THE PRIMEVAL FIREBALL

The earth is bathed in radio waves that appear to have originated at the time of the primordial "big bang." This radiation provides the cosmologist with a rare new clue to the nature of the universe

by P. J. E. Peebles and David T. Wilkinson

Modern cosmology undertakes to substitute observational science for myth and speculation in dealing with such issues as: How did the universe originate? What is it like now? What will be its fate? Unfortunately the observational evidence is meager. There is a wealth of data but one becomes lost in detail; there is need for observations of simple and large-scale phenomena, the essential bases of theory. As a matter of fact, most contemporary cosmologies stem from just one such observation: Edwin P. Hubble's discovery that other galaxies are moving away from ours, and are doing so at speeds that are greater the more distant the galaxy. This general recession is the basis for such widely different concepts as the "big bang" cosmology (which holds that the universe originated in a superdense state some seven billion years ago) and the "steady state" one (in which the universe looks exactly the same through all time—past, present and future).

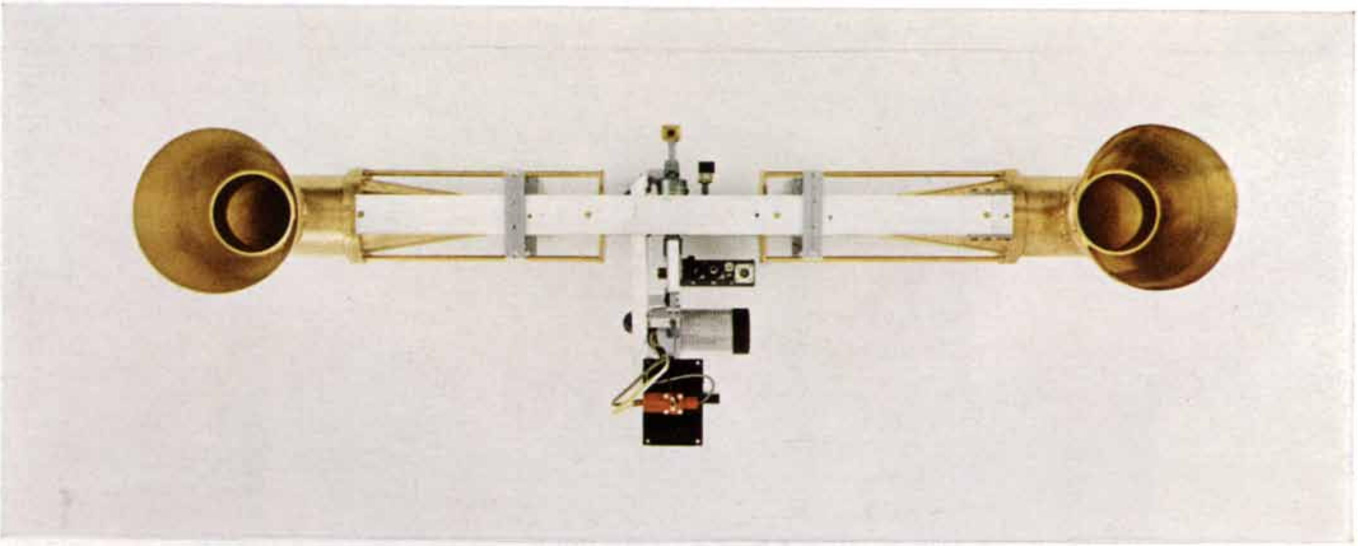
It now appears that radio astronomers have discovered another basic cosmological phenomenon that, like the recession of the galaxies, provides a view of the universe on a truly universal scale. It is low-energy cosmic radio radiation that apparently fills the universe and bathes the earth from all directions. Intense enough to be received by conventional radio telescopes, it has undoubtedly been detected, but not recognized, for years; indeed, it accounts for some of the "snow" seen on a television screen. When it was discovered by Arno A. Penzias and Robert W. Wilson of the Bell Telephone Laboratories about two years ago, they realized that it could not have originated in the earth's atmosphere or in our galaxy. It did fit in well, however, with an earlier suggestion by Robert H. Dicke of Princeton University that one ought to be able to detect a new kind of cosmic radio radiation: a "primeval fireball" of radiation surviving from the earliest days of the universe, when the universe was enormously hot and contracted. The theory and observation of this primeval fireball has been the subject of considerable work and excitement for us and several colleagues at Princeton: Dicke, P. G. Roll and R. B. Partridge.

The discovery and identification of this radiation must be considered a revolutionary development in cosmology. If, as we now believe, it is indeed the primeval fireball, it provides a view of the very early universe, just as optical radiation provides a look at the universe of more recent times. Our colleague John A. Wheeler has suggested an analogy: Compare man's observations of the evolving universe with the view downward from the observation platform of the Empire State Building. Street level corresponds to the beginning of the expansion of the universe. The most distant galaxy discovered so far then corresponds to a view down to the 60th floor, and the most distant quasi-stellar sources are at about the 20th floor. The fireball radiation is equivalent to a glimpse of something just half an inch above the street! With this expanded view of early events in the universe one may hope for a corresponding improvement in cosmological theory.

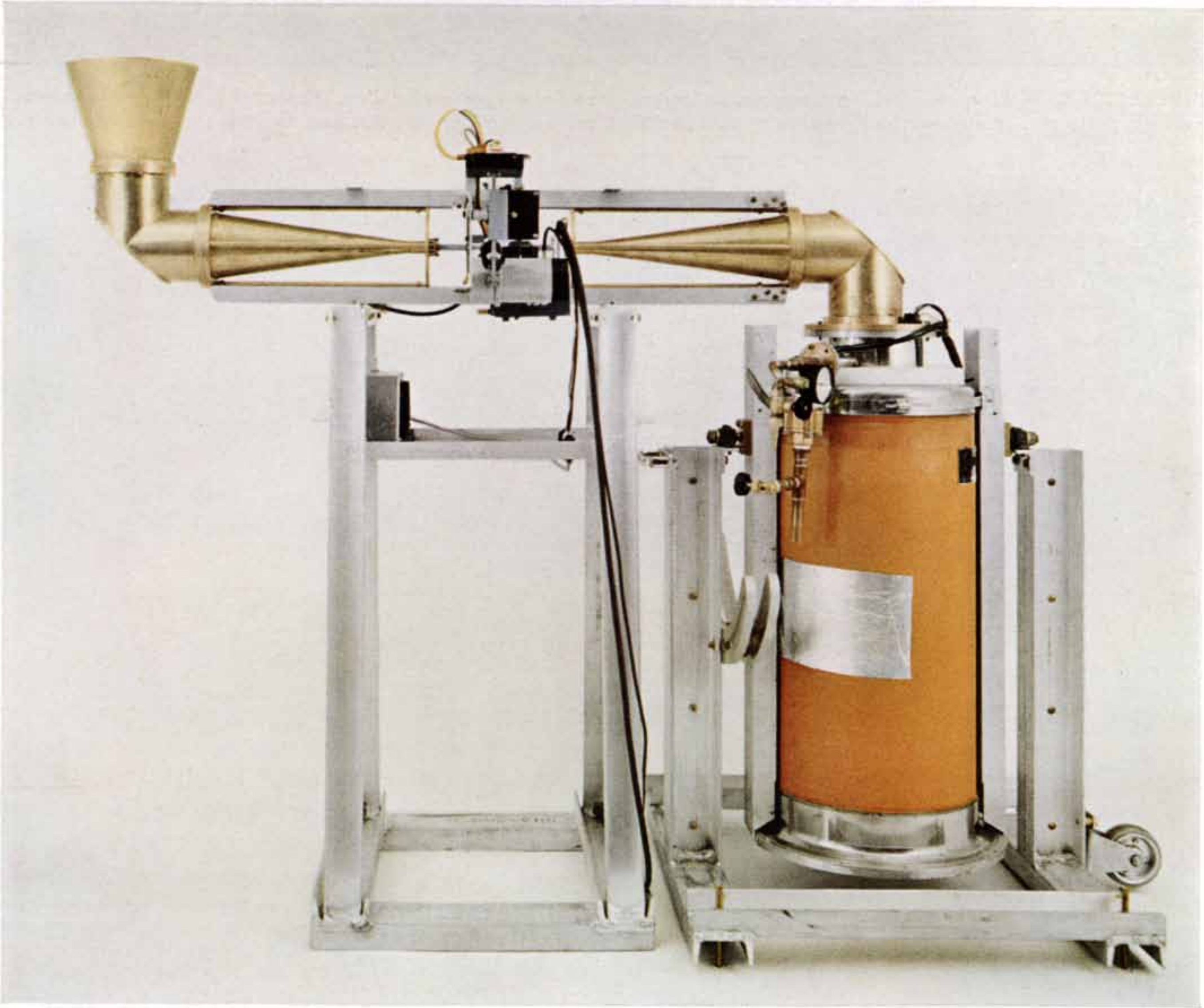
The concept of the primeval fireball is grounded on Hubble's observation of the general recession and the idea that flows from it: that the universe is in a state of rapid expansion. If this is so, according to big-bang theories at some time in the distant past—about seven billion years ago—all the matter in the universe must have been packed together in an inferno of particles and radiation. As the universe expanded out of this holocaust the matter cooled and condensed to form galaxies and stars. The radiation, which had started out as enormously energetic gamma rays, was also "cooled" by the expansion; its wavelength increased and it now appears mostly in the radio and microwave bands. The idea of a "fireball" dating from the big bang can be somewhat misleading, because what we have in mind is not radiation from some localized explosion off in one corner of the universe. The earth is immersed in this fireball; the radiation comes at us from every direction, and any observer anywhere in the universe should detect it as coming equally from all directions.

