Despite Reports of Its Death, the Big Bang Is Safe

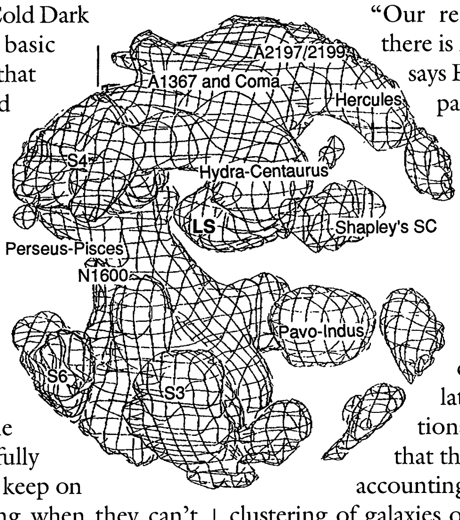
Even so, cosmologists are going to have to rethink a lot of what they thought they knew about what happened later

IS IT TRUE? HAS ALL OF MODERN COSMOLOGY really been pushed to the brink of collapse by one extraordinary observation? Are astronomers about to give up their belief that the universe began as an explosive Big Bang some 15 billion years ago?

Hardly. But many people certainly got that impression earlier this month, when major newspapers and magazines ran articles with headlines such as "Astronomers' New Data Jolt Vital Part of Big Bang Theory" (*The New York Times*, 3 January) and "Bang! A Big Theory May Be Shot" (*Time*, 14 January).

The articles were actually reporting on an important, but considerably less dramatic, result: a recently published British-Canadian survey* of galaxies that undercuts cosmologists' standard model of how galaxies formed in the first few billion years *after* the Big Bang. The basic assumption of this model is that galaxies are formed by the gravitational pull of an invisible, but massive haze of elementary particles known as "Cold Dark Matter" (CDM); the basic finding of the survey is that galaxies form clusters and superclusters on a much larger scale than standard versions of CDM can explain.

But for readers not familiar with the astrophysical subtleties, the clear implication of the news reports was that the Big Bang itself was in trouble. "Even people who read the story carefully said, 'How can scientists keep on believing in the Big Bang when they can't understand the details of what went on after?'" sighs the author of the *Times* story, veteran science reporter John Noble Wilford.



A structured environment. *The density of galaxies seen in the QDOT survey is displayed here in a cube some 600 million light-years on a side. Our own galaxy lies in the Local Supercluster (LS).*

Carlos Frenk

Actually, cosmologists have no problem with that belief at all. "Just because we can't predict tornadoes and earthquakes doesn't mean we throw out the round Earth theory," says the University of Chicago's David Schramm.

But in fairness to the reporters, Schramm also admits that much of this confusion has been created by the cosmologists themselves. Having enthroned CDM as the "standard" model of galaxy formation for much of the 1980s, they have become increasingly divided on the subject in recent years; the community has been ringing with declarations that "Cold Dark Matter is dead!" followed by equally loud declarations that "Cold Dark Matter is *not* dead!" The problem is that the disputants are all too often using the same words to mean different things—and are sometimes not being clear about the distinctions.

One researcher who does try to be clear is theorist Carlos Frenk of the University of Durham in the United Kingdom, one of the leading advocates of CDM and now a member of the team that did the recently reported survey. (The survey goes by the acronym QDOT, which stands for four of the institutions involved: Queen Mary and Westfield College in London, Durham, Oxford University, and the University of Toronto.)

"Our results don't say that there is no cold dark matter," says Frenk. The mysterious particles themselves may very well exist; indeed, computer simulations of their gravitational dynamics suggest that they do a very good job accounting for the structure and clustering of galaxies on scales up to several tens of millions of light-years.

What the new survey results do say, however, is that the universe is inconsistent with the "standard" CDM model, which incorporates a chain of specific—and quite possibly wrong—assumptions about such factors as the average mass density of the universe, and the messy details of how galaxy formation got started.

