The Cosmic Background Radiation and the New Aether Drift

Sensitive instruments have found slight departures from uniformity in the radiation left by the primordial "big bang." The experiment reveals the earth's motion with respect to the universe as a whole

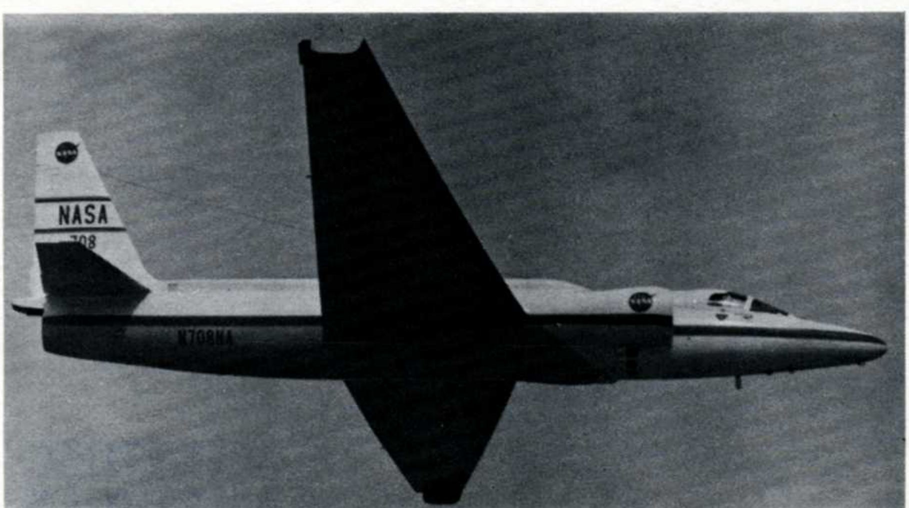
by Richard A. Muller

A curious radiation that bathes the earth almost uniformly from every direction has turned out to be a unique source of information about the nature and history of the universe. The faint radiation was identified 13 years ago during a search for noise sources capable of interfering with satellite communications systems. The "noise" proved to be of cosmic origin and soon became known as the three-degree cosmic black-body radiation because it has the spectral characteristics of a black body, or perfect emitter of radiation, whose temperature is about three degrees Kelvin (three degrees Celsius above absolute zero). Most astrophysicists now believe this microwave radiation was emitted shortly after the "big bang," the cataclysmic explosion in which the universe was created some 15 billion years ago. Not only is it the most ancient signal ever detected; it is also the most distant, coming from well beyond the quasars, the most remote luminous sources known. The three-degree radiation is a background in front of which all astrophysical objects lie.

The observation of the cosmic background radiation is the closest we have come to a direct study of the primordial explosion itself. The very existence of the radiation is the strongest evidence in favor of the big-bang theory. The isotropy of the radiation, that is, the uniformity of the radiation from different directions in space, tells us that the big bang, although it was unimaginably violent, also went quite smoothly. The slight departure from isotropy that has recently been discovered indicates that our galaxy is hurtling through the universe with the surprisingly high velocity of 600 kilometers per second. It is this cosmological velocity that has been called "the new aether drift," in reference to the "aether drift" that A. A. Michelson and E. W. Morley sought unsuccessfully to discover nearly a century ago by measuring the velocity of light over paths rotated at different angles with respect to the earth's motion in space. The three-degree cosmic background radiation provides an all-pervasive radiation "aether" for performing an analogous experiment.

The cosmic background radiation was discovered in 1965 by Arno A. Penzias and Robert W. Wilson of Bell Laboratories; its significance was immediately recognized by Robert H. Dicke and his group at Princeton University. Since then much has been learned about the spectrum of the radiation. Its intensity has now been studied at wavelengths ranging from 30 centimeters down to half a millimeter, confirming the initial conjecture that its spectral curve conforms to that of a black body at a temperature of three degrees K.

One of the most important observations reported by Penzias and Wilson was the constancy of the temperature of the radiation from different directions in space. Their measurements indicated that the temperature varies by less than 10 percent in any direction. Subsequent experiments set even lower limits on the departure from isotropy. Two independent groups have recently carried out measurements sensitive enough to show, however, that the temperature of the radiation is not precisely the same in all directions. One set of experiments was performed at Princeton by David T. Wilkinson and Brian E. Corey, the other set at the Lawrence Berkeley Laboratory of the University of California by a group that included George F. Smoot, Marc V. Gorenstein and me. It is now known that the temperature of the three-degree back-



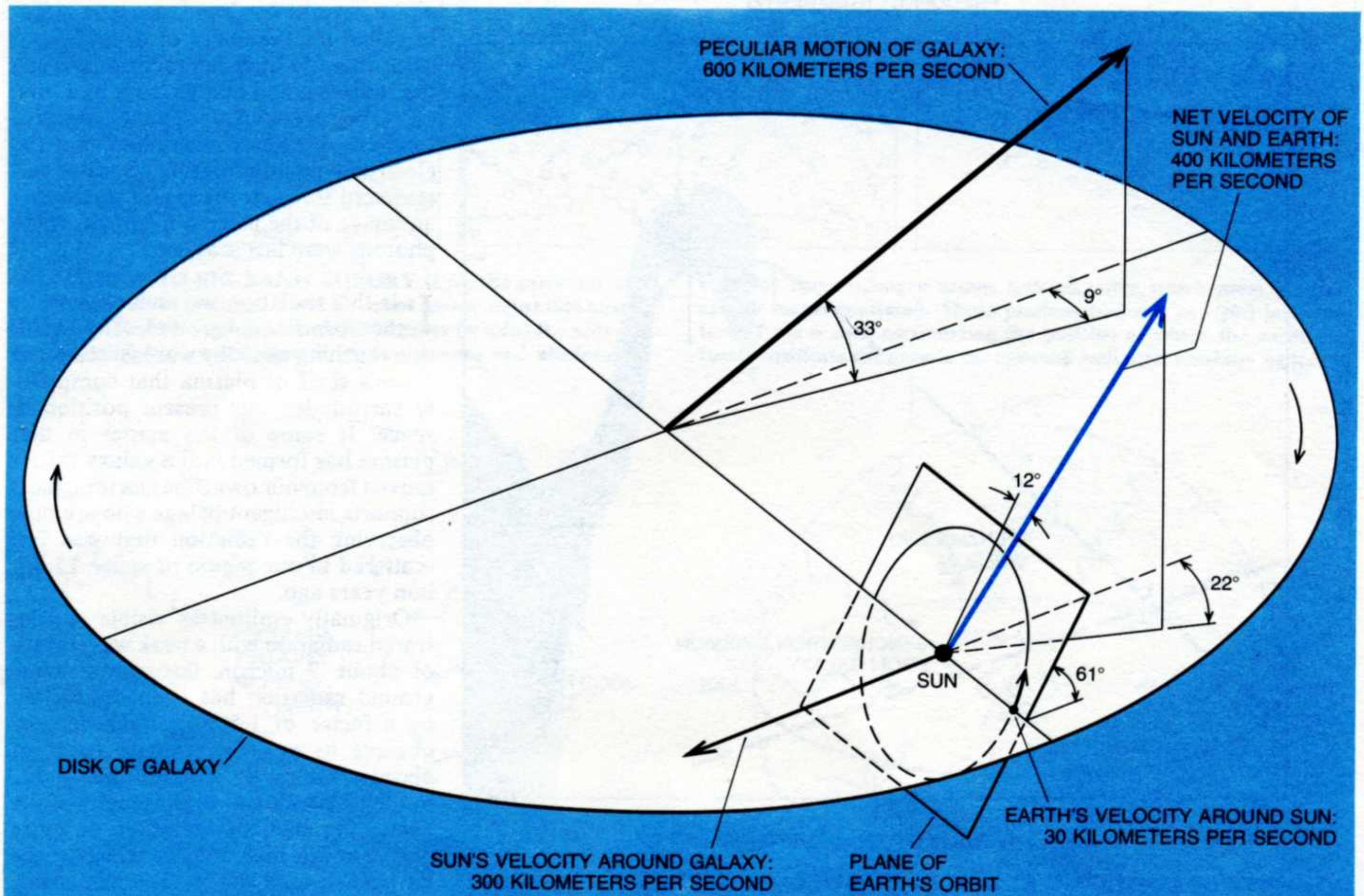
INSTRUMENT PLATFORM in the new aether-drift experiment was a U-2 aircraft operated by the National Aeronautics and Space Administration. Like the original aether-drift experiment performed nearly a century ago by A. A. Michelson and E. W. Morley, the new experiment was designed to measure the earth's motion with respect to a universal frame of reference, in this case the cosmic background radiation. That radiation, which is equivalent to the radiation emitted by a black body (a perfect radiator) with a temperature of about three degrees Kelvin (three degrees Celsius above absolute zero), is radiation left over from the fireball in which universe was created 15 billion years ago. U-2 has made 10 flights carrying an ultrasensitive microwave receiver designed by the author, George F. Smoot and Marc V. Gorenstein.

ground radiation varies by about a tenth of a percent across the sky, with the hottest region being in the direction of the constellation Leo and the coolest in the direction of Aquarius. The temperature varies smoothly between these two regions, following a simple cosine curve. This distinctive pattern ("the great cosine in the sky") leads us to identify the velocity of the solar system as the cause of the anisotropy. In order to explain how this conclusion has been drawn and what its significance is it is necessary to review the big-bang theory, the origin of the cosmic background radiation and just what it is that has been learned from the existence of the anisotropy.

