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Distribution of Galaxies, Clusters, and Superclusters

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Distribution of Galaxies, Clusters, and Superclusters

The distribution of matter in space is the key to understanding the past, present, and future of the universe. If the average mass density on the largest scales exceeds a critical level, then the expansion of the universe will eventually cease and reverse, ultimately ending in a 'Big Crunch'. Conversely, if the mean mass density in the universe is less than this critical value, the expansion of space will continue without end. The distribution of matter also reveals much about the cosmic history of the universe: matter was very smoothly distributed shortly after the Big Bang but is much less so now. When observations of how galaxies and CLUSTERS OF GALAXIES are spread throughout space are combined with observations of their spectroscopic and morphological properties, astrophysicists can place important constraints on how these systems formed, evolved, and, ultimately, elucidate the nature of the growth of structure in the universe. In particular, the relationship between the distribution of luminous matter (e.g., hot gas, stars, galaxies) and non-luminous matter (e.g., non-baryonic particles) is determined by the thermal properties of the non-baryonic 'dark' matter, the history of star formation, gravity, and the cosmological model. Hence, accurate predictions for the spatial distributions of galaxies and clusters as functions of time are fundamental requirements for any viable theory of how structure in the universe formed and evolves. Studying the distribution of galaxies and clusters over a range of distances and epochs has, consequently, been an area of much active research over the past 20 years. While there is still much that is unknown about the underlying mass distribution in the universe, substantial progress has been made owing to breakthroughs in astronomical instrumentation and detector technology, numerical simulation software and high-speed computer processors, and particle physics. What we do know is that the distributions of galaxies and clusters show a remarkable degree of inhomogeneity over distances spanning at least 150 megaparsecs (Mpc) and that the clustering properties of galaxies appear to depend on both the local environment the galaxy resides in and on the intrinsic properties of the galaxy. The precise nature of the DARK MATTER and the role of gas hydrodynamics (e.g., STAR FORMATION) in the evolution of structure, however, presently remain unsolved problems in astrophysics.

The cosmological principle, dark matter, and the clustering hierarchy

A guiding principle of cosmology has been that if one looks out to large enough distances, then the universe should be homogeneous and isotropic. This assumption is often referred to as the 'COSMOLOGICAL PRINCIPLE'. By isotropic, we mean that the global properties of the universe (and, therefore, the galaxy distribution) are not dependent the viewing direction. By homogeneous, we mean that observers in different parts of the universe will record the same basic picture of the universe at a given cosmic epoch. The gist of the cosmological principle is that there are no preferred directions or locations in the universe. Present observations suggest that the cosmological principle is valid but only on distance scales in excess of 150 Mpc or so. On smaller scales, we do see spatial variations in galaxy properties (and possibly even in certain cosmological parameters) which are presumably tied to substantial fluctuations in the underlying distribution of matter in space.

Early maps of the galaxy distribution on large scales, generated prior to the 1980s, were two dimensional—reproducing the distribution of galaxies on the plane of the sky. The third dimension, distance from our Galaxy, was only available for a small fraction of those galaxies. Nonetheless, these maps showed the distribution of galaxies to be highly non-random: when one galaxy is found, the likelihood of finding a nearby companion galaxy is significantly higher than Poisson statistics would predict.

Clustering in the universe is detected on many different scales. Our Milky Way Galaxy is a member of a group (named the LOCAL GROUP) of 24 galaxies spread over a region about 1 Mpc in radius. The Local Group contains a total mass in the range 3×10^{12} to 10^{13} solar masses. Groups like this are relatively common: on average, there is approximately one group for each 1800 cubic Mpc volume. Clusters of galaxies are approximately comparable in size, spanning 1–5 Mpc, but are considerably more massive and rarer than galaxy groups (figure 1). Clusters contain hundreds of galaxies in their central regions. The total cluster mass is usually at least 10^{14} solar masses and the richest systems can be 50 times more massive than that. The mass density within a cluster is typically at least 100 times the universal closure density[1]. Clusters of galaxies are the largest systems known to have reached dynamic equilibrium, a state in which the cluster's gravitational potential energy is twice its internal kinetic energy. Gravitationally bound structures may exist on larger scales still. Although quite rare, clusters of clusters (known as SUPERCLUSTERS) have been detected. These systems can contain in excess of 10^{16} solar masses, including up to 10 individual galaxy clusters spread across regions 10–30 Mpc in extent. Some superclusters are suspected of being bound systems but it is highly

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[1] The universal closure density is 1.88×10^{-29} grams per cubic centimeter. This is the minimum mean mass density required to eventually halt the present expansion of the universe.