This is consistent with the basic theoretical framework developed between 40 and 50 years ago by Albert Einstein, Willem de Sitter, Alexander Friedmann, Georges Lemaître and others. Basic to the work of all of them was the picture of an evolving universe that looks the same to all observers, no matter where they are. In particular such a universe has no boundary, no edge. It is also isotropic, which is to say that it looks much the same in any direction. The presence of matter causes a uniform curvature of space.

A good two-dimensional analogy to this uniformly curved three-dimensional space is the surface of a balloon. The galaxies are inelastic polka dots pasted on the surface. Since the universe is expanding, imagine that the balloon is being inflated. As the balloon expands, a bug standing on any dot would see all the spots around it moving away, and it would see the more distant dots moving away more rapidly. The model thus reproduces the general recession of galaxies and even Hubble's law: that the speed of recession is proportional to the distance of the galaxy. It also points up the fact that the universe has no preferred center. Although the bug sees all

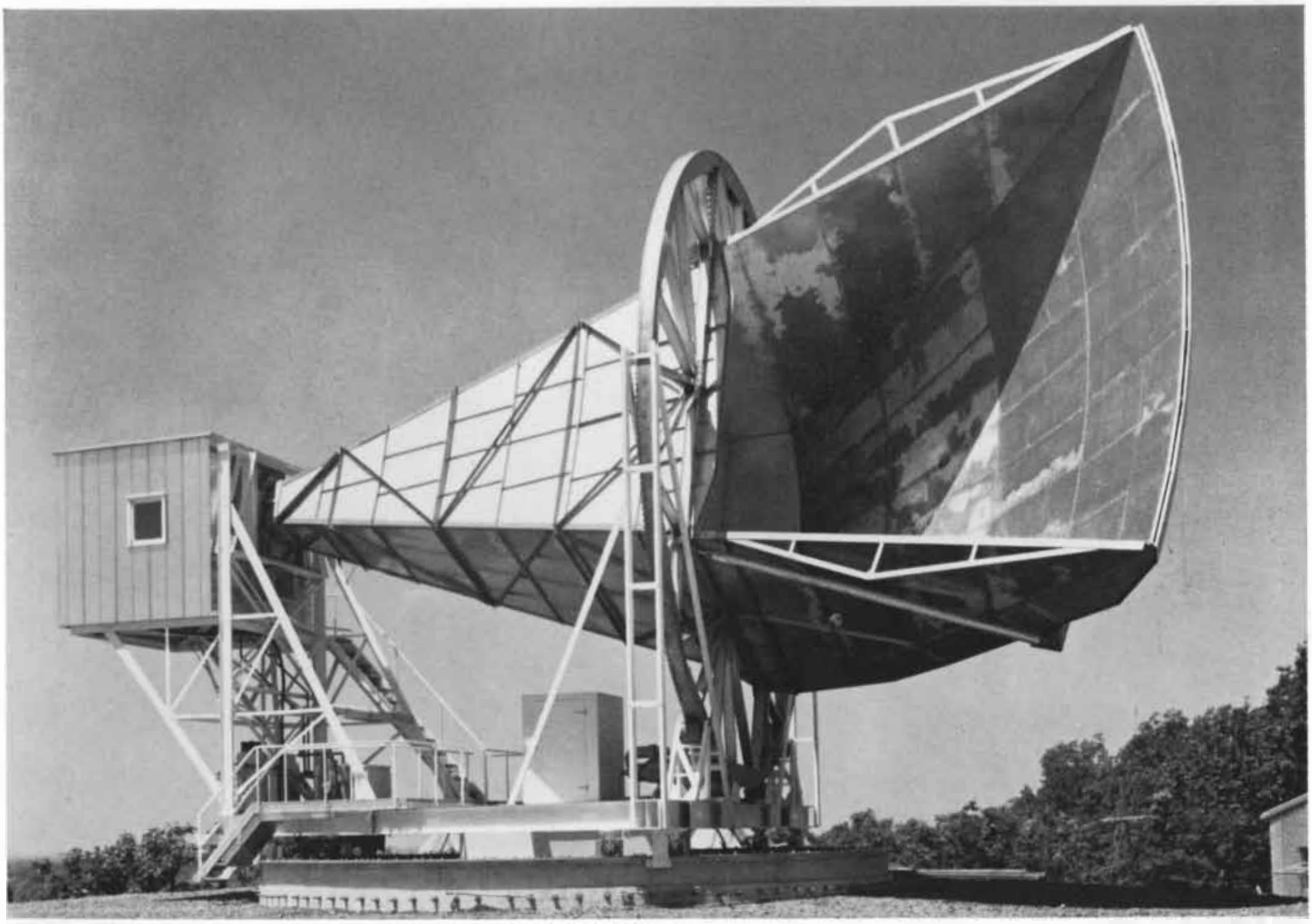


INSTRUMENT with which the primeval fireball is observed at Princeton University is a recent version of the Dicke radiometer, seen here from above. The antenna horns extend to the left and right and are directed upward to collect sky radiation; a switch, microwave receiver and amplifier are at the center. The instrument is operated both in this configuration and as illustrated below.



RADIOMETER is seen in a side view with one of the horns in position to receive radiation from the sky. The other horn of the radiometer is coupled to a wave guide leading to a reference source inside the orange Dewar flask. The source is immersed in boiling liquid helium and is therefore known to be radiating at 4.2 degrees Kelvin (degrees centigrade above absolute zero). The receiver input is switched back and forth between sky antenna and reference source and the intensities of the two are compared.

PRINCETON GROUP'S first fireball observations were made with an earlier version of the radiometer, here shown in position on the roof of the geology building. The slanted panels around the horn are wire-mesh screens that help to keep out ground radiation.



