

INTRODUCTION

Warp and Woof

WITH ALL RESPECT TO THE POET DYLAN THOMAS, WHO DEPICTED THE MOONLESS sky as “starless and bible-black,” a clear night is actually ablaze with specks of light. For a long time, we thought those isolated stars were the whole story. But researchers now realize that they are embedded in a filamentary structure of matter both dark and visible, called the cosmic web. In this issue, a News feature and three Perspectives bring us up to date on just what we know about the cosmic web and what we still want to know.

For starters, Adrian Cho (p. 47) surveys the many techniques astronomers are using to trace the web. Their goal is both simple and ambitious: to map everything they can see. Their tools include large-scale surveys of galaxies and galactic clusters, which probe the interplay of dark matter and dark energy; weak gravitational lensing, which detects matter by analyzing how it affects passing light; and techniques for viewing the universe through microwaves and other radiation outside the usual optical and infrared wavelengths. To make real progress, however, theorists must clear up some fundamental mysteries about how galaxies form and evolve.

As Ibata and Lewis explain (p. 50), the cosmic web shows up in our own galactic backyard. Galaxies are distributed not randomly but along the tendrils of the cosmic web, yet this pattern can only be explained by large amounts of connective dark matter. “Just like Swift’s big fleas and little fleas,” the authors write, these structures should occur at all distance scales, including within the Milky Way. Astronomers have marshaled a large observational effort to understand the web at various scales, but how do they make sense of the data?

This is where advances in modeling and theory can help. Faucher-Giguère *et al.* (p. 52) discuss supercomputer simulations that have enhanced our understanding of where the cosmic web came from. Tiny fluctuations in the very early universe have grown over billions of years into the massive cosmological structures we see today. The distribution of galaxies predicted by computer models has been dramatically confirmed by observational surveys, but much more needs to be done. New simulation techniques will have to provide higher resolution while modeling the cosmic web over immense distances.

These questions connect at the smallest scales too, as Nicastro *et al.* describe (p. 55). The exact nature of the dark matter that makes up 95% of the cosmic web remains baffling, but things aren’t much better for the remaining 5% that we can see. These are the baryons—protons and neutrons—that make up ordinary matter, yet we can account for only about half of the baryon mass predicted by the standard cosmological model. The missing baryons might be lurking in the cosmic web, and perhaps we could detect the warm-hot intergalactic matter, or WHIM, that could be their signature. Detecting these WHIMsical filaments will require both closer analysis of existing data and future observational missions.

Astronomers and physicists have given us a good picture of how the elaborate filigree of matter in the cosmic web arose from the whispering echoes of the Big Bang, and the view is stunning. Their continuing efforts to map the cosmic web should begin to nail down the nature of the missing matter, whether dark or light, and tell us more about how the universe came to be and how it is evolving.

—DAVID VOSS AND ROBERT COONTZ

Cosmic Web

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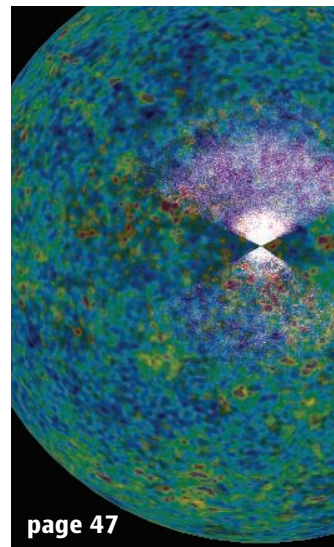
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Science

Drawn together. A cluster of galaxies and the inferred distribution of dark matter (haze) within it.

NEWS

Untangling the Celestial Strings

In an effort that weaves together astronomy, astrophysics, and cosmology, scientists are mapping the filamentary framework that gives shape to the cosmos

CHICAGO, ILLINOIS—All the universe is a tangled web, and all the stars and galaxies its captives. Fans of the Bard may groan, but that doggerel nicely sums up scientists' understanding of the cosmos. Unraveling that "cosmic web" presents astronomers, astrophysicists, and cosmologists with their next great challenge.

The web is the framework on which the universe is built. It consists primarily of "dark matter," mysterious stuff that makes up 85% of the matter in the universe but has revealed itself only through its gravity. Enormous filaments and blobs of the stuff condensed as the universe matured. Within them nestle the galaxies and their stars, creating streams of light stretching between inky voids. Even-stranger dark energy pervades everything, stretching space and affecting the evolution of the web.

That's the big picture. Now, scientists are turning to the details. What are the properties of dark matter and dark energy? Precisely how is the web organized? Exactly how do galaxies form in it? The web spans size scales from individual galaxies to the breadth of the observable universe. In its evolution, it traces the complexity we see today back through time to the big bang. And it bridges the conceptual divide between the reductive theories of cosmology and the rich and varied astrophysics of galaxies and clusters.

"To me, the really exciting part of astronomy and astrophysics in the next 15 years is how to interpret the light that we see in terms of the web of dark matter," says Howard Yee, an astronomer at the University of Toronto in Canada and one of 106 researchers who met

here last month* to discuss efforts largely aimed at mapping out the cosmic web. "We don't know how to say, 'Here [in the web], a galaxy will show up at a certain time and with a certain size.'"

The drive to trace the cosmic web is changing the practice of astronomy. Researchers are turning to the galaxies with renewed interest, says Michael Gladders, an astronomer at the University of Chicago. Only now, they are analyzing them en masse. "We're going to see a resurgence of what you might consider classical astronomy—looking at distinct objects at optical and infrared wavelengths—except millions of them at a time," Gladders says.

A recipe for the universe

Ten years ago, most theorists agreed that dark matter had to exist, as its gravity appears to hold the galaxies together. Then three observations in quick succession helped cosmologists nail down a precise list of ingredients for the cosmos.

In 1998, two teams used the light from exploding stars called type Ia supernovae to measure the expansion of the universe. To their surprise, they found that instead of slowing as expected, it's speeding up as though driven by dark energy (*Science*, 27 February 1998, p. 1298).

Meanwhile, astronomers were beginning huge surveys of the galaxies. Scientists used the 3.9-meter Anglo-Australian Telescope on

Mount Worrat in New South Wales, Australia, to measure the three-dimensional (3D) positions of 221,000 galaxies as part of the 2dF Galaxy Redshift Survey, which ran from 1997 to 2002. Others with the Sloan Digital Sky Survey, which began in 1998, have used a 2.5-meter telescope at Apache Point, New Mexico, to pinpoint 800,000 galaxies. The results of the surveys can help theorists probe the interplay between dark matter, whose gravity pulls galaxies together, and dark energy, which pushes them apart.

Then in 2003, NASA's Wilkinson Microwave Anisotropy Probe (WMAP) spacecraft mapped the afterglow of the big bang, the cosmic microwave background (CMB), to produce, in essence, the universe's baby picture. The universe supposedly sprang into existence infinitely dense and hot and immediately doubled its size 100 times over. After about 10^{-32} seconds of such "inflation," the expansion slowed, and 400,000 years later, the universe cooled enough to allow free-flying protons and electrons to form hydrogen atoms. That transformation freed light trapped by the particles, which has since stretched into microwaves and cooled to 2.725 kelvin.

(As light travels through the expanding universe, it is stretched, or "redshifted," to longer wavelengths. Scientist use redshift to mark cosmic history. Light whose wavelength has increased 200% has a redshift of 2 and was emitted when the universe was one-third its current size—about 10 billion years ago.)

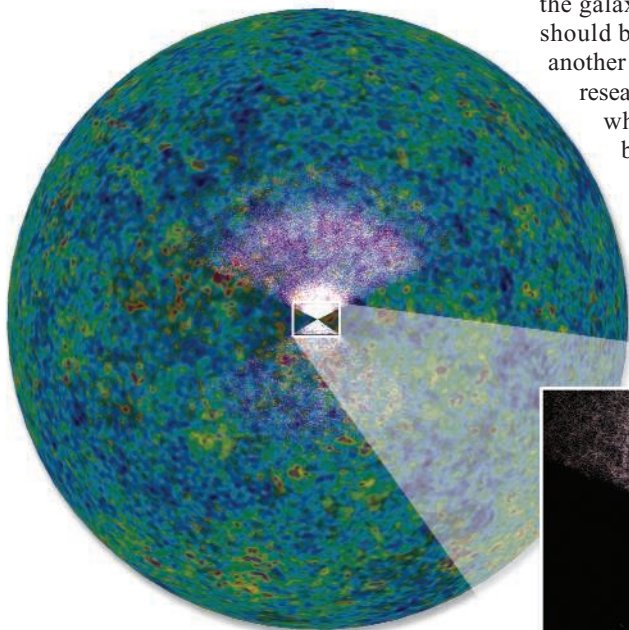
The CMB is not exactly uniform. Inflation magnified infinitesimal quantum fluctua-

* Cosmic Cartography: Mapping the Universe from the Big Bang to the Present, 3–6 December.

