ASTRONOMY

Near-Field Cosmology

Cosmological puzzles are usually tackled by studying distant objects. A recent meeting considered the ways in which observations of nearby galaxies can add to the picture.

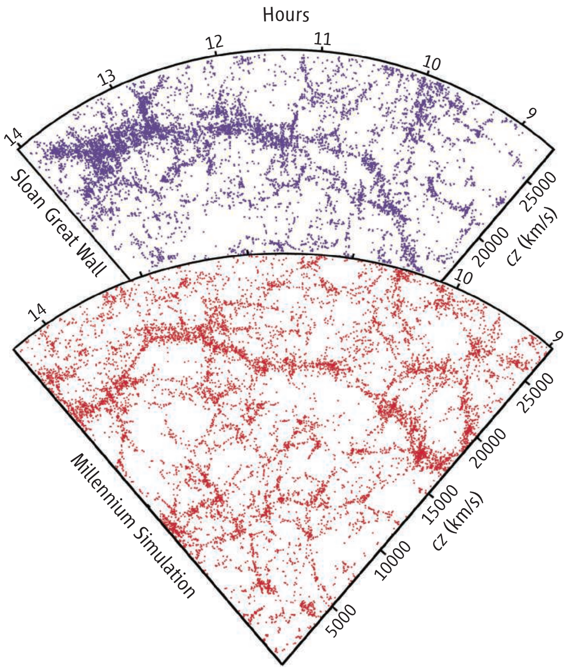
Joss Bland-Hawthorn and P. J. E. Peebles

These are exciting times for astronomy and cosmology. On the one hand, we find that the main predictions of Big Bang inflationary cosmology are confirmed by observations of distant objects. On the other hand, nearby galaxies continue to surprise and inform us. In February 2006, a group of 50 scientists convened in Aspen, Colorado, to discuss what we are learning about cosmology from detailed observations of the nearest galaxies (*1*).

Approximately 380,000 years after the Big Bang, the expanding universe became cool enough to allow ions and electrons to combine to form a gas of atomic hydrogen and helium. The free electrons had scattered and trapped the thermal radiation from the hot Big Bang; the abrupt elimination of these free electrons allowed the thermal radiation to move nearly without scattering. Precision measurements of the distribution of this radiation, most recently by the Wilkinson Microwave Anisotropy Probe (WMAP) satellite (*2*), are in beautiful agreement with the relativistic theory of how the present concentrations of mass in and around galaxies grew out of the distribution of mass at the time of release of the radiation.

But the story does not end there. The universe was ionized again in a process that is thought to have commenced some 100 million years after the Big Bang and is observed to be complete by the time the universe was 10 times that age. The study of this reionization is a topic for current research, but we do know that the first generations of massive stars likely played a major role. Observations of distant galaxies, seen as they were in the past because of the light travel time, show that many young galaxies were strong sources of ionizing radiation, but observations must reach still greater distances to show us the earliest generations of stars. This is a key science goal of the next generation of large telescopes, including the James Webb Space Telescope due to launch in the next decade.

A notable issue for Big Bang cosmology is that it requires only 4% of the mass of the universe to be in the form of baryons (particles such as protons and neutrons) of which stars and people are made. The rest is in "dark matter," which acts like a gas of particles that are not baryons, and "dark energy," which is the new name for Einstein's cosmological constant or something that acts like it. The evidence for the existence of these dark components is strong, but their properties are only loosely understood.



Simulated structures. Comparison of the galaxy distribution obtained from spectroscopic redshift surveys and theoretical mock catalogs. (**Top**) Galaxy distribution in a small section of the Sloan Digital Sky Survey, in which one of the largest observed structures in the universe has been detected. This "Sloan Great Wall" contains more than 10,000 galaxies and stretches over more than 1.3 billion light-years. (where *c* is the speed of light and *z* is the redshift). (**Bottom**) Mock galaxy survey with matching survey geometries and magnitude limits, constructed with semianalytic techniques to simulate the formation and evolution of galaxies within the evolving dark matter distribution of the Millennium Simulation (*8*).