The big bang was not simply an explosion of a clump of matter into an otherwise vast and empty space. Although such a picture would account for Hubble's law (the observation that distant galaxies are receding from us at a velocity proportional to their distance), it seems incapable of accounting for the uniformity with which matter and radiation fill space. The known universe appears to be so uniformly populated that astronomers accept the "cosmological principle": the belief that the universe is essentially the same everywhere. In addition, the idea of an exploding clump of matter sitting somewhere in space offers no natural way to account for the existence of the cosmic background radiation. Any radiation emitted at the time of the explosion would have left the vicinity of the original mass even faster than the matter would have left it, and the radiation would no longer be around to be observed.

In the big-bang theory there is no primordial clump of matter and no center to the explosion. Space is uniformly occupied; there is no outer edge to the distribution of matter. The big bang was not an explosion of matter within space but an explosion of space itself. According to Einstein's general theory of relativity, the "amount" of space between objects is not fixed, even if the objects retain their respective coordinate positions. In the calculations done in the big-bang theory the galaxies are usually assumed to be at rest as the amount of space between them increases. Any motion that leads to a change in a galaxy's coordinate position in this theory is referred to as a peculiar velocity, not because it is strange but because it is peculiar to the individual galaxy and is not part of an overall cosmic motion.

The rate of the expansion of space is reduced by the presence of matter and energy. If the average mass density of the universe is less than a critical value (about 10^{-29} gram per cubic centimeter), the expansion will go on forever. If the average mass density is more than the critical value, the expansion will slow to a stop and turn into an implosion. The mass density also determines the large-scale geometry of the universe. If the mass density is greater than the critical value, the volume of the universe is finite; otherwise the volume is infinite. So far the mass density of the universe has not been established accurately enough to say for sure whether the universe is finite or infinite. Fortunately for most of the calculations of the big-bang theory the issue is not critical. We shall assume that the average mass



ABSOLUTE MOTION OF THE EARTH through space has been determined by measuring slight differences in the temperature of the three-degree cosmic background radiation reaching the earth from various directions. The earth travels in its orbit around the sun at 30 kilometers per second and, as the sun's gravitational captive, is being swept around the center of the galaxy at 300 kilometers per second. The new aether-drift experiment shows that the earth's net motion in space is about 400 kilometers per second. The vector of the earth's net motion lies in the same plane as its orbit around the sun and at an angle tilted sharply upward (northward) from the plane of the galaxy. In this diagram the vector of the earth's net motion is depicted as a colored arrow centered on the sun, since the two bodies travel together. Both are being carried along by the galaxy's own "peculiar" motion through space (the motion peculiar to the galaxy and not a part of the overall cosmic motion). In order to account for the earth's motion with respect to the three-degree radiation the galaxy must be traveling at about 600 kilometers per second, or more than 1.3 million miles per hour, in the direction shown by the heavy black arrow.

density is equal to the critical value, which has the added advantage of implying that the average curvature of space is zero. Therefore we can work with the familiar Euclidean geometry.

The concept that the distance between two objects can change without the objects themselves moving seems strange because it is completely foreign to our everyday experience. It is hardly stranger, however, than the curvature of space itself. Fairy tales and much science fiction describe events in which space is flexible. What distinguishes the general theory of relativity from mere flights of fancy are specific equations that relate the geometry and volume of space to its previous history and to its mass-energy content.

Hubble's law fits naturally into the big-bang theory. The relation follows from two facts: not only is space uniformly occupied by matter but also space is being created at a uniform rate. Thus the greater the distance separating two galaxies, the greater the amount of space created between them. Hubble's observation that all galaxies are moving away from our own does not mean that our galaxy is at the center of the universe; a similar observation would be made from every other galaxy.

The uniform expansion of space applies only to distances on an intergalactic scale. It does not hold, for example, in the vicinity of massive objects such as the sun, where the geometry of space can be quite different. It also does not hold at the distances between the atoms in a molecule or the electrons in an atom. Such distances are determined by electromagnetic forces rather than gravitational ones. Even if the expansion of space tended to move the constituents of atoms and molecules apart, their internal electric fields would draw the constituents back. If this were not the case, human observers and their meter sticks would grow at the same rate as the universe, making the expansion of space unobservable.

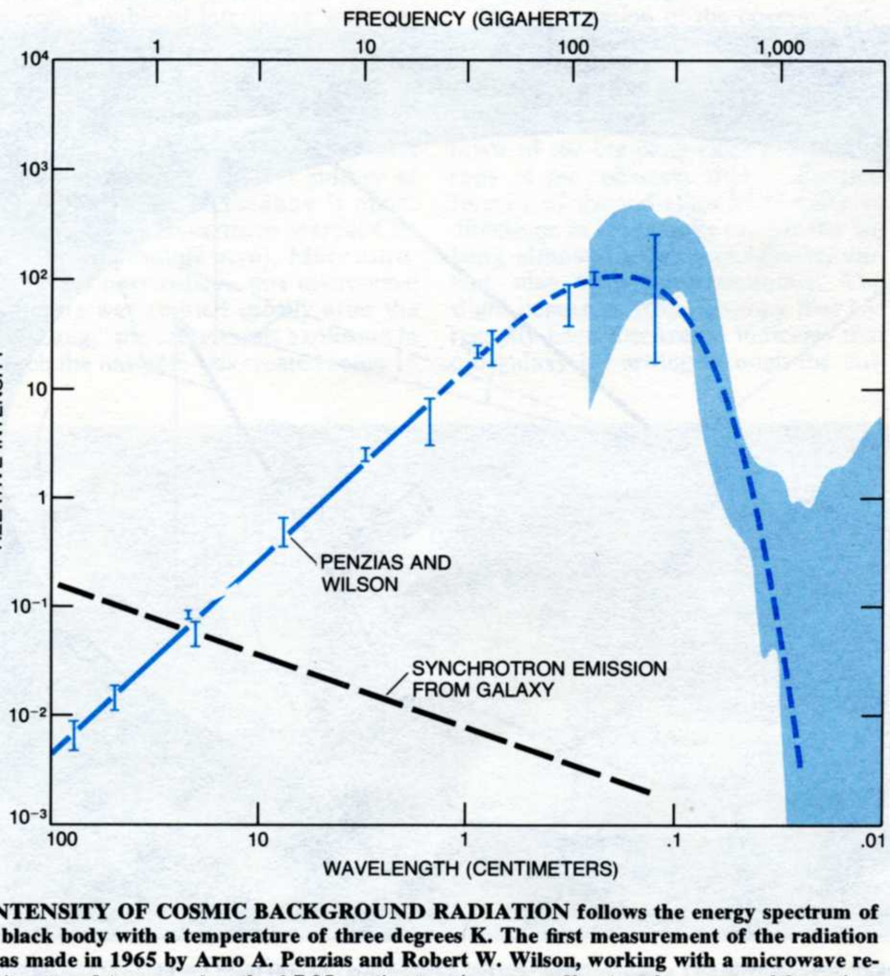
The great initial success of the big-bang model came when George Gamow, Ralph A. Alpher and Robert Herman extrapolated the expansion back to a period when the universe was more than 10^{30} times denser than it is now. They postulated that the early universe would be extremely hot and that the combination of high temperature and density would initiate thermonuclear reactions, converting the plasma of protons, electrons and neutrons into deuterons and helium nuclei. Within only a few minutes the expansion of the plasma would reduce the temperature and density below the level needed to sustain further reactions. The conversion would be incomplete and just sufficient to account for the present ratio of helium to hydrogen in the universe.

Another consequence of the Gamow-Alpher-Herman model, which went virtually unnoticed at the time, was that the hot plasma would emit and absorb electromagnetic radiation, just as the hot plasma at the surface of the sun emits light. The radiation would be scattered and rescattered by the free electrons until roughly half a million years after the big bang. At that time the density and temperature of the matter would have dropped to the point where its constituent ions (mostly protons and electrons) would unite to form electrically neutral atoms. This period (which actually lasted for several thousand years) is usually called the "moment of decoupling," since there is little interaction between the radiation and matter from that time on. The previously opaque universe suddenly becomes clear, allowing the electromagnetic radiation to travel unscattered through space and preserving an image of the plasma from which the photons were last scattered.

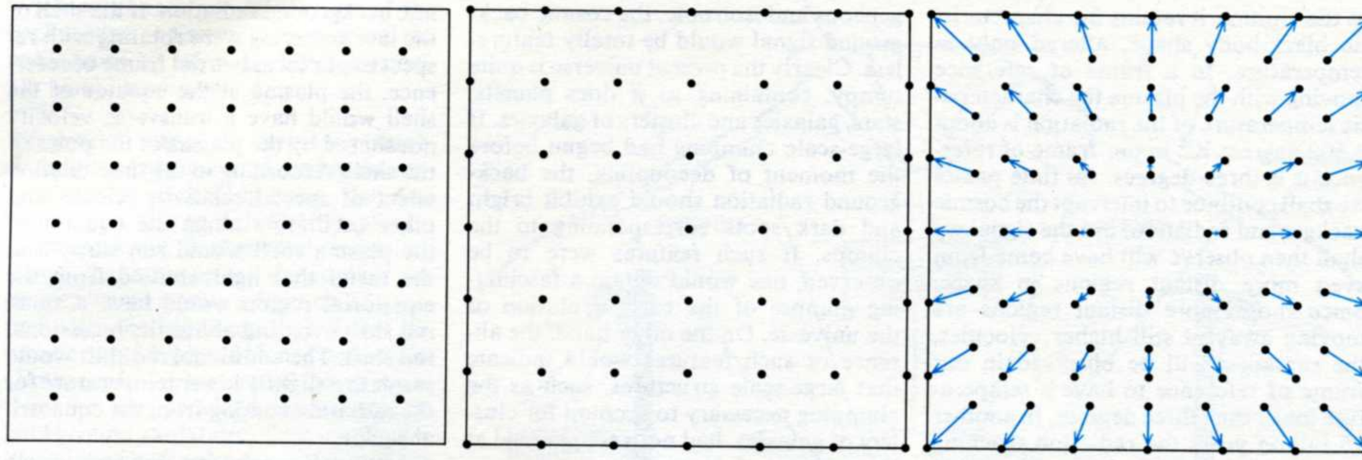
It is this radiation we now observe as the cosmic background. The radiation reaching us today was last scattered from a shell of plasma that completely surrounded our present position in space. If some of the matter in that plasma has formed into a galaxy far removed from our own, one can imagine it supports intelligent beings who are now observing the radiation that was last scattered in our region of space 15 billion years ago.