Cosmic Web

tions in the newborn universe, which eventually seeded the filaments in the cosmic web. The fluctuations also caused the temperature of the CMB to vary across the sky by about 0.001%. Analyzing the temperature ripples, and throwing in supernova and galaxy-cluster data, WMAP researchers found that, bizarrely, the universe consists of 73% dark energy, 23% dark matter, and 4% ordinary matter and is precisely 13.7 billion years old (*Science*, 19 December 2003, p. 2038).

“The CMB is a great gift because the fluctuations are big enough to measure but small enough to be easily understood,” says Gary



Hinshaw, a cosmologist at NASA’s Goddard Space Flight Center in Greenbelt, Maryland. “You can read the parameters right off the spectrum” of ripples. But plenty of questions remain, says cosmologist Edward “Rocky” Kolb of the University of Chicago. “The rough picture works,” he says, “but the details of how galaxies form, how they interact, and whether mergers and acquisitions [of galaxies] are important still need to be worked out.”

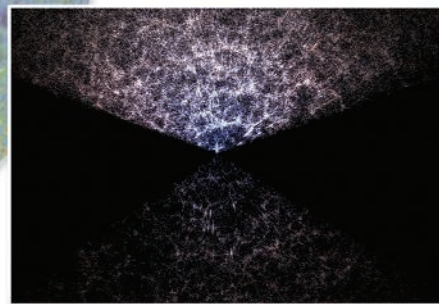
Filling in the fishbowl

Scientists hope to trace the web from near to far, from the present into the past. Humans have glimpsed the oldest light, the CMB, which appears to emanate from near the periphery of the observable universe 46.5 billion light-years away. (Everything farther away is rushing away so fast that its light will never reach us.) We’ve also started to explore the nearby cosmic web. So we’re a bit like fish in a murky bowl that see the smudgy glass and the castle next to them.

What’s in between remains to be discovered.

Primarily, researchers are charting the galaxies, which lie within the dark-matter strands. In 2005, they forged a link between the ripples in the distribution of the galaxies and those in the CMB. Before atoms formed and as matter settled into the primordial fluctuations, protons pushed against light, sending tsunami-like sound waves zipping through space. Leaving their imprint on the CMB, the waves traveled about 100 kiloparsecs—326,000 light-years—before atoms formed.

Stretched 1000-fold by the expansion of the universe, that length scale should show up in the galaxies, too. Given one galaxy, there should be an increased chance of finding another that distance away, precisely what researchers with the Sloan survey found when they compared the distances between galaxies, says Ravi Sheth, a cosmologist at the University of Pennsylvania. More-precise measurements of such “baryon acoustic oscillations” could give researchers another way to study the expansion of the universe and might help reveal whether dark



The fishbowl. The cosmic microwave background shown as a sphere with the galaxies surveyed by the Sloan Digital Sky Survey positioned inside it.

energy is part of space itself or is something flowing through it.

Scientists are also probing the web by counting clusters of galaxies, which form when individual galaxies fall into gargantuan clumps of dark matter. The size and number of the swarms reveal the distribution of dark matter. At the same time, the stretching effects of dark energy slow the formation of jumbo agglomerations. So simply tallying the abundance of clusters of different sizes at different redshifts promises to reveal properties of both weird substances, says Toronto’s Yee.

Moreover, clusters are relatively easy to spot with optical and infrared telescopes, he says. That’s because the galaxies in them tend to be old and filled with red giant stars, all of

which emit light of essentially the same color. So by looking at the colors of the galaxies, astronomers can immediately tell which ones belong to the same cluster and what the cluster’s redshift is. Using this technique, Yee and colleagues with the Red-Sequence Cluster Survey, which uses the Canada-France-Hawaii Telescope atop Mauna Kea in Hawaii, have been scanning 1000 square degrees of sky and have cataloged 20,000 clusters.

Researchers are striving to “see” the dark-matter filaments by observing how their gravity bends light from more distant galaxies and skews their images. Known as weak gravitational lensing, the technique allows scientists to detect dark-matter blobs directly, without looking at the stars or galaxies in them, says Gary Bernstein, a cosmologist at the University of Pennsylvania.

Because of weak lensing, the galaxies ever-so-slightly tend to line up, like fish in a school. Researchers first observed the effect in 2000, and last year, Richard Massey, an astronomer at the California Institute of Technology in Pasadena, and colleagues took a big step further. Using images of half a million galaxies from NASA’s Hubble Space Telescope, they compared the lensing of galaxies at three different distances to crudely map a bit of the 3D web, as they reported in the 18 January 2007 issue of *Nature*. Ultimately, researchers hope to perform such 3D studies over huge swaths of the sky, Bernstein says.

Looking with other eyes

Staring at galaxies with optical and infrared telescopes is not the only way to study the cosmic web. For example, radio astronomers can join the hunt for galaxy clusters by looking for pimple-like spots in the CMB. Those spots arise because of a bit of physics called the Sunyaev-Zel’dovich effect. Microwave photons from the CMB crash into the electrons in hot, ionized gas within galaxy clusters, explains Matt Dobbs, an astrophysicist at McGill University in Montreal, Canada. The collisions change the microwaves’ energy, creating the telltale distortion. Because the effect does not depend on the cluster’s own light, it should help to reveal fainter, more distant clusters, Dobbs says.

So far, most studies have probed the Sunyaev-Zel’dovich effect in clusters already found some other way. But the Sunyaev-Zel’dovich Array, a collection of eight 3.5-meter radio dishes in Owens Valley, California, is scanning 6 square degrees of sky in a blind search for new clusters. And the 6-meter Atacama Cosmology Telescope in Chile

and the 10-meter South Pole Telescope will scan 200 and 4000 square degrees of sky, respectively, which should reveal thousands of clusters.

Researchers needn't look only at galaxies. Most ordinary matter resides not in stars and galaxies but in huge clouds of neutral and ionized gas. Astronomers can detect neutral hydrogen by looking toward celestial beacons called quasars. Whenever a quasar's light passes through atomic hydrogen, some of it will be absorbed, creating a dip, or absorption line, in its spectrum. The wavelength of the dip reveals the cloud's redshift, the width of the dip reveals its temperature, and the depth of the dip reveals the amount of gas in the cloud, explains astronomer Michael Rauch of the Observatories of the Carnegie Institution of Washington in Pasadena, California. By studying many quasars, researchers hope to map out the distribution of gas in the web.

Scientists might be able to go even a step further in time. Atomic hydrogen emits radio waves of a distinct wavelength, 21 centimeters, when the proton in the atom flips. Researchers hope to exploit that radiation to detect the distribution of hydrogen back when the universe was less than a billion years old, when the first stars were forming. To do that, however, they'll need an observatory such as the proposed Square Kilometer Array, a collection of hundreds of radio dishes that astronomers propose to build in South Africa or Australia sometime in the next decade.

Our lumpy neighborhood

Galaxies form in the web's smaller knots, and scientists are striving to determine how they swirl into existence. That's important because in galaxies, the dark-matter-dominated picture blurs. "It seems to work well on the large scales," says Kathryn Johnston, an astrophysicist at Columbia University. "Where there seem to be some problems is on the small scales." For example, simulations predict that the Milky Way should be surrounded by many more small satellite galaxies than astronomers have seen (*Science*, 3 August, p. 594).

Theorists know so little about galaxy formation that in their cosmological simulations, they let the dark matter evolve by itself and "paint" the galaxies onto the clumps and strands at the end. To fill the voids in their understanding, scientists are studying our own galaxy. "The Milky Way is the only galaxy for which we can hope to get three-dimensional data about the positions and velocities" of individual stars, says Heidi Newberg, an astrophysicist at Rensselaer



Crash of the Titans.
The Milky Way formed through collisions like this one between distant spirals.

Polytechnic University in Troy, New York.

Most of the Milky Way's stars lie in its thin disk. But that disk resides in a fatter blob of dark matter known as a halo. Scientists once thought that the halo was smooth and that the stars in it were evenly distributed. In the past decade, that picture has changed thanks largely to star studies made by the Sloan survey. "As we keep looking deeper at the data, we keep seeing more and more lumps and things," Newberg says. "There are big lumps, little lumps, smeared-across-the-sky lumps. It's just lumps everywhere."

The halo seems to have been produced exclusively through the mergers of smaller galaxies, Newberg says. As the smaller galaxies fall in, the Milky Way's gravity tears them into sinuous "tidal streams," such as the Sagittarius stream, which arches over the disk. By measuring the positions and velocities of stars, researchers can determine, statistically, which ones belong to which stream. And they may be able to make clearer connections by comparing the stars' chemical content, Johnston said at the meeting.

