Anisotropy of the Cosmic Blackbody Radiation

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The universe is filled with thermal radiation having a current temperature of 2.75 K. Originating in the very early universe, this radiation furnishes strong evidence that the Big Bang cosmology best describes our expanding universe from an incredibly hot, compacted early stage until now. The model can be used to extrapolate our physics backward in time to predict events whose effects might be observable in the 2.75 K radiation today. The spectrum and isotropy are being studied with sophisticated microwave radiometers on the ground, in balloons, and in satellites. The results are as predicted by the simple theory: the spectrum is that of a blackbody (to a few percent) and the radiation is isotropic (to 0.01 percent) except for a local effect due to our motion through the radiation. However, a problem is emerging. Primordial fluctuations in the mass density, which later became the great clusters of galaxies that we see today, should have left an imprint on the 2.75 K radiation—bumpiness on the sky at angular scales of about 10 arc minutes. They have not yet been seen.

TWENTY YEARS AGO AN IMPORTANT AND PERVASIVE COMPONENT of our universe was discovered (*1*). The cosmic blackbody radiation (CBR) appears to be the remnant, cooled by expansion, of thermal radiation from a condensed primordial universe—the hot Big Bang. Two decades of intense experimental and theoretical activity have done little to change the basic ideas used to predict this radiation before its discovery (*2*). Since the hot Big Bang cosmological model was the basis for successfully predicting the main features of the CBR, and since all other models have failed even to explain the radiation, the hot Big Bang is now widely accepted as the essentially correct model for our universe.

The angular distribution on the sky of the CBR can tell us much about the universe at early epochs—long before stars, galaxies, or quasars were formed. Anisotropy experiments over a wide range of angular scales are addressing questions such as: What is the amplitude and spectrum of primordial density perturbations whence the galaxies and clusters of galaxies grew? To what degree did various parts of the universe have the same temperature, even though they were not yet connected by light speed when the CBR photons were emitted? What is the velocity of our Galaxy through the universal reference frame established by the CBR? Constraints imposed by CBR anisotropy measure have become valuable criteria for testing theoretical ideas about conditions and processes in the early universe.

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Is the Cosmological Model Correct?

Prediction and interpretation of anisotropy in the CBR rely heavily on the validity of the hot Big Bang model. Why should one believe anything based on such a fantastic extrapolation of current physics and astronomy? The hot Big Bang picture follows naturally from the observation that the universe is undergoing general expansion, the Hubble expansion. If time is allowed to run backward, it is possible to envision a condensed, hot early stage. A direct and inescapable consequence of this picture is intense, pervasive, thermal radiation, which played a dominant role in the dynamics of the early universe. As the universe expanded, the radiation cooled, keeping its thermal spectrum. Currently the radiation has a temperature of about 2.75 K, down from about 10^{30} K at the earliest epoch imagined by current physics (Fig. 1). Blackbody radiation at a temperature of 2.75 K has its peak intensity at a wavelength of 2 mm; the universe is literally filled with microwaves.

Calculations show that the radiation should survive the general expansion with little distortion or contamination of its spectrum (*3*). The best evidence that we are indeed looking at Big Bang radiation is the excellent agreement of spectral measures over three decades in wavelength—1 m to 1 mm. The measures fit well on a blackbody curve of temperature 2.75 K (Fig. 2). Three recent observations (*4*), made by entirely different techniques and among them covering most of the spectrum, are consistent with a temperature of 2.75 ± 0.05 K. Most older measures also agree with this temperature (*5*). No other cosmological model has explained this spectrum, and no known astrophysical radio source (other than the hot Big Bang) has such a spectrum.

The extreme isotropy of the CBR is additional evidence for the radiation's cosmological origin; local sources cannot be so evenly distributed around the sun. Also, after years of work, a small effect, originally predicted by Sunyaev and Zel'dovich (*6*), has now been observed (*7*) in the direction of hot plasmas known to exist in some clusters of galaxies. Hot electrons scatter a few of the CBR photons to higher frequencies, leaving a weak cold spot on the sky when observed at long wavelengths ($\lambda > 2$ mm). Detection of the effect has definitely placed the source of the CBR beyond the clusters of galaxies.

