2. Anisotropy of the blackbody radiation

(D.T. Wilkinson and F. Melchiorri)

INTRODUCTION

The 2.7 K microwave background radiation provides a sensitive probe of the universe in the interesting, but poorly understood, epoch around $z \sim 1000$. At this time (age $\sim 10^6$yr) the universe has cooled to $T \sim 4000$ K, the plasma combines, Thomson scattering ceases, and matter and blackbody radiation decouple. Subsequently, the radiation freely propagates to us, carrying the imprint of temperature fluctuations on the $z \sim 1000$ surface. The temperature fluctuations could have been caused by primordial density fluctuations, anisotropy in the expansion of the universe, or inhomogeneity in the initial temperature distribution; the $z = 1000$ surface we see was not causally connected at the time the radiation was released. Interpretation of the anisotropy measurements is complicated by the possibility that the matter may have been reionized (e.g. by massive stars), so the radiation may have been rescattered, possibly as late as $z \sim 7$.

This picture follows the standard hot big-bang cosmological model [1], and indeed measurements of the spectrum and isotropy of the 2.7 K radiation furnish much of the support for the model [2].

Remarkably, no anisotropy has been detected at a level of $\Delta T/T \sim 10^{-4}$ on angular scales from 1 arcminute to 90 degrees. The "dipole" effect is mostly, perhaps completely, due to the peculiar velocity of the sun through the radiation. Observational techniques and theoretical interpretations logically divide the subject into three regimes of angular scale.

SMALL SCALE ANISOTROPY (< 1°)

The large-scale structure seen in the current universe - clusters of galaxies, voids, strings, etc. - should have been forming at $z \sim 1000$ and had an angular size (as seen now) of a few arcminutes. If reionization is negligible, current estimates of the magnitude of perturbation of the background radiation based on the standard hot big-bang model are in the range $\Delta T/T \sim 10^{-4}$ to 10^{-5} [3]. The observational upper limits on this angular scale are approaching 10^{-5}, placing important constraints on the models for structure formation, the magnitude of initial density fluctuations, and the cosmological model.

Early searches for small scale anisotropy in the 2.7 K background are discussed by Partridge [4] and the theoretical predictions are reviewed by Hogan, Kaiser and Rees [5]. The current best limits are discussed below.

To achieve angular resolution of a few arcminutes, large radio telescopes are needed, so the observational work in this angular regime has been done from the ground. To achieve sensitivity of 10^{-5} K the lowest noise receivers ($\Delta T_{rms} < 10^{-2}$ K $s^{1/2}$) and the most uniform atmospheric conditions are resuired. Since many hours of integration time are required on each sky position, stable telescope and receiving systems, and careful control of ground radiation are essential.

The Green Bank 140' telescope and maser system has been used to place a limit of $\Delta T_{rms}/T < 2.1 \times 10^{-5}$ (95% confidence) at angular scales of 1-5 arcminutes [6]. At smaller angular scales the NRAO Very Large Array has produced the best limits : $\Delta T_{rms}/T < 10^{-3}$ at 18 arcseconds and 5×10^{-4} at 1 arcminute (95% confidence) [7, 8]. This limit was not dominated by system noise, so further improvement is expected. Parijski and his coworkers have reported early results from the RATAN-600 telescope [9] at a wavelength of 7.6 cm. The smallest sky signal, $\Delta T_{rms} < 3 \times 10^{-4}$ K (one sigma) is seen at an angular scale of about 7 arcminutes where Galactic radiation and point source confusion reach a minimum. Correlation with signals at other wavelengths, which are observed simultaneously, allows a tenfold reduction to a (1σ) level of 10^{-5} on scales from 4.5 to 9 arcminutes.

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The complicated issue of reducing and interpreting anisotropy data is carefully addressed by Lasenby and Davies [10] and by Partridge [4]. Because of the variety of spatial patterns used by the observers, each upper limit must be carefully interpreted in terms of the particular theoretical model being tested [6]. The actual detection of small scale anisotropy will be an important milestone in contemporary cosmology.

INTERMEDIATE SCALE ANISOTROPY (~ 1°)

Regions of the photon barrier at $z \sim 1000$ which are separated by a few degrees were not in casual contact at the time the 2.7 K photons left there. Therefore, even in the case of strong reionization this angular scale will provide useful informations because statistical mass clumping can cause anisotropy because the 2.7 K photons from different regions suffer different gravitational redshifts [11, 12]. This effect can grow with angular scale as $\theta^{1/2}$: most effects get weaker with θ.

Atmospheric inhomogeneities are a serious problem for ground-based observations at intermediate angular scales. Few observations have been attempted, the best being done from balloons with broadband bolometric detectors [13]. Thermal emission from patchy Galactic dust is the main problem for the broadband mm detectors, but multiband observations and correlation with radio and infrared sky maps can be used to separate signals due to dust and 2.7 K anisotropy [14].

LARGE SCALE ANISOTROPY

If the universe were anisotropic or inhomogeneous on large scales (in violation of Einstein's Cosmological Principle), an anisotropy should be seen in the 2.7 K radiation. No such intrinsic effect has been seen with amplitude greater than 0.1 mK [15, 16]. These results were obtained by high-sensitivity microwave radiometers (λ = 3 mm and 1.2 cm, respectively) carried above atmospheric water vapor by balloons. Most of the sky has been observed. The 1.2 cm observations are the most sensitive (ΔT_{rms} = 4 mK $s^{1/2}$), but residual Galactic radio emission is a problem. A wavelength of 3 mm seems about optimum, located between Galactic dust and radio emissions.

