

Galaxy clusters tighten constraints on the cosmic accelerator

Evidence from clusters and elsewhere suggests that the universe's accelerated expansion is driven by something that behaves like Einstein's cosmological constant.

Galaxy clusters are the largest gravitationally bound structures in the universe. They began to form about 10 billion years ago when the first galaxies and their massive mantles of dark matter clumped together. Most of a cluster's matter, however, lies between galaxies. Shocked by the assembly process and trapped by the cluster's gravitational potential, the baryonic component of the intracluster medium (ICM) reached, and remains at, temperatures in the x-ray-emitting range of 10^7 – 10^8 K.

Their ages, assembly, and x-ray emission make clusters valuable probes of one of the most momentous phenomena ever discovered: The universe's current rate of expansion is not slowing down, as one expects of a matter-dominated universe, but is speeding up. (See *PHYSICS TODAY*, June 1998, page 17.)

The x-ray glow from a cluster's ICM is detectable out to a redshift z of about 2. Type Ia supernovae, which featured in the discovery of the accelerated expansion 11 years ago, are detectable out to a z of 1. Because clusters, like supernovae, have certain standard properties and are spread over a range of redshift, they can reveal the expansion history of the universe. Steven Allen's group at Stanford University carried out such a study last year.¹ The results corroborated the pioneering supernovae surveys and their more sensitive follow-ups.

Unlike supernovae, clusters can also reveal how the expansion has influenced the growth of objects that inhabit the universe. That extra information could, in turn, distinguish among various explanations of what drives the accelerated expansion. In particular, it could say whether the expansion requires either a new field—dark energy—within general relativity or a new theory of gravity.

Alexey Vikhlinin of the Harvard-Smithsonian Center for Astrophysics and his collaborators have just published a study of how clusters grow as they age.² The study can't rule out new gravity, but like other studies it's consistent with general relativity and with the simplest kind of dark energy: Einstein's

cosmological constant. When combined with other, independent methods, the study yields the tightest constraints so far on the accelerating expansion.

From mass to structure

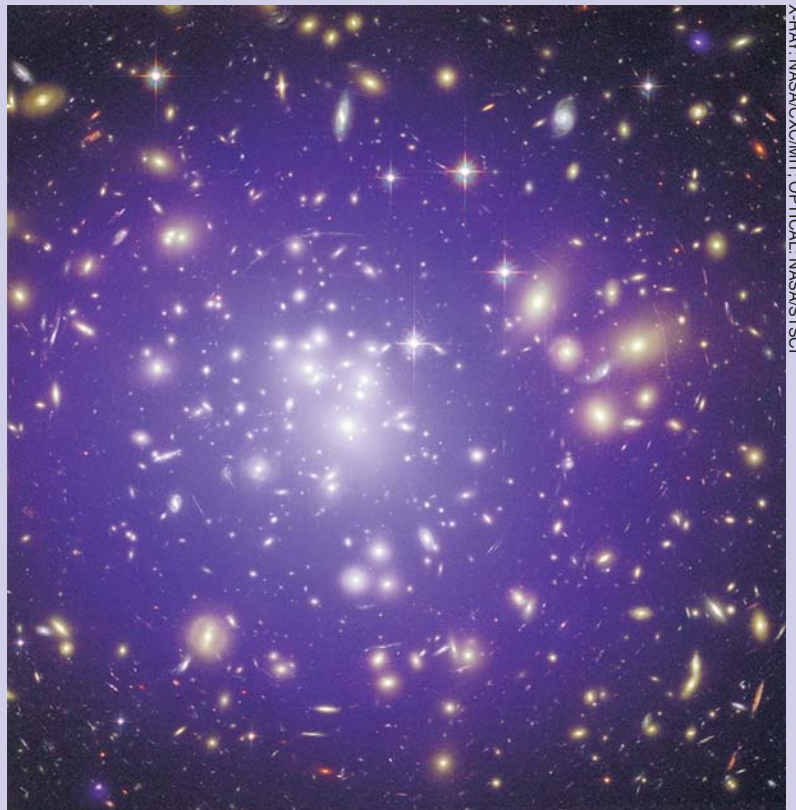
As the universe ages, matter becomes more diffuse and its energy density falls. Whatever is accelerating the expansion appears to have an energy density that has either remained constant since the Big Bang or barely varied. In the dense early universe, matter and radiation controlled the expansion's progress. But eventually, when the universe reached about half its current age ($z = 0.6$), matter's ability to retard the expansion was overcome by dark energy's

ability to accelerate it.