Perhaps the most dramatic application of the hot Big Bang model is the prediction that light elements would be produced at an early stage of the expansion—the epoch of nucleosynthesis (Fig. 1). In this model, when the universe was about 100 seconds old, the temperature ($\sim 10^9$ K), the expansion rate, and the densities of neutrons and protons were just right for the production of nuclei of light elements. From the current CBR temperature, the current mass density of the universe, the neutron lifetime, and measured nuclear reaction cross sections it is possible to calculate the abundances of primordial light nuclei (*8*). The predicted abundances agree well with observations (*9*) for helium (^{4}He and ^{3}He), deuterium (^{2}H), and lithium (^{7}Li). The final verdict is not yet in on this important result. Interpretation is difficult; it is hard to know for certain that the material being observed has not been contaminated (or depleted) by more recent processes in stars or in interstellar space. If the agreement between calculations and observations holds up under continuing scrutiny, we have extended our physical understanding into the very early universe and have taken a major step toward the events expected to occur even earlier than nucleosynthesis.

Early Measurements of Isotropy

Part of the evidence that the radiation discovered by Penzias and Wilson was the CBR hinged on its apparent isotropy—better than 10% as revealed by a review of their chart records. Later experiments (*10*) designed to look for anisotropy found none on large angular scales ($>10°$) to an accuracy of 0.2%. This result had two important implications. (i) The source must be cosmological; any source associated with our Galaxy would show anisotropy because the sun is far from the galactic center. (ii) The universe must be spherically symmetrical to a high degree—more round than a billiard ball. All anisotropic cosmological models, including a large class of models with axial symmetry, were shown to be unlikely representations of our universe.

The CBR was also found to be very isotropic on small angular scales. Letting an antenna beam (10 arc minutes) drift across the sky revealed no bumps larger than ± 6 mK, or $\Delta T/2.75 \sim 0.2\%$ (where T is absolute temperature) (*11*). This result quickly demonstrated that the newly discovered microwave background radiation did not come from discrete radio sources of a known type and that the surface where radiation last interacted with matter was very smooth on small angular scales. Such measures are currently being used to test models of the formation of the observed mass structures (galaxies and clusters of galaxies) from initial density perturbations. The extreme isotropy of the CBR, which at first provided support for the Big Bang model, is now becoming mildly embarrassing; as measurement accuracy improves, no anisotropy is being found at levels where effects are predicted by the simplest versions of the hot Big Bang model.

What Is Being Measured?

The CBR photons detected in isotropy experiments have not come directly from the primeval Big Bang. Photons are strongly scattered by free electrons at epochs when the matter in the universe is ionized. Consequently, the radiation carries with it the imprint of any mass inhomogeneity at the surface of last scattering. Where is this surface?

As the universe expanded out of its unimaginably condensed early stages, the temperature of the CBR decreased (Fig. 1). When the universe was about as hot as the sun's surface, two transitions having important implications for the CBR took place. (i) The energy density of radiation decreases faster than that of matter in the expanding universe; at an age of about 10^5 years the universe transforms from a radiation-dominated to a matter-dominated state (crossing lines in Fig. 1). Thereafter, the general expansion rate is determined mainly by the matter density. (ii) At a temperature of about 4000 K, the radiation can no longer keep the matter ionized and "decoupling" occurs. Electrons and protons combine to form neutral hydrogen having a much smaller cross section for scattering the radiation. Henceforth (if the matter is not reionized), radiation and matter expand independently with negligible interaction.

Thus, intense scattering at and before the decoupling epoch places an ultimate limit on how far we can see into the Big Bang with CBR photons; we can see at most to the photon barrier (PB) (Fig. 1). In astronomical terms we can see back to a redshift (*12*) of $z_{PB} = 1400$, far beyond the most distant known quasars at $z \approx 4$.

A word of caution is in order. If matter is somehow reionized after the decoupling era, the CBR photons could again be scattered so that we do not look all the way back to z_{PB}. To reionize the matter one might imagine a burst of star formation resulting in an intense flux of ionizing ultraviolet light. Even if this happens, a typical CBR photon was last scattered at $z \geq 10$, and it thus carries information to us from an otherwise unexplored cosmological epoch.

Measuring CBR Anisotropy

The instrument used to measure the microwave background is the Dicke radiometer, the standard receiver for radio astronomy. The output is usually calibrated in terms of source temperature, and sensitivity is limited by internally generated noise. Currently, CBR anisotropy is being measured with the best available technology—cryogenic maser amplifiers, cryogenic mixers, and bolometers cooled to a few tenths of a kelvin. These radiometers reach noise levels of $\sim 5\ \mathrm{mK}(t)^{-1/2}$, where t is the observation (integration) time in seconds. To achieve interesting signal levels of 30 μK, one must average about 8 hours of data; to reach this signal level requires extreme instrumental stability and a thorough understanding of systematic effects such as "foreground" radiation sources.

