

Cosmic sound waves rule

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In the microwave background and the distribution of galaxies, relic imprints of primordial sound waves have contributed to an extraordinarily detailed history of the cosmos. And they provide yardsticks for resolving a great mystery.

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Relativistic sound waves raced through the hot plasma that filled the universe for its first 380 000 years. That sound left an imprint that is still discernible in the cosmic microwave background and also in the large-scale distribution of galaxies. Measurements of the sound waves manifested in the CMB, coupled with a detailed understanding of the physics of sound waves in the plasma epoch, provide the foundation of our standard model of cosmology (see *PHYSICS TODAY*, April 2003, page 21). A new opportunity to track their imprint in the spatial distribution of galaxies as far back as we can see them opens a path to elucidating the mystery of dark energy and its role in the history of the cosmos.¹

Sound waves are oscillations of over- and underpressure that propagate longitudinally through a medium. For example, a loudspeaker creates a local overpressure in air; the overpressure then causes the compressed air to expand. That, in turn, compresses the neighboring air, so that the sound wave propagates. The primordial cosmos was peppered with slightly overdense, overpressured regions that initiated the propagation of sound waves of all wavelengths. Much as the resonant sounds of a drum inform us about its shape and size, so can the details of cosmic density fluctuations tell us about the evolution of the universe.

Gravity and sound

Our Big Bang cosmos began hot, dense, and smooth, with matter on expanding trajectories. Here “smooth” means that density variations and deviations of the velocity field from the overall expansion were small. The hot young universe was filled with energetic particles. What’s left today is a much colder ensemble of nuclei, electrons, photons, neutrinos, and some sort of dark matter that outweighs all the baryonic matter in the cosmos by a factor of about six.

By “baryonic matter” cosmologists mean the ordinary matter made of baryons (protons and neutrons) and electrons. The name slights electrons, which are leptons, but they contribute less than 0.1% to the mass of baryonic matter. By “dark matter,” one means nonbaryonic matter with negligible thermal velocity. Therefore it’s often called cold dark matter, with light neutrinos not included. Even though the constituent particles of the dark matter have not yet been identified, its cosmological role is largely specified by the re-

quirements that it be cold, stable, and immune to electromagnetism and the strong nuclear force.

The primordial cosmos was hot enough that the baryonic matter was ionized. It was dense enough that the mean interval between consecutive scatterings of a typical photon off free electrons was much shorter than the age of the cosmos at that time. As the cosmos expanded, the baryonic matter grew cooler and less dense, but more lumpy. After 380 000 years, its temperature fell below 3000 K, allowing the nuclei and electrons to bind into stable, neutral atoms. The number of free electrons suddenly fell by a factor of 10^4 and the mean interval between photon-electron collisions became longer than the age of the cosmos. That essentially decoupled the cosmic radiation field from matter. The transition took only about 50 000 years.

Decoupling was like the lifting of a universal fog. Photons could henceforth travel almost unimpeded. The photons liberated at decoupling are what we now see as the CMB. We are looking back 13.7 billion years to view light that was last scattered when the cosmos was only 380 000 years old, a thousand times smaller (in linear dimension), and a billion times denser, on average, than it is today.

Deviations from a perfectly homogeneous cosmos were produced at the earliest times, perhaps by quantum fluctuations during the inflation that is presumed to have exponentially expanded the cosmos in its first fraction of a second (see the articles in *PHYSICS TODAY* by Andrei Linde, September 1987, page 61, and by Robert Brandenberger, March 2008, page 44). The deviations from homogeneity then grew ever more pronounced throughout the rest of cosmic history, as a result of the gravitational force imbalances they themselves produced.

The decoupling transition from ionized to neutral gas had a profound impact on the evolution of the fluctuations. In the neutral cosmos with negligible radiation pressure, fluctuations are unstable primarily due to gravity. As shown in figure 1, overdense regions attracted matter more rapidly than the universal Hubble expansion could carry it away. Those regions became more overdense with time. Likewise, matter drained away from underdense regions, so they became more underdense. The contrast between over- and underdense regions became ever greater, ultimately giving