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Fossil evidence available in nearby galaxies is an important part of the research on such open issues. The Local Group contains two large spiral galaxies, our Milky Way and Andromeda, and about 40 dwarf galaxies. Halo stars—the stars outside the discs and luminous central bulges of the two spirals—have relatively low abundances of elements heavier than helium. These stars likely formed at early times, because nuclear burning in stars is forever increasing the amount of mass in heavy elements (*3*). Two stars in the halo of the Milky Way have very low heavy element content, with mass fractions in iron relative to hydrogen less than 1/200,000 the mass fraction in iron in the Sun (*4*). It is plausible that these stars are ancient, and if so, their very unusual mix of chemical elements provides vital information about the nature of the earliest generations of stars. This would include the elusive population that ionized almost all the neutral matter and produced the first heavy elements (as discussed at the meeting by JasonTumlinson and Takuji Tsujimoto).

Other ancient stars may be hiding in the centers of galaxies, where the mass density is high and conditions likely first favored star formation (in presentations by Jon Fulbright and Rosie Wyse). It would be fascinating to search for ancient stars with unusual heavy element abundances in the center of the Milky Way, but dealing with the crowds of stars and the obscuration by dust will require an extremely large ground-based telescope (20 to 40 m diameter) working at high angular and spectral resolution. This is a project for the future.

Modern computer simulations of how the Big Bang unfolded over 13.7 billion years to yield present-day galaxies can involve up to 10 billion particles (as presented by Simon White). These computations yield structures that look a good deal like real galaxies and clusters of galaxies, adding to the evidence that our picture for the evolution of the universe is on the right track. But close examination of the nearby galaxies shows discrepancies with what the simulations might lead one to expect. For example, our Local Group is expected to have a thousand small mass concentrations (*5*), but we infer the presence of fewer than 50 from the number of visible galaxies. It is plausible that when the universe was ionized, the heating of the gas in the smallest of the dark matter concentrations was sufficient to prevent the formation of any stars, leaving dark galaxies. But dwarf galaxies are observed. Consistent with that knowledge, the simulations indicate that some stars formed in small mass concentrations before or shortly after the disruption by ionization (as discussed by Andrey Kravtsov and Oleg Gnedin), producing almost dark galaxies. The challenge is to reconcile the large number of low-mass dark matter concentrations with the smaller number of observed dwarf galaxies. Ideas are being tested by ongoing searches for the faintest nearby galaxies and the study of their properties.

The simulations also indicate that a vast hierarchy of merging of the dark matter concentra-

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tions continues to the present day. As discussed at the meeting, such merging does happen: Dwarf galaxies spiral into larger ones, where they are torn apart to produce the star streams observed in the Milky Way and Andromeda galaxies (work presented by Amina Helmi; Mike Irwin; Heidi Newberg). But the patterns of heavy element abundances indicate that no major component of the Milky Way could have been assembled largely by accretion of dwarfs of the kind observed today (discussed by Eline Tolstoy). The two large galaxies in the Local Group certainly could have formed by merging of dwarfs in the early universe; the curious thing is that the dwarfs that were left behind have to be substantially different (*6*).

Another aspect of the merging issue concerns the tight concentrations of stars known as globular clusters. The color of a globular cluster—and likely its heavy element abundance—correlates with the luminosity of the host galaxy. Because globular clusters generally are old, this indicates either that the globulars became attached to the present host galaxy a long time ago—which does not naturally agree with the substantial recent merging in the simulations—or that the globulars were recently attached to the host galaxy but "knew" the luminosity of the host, which seems strange (discussed by Jean Brodie).

Another issue emerges from the Millennium Simulation, one of the largest such studies ever carried out (see the figure) (*7*). In this simulation there are satisfactory analogs of the Local Group (as presented by Simon White). A study of the local universe reveals that groups dominated by a few large galaxies, such as the Local Group, are common (discussed by Brent Tully). The issue debated at the meeting is whether such groups are common in the simulation. Related to this is the abundance of spiral galaxies like the Milky Way that have a modest bulge of quite old stars and a prominent disk of stars with a broad range of ages. Elegant examples form in simulations (presented by Matthias Steinmetz). But because the theory predicts substantial merging and accretion in nearby galaxies, which tend to destroy thin disks, a pressing issue is whether disk-dominated systems that contain old stars as well as young are as common in the simulations as they are observed to be nearby.