Microwave emission by O_2 and H_2O in Earth's atmosphere is a troublesome source of foreground radiation for ground-based observations. The intensity of atmospheric radiation varies across the CBR wavelength range (Fig. 2). Whenever possible, observations are made from mountaintops, balloons, or spacecraft to minimize or eliminate atmospheric noise. For observations requiring large ground-based radio telescopes, only unusually clear, cold, uniform atmospheric conditions can be tolerated. Another source of troublesome radiation is diffracted thermal emission from the ground—a 300 K source. Since accuracy approaching 30 μK is needed, ground radiation must be rejected, or understood, to 1 part in 10^7. This is a major problem for large antennas where screening of the ground is impractical. Finally, emission from inside our own Galaxy becomes a problem at wavelengths longer than about 5 mm. Currently, because the lowest noise receivers operate at the longer wavelengths, one must choose between more instrument noise or more noise from the Galaxy.

Since most microwave antennas are diffraction-limited, the angular scale of an observation is determined by the ratio of the observing wavelength to the antenna diameter. For large-scale anisotropy measurements, horns the size of musical instruments and beamwidths of $\sim 7°$ are used. Thus, observations from aircraft, balloons, and satellites are feasible. Small-scale anisotropy observations are made with a large radio telescope or even arrays of telescopes, and only ground-based instruments have been used to date.

Summary of Results

The best current results at all angular scales are summarized in Fig. 3. For angles smaller than 3°, ground-based antennas were used; above 3° the data were obtained from a U-2 aircraft (*13*), balloons, and recently a Soviet satellite. All results are upper limits except the dipole effect, which has been measured to an accuracy of 5%.

Early theories of galaxy formation predicted that the clumping of matter might cause fluctuations in the 2.75 K radiation as large as 1

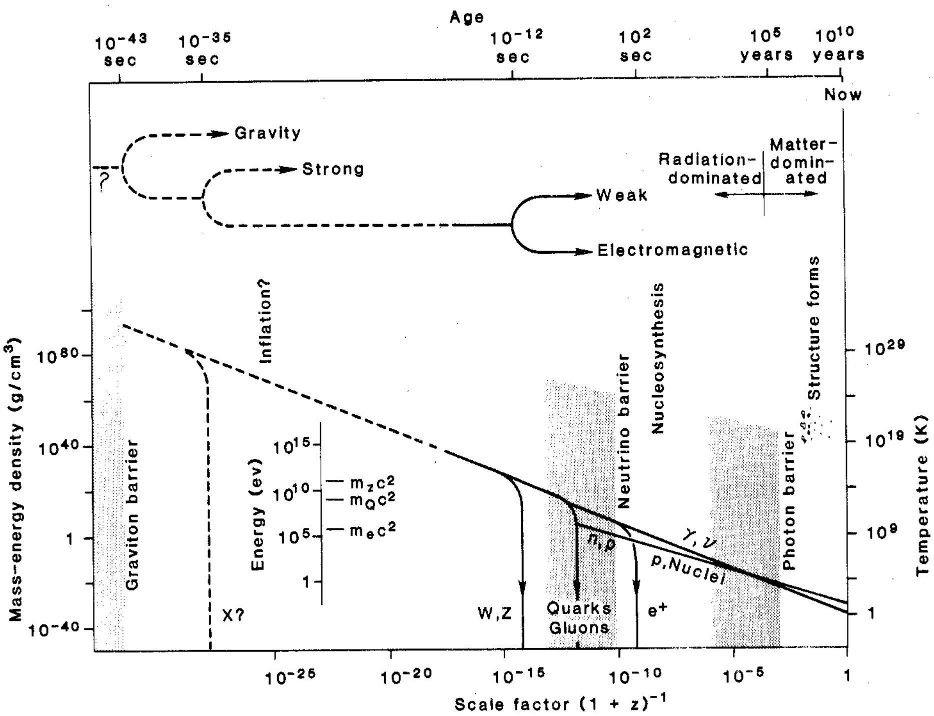

Fig. 1. A current view of the hot Big Bang, emphasizing new and unknown physics. Cosmic blackbody radiation brings us information about the universe to the right of the photon barrier at an age of 10^6 years, and the nucleosynthesis era is the current limit of direct extrapolation of astrophysical observations—abundances of light elements. Known physics carries us back beyond the synthesis of weak and electromagnetic interactions, an epoch determined by the masses of the newly discovered W and Z particles. The dashed lines indicate speculation based on current ideas from elementary particle physics; new, higher energy accelerators will begin to explore this regime. Finally, we are at the graviton barrier, an energy at which quantum gravity is expected to play a major role. Theoretical physics has not yet penetrated this barrier. [ν, Neutrino; γ, photon; p, proton; e, electron; n, neutron; m_Zc^2, m_Qc^2, and m_ec^2 are the energies associated with the masses of the Z particle, quark, and electron, respectively. The redshift z is defined in (*12*).]