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Figure 1. The galaxy cluster Abell 2218 as seen by the Hubble Space Telescope. The field of view spans a distance of about 415 kpc. The curved, faint galaxies are actually distant galaxies lying well beyond the cluster whose appearances have been distorted by the effect of the cluster's mass on the curvature of space. Such distortion, known as gravitational lensing, is one way the mass of a cluster can be estimated.

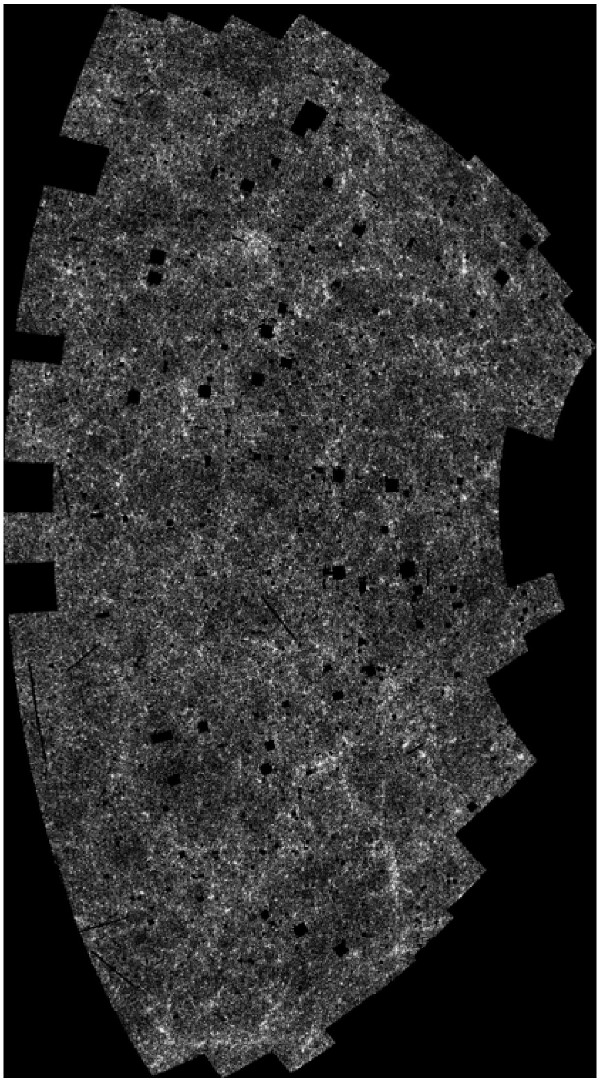

Figure 2. A map derived from digitized photographic sky survey plates showing the angular distribution of over 2 million galaxies in the southern galactic hemisphere. Blank regions in the map were skipped due to the presence of very bright stars.

unlikely they have had sufficient time to reach dynamical equilibrium.

Structure on scales in excess of 100 Mpc was not discovered until wide-area, three-dimensional galaxy surveys were first undertaken in the early 1980s. Three-dimensional surveys are essential for discovering the true nature of the galaxy, cluster, and supercluster distributions because projection effects hide substantial structures in two-dimensional maps like that in figure 2. Indeed, an amazing bubble-like network of voids and sheets of galaxies and clusters, extending for hundreds of Mpc, is revealed in these spatial surveys.

The clustering patterns that we see in the universe, from galactic scales and up, are believed to be governed by the gravitational potential of ubiquitous dark matter. The galaxies, which comprise less than 5% of all the matter in the universe, are simply tracers of the dark matter distribution. This remarkable realization is based on observations which infer the total mass in galaxies and in clusters of galaxies from the distribution of orbital velocities of the material inside these systems. The dynamical mass estimates derived in this way are typically 5–10 times larger than the masses estimated by summing up the luminous components (e.g., stars in the case of galaxies; galaxies and hot gas in the case of clusters). The implication is that most of the matter in the universe has not yet been directly detected by conventional astronomical instrumentation.

The nature of this dark matter is still not well understood. The hypothesis that dark matter consists solely of BARYONS (e.g., neutral gas, dilute plasma, massive planets, white dwarfs, neutron stars, and black holes) appears to be in conflict with observations of hot gas in clusters of galaxies (the gas comprises only about 10–20% of the total cluster mass), the tendency for dying stars to eject a substantial fraction of their mass back into interstellar space (and, hence, locking baryonic matter in stellar remnants is a very inefficient process), and limits on the number of massive planets, brown dwarfs, and very low mass stars from both gravitational microlensing surveys and deep Hubble Space Telescope images (the space density of such objects is too low to account for a significant fraction of the inferred total mass density in the universe).