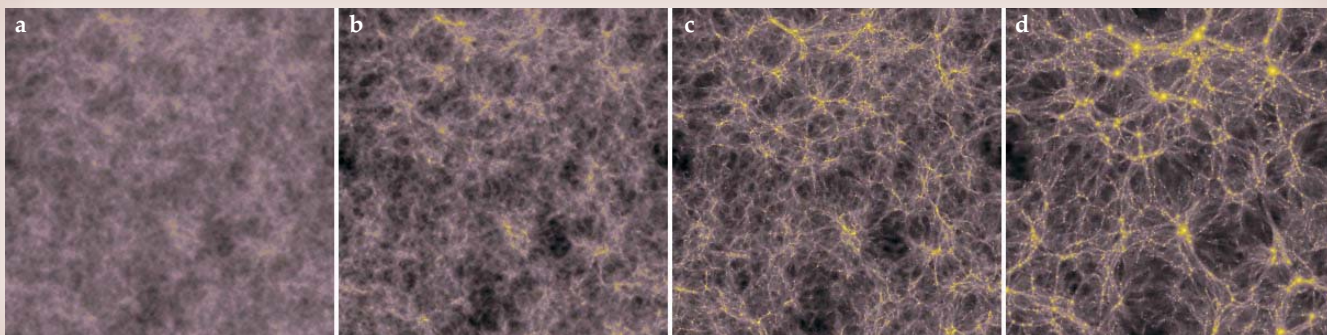


Figure 1. Computer simulation of the ever-increasing clustering of matter (dark plus baryonic) due to gravity in the post-plasma universe. Despite the overall Hubble expansion, initial low-contrast density perturbations (a) become more pronounced as overdense regions attract matter away from underdense regions. The result in recent times (d) is structures such as superclusters of galaxies and voids that extend over hundreds of millions of light-years. Yellow indicates regions of highest density. (Adapted from M. White et al., *Astrophys. J.* **579**, 16 (2002).

rise to the great galactic superclusters and voids of the present universe.

But in the ionized universe before decoupling, the radiation pressure imposed another key force on the baryons. For density perturbations spatially larger than a mean free path, the photons and plasma were coupled together to produce an effective baryon-photon fluid. Compression in the fluid was accompanied by an increase in the density, temperature, and hence pressure of the photons. The compressing plasma upscattered photons to higher energies. The increased radiation pressure opposed the compression. In fact it drove a consequent expansion that overshot the mean, producing an underdense, low-pressure region that, in turn, was compressed by the surrounding fluid.

The result was a sound wave similar in all respects to a sound wave in an ordinary fluid, except that the restoring force was the radiation pressure of the trapped photons. The radiation pressure overwhelmed gravity, forestalling the runaway gravitational instability of the post-plasma universe.

A remarkable property of the plasma sound waves in the epoch before decoupling is that their propagation speed was very high—nearly $1/\sqrt{3}$ of the speed of light. That's because the radiation pressure and energy density of the photon field were enormous compared to those of the baryons. The photon density just prior to decoupling was that of a 3000-K furnace. That's about 10^{12} blackbody photons per cubic centimeter. But the baryon density of the plasma was tiny—only about a thousand nucleons per cubic centimeter. Sound speed scales as the square root of a restoring force per unit of inertia, and the radiation pressure of an electromagnetic field is precisely $1/3$ of its energy density.

The cosmic microwave background

The most striking relics of the plasma epoch's sound waves are the so-called acoustic peaks in the power spectrum of the CMB's temperature anisotropy.² The temperature of the CMB is very nearly the same 2.725 K everywhere on the sky—after anisotropies due to the Milky Way foreground and our own motion through the galaxy have been subtracted off. But there remain spatial variations at the level of $30 \mu\text{K}$, which is only a part in 10^5 . Those variations result largely from variations in the density of the universe at the locations where the photons last scattered before arriving at our astronomical

instruments 13.7 billion years later.

Figure 2a shows the full-sky map of the CMB's temperature fluctuations recorded by the *Wilkinson Microwave Anisotropy Probe* (WMAP). It is essentially a freeze-frame image of the sound-wave pattern at the decoupling transition.³ The pattern of hot and cold spots in the map reveals an enhancement of structure on the angular scale of 0.6° . For quantitative analysis of the patterns, one constructs the power spectrum of the temperature fluctuations by decomposing the map into spherical harmonics (the spherical equivalent of a Fourier transform) and computing the fluctuation power as a function of angular scale on the sky. The result, shown in figure 2b, exhibits the series of acoustic peaks first anticipated by Andrei Sakharov in 1965.⁴ This harmonic sequence of peaks is the signature of the preferred 0.6° angular scale, just as a harmonic sequence of overtones is the signature of the fixed length of a violin string.