Mapped out?

Ultimately, the cosmic web may bridge the divide between cosmology on one hand and astronomy and astrophysics on the other. Cosmologists seek to reduce the universe to its most basic ingredients and rules. Astronomers and astrophysicists study the myriad objects in the heavens and try to explain how they work and whether they are related to one another. In principle, the cosmic web ties the two types of work together. Whether it will in practice remains to be seen, says Chicago's Kolb. "Ten or 20 years from now, we may look back and say it had that unifying effect," he says. "But we're too close to it now" to know if that will be the case.

Nevertheless, interest in the web is helping to change the craft of astronomy, fueling the drive to ever-larger surveys. For example, even as the Sloan survey continues, researchers with the Dark Energy Survey plan to use the 4-meter Blanco Telescope at the Cerro Tololo Inter-American Observatory in Chile to observe 5000 square degrees of sky and pinpoint 200 million galaxies. The first Pan-STARRS telescope on Mauna Kea will survey 3/4 of the sky—30,000 square degrees—starting this year. And researchers have proposed an 8.4-meter behemoth known as the Large Synoptic Survey Telescope that would use a 3-gigapixel camera to image 10 square degrees of the sky at a time and fix the positions and redshift of 3 billion galaxies starting in 2014.

Many embrace the bigger-is-better approach. "You're compelled to do this by the science," says Steven Myers, an astronomer at the National Radio Astronomy Observatory in Socorro, New Mexico. "I'm very enthusiastic for the new age of great survey projects."

Surveys are growing so large that some researchers are beginning to talk of spotting all the 100 billion bright galaxies in the observable universe. The cosmos will always provide new mysteries, says Timothy McKay, an astrophysicist at the University of Michigan, Ann Arbor, who works on both the Sloan survey and the Dark Energy Survey, but researchers should eventually chart all of its large features. "We should look forward to a future in which the universe we can observe will be observed," he says. "This cosmos incognita will be mapped out in our lifetimes."

Researchers won't run out of galaxies to observe for a while, however. In the meantime, they've got plenty to do as they try to weave a deeper understanding of the cosmos one conceptual thread at a time.

—ADRIAN CHO

PERSPECTIVE

The Cosmic Web in Our Own Backyard

Rodrigo A. Ibata¹ and Geraint F. Lewis²

On the largest scales, matter is strung out on an intricate pattern known as the cosmic web. The tendrils of this web should reach right into our own cosmic backyard, lacing the Galactic halo with lumps of dark matter. The search for these lumps, lit up by stars that formed within them, is a major astronomical endeavor, although it has failed to find the huge expected population. Is this a dark matter crisis, or does it provide clues to the complexities of gas physics in the early universe? New technologies in the coming decade will reveal the answer.

The universe is seen to be awash with billions of galaxies, some larger and many smaller than our own Milky Way. A census of the galaxies, however, reveals a startling property of our universe: Galaxies are not dotted randomly throughout the cosmos but are generally concentrated in groups or clusters, which are themselves connected by a multitude of filaments known as the cosmic web. At first sight, this observation stands in stark contrast to our knowledge of the state of the early universe, which was remarkably smooth, as inferred from the almost-uniform temperature of the cosmic microwave background over the sky (1, 2). This background radiation also reveals the seeds of galaxy formation, possessing tiny inhomogeneities that grew under the influence of gravity into the universe we see around us today. In recent years, it has become clear that the filamentary distribution of the galaxies can only be explained by requiring the presence of vast quantities of unseen material enveloping galaxies (3). Indeed, this dark matter is by far the dominant mass in the universe, and all visible material, such as stars and gas, essentially only goes along for the ride.

To explain the large-scale distribution of galaxies in the sky, dark matter must be “collisionless,” meaning that two pure dark matter entities would pass through each other like ghostly bodies, feeling only the mutual gravitational tug, with an absence of any material contact. This, of course, means that, whatever shapes the dark matter is inclined to take, these will only depend on the physics of gravity, which on the scale of galaxies is approximated well by Newton’s law of gravitational forces. Using these physical principles in a cosmological setting to predict the evolution of structure from an initially homogenous starting point early in the universe, computer simulations have shown that the natural outcome is the growth of roughly spherical dark matter “halos” (4), as

well as the development of tenuous filaments connecting them (5). A fascinating aspect of Newton’s law of gravity is that it makes no mention of any special distance scale over which gravity should work, and this means that, if additional forces such as gas and radiation pressure can be ignored, the

structure of the dark matter on the scales of clusters of galaxies will be similar to the structure of the dark matter on the scales of the smallest of galaxies (6) (nearly a factor of a billion lower in mass).

This is precisely what is seen in numerical models of the growth of cosmological structure, with massive halos of dark matter playing host to a multitude of smaller halos and filaments, and, just like Swift’s big fleas and little fleas, this hierarchical structure must continue on all scales (7), from clusters of galaxies, to the dark matter halos of galaxies like our own Milky Way, and down to the subcomponents of these galaxies. Testing the veracity of this prediction, that the cosmic web has strands that wind their way into our Galaxy (Fig. 1), has been the focus of a substantial observational effort by several research teams around the world.

The nearby filaments connect our Local Group of galaxies to the large-scale cosmic web, and computer models reveal that these filaments should channel a steady rain of pristine

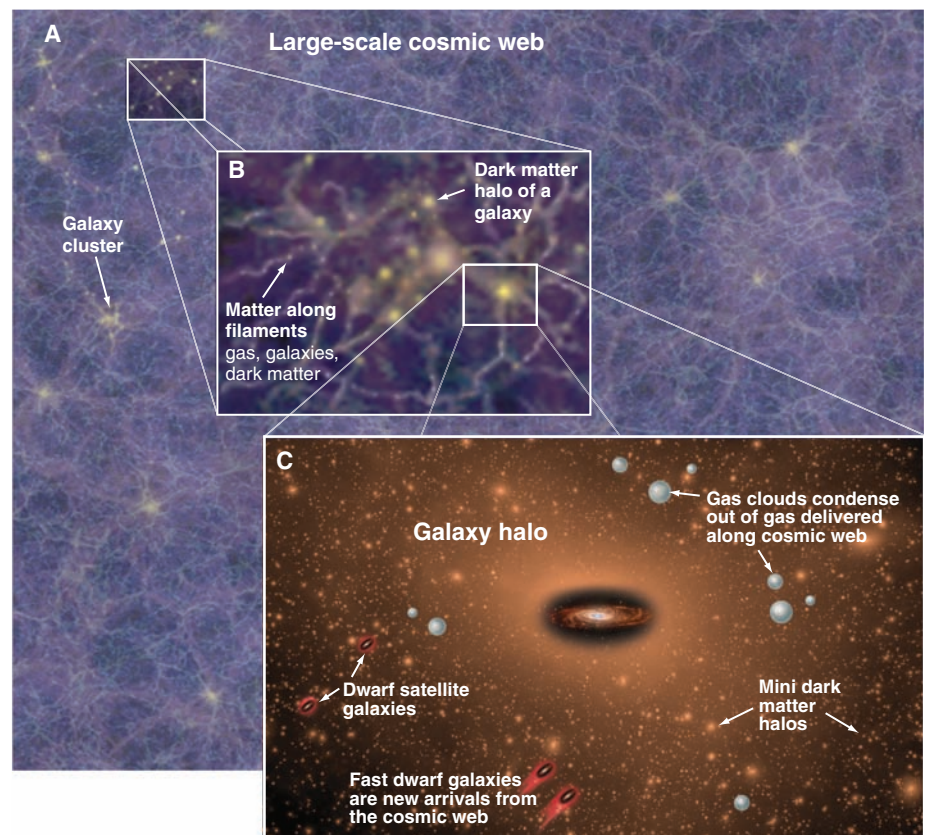


Fig. 1. Schematic diagram showing the position of a typical galaxy within the cosmic web. (A) On the very largest scales, clusters of galaxies are linked up by filaments of dark matter. (B) Within the filaments we find the dark matter halos of numerous galaxies, as well as very tenuous reservoirs of gas. (C) Zooming into halo of a galaxy like the Milky Way, theory predicts that the structure of the halo should be homologous to that of a cluster of galaxies, possessing a vast swarm of smaller subhaloes. Some of these subhaloes may be populated by stars (in which case we detect a dwarf satellite galaxy) and others may contain only gas, whereas the majority may be purely composed of dark matter and hence invisible.