The spatial distribution of galaxies and clusters can help constrain the nature of the dark matter because dramatically different configurations are predicted depending, for example, on whether or not the dark matter particles are highly relativistic (dubbed hot and cold dark matter, respectively). Candidates for non-baryonic dark matter include neutrinos, axions, and the weakly interacting massive particles predicted by supersymmetry models (photinos, higgsinos, zinos, and solar cosmions). Programs to detect the more exotic of these cosmological non-baryonic particles are underway.

Voids, sheets, filaments, and spikes

The frothy spatial distribution of about 10 000 galaxies in two nearly opposing directions is shown in figure 3. The data were obtained at observatories located in Arizona and Chile. In this figure, known as a cone diagram, each galaxy's position is shown as a point. Our own galaxy is located at the point where the wedges meet. The distance represented by the length of each wedge is about 120 Mpc. Several striking features are evident in this galaxy map (none of which were predicted by theory prior to the observations): large regions of very low galaxy density, somewhat misleadingly referred to as voids, extend for tens of Mpc. The voids are surrounded by a sheet-like network of galaxies often extending for several hundred Mpc. Indeed, one such coherent feature can be seen in figure 3 crossing from the mid-region of the northern cone diagram into and across the southern cone diagram. This feature has been dubbed the 'GREAT WALL'.

Clusters of galaxies can also be seen in the map as highly elongated clumps oriented towards the center of the diagram. This elongation is an artifact of the large, orbital velocities of galaxies about the cluster centers which can often approach 1000 km s^{-1}. These orbital velocities distort the spatial positions determined from the redshift measurements and result in the elongated appearance of clusters in such diagrams. If we could observe the cluster galaxies using a map based on distances not dependent on the REDSHIFT, such elongation would vanish.

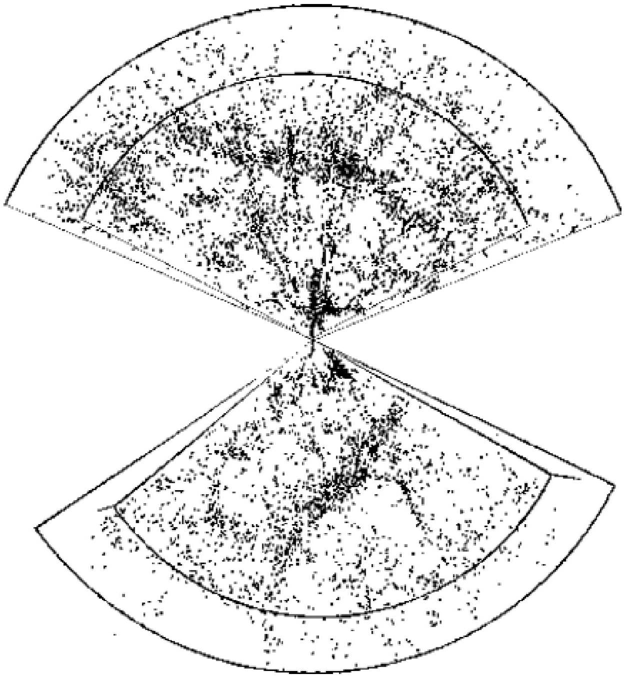

Figure 3. The spatial distribution of approximately 10 000 galaxies extending out to a distance of 120 Mpc. Galaxies from a small portion of the northern galactic hemisphere are shown in the upper cone diagram and those from a comparable region in the southern galactic hemisphere are shown in the lower cone diagram. These data are from a large redshift survey coordinated by the Center for Astrophysics at Harvard University.

The structures in this map are clearly comparable with the depth of the survey and, thus, wider and deeper surveys were undertaken in the 1990s to assess just how large the largest structures in the universe are (see GALAXY REDSHIFT SURVEYS). One technological development which made very large redshift surveys feasible was the multi-object spectrograph (MOS). The 10 000 redshifts above were measured one at a time on telescopes which had narrow fields of view ((1/7)th the area subtended by the full Moon). Multi-object spectrographs today allow up to 600 redshifts to be measured simultaneously from galaxies spread over an area of a few square degrees (roughly 15 times the area subtended by the full Moon).

