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Instability Phenomena in Systems of Galaxies

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To consider the problems of the dynamics of clusters and groups of galaxies it is essential to know their masses. The data available on the masses of galaxies are, unfortunately, poor.

Observations of the orbital motions in double stars are used to determine stellar masses. A great number of already determined orbits of visual and spectral doubles forms a sound basis for our knowledge of stellar masses. In contrast to this, we are in no position to determine the orbits in double galaxies, and attempts to make statistical use of the differences of radial velocities in double galaxies meet with considerable difficulties in introducing this or that hypothesis on the nature of motion (elliptical or hyperbolic). That is the reason why we must determine the masses of galaxies from measurements of rotation and of the internal motions within a given galaxy.

Unfortunately, the data obtained in this way accumulate very slowly. Thus the value commonly accepted at present of the mass of our Galaxy might very likely turn to be incorrect by a factor of the order of 2. The value of the mass of the Large Magellanic Cloud is very uncertain. Quite limited in scope is our knowledge of the masses of both giant and dwarf elliptical galaxies.

Nonetheless, the data available have made it possible to draw the following valuable conclusions as to the values of the ratio $f=M/L$:

(a) The ratio $f=M/L$ decreases at least 10 times when passing from the elliptical galaxies of high luminosity to the spirals and further to the irregular galaxies.

(b) The ratio f does not increase but, most probably, decreases when passing from supergiant elliptical galaxies through giant ones to the dwarf systems like those in Fornax and Sculptor.

As a result, the ratio of the masses, say, of the supergiant and the dwarf galaxies, turns out to be larger than the ratio of their luminosities.

Thus, for instance, the supergiant elliptical galaxy NGC 4889 in the Coma cluster surpasses by nearly one million times in luminosity the dwarf system discovered in Capricorn by Zwicky, and the ratio of the masses of systems is probably much larger.

Quite different is the picture in the case of stars. The luminosity there increases in proportion to a rather high power of the mass. This accounts for the fact that although the luminosity of stars can vary by hundreds of millions of times, their masses vary at most by about a thousand times and most of the stars have masses differing from the average by not more than a few times.

In consequence of this, the gravity field in any stellar cluster is determined almost equally by bright as well as by faint members of the cluster. Such is not the case, however, with clusters and groups of galaxies. Here the dwarf galaxies have almost no influence upon the structure of the gravity field, which is determined chiefly by a small number of supergiants and partly by the giant galaxies.

Zwicky (1957) has rendered great service proving the monotonic increase of the number of galaxies with decrease of luminosity (the monotonic form of the luminosity function). Probably, such an increase takes place in the majority of clusters and groups of galaxies. However, even in the case of a relatively large number of low-luminosity galaxies, their influence upon the structure of the field of gravitation inside and outside the cluster must be negligible. Suffice it to say that in the Local Group the total mass as well as the gravity field are determined mainly by two members—M31 and our Galaxy.

This circumstance makes it possible to achieve a certain simplification by solving a number of the problems regarding the dynamics of a cluster of galaxies at first for the small number of its massive members.

It is known that we observe multiple galaxies in great numbers. The question of the type of configuration of these systems can be raised as it has with multiple stars. The division of all configurations into two types will best suit our aims: *common configurations* and *configurations of the trapezium type*. The latter include multiple systems in which at least three members can be found having mutual distances of the same order of magnitude. These configurations cannot be steady and they disintegrate within a period of the order of several revolutions in the system.

The observations indicate that in *real stellar systems of the trapezium type* one of the components belongs to O or B spectral types. Such stars are of recent formation and the number of revolutions they complete in the system is expected to be small. However, the observations show that a few multiple stars of later spectral classes also possess trapezium-like configurations. Of course, the configurations we observe on the sky are projections of true space configurations. Therefore, even if there are *no* real trapezium configurations of later-type stars, when they are projected on the sky a small percentage ($\sim$8%) of *apparent* configurations of the trapezium type will appear. This is almost precisely the percentage of trapezium configurations observed in cases where the components of multiple stars do not belong to the O and B spectral types. In other words, there are no or almost no *real* configurations of the trapezium type among the late-type multiple stars.

Quite reverse is the case with multiple galaxies. Out of the 132 multiple galaxies, as pointed out in one of our papers (Ambartsumian 1956) in Holmberg's catalogue of the double and multiple galaxies (Holmberg 1937), 87 have configurations which should, doubtless, be classed as trapezium type. Thus, systems of galaxies of the trapezium type are markedly dominant, and most of the multiple galaxies are of recent formation; i.e., their components could have made, from the moment of the formation of the system, *but a few revolutions*.