mK at angular scales of a few arc minutes. These models have been ruled out by observations. Some current models predict fluctuations at the 30 μK level—just below the observational limits. Nearly everyone agrees that, if fluctuations are not seen at the 3 μK level ($\Delta T/T \approx 10^{-6}$) something is seriously wrong with our standard ideas about the decoupling process and the formation of the observed structure in the matter distribution. However, that level of accuracy (3 μK) is an extreme challenge to observers. Instrument noise and foreground radiation effects must be further reduced by a factor of 10; some observers doubt that such an advance is possible, even with the best of known technology.

The dipole result is interpreted as mainly due to our velocity through the 2.75 K radiation. The magnitude and direction of this velocity was a surprise to most astronomers. It was expected that the sun's motion would be mostly a result of our known orbital velocity around the center of our Galaxy—a speed of 300 km sec^{-1}. The CBR dipole measurement gives a velocity of about this magnitude, but the direction is nearly opposite to that expected. The natural interpretation is that the whole Galaxy is moving at about 600 km sec^{-1}, and the sun's orbital velocity subtracts from that. The Galaxy's motion turns out to be in the general direction of the Virgo cluster of galaxies, thus encouraging those astronomers who believed that our Galaxy is a member of the Virgo cluster and gravitationally bound to it (*14*). More recently, velocity measures of the nearest several thousand galaxies have supported this picture. The velocity obtained from CBR dipole measures is providing a valuable basis for understanding the dynamics of galaxies in the local universe. Few parameters of fundamental cosmological interest are known to an accuracy of 5%.

Anisotropy at Large Angular Scale

A map of the sky, made with a small balloon-borne radiometer operating at a wavelength of 1.2 cm, is shown in Fig. 4 (*15*); the dipole effect is plainly seen. At the Lawrence Berkeley Laboratory, Lubin and his colleagues have obtained a similar map at a wavelength of 3 mm (*16*). Each of these two measures of the dipole effect was made during two nighttime flights from the National Scientific Balloon Facility (*17*) in Palestine, Texas, and a single balloon flight from the National Institute for Space Research, São José dos Campos, Brazil. Operational difficulties and a limited number of launch sites make full sky coverage difficult to achieve from balloon-borne platforms.

Also in Fig. 4, one sees the foreground radiation of our Galaxy, concentrated along the galactic plane. At a wavelength of 1.2 cm, the CBR measure is significantly contaminated by galactic emission, which must be estimated and removed by extrapolating from maps made by using longer wavelengths, which are dominated by galactic radiation. At 3-mm wavelength, galactic radiation has weakened

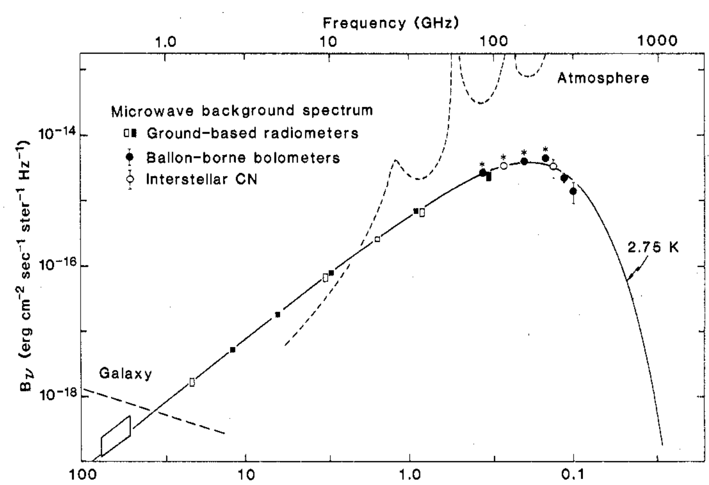

Fig. 2. Measures of the surface brightness B_ν of the CBR. The spectrum of a 2.75 K blackbody emitter is also shown; agreement between the measures and the predicted spectrum is excellent. Filled squares and circles are recent results. Open squares are old results included for comparison. Open circles represent astronomical measures of interstellar cyanogen (CN) molecules used as thermometers. Asterisks indicate that the symbol is larger than the error bar. Measures are hampered by radiation from our Galaxy at long wavelengths and from Earth's atmosphere at short wavelengths.