One of the first large MOS surveys to be completed, known as the Las Campanas Redshift Survey (LCRS), measured about 24 000 redshifts in two directions 132° apart. The distribution of galaxies from this survey is shown in figure 4. The depth of the LCRS

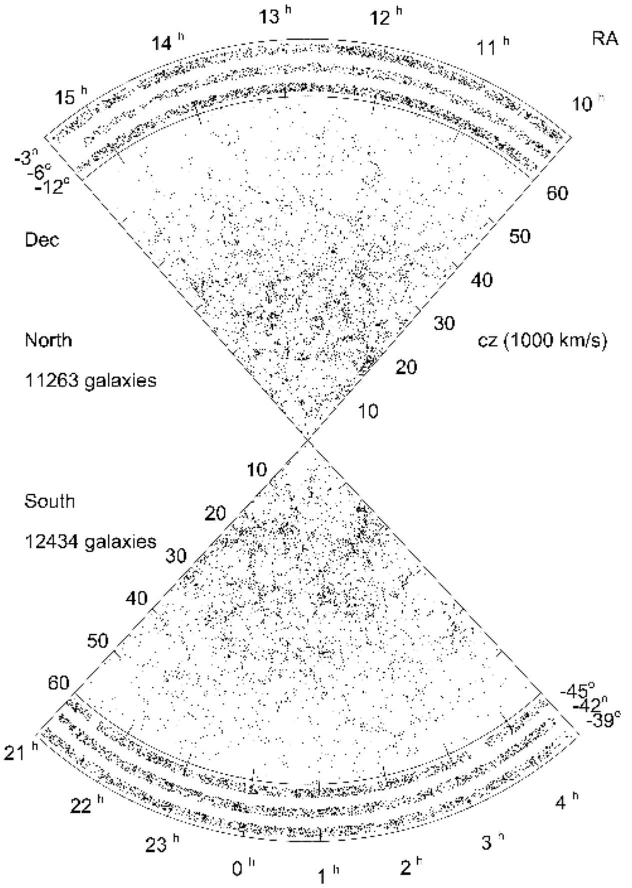

Figure 4. The spatial distribution of approximately 24 000 galaxies extending out to a distance of 600 Mpc. These are the results from the Las Campanas Redshift Survey conducted by an international team of astronomers using a Chilean telescope equipped with a multi-object spectrograph. The 3 bands going across the top and bottom show the projected distribution of the galaxies on the sky. Although the depth of this survey is substantial, it only subtends 0.3% of the entire sky.

was nearly 5 times greater than that in figure 3. Yet the structures found were comparable in size suggesting that perhaps there are no substantial inhomogeneities much larger than 120 Mpc. However, the LCRS only includes distances for a fraction of all the galaxies in this part of the sky due to time and telescope constraints. As a consequence, the structure in the LCRS map is not as clearly delineated as that in a survey which completely samples the galaxy distribution, such as the one in figure 3. Any conclusions regarding the existence of structures on scales larger than 120 Mpc or so must therefore be tempered by the fact that the survey has only done a partial sampling of the galaxy and cluster distribution.

The results of the most extensive redshift survey of clusters of galaxies is shown in figure 5. The radius of the survey is 240 Mpc and includes about 50% of the ~1000 clusters actually residing in this volume.

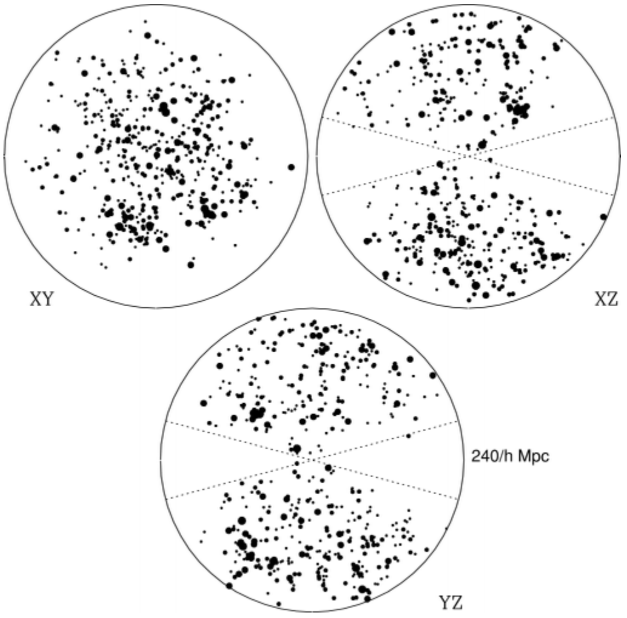

Figure 5. Three views of the spatial distribution of the richest ~480 clusters within a radius of 240 Mpc, centered on our Galaxy. Each dot represents a cluster and the dot size is proportional to the number of bright galaxies in the central region of the cluster. The empty wedges in the XZ and YZ projections are due to the blockage by the disk of our Galaxy.

