DYNAMICS OF SUPERCLUSTERS AS THE MOST POWERFUL TEST FOR THEORIES OF GALAXY FORMATION

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Abstract. Analysis of Brown's (1964, 1968) data on the orientation of galaxies inside superclusters confirms his conclusion that the directions of the major axes of the galaxies are significantly correlated. For a number of superclusters, the minor axes are found to be oriented along the direction of the flattening of the supercluster as a whole. By analogy with the Local Supercluster where the same phenomenon is associated presumably with the rotation established by de Vaucouleurs (1959), one may conclude that, in general, superclusters rotate. It is shown that rotation on scales as large as these cannot be explained by tidal or by any local effects, and must have a primeval nature analogous to the 3 K microwave background. Rotation on such scales contradicts the standard idea of galaxy formation from density fluctuations but favours the concept of primeval whirls which gave rise to pregalactic density inhomogeneities.

1. Introduction

When comparing the various theories of the formation of galaxies and their agglomerates with observations, the galaxies themselves are often used as a test, in particular the relationships between their main dynamical characteristics such as mass and radius, mass and angular momentum, etc. Since the galaxies have now reached a state such that the initial conditions are largely obliterated, these are not sensitive tests and it is difficult to determine the nature of the pregalactic structure in this way. For example, the conclusion about the necessity of pregalactic turbulence, on which von Weizsäcker (1951) has insisted, is based on comparatively subtle effects. It is therefore very desirable to find more clear and obvious traces of the initial conditions and seems reasonable that such traces manifest themselves principally on the scales of clustering of galaxy clusters, i.e. of second-order clusters (superclusters). These expectations are supported by an estimate based on observational data by de Vaucouleurs (1959) that the duration of the differential expansion of the Local Supercluster is of the order of 10^{10-11} yr. Consequently, at least some initial conditions which characterize the pregalactic medium may be expected to be 'frozen' into the dynamical properties of superclusters.

2. Existence of Superclusters

Although the existence of superclusters has been questioned for many years, an ever-growing number of papers indicate that superclusters are real. The most convincing proof has been given recently by Bogart and Wagoner (1973), who calculated the mean nearest-neighbour angular distance, $\langle\theta\rangle$, between the galaxy clusters belonging to the same Abell distance group, and compared it with the analogous value, μ, obtained from a random distribution of clusters. Their results show that,

John R. Shakeshaft (ed.), The Formation and Dynamics of Galaxies, 85–91.

https://doi.org/10.1017/S0074180900024335 Published online by Cambridge University Press

within the distance groups 5 and 6, $\langle\theta\rangle < \mu$ with very high significance, i.e. that clustering into superclusters really occurs. Specifically, $\langle\theta\rangle = 0.8\ \mu$, i.e. the cluster density in superclusters is twice as high as that in the surrounding regions.

It should be noted, however, that for clusters belonging to very different distance groups Bogart and Wagoner found $\langle\theta\rangle > \mu$, implying that clusters mutually separated along the line of sight seem to avoid each other on the sky. They could not explain this anticorrelation which is simply absurd from the physical point of view. At first glance, the lack of an explanation for this effect compromises the validity of their conclusions about the existence of superclusters but Bozhich and Ozernoy (1974) have shown that the inequality $\langle\theta\rangle > \mu$ for clusters of different distance groups, as well as the inequality $\langle\theta\rangle < \mu$ within the same distance groups, are corollaries of the same phenomenon, namely the clustering of galaxy clusters into superclusters.

The available data on isotropy of the 3 K microwave radiation provide growing evidence that the clustering of galaxy clusters into systems of higher order cannot be infinite as in Charlier's hierarchical models. At the same time the presence of second-order clusters does not contradict the upper limits on fluctuations of the microwave radiation, or of the X-ray background (Webster, 1972; Brecher, 1972).

3. Evidence in Favour of Rotation of Superclusters

3.1. Rotation of the Local Supercluster

3.1.1. *Direct Evidence*

Although for a long time the high degree of flattening of the local Supercluster suggested that it was rotating, more detailed evidence of this rotation superimposed on the differential expansion was obtained only in 1958 by de Vaucouleurs (1959). This was based on the interpretation of the anisotropic radial velocity field of galaxies, and in this sense it is analogous to the proof of the rotation of our Galaxy given by Oort long ago. However, the assumed law of rotation and other parameters were chosen by de Vaucouleurs (1959) rather arbitrarily and were justly criticized by van Albada (1962).

According to de Vaucouleurs and Peters (1968), and de Vaucouleurs (1972), who gave a better founded discussion with revised parameters, the rotational velocity of the Local Group at the distance of 10 Mpc from the centre of the Local Supercluster is of the order of 400 ± 100 km s^{-1}, but the inaccuracy of this value is still too large to consider the rotation as indisputable.