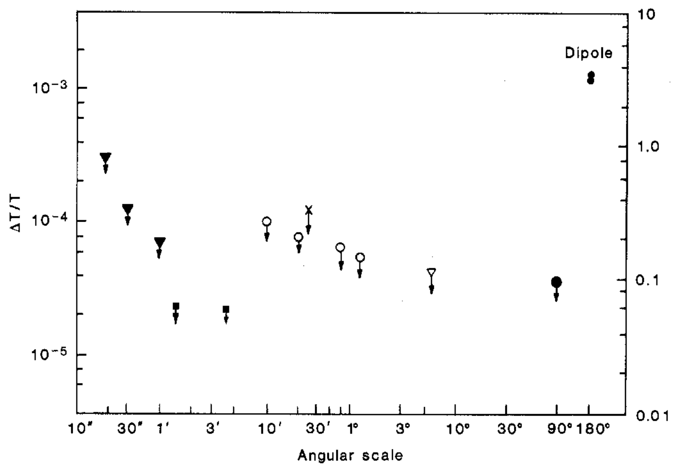

Fig. 3. Current results of searches for anisotropy in the CBR on all angular scales. Except for the dipole effect at 180° all results are upper limits (95% confidence level). ΔT is the fluctuation of the CBR temperature. Symbols indicate the sources of the data: ▼, the Very Large Array interferometer, Socorro, New Mexico; ■, the 140′ telescope in Green Bank, West Virginia; ○, the RATAN-600 telescope in Zelenchukskaya, U.S.S.R.; X, a special instrument at Testa Grigia alpine station, Italy; ▽, instruments carried by a balloon launched from Sicily; ●, instruments on balloons launched from Palestine, Texas, and São José dos Campos, Brazil.

enough that the Berkeley map does not show it. However, higher instrument noise and concern about possible radiation from galactic dust cause the overall uncertainty in the dipole result to be about the same as in the 1.2-cm observation.

The results of these two dipole measures roughly agree (Table 1). A dipole distribution of radiation temperature is expected from the motion of the sun through the CBR. The effect is basically a Doppler shift (*18*), and the amplitude of the dipole equals (2.75 K) v/c, where v/c is our speed relative to the speed of light. Averaging the results in Table 1 gives a velocity for the sun of 360 km sec^{-1} toward the constellation Leo. If we now subtract the known velocity of the sun relative to the galactic center (300 km sec^{-1} toward Cygnus) we obtain the velocity vector of our Galaxy with respect to the CBR. The result is a galactic velocity of 600 ± 50 km sec^{-1} toward galactic longitude 265° and galactic latitude +25°, in the constellation Hydra. A galactic speed of 600 km sec^{-1} is somewhat large compared with typical random speeds for galaxies in a cluster. Our velocity is in a direction lying within 45° of the Virgo cluster, which is a significant mass clump about 50 million light years from our Galaxy and the most likely nearby attractor. The reason that we are not falling directly toward Virgo is not completely understood, but probably we and the Virgo cluster are part of an even larger system of galaxies that is moving with respect to the CBR.

Earth's orbital velocity around the sun has been detected in the large-scale anisotropy data (*15, 16*). Because of the extreme sensitivity of the instruments, they are flown only at night (and near the time of new moon). To obtain sky coverage two flights, about 6 months apart, are needed. In that time Earth's orbital velocity has reversed. Subtracting the two data sets gives the orbital speed, 33 ± 6 km sec^{-1}, which compares favorably with the expected value of 30 km sec^{-1}.

A Soviet satellite, Prognoz-9, recently mapped the CBR at a wavelength λ = 8 mm (*19*). The resulting map (Fig. 5) resembles the 1.2-cm map of Fig. 4. An important early result from Prognoz-9 is the point in Fig. 3 at 90°. This limit on the possible quadrupole effect is somewhat better than earlier limits (*15, 16*) and may improve as data analysis progresses. The Soviet satellite had a highly eccentric orbit, taking it to twice the moon's distance from Earth. Thus, a major systematic error—Earth's thermal radiation—is reduced significantly. Also, the cool, stable environment possible in a spacecraft can provide nearly optimum surroundings for sensitive cryogenic receivers. A U.S. satellite—the Cosmic Background Explorer (COBE)—will carry three microwave radiometers to map large-scale anisotropy in the CBR (*20*). A West Coast space shuttle launch is planned for early 1989. The Soviet team also plans to orbit radiometers at three different frequencies in 1990 or 1991.

Large-scale anisotropy will have been well studied by the end of the century. We can anticipate knowing our velocity with respect to the CBR with better than 1% accuracy, which will give an important basis for studies of the dynamics of galaxies and clusters within the galactic neighborhood. Equally important is the search for intrinsic fluctuations in the CBR intensity on large angular scales, greater than the 7° antenna beamwidths.