HORN ANTENNA of the Bell Telephone Laboratories receiver at Holmdel, N.J., was originally designed to collect signals reflected from Echo satellites. This was the antenna with which Arno A. Penzias and Robert W. Wilson first detected the fireball radiation.

the spots moving away from it, the bug should not conclude that it is on a preferred spot; another bug on another spot sees the same thing. Similarly, the general recession of the galaxies does not mean that the earth is at the center of the universe; an observer in any other galaxy would see the same general movement away from him.

On this model the primeval fireball radiation might be represented by a number of ants crawling over the surface of the balloon. They are uniformly distributed, and they crawl about in all directions. The number of ants in any given area of the surface decreases as the balloon is blown up. In the same way the density of photons in the primeval fireball decreases as the universe expands. Note also that no matter which way the ants move they will always move toward polka dots that are receding from them, and they must continuously lose energy as a result of this chase. In the real universe the photons of the fireball are always chasing galaxies that are receding from them, so that the photons undergo a continuous energy loss that accounts for the increase in their wavelength.

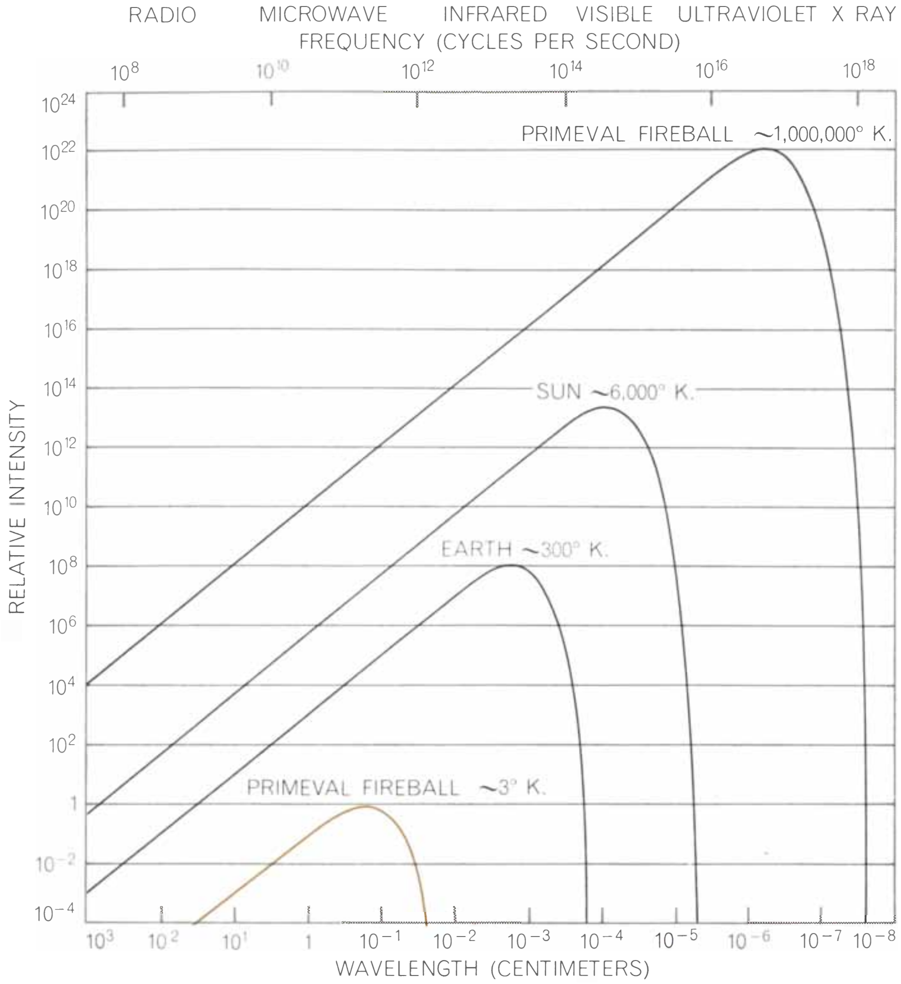
Based on this picture of the expanding universe it was possible to make two predictions about the nature of primeval fireball radiation. The first was that because it was emitted by a source (the condensed universe) in thermal equilibrium, its intensity should vary with wavelength in the manner characteristic of an ideal thermal radiator, or "black body." A severe test of whether the newly discovered radiation was indeed the primeval fireball would therefore consist in tracing out the observed intensity as a function of wavelength and seeing if the measurements fell on the black-body curve. The second major prediction was simply that the fireball radiation should be isotropic; that is, since the radiation presumably fills the universe and the earth is immersed in it, the observed intensity of the radiation should be the same in every direction.

There is a "window" through which one can observe the fireball radiation: the range of wavelengths from about one to about 20 centimeters. (At longer wavelengths radiation from our own galaxy is so strong that it submerges extragalactic signals; at less than one centimeter the earth's atmosphere radiates too strongly.) Radio astronomers have been observing through this window for many years but they overlooked the fireball because the methods that ordinarily enable one to separate signals of interest from background noise do not work in the case of the fireball radiation. For example, one can detect a weak signal when it is concentrated in a characteristic line in the electromagnetic spectrum. This is the case for the 21-centimeter emission of atomic hydrogen in interstellar clouds. Unfortunately the fireball radiation would have a smooth spectrum, much like that of terrestrial background noise, so that it would be hard to isolate in this way. One can also isolate extremely weak signals by scanning the antenna beam across a suspected localized source. The fireball was expected not to be localized, however, but to be spread across the entire sky as a uniform "glow."

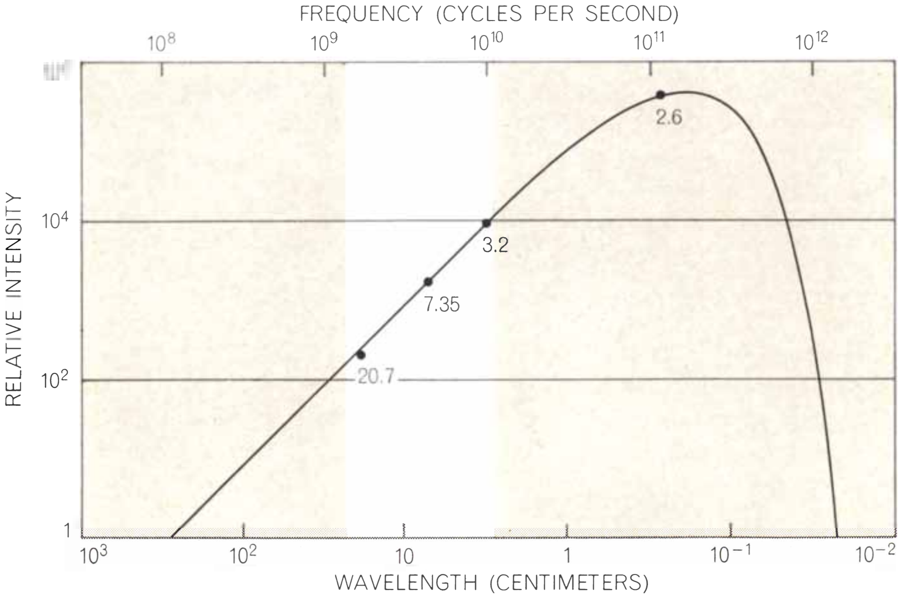
It was clear that the search for a primeval fireball called for a new and different kind of radio telescope, and in the fall of 1964 our group undertook to build such an instrument. The heart of our telescope is a modified microwave receiver known as a Dicke radiometer. Designed by Dicke in 1945, this instrument bypasses the noise generated within the receiver itself, which is about 1,000 times more intense than a weak signal such as the fireball. Dicke overcame the receiver noise problem by putting a switch between the antenna and the receiver that periodically—say 100 times a second—shifts the receiver input from the antenna to a reference source and back again [*see illustration on page 33*]. The receiver output therefore contains a 100-cycle-per-second signal whose strength depends on the difference between the radiation power collected by the antenna and the power emitted by the reference. Since the power of the reference source is known, the strength of the 100-cycle signal becomes a measure of the antenna power. This signal is still buried in receiver noise but is easily separated and measured by an amplifier sharply tuned to 100 cycles per second. In this way one can easily measure antenna power thousands of times weaker than the receiver noise.