How did the sound waves select a preferred angular scale? The temperature anisotropy of the CMB is the result of a pattern of density fluctuations on a spherical surface—more accurately a thin spherical shell of the universe—centered on us. We are viewing that shell from a large distance. The preferred angular scale is the result of a preferred length scale on that “surface of last scattering.”

That characteristic length, often simply called the acoustic scale, is the distance that a sound wave propagating from a point source at the end of inflation would have traveled before the decoupling transition that ended the plasma epoch. Since then, the Hubble expansion has stretched the cosmos about a thousandfold, so that now the radius of a spherical sound wave that had been propagating from the start of the plasma epoch to its end is 480 million light-years. Cosmologists prefer to use a “comoving” coordinate system that dilates with the Hubble expansion. Two points otherwise at rest have a constant comoving separation, with the value given by convention as their true separation today. After decoupling, the acoustic scale is a constant comoving separation of 480 Mly.

The acoustic peaks of the CMB's temperature fluctuation provide some of our strongest cosmological information (see the article by Charles Bennett, Michael Turner, and Martin White in *PHYSICS TODAY*, November 1997, page 32):

► The harmonic spacing of the peaks argues strongly that

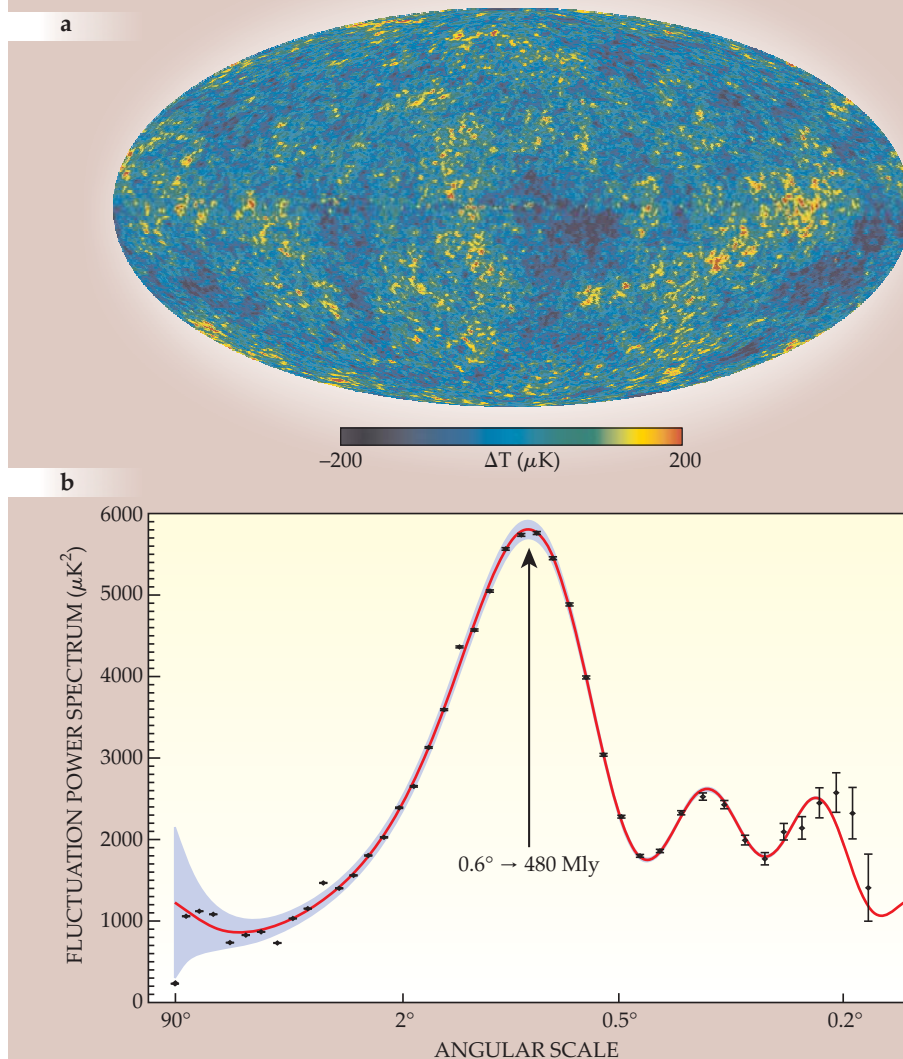


Figure 2. (a) Small spatial fluctuations ΔT in the almost perfectly isotropic 2.725 K temperature of the cosmic microwave background, as recorded by the *Wilkinson Microwave Anisotropy Probe*.¹² **(b)** The power spectrum of the temperature fluctuations, plotted as a function of their angular size on the sky, comes from a spherical-harmonic analysis of the WMAP data.¹² It reveals a harmonic sequence of acoustic peaks attributed to sound waves propagating in the hot primordial plasma that filled the cosmos for its first 380 000 years. The first acoustic peak, at 0.6° , manifests the distance a primordial sound wave could propagate before the abrupt end of the plasma epoch. In the subsequent thousandfold Hubble expansion of the cosmos, that characteristic distance has been stretched to 480 million light-years. The curve is the best cosmological-model fit to the data points, and the gray swath indicates the irreducible random variance for different cosmic variance points.

the initial fluctuations in the early universe were adiabatic. That is, all particle species varied together in density. Such joint fluctuations confirm a key prediction from inflation theory, which attributes them to primordial wrinkles in space-time at the beginning of inflation.