Originally emitted as visible and infrared radiation with a peak wavelength of about .7 micron, the cosmic background radiation has been red-shifted by a factor of 1,500, so that we now observe its peak wavelength to be at about a millimeter. The red shift is due to the tremendously high velocity of the expanding shell of radiation, or more properly the high rate at which space between us and the shell is increasing. The radiation itself has not changed its wavelength. Rather, we are observing it in a frame of reference that is "moving" at 99.9 percent the speed of light with respect to the matter that emitted it 15 billion years ago.

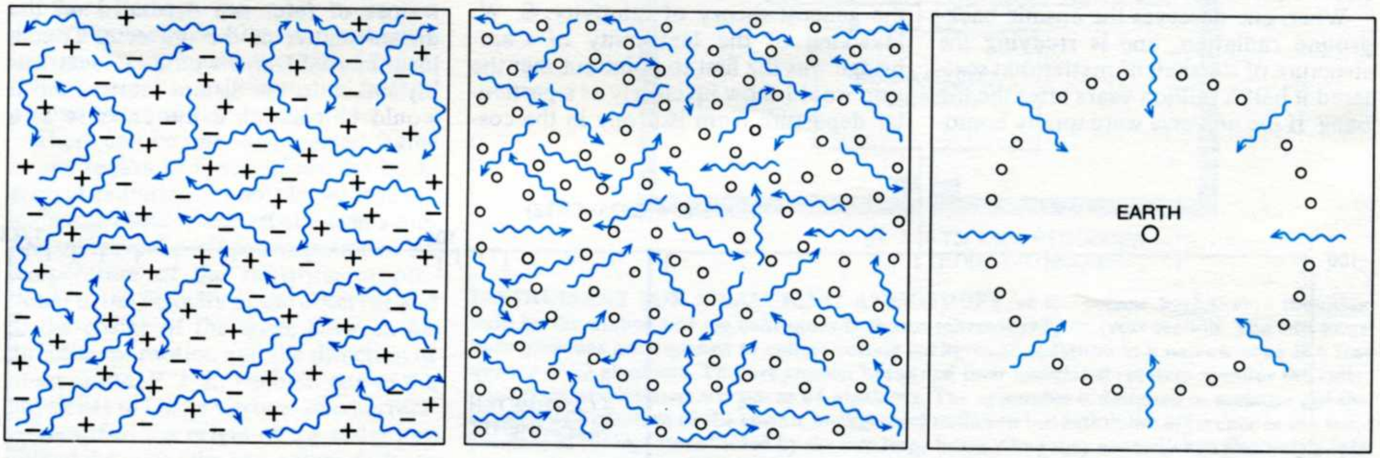
A remarkable feature of a black-body spectrum is that when it is viewed in a frame of reference moving with respect



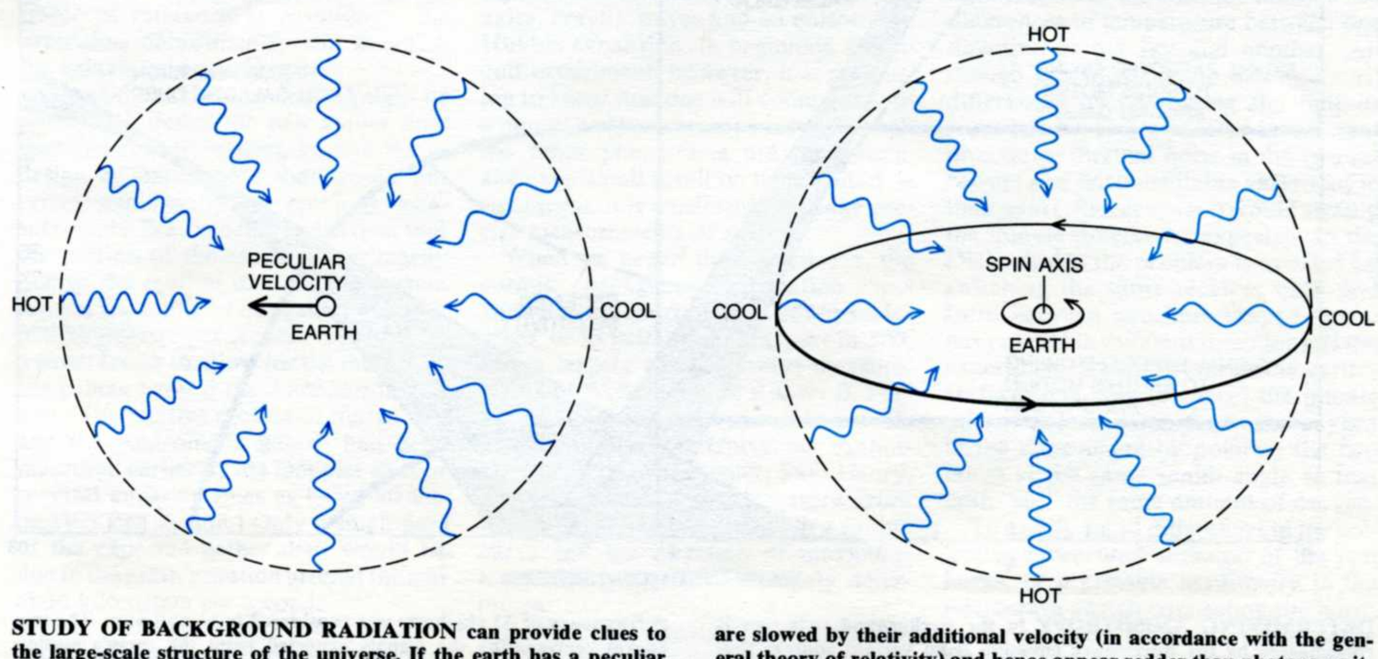
INTENSITY OF COSMIC BACKGROUND RADIATION follows the energy spectrum of a black body with a temperature of three degrees K. The first measurement of the radiation was made in 1965 by Arno A. Penzias and Robert W. Wilson, working with a microwave receiver tuned to a wavelength of 7.35 centimeters (corresponding to a frequency of four gigahertz). Most of the subsequent measurements were also done at single wavelengths, indicated by the vertical bars. Recently, however, Paul L. Richards and his co-workers at the University of California at Berkeley have measured the higher-frequency portion of the curve with a wide-band technique, obtaining the results indicated by the colored area. The broken line represents synchrotron radiation from our galaxy: radiation emitted by electrons as they spiral around lines of magnetic force. At frequencies below 10 gigahertz the anisotropy, or the directional nonuniformity, of the synchrotron emission masks the anisotropy in the background radiation.



UNIFORM EXPANSION OF SPACE accounts for the "law" discovered by Edwin P. Hubble of the Mount Wilson Observatory 50 years ago when he observed that distant galaxies are receding at a velocity proportional to their distance. Here the expansion of space is represented by the change in the spacing of galaxies (*dots*) in the arrays at the left and in the middle. In the diagram at the right the two arrays are superposed. Connecting arrows show the distance traveled by each galaxy as viewed from the central galaxy. The same pattern would be observed from every other galaxy. Although the space between the galaxies expands, the size of each galaxy remains the same.



ACCORDING TO BIG-BANG THEORY (*left*), the early universe is filled by protons (*plus signs*) and electrons (*minus signs*) that absorb and reemit photons (*color*). After 500,000 years (*middle*) the universe has expanded and cooled enough for the protons and electrons to combine into hydrogen atoms (*circles*), after which most photons are no longer scattered. Those photons (*redrawn at right*) last scattered from a shell surrounding the position at which the earth will form constitute the cosmic background radiation reaching us today.