Two more sources of terrestrial noise had to be overcome. One was thermal radiation from the ground, which fills half the space around an antenna and tends to leak into the usual parabolic antenna. This problem can be largely avoided by using a horn-shaped antenna,

REFERENCE SOURCE (*foreground*) **for the Princeton radiometer is made of metal-coated fiber-glass spikes. It has been removed from the Dewar flask and the pipelike wave guide that is normally coupled to the antenna horn. Wires on wave guide lead to thermocouples.**



"BLACK BODY" SOURCES of thermal radiation emit across a broad spectrum, the intensity of the radiation varying with wavelength as shown here for several sources. The shape of the curve persists as its position changes according to the temperature of the source. The top curve is for the fireball radiation billions of years ago, the bottom one for the radiation now.



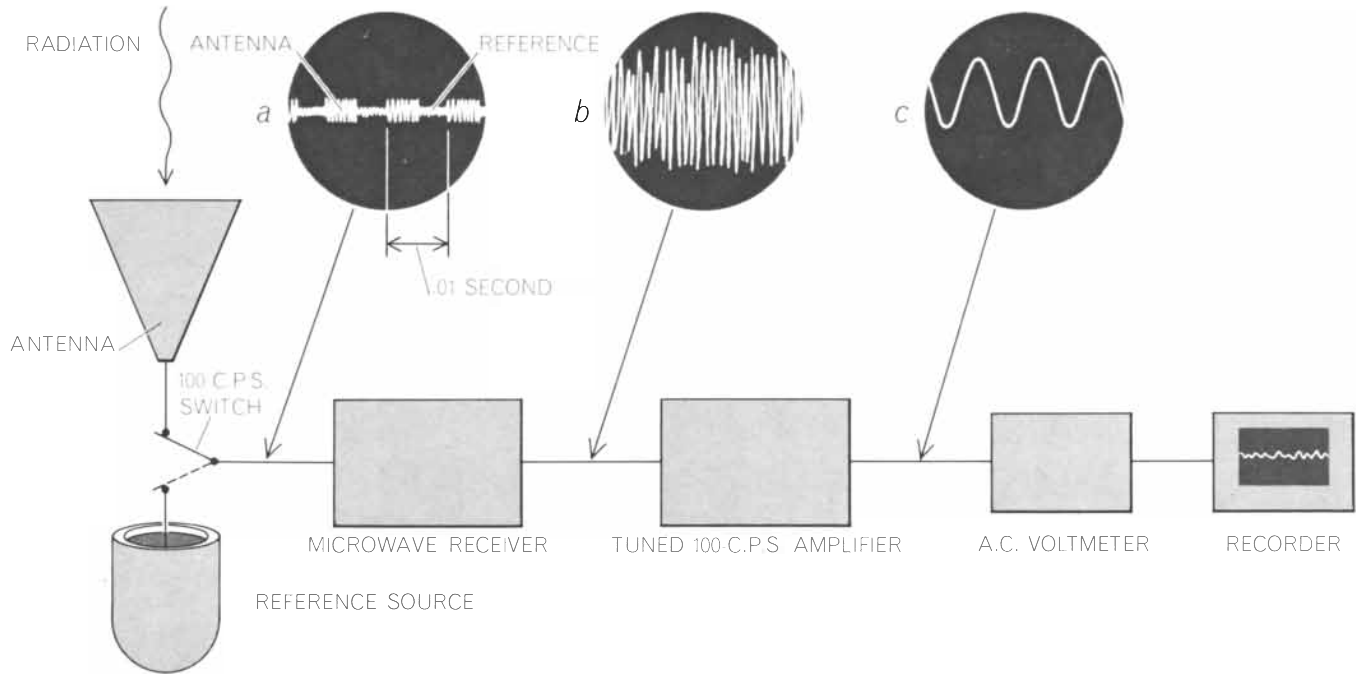
FIREBALL'S INTENSITY has been measured at four wavelengths and conforms to a three-degree black-body curve. Radiometer observations are hampered on either side of a central "window" (*white area*) by galactic (*left*) and atmospheric (*right*) radiation. Measurements at 2.6 millimeters can be obtained by observing light absorption of molecules in space.

which is less sensitive to ground radiation. The other source of terrestrial noise is radiation from oxygen and water molecules in the atmosphere. This emission can be measured and subtracted out if one tips the antenna beam to various angles from the vertical, thus increasing the length of the path through the atmosphere and therefore changing the atmospheric radiation component in a predictable way.

As it happened, the Bell Telephone Laboratories facility at Holmdel, N.J., already had a horn-shaped antenna, originally designed to receive signals reflected by the Echo satellites. Penzias and Wilson had modified the receiver for radio astronomy. Their instrument had all the properties necessary to uncover a primeval fireball, and it now developed that Penzias and Wilson had been attempting for some time to track down excess radio noise thought to be originating within the instrument itself. When Penzias heard what we were doing at Princeton, he invited us to visit Holmdel. What we saw there left us in little doubt that the Holmdel workers' excess noise was in fact extraterrestrial radiation—and was probably the fireball.

As we have already mentioned, the most crucial test of whether or not this new radiation is the primeval fireball is to trace out the spectrum and see if it is that of a black body. The Holmdel result constituted a first measurement of the possible fireball, at a wavelength of 7.35 centimeters. Fortunately the Princeton instrument had been designed to detect radiation of a wavelength different from the one received at Holmdel. We continued our work and about six months later measured a cosmic radiation intensity at 3.2 centimeters that fit in perfectly with the concept of a primeval fireball. Since that time still more measurements have been made at other wavelengths, including a radiometer measurement at 20.7 centimeters by T. F. Howell and J. R. Shakeshaft at the University of Cambridge. All the points so far fall on a typical black-body curve, one appropriate for a source with a temperature of three degrees Kelvin (degrees centigrade above absolute zero), and so the evidence is strong that we are indeed observing the primeval fireball [*see bottom illustration at left*].

The nature of the radio window, however, is such that direct observation at short wavelengths—in the most interesting region where the black-body curve rises to a peak and then falls off steeply—is almost impossible. At such wave-



DICKE RADIOMETER can detect signals far below the level of receiver-generated noise. A switch shifts the receiver input from antenna to reference source and back at, say, 100 cycles per second, producing a signal whose amplitude varies at 100 cycles according to the level of the antenna and the reference-source power (*a*). This small signal is obliterated by receiver noise, in which the 100-cycle signal becomes buried (*b*). The desired signal is recovered by filtering out the unwanted frequencies and amplifying the 100-cycle component. The resulting signal (*c*) is fed to a voltmeter that drives a recorder. The displacement of the recorder trace is proportional to the difference between the radiation power being collected by the antenna and the power emitted by the reference source.

