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The Cosmic Web in Our Own Backyard

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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.

he 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 almostuniform 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 highvelocity 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 population 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,

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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 (WFMOS) 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

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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 continual 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.

References

- 1. G. Smoot et al., Astrophys. J. 396, L1 (1992).
- 2. D. Spergel et al., Astrophys. J. 170 (suppl.), 377 (2007).
- 3. V. Springel et al., Nature 435, 629 (2005).
- 4. J. Navarro, C. Frenk, S. White, Astrophys. J. 490, 493
- (1997).
- A. Klypin, S. Shandarin, Mon. Not. R. Astron. Soc. 204, 891 (1983).

- 6. B. Moore et al., Phys. Rev. D 64, 063508 (2001).
- 7. J. Diemand, B. Moore, J. Stadel, Nature 433, 389 (2005).
- 8. S. Chapman et al., Astrophys. J. 662, L79 (2007).
- 9. S. Majewski et al., Astrophys. J. 670, L9 (2007).
- R. Braun, D. Thilker, Astron. Astrophys. 417, 421 (2004).
- 11. R. Ibata, G. Lewis, M. Irwin, E. Totten, T. Quinn, *Astrophys. J.* **551**, 294 (2001).
- 12. B. Yanny et al., Astrophys. J. 540, 825 (2000).
- R. Ibata, M. Irwin, G. Lewis, A. Ferguson, N. Tanvir, *Nature* 412, 49 (2001).
- 14. V. Belokurov et al., Astrophys. J. 654, 897 (2007).
- 15. B. Willman et al., Astrophys. J. 626, 85 (2005).
- N. Martin et al., Mon. Not. R. Astron. Soc. 371, 1983 (2006).
- A. Klypin, A. Kravtsov, O. Valenzuela, F. Prada, *Astrophys.* J. 522, 82 (1999).
- J. Bullock, A. Kravtsov, D. Weinberg, Astrophys. J. 539, 517 (2000).
- 19. K. Venn et al., Astron. J. 128, 1177 (2004).
- L. Sales, J. Navarro, M. Abadi, M. Steinmetz, Mon. Not. R. Astron. Soc. 379, 1464 (2007).
- K. Johnston, L. Hernquist, M. Bolte, Astrophys. J. 465, 278 (1996).
- K. Freeman, J. Bland-Hawthorn, Annu. Rev. Astron. Astrophys. 40, 487 (2002).

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Numerical Simulations Unravel the Cosmic Web

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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.

osmologists 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 bestestablished 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 (Ly α) 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 "Ly α 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 Ly α 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 Ly α clouds are in fact cosmological.

Inspired by research on the interstellar medium, the Ly α 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 Ly α 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 $Ly\alpha$ 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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