In short, present-day cosmological simulations do not give a very complete account of the finer details of the nearby universe. This is in part a result of the extreme difficulty of understanding the gas dynamics that determines how matter settles into galaxies and collapses from there to form much denser stars, and how stellar winds and explosions stir up the remaining gas and control the rate at which new stars form. Dealing with all this in full detail is far beyond the capabilities of modern computers. But we have observations of forming stars to teach us what happens, and what we are learning is being applied to increasingly detailed simulations of this complex process.

Also to be borne in mind is that the problems with the simulations may be highlighting the need for improved physics. After all, the simulations invoke many parameters to describe the 4% of the universe that is made of baryonic matter, while using only a few to describe the remaining 96% in dark matter and dark energy. It was surprising to find that we must postulate dark matter. Dark energy was another surprise, and the dark sector may surprise us yet again.

References and Notes

1. Aspen Center for Physics workshop on Local Group Cosmology, Aspen, CO, 5 to 11 February 2006.
2. D. N. Spergel *et al.*, http://arxiv.org/abs/astro-ph/0603449 (2006).
3. The Big Bang produced mostly hydrogen and helium, whereas most of the heavier elements were produced in stars and returned to the interstellar medium by supernovae and winds, in a process that cycled through generations of stars.
4. T. Beers, N. Christlieb, *Annu. Rev. Astron. Astrophys.* **43**, 531 (2005).
5. A. R. Zentner, J. S. Bullock, *Astrophys. J.* **598**, 49 (2003) and references therein.
6. B. Robertson *et al.*, *Astrophys. J.* **632**, 872 (2005).
7. German Astrophysical Virtual Observatory simulation query page (www.g-vo.org/mpasims).
8. V. Springel *et al.*, *Nature* **435**, 629 (2005).

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CHEMISTRY

A Golden Boost to an Old Reaction

Gold catalysts promote selective reduction of aromatic nitro compounds to anilines, providing a new way to synthesize industrially important products.

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Functionalized aminobenzenes [anilines (see the figure)] are important intermediates for the manufacture of many agrochemicals, pharmaceuticals, dyes, and pigments. To yield anilines, aromatic nitro compounds must be reduced in a hydrogen-addition or hydrogenation reaction. The hydrogenation of simple aromatic nitro compounds poses few problems and is carried out catalytically on very large scales. But when other reducible groups are present in the molecule, it is difficult to reduce the nitro group selectively in a catalytic process. In such cases, the use of older, noncatalytic manufacturing processes prevails despite the large amounts of waste produced by these processes. On page 332 of this issue, Corma and Serna (*1*) report a promising new, highly chemoselective catalyst to make anilines.

There are few generally applicable catalytic systems for the selective reduction of a nitro group in the presence of $\mathrm{C{=}C}$, $\mathrm{C{\equiv}C}$, $\mathrm{C{=}O}$, $\mathrm{C{=}N}$, or $\mathrm{C{\equiv}N}$ groups. In light of the industrial importance of functionalized anilines, it is surprising that in the past decade, relatively little research has been carried out to develop new catalysts for this task. Today's state of the art was mainly established in the mid-1990s (*2*). Corma and Serna now show that gold particles supported on $\mathrm{TiO_2}$ or $\mathrm{Fe_2O_3}$ catalyze the reduction of various functionalized aromatic nitro compounds without hydroxylamine accumulation (a common problem in such reactions) and with high chemoselectivity. The work should give a strong impulse to new research efforts for this important transformation.

Why it is so difficult to selectively reduce a nitro group in preference to other groups present in the molecule? More than 100 years ago, Haber (*3*) proposed the reaction network shown in the figure to explain the electrochemical reduction of aromatic nitro compounds. Obviously, the sequence of reactions is complex. Furthermore, the intermediates formed in this process are very reactive species that can react with each other as well as with other chemicals.

The intermediates proposed by Haber have all been verified, and it has been generally accepted that catalytic hydrogenation reactions in principle proceed via the same routes. The major difference to the electrochemical variant is that the catalyzed reaction steps—especially the splitting of the H-H bond and the addition of H to the various intermediates—occur while the molecule is adsorbed on the catalytic surface.

The reduction to anilines occurs in several steps, either by the direct route via nitroso and hydroxylamine intermediates (see the figure, left) or via a condensation route (see the figure, right); the latter route is favored under basic conditions. The first two reduction steps in the direct route tend to be fast, and the nitro and nitroso compounds are strongly adsorbed on the catalyst surface. In

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