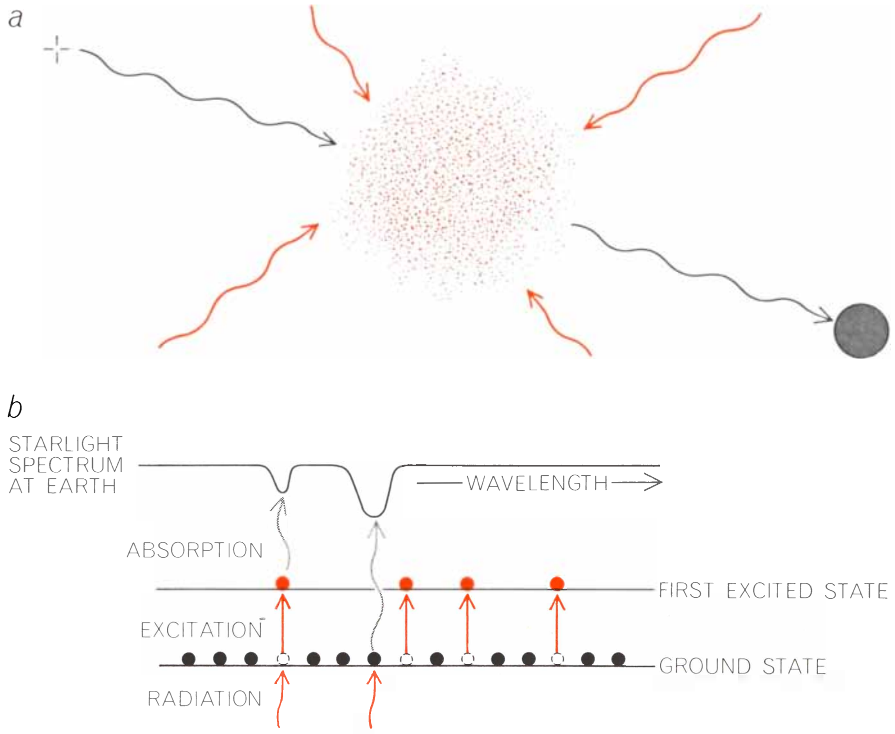
lengths one encounters technical problems in building a sensitive radiometer, and atmospheric emission becomes too strong for ground-based observations. These limitations have now been bypassed by an ingenious scheme for measuring the radiation temperature by reading a "molecular thermometer" in interstellar space.

The method depends on the fact that molecules of the carbon-nitrogen compound cyanogen (CN) in interstellar gas clouds are being bathed, along with everything else in the universe, in the black-body radiation of the primeval fireball. It happens that the cyanogen molecule is excited from its ground, or lowest-energy, state into its first excited state by radiation at a wavelength of 2.6 millimeters—a rather long wavelength for such a transition. A certain fraction of the molecules of cyanogen in a cloud exposed to 2.6-millimeter radiation will therefore be in the excited state rather than the ground state, and the size of the fraction is a measure of the intensity of the radiation. The fraction can be measured because the absorption of light by cyanogen molecules accounts for absorption lines in the spectra of certain stars, and light absorbed by molecules in the ground state has a slightly different wavelength from that absorbed by molecules in the excited state. A cloud of partially excited cyanogen molecules therefore causes two or more absorption lines to appear in the spectrum. The relative strength of the absorption lines characteristic of various states therefore gives the proportion of the molecules that are in each state. As long ago as 1941 Andrew McKellar of the Dominion Observatory in Canada used this method to calculate the degree of excitation of cyanogen molecules absorbing light from the star Zeta Ophiuchi. He reported that the molecules were excited as if by radiation with a temperature of 2.3 degrees K. The connection between this finding and a possible primeval fireball was not recognized; the molecules were assumed to be excited by collisions with other particles.

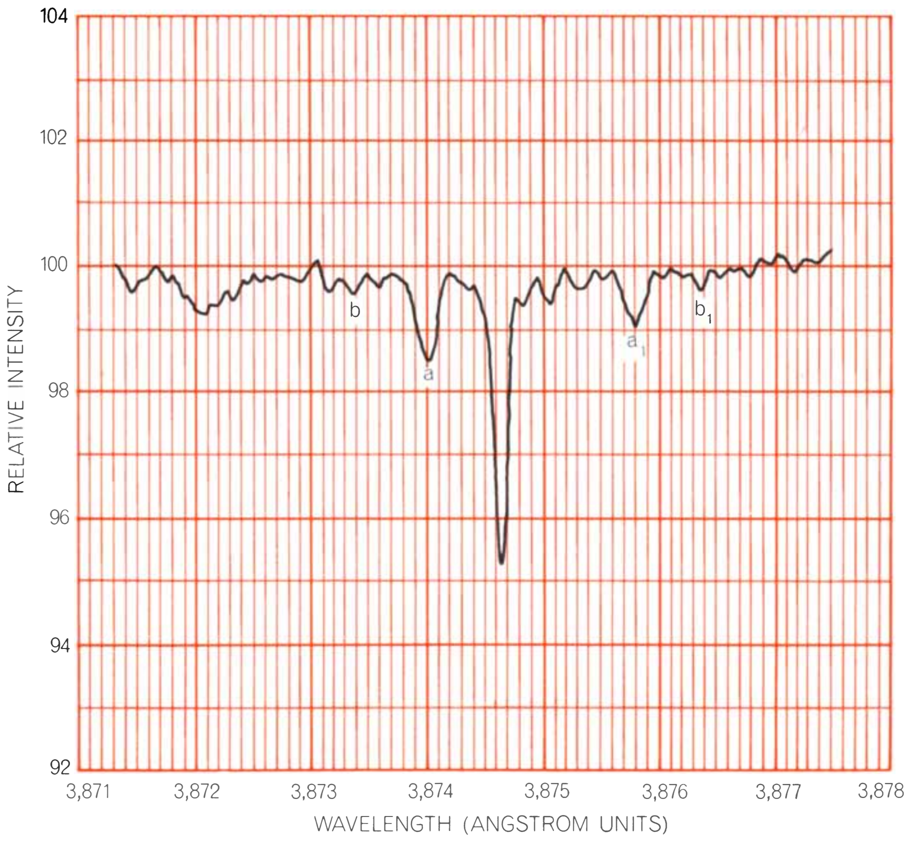
When the fireball hypothesis became generally known, George B. Field of the University of California at Berkeley and Neville J. Woolf of the University of Texas independently pointed out that interstellar cyanogen could be used as a probe to test for fireball radiation in space—and that McKellar's excitation temperature of 2.3 degrees was remarkably close to the three-degree temperature obtained from direct measurements. Field and John L. Hitchcock then reported a new value for the cyanogen excitation temperature. Working with spectra for Zeta Ophiuchi and Zeta Persei made by George H. Herbig of the Lick Observatory, they calculated a temperature range of from 2.7 to 3.4 degrees. The fact that two clouds in very different parts of the sky showed about the same excitation temperature provided an important check on the universality of the excitation mechanism—a necessary feature of fireball excitation.

At the same time Patrick Thaddeus and John F. Clauser of the Institute for Space Studies made some new measurements of Zeta Ophiuchi and obtained a result of 3.75 degrees. Clauser then developed a technique for summing, in digital form, the faint spectra on large numbers of star plates from the Mount Wilson Observatory. The technique has been used to examine the cyanogen absorption lines in the spectra from eight widely distributed stars. In every case the excitation temperature is about three degrees.

The cyanogen measurements are important results. Not only do they pin down the crest of the black-body curve but also they help to eliminate any cause of cyanogen excitation other than fireball radiation. The frequency and energy of particle collisions, for example, would be expected to vary from cloud to cloud depending on local conditions. The results for eight different clouds argue against such local excitation. Note, further, that we have here a very strong test for the fireball hypothesis: If just one cloud is found with a strong ground-state



CYANOGEN MOLECULES in space are bathed in fireball radiation (*colored arrows*) and absorb optical radiation (*black arrows*) on its way to the earth from a star (*a*). The wavelength absorbed depends on whether a molecule is in the "ground" state or in an excited state to which it is raised by fireball radiation (*b*). The amount of absorption at each wavelength depends on the number of molecules in each state. The starlight spectrum indicates the fraction of molecules in each state of excitation and thus the intensity of the fireball.



