

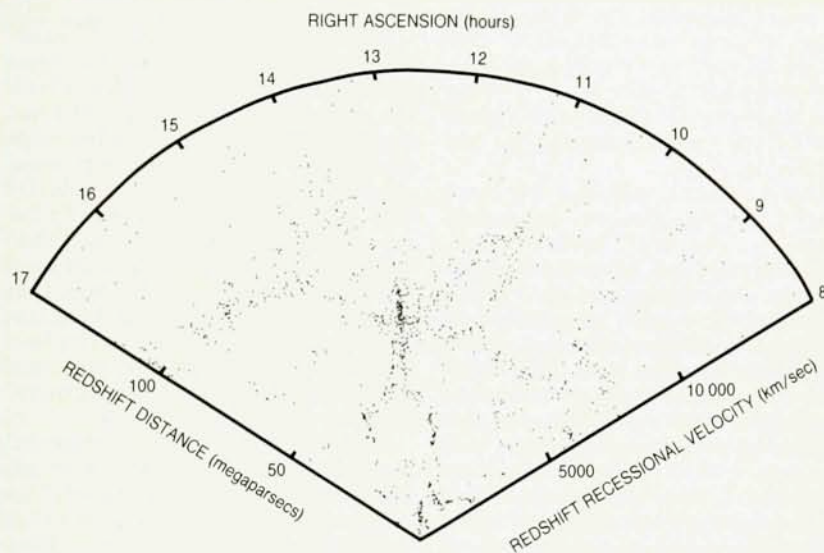
Redshift surveys of galaxies find a bubbly universe

"The distribution of galaxies in [our] redshift survey is like a slice through the suds in the kitchen sink." With this deceptively mundane metaphor, a report in the 1 March issue of *Astrophysical Letters* presents¹ us with an astonishing new view of structure in the cosmos on the largest scale we know about. The authors, Valerie de Lapparent, Margaret Geller and John Huchra of the Harvard-Smithsonian Center for Astrophysics, conclude from a complete compilation of the redshifts of the 1100 brightest galaxies in an extensive strip of sky near our galactic north pole that the galaxies are sharply concentrated at the surfaces of contiguous, bubblelike structures with diameters as large as 50 megaparsecs (150 million light years).

The interiors of the bubbles appear to be largely devoid of luminous matter. The gigantic and unanticipated void discovered in the constellation Boötes five years ago (*PHYSICS TODAY*, January 1982, page 17), far from being a peculiarity, now appears to be a thoroughly typical feature, it and its fellows filling the universe like a soapy froth.

Simply noting the angular coordinates of galaxies on the celestial sphere tells us rather little about their three-dimensional distribution in space. The third (depth) dimension is supplied by measuring the redshift, and hence the recessional velocity, of each galaxy in the survey. One then translates the recessional velocity into a distance (from us) by making the canonical assumption of the general Hubble expansion of the universe. Most of the galactic redshifts in the Harvard-Smithsonian survey were measured for spectral lines in the visible. A very similar picture of the grand distribution of galaxies emerges² from a radio-telescope survey of 2700 galaxies in another patch of sky, just completed by Martha Haynes (Cornell) and Riccardo Giovanelli (Arecibo), who measured redshifts by way of the 21-cm hyperfine line of neutral atomic hydrogen gas for those galaxies with sufficiently strong emission at this radiofrequency.

If the cosmos really does look like what these redshift-survey groups



Optical-redshift survey by the Harvard-Smithsonian group of all 1099 galaxies brighter than magnitude 15.5 in a thin slice of sky (declination from 26.5° N to 32.5° N) extending from 8 to 17 hours right ascension. The scatter plot shows right ascension vs. apparent recessional velocity, summed over the narrow range of declinations. Redshift velocities are converted to distance scale at left by assuming 100 km/sec Mpc for the Hubble constant. The "finger of God" pointing straight at us from 13 hours is an artifact due to the large velocity dispersion within the Coma cluster. Because of the brightness cutoff at magnitude 15.5, the plot is sparse beyond 10 000 km/sec (100 Mpc), showing only atypically luminous galaxies in those outer reaches of the survey. At closer distances, the distribution of galaxies appears to be dominated by "bubbles" with diameters as large as 50 Mpc.