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dwarf galaxies, comprising stars and dark matter, into the local environment. Because they fall in from large distances and accelerate over a large fraction of the age of the universe, those dwarf galaxies that are in the process of arriving today can be expected to exhibit very large speeds, and this is precisely what has been detected recently with two new high-speed galaxies in the vicinity of Andromeda, And XII (8) and And XIV (9); these are probably among the newest arrivals to the Local Group of galaxies.

Gas is also conveyed into galaxies along the filaments, but because of pressure forces this is rapidly slowed down, first shock heating and then condensing into clouds that fall into the center of the gravitational well and contribute to the buildup of the gaseous disk component of galaxies. For several decades, we have known that clouds of atomic hydrogen, known as high-velocity clouds, surround the Milky Way, and beautiful radio observations of the Andromeda galaxy (10) have recently shown a similarly rich distribution of cold gaseous structures raining down upon that galaxy. Hence, both large galaxies within the Local Group appear to be continually accreting gas fed to them from the cosmic web.

But what is the future of the recently accreted dwarf galaxies? Some may pass straight through the Local Group, but orbits of others will be degraded over time through the process of dynamical friction, eventually bringing them into the powerful tidal fields of the massive galaxies. Once a dwarf has strayed too close, these tidal forces act to steadily shred it, ripping off stars and gas to form extensive tidal streams of stars that envelope the galaxy. Two prominent examples, the Sagittarius and the Monoceros streams (11, 12), are visible within the Milky Way, with the Giant Stellar Stream (Fig. 2) dominating the halo of Andromeda (13). Many smaller, fainter streams, allowing us to get an accurate picture of the current rate of assimilation of stars into these galaxies, accompany these debris tails. Clearly, the process of galaxy formation for both the Milky Way and Andromeda galaxies is still under way, with the break-up of these dwarf galaxies directly contributing to the stellar populations in the galactic disk and halo, all ultimately fed by the cosmic web.

Although observations confirm the drizzle of new material into the Local Group and ultimately onto galaxies, from our computer models we also expect a large population of small dark matter halos to accompany the Milky Way and Andromeda. But what do surveys of our own backyard actually reveal? Although some dwarf satellite galaxies have been known since time immemorial (the Large and Small Magellanic Clouds were known to ancient inhabitants of the Southern Hemisphere), recent discoveries from the Sloan Digital Sky Survey (14) show that the Milky Way does indeed play host to a much larger pop-

ulation of small dwarf galaxies than previously known, with the puniest of these having masses that range down to a millionth of that of our own Galaxy (15). The work of our own team using the giant, wide-field camera of the Canada-France-Hawaii Telescope (Fig. 2) indicates that a similar population is also present around our nearest large neighbor, the Andromeda galaxy (16).

However, a major problem remains; the dark matter paradigm predicts that a myriad of dark matter halos, literally thousands of them, should be seen orbiting these giant galaxies, many more than the 20 or so dwarf galaxies that are actually observed (17). So, where are the missing galaxies? This question has been the root of substantial argument, with many experts suggesting that the dark matter halos are there but are not visible

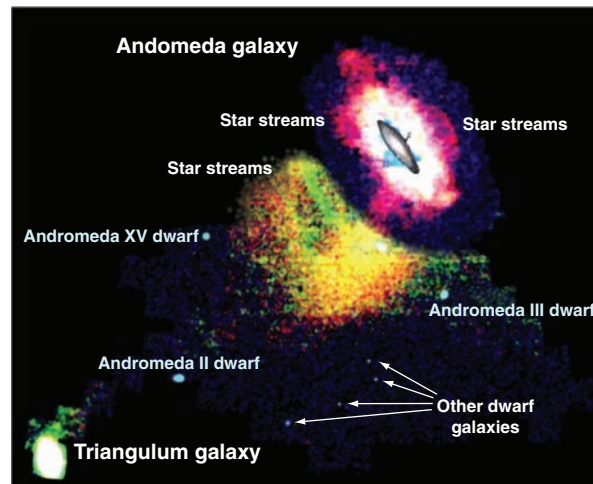


Fig. 2. Stellar structures detected between the Andromeda and Triangulum galaxies, two neighboring galaxies to our own, which are separated by about 700,000 light years. Andromeda, which is a classical spiral galaxy similar to our own Milky Way, has a disklike main body, but at large distances we detect numerous satellite galaxies and star streams. The star streams are the remnants of ancient satellites that have been destroyed by the powerful gravitational tides of Andromeda.

because star formation was extinguished early in the history of these tiny galaxies (18). Although astronomers are now examining more novel approaches, such as gravitational lensing, to search for small-scale dark matter halos that are truly dark, some have suggested that perhaps they are just not there. This would have far-reaching consequences for fundamental physics because our favored dark matter model would need to be reexamined.

Although the number of dark matter halos may not meet our theoretical expectations, studying our local dwarf galaxy population can provide important clues to the origins of the Milky Way and the Local Group of galaxies. Given that our best model of galaxy formation predicts that the Milky Way grew over time through the assimilation of such dwarf galaxies,

the existence of the Sagittarius dwarf galaxy, with its accompanying stellar stream that is depositing stars into the halo of the Milky Way, demonstrates that this formation mechanism is at least partially true. Nevertheless, there are problems with this scenario: Recent detailed chemical analyses indicate that the dwarfs we see around us today could not be the basic building blocks from which the majority of the Milky Way was constructed because they have a different distribution of chemical elements (19). However, in this picture, the surviving dwarf galaxies possess unusual properties compared with those of the bulk of the original population, being on average both more distant and less massive than those that were assimilated in the formation of the Galaxy. Proponents of the hierarchical formation

picture assert that this selection bias may account for the difference in chemical makeup of the remaining dwarfs compared with that observed in the halo of the Milky Way (20). What is needed to settle this issue is a detailed study of remnants of ancient accreted galaxies to compare to “normal” stars; the difficulty is identifying bona fide remnants.

It is now clear that the Milky Way and the entire Local Group are dynamically evolving entities, greatly influenced by the cosmic web; can we guess where the breakthroughs in the study of this lie? We know that the tidal debris from a disrupted satellite galaxy will take a long time to disperse, and hence galaxies should be riddled with the fossil evidence of past accretion events (21). The steadily growing field of galactic archaeology uses kinematic and chemical fingerprinting, determining the precise

chemical makeup of the star, to search for groups with a common origin (22); stars that are born together, either within the Galaxy or brought in through accretion, will possess many common properties. We are patiently awaiting the arrival of massive multifiber systems, especially the proposed Wide Field Multi-Object Spectrograph (WFOS) on an 8-m-class telescope, to provide the massive data sets to begin to disentangle the complex accretion history and dynamical mixing of large galaxies.

Probably the most important contribution to this field will come from the GAIA experiment. Starting in 2011, this cornerstone project of the European Space Agency will map and measure the motions of over a billion stars in our Galaxy with precision orders of magnitude greater than what is currently possible. Coupled with the

detailed chemical analysis provided by WFMOS, we will, for the first time, be able to reunite the long-dispersed stars from ancient accretion events, completely dissecting the Milky Way and laying bare its history. We will then be able to directly determine to what extent the Galaxy was built from dwarf galaxies that fell in through the local cosmic web.

What are the future challenges in understanding our local cosmology? Clearly, we are entering the age where near-field archaeologists will be awash with observational data, and we will be faced with the kinematics of a billion stars and detailed chemistry of several million stars not only in the Milky Way but also within our nearest neighbors. The resulting data challenges are substantial, and novel data-mining techniques will be required to cross-match the kinematic and chemical fingerprints to uncover stellar siblings. But how are the results of this to be interpreted? Again, astronomers will have to rely on the power of numerical simulations to examine in detail the growth of the Milky Way through the con-

tinual accretion of dwarf galaxies. However, it is important to remember that a galaxy like our own Milky Way contains roughly 200 billion individual stars, embedded within a much more massive dark matter halo, and as of yet no computer can track the complex gravitational interplay between these many bodies. Hence, our current simulations, where a single particle will represent roughly 10 to 100 thousand stars, present us with an exceedingly crude, sledgehammer view of the subtleties of galaxy formation, and we will need a revolution in computer power before we truly understand the origins of the Milky Way galaxy and its relation to the cosmic web.

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PERSPECTIVE

Numerical Simulations Unravel the Cosmic Web

Claude-André Faucher-Giguère,* Adam Lidz, Lars Hernquist

The universe is permeated by a network of filaments, sheets, and knots collectively forming a “cosmic web.” The discovery of the cosmic web, especially through its signature of absorption of light from distant sources by neutral hydrogen in the intervening intergalactic medium, exemplifies the interplay between theory and experiment that drives science and is one of the great examples in which numerical simulations have played a key and decisive role. We recount the milestones in our understanding of cosmic structure; summarize its impact on astronomy, cosmology, and physics; and look ahead by outlining the challenges faced as we prepare to probe the cosmic web at new wavelengths.