SPECTRUM of light from the star Zeta Ophiuchi was made by John F. Clauser of the Institute for Space Studies by summing the densitometer traces of a number of star plates. The deep trough marks the absorption line characteristic of the cyanogen ground state. Two dips (a, a_1) mark the two lines of the first excited state. Dips b and b_1, characteristic of the second excited state, may, if better resolved, provide a measurement at 1.3 millimeters.

absorption line and no excited-state line, we shall have to conclude that there is no cyanogen excitation in that cloud and therefore that the primeval fireball does not exist.

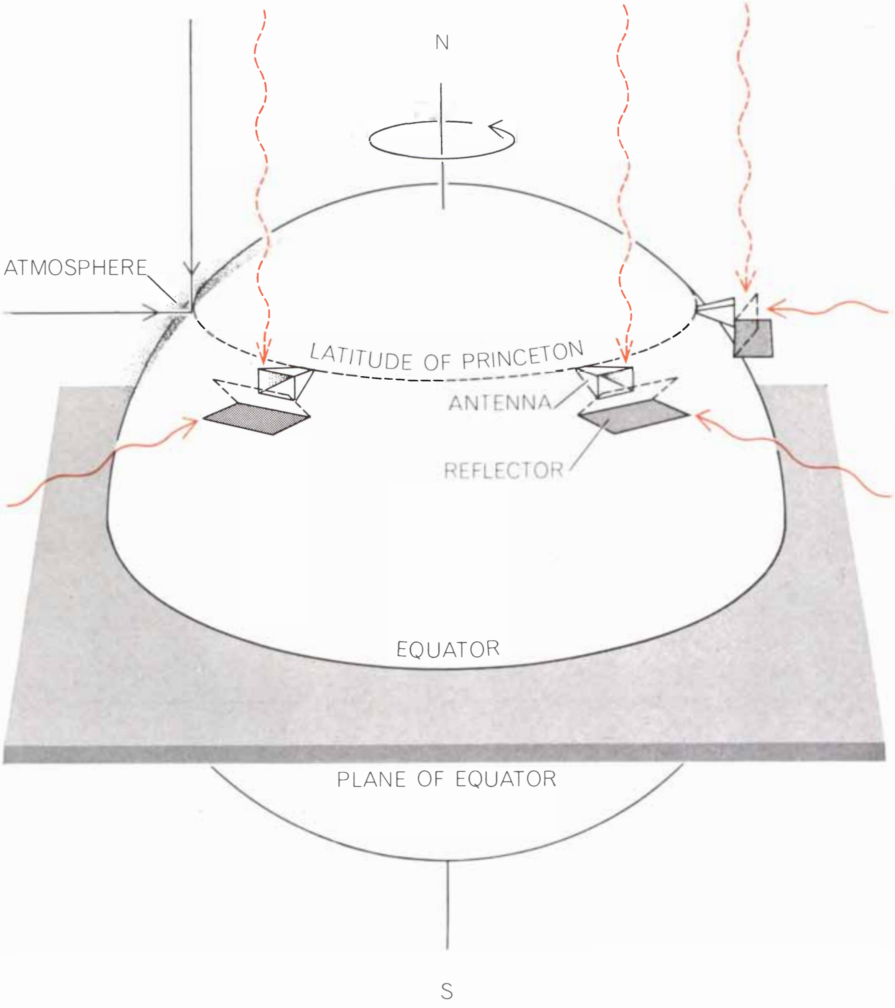
If one assumes that the universe in fact is isotropic, and if this newly discovered radiation in fact is the primeval fireball, the radiation should be isotropic. (Even the first assumption—that the universe is isotropic—should not be regarded as a self-evident principle. It is comforting to state assumptions as principles, but one must recognize the kinship between an assumption of isotropy and the old assumption that the earth is at the center of the universe. Both assumptions fit the poor observational data available at the time—and also the philosophical tenets of the day.) For the first time we now have a precise observational "handle" on the shape of the universe, and one of our current experiments at Princeton is aimed at making use of that handle.

We point the horn of our 3.2-centimeter radiometer toward the south at an angle of 45 degrees from the zenith so that it is directed approximately parallel to the plane of the earth's equator [*see top illustration on opposite page*]. As the earth rotates, the radiometer scans around this plane once a day. We cannot simply look at the record for daily variations and attribute them to some anisotropy in the primeval radiation; there are inevitably large daily effects due to solar heating, atmospheric changes and other phenomena. We correct for these variations by deflecting the antenna beam in the direction of the pole star every 15 minutes. Since that is a fixed point in the sky, it serves as a reference to which we can compare the reading along the equatorial plane. Keeping the apparatus running for many months further reduces the daily variations. Since any irregularity in the radiation would be fixed in relation to the stars, and therefore would traverse the antenna beam at different times of the day during different seasons of the year, we partly average out effects that have a period of one solar day. After about a year the experiment shows no differences between equatorial and polar radiation intensities greater than about .015 degree, which is to say it reveals no anisotropy greater than about ±.5 percent [*see bottom illustration on opposite page*].

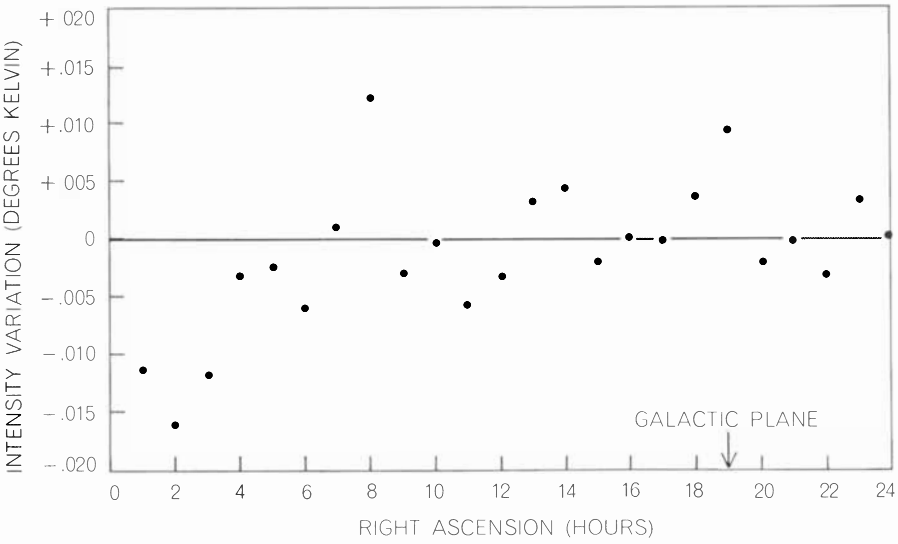
Whatever the final explanation for what we now believe to be fireball radiation, it must account for this remarkable isotropy. The source cannot be our own galaxy; the solar system is off to one side of the galaxy, and the radiation would have to be more intense in the direction of the main body of the galaxy. If the source were in the solar system itself, there would be recurring variations each solar day, but there are no such effects. It seems clear that the radiation must be extragalactic.

