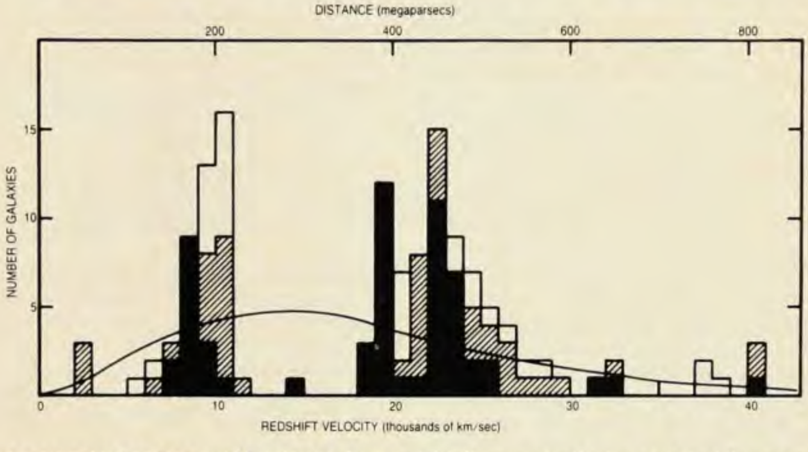
Deep redshift survey of galaxies suggests million-Mpc³ void

Surveying the redshifts of bright galaxies out to 800 megaparsecs, a group of astronomers has found preliminary evidence for the existence of a gigantic void—a million-cubic-megaparsec volume devoid of bright galaxies—in the northern sky. In a recent *Astrophysical Journal Letter*,[1] Robert Kirshner (University of Michigan), Augustus Oemler (Yale), Paul Schechter (Harvard–Smithsonian and Kitt Peak) and Stephen Shectman (Mount Wilson and Las Campanas Observatories) report that their deep redshift surveys of three small angular regions in the constellation Boötes show identical 6000-km/second gaps in the velocity distribution of galaxies down to 16th magnitude. The three sampled regions, each 1.4° square, form a roughly equilateral triangle on the celestial sphere, about 35° on a side. Assuming that the entire triangular region will ultimately prove to be "empty" in this same 6000-km/second velocity interval, centered at 15 000 km/second, one would deduce the existence of a void more than 100 megaparsecs across, about 300 Mpc (10^9 light years) distant from us.

The conclusion that the three small regions surveyed, with a total of only 133 galaxies brighter than magnitude 16.3, are typical of the entire region they encompass is, for the moment, a leap of faith, strengthened by the striking coincidence that each is empty in precisely the same velocity (redshift) interval. More comprehensive (but shallower) surveys of the northern sky, out to distances of only about 100 Mpc, have found firm evidence for voids up to 34 Mpc across.

Such lesser voids, two orders of magnitude smaller in volume than that suggested by the deeper survey of Kirshner and his colleagues, are consistent with the results of computer simulations of gravitational clustering of galaxies orginally distributed more-or-less uniformly in the early Cosmos. But if this larger 10^6 Mpc³ void holds up as the Kirshner group continues its deep survey in Boötes, theories starting with such random distributions at the epoch of galaxy formation may have to give way to cosmological models that favor a nonuniform initial distribution of galaxies.



Recessional velocities of 133 galaxies, from a redshift survey by Kirshner *et al.* of three small angular fields (three different shadings) in Boötes. Corresponding distances, assuming a Hubble constant of 50 km sec^{-1} Mpc^{-1}, are shown on the top scale. The smooth curve indicates the expected velocity distribution of galaxies in the absence of clustering, for a brightness cutoff at magnitude 16.3. Although separated from one another by 35°, all three fields show the same 6000-km/sec velocity gap centered around 15 000 km/sec, suggesting a volume of more than 10^6 Mpc³ severely depleted of bright galaxies, about 300 Mpc distant from us.

Redshifts are translated into distance by the Hubble law, which asserts that the recessional velocity of a distant light source is proportional to its distance from us in the expanding universe. Bearing in mind the fact that the Hubble proportionality constant H is still uncertain by about 40%, we are using the conventional value, $H = 50$ km sec^{-1}Mpc^{-1}, to convert the raw recessional-velocity (redshift) data into distances.

Because redshift measurements of galaxies are much more laborious than simple angular determinations of position on the celestial sphere, traditional studies of galactic clustering have used primarily two-dimensional angular compilations of galactic positions. In the past few years, however, the development of high-quantum-efficiency digital detectors for optical telescope spectrometers has begun to give intergalactic astronomers easier access to the third dimension—distance along the line of sight—by way of better redshift measuring capacity.