Quantifying clustering

The constraints that the above surveys place on theories of structure formation and dark matter models come from a variety of statistical quantities which measure the degree to which the galaxy and cluster distributions differ from a purely random configuration. One of the most widely used of these statistics is the two-point correlation function, $\xi(r)$. The two-point correlation function measures the probability of finding one galaxy separated by a distance r from another galaxy. The observations above reveal that $\xi(r)$ is well represented by a power law of the form

$$\xi(r) = \left(\frac{r_0}{r}\right)^{\gamma} \qquad (1)$$

where r_0 is known as the correlation length. The correlation length is the distance scale at which there are twice as many pairs of objects than expected if the distribution of objects were completely random. For galaxies, the best-fit parameters for $\xi(r)$ are $r_0 = 5.5 \pm 1$ Mpc and $\gamma = 1.8 \pm 0.05$. If the distribution of galaxies were random, one would expect $\xi(r) = 0$ at all scales. The constraints on $\xi(r)$ mirror the visual impression given by the redshift surveys—the galaxy distribution is strongly clustered, not random. Remarkably, the correlation function of clusters of galaxies has a slope nearly identical to that for galaxies ($\gamma = 1.9 \pm 0.3$) but the correlation length is significantly larger, $r_0 = 20\pm8$ Mpc. The agreement between the shape of $\xi(r)$ for galaxies and clusters suggests that these two rather different types of stellar systems trace the same underlying mass distribution. An additional constraint from the redshift surveys of galaxies and clusters is that the power-law representation of $\xi(r)$ appears to be valid on scales up to at least 40 Mpc and perhaps as high as 60 Mpc.

The correlation function parameters above are mean values for large samples of galaxies and clusters. The values are not universal, however. There is a highly significant dependence of the correlation length on the luminosity of the galaxies being studied and on their morphology. For example, it has recently been established that the correlation function of the most optically luminous galaxies ($L_{\text{opt}} \geq 5 \times 10^{43}$ erg s^{-1}) have correlation lengths of ~16±2 Mpc, approaching that of clusters of galaxies, whereas the intrinsically faintest galaxies have correlation lengths as low as 4 Mpc. It has also been established that the likelihood of finding a neighbor galaxy within 1 Mpc from an elliptical is about twice as high as that for finding a companion within the same volume from a spiral galaxy. Thus, although all the distribution of all galaxies is determined by the underlying matter distribution, elliptical galaxies and/or luminous galaxies appear to be more efficient tracers of regions in space with the highest densities. The cluster correlation function parameters also appear to depend weakly on the cluster's x-ray luminosity: the most luminous x-ray clusters ($L_X \geq 1.4 \times 10^{44}$ erg s^{-1}) have $r_0 \approx 35\pm15$ Mpc, compared to $r_0 \approx 15\pm4$ for the least rich (and least x-ray luminous) systems.

The power spectrum, $P(k)$, is the Fourier transform of $\xi(r)$ and provides a complementary but important constraint on the clustering properties of galaxies and clusters: broad features in the correlation function are narrow in Fourier space and vice versa (see CORRELATION FUNCTION AND POWER SPECTRA IN COSMOLOGY). An analysis of the distribution of galaxies in the LCRS revealed there is a significant 'spike' in the power spectrum on scales near 100 Mpc. Deeper redshift surveys, known as 'pencil beam' surveys because they cover very small solid angles but probe great distances, also have detected excess clustering signatures on scales of up to 130 Mpc. Indeed, the results from the first pencil beam surveys showed there appeared to be quasi-periodic spikes in the radial distribution of galaxies, occurring every 120–130 Mpc. These features are surprising since it is not understood why there should be such a preferred size scale. One interpretation is that structures on large scales, like the network of walls and voids seen in the wide area redshift surveys, have characteristic sizes. But what determines these characteristic scales? Some of this excess power could be the lingering effects of the properties of the plasma that existed in the very early universe. But at present we do not really understand the origins of these remarkable features in the galaxy distribution. Nonetheless, the global shape of the galaxy and cluster power spectra are similar, suggesting again that clusters and galaxies are tracing similar perturbations in the matter distribution. The amplitude of $P(k)$ for the richest clusters is, on average, a factor of ~2–3 higher than that for poorer clusters, consistent with differences seen in their respective $\xi(r)$. In turn, the rich cluster $P(k)$ amplitude is about 12–16 times higher than that derived for galaxies in the LCRS.