In particular, says Frenk, the QDOT survey provides some of the strongest statistical evidence to date that galaxies in the real universe cluster into structures on scales of hundreds of millions of light years, far larger than those typically seen in computer simulations based on standard CDM. Although this is a problem for the standard CDM model, it was not unexpected, Frenk says, since astronomers have been finding hints of such structures for several years now. In 1986, for example, one group found that our galaxy and every other galaxy for hundreds of millions of light-years are being pulled toward an enormous concentration of mass that was soon dubbed the Great Attractor. In 1989, another group discovered the Great Wall, a sheet of galaxies extending through the universe for even greater distances.

But as intriguing as such discoveries were, says Frenk, they provided nothing more than anecdotal evidence. Speaking as one who has done innumerable computer simulations, he can testify that very large structures will occasionally be produced by CDM or almost any other reasonable model of galaxy formation. So the only way to test such models rigorously is to compare the simulations to the real universe in a statistical sense: How frequently do structures of a given size occur?

The trick, of course, is to measure the distribution of real galaxies over a volume of the universe sufficiently large to give meaningful statistics. To accomplish that, says Frenk, the QDOT team started with the most complete catalog of nearby galaxies available: the 12,000 galaxies compiled in 1983 by NASA's Infrared Astronomy Satellite (IRAS). Next, says Frenk, the QDOT group randomly selected some 2100 of these galaxies, and spent several years at various observatories around the world determining the galaxies' redshifts due to cosmic expansion. (Doing this for all the IRAS galaxies would have taken a prohibitive amount of telescope time.) Since each galaxy's redshift is approximately proportional to its distance from Earth, the QDOT team was then able to construct a map of the galaxies in three dimensions.

As expected, says Frenk, statistics derived from this map agree very well with the standard CDM simulations for structures on the scale of galaxies and clusters of galaxies. But on the largest scales, looking at structures measured in the hundreds of millions of light-years, the real universe turns out to have twice as much structure as the standard CDM simulations.

So is a discrepancy of just a factor of 2 all that bad? It depends on how you look at it, says Frenk: "A few years ago, cosmologists would have been happy to get within a factor of 10." But these days, the observations and

* W. Saunders, *et al.*, "The density field of the local Universe," *Nature* **349**, 32 (1991).

the simulations have improved so much that that factor of 2 looms very large indeed. Somehow, he says, the long chain of assumptions going into the standard CDM model has a weak link. The question is where.

By far the most radical possibility is what so many readers assumed after seeing the recent news articles: that the Big Bang theory itself is wrong. But almost no reputable astronomer is willing to accept that. Indeed, as Chicago's Schramm points out, "The Big Bang theory is in better shape than ever."

The theory rests on three observational pillars, he explains. The first is the discovery, originally made in the 1920s, that the universe is expanding. The second is the observation of the Big Bang's "afterglow": a cold wash of microwave photons known as the cosmic background radiation. Originally predicted in the 1940s, and first observed in 1965, these photons are now getting their most exacting examination ever from NASA's Cosmic Background Explorer (COBE) satellite. Last year COBE precisely measured the radiation's temperature—2.735 K—and found it to be smooth and uniform to a few parts in 10^5, just as most theorists had expected. In the very near future, COBE should refine that measurement to one part in 10^6.

The third observational pillar, says Schramm, is the cosmic abundance of light elements such as helium and deuterium, as measured in stars and interstellar gas clouds. The Big Bang theory predicts that these elements were largely created from hydrogen by thermonuclear reactions during the universe's first 3 minutes of existence. And in fact, he says, calculations based on nuclear reaction rates measured in the laboratory turn out to predict abundances very close to what astronomers find.

But if the Big Bang remains intact, then the weak link in the standard CDM model has to be found elsewhere. One possibility, says Frenk, is to give up on the model's second major assumption: that the average mass density of the universe is almost exactly equal to a certain "critical" density, which is the density at which gravity will just barely bring the expansion of the universe to a halt in the far distant future. Its value is estimated to be roughly 6 hydrogen atoms per cubic meter at the present age of the universe.