If the earth is moving in relation to the local frame of reference defined by the average motion of the primeval fireball radiation, the radiation should seem a little hotter when we observe in the direction of the earth's motion and a little colder when we look "backward." One cannot be sure what the total velocity of the earth should be in relation to this standard, but we do know the earth is moving around the center of our galaxy at 200 kilometers per second. If we suppose the center of the galaxy is at rest in this frame of reference, the radiation would appear to be .07 percent hotter (or more intense) than average in the direction of the earth's motion (toward the constellation Cygnus) and .07 percent colder than average 180 degrees away. Since our instrument scans in the plane of the Equator, however, we should not observe this full effect but rather a variation of about .04 percent from the mean [*see bottom illustration on next page*]. This is about half of the upper limit (roughly .1 percent) that we have been able to set so far for an anisotropy that has a period of 24 hours. (The radiation would appear hottest and coldest at 12-hour intervals.) We are now trying to improve the observations to a point at which we can actually see this effect of the earth's "absolute" motion through space.

Unequivocal proof of the phenomenon of a primeval fireball would seem to rule out a number of competing cosmologies. The steady-state theory would be ruled out because its universe was never in a dense state and therefore could not have manufactured black-body radiation. The fireball also creates severe difficulties for any cosmology that includes a visible edge to the matter-filled part of space, for example the cosmology of Oskar Klein and Hannes Alfvén [see "Antimatter and Cosmology," by Hannes Alfvén; Scientific American, April]. If there is a visible boundary, then any radiation produced in the early days of the universe must long since have left the universe. Proponents of a visible-edge cosmology must therefore find a contemporary source for the radiation we attribute to a fireball. Unless the earth is right at the center of the universe—something most people would be reluc-



ISOTROPY is measured by pointing the horn antenna in the direction of the plane of the earth's equator and periodically raising a reflector that deflects radiation from the direction of the pole star into the horn. As the earth turns the radiometer measures the difference between the equatorial and the polar (or constant) radiation intensity. The length of the path through the atmosphere is the same in both directions (*left*), eliminating one source of error.



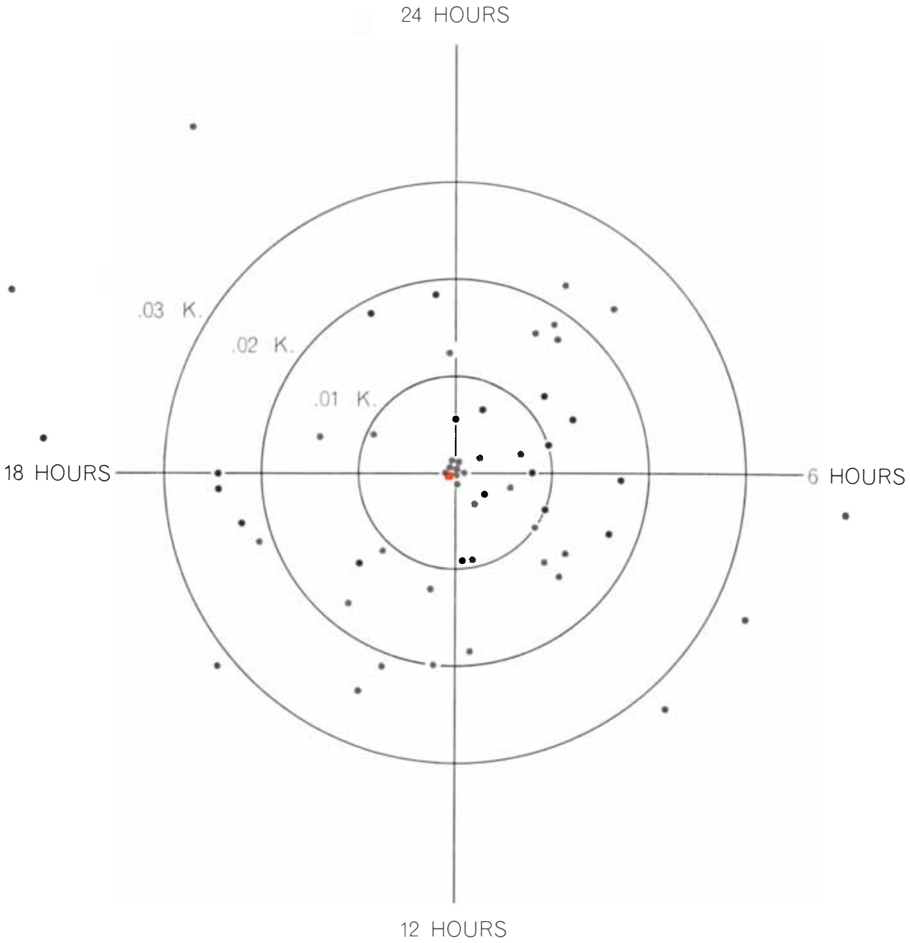
RESULTS of isotropy experiment, after about a year, indicate no anisotropy greater than about ±.5 percent. Each point represents the average difference between the equatorial radiation temperature in a given direction and the constant polar radiation temperature; the probable error in each point is about ±.003 degree. The scatter appears to be primarily random, although the dip at two hours may be real; more measurements are required to be sure.

tant to suppose—no contemporary source within the universe could produce the isotropic radiation we observe.

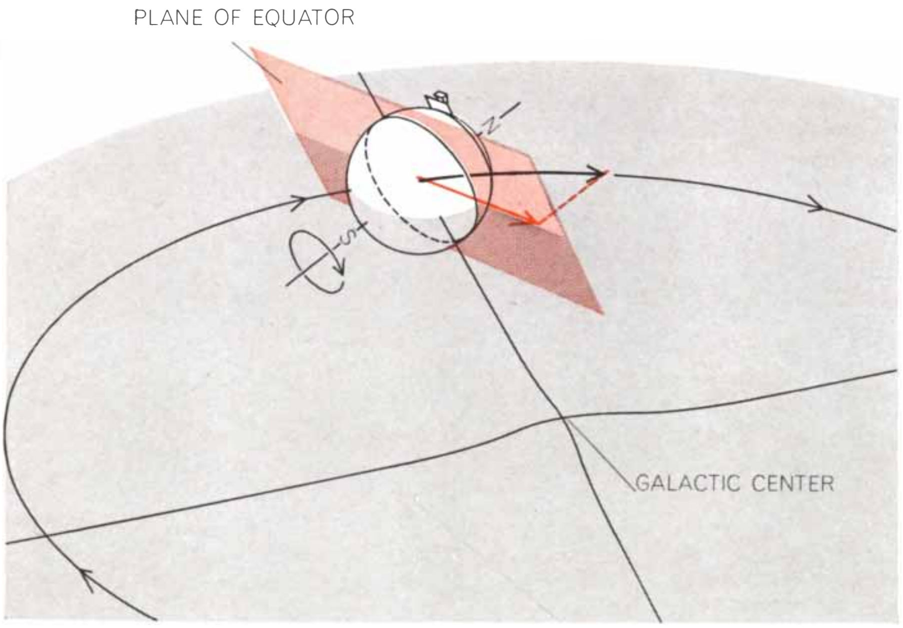
Our discussion of cosmology so far has been merely descriptive, but if cosmology is to be a respectable science it must attempt numerical confrontations between theory and observation. Such a confrontation is provided by what cosmologists are now calling the "helium problem." There is a theoretical connection between the temperature of the primeval fireball and the amount of helium in the matter that came out of the big bang and eventually condensed into galaxies. It is worth examining as an example of the development of cosmological ideas and of the way in which a single observational result can prompt new theoretical work that in turn calls for new observations.

