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The Universe's Invisible Hand

Dark energy does more than hurry along the expansion of the universe. It also has a stranglehold on the shape and spacing of galaxies

By Christopher J. Conselice

What took us so long? Only in 1998 did astronomers discover we had been missing nearly three quarters of the contents of the universe, the so-called dark energy--an unknown form of energy that surrounds each of us, tugging at us ever so slightly, holding the fate of the cosmos in its grip, but to which we are almost totally blind. Some researchers, to be sure, had anticipated that such energy existed, but even they will tell you that its detection ranks among the most revolutionary discoveries in 20th-century cosmology. Not only does dark energy appear to make up the bulk of the universe, but its existence, if it stands the test of time, will probably require the development of new theories of physics.

Scientists are just starting the long process of figuring out what dark energy is and what its implications are. One realization has already sunk in: although dark energy betrayed its existence through its effect on the universe as a whole, it may also shape the evolution of the universe's inhabitants--stars, galaxies, galaxy clusters. Astronomers may have been staring at its handiwork for decades without realizing it.

Ironically, the very pervasiveness of dark energy is what made it so hard to recognize. Dark energy, unlike matter, does not clump in some places more than others; by its very nature, it is spread smoothly everywhere. Whatever the location--be it in your kitchen or in intergalactic space--it has the same density, about 10^{-26} kilogram per cubic meter, equivalent to a handful of hydrogen atoms. All the dark energy in our solar system amounts to the mass of a small asteroid, making it an utterly inconsequential player in the dance of the planets. Its effects stand out only when viewed over vast distances and spans of time.

Since the days of American astronomer Edwin Hubble, observers have known that all but the nearest galaxies are moving away from us at a rapid rate. This rate is proportional to distance: the more distant a galaxy is, the faster its recession. Such a pattern implied that galaxies are not moving through space in the conventional sense but are being carried along as the fabric of space itself stretches [see "Misconceptions about the Big Bang," by

Charles H. Lineweaver and Tamara M. Davis; *Scientific American*, March 2005]. For decades, astronomers struggled to answer the obvious follow-up question: How does the expansion rate change over time? They reasoned that it should be slowing down, as the inward gravitational attraction exerted by galaxies on one another should have counteracted the outward expansion.

The first clear observational evidence for changes in the expansion rate involved distant supernovae, massive exploding stars that can be used as markers of cosmic expansion, just as watching driftwood lets you measure the speed of a river. These observations made clear that the expansion was slower in the past than today and is therefore accelerating. More specifically, it had been slowing down but at some point underwent a transition and began speeding up [see "Surveying Space-time with Supernovae," by Craig J. Hogan, Robert P. Kirshner and Nicholas B. Suntzeff; *Scientific American*, January 1999, and "From Slowdown to Speedup," by Adam G. Riess and Michael S. Turner; *Scientific American*, February 2004]. This striking result has since been cross-checked by independent studies of the cosmic microwave background radiation by, for example, the Wilkinson Microwave Anisotropy Probe (WMAP).

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One possible conclusion is that different laws of gravity apply on supergalactic scales than on lesser ones, so that galaxies' gravity does not, in fact, resist expansion. But the more generally accepted hypothesis is that the laws of gravity are universal and that some form of energy, previously unknown to science, opposes and overwhelms galaxies' mutual attraction, pushing them apart ever faster. Although dark energy is inconsequential within our galaxy (let alone your kitchen), it adds up to the most powerful force in the cosmos.

Cosmic Sculptor

As astronomers have explored this new phenomenon, they have found that, in addition to determining the overall expansion rate of the universe, dark energy has long-term consequences for smaller scales. As you zoom in from the entire observable universe, the first thing you notice is that matter on cosmic scales is distributed in a cobweblike pattern--a filigree of filaments, several tens of millions of light-years long, interspersed with voids of similar size. Simulations show that both matter and dark energy are needed to explain the pattern.