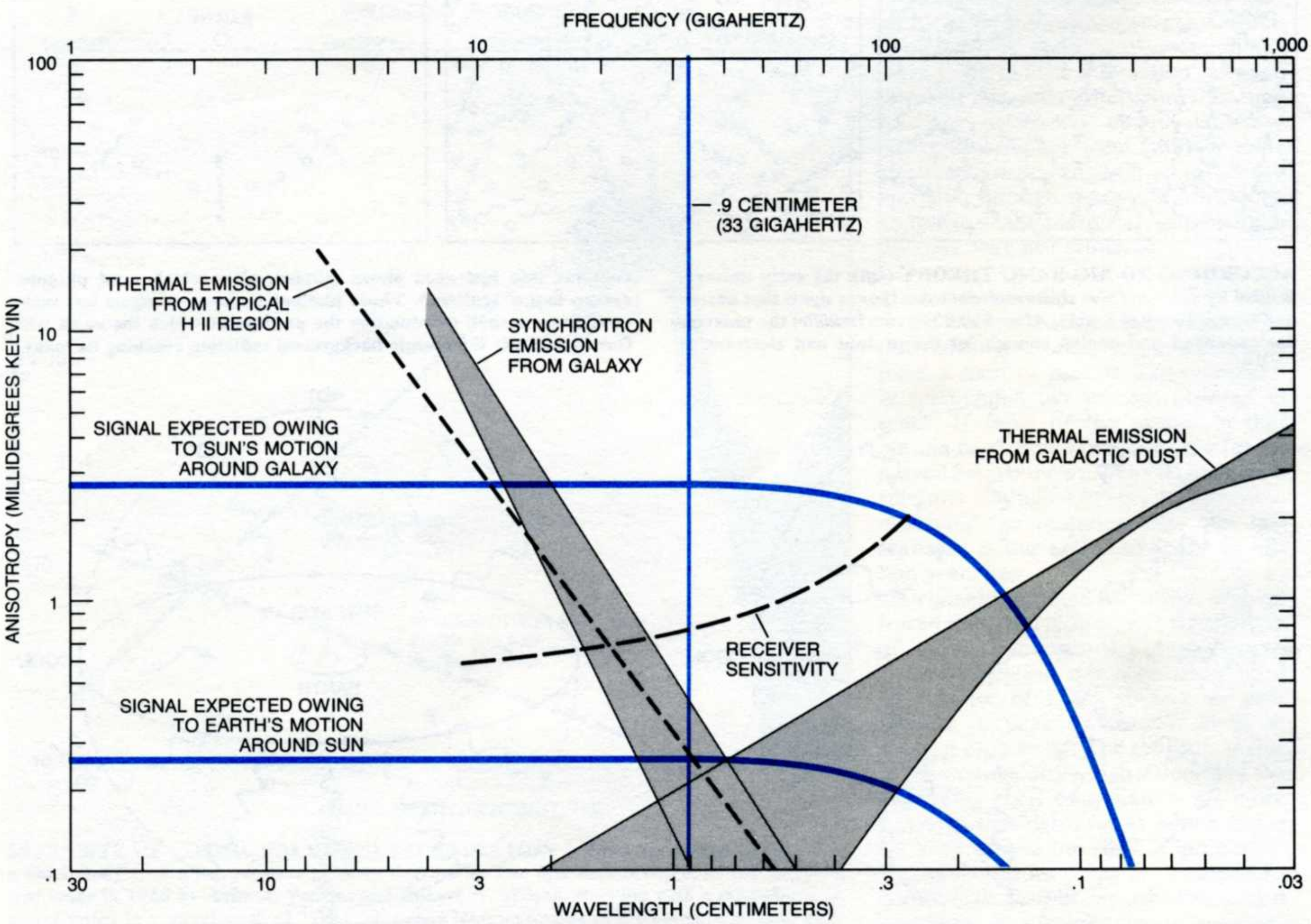
STUDY OF BACKGROUND RADIATION can provide clues to the large-scale structure of the universe. If the earth has a peculiar velocity (*left*), the radiation is slightly "bluer" (hotter) in the direction of motion and "redder" (cooler) in the opposite direction. If the shell of matter that last scattered the radiation was spinning with respect to our local inertial frame, the photons emitted at the shell's equator are slowed by their additional velocity (in accordance with the general theory of relativity) and hence appear redder than photons emitted toward its poles. The two possibilities can be distinguished by differences in the pattern of the observed temperatures. The temperature of the radiation will vary in the first instance as the cosine of the angle in the sky and in the second instance as the square of the cosine.

to the emitter, it retains the characteristic black-body shape, altered only in temperature. In a frame of reference moving with the plasma the characteristic temperature of the radiation is about 4,500 degrees K.; in our frame of reference it is three degrees. As time passes we shall continue to intercept the cosmic background radiation, but the signal we shall then observe will have come from even more distant regions in space. Since those more distant regions are moving away at still higher velocities, the radiation will be observed in our frame of reference to have a temperature lower than three degrees. In another 15 billion years the radiation reaching our present position in space should have a temperature of about 1.5 degrees. It will also be radiation emitted at the decoupling time, but from a region far more distant in space than the radiation we are observing today.

When one observes the cosmic background radiation, one is studying the structure of the shell of matter that scattered it half a million years after the big bang. If the universe were totally homogeneous and isotropic, the cosmic background signal would be totally featureless. Clearly the present universe is quite lumpy, containing as it does planets, stars, galaxies and clusters of galaxies. If large-scale clumping had begun before the moment of decoupling, the background radiation should exhibit bright and dark spots corresponding to the clumps. If such features were to be observed, one would obtain a fascinating glimpse of the early evolution of the universe. On the other hand, the absence of such features would indicate that large-scale structures, such as the clumping necessary to account for clusters of galaxies, had not yet appeared at the moment of decoupling.

The background radiation also provides an opportunity for testing some of the more speculative theories of the universe. For example, the universe may be spinning, a possibility allowed by the general theory of relativity. S. W. Hawking of the University of Cambridge was the first to point out that the spin would show up clearly as a particular departure from isotropy in the cosmic background radiation. If the shell of the last scattering were rotating with respect to our local inertial frame of reference, the plasma at the equator of the shell would have a transverse velocity not shared by the plasma at the poles of the shell. According to the time-dilation effect of special relativity, clocks and other oscillators along the equator of the plasma shell would run slow, with the result that light emitted from the equatorial region would have a small red shift over and above the recessional red shift. The additional red shift would result in a slightly lower temperature for the radiation coming from the equatorial region.

Although a spinning universe would be detectable according to the general theory of relativity, it would not be detectable according to a principle stated by Ernst Mach. Mach postulated that the very existence of local inertial frames of reference depended on the distant matter of the universe. Thus a local inertial frame would be inextricably linked to the distant matter, and it would be rotating if the universe as a



DETERMINING ANISOTROPY in the background radiation is complicated by the microwave emission from various sources that are themselves anisotropic. H II regions, for example, are concentrations of gas and dust heated by young stars. For the new aether-drift experiment it was necessary to select a frequency at which the expected anisotropy of the background radiation would predominate. A frequency of 33 gigahertz was considered to be optimum. The two curves representing the signals expected from the earth's motion around the sun (30 kilometers per second) and the sun's motion around the center of the galaxy (300 kilometers per second) are computed on the assumption of zero velocity for the galaxy. The experiment reveals that the galaxy's velocity is 600 kilometers per second.

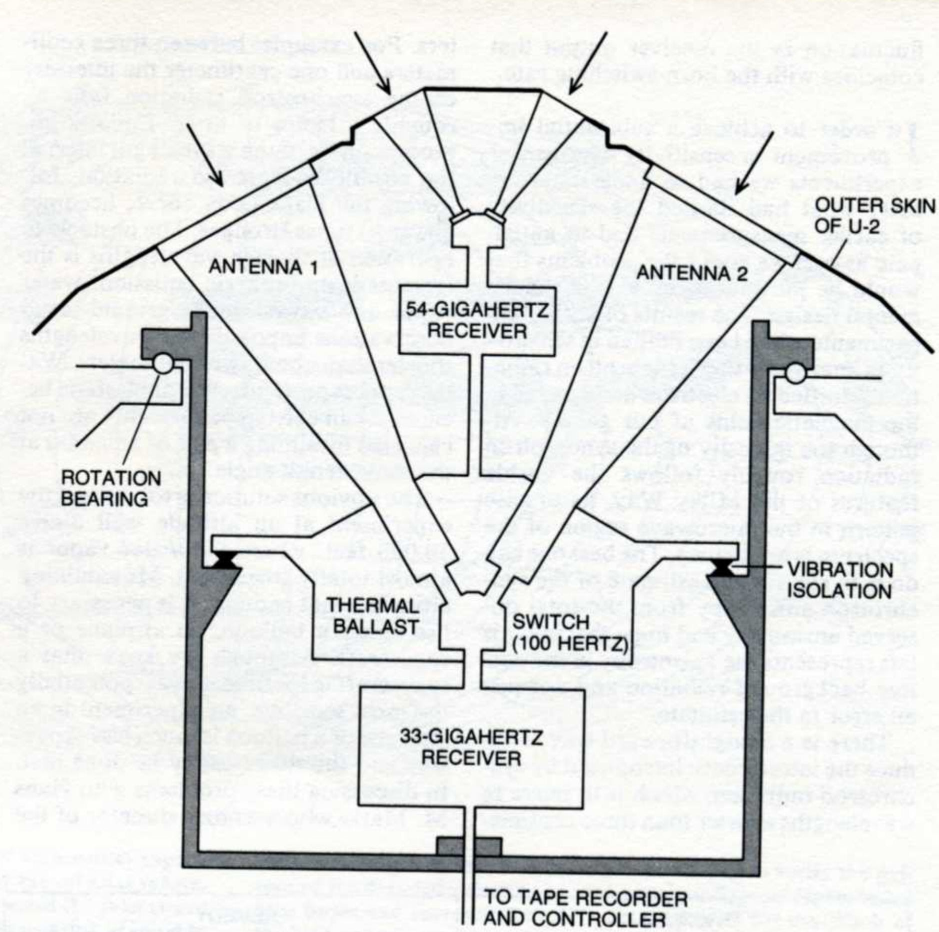
whole were rotating. If analysis of the background radiation were to reveal the universe to be spinning, Mach's principle would be disproved.

If gravity waves of very long wavelength were generated during the early moments of the big bang, they too should give rise to a distinctive pattern in the cosmic background radiation. (Since the moment of decoupling for gravity waves is only a fraction of a second after the big bang, their direct detection would provide an even earlier glimpse into the history of the universe than the one provided by the cosmic background radiation.) One might also discover anisotropies revealing that the universe has not expanded uniformly in strict accordance with Hubble's law. Such phenomena would tend to form different patterns in the sky, making it possible to distinguish them from one another. Perhaps the most distinctive pattern to look for, however, is the anisotropy caused by the motion of the solar system with respect to the shell of plasma that emitted the radiation.