'Biasing'

The above results demonstrate that not all extragalactic objects trace the underlying mass distribution in the same way. Indeed, this conclusion represents a substantially new paradigm in cosmology. Prior to the early 1980s it had usually been assumed that a one-to-one relation existed between fluctuations in the distribution of galaxies and fluctuations in the distribution of mass. We now realize that not only is the relationship not a direct one but it probably is not even a linear one and may depend on time and size scale, as well. Galaxies and clusters are thus deemed 'biased' tracers of the matter distribution and much research is now in progress to understand the physical mechanisms which can account for this more complex relation between the galaxy, cluster, and matter distributions.

The dependence of the clustering properties, such as the correlation length, on the mass of the system have been explained in terms of the statistics of 'rare peaks' in a distribution. Fluctuations in the density of mass in the universe occur on many scales. Superposed on the largest fluctuations are smaller ones. If galaxies and clusters of galaxies form at sites which achieve some minimum density enhancement, then there will be a preference for the most massive and most luminous objects to form at those sites which already have elevated mass density levels by virtue of sitting atop the peak of a larger scale fluctuation. The highest density peaks in the mass distribution, however, occur less frequently—one has to search a larger volume to find a large density peak than a small peak. It has been proposed that a universal relation can be made between the mean separation between objects, d_i, and their correlation length, r_0, of the form

$$r_0 = (0.3 \pm 0.1) d_i \tag{2}$$

implying that objects with larger separations (which tend to be more massive systems) will exhibit stronger clustering[2]. Does the trend between clustering strength and mass extend to superclusters? The answer is unclear because there are too few superclusters known at present to perform robust computations. Surveys initiated in

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[2] The mean interobject separation is defined as $d_l = (n_i)^{-1/3}$ where n_i is the mean space density of the objects.

1998 may yield enough additional superclusters to address this question.

Although early versions of structure formation theory based upon a universe dominated by cold dark matter (CDM) did predict a trend towards higher correlation lengths as the galaxy and cluster mass increased, these same models did not come close to predicting the actual observations in which the richest clusters are 10–20 times more strongly clustered than are galaxies. The resolution of this discrepancy was to postulate that galaxies and clusters are biased tracers of the mass. These biased CDM models are more successful at reproducing the actual galaxy distribution, but there remain other significant observations with which the models do not agree very well. This is probably because either the dark matter properties assumed are not accurate and/or the specific biasing model is not accurate.

Statistics like $\xi(r)$ and $P(k)$ are not sufficient to unambiguously describe the galaxy and cluster distributions. Distributions that appear dramatically different to the eye can often have similar two-point correlation functions. This is because the eye is sensitive to high-order moments of the distribution (such as 'wall'-like bands of galaxies surrounding large, underdense volumes). Statistics which measure the high-order moments of the distributions thus provide superior discrimination between cosmological models as well as some of the best constraints on the degree of biasing and, thus, on the reliability of galaxies and clusters as tracers of the mass. Current constraints on the higher moments (orders 3–6) of the galaxy and cluster distributions suggest that while galaxies and clusters are sampling the same underlying matter distribution the biasing between them is non-linear.

Cosmic flows

The above observations demonstrate both the power and limitations of mapping structure with redshift surveys. While such surveys succeed in revealing extensive and intricate structures on many scales, the physical interpretation of the structure is complicated by the fact that the tracers of the structure are biased. However, there is a complementary approach to mapping structure which takes advantage of the fact that all the matter in the universe is subject to its own mutual gravitational force. Inhomogeneities in the mass distribution can induce motions of galaxies and clusters (dubbed 'peculiar' velocity by astronomers) which are unrelated to the expansion of space. On scales larger than about 10 Mpc, a three-dimensional map of these motions can be used to infer the masses and probable locations of the responsible structures because the induced velocities are linearly proportional to the gradients in the gravitational field[3]. The beauty of such measurements is that they provide a more direct method for mapping the mass distribution and many of the concerns about biased tracers are moot. Peculiar velocity observations are, however, difficult to perform accurately.