3.1.2. *Indirect Evidence Based on the Orientation of Galaxies*

Reinhardt and Roberts (1972), using independent data on the position angles of spiral galaxies and on the decrease of the proportion of flat galaxies with supergalactic latitude, have shown recently that the orientation of their minor axes correlates with the direction of the poles corresponding to the flattening of the Local Supercluster. In other words, the angular momentum vectors of galaxies tend to coincide with the rotational axis of the Supercluster itself.*

3.2. Rotation of other superclusters

In contrast to the Local Supercluster, the radial velocities of galaxies belonging to other superclusters are not known accurately enough to reveal the rotation. Nevertheless, in addition to the significant flattening of many known superclusters, data of three other kinds also support the hypothesis of supercluster rotation: (i) the correlated orientation of galaxies in all superclusters investigated; (ii) the correlated orientation of radiosources; (iii) the rotation of some clusters. Let us consider these in more detail.

3.2.1. *Correlated Orientation of Galaxies*

Brown (1964, 1968) measured by eye the position angles of about 9000 galaxies on the plates of the *Palomar Sky Survey* and pointed out that the major axes of galaxies belonging to the supercluster in Pisces are predominantly oriented along the direction of extension of the supercluster itself. The same situation is observed in the supercluster in Ursa Major.

Reinhardt (1972), by re-analysing Brown's data, showed that for 11 representative groups of galaxies the hypothesis of non-random orientation is significant at below the 5% level, and for 9 of them at below the 1% level. The selection effects fail to explain these results.

Bozhich and Ozernoy (1974), using the same data, also came to the conclusion that the distribution of galaxy position angles is non-random, though with more modest significance level. Specifically, for four groups it appeared to be between 0.1% to 1%, in six groups from 1% to 5% and only in one group greater than 5%. These results are presented in Table I. In all the samples the conclusion about the

TABLE I

Significance levels (per cent) of the hypothesis that the position angles are distributed at random

Constellation	Apparent diameter	Flat galaxies	Spheroidal galaxies	All forms
Pisces		1.74	31.0	30.4
Virgo	$D > 65''$	0.21	2.0	3.5
Ursa Major	$D > 50''$	0.38	2.1	19.4
Ursa Major	$36'' < D < 50''$	0.52	3.1	8.8
Hydra	$D > 65''$	4.2	–	–
Hydra	$36'' < D < 65''$	0.12	1.2	0.1

* This statistical law permits, of course, large deviations. For example, the rotation axis of our Galaxy deviates from the direction of the supergalactic centre by 16°. Nearly the same situation takes place in the case of M31 whose rotation axis is aligned with that of our Galaxy within 11–18°. It is of interest that the directions of rotation of the Galaxy and of M31 are apparently the same, indicating that the angular momentum of the pregalactic substratum from which the Local Group of galaxies formed was significantly different from zero.

non-random distribution of position angles is much more significant for flattened galaxies than for spheroidal ones. When galaxies of all forms are taken together, it is then not possible to reject the hypothesis of a uniform distribution of position angles. The mixing of galaxies of different distance groups also lowers the significance of the non-uniformity found.

We considered also the distribution of position angles in the region which Brown names a remnant of the supercluster in Pisces. In contrast to the remaining 11 groups of galaxies, this region contains no excess concentration of galaxies. Although these galaxies are not divided into groups of different flattening, the distribution of their position angles is sharply non-uniform at the significance level 2×10^{-7} (!). Hence we may conclude that regions with a pronounced orientation of galaxies are not necessarily those of high galaxy density.

Although the non-uniformity in distribution of galaxy position angles in superclusters is significant, the predominant orientation of the axes is not very noticeable. It is possible that the orientation was much more significant at the very early stages of galaxy evolution, and was later smoothed by tidal forces.

3.2.2. *Correlated Orientation of Radiosources*

Thiel (1972) using 205 radiosources with $z<0.1$ showed that they are oriented non-randomly at a significance level below 2%. Willson (1972) also found a clear correlation of major axes of radiosources on the scale of clusters and even of superclusters. Tight correlation between the orientation of clusters and their central supergiant cD-galaxies (Sastry, 1968) generating radio-components is evidence that the radio-source orientation is of physical nature. This orientation is probably connected with the correlated orientation of parent galaxies, i.e. finally with the rotation of clusters and superclusters, rather than with the metagalactic magnetic field. All the attempts to discover the latter on scales of superclusters are far from convincing.

3.2.3. *Rotation of Some Clusters*

If superclusters possess rotation indeed, at least some of their clusters ought to rotate (clearly, the inverse conclusion is not necessarily valid). Such rotations have been actually discovered (with differing reliabilities) from the analysis of radial velocities of galaxies, for the Coma cluster (Kalinkov, 1968a, b; Gorbachev, 1969), for the Hercules cluster (Kalinkov, 1971) and for some others.

For the Coma cluster the direction of the rotation axis is found to coincide with the minor axis of isodensity (Gorbachev, 1969). The system of clusters included in the Hercules supercluster is extended in a direction having a position angle $p = -10°$. It is interesting that the mean position angle of galaxy pairs in the clusters I–V of this system is nearly the same: $p = -3\overset{\circ}{.}7$ (Karachentsev, 1964). Hence, the direction of rotation, indicated by the orbital planes of galaxy pairs, correlates with the direction of proposed rotation of the whole Hercules supercluster.