From a strictly observational point of view, this assumption has always been a tough one to justify, says Frenk. When astronomers try to add up the mass of all the visible stars and galaxies, averaging over the immense distances between them, they only find a fraction of the critical density. Moreover, even when they assume that there is lots of dark, unseen gas and dust floating around between the visible stars, they still can't push the total any higher than about 20% of the critical density; if it were any more than that, the Big Bang would have generated helium and the other light elements in proportions far different from what is observed.

From a theoretical point of view, however, the assumption of critical density has always been very appealing, says Frenk. Particle physicists, for example, have argued that subtle quantum effects may well have caused the universe to undergo a period of extraordinarily rapid "inflation" during its first instants of existence. Among other things, this inflation would have forced the average density of the universe to be almost precisely equal to the critical density, no matter how it started out.

Moreover, this same argument explains why at least 80% of mass in the universe seems to be missing: quantum effects related to the ones that caused the inflation would have brought forth a haze of massive elementary particles in precisely the right number to make up the difference. These hypothetical particles, which have been given names such as "photinos" and "axions," would still be around today—as dark matter. They would permeate the cosmos with enough mass to dominate the evolution of the galaxies, but they would interact so weakly with ordinary matter that they would be completely invisible. (Another possibility is that the dark matter is composed of neutrinos, which are not at all hypothetical; many physicists now suspect that neutrinos possess at least a tiny mass.)

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>
> —DAVID SCHRAMM

Given this tension between past observations and theory, says Frenk, it's intriguing that theory now seems to be winning out. By analyzing the motions of a great many galaxies, as well as their positions, the QDOT survey and several similar efforts have recently begun to make the first real measurements of the total mass density on very large scales—dark matter included. (*Science*, 4 January, p. 30.) And the results, although subject to large uncertainties, are quite consistent with the universe's having critical density.

But if the assumptions about the Big Bang and critical density are reasonably secure, says Frenk, then the problem probably lies with the remaining assumptions of the CDM model. One such assumption is that the particles are slow-moving, or "cold." On scales of galaxies and clusters, computer simulations with the slow-moving particles have generally looked more realistic than simulations with fast-moving, or "hot" particles, which is why theorists have preferred the cold kind. But as their faith in standard CDM erodes, they are increasingly returning for a serious look at Hot Dark Matter.

Also up for grabs, Frenk says, is the assumption that the quantum effects responsible for cosmic inflation also planted the "seeds" for galaxy formation, in the form of tiny irregularities in the cosmic mass density. The idea is that the immense gravitational mass of the dark matter would have caused those seeds to grow over the eons to form the galaxies and clusters we see today.

If so, says Frenk, then the COBE satellite should eventually be able to detect those irregularities as tiny deviations from the smoothness of the cosmic background radiation—or else to show that they didn't exist. But pending that result, he says, many people in the field are skeptical anyway: calculations suggest that these inflationary quantum seeds would not have extended over large enough distances to have produced the very large scale structures seen today. Thus, many researchers are now exploring alternatives to standard CDM in which the seeds are planted by other means. Schramm, to take just one example, argues that all the problems of CDM would go away if the cosmic density fluctuations were produced not by inflationary quantum effects in the first instants of the Big Bang, but by a different set of quantum effects millions or even billions of years after the Big Bang.

Frenk himself, meanwhile, is looking for alternatives to the last and weakest assumption of standard CDM: "biasing." If you think of the dark matter distribution as a range of density peaks and valleys, he explains, then this biasing assumption is tantamount to saying that visible galaxies tend to form only at the highest mountaintops. The assumption is totally ad hoc, and really only codifies our ignorance about how interstellar gas actually condensed into stars and galaxies. He wants to do better.

In sum, says Frenk, this is a time of turmoil for cosmology—not because the Big Bang is in trouble, but because the scientists in the field are being forced to reevaluate what they thought they knew about galaxy formation. "I've been working on standard CDM for nearly 10 years, and it's a bit disappointing to see it fail," says Frenk. "But it's also exciting."

■ M. MITCHELL WALDROP