think they see, "these features pose serious challenges to current models for the formation of large-scale structure," says the paper of Lapparent and company. Standard gravitational clustering models, they argue, "are unlikely to match the observations." These new data have in fact focused particular attention on a theoretical approach that began in 1981 with a paper by Jeremiah Ostriker and Lennox Cowie at Princeton and a similar speculation by Satoru Ikeuchi at Hokkaido University. They suggested that spherical shock waves propagating outward from primordial explosive "seeds"—very active first-generation galaxies, quasars or even individual supernova explosions—would clear out bubblelike voids in the universe, generating and sweeping aside other galaxies. Thus, they

calculated, one would expect to see spherical voids as large as 5 megaparsecs across, with galaxies piled up at their surfaces. Recent work along these lines has considerably generalized the original Ostriker-Cowie-Ikeuchi scenario, but whether such mechanisms can produce voids with diameters on the order of 50 Mpc remains an open question.

Like Ostriker and his colleagues, Yakov Zel'dovich and coworkers in the Soviet Union have invoked hydrodynamic as well as gravitational mechanisms to generate large-scale structure in the distribution of galaxies. But Zel'dovich's "pancake model," first put forward in the early 1970s, proposes that galaxies form and cluster on the surfaces of flat shock-front sheets rather than expanding spherical bubbles.

Much of the motivation, in fact, for the large-scale galaxy surveys of recent times has been the desire to discern the highly concentrated "cosmic filaments" of galaxies one would expect to find at the lines marking the intersections of Zel'dovich pancakes.

The redshift survey of 1100 galaxies reported by the Harvard-Smithsonian group includes almost 600 redshift measurements carried out last spring by Huchra and Lapparent—mostly at the 60-inch telescope on Mount Hopkins in Arizona. The remaining 500-odd galaxies were measured in a mélange of earlier redshift surveys, mostly concentrating on the center of the gigantic Coma cluster of galaxies. This earlier survey work was in large measure intended to determine whether this "supercluster" might exhibit structure of the kind predicted by the Zel'dovich model.

Not wanting to prejudice the issue, Huchra and his colleagues determined to make a "complete" survey of a well-defined strip of sky rather than concentrate on a particular structure. They undertook to compile the redshift of every galaxy with an apparent optical brightness greater than magnitude 15.5 in a 6°-wide strip of declination centered about 30° north of the celestial equator and extending around the horizon from 8 hours right ascension (in Gemini) to 17 hours (in Hercules). This thin wedge slices through much of the Coma cluster, and its proximity to our own galactic north pole frees the observer from most of the obscuring dust and gas concentrated in the plane of the Milky Way.

To convert observed redshifts to distances, one has to assume a numerical value for the Hubble constant. But the Hubble constant is not very well known; serious estimates range from 50 to 100 km/sec per megaparsec. We will therefore adopt the convention that sets the Hubble constant at 100 km/sec/Mpc for convenience of communication and calculation, with the caveat that if 50 km/sec/Mpc turns out to be nearer the truth, all the distances we speak of must be doubled.

With its apparent-brightness cutoff imposed at magnitude 15.5, the Harvard-Smithsonian survey is said to achieve a "survey depth" of 100 Mpc. That is to say, a galaxy of typical intrinsic brightness would look like a 15.5-magnitude object if it were 100 Mpc away. Although the survey measures recessional velocities as large as 15 000 km/sec for atypically luminous galaxies, it is presumed to be reasonably complete only for velocities up to 10 000 km/sec—corresponding to a depth of 100 Mpc.

So extensive and complete a redshift survey is feasible nowadays thanks to several technological advances in re-

cent years. In the late 1960s astronomers began to replace photographic plates with electronic detectors for the taking of spectroscopic data. But at first only the largest optical telescopes were outfitted with such digital devices; "and there's never enough observing time available at the largest telescopes for survey work," Huchra told us. Not until the late 1970s were photon-counting arrays installed on the spectrographs of the smaller optical telescopes one could use for surveys. "Nowadays we can get an optical redshift for a typical galaxy in about half an hour," says Huchra. "The easy ones take five minutes."