The non-spherical form of the clusters which may be clearly seen from the data of the Zwicky catalogue is evidence for the wide spread of rotation of galaxy clusters.

Kostjuk (1971) found that there is only an insignificant increase in the mean sphericity when going from open to compact clusters.

A more detailed analysis of cluster rotation naturally requires more reliable and numerous data but, nevertheless, the above mentioned indirect evidence in favour of cluster rotation does not contradict the assumed rotation of superclusters.

4. Rotation of Superclusters as a Test for Theories of Galaxy Formation

The existence of rotation scales as large as galaxy clusters and, moreover, as superclusters cannot be ignored by any theory of galaxy formation. Let us consider whether this rotation is compatible with the existing concepts.

4.1. Concept of Adiabatic Density Perturbations

As to galaxy clusters, their rotation, as was suggested by Peebles (1971), might be conditioned by the mutual tidal action of perturbations still at the stage of protoclusters. However, when considered in detail, this idea encounters several serious difficulties:

(a) The clusters having minimal masses near to $M_d \approx 3 \times 10^{13} - 10^{14}\ M_\odot$ (those with smaller masses having dissipated in the course of gradual recombination, according to Peebles and Yu (1970), Chibisov (1972)) should possess the minimum rotation and their form should be close to spherical (Chibisov, 1972). However, the observed clusters of minimal mass (pairs, triplets, poor clusters etc.) have irregular forms and apparently quite large specific angular momenta.

(b) Such an angular momentum, as is shown by numerical estimates, could hardly be obtained in the tidal theory. These difficulties are especially obvious in the case of the Local Supercluster. The specific angular momentum of the orbital motion at the distance of the Local Group from the centre of the Supercluster ($R \sim 10$ Mpc) is equal to 10^{33} (R/10 Mpc) cm^2 s^{-1}, more than 10^3 times that of the specific spin angular momentum of our Galaxy. Meanwhile, for the latter the tidal theory gives an estimate approximately one order less than that observed (Peebles, 1971). For more massive systems the difference between the predictions of tidal theory and the observations becomes still greater.

(c) Starting from the non-linear theory of adiabatic perturbations by Zel'dovich (1970), Doroshkevich (1972) showed that the angular velocity vectors of galaxies must be parallel to the plane of symmetry of the cluster. However, this conclusion is in sharp contradiction with the observed orientation of galaxies in superclusters, where the rotation axes of galaxies are mostly directed along the minor axis of a supercluster (see Section 3).

Consequently, the concept of galaxy formation which takes no account of whirls as an initial condition meets significant difficulties in explaining the origin of rotation at the later evolutionary stages on scales as large as clusters and especially superclusters.

4.2. Concept of Whirl Perturbations

The correlation between directions of galaxy rotation on scales of about 100 Mpc means, in fact, that the rotation has a cosmological rather than local origin. Just the same statement serves as a basis for the whirl concept of the origin of galaxies and their clusters (see e.g., Ozernoy and Chibisov, 1970; Ozernoy, 1971; for a review, see Ozernoy, 1973). The quantitative parameters characterizing rotation of galaxy clusters and of the Local Supercluster may be explained by the whirl concept. Without going into details, let us note only the possibility of accounting for the flat form of superclusters by their rotation. In the literature (e.g. de Vaucouleurs and Peters, 1968; Reinhardt and Roberts, 1972) this is considered as hardly probable, due to the fact that the rotational period of the Local Supercluster exceeds greatly the age of the Metagalaxy. However, the ratio of the turn-over time, $T = 2\pi r/v$, to the cosmological time, t, is changed in the course of the cosmological expansion. Neglecting the difference between the rate of expansion of the Local Supercluster and that of the Metagalaxy*, we have $r \propto (1+z)^{-1}$, $v \propto (1+z)$. Thus $T \propto (1+z)^{-2}$, while $t \propto (1+z)^{-3/2}$. The ratio T/t falls to unity approximately at the moment of recombination ($z \sim 10^3$). It is clear that at such an early epoch neither tidal nor any local effects can produce rotation on the scales of interest. Consequently, the rotation of superclusters is of a primeval nature and their flat form is related, not to the present rotation, but to a far cosmogonical past.

5. Conclusion

As has been suggested above, for the choice between different theories of galaxy formation the most informative data are those connected with the largest agglomerates of galaxies, rather than with the galaxies themselves. Specifically, data concerning rotation of the Local Supercluster as well as other superclusters provide serious difficulties for the classical ideas on the origin of galaxies from primeval density fluctuations. These data are, on the contrary, strong evidence in favour of the whirl (turbulent) cosmogonical theory. The accumulation of further information concerning the kinematics of superclusters and, in particular, their rotation will not only influence our ideas on the cosmogony of galaxies, but will be of great importance for cosmology as a whole.

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* This simplification cannot be used in order to calculate, in the framework of the whirl theory, the present rotational velocity of the Local Supercluster. These calculations will be given elsewhere.

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