Galaxies began to assemble into clusters before dark energy attained its dynamical predominance. Observing clusters in x rays, their most luminous band, offers a potentially sensitive probe of dark energy for z up to about 1.

Clusters are so large that each one can be presumed to have scooped up the same universal mix of baryonic and dark matter when it formed. The fraction, by mass, of x-ray-emitting plasma should therefore be the same from cluster to cluster, regardless of size, mass, or redshift.

In their 2008 study, Allen and his group exploited that property to derive redshift-independent distances to the sample's 42 clusters. Having also deter-



X-RAY: NASA/CXC/MIT; OPTICAL: NASA/STSC

Figure 1. Abell 1689 is one of the biggest, most massive galaxy clusters. The x-ray emission, measured by the *Chandra* orbiter and shown here in purple, comes from hot baryons that occupy the cluster's gravitational potential. The cluster's temperature distribution (not shown) indicates the cluster has merged with another cluster. Whether Abell 1689 can continue to fatten depends in part on how fast the universe is expanding.

mined the redshifts from optical or x-ray spectra, Allen had a set of 42 distance–redshift relations. Only a model with dark energy, or something like it, was consistent with a constant, universal fraction of x-ray-emitting plasma.

Allen used clusters as standard candles and assumed that clusters contain a fair sample of the universe’s matter. Vikhlinin, by contrast, looked at how the expansion has influenced cluster growth. His key starting point was a paradigm called Λ CDM (Λ , Einstein’s cosmological constant, is shorthand for the simplest kind of dark energy; CDM stands for cold dark matter). According to Λ CDM, the density fluctuations that begat the first structures had a simple power-law spectrum. Evidence for that spectrum appears in the cosmic microwave background; further support comes from computer simulations of large-scale structure.

Clusters didn’t form directly from those first fluctuations but were assembled from what those fluctuations produced: protogalaxies. That distinction is important because the nonlinear assembly of clusters goes beyond the linear, perturbative physics of Λ CDM density fluctuations. Observations and computer simulations provide some confidence that the density-fluctuation spectrum relates to the initial cluster mass spectrum in a conceptually straightforward way.

How the cluster mass spectrum evolved over time depends in part on the expansion history of the universe. Expansion weakens the tendency of clusters both to gather together in superclusters and to merge with each other. The more vigorous the expansion, the less mass put on by clusters as they age.

Cluster masses

Determining a cluster’s mass might seem straightforward. The baryons’ x-ray emission depends on the baryons’ number density and temperature. The temperature, in turn, depends on the depth of the gravitational potential and therefore on the total amount of matter, both baryonic and dark.

Relating temperature to total mass requires hydrostatic equilibrium, which doesn’t always prevail. Some clusters harbor active galactic nuclei that blow out vast regions of lower-density plasma. Some clusters, like the Bullet cluster, are undergoing violent mergers. (See *PHYSICS TODAY*, November 2006, page 21.) And some clusters,