Availing themselves of such new instrumentation, Marc Davis and his Harvard–Smithsonian colleagues (Davis is now at Berkeley) have undertaken a comprehensive redshift survey of bright galaxies in the northern sky. They have now catalogued several thousand such galaxies, but their measurements only extend out to redshift velocities of less than 10 000 km/sec (200 Mpc). In compilations of such data, several voids with dimensions on the order of 30 Mpc have already been identified. Kirshner and his colleagues have chosen to look deeper—out to redshift velocities of 40 000 km/sec, corresponding to 800 Mpc. At such distances, of course, data are gathered much more slowly; one can only sample small angular bins rather than covering extensive regions of sky.

Kirshner, Oemler, Schechter and Shectman have taken the bulk of their galactic redshift data at the Mount Palomar 200" telescope, the Kitt Peak 2.1-meter telescope and the Multiple Mirror Telescope on Mount Hopkins. To take proper account of the decrease of apparent brightness with distance, one must impose a clean magnitude cutoff on the observed sample. One also needs information about the distribution of absolute galactic bright-

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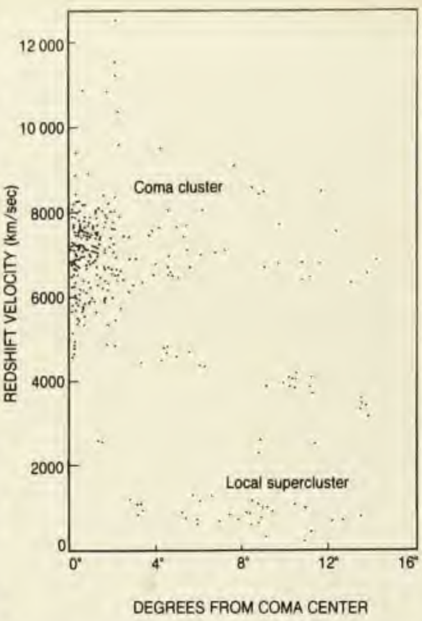
nesses. The Kirshner group did the necessary brightness measurements with photographic Schmidt plates (sensitive primarily in the red) exposed at the Palomar 1.3-meter Schmidt telescope. In the three 1.4° angular bins of their published redshift survey, the group found 133 galaxies brighter than magnitude 16.3.

These three small angular bins in Boötes were in fact only half of the survey originally undertaken by Kirshner and his colleagues. Three more fields were surveyed in the southern galactic hemisphere. But "the distribution of galaxy redshifts in the three northern fields is so striking that a more direct discussion seems appropriate," their *Astrophysical Journal Letter* tells us, by way of explanation for this separate publication of the findings in Boötes.

The figure showing the redshift velocity distributions of the galaxies found in the three small northern fields (three different shadings) tells the whole surprising story. The smooth curve peaking near 15 000 km/sec is the velocity distribution one would expect to see if the three fields were populated with mean galactic density and the spatial distributions of galaxies were uniform (no clustering).

The histogram of observed redshift shows a very different picture. There are almost no galaxies to be seen in the redshift velocity interval from 12 000 to 18 000 km/sec, exactly where one would have expected the distribution to peak. Furthermore, all three observing fields are depleted in precisely the same 6000 km/sec velocity range, despite the fact that they are separated from one another by 35°. Applying the Hubble law, one concludes that all three fields are almost empty of bright galaxies in the distance interval from about 240 to 360 Mpc. At this distance, 35° implies a separation between the three fields of about 180 Mpc normal to the line of sight. Thus, if the entire triangular region were as empty in this 6000-km/sec velocity range as the three small fields at its corners, one would have a volume of about 1.4×10^6 Mpc^3 essentially devoid of normally bright galaxies.

The crucial fact that makes the result interesting, Oemler told us, is that the velocity gap is just about the same for all three fields. Richard Gott, who does computer simulations at Princeton of gravitational clustering of galaxies, pointed out to us that a single 6000-km/sec gap in any one of these small angular regions, with a population of about 45 galaxies, would not be at all surprising. From Poisson statistics alone one would expect fluctuation of about 15% in so small a population; and standard gravitational clustering theory, he explained, would have in-



Coma cluster of galaxies is seen in scatter plot by Chincarini and Rood[2] of redshift velocity *vs.* angular distance from center. Assuming a Hubble constant of 50 km sec^{-1} Mpc^{-1}, most galaxies are within 20 Mpc of center. But the authors find evidence for correlations out to 100 Mpc in Coma and other "superclusters."

creased such statistical fluctuations about tenfold between the epoch of galaxy formation and the present day. Even three such gaps would not be much cause for excitement. But the fact that they coincide so precisely, Gott admits, makes one sit up and take notice.