A small fraction of the Harvard-Smithsonian-survey redshifts come from 21-cm radio data. The 21-cm work has been greatly facilitated in the last decade by the development of low-noise amplifiers. The radio redshift measurements are restricted to galaxies with sufficient neutral atomic hydrogen—mostly "late-type" spiral galaxies. The advantage of an optical over a radio survey, Huchra contends, is that one can measure twice as many galaxies in a given patch of sky. Therefore, he points out, one can discern structure in the three-dimensional distribution of galaxies with greater clarity.

"The importance of our survey," Huchra suggests, "is that it's broad, homogeneous, deep and unbiased. The older surveys just looked at what they took to be interesting structures. They misread the forest by concentrating on the most interesting trees. They thought they were seeing the Zel'dovich filaments. We measured everything, even out in the boonies."

What Huchra, Lapparent and Geller found in their predesignated wedge of the cosmos is shown in the figure on page 17, a scatter plot of galactic redshift velocities (depth) versus right ascension—the azimuthal angular coordinate around the North Star. This scatter plot essentially integrates over the third coordinate—declination, the polar angle as measured from the projection of the equator on the celestial sphere. Because the range of declinations in this survey is very narrow—from 26.5° to 32.5° north—one must think of this distribution as a very thin slice through the cosmos. At 100 Mpc (10 000 km/sec) the slice is only about 10 Mpc thick, much thinner than the scale of the largest structure manifested by the survey.

We must begin the examination of the redshift scatter plot with a warning. The most prominent feature in the plot, the straight dark string of galaxies seeming to point directly at us (that is, the apex) from 13 hours right ascension is not what it seems. It is a well-known artifact of the kind referred to as "fingers of God." It ap-

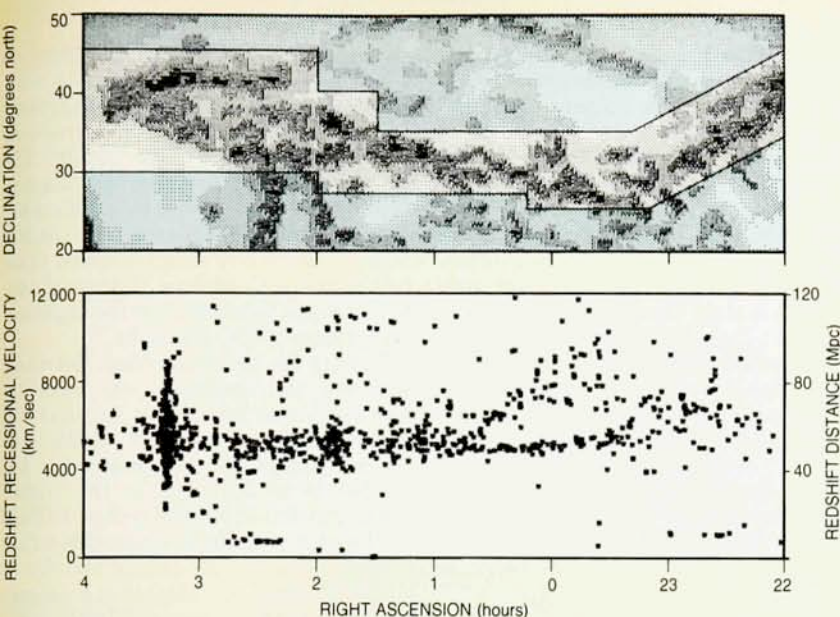
pears to be a dense chain of galaxies extending directly along the line of sight for almost 50 Mpc.

But this is a case where translating radial-velocity redshifts into Hubble distances is wrong. The line is clearly associated with the Coma cluster. Whenever one has a very large, gravitationally bound cluster of galaxies like the Coma cluster, the virial theorem tells us, its equilibrium internal kinetic energy will be correspondingly great, manifesting itself in a large, non-Hubble dispersion of "peculiar recessional velocities," which do not translate directly into distance along the line of sight. They simply indicate that in a large gravitating system the grand pattern of Hubble-expansion velocities is distorted by large "local" velocities of galaxies orbiting every which way in the cluster's gravitational field.