There can be only one inertial frame in any region of space where the background radiation is completely isotropic. In any other frame an observer's motion will reveal itself as a variation in the temperature of the radiation proportional to the velocity of the observer and to the cosine of the angle between his direction of motion and the direction of observation. P. J. E. Peebles, one of the physicists in Dicke's group who correctly identified the origin of the radiation, coined the term "the new aether drift" to describe the expected motion. Although it is not motion with respect to some frame of reference fixed in space, it is motion with respect to the most natural frame of reference in cosmology: the expanding coordinate system in which the galaxies are nearly at rest.

It was the realization that it might be possible to detect the new aether drift that inspired my colleagues and me to design an experiment that would improve significantly on previous measurements. We expected to discover that the motion of the earth was primarily due to the motion of the solar system around the center of our galaxy at about 300 kilometers per second, modified by a small factor to allow for the motion of the galaxy toward the Andromeda galaxy. (The relative motion of our galaxy and the Andromeda galaxy had been measured earlier by the Doppler shift of spectral emission lines as being 80 kilometers per second.) Only a small part of the expected aether drift would be due to the earth's motion around the sun at 30 kilometers per second.

Why were we excited about measuring such a well-known quantity? Our main interest was in the other possible effects: the spin of the universe, early



INSTRUMENT FOR MEASURING ANISOTROPY of the cosmic background radiation built by the author and his colleagues is shown schematically in cross section. The two large horn antennas are designed to collect cosmic background radiation in a narrow cone at a frequency of 33 gigahertz. The two smaller horns and their associated receiver monitor the emissions from atmospheric oxygen at 54 gigahertz. The apparatus is designed to measure not the absolute temperature of the cosmic background radiation but rather the difference in the temperature of the signals collected by the two large horns when they are switched alternately into a common receiver 100 times a second. To compensate for possible asymmetries in design and construction the apparatus is rotated 180 degrees every 64 seconds during collection of data.

signs of the formation of clusters of galaxies, gravity waves and an anisotropic Hubble expansion. In beginning a difficult experiment, however, it is reassuring to know that one will come out with a nonzero value of some kind. Although the other phenomena are interesting, and even a null result on them would be significant, it is frustrating to make precise measurements of zero.

When we began the experiment, the cosmic background radiation was known to be isotropic to a few millidegrees, or to better than one part in 500, owing largely to the careful measurements of Wilkinson and Robert B. Partridge of Princeton and Edward K. Conklin of Stanford University. Another Princeton experimenter, Paul Henry, had detected a small departure from isotropy, but his data did not fit a simple curve and the direction of maximum temperature was not accurately determined.

For our measurements we planned to use an instrument of the same general design as the one used in the preceding studies: a Dicke radiometer. With this device one measures not the absolute temperature of the cosmic radiation but differences in temperature between one direction in the sky and another. Although one might try to measure such differences by comparing the outputs from two receivers pointed in different directions, thermal noise in the two receivers and uncontrollable variations in their gain ("flicker noise") would swamp the minute differences expected. In the Dicke design the problem is avoided by switching the same receiver back and forth between two horn-shaped antennas pointed in different directions. If the experiment is carried out at the earth's surface, one tries to cancel the intense microwave emission from the oxygen in the atmosphere by pointing the two horns at the same zenith angle so that both "see" the same amount of oxygen.

To nullify small differences in the collecting power and emission of the two horns, or a possible asymmetry in the microwave switch connecting the horns to the receiver, the entire apparatus is rotated, interchanging the positions of the horns once a minute. With these precautions any asymmetry in the background radiation should show up as a fluctuation in the receiver output that coincides with the horn-switching rate.

In order to achieve a substantial improvement in sensitivity over earlier experiments we had to understand exactly what had limited the sensitivity of earlier measurements and to anticipate as best we could the problems that would be introduced by a new experimental design. The results of earlier experimenters had been limited in sensitivity primarily by the "synchrotron radiation" emitted by electrons accelerated in the magnetic fields of our galaxy. Although the intensity of the synchrotron radiation roughly follows the visible features of the Milky Way, its precise pattern in the microwave region of the spectrum is not known. The best one can do is to subtract an estimate of the synchrotron anisotropy from the total observed anisotropy and hope that what is left represents the anisotropy in the cosmic background radiation and not just an error in the estimate.

There is a straightforward way to reduce the interference introduced by synchrotron radiation, which is to move to wavelengths shorter than three centimeters. For example, between three centimeters and one centimeter the intensity of the synchrotron radiation falls by roughly a factor of three. Equally important, in the same wavelength interval the cosmic background radiation, following the black-body curve, becomes about 10 times stronger. The obstacle to operation at shorter wavelengths is the increased atmospheric emission: water vapor and oxygen make ground-based observations impossible at wavelengths shorter than about two centimeters. Water vapor is particularly troublesome because it can exist in patches that are not canceled by aiming a pair of antennas at the same zenith angle.

The obvious solution is to conduct the experiment at an altitude well above 50,000 feet, where the water vapor is almost totally frozen out. Mountaintop altitude is not enough. It is necessary to use either a balloon, an airplane or a spacecraft. Although we knew that a spacecraft experiment was potentially the most sensitive, an experiment in an airplane or a balloon is much less expensive and should certainly be done first. In discussing these problems with Hans M. Mark, who was then director of the Ames Research Center of the National Aeronautics and Space Administration, and Luis W. Alvarez of the Lawrence Berkeley Laboratory, we decided that the U-2 aircraft being operated by NASA for the study of earth resources would be an ideal platform for our experiment. At about the same time (mid-1973) Corey and Wilkinson at Princeton elected to use the gondola of a balloon as a platform for their anisotropy measurements. I shall not describe their experiment but instead concentrate on the problems that had to be solved for our U-2 undertaking.

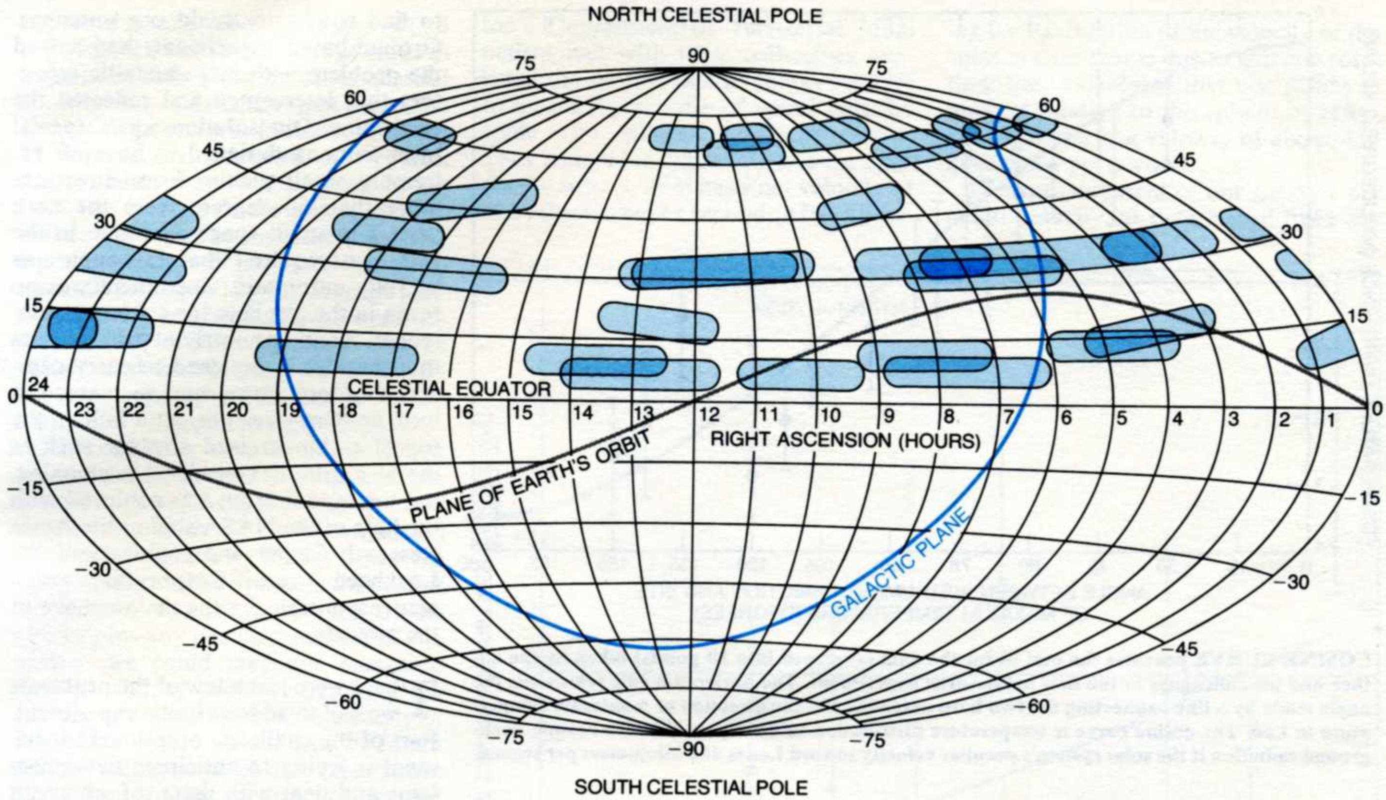
For an airborne experiment the time available is sharply limited, which meant that our receiver had to be as sensitive as possible. (In an experiment that can be conducted from the ground data can be averaged over many observations and provide sensitive results even without a low-noise receiver.) Unfortunately microwave receivers become progressively less sensitive at wavelengths below three centimeters. The constraints presented by receiver technology, the need to avoid troublesome interference from synchrotron emission at wavelengths much longer than 1.5 centimeters and strong atmospheric emission lines at wavelengths of several millimeters led us finally to choose a wavelength of .9 centimeter (a frequency of 33 gigahertz, or 33 billion cycles per second) as being optimum for the experiment. At that wavelength we thought our apparatus would be sensitive enough to detect an anisotropy of less than a thousandth of a degree, which would be more than adequate to determine the velocity at which the solar system is being swept around the galactic disk.