A strong dipole signal is observed in the 2.7 K radiation : amplitude 3.3 ± 0.3 mK, declination - 6° ± 3°, right ascension $11.2^h \pm 0.2^h$ [15, 16]. The dipole pattern measured by balloon-borne bolometers [2, 17] is less accurate, due to limited sky coverage and Galactic dust emission, but the results are in agreement with the radiometer measurements.

Most of the observational dipole anisotropy is due to the motion of the sun through the radiation, although one cannot rule out a small contribution from intrinsic cosmic anisotropy. If the sun's motion due to Galactic rotation is subtracted from the observed solar motion with respect to the 2.7 K radiation, the peculiar velocity of the Galaxy (or Local Group) is obtained : V_{LG} = (610 ± 50) km/sec, towards $\alpha = 10.5^h \pm 0.4^h$ and δ = - 26° ± 5° [18]. This velocity vector is directed 49° away from the Virgo cluster and 17° away from the velocity vector measured with respect to Sbc galaxies [19].

The small dipole signal due to the Earth's motion has been detected (7σ level) [18] and the spectrum of the dipole signal [20] is in agreement with that expected for backbody radiation. The dipole's spectrum has recently been used as a sensitive test for photon mass [21].

SUNYAEV - ZEL'DOVICH EFFECT

When the 2.7 K photons travel through the hot plasmas in the central regions of some clusters of galaxies, they are Compton scattered upwards in frequency by the energetic electrons. The result is a distortion of the blackbody spectrum which diminishes the intensity at longer (cm) wavelengths but increases the appa-

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parent temperature at short (mm) wavelengths [22]. The effect is estimated to be about 10^{-3} K for clusters having plasmas with strong, smooth x-ray emission [23,24].

Since the plasma clouds are about an arcminute in diameter, large ground-based telescopes must be used for observations, and the problems are similar to those of searches for small-scale anisotropy. Years of work, and much telescope time, have been devoted to this problem [25, 26, 27, 10] with some marginal detections reported. Based on this experience, recent observations at Owens Valley [28] and at Greenbank [29] have detected the Sunyaev-Zel'dovich effect with good statistical accuracy and (more importantly) small systematic corrections. The clusters 0016 + 16, A2218 and A665 show clear, reproducible decrements at their central positions. Attempts [30] to detect the excess signal expected at millimeters wavelengths have been unsuccessful, so far. Atmospheric inhomogeneity is a very severe problem even at mountaintop observatories.

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3. Clusters of Galaxies

(Jaan Einasto)

Abell and Corwin (34.160.040) have continued the search of southern clusters on photographs taken with the U.K. Schmidt telescope at Siding Spring. A catalogue is in preparation, it continues the Abell catalogue toward southern declinations. West (32.160.019, 32.160.036, 34.160.044) has initiated a study of distant southern clusters with automatic identification of clusters and objective evaluation of their properties. Noonan (30.160.006) and Sarazin et al. (31.160.030) have listed clusters with published redshifts. Numerical simulations have demonstrated the presence of bias in observed clusters as difined by Abell (33.160.006), ranked absolute magnitudes of galaxies are distance dependent (33.160.081), some clusters may be due to projection effects (34.160.009).

Kraan-Korteweg has presented a complete sample of bright members of the Virgo cluster and derived the luminosity function and kinematical parameters (30.160.049 31.160.013). Binggeli, Sandage and Tarenghi (1984) have started a program to study faint galaxies in the Virgo cluster using der Pont 2.5-m reflector. Near infrared photometry of 81 disk galaxies has been done in (34.160.097), structural parameters of 20 galaxies are derived from Fourier and momentum analyses of luminosity profiles (32.160.026). Rocket ultraviolet photometry has been done in (32.160.025). The effective radius and central surface brightness decrease with decreasing luminosity, but there is no difference between S0 and later Hubble type galaxies of same luminosity. Kinematics of the Virgo clusters has been studied also in (31.160.072, 31.160.011, 33.160.036, 33.160,039).

Extensive 21-cm HI observations in Westerbork and Arecibo (30.160.044, 33.160.003, 33.160.032, 33.160.076, 34.160.005, 34.160.051) have demonstrated that galaxies in the Virgo cluster core have smaller HI extent and are HI deficient by a factor 2 to 2.7 in respect to galaxies of the same morphological type outside the core. The HI deficiency depends on the velocity of a galaxy in respect to the cluster suggesting a ram pressure sweeping of the intracluster gas. It is shown that Virgo cluster galaxies are dust poor compared to field galaxies (van den Bergh 1984).

The distribution of radial velocities of galaxies in the vicinity of M87 has demonstrated the presence of background clusters (and probably superclusters) of galaxies at redshifts V = 20200 and 26200 km/s (31.160.029, 34.157.034, Huchra and Brodie 1984).

An extensive radio and optical survey of galaxies in 9 nearby clusters (30.158.060, 30.158.061, 30.158.323, 31.158.324, 32.160.027, Bothun, Schommer, Sullivan 1984) shows that most clusters do not contain gas-deficient spirals. The Coma cluster is the only cluster in the sample exhibiting a large fraction of HI-deficient spirals and having other characteristics consistent with present day spiral-to-S0 conversion. In general initial conditions of formation and variations in star formation histories have been more important than environmental influences. The key parameter may be the amount of neutral hydrogen remaining after star formation in the bulge has ceased. 21-cm observations of X-ray galaxies in A1367

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