SUPERCLUSTERS
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General background
Superclusters are clusters of galaxy groups and clusters and represent the largest structure in the universe. Shapley noticed already in 1930 the unusually large concentration of galaxies in Centaurus, Zwicky did the same in 1937 in Pisces and Abell proposed in 1958 that clusters themselves seemed to be organized into even larger structures. However, it was not until the 1980's that the idea of superclusters really started to sink in and substantial research got underway. It was recognized that our own Local Group is part of a larger conglomerate of groups and clusters named the Virgo Supercluster or the Local Supercluster, and redshift surveys identified other similar huge structures in the nearby universe such as the Coma Supercluster and the Perseus-Pisces Supercluster. The scale size of these structures were up to 50 MPc (clusters are typically 1-2 MPc), and in between them seemed to be almost empty voids of similar size.
Superclusters are objects of naturally fuzzy definition and boundaries, as they represent a level of the complex hierarchical structure of the gravitationally interacting universe. In 1989 the Great Wall was discovered (Geller and Huchra, 1989), which further complicated the picture. The Great Wall is a sheet of galaxies, groups and clusters confined to a structure 150 times 50 MPc large but only 5 MPc thick. Since then it has become clear that most large-scale structure in the universe occurs in similar thin sheets/filaments. Our own Local Supercluster is a highly flattened structure aligned closely to the Super-galactic Plane. Different authors use different approaches in describing these structures - some see walls and filaments as flattened Superclusters while others envision a cellular universe where a network of walls interconnect denser regions/intersections representing Superclusters. There does seem to be a certain difference - walls are dominantly made of single galaxies and galaxy groups while Superclusters contain a higher fraction of rich clusters.

The typical Supercluster contain a few clusters and have a mass of $10^{15} - 10^{17}M_\odot$. The average separation between them are of the order 100 MPc which translates to a total number of about 10 million in the visible universe. One interesting question that arises is how anisotropy in their distribution affects their motion in relation to the Hubble flow, which we will look at later.
What can we say about the dynamics of these large structures? From the observational estimates of their mass and size we can calculate the free-fall time

\[ t_{ff} = \frac{R}{\sqrt{V_{ff}}} = \frac{R}{\sqrt{\frac{2GM}{R^{1/2}}}} = \frac{R^{3/2}}{2GM} = \frac{5000 \cdot 3.1 \times 10^{16}}{2 \cdot 6.67 \cdot 11 \cdot 10^{16} \cdot 2c30} \approx 4 \times 10^9 \text{years} \]

Since the free-fall time of 40 billion years is much larger than the Hubble time, Superclusters are dynamically young and individual clusters have not passed through the system for the first time.

The Local Supercluster

Also known as the Virgo supercluster, this is the supercluster which our Local Group is part of. It has a disk/halo morphology with 2/3 and 1/3 mass resp. It contains about 100 galaxy groups/clusters and has a diameter of about 50 MPc. The LSC is dominated by the Virgo cluster 15 MPc away, which has over 2000 galaxies. The Local Group is located near the edge of the disk. Through kinematic observations, the mass of the LSC is estimated at \(10^{15} M_\odot\) which implies a large content of dark matter.

The entire Local Supercluster is being drawn toward a region called the Great Attractor, which is 40 MPc away in the Centaurus Supercluster. This region has mass of thousands of galaxies.
The Supergalactic Plane was originally defined from a flattened overdensity of local galaxies. The Z axis of the SGP points toward $l=47^\circ, b=6.3^\circ$ and so is almost perpendicular to the Milky Way plane. It was eventually realized that the plane of the Local Supercluster largely coincides with the SGP - the LSC is a highly flattened structure as many other superclusters.

**Observational techniques**

Reliable 3-D mapping of galaxies and clusters is difficult and time-consuming. Superclusters are identified from:

1) Cluster redshift surveys
2) Galaxy redshift surveys
3) Velocity field analysis

One should be careful in drawing conclusions from redshift-density surveys - systematic effects in peculiar velocities can betray the distance to the galaxies and artificial effects can emerge. The survey is always biased in the way galaxies are selected as well.

A direct redshift-distance translation from Hubble’s law often indicates very thin structures such as the Great Wall. But in a dynamically young flattened system viewed face-on, objects might show systematic peculiar velocities in an infall situation towards the plane. Objects closer to us would be accelerated away from us and so map to higher distance than they are. And objects on the far side would be accelerated towards us and be mapped at a smaller distance than they are. The result is that the structure looks more spatially squeezed than it is. Baffa et al. (1993) show that this effect is indeed happening in the thin Perseus-Pisces Supercluster by using the Tully-Fisher relationship to obtain independent estimates of galaxy distances.

On the other hand - in denser systems where virialization might have happened in the cores and peculiar velocities are higher, the opposite might occur and clusters are mapped into overly elongated structures. This effect is known as the "finger of God" and appears for systems such as the Coma Supercluster.