A major problem in an airborne experiment is the instability of the platform, which makes it difficult to ensure that both antenna horns are pointing at the same zenith angle and hence seeing the same volume of oxygen. We solved the problem by monitoring the zenith angle with a second radiometer tuned to a wavelength of .55 centimeter (a frequency of 54 gigahertz), a wavelength particularly sensitive to emission from atmospheric oxygen. With this arrangement we would be able to detect any asymmetry of the oxygen signal, whether it was due to a tilted airplane or to a tilted atmosphere. Since the earth is not a sphere but a quasi ellipsoid, the atmosphere is indeed often tilted with respect to the ground; the atmosphere is also tilted by weather fronts. If the tilt were large, the pilot would be asked to bank the plane in compensation. (The maneuver turned out not to be necessary.)

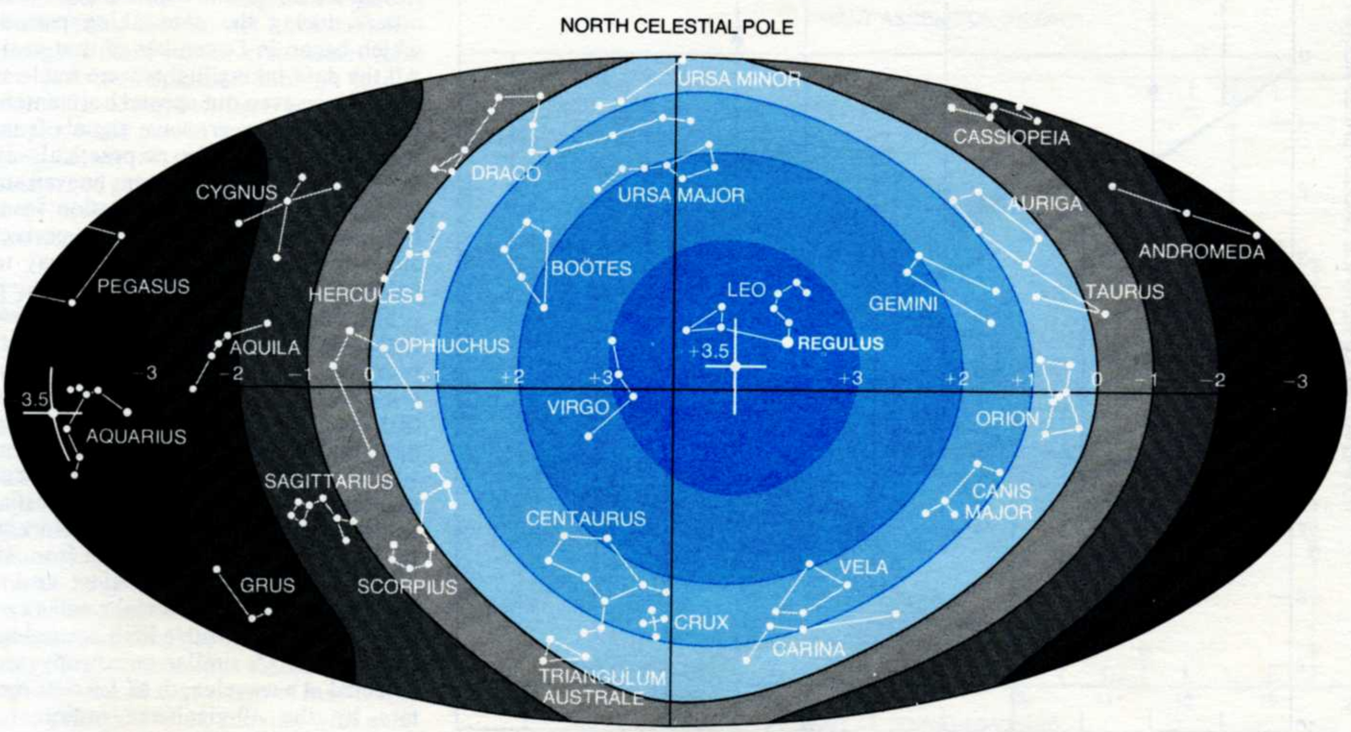
The size of our apparatus was severely limited by the space available within the rear hatch of the U-2, which made the design of the antennas particularly difficult. Since the earth is an intense emitter of microwave radiation, we had

PROBLEM	REMEDY
Synchrotron emission from galaxy	Make measurements at frequency above 10 gigahertz
Emission from galactic dust	Make measurements below 100 gigahertz
Emission from atmospheric water vapor	Collect data at altitude above 15 kilometers (with U-2)
Emission from atmospheric oxygen	Use twin horn antennas at high altitude and monitor oxygen emission at 54 gigahertz
Emission from sun	Fly at night
Emission from earth	Use dual-mode corrugated horns with narrow field of view
Emission from horn antennas	Symmetrize emission by careful temperature control
Thermal noise in receiver	Integrate signal for 20 minutes
Receiver flicker noise (= 1/frequency)	Switch between two horn antennas 100 times per second
Asymmetry of airplane	Reverse flight path every 20 minutes
Asymmetry in experimental apparatus	Rotate equipment itself every 64 seconds
Bias from earth's magnetic field	Carefully shield microwave switches
Radio emission from U-2	Place metallic shields around sensitive parts and minimize communications to U-2
Geometric distortion of atmosphere due to nonsphericity of earth	Determine "zenith" from oxygen signal rather than from earth's horizon or flight instruments

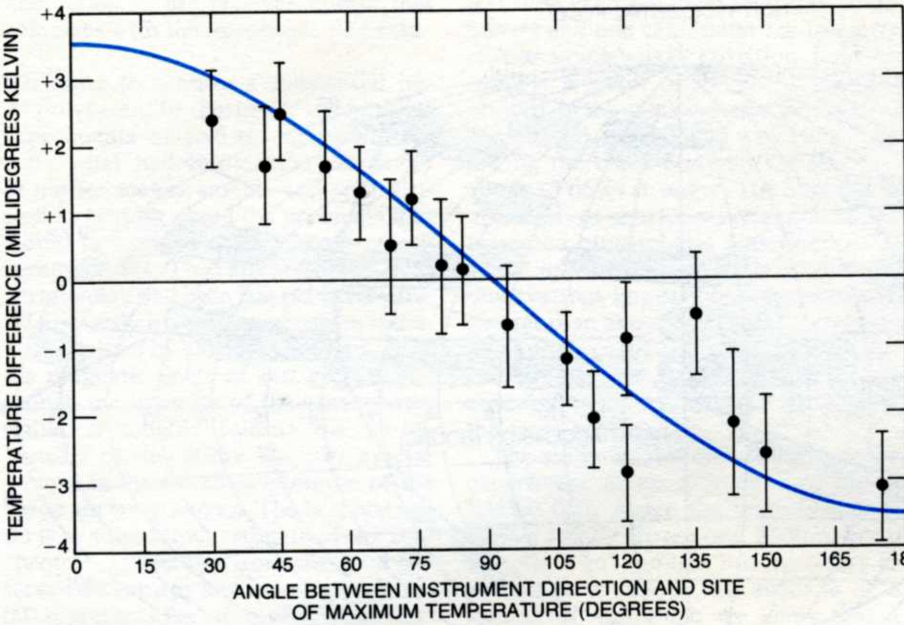
PRINCIPAL PROBLEMS associated with measuring the anisotropy of the background radiation are listed with the remedies adopted by the investigators. They and their associates spent three years planning the experiment and building the equipment before the first test flight.



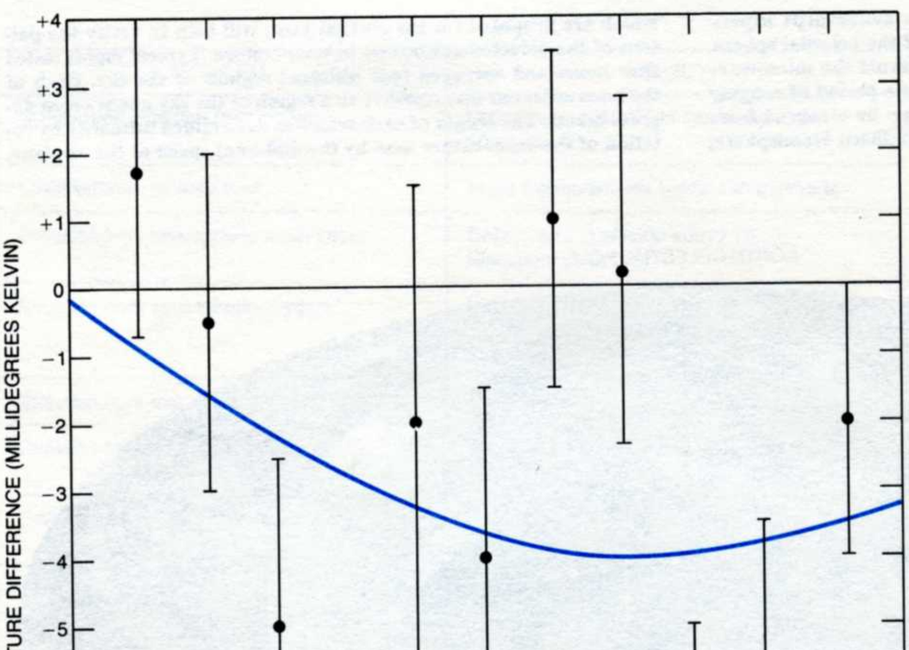
REGIONS OF SKY SURVEYED by the new aether-drift experiment are plotted on an equal-area projection of the celestial sphere. All the flights were made at night (in order to avoid the microwave emission from the sun) and were spread out over a period of roughly a year (in order to scan as much of the sky as can be observed from a base in northern California). Flights in the Southern Hemisphere, which are proposed for the current year, will help to verify the pattern of the detected anisotropy in temperature. Typical flights lasted four hours and surveyed four different regions of the sky. Each of the horn antennas was sensitive to a region of the sky about seven degrees across. The length of each scan was determined primarily by rotation of the earth rather than by the 400-knot speed of the airplane.