Anisotropy at Small Angular Scale

The search for anisotropy in the CBR at small angular scale requires relatively large radio telescopes. Antenna beamwidth is determined by diffraction to be approximately λ/D radians, where D is the telescope diameter; a beamwidth of 1 arc minute at λ = 1 cm requires $D > 40$ m. Thus, small-scale measurements are made with large ground-based radio telescopes equipped with low-noise receivers. For example, the points between 1 and 5 arc minutes in Fig. 3 were obtained (*21*) with the 40-m telescope at Green Bank, West Virginia (*22*). With its cryogenic maser amplifier at λ = 1.5 cm, this system is one of a few in the world capable of studying small-scale anisotropy with the required sensitivity. Even so, several hundred hours of observation under good atmospheric conditions were required to obtain an upper limit of 2.1×10^{-5}. This represents a major commitment of a fully scheduled national telescope; clearly the thousands of hours necessary for observations to approach a sensitivity of $\Delta T/T \sim 10^{-6}$ cannot be obtained here. Fortunately, a similar system at the Owens Valley Radio Observatory of California Institute of Technology is now being dedicated to the search for small-scale anisotropy.

Besides beam size, sensitivity, and clear skies, these observations require understanding of ground radiation reaching the receiver through antenna sidelobes. Typically, ground radiation accounts for a few kelvins of radiation temperature, and its contribution to the anisotropy signal is ~0.1 K. Thus, to look for sky signals of 30 μK, changes in the ground effect must be controlled or understood to better than 1 part in 10^4. This is a severe problem because the antenna beam must be moved on the sky, thus changing its response to the hot ground. Variable ground radiation has been the hardest problem to overcome in a long series of searches for fine-scale anisotropy. In the experiment which resulted in the 1 to 5 arc minute points in Fig. 3, the sophisticated sky scanning technique used was developed only after several unsuccessful observing sessions.

The points to the left in Fig. 3 (angular scale ≤1 arc minute) are measured with a relatively new technique (*23*), and work is currently under way to improve them. The Very Large Array interferometer (*22*) is being used to map small regions of the sky. The map is analyzed for bumps in the background level at various angular scales. This technique is an important departure from past "single-dish" searches for small-scale anisotropy and may initiate a new method of observation that uses close-packed arrays of radio antennas.

The four points (open circles) between 10 and 75 arc minutes are the result of a Soviet study with the RATAN-600 telescope (*24*). This unique facility is capable of making narrow beam measures at λ = 7.6 cm. Measures at this wavelength are troubled by confusion with conventional weak radio sources covering the sky. Parijskij and his colleagues hope to identify CBR fluctuations on the basis of their larger angular size and unique (blackbody) spectrum. Spectral measures will be important in identifying true primordial fluctuations, once candidates are found at a single frequency.

The points in Fig. 3 at angular scales of 25 arc minutes (*25*) and 6° (*26*) are the results from the Italian group led by Melchiorri. The data were collected with special instruments from an observatory high in the Alps (*24*) and from a balloon (*25*). The point at 6° has attracted particular theoretical attention. On this angular scale the PB (Fig. 1) was not causally connected by light speed at the time the observed photons were emitted. How then did the radiation manage to reach the same temperature (to better than 4 parts in 10^5) over the whole sky?

Another fundamental problem raised by the extreme smoothness of the CBR is how the mass in the universe became so clumpy without perturbing the radiation on small angular scales. The simplified argument goes as follows: (i) We see mass clumping now with density contrast

$$\left(\frac{\Delta\rho}{\rho}\right)_{\text{now}} \approx 1$$

(ii) Gravitational force makes the density (ρ) in clumps grow as $(z + 1)^{-1}$, so, at $z \sim 10^3$ (decoupling epoch), the mass density fluctuations must have been at least

$$\frac{\Delta\rho}{\rho} \geq 10^{-3}$$

(iii) For adiabatic perturbations in the early universe, we expect

$$\frac{\Delta T}{T} \approx \frac{1}{3}\frac{\Delta\rho}{\rho} \geq 3 \times 10^{-4}$$

Since observed limits on $\Delta T/T$ are well below this level (Fig. 3), something is wrong with the argument.

Table 1. The most accurate current measures of the dipole anisotropy in the cosmic blackbody radiation. The results have been transformed to the sun's frame of reference. Error in the amplitude is partly due to calibration, and errors in the right ascension and declination are from receiver noise.