The observational study of large-scale cosmic velocity fields began in 1976, with the discovery that the temperature of the COSMIC MICROWAVE BACKGROUND (CMB) is a few millidegrees warmer in one direction and equally cooler in the opposite direction. This signature was quickly interpreted as due to motion of our Galaxy relative to the CMB, motion that is assumed to be due to an imbalance in the gravitational tug of the various structures which surround our Galaxy. (If matter were uniformly distributed around us, the gravitational forces would cancel, on average, and no motion would be induced. However, as seen in the redshift surveys matter is very far from uniformly distributed.) Subsequent measurements of this anisotropy from the Cosmic Background Explorer (COBE) satellite have yielded a highly accurate measurements of this motion: 620 km s^{-1} towards the direction l = 270.8°, b = +29.1°, when measured with respect to the center of the Local Group. Since the CMB is the most distant reference frame possible (it originates at a redshift of ~1000, when the universe was only a few hundred thousand years old), it is quite reasonable to presume that the structures causing this motion are much closer.

In order to measure the peculiar velocity of an extragalactic object, one needs to know both its redshift and its distance. In this case, the distance must be determined *independently* from the redshift. This is because the observed redshift contains contributions from both the expansion of the universe and from any gravitationally induced velocity. The contribution solely from the expansion (referred to as the recession velocity) can be determined directly from the redshift-independent distance via HUBBLE'S LAW. The peculiar velocity is then the difference between the observed redshift and the recession velocity. There are presently at least seven independent methods which can be used to determine distances to galaxies and clusters, albeit not all methods work on all galaxy systems nor do they all yield the same measurement accuracy. However, the common principle in all of these methods is that there exists some observable quantity (other than redshift) that can be used to estimate the distance. In many of these methods, the distance is inferred by comparing an estimate of the object's intrinsic luminosity with its apparent (observed) luminosity.

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[3] On scales less than 5 Mpc, the relationship between induced velocity and mass becomes highly nonlinear making reconstruction of the underlying structure from peculiar velocities extremely difficult.

Using such techniques, redshift-independent distances (and, hence, peculiar velocities) can be established for large samples of galaxies and clusters in different parts of the sky. From such datasets, the motions of galaxies can be charted and the presence of fluctuations in the matter distribution then inferred. The two largest galaxies in the Local Group, our Milky Way and the Andromeda galaxy, are separated from one another by about 700 kpc. Two massless particles sitting that far apart in our expanding universe would be traveling away from one another at more than 50 km s^{-1}. In fact, these two galaxies are moving towards one another at about 70 km s^{-1}. This observation has led to estimates of the combined mass of these two spiral galaxies. The entire Local Group itself is moving due, in part, to the gravitational pull of the VIRGO CLUSTER which lies about 16 Mpc away. But the Virgo cluster mass is sufficient to explain only about 40% of the CMB velocity. Additionally, the CMB velocity vector is misaligned with the position of the Virgo cluster by 47°. Additional structures at larger distances must, therefore, play a role.

One of the first peculiar velocity surveys to detect these structures was conducted in the mid-1980s using distances to over 300 elliptical galaxies. A startling result was found: a vast number of galaxies within a sphere nearly 100 Mpc in diameter appear to share a common motion towards a massive aggregate of matter. Such a motion is referred to as a 'bulk flow' and since so many galaxies participate in it, the aggregate was dubbed the 'Great Attractor'. The bulk flow vector was 600±104 km s^{-1} towards $l = 312^{\circ}$, $b = 6^{\circ}$ (angular error is ~±10º), close to the CMB velocity of 620 km s^{-1} but about 45º from its apex. Subsequent surveys indicate that the 'Great Attractor' is a moderately rich supercluster lying between 40–50 Mpc from our Galaxy. The Great Attractor itself may be participating in a bulk flow suggesting that the origin of the flow is due, in part, to structure on scales larger than 50 Mpc.

Do such bulk flows extend to scales of 100 Mpc or larger? If so, then the cosmological principle is not valid on scales even as large as 100 Mpc. With this key question as a driver, several groups set out to explore the velocity field on scales 4 times larger than the original 'Great Attractor' survey. Initial results from some of these surveys suggest there is evidence for bulk flows of 600–800 (±150–300) km s^{-1} which extend out to scales of 100 Mpc or more. The different surveys have not all yielded consistent directions for these flows, however. There is some evidence to suggest that these very large-scale flows point to within ±30º of the Shapley supercluster, a system with a mass of a few × 10^{16} solar masses located 150 Mpc from the Local Group and towards $l = 312^{\circ}$, $b = 30^{\circ}$. The results are controversial and this is presently a research area of much active observational work. One challenge of measuring bulk flows on such large-scales is that the signal is small and often must be extracted from noisy data. If very large-scale bulk flows turn out to be a reality, then present models for structure formation in the universe will require substantial revision (if not outright rejection).

The Hubble bubble?