The story begins in about 1930 with the pioneering work of R. C. Tolman on thermodynamics and thermal radiation in an expanding universe. In 1938 C. F. von Weizsäcker tried theoretically to produce the heavy elements by "cooking" hydrogen in an early "superstar" stage of the universe, which later exploded into the expanding universe. George Gamow pointed out in 1948, however, that according to general relativity the universe could not have existed in a static, high-temperature state. He proposed instead that the elements were largely formed—and also that black-body radiation was emitted—during the early and very rapid expansion of the universe. Later calculations showed that although helium would have been produced in such a stage, it was impossible to account for the formation of heavier elements. An improved theory of element formation in stars finally eclipsed theories of element formation in the big bang itself, and the idea of thermal radiation in a big bang dropped out of sight. It is remarkable, however, that this theory, as developed by Gamow, Ralph Alpher, Robert Herman and others, implied that the present temperature of the fireball would be about equal to the observed value of three degrees K.

Dicke arrived at the idea of a primeval fireball from a different direction. In the summer of 1964 he was considering not the origin of the elements but the origin of the universe. It is difficult to explain the apparently spontaneous creation of matter that is called for if one associates the beginning of the expansion of the universe with its actual origin. Dicke therefore preferred an oscillating model, in which the present expansion of the universe is considered to have been preceded by a collapsing phase.

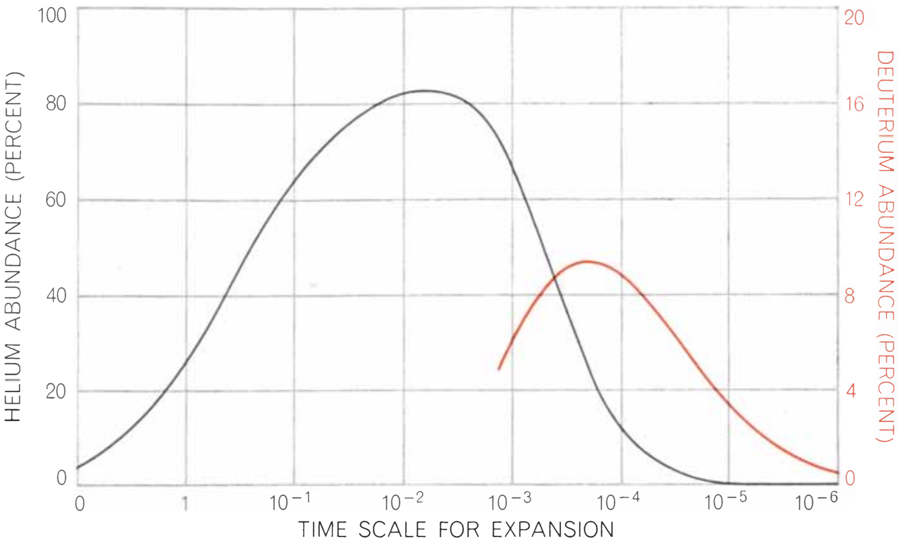


ISOTROPY DATA were analyzed in an effort to bring out any 24-hour periodicity. Each point gives the magnitude and direction of the maximum difference between equatorial and polar radiation temperatures on a day's run. (Solid dots are full runs, gray dots runs that were incomplete and were given half-weight.) The vector sum of all points yielded a maximum difference of about .001 degree K., an anisotropy of .03 percent (*colored square*).



EARTH'S MOTION around the galaxy should be detectable as an apparent increase in radiation intensity in the direction of motion and a decrease in the opposite direction (see text). The direction of motion is not the same as the direction (in the plane of the Equator) in which the radiation is being observed, however. The observed effects should therefore be proportional to the equatorial projection (*colored arrow*) of the velocity of the earth.

The contraction of the universe would have heated up its contents, producing thermal radiation when the universe became dense enough; the temperature would have risen to at least 10 billion degrees, at which point complex nuclei would have evaporated, yielding pure hydrogen. Such a process could account for the elimination of heavy elements—the "ashes" from the hydrogen burned in stars in the previous cycle. Dicke, in other words, introduced the fireball to eliminate the heavy elements rather than to produce them.



PRIMORDIAL ABUNDANCE of helium (*black*) and deuterium (*color*) is plotted for various assumptions about the rate of expansion of the universe. Unity on the horizontal scale corresponds to the time scale for expansion predicted by the general theory of relativity.

Perhaps because we are by training physicists rather than cosmologists, our group at Princeton was unaware for some time that there was a history of theoretical work on a primeval fireball and element production in the big bang. Having begun with the fireball idea, we reached the problem of element formation by a roundabout route. As our search for the fireball was getting under way we were concerned about how we would interpret the results we hoped to obtain. (One particularly wants to know this ahead of time when an experiment is highly speculative, as this one certainly was before the Bell Laboratories results became known.) We were anxious to establish some connection between a possible primeval fireball and some other observable quantity, so we asked ourselves what physical processes might be appropriate to the conditions encountered as the expansion of the universe is traced back in time to ever higher densities and temperatures.

We found that in the early stages of expansion conditions would have been right for the conversion of significant amounts of hydrogen to helium. The fractional amount of hydrogen that would have been converted to this primeval helium depends on two observable quantities: the present mean mass density in the universe and the present temperature of the primeval fireball. Given the present mass density, the primeval helium abundance would be lower for higher values of the present fireball temperature. This is because the helium would have formed at a certain temperature (about a billion degrees) and the amount of helium that formed would depend on the mass density at the epoch in which it formed. The higher the present fireball temperature, the less the radiation can have cooled since the epoch of helium production; the correspondingly lesser expansion of matter means a larger mass density at the helium epoch, and therefore more helium production.

We decided that if the present fireball temperature were 10 degrees K. or more, the primeval helium abundance could be well below the observed helium abundance in the sun. This seemed desirable because the sun also contains heavier elements thought to have been produced in earlier generations of stars, and we assumed that these earlier generations would also have produced substantial amounts of helium. It turned out, of course, that the fireball temperature is certainly not 10 degrees but rather three degrees. This pushes the calculated primeval helium abundance up to the range of 27 to 30 percent by mass, or just about the observed abundance of helium in the sun. That seemed surprisingly high.

Before considering the observational evidence that might confirm or rule out this theoretical finding, we should examine the assumptions that underlie the calculation. A number of variables from nuclear physics are involved, many of them actually measured and the rest derived from theory in which there is a good deal of confidence because it works well in conventional applications. Another basic ingredient in the calculation is the gravity theory, which determines how fast the universe would have expanded through the period of helium production. Here there are grounds for suspicion, because the conventional gravity theory—the general theory of relativity—has not been tested by a wide range of observations. The primordial helium abundance can be computed for various assumptions about the rate of expansion of the universe [*see illustration above*]. If the universe actually expanded just slightly faster than general relativity predicts, an unacceptably high amount of helium would have been produced. If the expansion rate were increased by a factor of about 10,000, the helium production would be acceptable but there would be too much deuterium. To avoid this requires an expansion rate so great that there would have been relatively little primeval helium. The principal competitor of general relativity, a generalization developed by Carl Brans and Dicke, predicts a faster expansion that might carry over into this area of negligible helium. If the rate of expansion could be shown to be somewhat slower, this difficult situation could be eased, but no one has suggested a reasonably attractive way to do this.

For the moment we are content to frame this question: Was the initial helium abundance in our galaxy very low or was it about equal to the solar value? The choice between these two clear-cut alternatives depends on the helium content of the oldest stars in the galaxy. Unfortunately these stars closely guard the secret of their helium abundance. They are small stars and generally have cool surfaces in which the spectral lines of helium are not seen, and so one cannot use the spectroscopic techniques that have been satisfactory for more massive stars with hotter surfaces. As for these massive stars, their lifetimes are relatively short, and the ones that formed early in the history of the galaxy have already burned out. The answer to the helium problem will be hard to obtain, but it will eventually add a fascinating piece of information to observational cosmology.