Cosmologists envision a universe made up of filaments, knots, and sheets reminiscent of pancakes (1), dubbed the “cosmic web” by Bond and collaborators (2). This picture of the cosmos—now well entrenched even in popular culture—is, however, much more than mere fantasy. Indeed, it is one of the best-established results of cosmological research and underpins much of our contemporary understanding of large-scale structure and galaxy formation.

After Schmidt’s spectroscopic observations of a distant quasar (a fantastically bright point source located at a cosmological distance, later understood to be powered by a supermassive black hole

accreting from its host galaxy) in 1965 (3), Gunn and Peterson (4) and (independently) Scheuer (5) and Shklovski (6) pointed out that the spectra of distant quasars should show absorption by neutral hydrogen along the line of sight blueward of their Lyman- α ($\text{Ly}\alpha$) emission line. Refining this calculation, Bahcall and Salpeter (7) argued that the clumpy intergalactic gas should give rise to a collection of discrete absorption lines, termed the “ $\text{Ly}\alpha$ forest.” The following year, observers, particularly Lynds and co-workers (8), indeed saw those lines.

Their exact nature, however, gave rise to a more extended and heated debate. Were the lines—then poorly resolved—really of cosmological origin, or were they instead associated with the quasars themselves? The extreme conditions needed for quasar ejecta to produce the $\text{Ly}\alpha$ forest (9), the random redshift distribution of the

absorption lines (10), as well as the association of metal-rich systems with intervening galaxies (11), eventually left no doubt that most of the $\text{Ly}\alpha$ clouds are in fact cosmological.

Inspired by research on the interstellar medium, the $\text{Ly}\alpha$ absorbers were originally envisioned as dense, cool clouds confined by pressure within a hotter, tenuous intercloud background (12, 13). However, this model raised questions of its own, namely, how did the clouds form in the first place? Ultimately, the model simply failed to account for the observed distribution of neutral hydrogen column densities, and other confinement mechanisms involving gravity were also found unsatisfactory.

The key breakthrough in elucidating the nature of the $\text{Ly}\alpha$ forest came as astrophysicists tried to understand the formation of structure in the universe. In our current model of structure formation, tiny fluctuations in the primordial plasma grew through the gravitational instability, eventually forming a cosmic network of knots, filaments, and sheets. Because gravity is a purely attractive force, regions of slightly higher density in the early universe accrete matter from their surroundings and grow more overdense with time. As the universe evolves, the cosmic web sharpens: Underdense regions, known as voids, empty material onto the filaments, and this material subsequently flows into overdense knots (Fig. 1). On large scales, where gas pressure can be neglected, intergalactic neutral hydrogen should trace this web.

What if, then, the $\text{Ly}\alpha$ forest were simply a representation of the cosmic density field? This was a far-reaching question transcending intergalactic clouds, for its answer not only would provide a powerful test of structure formation

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models but also would potentially leave us with a new and exquisitely detailed astrophysical and cosmological probe.

After promising analytical calculations, particularly by Rees (14), suggested that absorption by gas confined in dark matter “mini-halos” could account for the basic properties of the Ly α forest, two major developments in the 1990s al-

initial conditions motivated by the cosmic microwave background down to the current epoch [see discussion and references in (17)]. Zel’dovich did anticipate the cosmic network of filaments, knots, and sheets seen in the simulations. However, the detailed simulations turned the model into a quantitative one, with predictions worthy of comparison against the exacting data now available. Assum-

The discovery of the cosmic web in the Ly α forest has had a broad and profound impact beyond confirming the gravitational instability paradigm for structure formation and explaining the basic properties of the intergalactic medium in a cosmological context. In current hierarchical models of structure formation, condensed objects such as galaxies are thought to form in the denser clumps of the cosmic web. The same numerical simulations that were so successful in explaining quasar absorption systems can thus be used to theoretically calculate the spatial distribution of galaxies, another prediction that can be put to stringent test by observations, and indeed has been vindicated by galaxy surveys. The intergalactic medium probed by current observations is almost fully ionized, owing to the ultraviolet radiation field from star-forming galaxies and the super-massive black holes powering quasars. The imprint of the cosmic web in the Ly α forest, arising from the small residual fraction of neutral gas, thus also traces the cosmic radiation content, providing a unique record of the cosmic history of star formation and black hole growth (20).

Observations of the cosmic web have reached beyond astrophysics and into fundamental physics as well. In the paradigm of structure formation that the Ly α forest has been instrumental in establishing, the cosmic web is nothing but an evolved snapshot of the tiny primordial fluctuations produced at the very beginning, in an epoch of “inflation” during which the universe expanded by more than 25 orders of magnitude in size. By measuring the detailed properties of the cosmic web, we can constrain the properties of inflation itself and the physical mechanisms driving it (21, 22). In addition, an overwhelming number of lines of evidence, including galactic rotation curves, the velocity dispersions of galaxy clusters, and gravitational lensing, indicate that the cosmic matter budget is dominated by invisible “dark matter.”

Owing to its lack of nongravitational interactions with the rest of the universe, however, the nature of dark matter remains largely a mystery. The leading dark matter candidate is an exotic particle, never yet observed in Earth-bound laboratories, generically referred to as a “weakly interacting massive particle,” or WIMP. Observations of large-scale structure through galaxy surveys first ruled out the neutrino as a candidate for “hot” dark matter (23), leading to the present cold dark matter paradigm, and are now putting severe upper limits on the neutrino’s mass (24). The Ly α forest, being more sensitive to smaller scales on

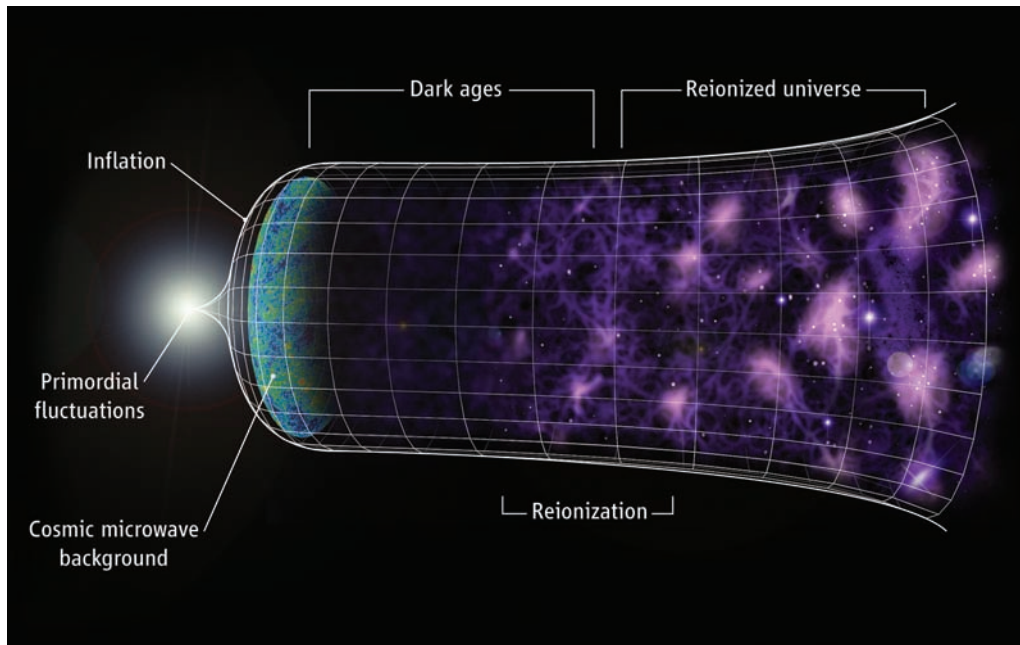


Fig. 1. View of the expanding universe illustrating the evolving cosmic web. Primordial fluctuations of quantum mechanical origin are stretched by an early superluminal phase of expansion known as “inflation.” Four hundred thousand years after the Big Bang, these fluctuations imprint tiny anisotropies in the cosmic microwave background as electrons and protons combine to form neutral hydrogen. As the universe continues to expand, these fluctuations grow through the gravitational instability, eventually giving rise to the first stars and galaxies, whose radiation reionizes the intergalactic medium, thereby ending the cosmological “dark ages.” The cosmic web sharpens as the universe becomes more mature and becomes visible in the Ly α forest and in the spatial distribution of galaxies.

lowed astrophysicists to tackle the question with unprecedented precision: the advent of high-resolution spectrographs and numerical cosmological simulations. The new High Resolution Echelle Spectrometer (HIRES) spectrograph installed at the Keck Observatories on Mauna Kea, Hawaii, provided quasar spectra with fully resolved Ly α forests. At about the same time, the Cosmic Background Explorer (COBE) satellite had recently detected small anisotropies, subsequently mapped in sharp detail by the Wilkinson Microwave Anisotropy Probe (15), imprinted on the cosmic microwave background when the universe was only 400,000 years old (16). The COBE observations fueled efforts to model the growth of structure in the universe. Did the minuscule fluctuations in the very early universe observed by COBE actually evolve into the rich structure observed by astronomers? After advances in computer algorithms and technology, first-principles simulations traced the hydrodynamic evolution of cosmic structures from

ing that the Ly α forest originated from absorption by intervening neutral hydrogen, it was then straightforward to produce mock spectra, which could be tested directly against the actual observations (Fig. 2).