► The relative heights of the acoustic peaks in figure 2b yield precision measurements of the baryon density and the density of the cold dark matter. Higher baryon density enhances the odd-numbered acoustic peaks relative to the even-numbered ones, while lower dark-matter density enhances all of the peaks. The CMB data from WMAP and from microwave telescopes on the ground have by now determined the baryon density to within 3% and the total density of baryonic plus dark matter to within 5%. Those uncertainties shrink even further when one adds astrophysical observations of the more recent universe. Upcoming data from the WMAP and *Planck* satellites and from ground-based measurements of higher CMB harmonics are expected to improve the density determinations to about 1% accuracy.

► Finally, the positions of the peaks in the angular power spectrum are a manifestation of the preferred acoustic length scale. If one knows that length, one can infer our distance from the surface of last scattering. That distance depends sensitively on the spatial curvature of the intervening universe,

and on the history of dark energy in the past 10 billion years. The CMB data have already determined that the cosmic radius of curvature, if not infinite, is certainly larger than the radius of the currently visible universe.

Dark energy and the distance scale

The present-day acceleration of the Hubble expansion is one of the most important topics in modern cosmology. A decade ago, studies of distant supernovae revealed this cosmic acceleration by observing that supernovae of a given redshift appeared fainter than expected.⁵ In the expanding universe, the redshift z of a cosmologically distant object tells us that the cosmos has stretched by a factor of $1/(1+z)$ since the observed light began its journey. Thus the relationship of distance to redshift depends on the history of the cosmic expansion (see the article by Saul Perlmutter in *PHYSICS TODAY*, April 2003, page 53).

The unanticipated faintness of the distant supernovae can be explained if the cosmic expansion has been speeding up in recent times. One would have expected that gravity is inexorably slowing the Hubble expansion down. Instead, it looks as if the expansion is being pushed by a long-range repulsive force that has overwhelmed gravity only in the past few billion years. Albert Einstein's cosmological constant is

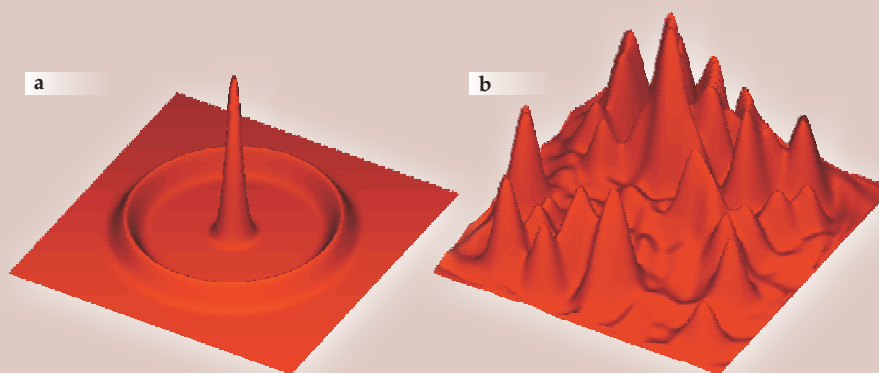


Figure 3. Sound waves propagating in the plasma epoch. **(a)** A spherical sound wave from a small overdense region at the start of the plasma epoch spreads until baryonic matter decouples from radiation 380 000 years later, when the plasma has cooled enough for neutral hydrogen to survive. The radius of the acoustic shell (seen here as a ring) provides cosmologists a characteristic length scale—essentially the sound speed times the duration of the plasma epoch.