We cannot, therefore, believe in the great radial extension implied by these fingers of God pointing directly at us from all the superclusters. But apparent structure in any other direction is quite reliable, says Geller, the theorist of the Harvard-Smithsonian group. She points particularly to the long curved line immediately to the left of the Coma finger. "It's just off the line of sight and looks so remarkably like a slice through the surface of a bubble that one of the first people we showed it to said we must have cheated." This curved shell turns out to contain a higher fraction of spiral galaxies than does the adjacent Coma core. It's not understood why this is so, but the observation lends credibility to the curved shell as a real structure distinct from the Coma finger.

In fact the whole scatter plot out to the nominal survey depth of 100 Mpc appears to be dominated by such sharp, circular bubble boundaries, with hardly any galaxies above the brightness cutoff seen inside the bubbles. The bubbles have diameters all the way up to 50 Mpc. Geller points out that 50 Mpc is just about the largest structure scale one can hope to see clearly in a survey of this depth. It may be, she speculates, that bubbles will appear on even larger scales when deeper and broader surveys are completed.

The thin-slice survey published by Lapparent and her colleagues can show only a cross section of the sudsy structure they suppose to extend in three dimensions. Can one be sure these are really spherical bubbles? Supporting evidence comes from the group's partially completed surveys of declination slices on either side of the completely surveyed 6° slice. In these adjacent slices the group has not yet completed the redshift measurement of the fainter galaxies. Nonetheless, Geller told us, the spherical character of the bubbles is manifesting itself rather



Pisces-Perseus filament is a well-known feature extending across the celestial sphere in the upper panel from 4 to 22 hours right ascension. This scatter plot indicates the angular positions of all galaxies optically brighter than magnitude 15.7. It contains no information about the third (depth) dimension. The recent radio-redshift survey data (lower panel) for a thousand galaxies within the filament boundaries (unintented) provide the three-dimensional information that convince Martha Haynes and Riccardo Giovanelli, who compiled these 21-cm redshifts, that the Pisces-Perseus filament is a true linear filament in space. The vertical artifact at 3 hr 15 min right ascension is the "finger of God" due to the Perseus cluster. It is not a true indicator of extension in depth.

clearly as the cross-sectional circles grow or shrink from slice to slice.

This three-dimensional picture of a universe packed tight with bubbles is also supported by the 21-cm radio survey of Haynes and Giovanelli, which has the advantage in this regard of being much wider in declination, ranging from the celestial equator up to 50° north—a bite rather than a slice out of the celestial sphere. Extending over six hours of right ascension around the Pisces-Perseus supercluster of galaxies, this survey covers almost six times the solid angle of the Harvard-Smithsonian survey. Because of limited observing time and the limitations inherent in radio surveys, however, Haynes and Giovanelli have compiled only 2700 radio redshifts. In that sense the 21-cm survey is less than half as "complete" as the optical survey, and the bubble structure is consequently not as crisply delineated.

On the other hand, Haynes points out, the 21-cm survey easily measures the redshifts of some galaxies that are too faint for an optical survey limited to magnitude 15.5. This is particularly true in the Perseus-Pisces region, whose proximity to the Milky Way plane presents difficulties for optical observation. "We're not looking at exactly the same things," Haynes reminds us. Spiral galaxies are less clustered together than are elliptical galaxies. Therefore, Haynes contends, radio surveys are more likely to discern the optically faint galaxies one might expect to populate the voids.

"The world is not all bubbles," Haynes told us. The 21-cm survey discerns a ridge of galaxies running between the Perseus and Pisces clusters. Haynes and Giovanelli explicitly identify this structure as a filament.

To skeptics who dismiss such filaments as "Martian canals," Giovanelli responds, "If the Pisces-Perseus filament is a canal, it's the kind that holds water."

Theory. Can gravity alone account for this bubbly universe with a structure scale on the order of a hundred million light years? Simple Newtonian arguments tell us that random density fluctuations from place to place in the early universe would become more pronounced with time as matter gravitates together. Clusters become denser and voids become emptier. But if one starts with density fluctuations on all spatial scales, large-scale coherence will be destroyed by fragmentation into subclusters. Without invoking a mechanism that kills small-scale fluctuations, or some other trick, it is very difficult to get 50-Mpc voids in the present epoch from purely gravitational mechanisms.