That finding is not terribly surprising, though. The filaments and voids are not coherent bodies like, say, a planet. They have not detached from the overall cosmic expansion and established their own internal equilibrium of forces. Rather they are features shaped by the competition between cosmic expansion (and any phenomenon affecting it) and their own gravity. In our universe, neither player in this tug-of-war is overwhelmingly dominant. If dark energy were stronger, expansion would have won and matter would be spread out rather than concentrated in filaments. If dark energy were weaker, matter would be even more concentrated than it is.

The situation gets more complicated as you continue to zoom in and reach the scale of galaxies and galaxy clusters. Galaxies, including our own Milky Way, do not expand with time. Their size is controlled by an equilibrium between gravity and the angular momentum of the stars, gas and other material that make them up; they grow only by accreting new material from intergalactic space or by merging with other galaxies. Cosmic expansion has an insignificant effect on them. Thus, it is not at all obvious that dark energy should have had any say whatsoever in how galaxies formed. The same is true of galaxy clusters, the largest coherent bodies in the universe--assemblages of thousands of galaxies embedded in a vast cloud of hot gas and bound together by gravity.

Yet it now appears that dark energy may be the key link among several aspects of galaxy and cluster formation that not long ago appeared unrelated. The reason is that the formation and evolution of these systems is partially driven by interactions and mergers between galaxies, which in turn may have been driven strongly by dark energy.

To understand the influence of dark energy on the formation of galaxies, first consider how astronomers think galaxies form. Current theories are based on the idea that matter comes in two basic kinds. First, there is ordinary matter, whose particles readily interact with one another and, if electrically charged, with electromagnetic radiation. Astronomers call this type of matter "baryonic" in reference to its main constituent, baryons, such as protons and neutrons. Second, there is dark matter (which is distinct from dark energy), which makes up 85 percent of all matter and whose salient property is that it comprises particles that do not react with radiation. Gravitationally, dark matter behaves just like ordinary matter.

According to models, dark matter began to clump immediately after the big bang, forming spherical blobs that astronomers refer to as "halos." The baryons, in contrast, were initially kept from clumping by their interactions with one another and with radiation. They remained in a hot, gaseous phase. As the universe expanded, this gas cooled and the baryons were able to pack themselves together. The first stars and galaxies coalesced out of this cooled gas a few hundred million years after the big bang. They did not materialize in random locations but in the centers of the dark matter halos that had already taken shape.

Since the 1980s a number of theorists have done detailed computer simulations of this process, including groups led by Simon D. M. White of the Max Planck Institute for Astrophysics in Garching, Germany, and Carlos S. Frenk of Durham University in England. They have shown that most of the first structures were small, low-mass dark matter halos. Because the early universe was so dense, these low-mass halos (and the galaxies they contained) merged with one another to form larger-mass systems. In this way, galaxy construction was a bottom-up process, like building a dollhouse out of Lego bricks. (The alternative would have been a top-down process, in which you start with the dollhouse and smash it to make bricks.) My colleagues and I have sought to test these models by looking at distant galaxies and how they have merged over cosmic time.

Galaxy Formation Peters Out

Detailed studies indicate that a galaxy gets bent out of shape when it merges with another galaxy. The earliest galaxies we can see existed when the universe was about a billion years old, and many of these indeed appear to be merging. As time went on, though, the fusion of massive galaxies became less common. Between two billion and six billion years after the big bang--that is, over the first half of cosmic history--the fraction of massive galaxies undergoing a merger dropped from half to nearly nothing at all. Since then, the distribution of galaxy shapes has been frozen, an indication that smashups and mergers have become relatively uncommon.

In fact, fully 98 percent of massive galaxies in today's universe are either elliptical or spiral, with shapes that would be disrupted by a merger. These galaxies are stable and comprise mostly old stars, which tells us that they must have formed early and have remained in a regular morphological form for quite some time. A few galaxies are merging in the present day, but they are typically of low mass.