The obvious next step, Oemler told us, is to survey additional regions interior to the triangle. If the three coincident gaps are really an improbable statistical fluke rather than indicators of a gigantic void, it will soon become clear. The new surveys are already in progress. The published data, he cautions, ought not to convince anyone that the million-Mpc^3 void is real—but they are very suggestive. Almost as interesting as the velocity gap, he points out, are the two striking population enhancements seen on both sides of it. The nearer enhancement at least, at about 200 Mpc, seems clearly to be an extensive feature. It was seen in an earlier survey by the group to cover a significant fraction of the northern galactic cap.

Galaxy formation and clustering. If the million-Mpc^3 void proves to be real, how would one account for it? Simple Newtonian arguments tell us that if the galaxies were originally distributed in uniform, random fashion throughout the early Cosmos, gravitational interaction would have enhanced initial random population fluctuations as the Universe expanded. Positive and negative departures from the mea[n den]sity of galaxies would grow in amp[litu]de as galaxies gravitated toward [one] another. Clusters become den[se]r and voids grow emptier. One descr[ib]es the degree of clustering observed in the present epoch by a "two-point correlation function," which tells us the excess probability (relative to the overall mean) of finding a second galaxy at a given distance when one is already standing on a galaxy.

James Peebles and his Princeton colleagues have studied two-point (and higher-order) correlations extensively, using mostly two-dimensional angular compilations of galaxy positions, and they have attempted to reproduce the empirical correlation functions by means of gravitational-clustering models. From the two-dimensional data (without much redshift depth information) they found that the correlation functions fall rapidly to zero beyond 10 or 20 megaparsecs. That is to say, on any scale larger than 20 Mpc the distribution of galaxies should be quite uniform. Typical galactic clusters like our own Andromeda group are in fact only a few Mpc across.

Peebles has been able to reproduce the empirical correlation function quite well analytically by assuming that the protogalaxies were originally uniformly distributed with random Poisson fluctuations in the epoch of galaxy formation, when the Universe was about 1/10 its present diameter. If one assumes that the mean mass density of the Universe is close to its critical closure value, these statistical fluctuations grow linearly with the diameter of the expanding Universe, yielding a present-day correlation function very close to that actually observed.

How then can one account for the 30-Mpc voids seen in the shallower surveys, let alone the supervoid—more than 100 Mpc across—suggested by the Kirshner data? Gott, and his Princeton colleagues Edwin Turner and Herbert Axelrod, working with Sverre Aarseth (Cambridge), have performed extensive computer simulations of gravitational clustering as the Universe expands by a factor of ten, starting from a uniform distribution of galaxies with various initial fluctuation spectra—Poisson fluctuations and other plausible spectra with somewhat larger statistical fluctuations. In a 4000-galaxy simulation they found, to their surprise, that voids as large as 32 Mpc across were being generated, even though the overall correlation function reproduced well the empirical correlation function that vanishes rapidly above 20 Mpc. It is hard to extrapolate from 4000 galaxies to realistic larger populations, Gott told us. But he doubts that his model, which differs little in its essentials from that of Peebles, would generate 100-Mpc voids even with larger simulation populations.

A possible way out of the dilemma is to abandon the hypothesis that the protogalaxies were in fact uniformly distributed in three dimensions. Yaakov B. Zeldovich at the Institute for Applied Mathematics in Moscow has developed a model in which the galaxies were formed not primarily by gravitational accretion but rather by the complex hydrodynamic interaction of massive gas clouds. In such a model, galaxies are formed preferentially on sheets in space, with regions devoid of galaxy formation between the two-dimensional sheets. In the time since the galaxy formations, these initial sheets would have been smeared out to some extent by gravitational clustering; but large voids might remain as vestiges of the original nonuniform distribution. The Zeldovich model has not yet been worked out in sufficient quantitative detail to permit a meaningful comparison with the observational data, Oemler told us.

One paradox, however, is harder to get around, Oemler points out. If voids like that suggested by the Kirshner group data are common, the 3-K cosmic microwave background ought to be much less uniform than we know it to be. The group quotes an upper limit of $1/10$ for the ratio of the density of bright galaxies in the Boötes void (if the three samples are representative) to the mean galactic density in normal regions. The 3-K microwave background has its origin at the time of "recombination"—the period when the early Universe first became cool enough to sustain neutral atoms. The Universe has expanded by about a factor of 1000 since the time of recombination. Therefore, the standard argument goes, density fluctuations would have grown by a factor of 1000 in the interim. Thus, today's tenfold depletion in the supervoid would have its origin in a 1% density fluctuation at recombination.