The results of these analyses showed that the simulations were exactly right. In particular, the calculations of (18, 19) demonstrated correspondence between observations and theory over nearly eight orders of magnitude in the strength of the absorbing structures, at the time an unprecedented achievement in numerical cosmology. The level of agreement has only improved over the past decade as simulations and observations have been refined and as our knowledge of the underlying cosmological model has become firmer. The conclusion appears inescapable: The primordial fluctuations seen in the cosmic microwave background did grow by five orders of magnitude over billions of years, precisely as calculated, to form the observed cosmic web.

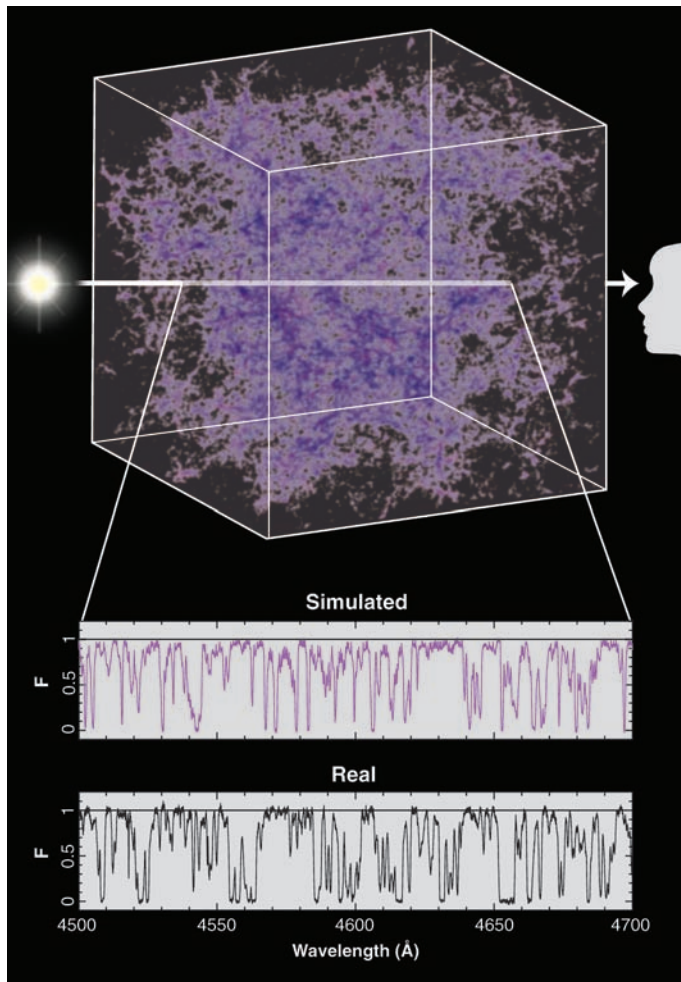


Fig. 2. Illustration of the Ly α forest. An observer looks at a distant quasar. Neutral hydrogen tracing the cosmic web produces absorption features, collectively known as the Ly α forest, in the quasar spectrum. The figure shows a line of sight through a cosmological simulation, with the resulting mock Ly α forest compared to the spectrum of an actual quasar, known as Q1422, and located at redshift $z = 3.6$ (spectrum courtesy of M. Rauch, Observatories of the Carnegie Institution of Washington, Pasadena, CA, and W. Sargent, California Institute of Technology, Pasadena, CA). The similarity between the mock and actual spectra is remarkable, unambiguously elucidating the nature of the Ly α forest as the imprint of cosmological fluctuations. Each spectrum has been normalized by its continuum level.

the order of 1 megaparsec, currently provides the most rigorous constraints on intermediate models of “warm,” more massive, dark matter (25, 26).

The bulk of research on cosmic structure, in particular from the Ly α forest and galaxy surveys, has thus far focused on observations in the optical part of the electromagnetic spectrum. Astronomy, however, is an increasingly multi-wavelength endeavor, and the study of the cosmic web is poised to follow this trend as new frontiers are explored. Accordingly, new opportunities for novel theoretical calculations and observational discoveries abound.

One of the most exciting frontiers of contemporary cosmology is the early universe, when the first stars and galaxies formed and illuminated their surroundings. During this epoch of “reionization,” electrons were unbound from hydrogen atoms (which had combined to become neutral at the time the anisotropies were imprinted in the cosmic microwave background) by ultraviolet radiation, which had begun filling intergalactic space. Neutral hydrogen before and during reionization can potentially be observed through its emission of 21-cm radio radiation. Several low-frequency observatories—such as the Murchison

Widefield Array (MWA) in Western Australia, the Low Frequency Array (LOFAR) in the Netherlands and, ultimately, the Square Kilometer Array (SKA)—are being planned, constructed, or entering service to detect this redshifted emission. Simultaneously, ever more powerful infrared telescopes are attempting to discover the first sources of light directly. This is in fact a primary scientific goal of the James Webb Space Telescope, the Hubble Space Telescope’s successor scheduled for launch in 2013, as well as of very large ground-based observatories.

New windows are also now opening on the lower-redshift universe. A new ultraviolet spectrograph, the Cosmic Origins Spectrograph (COS), will be installed aboard Hubble during its 2008 servicing mission and will provide a direct and detailed probe of the cosmic distribution of helium at intermediate redshifts. Because more energetic photons are required to doubly ionize helium, it is thought to have been fully ionized later than hydrogen, near the peak of quasar activity. The study of helium reionization thus promises to become a powerful probe of quasar activity and its feedback on the intergalactic medium in the very near future.

At still lower redshifts, the nonlinear growth of cosmic structure shocks the intergalactic medium, heating it to temperatures up to 10^7 K (27, 28). The high temperatures in the local “warm-hot intergalactic medium,” or WHIM, imply that yet heavier elements are ionized and hence that higher-energy wavelengths, including x-rays, are the probes of choice for this physical regime.

Each of these observations is, however, accompanied by theoretical challenges. The epochs of hydrogen and helium reionization involve non-equilibrium radiative transfer phenomena, which are only beginning to be included in cosmological simulations. Simulations must evolve large regions of the universe to overcome cosmic variance and capture the large scales of reionization, yet high resolution is needed to resolve the sources and sinks of radiation, as well as the clumpiness of the gas. At the present time, approximations are used to treat the problem with available computational resources and explore the important effects without resorting to prohibitive, fully self-consistent radiation hydrodynamics (29, 30). Feedback processes such as galactic winds and metal enrichment are only crudely, if at all, included and may be particularly important to understand the low-redshift high-energy absorption. Moreover, star and galaxy formation and quasar activity are often modeled using prescriptions, which, albeit physically motivated, do not offer the satisfaction of ab initio calculations.

As the rich array of new and diverse observations promises a wealth of surprises, will the theoreticians be clever enough to provide results with true predictive power for the multiwavelength cosmic web?

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PERSPECTIVE

Missing Baryons and the Warm-Hot Intergalactic Medium

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Stars and gas in galaxies, hot intracluster medium, and intergalactic photo-ionized gas make up at most half of the baryons that are expected to be present in the universe. The majority of baryons are still missing and are expected to be hidden in a web of warm-hot intergalactic medium. This matter was shock-heated during the collapse of density perturbations that led to the formation of the relaxed structures that we see today. Finding the missing baryons and thereby producing a complete inventory of possibly the only detectable component of the energy-mass budget of the universe is crucial to validate or invalidate our standard cosmological model.

Despite recent progress in cosmology in assaying the energy and mass budget of the universe, very little is still known about the nature and origin of most of its constituents. Within the framework of our standard cosmological model (SCM) (1, 2), most (95%) of the universe (or Ω_b , the mass density of the universe divided by the critical density required to close the universe) is composed primarily of “dark” energy (70%) and “dark” matter (25%), both dubbed “dark” as a reflection of our inability to directly detect and identify them. Less well known is that the situation is only marginally better for the universe’s remaining 5% of detectable matter.