The virtual cessation of mergers is not the only way the universe has run out of steam since it was half its current age. Star formation, too, has been waning. Most of the stars that exist today were born in the first half of cosmic history, as first convincingly shown by several teams in the 1990s, including ones led by Simon J. Lilly, then at the University of Toronto, Piero Madau, then at the Space Telescope Science Institute, and Charles C. Steidel of the California Institute of Technology. More recently, researchers have learned how this trend occurred. It turns out that star formation in massive galaxies shut down early. Since the universe was half its current age, only lightweight systems have continued to create stars at a significant rate. This shift in the venue of star formation is called galaxy downsizing [see "The Midlife Crisis of the Cosmos," by Amy J. Barger; *Scientific American*, January 2005]. It seems paradoxical. Galaxy formation theory predicts that small galaxies take shape first and, as they amalgamate, massive ones arise. Yet the history of star formation shows the reverse: massive galaxies are initially the main stellar birthing grounds, then smaller ones take over.

The universe has run out of steam since it was half its current age. Mergers have ceased, and black holes are quiescent.

Another oddity is that the buildup of supermassive black holes, found at the centers of galaxies, seems to have slowed down considerably. Such holes power quasars and other types of active galaxies, which are rare in the modern universe; the black holes in our galaxy and others are quiescent. Are any of these trends in galaxy evolution related? Is it really possible that dark energy is the root cause?

The Steady Grip of Dark Energy

Some astronomers have proposed that internal processes in galaxies, such as energy released by black holes and supernovae, turned off galaxy and star formation. But dark energy has emerged as possibly a more fundamental culprit, the one that can link everything together. The central piece of evidence is the rough coincidence in timing between the end of most galaxy and cluster formation and the onset of the domination of dark energy. Both happened when the universe was about half its present age.

The idea is that up to that point in cosmic history, the density of matter was so high that gravitational forces among galaxies dominated over the effects of dark energy. Galaxies rubbed shoulders, interacted with one another, and frequently merged. New stars formed as gas clouds within galaxies collided, and black holes grew when gas was driven toward the centers of these systems. As time progressed and space expanded, matter thinned out and its gravity weakened, whereas the strength of dark energy remained constant (or nearly so). The inexorable shift in the balance between the two eventually caused the expansion rate to switch from deceleration to acceleration. The structures in which galaxies reside were then pulled apart, with a gradual decrease in the galaxy merger rate as a result. Likewise, intergalactic gas was less able to fall into galaxies. Deprived of fuel, black holes became more quiescent.

This sequence could perhaps account for the downsizing of the galaxy population. The most massive dark matter halos, as well as their embedded galaxies, are also the most clustered; they reside in close proximity to other massive halos. Thus, they are likely to knock into their neighbors earlier than are lower-mass systems. When they do, they experience a burst of star formation. The newly formed stars light up and then blow up, heating the gas and preventing it from collapsing into new stars. In this way, star formation chokes itself off: stars heat the gas from which they emerged, preventing new ones from forming. The black hole at the center of such a galaxy acts as another damper on star formation. A galaxy merger feeds gas into the black hole, causing it to fire out jets that heat up gas in the system and prevent it from cooling to form new stars.

Apparently, once star formation in massive galaxies shuts down, it does not start up again--most likely because the gas in these systems becomes depleted or becomes so hot that it cannot cool down quickly enough. These massive galaxies can still merge with one another, but few new stars emerge for want of cold gas. As the massive galaxies stagnate, smaller galaxies continue to merge and form stars. The result is that massive galaxies take shape before smaller ones, as is observed. Dark energy perhaps modulated this process by determining the degree of galaxy clustering and the rate of merging.

Dark energy would also explain the evolution of galaxy clusters. Ancient clusters, found when the universe was less than half its present age, were already as massive as today's clusters. That is, galaxy clusters have not grown by a significant amount in the past six billion to eight billion years. This lack of growth is an indication that the infall of galaxies into clusters has been curtailed since the universe was about half its current age--a direct sign that dark energy is influencing the way galaxies are interacting on large scales. Astronomers knew as early as the mid-1990s that galaxy clusters had not grown much in the past eight billion years, and they attributed this to a lower matter density than theoretical arguments had predicted. The discovery of dark energy resolved the tension between observation and theory.