Research group	Dipole amplitude (mK)	Right ascension (hours)	Declination (degrees)	Reference
Berkeley	3.46 ± 0.17	11.3 ± 0.1	−6.0 ± 1.4	(*16*)
Princeton	3.18 ± 0.17	11.2 ± 0.1	−8 ± 2	(*15*)

Adiabatic perturbations were, and still are, the most natural for most models of density fluctuations in the early universe. But the fluctuations could be "isothermal"; then the predicted $\Delta T/T$ (due to Doppler shift) could be smaller than the observed limits. Or perhaps mass clumps did not grow by the relatively slow process of gravitational collapse, but were blown together by explosive events (supernovas) during the galaxy formation era (*27*). In this picture the density contrast is not related in a simple way to $\Delta T/T$. Yet another possibility is that the radiation could have been smoothed by scattering at a later time ($z_{\text{scatter}} < z_{\text{PB}}$) from reionized matter. This picture has problems with isotropy at larger angular scales and with finding a realistic model for obtaining an exceedingly smooth reionized medium on all angular scales.

An intriguing idea currently under study is that the universe is filled, and dominated, by a sea of unknown cold dark matter—theoretically attractive particles, difficult to detect in the laboratory (axions, photinos, and so forth). To assess the effect of such a sea on $\Delta T/T$ requires a detailed computation of the decoupling process. Two groups (*28*), working independently, arrived at similar conclusions: models of cold dark matter may resolve the conflict between $\Delta T/T$ and models with adiabatic fluctuations, but only if we live in a dense universe that is closed, or nearly closed.