ANISOTROPY OF THE BACKGROUND RADIATION, as deduced from the U-2 survey, is plotted on the celestial sphere in contours of one millidegree K. The "hottest" spot, indicating the direction of the earth's maximum relative motion toward the background radiation, lies in the constellation Leo at right ascension 11 hours (±.5 hour) and latitude six degrees (±10 degrees). The "coldest" spot, the direction in which the radiation is most "reddened" by the earth's relative motion away from the incoming photons, lies 180 degrees away in Aquarius. If the temperature difference between hottest and coldest points is plotted against distance, the result is a cosine curve.



COSINE CURVE provides the best fit for the data (averaged into 18 points) taken by the author and his colleagues in the new aether-drift experiment. The horizontal axis represents the angle made by a line connecting the two horn antennas and the direction of maximum temperature in Leo. The cosine curve is temperature distribution to be expected in the cosmic background radiation if the solar system's peculiar velocity toward Leo is 400 kilometers per second.



FIRST SIGNIFICANT DEVIATION FROM ISOTROPY in the cosmic background radiation was detected by Paul Henry of Princeton University with an instrument that was carried aloft by a balloon. The anisotropy in the radiation shows up in the preponderance of data points lying below the zero line. The scatter in the points, however, made it impossible to establish distribution of anisotropy or to determine precisely direction of maximum temperature.

to find a way to shield our antennas. Ground-based experiments had solved the problem with large metallic reflectors that intercepted and reflected the earthshine. Our solution was a special horn antenna designed to have an extremely small pickup from directions more than 60 degrees from the horn axis. The small space available in the U-2 also required that the apparatus be fully automatic, since there was no room in the airplane for a scientist passenger. Another nontrivial problem was that the U-2 is designed to carry cameras that look down, and we wanted to look up. One does not cut a hole in the top of a skin-stressed airplane such as the U-2 without considerable planning, but the modification was achieved with the help of the NASA staff at the Ames Research Center and engineers of the Lockheed Aircraft Corporation, which was responsible for the maintenance of the aircraft.

These were just a few of the problems we had to address in the experiment. Part of the challenge of a novel experiment is trying to anticipate new problems and deal with them. Much credit belongs to my collaborators Smoot and Gorenstein, who had the chief responsibility for transforming a theoretical plan into a successful experiment.

After three years of planning, construction and testing we mounted the apparatus in the U-2 in July, 1976. We made various modifications after a series of test flights and continued to make others during the data-taking period, which began in December of that year. All the data-taking flights were made at night, since even our special horn antennas picked up microwave signals from the sun. There was also no practical way to shield our apparatus from uneven solar heating. Microwave emission from the moon, when it was at the correct angle for it, provided a handy way to calibrate the receiver gain in flight.

The data collected from the first few flights revealed an unmistakable departure from isotropy in the cosmic background radiation. To get a clear picture of the anisotropy, however, we had to have flights spread out over a full year so that the antennas could scan as large a fraction as possible of the celestial sphere visible from northern California. By the end of last year the data from 10 flights plotted into the distinct cosine curve one would expect if the solar system were moving with a high cosmological velocity. A similar anisotropy was detected at a wavelength of 1.6 centimeters by the 19-gigahertz radiometer flown in the gondola of a balloon by Corey and Wilkinson. In both the Berkeley and the Princeton experiments the magnitude of the anisotropy was consistent with that first reported by Henry.

Our data indicate that the temperature of the cosmic background radiation reaches a maximum of .0035 degree (3.5 millidegrees) above the average value in a direction defined, in the usual celestial coordinates, as 11 hours right ascension and six degrees north latitude, or about 15 degrees east-southeast of Regulus, the brightest star in the constellation Leo. The velocity of the solar system in that direction can be computed by dividing the maximum temperature difference, .0035 degree, by the average temperature of the cosmic background radiation, 2.7 degrees (the best current value), and multiplying the result by the velocity of light. The answer is a velocity of 390 kilometers per second.

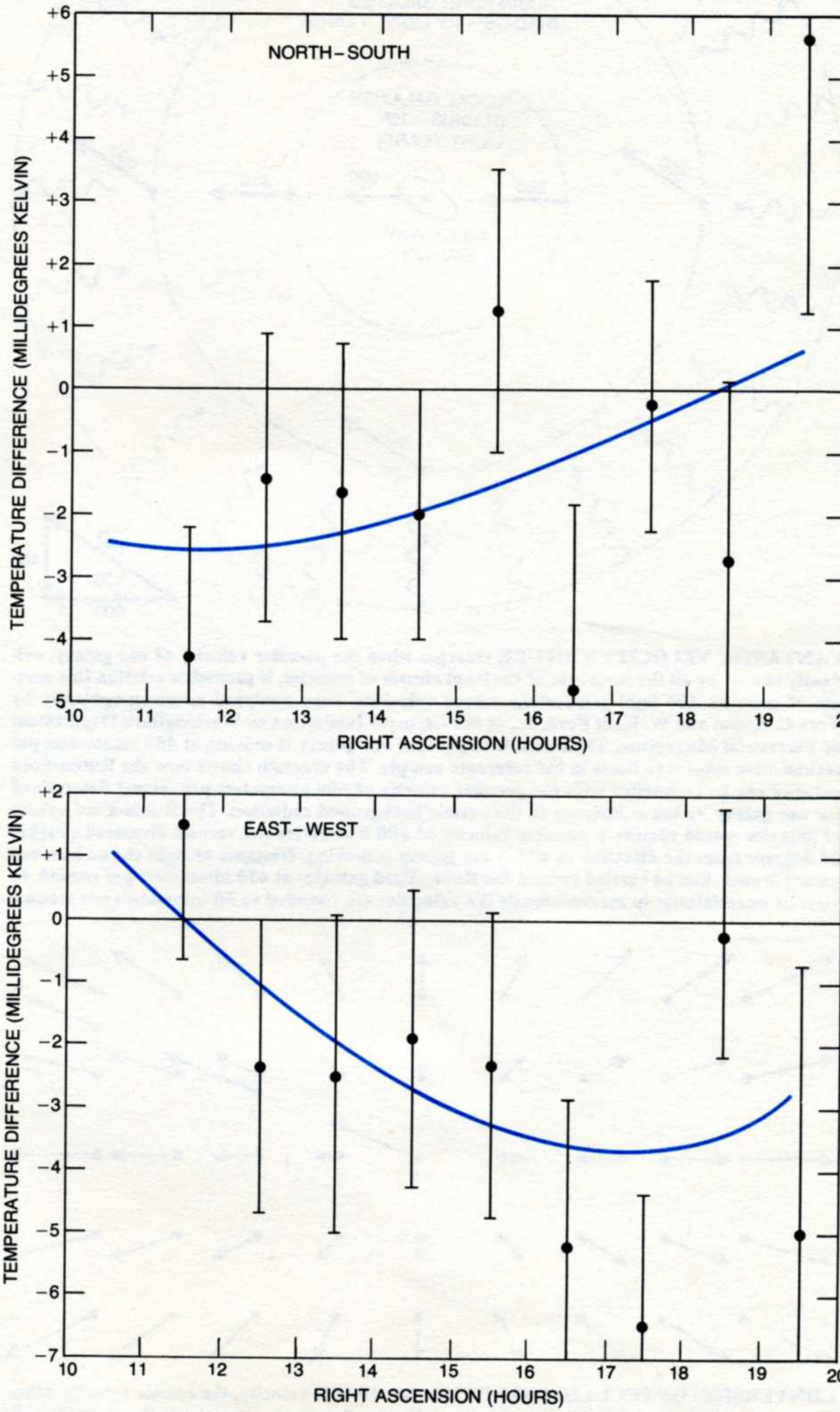
Although this velocity is not much greater than that of 300 kilometers per second expected from the solar system's motion around the center of the galaxy, it is in a different direction. Since the velocity of the solar system is the sum of the velocity due to the rotation of the galaxy plus any peculiar velocity of the galaxy, we could take our measured number and by properly handling the vectors calculate the peculiar velocity of the galaxy. When we did this, we found that the galaxy must be moving at about 600 kilometers per second with respect to the cosmic background radiation.

Except for the cosine variation in temperature the background radiation was found to be isotropic to better than one part in 3,000, placing strict limits on several of the phenomena I have mentioned. If the universe is rotating, its rate of rotation must be less than 10^{-9} second of arc per century. If large-scale gravity waves exist, they do not have sufficient energy to close the universe or to reverse the Hubble expansion into an implosion. The expansion itself must be isotropic to one part in 3,000. There is also no evidence of the early formation of clusters of galaxies, indicating that very-large-scale clustering did not exist at the moment of decoupling.