An example of how dark energy alters the history of galaxy clusters is the fate of the galaxies in our immediate vicinity, known as the Local Group. Just a few years ago astronomers thought that the Milky Way and Andromeda, its closest large neighbor, along with their retinue of satellites, would fall into the nearby Virgo cluster. But it now appears that we shall escape that fate and never become part of a large cluster of galaxies. Dark energy will cause the distance between us and Virgo to expand faster than the Local Group can cross it.

By throttling cluster development, dark energy also controls the makeup of galaxies within clusters. The cluster environment facilitates the formation of a zoo of galaxies such as the so-called lenticulars, giant ellipticals and dwarf ellipticals. By regulating the ability of galaxies to join clusters, dark energy dictates the relative abundance of these galaxy types.

Space is emptying out, leaving our Milky Way galaxy and its neighbors an increasingly isolated island.

This is a good story, but is it true? Galaxy mergers, black hole activity and star formation all decline with time, and very likely they are related in some way. But astronomers have yet to follow the full sequence of events. Ongoing surveys with the Hubble Space Telescope, the Chandra X-ray Observatory and sensitive ground-based imaging and spectroscopy will scrutinize these links in coming years. One way to do this is to obtain a good census of distant active galaxies and to determine the time when those galaxies last underwent a merger. The analysis will require the development of new theoretical tools but should be within our grasp in the next few years.

Striking a Balance

An accelerating universe dominated by dark energy is a natural way to produce all the observed changes in the galaxy population--namely, the cessation of mergers and its many corollaries, such as loss of vigorous star formation and the end of galactic metamorphosis. If dark energy did not exist, galaxy mergers would probably have continued for longer than they did, and today the universe would contain many more massive galaxies with old stellar populations. Likewise, it would have fewer lower-mass systems, and spiral galaxies such as our Milky Way would be rare (given that spirals cannot survive the merger process). Large-scale structures of galaxies would have been more tightly bound, and more mergers of structures and accretion would have occurred.

Conversely, if dark energy were even stronger than it is, the universe would have had fewer mergers and thus fewer massive galaxies and galaxy clusters. Spiral and low-mass dwarf irregular galaxies would be more common, because fewer galaxy mergers would have occurred throughout time, and galaxy clusters would be much less massive or perhaps not exist at all. It is also likely that fewer stars would have formed, and a higher fraction of our universe's baryonic mass would still be in a gaseous state.

Although these processes may seem distant, the way galaxies form has an influence on our own existence. Stars are needed to produce elements heavier than lithium, which are used to build terrestrial planets and life. If lower star formation rates meant that these elements did not form in great abundance, the universe would not have many planets, and life itself might never have arisen. In this way, dark energy could have had a profound effect on many different and seemingly unrelated aspects of the universe, and perhaps even on the detailed history of our own planet.

Dark energy is by no means finished with its work. It may appear to benefit life: the acceleration will prevent the eventual collapse that was a worry of astronomers not so long ago. But dark energy brings other risks. At the very least, it pulls apart distant galaxies, making them recede so fast that we lose sight of them for good. Space is emptying out, leaving our galaxy and its immediate neighbors an increasingly isolated island. Galaxy clusters, galaxies and even stars drifting through intergalactic space will eventually have a limited sphere of gravitational influence not much larger than their own individual sizes.

Worse, dark energy might be evolving. Some models predict that if dark energy becomes ever more dominant over time, it will rip apart gravitationally bound objects, such as galaxy clusters and galaxies. Ultimately, planet Earth will be stripped from the sun and shredded, along with all objects on it. Even atoms will be destroyed. Dark energy, once cast in the shadows of matter, will have exacted its final revenge.