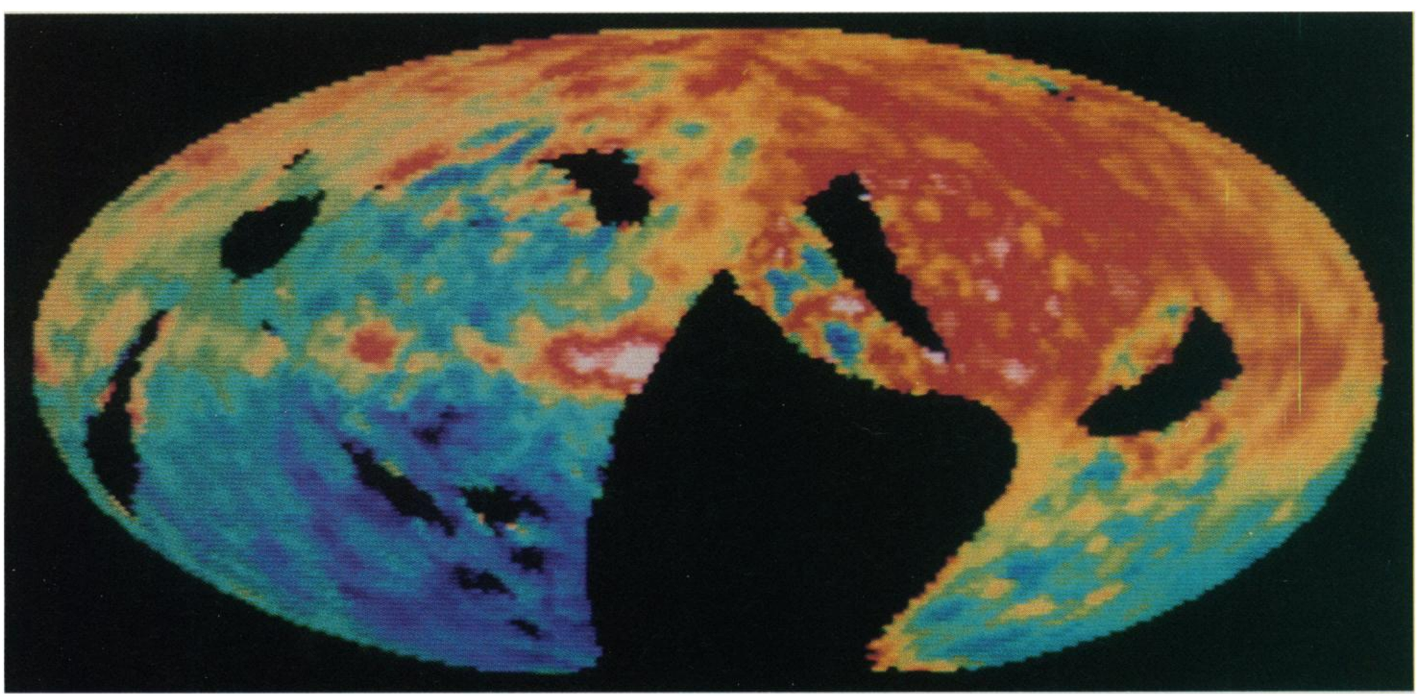

Fig. 4. The sky at λ = 1.2 cm as seen by a balloon-borne maser radiometer. A constant level of about 2.75 K has been removed, leaving the ±3 mK dipole effect as the dominant feature; half of the sky is warm (red and yellow) and half is cold (blue and green). The distribution fits a cosine law. The map is shown here in galactic coordinates with the Milky Way on the equator and the galactic center in the center of the picture. Radiation from the Milky Way is plainly visible with a particularly bright region toward the center and a dimmer (red) spot to the left in Cygnus. Galactic rotation carries the sun toward Cygnus, so the dipole effect would have its warm lobe centered here if the galactic center were at rest with respect to the 2.75 K radiation.

Conclusions

The search for anisotropy started out as an attempt to measure our velocity through the CBR and to look for imprints left by density fluctuations or other inhomogeneous physical processes in the early universe. Aside from measures of the dipole effect, the results have been disappointing. No intrinsic anisotropies have been found in the temperature of the CBR above $\Delta T/T \approx 10^{-4}$. The microwave sky glows with incredible smoothness—a 0.1% cosine distribution, but no ripples on smaller angular scales at 10% of that level. Still, the driving force behind plans for even more sensitive measures is the importance of directly seeing the original fluctuations in the early universe or of finding evidence for unforeseen processes at these unexplored epochs of the Big Bang. Measurement of the amplitude and angular spectrum of density fluctuations at $z = 1000$ would be important for theoretical models of earlier and later physical processes.

However, even the upper limits established by anisotropy searches have proved to be important touchstones for theoretical models. The simplest models for the formation of observed mass structure have serious problems satisfying current $\Delta T/T$ limits at small angular scales. There has always been a major problem explaining how the early universe came to thermal equilibrium when only small pieces (as seen now) were causally connected by light signals. The resolution of this problem is one of the main successes of the inflationary universe model. Inflation proposes an epoch of enormous expansion in the very early universe which causes communication between parts much larger than the region bounded by our event horizon at a distance of c times the age of the universe. In this picture, thermal equilibrium and large-scale isotropy are established during the inflation.

In our current Big Bang cosmology we find few opportunities to empirically penetrate to the beautiful physics envisioned in Fig. 1. However, recent attempts to apply ideas from particle physics to the very early universe raise the possibility of finding cosmological remnants—particles of cold dark matter, cosmic strings, and so forth—that could open new windows to unexplored cosmic epochs, as did the discovery of the 2.75 K radiation. Searches for these remnants will be risky, difficult, and only weakly guided by theory. But, as in the search for anisotropy in the CBR, success will bring the exciting possibility for quantitative study of the conditions and the physics of our origins.

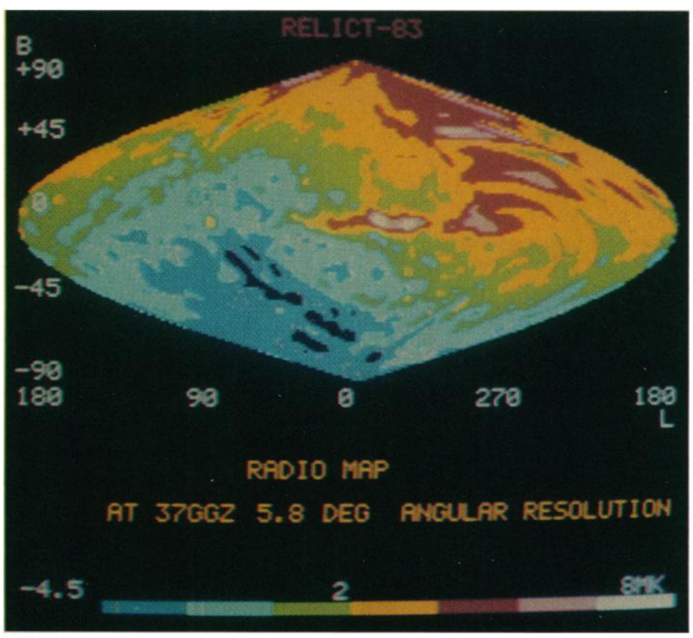

Fig. 5. Early results from the Soviet RELICT experiment aboard the Prognoz-9 spacecraft. This map made at $\lambda = 8$ mm shows the dipole effect and the galactic plane also seen in Fig. 4 at $\lambda = 1.2$ cm. [Photograph provided by N. S. Kardashev and I. A. Strukov of the Space Research Institute, Moscow]

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