The trick employed in recent computer simulations by Marc Davis and Simon White at Berkeley is the invocation of "biased galaxy formation." They begin with the spectrum of random density fluctuations on all scales derived from the "inflationary" scenario of the earliest moments of the universe, as proposed by the elementary-particle theorists. "We don't really know how to generate galaxies," Davis told us, "but we do know that the starting spectrum in the inflationary theory is consistent with the observed short-range correlations among galaxies in the present epoch only if the distribution of visible matter is not the same as the underlying, dominant mass distribution of the cosmos."

Thus one is led to the speculations about unobserved "dark matter" that also emanate from a variety of other

theoretical and observational considerations. The inflationary theory, for one, insists that the mass density of the cosmos is precisely that required to just "close" the universe gravitationally. This density would be orders of magnitude greater than what we see of luminous matter. The dark-matter speculations fall into two camps—"hot" and "cold" dark matter. In either case, the dark matter would interact with ordinary baryonic matter only by way of the weak and gravitational interactions. The hot dark matter would consist of very light, energetic particles; neutrinos with a rest mass on the order of 10 eV are the prime candidates. The hypothetical particles of cold dark matter, on the other hand, generally have masses on the order of a GeV—photinos, quark nuggets or even tiny, primordial black holes. Axions, despite their minuscule presumed mass, also fall into the cold category, because they are supposed to have very low energies.

The Zel'dovich pancake theory invokes the "free streaming" of hot dark matter in the radiation-dominated epoch that ended about 10^4 years after the Big Bang to kill off the small-scale fluctuations. This leaves the field to the surviving large-scale density fluctuations in the gases filling the pregalactic universe, which, Zel'dovich concludes, would sharpen up into shock-wave sheets by a nonlinear hydrodynamic mechanism analogous to the breaking of waves on a sloping shore. Finally, the fragmentation of these planar shock waves would initiate the formation of galaxies, with particular concentrations forming in filamentary chains at the intersections of such sheets.

Davis, however, tells us that detailed

calculations by himself, White and Carlos Frenk have demonstrated³ that the hot-dark-matter theories are inconsistent with the empirical correlation functions of short-range galactic clustering compiled by James Peebles and his colleagues at Princeton. Such local clustering is characterized by correlation lengths on the order of 5 Mpc. The Peebles correlation lengths would have to be much longer than this if the pancakes were indeed formed *before* the galaxies, as implied by the Zel'dovich theory. The creation of large-scale structure by way of Zel'dovich pancakes is consistent with the observed correlation functions only if the pancakes are much younger than the first epoch of galaxy formation.

Unlike the hydrodynamic theory of Zel'dovich, the recent simulations by Davis and White are purely gravitational—until one gets to the actual formation of galaxies. Because they take the underlying dark matter to be cold, Davis and White cannot invoke the free streaming of relativistic particles in the early universe to get rid of small-scale fluctuations. Therefore the underlying mass distribution of the cosmos would presumably not exhibit the long-range coherence observed in the new redshift surveys of the galaxies. But the formation of galaxies, they assume, is "biased." Because one doesn't really know how galaxies are created, they take the liberty of assuming that galaxy formation may involve density thresholds that greatly exaggerate the underlying dark-matter distribution. In this way, the simulations of Davis and White have in recent weeks succeeded in creating void diameters as large as 50 Mpc. Whether these simulations can reproduce the very thin, sharp, spherical shells Huchra and company seem to see depends sensitively on the details of the unknown galaxy-formation mechanism.

"These large bubbles were not anticipated by any of the standard theories," Ostriker told us. Nor did the original Ostriker-Cowie-Ikeuchi theory envision bubble diameters greater than 5 Mpc. In the "standard" theories, he explained, everything is determined by growth from the initial spectrum of fluctuations. "What goes in is what comes out. There is no amplification mechanism." The essentially new feature introduced by Ostriker, Cowie and Ikeuchi is amplification by a kind of chain reaction. The seed explosion generates a spherical shock wave. The formation of galaxies on the expanding shock front provides a feedback mechanism, a chain reaction of galaxy formation that constitutes a source of nonlinear amplification. "You get an enormous output from a small input."