As baryons—the protons and atomic nuclei that constitute the ordinary matter of which stars, planets, and ourselves are made—this remaining matter should, in principle, be in a form that we can detect and measure in its physical state. We know from absorption line spectroscopy of distant quasars that clouds of baryons were present in the early universe about 10 billion years ago (redshift $z \cong 2$) (3, 4), in the form of photo-ionized diffuse intergalactic gas, accounting for at least three-quarters of the total baryon mass in the universe as inferred by both cosmic microwave background anisotropies (1, 2) and “big-bang nucleosynthesis” predictions when combined with observed light-element ratios at $z > 2$ (5) ($\Omega_b > 3.5\%$, i.e., $>73\%$ of the estimated baryon

mass in the universe). However, these clouds of photo-ionized intergalactic gas became more and more sparse as time moved toward the present and structures (galaxies, galaxy groups, and clusters)

started to be assembled. Only a small fraction of the baryons that were present in the intergalactic medium at $z > 2$ are now found in stars, cold or warm interstellar matter, hot intracluster gas, and residual photo-ionized intergalactic medium. Today we can account for less than 50% of the baryon mass predicted by the SCM, implying that at least 50% of the baryons are now “missing” (6, 7) (Fig. 1).

The leading theory of cosmological structure formation (known as Λ -CDM; or, cold dark matter models including dark energy, designated by the cosmological constant Λ) predicts that, as the universe evolves toward the present and density perturbation grows to form structures, baryons in the diffuse intergalactic medium accelerate toward the sites of structure formation under the growing influence of gravity and go through shocks that heat them to temperatures of millions of kelvin. These “missing baryons” may have become difficult to detect by being concentrated in a filamentary web of tenuous (baryon density

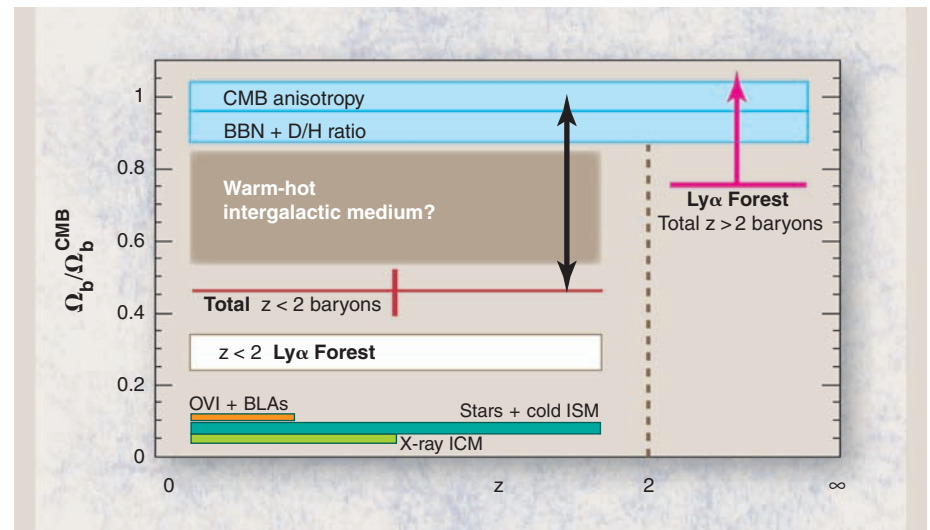


Fig. 1. Baryon density in the universe, at all redshifts, normalized to the cosmological mass density of baryons derived from cosmic microwave background (CMB) anisotropy measurements. Two completely independent measures, based on anisotropies of the CMB, on one hand, and on observations of the deuterium-to-hydrogen (D/H) ratio combined with big bang nucleosynthesis (BBN) models, on the other, nicely converge toward a total cosmological mass density of baryons in the universe of $\sim 4.5\%$ (cyan shaded rectangle). At redshifts $z > 2$, nearly all the expected baryons are found in the Ly α forest (magenta lower limit; the measure is a lower limit due to uncertainties in the ionization correction). At $z \leq 2$, however, adding up the baryons observed in stars and cold interstellar medium (ISM) in galaxies, residual low- z Ly α forest, OVI and BLA absorbers, and x-ray hot gas in clusters of galaxies accounts for less than half of the expected cosmological mass density of baryons in the universe (red point). The rest of the baryons still elude detection, and hence are “missing baryons.” A theoretical solution to this problem has been relatively recently offered by hydrodynamical simulations for the formation of structures in the universe.

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Cosmic Web

$n_b \cong 10^{-6}$ to 10^{-5} cm^{-3} , corresponding to overdensities of $\delta = n_b/\langle n_b \rangle \cong 5$ to 50, compared with the average baryon density in the universe ($\langle n_b \rangle = 2 \times 10^{-7}$ cm^{-3}) warm-hot intergalactic medium (WHIM) that has been continuously shock-heated during the process of structure formation [e.g., (8)]. This matter is hot (10^5 to 10^7 K) and is so highly ionized that it can only absorb or emit far-ultraviolet (FUV) and soft x-ray photons, primarily at lines of highly ionized (Li-like, He-like, or H-like) C, O, Ne, and Fe [e.g., (9)].

If identifying the mysterious dark energy and dark matter is challenging, then the problem of missing baryons is more acute. One could even

filaments; optical and infrared multifilter photometry and spectroscopy measure the galaxy density around WHIM filaments, and so map dark-matter concentrations in the universe. These observations can then be used to feed and hence refine new simulations, to study and address the fundamental problem of feedback between virialized structures and the surrounding diffuse intergalactic medium. All this has only relatively recently become possible thanks to the advent of sufficiently high-resolution x-ray and UV optics {Chandra and Hubble Space Telescope (HST) and spectrometers [gratings on Chandra, HST, XMM-Newton (XMM, X-ray Multimirror Mis-

nation that is not yet available. The most promising observational strategy with current instrumentation is to search for the WHIM in absorption (as discrete absorption lines) in the UV and x-ray spectra of bright, intrinsically featureless, background astrophysical sources.

At WHIM temperatures, the dominant ions of oxygen (the most abundant metal in gas with solar-like composition) are OVII ($\cong 80\%$ of oxygen in the entire WHIM temperature range) and OVI ($\cong 20\%$ of oxygen at the low end of the WHIM temperature distribution). The strongest transitions from these ions are the OVI $1s^2 2s \rightarrow 1s^2 2p$ doublet at 1031.9 and 1037.6 Å (UV) and the OVII K α resonant at 21.6 Å (x-rays). The key to the detectability of an absorption line is the transition contrast, i.e., the ratio between the line wavelength and its equivalent width (EW), compared with the spectrometer resolving power. The line transition contrast expected from the WHIM is similar in the UV and the x-ray band: $[1031.9/\text{EW}(\text{OVI}_{1031.9})] \geq 1500$ to 15,000 versus $[21.6/\text{EW}(\text{OVII}_{21.6})] \geq 2700$ to 27,000. However, although the resolving power of the current UV spectrometers is similar to or better than the OVI transition contrast, in the x-ray band the situation is worse. Consequently, despite the dominant distribution of OVII expected in the WHIM (tracking 70 to 80% of the WHIM mass) compared to OVI, the search for the WHIM, so far, has been much more fruitful in the UV than in the x-ray band [e.g. (7, 13)].

Hydrodynamical simulations for the formation of LSS in the universe [e.g., (8)] successfully reproduce the measured number of OVI absorbers per unit redshift interval with EW larger than a given threshold (7, 9). Danforth and Shull (7) estimated the contribution of the WHIM baryons detectable through OVI absorption down to an OVI column density of $N_{\text{OVI}} > 10^{13.4}$ cm^{-2} (i.e., the low-temperature end of the WHIM mass distribution) to Ω , and found that it is, at most, only 10% of the missing baryons ($\Omega_{\text{OVI}} = 0.22\%$).