(b) The later universe evolved from a hodgepodge superposition of such spherical sound waves, but the characteristic size can still be extracted from statistical correlations in the large-scale distribution of galaxies.

one possible explanation, but cosmologists attribute the phenomenon more generally to “dark energy.” The small, unchanging vacuum energy density implied by Einstein’s cosmological constant is just one of several possibilities.⁶

The claim of an accelerating cosmic expansion and the idea of a mysterious dark energy as its cause are so revolutionary that they demand particularly strong evidence. After all, distant supernovae might look weak simply because early supernovae *were* weak, or because something happens to their light on the way here. But additional evidence from the angular scale of the CMB acoustic peaks has convinced most cosmologists that the expansion really is accelerating. The cause, however, remains unknown.

Is the dark-energy density constant in time, or might it be evolving dynamically? The key to finding out hinges on our ability to measure cosmological distances to high accuracy. Having discovered dark energy as a 10–30% effect in distance, we must now study it at a precision of better than 1%. That is an observational challenge because the measurement of distance is a long-standing problem in cosmology.

The acoustic oscillations from the early universe provide a new opportunity to measure distances at different redshifts. That’s because the effect of the sound waves is not limited to the CMB photons. The sound waves also perturbed the baryons, which couple gravitationally to the dark matter. Thus the length scale that was imprinted by the sound waves persists to the present time in the clustering of matter on large scales.

It’s useful to think about the physics of a single small region just after inflation, more dense in plasma and dark matter than its surroundings. Because the local plasma overdensity corresponds to a region of overpressure, it launches a spherical sound wave that carries the plasma overdensity away from the center. At the decoupling transition, the liberated photons stream away from the baryons. The sound wave stops abruptly, depositing the baryons in a spherical shell whose radius is simply the distance the sound wave has propagated (see figure 3a). Meanwhile, the overdensity in the pressureless dark matter remains at the initial location. The dark matter in the center and the baryons in the spherical shell both seed gravitational instabilities and generate overdensities that grow more pronounced with time, eventually forming galaxies at both the center and the shell.

Of course the real cosmic density field is a superposition

of many such shells (figure 3b), but the spatial correlation of galaxies is still enhanced at a comoving distance corresponding to the size of the shell at decoupling. So galaxies in any redshift era are somewhat more likely to be separated by a comoving distance of 480 Mly than by, say, 400 or 600 Mly. That preferred distance should show up as a peak—the so-called baryon acoustic oscillation peak—in the Fourier power spectrum of a sufficiently high-statistics study of positional correlations among galaxies. The box on page 48 describes the origin of the baryon acoustic peak in more detail.

The radius of the shell in figure 3a is the sound speed integrated over the time interval from inflation to decoupling. The precise calculation of the acoustic scale depends on the baryon density and on the overall density of baryonic plus dark matter. The baryon density affects the plasma’s inertia and hence the sound speed. The total matter density affects the cosmic expansion rate and hence the duration of the plasma epoch. Fortunately, the two densities can be cleanly determined from the CMB power spectrum. With the *WMAP* data, the resulting 480-Mly comoving correlation distance is predicted to 1.3% precision. CMB measurements in the next decade should improve that precision to about 0.2%.

For pedagogic simplicity, we have adopted the language of traveling waves.⁷ But one can equally well think in terms of standing waves, in which the amplitudes of the initial density perturbations evolve over time. Because each Fourier mode of the perturbation evolves separately, the standing-wave representation is more suitable for precision calculation and is more easily connected to the power spectrum of the primordial fluctuations.¹

Because the length scale of the baryon acoustic peak can be calculated from known physics and well-measured quantities, its apparent position in clustering surveys of galaxies at a given redshift provides a cosmic distance scale. The more distant the galaxies are from us, the smaller is the angle subtended by the preferred comoving separation of 480 Mly. By measuring angular correlations within a large enough assemblage of galaxies, one can infer how far away it is.