The Sloan Digital Sky Survey has enabled a big step forward in automated redshift mapping of galaxies, and provides a useful modern tool for large-scale mapping of thousands of clusters.

**Describing clustering**

There is yet no quite satisfying statistical method to mathematically describe the strength and prevalence of superclusters, walls and filaments. One way is to use the two-point correlation function $\xi(r)$: it describes how much higher the chance of finding an object within a volume is depending on the distance to a given (random) one.

$$\xi(r) = \frac{< n(x) \cdot n(x+r) >}{< n >^2} - 1$$
Note the normalization requirement

\[ \int \xi(r) dV = 0 \]

which requires anti-correlation values for some domains.

Data from the Las Campanas galaxy survey show that there is a strong correlation for small \( r \), and then crossing over to an anti-correlation for \( r \approx 20-80 h^{-1} \) MPc, and flattening out at zero for scales larger than \( 100 h^{-1} \) MPc, roughly the scale of the largest structures in the universe. Parametrizing the correlation function \( \xi(r) = \left( \frac{r}{r_0} \right)^\gamma \) gives \( r_0 = 5 h^{-1} \) MPc and \( \gamma = -1.8 \), with the term \( r_0 \) referred to as the correlation length.

The Fourier Transform of \( \xi(r) \) is the power spectrum \( P(k) \):

\[ P(k) = \int \xi(r) \exp(ik \cdot x) d^3 x = 4\pi \int \xi(r) \text{sinc}(kr)r^2 dr \]

It is usually the shape of the power spectrum which is compared to predictions of different cosmological models.

The correlation analysis can also be done using clusters as the fundamental objects instead of galaxies. The majority of clusters are associated with Superclusters, while fewer galaxies are part of clusters. The cluster correlation therefore becomes stronger than the galaxy correlation with a correlation length of 22 MPc. The power-law scaling is the same at \( \gamma = -1.8 \).

Finally, Bahcall(1990) claims weak correlation for \( r=100-150 \) MPc suggesting that superclusters themselves could be further clustered with a typical separation of this scale.

**Large-scale structure at high z**

What can we say about supercluster structure at early times? Both quasars and radio galaxies at high \( z \) show clustering above galaxy correlation level, meaning that large-scale structure exists at early times and that these objects preferentially are located in groups/clusters compared to non-active galaxies. This is a useful observation for models of early-type AGN.

In the hierarchical picture of galaxy formation, too much large-scale structure at high \( z \) is not really expected. However, several studies have found strong indications of clustering and superclustering in this domain. Clustering of quasars was quantified already in 1988 by Iovino and Shaver, and Bahcall and Shoksi showed this to be associated with superclustering. West(1991) found that radio galaxies not only cluster, but also show alignment of their spin axis pointing towards neighboring radio galaxies and quasars. The analogy of beads lined up along a string is often used. For intermediate redshift (\( z \) up to 2), periodic structures show up in pencil-beam surveys and indicate that large scale structure is not a very recent trend.

In 2004 a 100 MPc long string of galaxies was detected at redshift \( z=2.38 \) (Woodgate et al., 2004) which goes against many hierarchical computer models.
since the universe should not have had time to form such large structures by then (about 2.5 billion years old). Further data from this very early epoch will be forthcoming within the next few years.

In summary, all high redshift surveys seem to indicate that large-scale structured formed very early in the universe and so puts constraints on cosmological evolution models.

**Formation theory**

The question of how the large-scale structure of galaxies came to is a cosmological question largely equivalent to understanding how small density pertubations came to and evolved in the very young universe, and what the character and role of dark matter is. As such superclusters play an important role in constraining evolutionary models.

Superclusters have a present matter density just a few times above the universal average. If we express

\[ \rho(t) = \rho_u(1 + \delta(t)) \]

We have \( \delta(t) \approx 1 \). Standard theories of the cosmological expansion yields in the matter-dominated era the two limits for small perturbations:

\[ \delta \sim t^{2/3} z \gg \frac{1}{\Omega_0} - 2 \]

\[ \delta \sim \text{constant} \ z \ll \frac{1}{\Omega_0} - 2 \]

Which illustrates how density fluctuations evolve; at early times growth is strong but dies out as the expansion dilutes the region and thereby its ability for further contraction. The end of growth occurs approximately at \( z \approx \frac{1}{\Omega_0} \). Note that the above relation is for large-scale structure only, density fluctuations in general depends on the scale of the region.