An alternative, and complementary, way of searching for the missing mass in the local universe is to look for hydrogen absorption in the form of broad Ly α absorbers (BLAs). At WHIM temperatures most of the H is ionized, but the residual HI (neutral hydrogen) can still imprint Lyman series absorption onto the UV spectra of background objects; these absorption lines must therefore be broad (with widths given by Doppler parameter $b \geq 42$ km s^{-1} , for temperatures $\log T \geq 5$). Richter and collaborators (13) analyzed HST spectra from the lines of sight to four bright active galactic nuclei (AGN) and found that the fraction of Ω detectable through BLAs down to $N_{\text{HI}}/b > 10^{11.3}$ $\text{cm}^{-2} \text{ km}^{-1} \text{ s}$ is $\Omega_{\text{BLAs}} = 0.27\%$, similar to the contribution to Ω detectable through OVI absorbers, and again only $\sim 10\%$ of the missing baryons. These studies prove not only that both BLAs and OVI absorbers can be considered potential good tracers of the WHIM, but also that

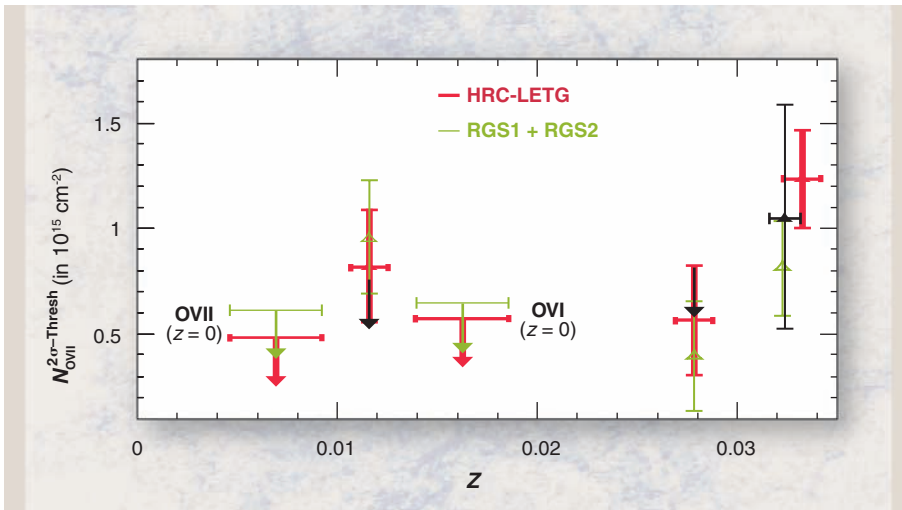


Fig. 2. Measurements (with associated 1σ errors) and 2σ upper limits of OVII column densities from $z = 0$ to $z = 0.03$ (the redshift of Mkn 421), as derived from the Chandra LETG (red symbols) spectrum of Mkn 421 (14, 15) and our (green symbols) and Rasmussen *et al.*'s (17) (black symbols) analyses of the XMM-Newton RGS spectrum of Mkn 421. The two bins at $z = 0$ to 0.004 and $z = 0.020$ to 0.024 contain absorption lines both in the LETG and RGS spectra, noncontroversially identified as $z = 0$ OVII and OVI transitions, and are not shown in this figure. In Rasmussen *et al.*, analysis of the RGS spectrum, the upper limits at $z = 0.011$ and $z = 0.027$ (black arrows) are fully consistent with the Chandra measurements within their 1σ statistical errors (red points). Moreover, in our analysis of the RGS spectrum of Mkn 421, we actually detect absorption lines at these two positions (green points at $z = 0.011$ and $z = 0.027$), with intensities consistent with those of the lines detected in the Chandra spectrum of Mkn 421.

argue that baryons represent the only directly detectable component of the predicted mass-energy budget of the universe [e.g., (10, 11)]. Moreover, determining the physical conditions, metal (heavy element) content, dynamics, and kinematics of these baryons, as a function of cosmic time, gives us a unique set of tools to study the evolution of large-scale structure (LSS) in the universe and the feedback mechanisms of gas ejected from galaxies and quasars onto LSS in the framework of such models [e.g., (12)].

This program of tracking the cosmic baryons can only be carried out by exploiting the synergies between multiwavelength observational approaches and theoretical computations: High-resolution x-ray and UV spectroscopy measures (i) relative and absolute metal content, (ii) ionization correction, and so (iii) mass of the WHIM

sion)] plus the Far Ultraviolet Spectroscopic Explorer (FUSE)}, on one hand, and the rapidly increasing power of today's computational resources (such as high-resolution hydrodynamical simulations, refined and extended atomic-data computations, nonequilibrium postshock ionization modeling), on the other.

Because of the extreme low density (1 to 10 particles per cubic meter) and relatively small size (1 to 10 Mpc) of the WHIM filaments, the intensity of the signal expected from the WHIM observables (either in emission or in absorption) is low, both in the UV and in the x-ray band. This makes the search for the missing baryons particularly challenging.

Direct detection of the emission signal from the WHIM requires ideally large field of view and effective area imager-spectrometers, a combi-

the WHIM itself has mostly likely been already detected through these two transitions in the UV band. However, owing to the high temperature of the WHIM, only a relatively small fraction of the WHIM distribution can be probed by BLAs and OVI absorbers; the vast majority (70 to 80%) of the missing mass remains to be found via the x-ray band.

Owing to the observational difficulty of making these measurements, they are controversial. The statistically strongest evidence to date comes from a Chandra LETG (low-energy transmission grating spectrometer) spectrum of the nearby ($z = 0.03$) blazar Mkn 421 that shows a number of absorption lines, some identified with two different intervening WHIM systems at $z = 0.011$ and $z = 0.027$ (14, 15) at significances of 3.5σ and 4.9σ , respectively. However, analysis of a better signal-to-noise (S/N), but poorer spectral resolution, XMM-Newton reflection grating spectrometer (RGS) spectrum of Mkn 421 does not show some of these absorption lines (16–18). We note (16), however, that both sets of observations are consistent within observational errors (Fig. 2). Further observations are thus required to definitely confirm or rule out the proposed WHIM detections along this line of sight.

Deep WHIM studies require both the UV and the x-ray bands. The x-ray band is crucial to detect the WHIM systems and derive an accurate ionization correction. The UV band is vital to measure the associated amount of HI and hence the baryonic mass in each system, which otherwise depends on the ratio of heavier elements to hydrogen (the “abundances”). The full potentiality of UV WHIM studies will be available only after the Shuttle Servicing Mission 4 has restored spectral capabilities to the HST; the new COS UV spectrograph will provide spectra of accurately selected bright x-ray targets with a S/N ratio sufficient to detect BLAs. In the x-ray band, the situation is far more challenging because future instruments are some way off. Current observational facilities should first be exploited to their limits.

According to theory, the chances of finding a WHIM filament along a random line of sight in

the universe increases with (i) the crossed path length between the observer and the beacon used to obtain x-ray images of the intervening space, and (ii) the inverse of the baryon column density in the filament: The larger the amount of baryons in the filament, the lower the probability of finding one. Observationally, instead, the chances of detecting such systems increase with the square root of (i) the detector throughput (the effective area A_{eff}), (ii) the spectrometer resolving power ($R = \lambda/\Delta\lambda$), and (iii) the amount of dedicated observing time (Δt); for a given instrument, A_{eff} and R are fixed parameters, and only the observation exposure Δt can be chosen.

It can be shown that detection of the WHIM is within the reach of current instrumentation, but it requires very long observations, on the order of several million seconds. Hydrodynamical simulations predict (9) a 95.5% chance of finding at least one OVII WHIM system with a column density $N_{\text{OVII}} \geq 8 \times 10^{14} \text{ cm}^{-2}$ along any random line of sight between $z = 0$ to 0.3. This probability increases to 99.7% when N_{OVII} is less than half this value. For background targets with a quiescent soft x-ray flux of $\geq 1 \text{ mCrab}$ (of which there are few), ~ 2 to 3 Ms and ~ 10 Ms are required, with either the LETG or the RGSs, to become sensitive, at a statistical significance $\geq 3\sigma$, to $N_{\text{OVII}} = 8 \times 10^{14} \text{ cm}^{-2}$ and $N_{\text{OVII}} = 4 \times 10^{14} \text{ cm}^{-2}$, respectively. Combined LETG and RGS exposures of up to ~ 10 Ms, therefore, would certainly allow us to either detect the WHIM or to disprove models.

Deep WHIM studies, however, await future missions. Constellation-X (19) [and to a similar extent XEUS (20) or any of the several proposed mission concepts dedicated to WHIM studies, e.g., Pharos (21) or Edge (22)] will allow us to study ~ 60 different lines of sight toward all the available extragalactic targets at $z \geq 0.3$ and with quiescent soft x-ray flux $\geq 0.2 \text{ mCrab}$, with average exposures of $\leq 100 \text{ ks}$ each. Lowering the flux threshold by a factor of only 2 (from 0.2 to 0.1 mCrab) would more than double the number of available targets, and hence the number of

lines of sight, requiring only twice as deep exposures per line of sight.

Alternative baryon reservoirs had been proposed before hydrodynamical simulations, run in the framework of a Λ -CDM universe, became available, which include, for example, large amounts of cold molecular gas around galaxies (23) or tenuous intragroup hot gas [e.g., (7)]. However, these scenarios clash with the outcome of Λ -CDM simulations, which all agree in predicting the WHIM as the main reservoir of baryons in the local universe. In the next decade, we will be in a position to trace all the WHIM baryons in the universe and so either see whether the missing baryon problem still holds or validate theoretical predictions and the SCM.

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