Distances in cosmology must be measured in two different ways, depending on whether the separation is along the line of sight or in the transverse direction. One can infer radial separations Δr_r along the line of sight by measuring differences in cosmological redshift. One infers separations

Emergence of the baryon acoustic peak

The successive panels in the figure show a calculation of an acoustic wave spreading from a pointlike primordial density perturbation, and its subsequent effect on various forms of matter and radiation. Each panel is labeled by its time since the end of inflation and the corresponding redshift z . Each shows mass profiles of overdensity versus radial distance from the initial perturbation for the various components of the cosmos: nonbaryonic cold dark matter (black), ordinary baryonic matter made up of nuclei and electrons (blue), the cosmic photon field (red), and the neutrino background (green).

All the overdensities begin as tiny perturbations on a nearly homogeneous universe. Radii are given in a comoving coordinate system that is expanding along with the universe. Two observers at rest with respect to the cosmic microwave background remain at constant comoving separation.

(a) The simulation begins with a primordial perturbation in which a small patch of space is slightly denser than the rest of the universe. The perturbation is adiabatic, so that all species of particles have the same initial perturbation. Because there is a net overdensity in this small region, a net gravitational force attracts matter from distant regions toward the origin.

(b) At early times, the universe is ionized and the nuclei and electrons are tightly coupled to the photon field. The initial overdensity of the photons creates a radiation overpressure that travels away from the origin as a sound wave in the baryon–photon plasma fluid. Meanwhile, the cold dark matter, slow and impervious to photons, stays near the origin while the relativistic neutrinos stream freely away.

(c) The sound wave continues outward in the baryon–photon plasma, traveling at $c/\sqrt{3}$. The cold-dark-matter perturbation has also been spreading because the outgoing sphere of photons and neutrinos has decreased the gravitational pull toward the origin, causing the converging velocity flow of the initial perturbation to pool at finite radius rather than at the origin. That's also why the neutrinos don't appear as a sharp spike in radius.

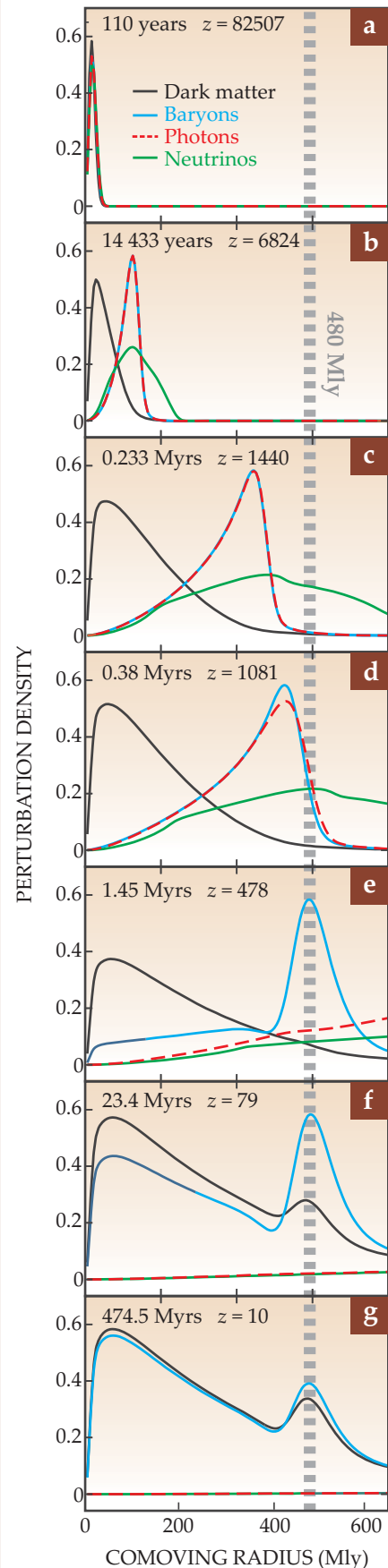
(d) By $z = 1081$, the universe has cooled enough that the electrons and nuclei combine to form neutral atoms. Photons decouple from the baryonic matter, and most of them have never again scattered off an electron. The sound speed plummets.

(e) With the photons completely decoupled, the shell of baryons that had been propagating with the sound wave grinds to a halt in the comoving coordinates at a radius of 480 Mly (dashed gray line).

(f) In the absence of significant radiation pressure, gravitational instability takes over the distribution of baryons. Their overdensity in the shell attracts dark matter from its more homogeneous reservoir, while the dark-matter overdensity near the origin attracts baryons back toward where they started. Because there's much less baryonic than dark matter, the density contrast between the acoustic peak and its surroundings drops.