Gravitational attraction towards massive structures is not the only means available for generating a large bulk flow, however. If the expansion of the universe were dependent on one's location, then flows could be a direct consequence. Another way to ask this question is: is the Hubble constant (H_0) really constant? The answer is no. A more accurate description of this term would be the Hubble parameter. The Hubble parameter does vary with cosmic age—the temporal dependence is a consequence of the deceleration of the expansion caused by the matter in the universe. The amplitude of the time dependence, however, only becomes significant when surveys span very large distances (and, hence, a large dynamic range in 'look-back' time). Variations in the value of H_0 as a function of location, however, are also possible if the fluctuations in the mass distribution are sufficiently large. The expansion of space within a large underdense region will proceed at a faster rate than that in a large overdense region. The size of the voids and walls seen in the galaxy distribution are, in principle, large enough to yield measurable variations in the Hubble parameter on scales of 100–200 Mpc. As figure 3 shows, the region of space surrounding our Galaxy is underdense relative to, for example, the 'Great Wall' structure which lies about 70–100 Mpc away. One possible explanation, then, for a large peculiar velocity on the scale of 100–200 Mpc is that our Galaxy resides in a region of space where the local expansion rate is faster than that on much larger scales. To date, the observational constraints on the spatial variation of the Hubble parameter are less than 5% on scales of 150 Mpc. Although small, this can still amount to a few hundred km s^{-1} and thus such effects may indeed be at work.

Future observations and outstanding problems

One key challenge posed by all these observations is to understand how the universe evolved from its highly homogeneous state shortly after creation to the present epoch where large inhomogeneities on scales of 100 Mpc, or more, are relatively common. The models which appear most consistent with the majority of the observations are those which call for a CDM-dominated open universe and/or an open universe with CDM plus some hot dark matter component such as neutrinos. The observations may also be consistent with a non-zero cosmological constant (Λ). If the large-amplitude, large-scale bulk flows persist, however, some revisions to these models will be required.

While much progress has been made in mapping the structures in the universe, we still have a ways to go. At present, the fraction of the local universe for which we have reliable maps of the galaxy and cluster distributions is a mere 1%, akin to trying to infer the geography of the entire surface of the Earth from a map of the eastern half of the United States. Some fundamental astrophysical problems in the study of the distribution of galaxies, clusters, and superclusters still remain unsolved. Are there galaxian structures on scales beyond 300 Mpc? Are there bulk flows which indeed extend beyond 100 Mpc? Just how complex is the relationship between the galaxy distribution and the matter distribution? What structure existed when the universe was half or even one tenth its present age? What is the precise nature of the dark matter in the universe?

Given the limited amount of telescope time available to conduct surveys of the galaxy and cluster distributions, astronomers have had to balance the desire to cover large areas of the sky (and hence sample many nearby regions of space) and the desire to probe the galaxy distribution at great distances (to study the evolution of structure). Fortunately, as multi-object spectrographs improve and more large-aperture telescopes are constructed, including a few observatories solely dedicated to spectroscopic surveys, the trade off between area and depth is becoming less of an issue. Facilities exist now which will enable astronomers to conduct surveys that both cover moderately large areas and extend to quite large distances (and, hence, probe farther back into time). Three-dimensional surveys of a million or more nearby galaxies, and of thousands of galaxy clusters, are underway. The study of large-scale structure at high redshift is also now becoming accessible. It is likely the next decade will see many breakthroughs in this particular area thanks to an array of large optical and near-infrared optimized telescopes being commissioned over the next several years.

The COBE satellite provided constraints on the distribution of fluctuations in the matter distribution in the very young universe but only on extremely large scales (greater than 600 Mpc). CMB observatories in space to be launched early in the 21st century will yield exquisite constraints on the early matter distribution on scales comparable with those probed by existing redshift surveys and, thus, provide a direct point of comparison for evolutionary studies. Like the peculiar velocity surveys, the CMB studies are attractive because the fluctuations in the microwave background are direct, unbiased tracers of the underlying matter distribution.

But our ability to observe the universe must be matched with an equal ability to interpret and understand the observations. Thanks to revolutions in computer processing power and data storage capacity, experiments to simulate large segments of the cosmos are now underway (see UNIVERSE: SIMULATIONS OF STRUCTURE AND GALAXY FORMATION). These simulations track the trajectories of a billion particles as they evolve over cosmic time to form structure. Such new tools will provide theoretical predictions at a level of detail and accuracy hitherto unavailable. And since the differences between some cosmological models are quite subtle, such a capability is indispensable.

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