epoch along with any distortions that are impressed during this most recent period. Measurement of the spectral form of the relict CMBR is, therefore, a probe of the thermal history of the universe back to the recombination epoch and beyond to $z \approx 3 \times 10^6$.

The CMBR spectrum has been measured in the frequency range 60 to 600 GHz by the FIRAS instrument on COBE (Mather et al. 1994). Lower frequency measurements of the CMBR spectrum extend down to 600 MHz (reviewed in Kogut et al. 1991). No spectral distortions have been observed to-date and the observed spectrum fits well with a Planck spectrum with temperature $T = 2.726 \pm 0.01$ K. The observations have yielded upper limits on possible distortions: the Compton scattering y-distortion parameter is constrained to be $< 2.5 \times 10^{-5}$, the Bose Einstein μ-distortion parameter is constrained to be $< 3.3 \times 10^{-4}$. However, it may be noted that the absence of distortions at these measurement precisions is not surprising: 'standard' theories for the thermal history of the universe predict recombination distortions at levels $\Delta T / T \leq 10^{-6}$ as compared to the observed rms error of 10^{-4} at the peak of the spectrum in the COBE-FIRAS observations; structure formation from COBE-DMR normalized scale invariant CDM perturbations predicts $\mu \approx 10^{-10}$. *Observations* constrain hypothetical exotic processes but *are far from reaching the level of inevitable distortions.*

Structure formation is hypothesized to be seeded by density perturbations in the early universe whose dynamical growth is driven by gravitational instability. A primordial perturbation spectrum is believed to evolve through dynamical and astrophysical processes to form the present-day observed galaxies and large scale structures: the galaxy distribution. The CMBR photons observable today were last scattered by the baryons at the recombination epoch: $z \approx 1100$. The density perturbations at this last-scattering-surface are expected to cause temperature fluctuations in the scattered CMBR as observed today: the CMBR is predicted to have a temperature anisotropy spectrum that is related through coupling mechanisms like gravitational potential variations due to the density perturbations, isentropic nature of the density perturbations, Doppler scattering off baryons moving with peculiar velocities induced by the density perturbations—to the spectrum of the density perturbations at the last-scattering-surface. Secondary CMBR anisotropies are additionally predicted to be inevitably impressed on the CMBR during its propagation in the post-recombination universe: for example, due to the growing nature of the perturbations, due to scattering off bulk flows in reionized baryons at the epoch of non-linearity and astrophysical galaxy formation, due to the scattering off hot electrons in deep cluster potential wells. CMBR anisotropies may also be erased on smaller angular scales during the propagation through recombination and ionized intergalactic gas in any reionization epoch. The final processed CMBR anisotropy spectrum observable today is a probe of the primordial seed density perturbation spectrum as well as the mechanisms that impress and erase anisotropies. Our expectations of CMBR anisotropies in different cosmological models are reviewed by White, Scott & Silk (1994).

Measurements of CMBR anisotropy on large angular scales, $\theta > 7$ degrees, have been made by the COBE-DMR experiment (Smoot et al. 1992), and confirmed by the MIT group (Meyer et al. 1991) Observations of CMBR anisotropy have also been made on the scale of several degrees in the TENERIFE experiment (Hancock et al. 1994). These measurements imply temperature anisotropy at the level of one part in 10^5. On intermediate scales of about a degree, there are several experiments claiming detections of anisotropy; for example, the PYTHON, AGRO, SP91, SASTAKOON, MAX GUM and μP scans, and the MSAM experimental groups. On small scales of a few arcmin, there are no positive detections to date; the VLA, OVRO and ATCA (Subrahmanyan *et al.* 1993) groups have all made sensitive measurements and placed upper limits on the level of anisotropy on these scales. Observational techniques and recent results are reviewed by Readhead & Lawrence (1992) and Subrahmanyan (1996). Current trends in observations are indicative of a CMBR anisotropy spectrum that is flat on the largest angular scales, as is expected for a scale-invariant perturbation spectrum, rises to a peak on scales of about a degree, as is expected due to 'Doppler peaks' at the recombination epoch, and then cuts off on arcmin scales, as is expected due to the finite thickness of the recombination phase. The form and magnitude of the observed CMBR anisotropy spectrum on large angular scales is in agreement with the expectations from 'standard' theories of structure formation; however, *observational precision will have to improve on intermediate and small scales before the anisotropy spectrum can become a useful tool for probing the recombination epoch and post-recombination evolution.*

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