(g) By redshift 10, around the time when galaxies are beginning to form, the dark matter and baryons are almost in lockstep. We are left with an overdensity centered at the origin and on a shell at 480 Mly due to the imprint of the sound wave. Both overdense regions are more likely to form galaxies than are less dense neighboring regions. That is, one expects to see a small excess of galaxy pairs separated by about 480 Mly. And indeed that predicted excess has now been found in large redshift surveys of galaxies (see figure 4).

Of course the universe has many such patches, some overdense, some underdense, all overlapping. So don't expect to see bull's-eye patterns in the data. But the characteristic comoving length can be found statistically, and it can serve as a cosmological yardstick. (Figure adapted from ref. 11.)



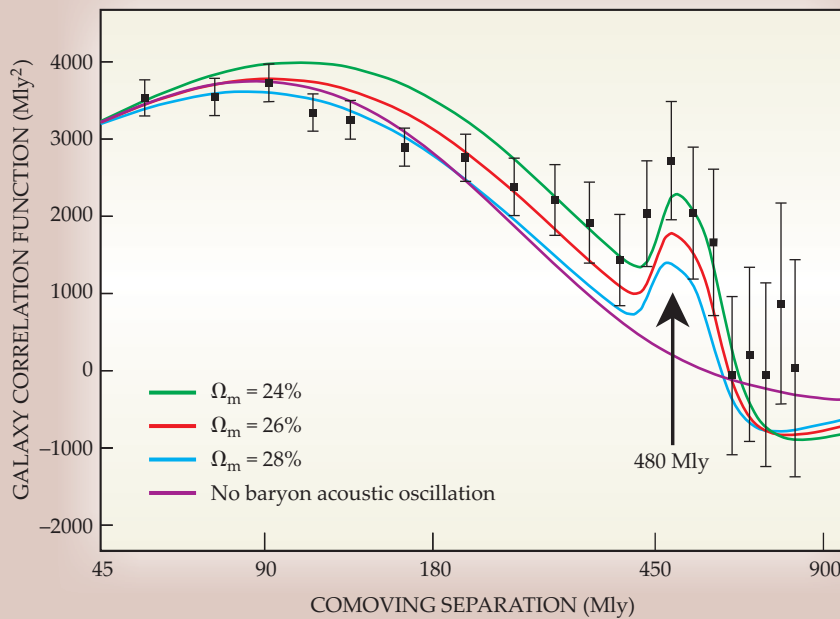


Figure 4. Predicted baryon-acoustic-oscillation bump shows up at a comoving separation of 480 million light-years in a galaxy correlation function deduced from the Sloan Digital Sky Survey of galaxy celestial positions and redshifts. (Comoving separation is distance in a coordinate system that dilates with the Hubble expansion. The distance is quoted as it would be today.) The correlation function is the excess probability of finding one galaxy a particular distance from another, here multiplied by the square of the comoving separation because the probability alone falls so steeply with distance. The excess probability represented by the acoustic peak at 480 Mly is only about 1%, far weaker than the

strong astrophysical correlations within galaxy clusters that span, say, 50 Mly. This single peak corresponds to the whole set of harmonic peaks in figure 2b, just as the fixed length of a violin string corresponds to a harmonic sequence of overtones. Colored curves are predictions for various total-mass densities Ω_m in the current cosmos and for a cosmos without acoustic oscillations. The mass densities are given as percentages of the total mass-energy density predicted by inflation. (Adapted from ref. 10.)

Δr_T in the transverse direction by measuring angles on the sky. Both types of measurement offer the opportunity to study the cosmological expansion history.

The acoustic scale r_A imprinted in the correlation among galaxies is, however, an intrinsically isotropic pattern. Along the line of sight, r_A produces a preferred separation Δz in redshift:

$$\Delta r_R = r_A = c\Delta z / H(z),$$

where $H(z)$ is the Hubble parameter at the redshift of the assemblage of galaxies. The Hubble parameter is the cosmic expansion rate at the time corresponding to z .

In the plane normal to the line of sight, the acoustic scale produces a preferred angular separation $\Delta\theta$:

$$\Delta r_T = r_A = (1+z) D(z) \Delta\theta,$$

where $D(z)$, the so-called angular-diameter distance, is given by an integral involving $H(z)$ over the period from z to the present ($z=0$).