At recombination \( t \approx 0.3 \text{Myrs} \) we get if structure is still growing until today:

\[ \delta_{\text{rec}} = \delta(t_0) \left( \frac{t_{\text{rec}}}{t_0} \right)^{2/3} = \left( \frac{3e - 4}{13.7} \right)^{2/3} \approx 10^{-3} \]

The COBE satellite measured temperature fluctuations on the scale of \( 10^{-5} \) with a beam resolution corresponding to \( 10^{20} M_\odot \) region. Relating these numbers to corresponding density fluctuations on supercluster scales yields \( \delta \approx 10^{-3} \), giving credibility to the theoretical framework for the primeordeal origin of these structures but also seeming to require a matter density around one, as predicted by inflation. (Note though that the calculation we have done here is very approximate.)

The sequence of structure formation in the early universe is still uncertain. Gravitational collapse occurs when an objects potential energy becomes larger than its thermal/kinetic energy. This conditions relates the clouds size to its density and sound speed through the Jeans length:

\[ \lambda_J = \frac{c_s}{2} \sqrt{\frac{\pi}{G\rho}} \]
and the corresponding Jeans mass:

\[ M_J = \frac{\pi}{6} \lambda_J^3 \rho \]

The Jeans length and Jeans mass grew during the early expansive phase, and at the time of recombination it had values of about 100 MPc similar to the largest scale structure today. After recombination its value drops dramatically down to the size of globular clusters, due to a complete change in the sound speed.

However, as baryonic matter from Big Bang theory cannot account for more than a fraction of the apparent mass density of the universe, dark matter is today a standard ingredient in cosmological theory and structure formation. And with the use of WIMPs, it is possible to change the formation scenario to a bottom-up picture since WIMPs can collapse earlier into small fragments than baryonic matter and then catalyse structure formation on a fast time-scale. Cold Dark Matter refers to WIMPs with masses large enough that their sound speed drops quickly and they can begin to form small structures long before recombination. This leads to a bottom-up scenario. Hot Dark Matters implies WIMPs with small masses and so leaves the dynamic much the same as in the baryonic scenario.

The existence of WIMPs is favored by many astronomers and observations of the spectrum of structure so far seems to favor the CDM version since the HDM seems to have problems accounting for a lot of the smaller scale structure. However, observations of large-scale structure at very high redshift clashes with the time-scales typically required by CDM models to allow these to form. Perhaps a mixture of the two comes closest to the true picture.

It is also possible that dark matter is distributed with smaller density anisotropy than luminous matter and so the true density power spectrum is weaker than luminous matter seems to indicate. The problem with constraining cosmological models is that they really predict the behaviour of dark matter while we can only observe luminous baryonic matter.

Current research - density anisotropy around the Local Supercluster

As inhomogeneities build up in the universe, objects will obtain peculiar velocities superimposed on the large scale Hubble flow. Measurements of Doppler shifts on the cosmic microwave background reveal that the whole Local Group seems to have a peculiar velocity of 630 km/s in the direction towards the Virgo cluster. Observing other groups and cluster also reveal a peculiar radial velocity component towards Virgo. (Note that this is the velocities on top of the Hubble expansion though - most galaxies are still receding from each other). However, estimating the mass and distance to Virgo yields a much smaller expected infall velocity at our position of 240 km/s, and similar discrepancies for the other clusters.

In 1988 Lynden-Bell showed that there existed a systematic distortion of the peculiar velocities of 400 nearby galaxies within 40 Mpc. The whole Local Supercluster is streaming in a bulk flow towards the direction of the Hydra-Centaurus Supercluster some \(40h^{-1}\) Mpc away, and for the Local Group this was responsible for a 570 km/s motion. Lynden-Bell identified a region labelled
the Great Attractor, somewhat behind the Centaurus wall, as a gravitational superdensity responsible for a streaming flow of surrounding superclusters, with a mass of $3 \cdot 10^{16} M_\odot$. The Great Attractor has since then been relocated to more inside the Centaurus complex, but despite being a dense region of rich clusters, all of the dynamically derived mass has not been accounted for. There was also a lack of evidence for cluster falling in towards the region from the other side. Several articles at the turn of the century made it more and more clear that the mass of the GA was not as large as initially believed and that a substantial part of the peculiar velocity of the Local Supercluster was induced by anisotropy at still larger scales. Still other authors have claimed such influence would be negligible.

Kocevski/Ebeling (2006) have used triple X-ray selected catalogues to determine the contributions to the dipole anisotropy. The X-ray selection has supposedly several advantages over previous optical selections, being better correlated with mass, tracing the most dominant clusters, and suffering less extinction in the galactic plane. They map the dipole magnitude as function of distance, and find that the Shapley Superclusters and other superclusters at $130 h^{-1} - 180 h^{-1}$ MPc account for 56% of the LG peculiar velocity, and the Great Attractor 44%. Only at over 200 MPc can the local density anisotropies be considered isotropic.

The article illustrates the strong dynamics of supercluster interaction and the fact that we have to go to rather large scales before we can start to consider the universe isotropic.

References

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