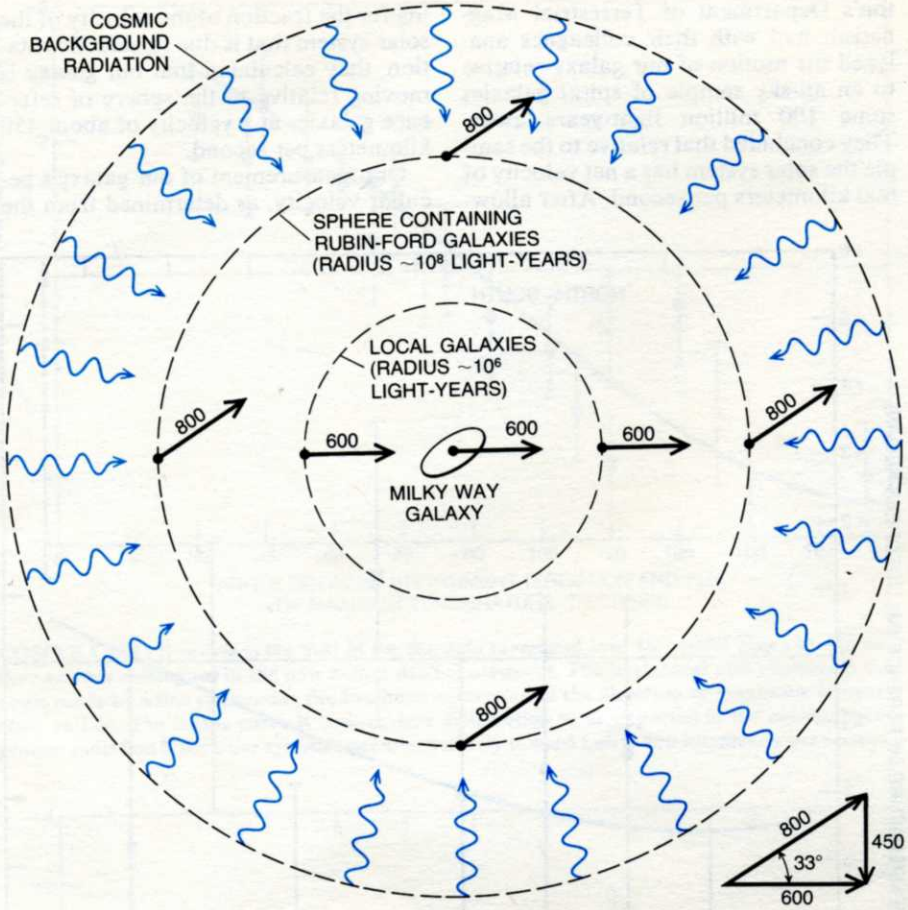
Perhaps the most fascinating and unexpected result of the experiment is the size of the implied cosmological velocity of the galaxy. Since the motion of our galaxy relative to the Andromeda galaxy is small (80 kilometers per second), the Andromeda galaxy must share this high velocity through space. Moreover, it is known that the peculiar (non-Hubble) motion of our local group of galaxies relative to the nearest large cluster of galaxies, the Virgo cluster, is small; thus the entire Virgo cluster must have a cosmological velocity similar to ours. The picture that emerges is of a vast volume of space, tens of millions of light-years in radius, moving with a velocity of roughly 600 kilometers per second with respect to the distant universe.

The picture becomes more complicated when we look farther out into the local regions of space. Prior to our work Vera C. Rubin and W. Kent Ford, Jr., of the Carnegie Institution of Washington's Department of Terrestrial Magnetism had with their colleagues analyzed the motion of our galaxy relative to an all-sky sample of spiral galaxies some 100 million light-years away. They concluded that relative to the sample the solar system has a net velocity of 600 kilometers per second. After allowing for the fraction of the velocity of the solar system that is due to galactic rotation, they calculated that our galaxy is moving relative to the sphere of reference galaxies at a velocity of about 450 kilometers per second.

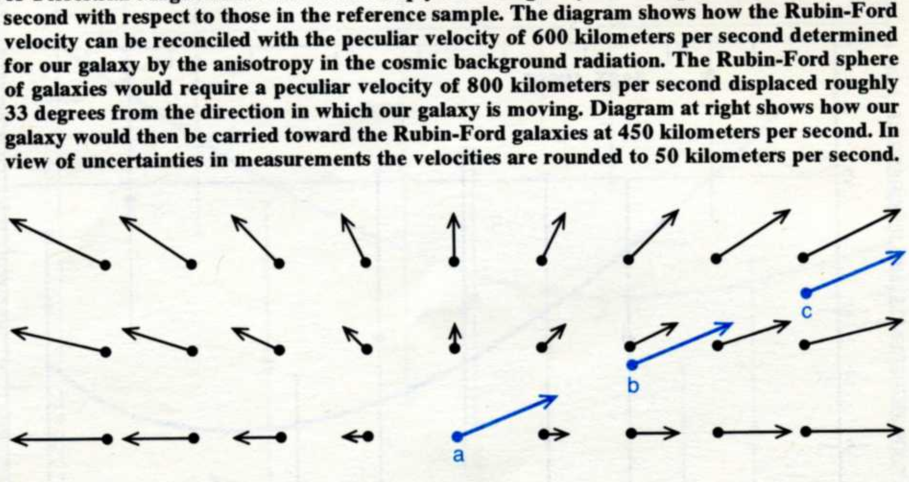
Our measurement of our galaxy's peculiar velocity, as determined from the



SECOND PRINCETON EXPERIMENT, conducted by David T. Wilkinson and Brian E. Corey with a balloon-borne instrument operating at a frequency of 19 gigahertz, supports the Berkeley U-2 measurements. Because the Princeton workers plot their data differently (with a north-south projection and an east-west projection) the similarity between their results and the Berkeley ones is not readily apparent. It is clear, however, that the Princeton data define cosine curves. Princeton group concluded that the earth is moving at 300 (±70) kilometers per second toward right ascension 12 (±2) hours and latitude −10 (±20) degrees in the celestial sphere.



FANTASTIC VELOCITY PICTURE emerges when the peculiar velocity of our galaxy, evidently shared by all the members of the local cluster of galaxies, is plotted in relation to a sample of galaxies 10^8 light-years away whose velocities were analyzed spectrographically by Vera C. Rubin and W. Kent Ford, Jr., of the Carnegie Institution of Washington's Department of Terrestrial Magnetism. Their results imply that our galaxy is moving at 450 kilometers per second with respect to those in the reference sample. The diagram shows how the Rubin-Ford velocity can be reconciled with the peculiar velocity of 600 kilometers per second determined for our galaxy by the anisotropy in the cosmic background radiation. The Rubin-Ford sphere of galaxies would require a peculiar velocity of 800 kilometers per second displaced roughly 33 degrees from the direction in which our galaxy is moving. Diagram at right shows how our galaxy would then be carried toward the Rubin-Ford galaxies at 450 kilometers per second. In view of uncertainties in measurements the velocities are rounded to 50 kilometers per second.



CONVERSION OF PECULIAR VELOCITY into Hubble velocity, the cosmic velocity of expansion, can be expected to take place in time. The vector arrow *a* represents the current peculiar velocity of our galaxy, shown embedded in a space that is expanding uniformly. As our galaxy moves outward it will overtake other galaxies (*b*) until it reaches a region (*c*) where its velocity matches that of neighboring objects. Our galaxy will then no longer exhibit a peculiar velocity; its motion with respect to nearby matter will tend toward zero. A similar argument shows that in the past our galaxy's peculiar velocity must have been greater than it is today. This line of reasoning is invalidated, of course, if the peculiar velocity arises from a local effect, such as the rotation of a cluster of galaxies, in which case the peculiar velocity would oscillate.

cosmic background radiation, not only is a third greater than the Rubin-Ford velocity but also differs in direction from theirs by more than 100 degrees. The two sets of velocity measurements can be reconciled by assuming that the Rubin-Ford sphere of galaxies is moving with a cosmological velocity of about 800 kilometers per second in a direction offset by approximately 33 degrees from the direction in which we are drifting at 600 kilometers per second through the radiation "aether" left by the big bang.

This remarkable picture is even more surprising when one realizes that a high peculiar velocity today may imply a still higher one in the past. As a galaxy moves through space with a high peculiar velocity it eventually catches up with other galaxies whose recessional velocity corresponds to the average Hubble expansion. Hence a high peculiar velocity is gradually transformed into a typical Hubble velocity, with the net result that peculiar velocities must decrease with time. Extrapolating backward, one finds that at the moment of decoupling the peculiar velocity of the stuff of which our galaxy was made must have been close to the speed of light. On the other hand, if the peculiar velocity were due to local turbulence or to orbital motion around a distant point, such an extrapolation might not be correct. The velocity of our local group of galaxies with respect to the nearby (on a cosmic scale) Rubin-Ford galaxies does in fact suggest there is considerable turbulence in the universe.

Before one accepts this turbulent picture of the large-scale structure of the universe, one should recall that our observation of the cosmic background radiation shows that except for the cosine component the radiation is uniform to at least one part in 3,000. It is not obvious how to reconcile the featureless nature of the background radiation with a high degree of local turbulence. To be sure, the local peculiar velocities are characteristics of the present universe, whereas the background radiation is a snapshot of the universe taken 15 billion years ago. Conceivably the universe possesses some large-scale structure, such as the rotation of a supercluster of galaxies, that will reconcile the apparently contradictory results.

Perhaps the most perceptive criticism of the homogeneous isotropic big-bang model is that it is far too simple to represent reality. One is easily tempted to assume that the unknown is simple. It is possible, indeed likely, that there are large-scale structures that play an essential role in determining the nature of the universe. With recent measurements of the large-scale clustering of galaxies and the anisotropy of the cosmic background radiation we may be just beginning to detect that structure.