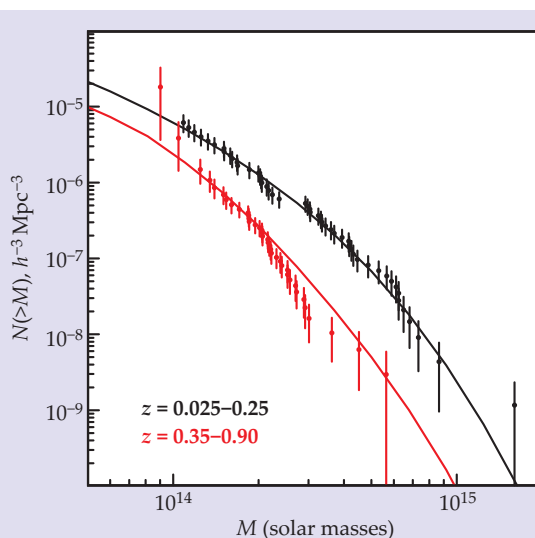


Figure 2. Cluster mass functions reflect how clusters grow through merging. Plotted here is the number density of clusters of mass M or larger as a function of M . As expected, bigger clusters are more numerous in the recent epoch (black points) than at the earlier epoch (red points). The discrepancy would be higher still if dark energy hadn’t inhibited merging. The curves correspond to a model in which various cosmological parameters were fixed at previously determined values and only the (overall) normalization was allowed to vary. (Adapted from ref. 2.)

like Abell 1689, are digesting past mergers (see figure 1).

Vikhlinin and his collaborators drew their sample of 86 clusters from observations made by the *ROSAT* observatory, which flew from 1990 to 1999. *ROSAT*’s x-ray telescope scanned the entire sky during the first phase of its mission. The second, longer phase was devoted to observations of specific targets, some of which were clusters. Clusters also appeared as serendipitous background objects.

ROSAT’s x-ray telescope was sensitive enough to yield accurate masses for the bright, nearby clusters in the all-sky survey. For the fainter, more distant clusters in the targeted observations, Vikhlinin turned to the *Chandra* observatory. Even with *Chandra*’s high-resolution data, Vikhlinin and his colleagues had to carry out several different calibrations to ensure that what they measured (brightness and temperature) yielded accurate total masses.

Some clusters, including Abell 1689, have masses determined independently by weak gravitational lensing. (See the article by Leon Koopmans and Roger Blandford, *PHYSICS TODAY*, June 2004, page 45.) A foreground cluster distorts the shapes of more distant galaxies behind it. You can see the effect in figure 1. With a big enough set of clearly measured distortions, the foreground cluster’s mass—even its mass distribution—can be inferred.

Simulated clusters provided another crosscheck. Vikhlinin’s colleague Daisuke Nagai of Yale University created model clusters of known mass, calculated the expected luminosity and temperature distributions, and then “observed” the clusters to determine which quantities correlate reliably with mass. Nagai’s simulations confirmed a sug-

gestion by another of Vikhlinin’s colleagues, Andrey Kravtsov of the University of Chicago: The mass of the luminous gas times its temperature provides a robust measure of total mass—even for clusters still recovering from a merger. Having determined the clusters’ total masses, the team could plot the cluster mass function—that is, the number density of clusters bigger than mass M as a function of M .

The mass functions for two broad redshift bins are shown in figure 2. Thanks to ongoing merging, massive clusters are more numerous at recent times than they are at earlier times, as reflected in amplitudes of the mass functions. But if the universe’s expansion weren’t accelerating, the difference between the amplitudes would be larger.

To convert that difference into a cosmological measurement, Vikhlinin and his colleagues constructed a model and fitted it to their mass functions. The model has six parameters, three of which characterize the mass–energy content of the universe: Ω_M , the normalized mass–energy density of all the matter in the universe; Ω_Λ , the normalized mass–energy density of dark energy; and w , dark energy’s equation-of-state parameter: its pressure over its density. Two other parameters characterize the past and present structure of the universe: n_s , the power law index of the primordial density fluctuations, and σ_8 , the total mass enclosed in a typical sphere of radius 8 megaparsecs in the present universe. Hubble’s constant is the sixth parameter.

Computing the model for each set of parameters was demanding. Each fit required 20 days of computer time on several workstations. Various combinations of free and fixed parameters were evaluated. Overall, the cluster mass

Newborn babies feel the beat

When you tap your foot in time to your favorite song, you're engaging in a process called beat induction: You pick out a periodic pulse from a nonrepetitive sequence of sounds, and you anticipate the next pulse in time to lift your foot and lower it again. The downbeat, or beginning of a rhythmic unit, might be louder or longer than the surrounding notes, but it doesn't have to be—a regular downbeat can be induced even if

it's not marked by any special stress. Now, researchers in Hungary and the Netherlands, led by István Winkler of the Hungarian Academy of Sciences in Budapest and Henkjan Honing of the University of Amsterdam, have found that three-day-old infants are also capable of beat induction—a potentially important step toward understanding how older infants and children learn to process the sounds they hear.