If such 1% density fluctuations were common at recombination, we should be seeing 1% fluctuations from point to point in the blackbody temperature of the cosmic microwave background today. In fact, the 3-K background is observed to be smooth to one part in 10^4. (The well-known anistropy due to our motion toward the Virgo cluster is a large-scale feature unrelated to such local fluctuations.)

The smoothness of the microwave background is a more serious problem, Oemler told us, than the disagreement with specific models such as those of Peebles and Gott. But here too, there are possible ways out. Perhaps the observed depletion of bright galaxies in the Boötes void exaggerates the overall depletion of mass density in such voids. A relatively shallow density trough, the Kirshner group argues, might well have inhibited galaxy formation, producing a void whose depletion of bright galaxies is much more pronounced than its true mass depletion. After all, Oemler says, we can only see the mass that shines brightly.

Another possibility would be a lumpy cosmic distribution of massive neutrinos. If neutrinos do have rest masses on the order of 10 eV, as is now widely speculated (PHYSICS TODAY, July 1981, page 17), they would represent a major fraction of the mass of the Universe. It may be, Oemler told us, that the neutrino spatial distribution exhibits strong fluctuations. If the "normal" matter "fell" into this lumpy neutrino distribution much later than the epoch of recombination, he argues, we would be seeing a microwave background much smoother than the present-day distribution of visible matter.

Note added in proof: Since writing this story we have heard from Davis that his group has recently identified a void they believe to be more than 50 Mpc in diameter. This void is also in Boötes, but at a distance from us of 140 Mpc it is only half as far away as the Kirshner void. The Davis report will be published in the *Astrophysical Journal* in March. —BMS

References

1. R. P. Kirshner, A. Oemler Jr, P. L. Schechter, S. A. Shectman, Astrophys. J. **248**, L57 (1981).
2. G. Chincarini, H. J. Rood, Sky and Telescope **59**, 364 (1980).

Supermultiplets in doubly excited atoms

Take an excited hydrogen atom, add a second excited electron, and you change the calculation of energy levels from an easy problem to a formidable task. In such doubly excited atoms, the dominance of electron correlations considerably alters the single-particle shell structure. Alternative formulations of the electronic states in terms of hyperspherical coordinates have greatly elucidated the angular and radial correlations. That progress was recently boosted by the insight from dynamical group theory: A supermultiplet classification gives striking order to the energy spectrum and predicts which electron states become mixed. This supermultiplet classification visually depicts the doubly excited atom as a linear triatomic molecule having the electrons across the nucleus from one another and exhibiting collective rotational and bending motions. This new view is compatible with that of the hyperspherical approach. All the varying perspectives were discussed last month at the meeting of the APS Division of Electron and Atomic Physics in New York.

The supermultiplet classification[1] and its interpretation as the spectrum of a rotor-vibrator[2] (ro-vibrator) were proposed by two chemists—David R. Herrick (University of Oregon) and Michael E. Kellman (now at Northeastern University). Their work built on group-theory research done in the early 1970s by Carl Wulfman (University of the Pacific) and by Oktay Sinanoğlu (Yale University) together with Herrick. The application of dynamical group theory to the problem of correlated motion of electrons in atoms has not been extensive in the past, perhaps because the Hamiltonian was known and provided a starting point for calculations of the energy levels or charge distributions.

Historically, the importance of electron correlations was first underscored by the deviation of the observed helium photoabsorption spectrum from that anticipated by independent-electron models. (See the review by Ugo Fano, PHYSICS TODAY, September 1976, page 32.) The need to include electron correlations led Fano and his students at the University of Chicago to adopt hyperspherical coordinates, which describe the positions of the two electrons relative to each other as well as to the nucleus. Joseph Macek (University of Nebraska) constructed a wave function that was approximately separable in the joint-electron radial coordinate R. Chii-Dong Lin (Kansas State University) extended this approach to write a wave function in which both the angular and radial correlations are approximately separable. The separability in hyperspherical coordinates relates to the separability of the rotational and vibrational modes found in the group-theory picture, but the precise correspondence has yet to be established. The nodal patterns calculated by this method infer the same structure as does the recent group-theory computation, although the hyperspherical approach is limited to the comparison of states of a single Russell–Saunders symmetry. One strength of the hyperspherical approach is that it delineates the radial as well as the angular correlations, whereas the dynamical group theory treats only the angular correlations.

The power of the group-theory approach in classifying the energy spectrum of doubly excited (or autoionized) atoms is illustrated in figure 1 for the specific case of the $n = 3$ shell of doubly excited helium. In the figure the energy levels were calculated by a standard