The efficiency of such a chain reaction of detonations depends on when it started. Ostriker's student, Edmund Bertchinger, has recently calculated⁴ that if a seed explosion occurred in the era of "Compton cooling," when the radiation background that has now cooled to a 3-K whisper in the microwave spectrum was still very intense, Compton scattering would have provided a cooling mechanism so efficient that the chain reaction could amplify through many successive generations of detonations. Starting with a single supernova, Bertchinger calculates, one could sweep out a bubble diameter of 50 Mpc. However, Joseph Silk (Berkeley) raises the objection that the 3-K microwave background would be much less smooth than we know it to be if the bubbles had really begun as early as the Compton era.

If the seed explosion occurs in a more recent epoch, when cooling is much less efficient, one would have to start out with a whole first-generation galaxy, which is estimated to spew out a total energy of about 10^{61} ergs in a relatively short time, as abundant supernova activity binds a small fraction of the galaxy's original inventory of hydrogen and helium into heavier elements. In that case, one gets only a few generations of detonations, and a bubble diameter of at most 5 Mpc. Furthermore, the bubble diameter increases only as the *fifth* root of the energy output. Therefore, unless one can come up with a lot more energy in the explosive seed, it is difficult to generate holes that will by now have grown larger than 5 Mpc.

The theory in this original form was primarily concerned with the formation of galaxies on the expanding shock waves; it was not thought of as a theory of large-scale cosmic structure. But two years ago Bertchinger and Ostriker discovered⁵ a general expanding solution of the theory that would propagate in a self-similar manner, eventually cramming the cosmos full of bubbles. The same solution was discovered independently by theoretical groups at Caltech and Hokkaido. With this general solution, one need no longer invoke explosive seeds. Bubble propagation could be initiated simply by sufficiently large negative density fluctuations. But for the moment, Ostriker told us, it's still difficult to explain why the bubbles observed in the new redshift surveys are so very large. He and his colleagues are currently investigating whether the merging of bubbles in this theory would yield bubble diameters much larger than 5 Mpc in the present epoch.

Silk thinks that asking a single mechanism to explain both galaxy formation and the creation of large-scale

structure is asking too much. This, he suspects, is the essential difficulty with the theories of Zel'dovich and Ostriker. Silk is pursuing a different course—as yet without a definitive result. He prefers a scenario in which the galaxies are made first, followed by a different, later mechanism that generates the 50-Mpc structure now being revealed to us by the redshift surveys. "None of the theories put forward thus far explains everything," Silk contends.

To help the theorists along, Ostriker suggests, the observers will have to look for fainter galaxies, to see just how empty the voids really are. Radio and optical-absorption searches will be needed to study gases in the voids. Furthermore, if we are indeed sitting on the edge of an expanding bubble, the Hubble constant as determined from the redshifts of our neighbors is larger than the true, universal Hubble constant by 20 or 30%. One can investigate this by using "standard candles"—galaxies of known intrinsic brightness—to make distance determinations independent of redshifts.

—BERTRAM SCHWARZSCHILD

References

1. V. de Lapparent, M. J. Geller, J. P. Huchra, *Astrophys. J. Lett.* **302**, L1 (1986).
2. M. P. Haynes, R. Giovanelli, submitted to *Astrophys. J. Lett.* (1986).
3. M. Davis, S. White, C. Frenk, *Mon. Not. R. Astron. Soc.* **209**, 27P (1984).
4. E. Bertchinger, *Astrophys. J.* **295**, 1 (1985).
5. E. Bertchinger, *Astrophys. J. Suppl. Ser.* **58**, 1 (1985). E. Vishniac, J. P. Ostriker, E. Bertchinger, *Astrophys. J.* **291**, 399 (1985).

PBFA-II is on the air at Sandia National Lab

The second-generation light-ion-beam fusion accelerator at Sandia, PBFA-II, was successfully fired for the first time in December. This \$48 million machine is ultimately meant to deliver megajoules of pulsed energy—ten-nanosecond beam pulses of 20–30-MeV ions of lithium or other light species—to a D-T fusion pellet. The goal is to compress the pellet to a thousand times normal density, approaching the conditions for thermonuclear ignition.

Pellet experiments are still years off. Last month the 36 Marx generators, the sophisticated capacitor banks that initiate the accelerating voltage pulse, successfully delivered their full 13-MJ capacity with a time spread of only 27 nanosec. Further downstream, the highly innovative plasma opening switch has begun functioning. □