The role of dark energy in accelerating the cosmic expansion is revealed in the evolution of $H(z)$ and hence in the derivative of D with respect to z . By determining both H and D at different redshifts, the measurement of the baryon acoustic peak probes the history of dark energy. The method exploits the measurement of redshift and celestial angle—both of which observers can do with exquisite precision—to determine that most troublesome quantity, cosmological distance.

Finding the baryon acoustic peak

To measure the correlation imprinted on the galaxies by the sound waves, one needs three-dimensional maps of their cos-

mic distribution. In an expanding universe, galaxy redshift surveys do that rather straightforwardly. They turn 2D images of the sky into 3D maps by making spectroscopic observations of galaxies to determine their Doppler redshifts. For galaxies distant enough that their non-Hubble motion along the line of sight can be neglected, redshift is monotonically related to distance. So a galaxy redshift survey becomes, in effect, a 3D map of the universe—albeit one whose radial dimension z has a nontrivial relation to actual distance.

Galaxy redshift surveys have been a mainstay of cosmology since the days of Edwin Hubble (1889–1953). They underpin most of our understanding of galaxy evolution and large-scale structure. But the detection of the baryon acoustic peak requires enormous surveys. Only the most recent have finally mapped enough volume to see this weak large-scale feature. Not until 2005 did teams from the Sloan Digital Sky Survey⁸ and the 2-Degree Field Galaxy Redshift Survey announce the detection of the sought-after baryon acoustic peak.^{9,10}

Figure 4 shows the correlation function of galaxies measured by the Sloan survey, with the acoustic peak at the comoving separation predicted by WMAP measurements and the standard cosmological model. Although the detection is of only modest statistical significance, the narrowness of the acoustic peak allows its position to be determined to 4% precision. That implies a 4% measurement of the ratio between the distance to objects at $z=0.35$ (a typical redshift in the survey's galaxy sample) and our enormously greater distance from the CMB's last-scattering surface at $z=1090$. It also measures our absolute distance from the galaxies at $z=0.35$ to about 5%.

A new generation of galaxy surveys will vastly extend

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our map of the cosmos. The baryon acoustic peak and its application to dark energy is currently the most prominent driver for surveys of very large cosmic volumes. The technical challenge is to acquire large numbers of faint galaxy spectra. Over the next five years, the planned new surveys will measure a million galaxies and determine the position of the baryon acoustic peak to 1% accuracy. By the end of the next decade, the numbers could reach 100 million galaxies, improving the acoustic scale measurement to nearly 0.1%. That would map most of the sky out to redshifts of 2–3, where most of the dark-energy information is expected to reside.

The baryon-acoustic-peak method has become one of the most promising ways of studying dark energy. It superbly complements the study of distant type Ia supernovae that discovered dark energy in the first place. The supernovae are easiest to measure at low redshift, where the total cosmic volume limits the acoustic-peak method, which gains in precision at higher redshift. It relies on a distance scale whose well-understood physical underpinnings are validated in considerable detail by the CMB anisotropy data.

The supernova method uses the relative observed brightnesses of supernovae at different redshifts to measure a distance ratio. The baryon acoustic peak, on the other hand, calibrates the distance scale in nearly absolute terms. Using supernovae together with the acoustic peaks in both the galaxy and CMB data will allow us to measure the cosmic distance scale to great precision across the full range of redshifts with a solid physical calibration.

Dark energy can also be studied through its effects on the clustering of matter. Of course it could be that the accelerating Hubble expansion, rather than being a manifestation of dark energy, is actually the signal of a departure of nature from the general theory of relativity. In the correct new theory, density perturbations might behave differently from what general relativity predicts for a cosmos with the same expansion history. So a combination of precision probes that measure the growth of large structures and probes like supernovae and acoustic peaks that measure the overall expansion rate should let cosmologists test the physical cause of the acceleration.

This is a marvelous moment in the investigation of the cosmos. An impressively diverse set of observations has led to a standard cosmological model that is robust in its cross-checks, deeply puzzling in its ingredients, and far-reaching in its implications for fundamental physics. The sound waves that rang through the early cosmos are a prominent aspect of that model. They were predicted 40 years ago, and now they provide one of our best cosmological tools. The simplicity of sound waves is a hallmark of freshman physics. That same physics, applied on the largest scales, is bringing our universe into ever-closer reach.

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