The researchers had 14 babies listen to a repeating synthesized drum rhythm from which notes were sporadically omitted. Because newborns can't be asked to tap their feet, their reactions were monitored using electroencephalography: the measurement of electrical activity in the brain via electrodes affixed to the head, as shown in the photo. When the omitted sound was a downbeat, the electrodes picked up a strong discriminative response, but when a note in any other position was left out, the infants showed no measurable response.¹

The result suggests that beat induction is either innate or learned in the womb—but those two possi-

bilities are not as distinct as they might seem. "Normal development of the brain requires some stimulation," Winkler explains. "Rather than clarifying the issue of which capabilities are innate and which are learned, experiments that isolated animals from certain types of stimulation—within the womb or right after birth—produced animals with severe brain dysfunctions." The human fetus can hear and process sounds for some months prior to birth, and Winkler suspects that exposure during that time to rhythmic sounds such as the mother's heartbeat is probably necessary for the development of beat-induction ability. But it may not be the whole story: The rhythm used in the experiment is more complex than a heartbeat, and the distinction between important and unimportant beats in the drum sequence is not something that could obviously be learned by listening to a simple repeating sound pattern. Winkler concludes, "In any reasonable meaning of the expression, human babies are born with the ability to detect the beat in rhythms."

The researchers did not attempt to determine whether some of the infants were better at beat induction than others. But they are embarking on an investigation with the related goal of testing whether there is a relationship between the perception of musical rhythm at birth and the ability to properly time vocal communication later in infancy—for example, how to take turns making sounds in a "proto-conversation" with a parent. Ultimately, they hope to develop a way to screen for communication problems at an early age. As Winkler explains, "Communication skills affect attachment to the parents, and that has a strong effect on development in many important areas." (Photo courtesy of Gábor Stefanics, Hungarian Academy of Sciences.)

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Reference

1. I. Winkler et al., *Proc. Natl. Acad. Sci. USA* (in press), doi:10.1073/pnas.0809035106.

functions are consistent with the Λ CDM paradigm. The curves in figure 2 correspond to a model in which all the parameters except σ_8 , which serves to normalize both mass functions, were fixed at previously established values.

Perhaps the parameter of most interest is w . If the equations of general relativity require a cosmological constant, then empty space will act as if permeated by fluid that exerts negative pressure and speeds up the universe's expansion. In 1968 Yakov Zel'dovich showed that the vacuum energy of quantum field theory is mathematically equivalent to Einstein's cosmological constant. In either case $w = -1$.

Using the cluster data alone, Vikhlinin and his colleagues find that $w = -1.14 \pm 0.21$. Combining cluster data with other, independent methods of determining w , they obtained a value of 0.991 with a statistical error of ± 0.045 and a systematic error of ± 0.039 . The combined result represents an increase in accuracy of a factor of 2.

Vikhlinin's model presumes w varies with neither time nor space. Both possibilities feature in various alternatives to vacuum energy. And if general relativity fails on large scales, the discrepancy would show up as a variable w .

Current observations, including Vikhlinin's, don't place strong constraints on the variation of w , but there are clues from the early universe. The density fluctuations that left their stamp on the cosmic microwave background and the nucleosynthesis of light elements both occurred in the universe's first billion years. Neither phenomenon requires dark energy to account for its observable effects. That's no problem for constant w . If, at that early epoch, dark energy had the same strength as it has now, matter and radiation predominated.

More accurate probes will determine whether w does vary. One promising tack is to look for the influence of dark energy on scales far larger than galaxy clusters. Those structures can be tied more directly to the primordial density fluctuations than clusters can. However, observing them will require a three-dimensional map of the universe similar to, but more accurate than, those derived by the Sloan Digital Sky Survey and 2dF (Two Degree Field system). So far, dark energy remains mysterious and general relativity remains safe.

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References

1. S. W. Allen et al., *Mon. Not. R. Astron. Soc.* **383**, 879 (2008).
2. A. Vikhlinin et al., *Astrophys. J.* (in press).