However, two remarks are to be made in this connection: (1) The periods of revolution in the multiple and double galaxies should be of the order of 10^9 years. Therefore, the multiple systems we have observed could possibly be of the age of 5×10^9 years or more. In the sense of instability of multiple systems, the galaxies are probably young, although their age can be in some cases three or four times more than 5×10^9 years. (2) The instability of trapezium configurations has not yet been given a clear-cut mathematical treatment. However, proceeding from simple considerations it should be evident that the above-mentioned time of dissolution (several periods of revolution) holds true only for cases where the masses of all three components on which the trapezium configuration is based are of the same order of magnitude; otherwise the system can exist considerably longer. Furthermore, the components must be of comparable luminosity. A substantial number of the observed multiple galaxies in fact meets this requirement. In particular, in such systems as Stephan's Quintet and Seyfert's Sextet the differences in stellar magnitudes are comparatively small. By contrast, trapezium configurations where one of the components is much brighter than the others (for example, the system M31, M32, and NGC 205) are, presumably, much more stable.

On the other hand, there cases where a cluster of galaxies contains a considerable number of members, three or four of which are noticeably brighter than the rest (and therefore contain the greater part of the mass) and together form a trapezium configuration. Considering only the interaction of these brighter galaxies, it can be asserted that such systems should be unstable. For example, the four galaxies NGC 3681, 3684, 3686, and 3691 form a typical multiple system of the trapezium type; at least a dozen other much fainter galaxies are included in this system, but the system is evidently unstable. The galaxies NGC 7383-7390 form part of a small cluster containing six bright members and more than a dozen faint components. The bright members constitute a trapezium-type system. Finally, the three galaxies, NGC 3613, 3619, and 3625, form a small group containing at least eight fainter objects. In this case there are fainter objects of considerable angular diameters and low surface luminosity. Again we have an unstable group, although this group is not, apparently, a cluster of its own, but forms a condensation in the Ursa Major Cloud.

The arguments put forth in our previous papers speak in favor of the *joint formation* of the members of each cluster or physical group of galaxies. We refrain from repeating these arguments, but because we still encounter published assertions as to the possibility of forming groups and clusters of galaxies from independent members of the general metagalactic field, a new argument will be advanced. This is based on the existence of systems of a few very bright galaxies and a larger number of faint ones. In principle, it is possible to understand the dynamical formation of one physical pair by the accidental encounter of three galaxies. Generally speaking, this pair in the course of time can capture other galaxies too. However, the exchange of large amounts of energy must take place between the interacting galaxies, and to achieve this end the interacting galaxies must have masses of about the same order. Let us assume that a multiple system of three or more massive galaxies has come into being in this manner (although this can be proved to be highly improbable); no galaxy of an essentially small mass (say by two orders less) can then ever be captured by such a group, because the exchange of kinetic energies in the case of large mass ratio is always negligibly small. Thus, the mechanism of capture meets with new difficulties in any attempt to account for the existence of galaxies of small mass in groups and clusters. This difficulty applies to all three of the above examples of multiple systems of bright galaxies with an additional number of fainter members, and also to the case of a *pair* of bright galaxies NGC 521, 533, which has a number of very faint companions.

The great difference in distribution of bright and faint members is most apparent in the large spherical clusters of galaxies. The bright members are densely concentrated, while the faint ones occur relatively more frequently on the periphery. This phenomenon was given special consideration by Zwicky, who showed that the Coma cluster is of very large dimensions if we judge from the distribution of galaxies of low luminosity. However, the case is completely different with irregular clusters. According to Reaves (1956), faint galaxies of low surface luminosity in the Virgo cluster reveal approximately the same distribution and, consequently, same degree of concentration as bright galaxies.

Such a picture occurs also in the case of the objects of low surface brightness and small density gradient in the well-known cluster in Fornax. As Hodge points out (1959), the search for similar objects in regions neighboring the cluster has led to negative results. Finally, in the above-mentioned case of NGC 3613, 3619, and 3625, galaxies of low surface brightness and low luminosity do not spread far beyond the bounds determined by the group of bright galaxies.

These examples bear testimony to the fact that equipartition of energies between the bright and the faint members of the irregular clusters is out of the question, and that phenomena of instability are expressed in irregular clusters much more sharply than in the spherical ones.

The existence of a great number of trapezium configurations signifies that many of the multiple galaxies are unstable formations. If this is the case, we have no right to assume *a priori* that the multiple galaxies should be negative-energy systems. In the case of simple double stars (we exclude O and B stars) it could be asserted without any knowledge of their orbits that, for the most part, they have negative total energies. In fact, if the majority of the multiple stars had positive total energy then the time of disintegration would be only a few tens of thousands of years, and within such a period most of the multiple stars would be replaced by stars of a new generation. In other words, positive total energy would lead to an erroneous conclusion about the rate at which stars are formed in the Galaxy.

Yet in the case of multiple *galaxies* the assumption of positive total energy for most of them does *not* lead to similar erroneous deduction. The age of the component galaxies derived in this way is but a few times less than that accepted for our Galaxy. Therefore we infer that the sign of the energy of the multiple galaxies, groups and clusters of galaxies should be determined in each case, relying upon observational data.

The reasons put forth above support the view that the *a priori* assumption of positive total energy in a number of systems of galaxies cannot be regarded as more audacious than, say, the assumption that almost all such systems possess negative energy. Nevertheless, let us consider the facts: The data show that, if negative total energy is assumed for a number of multiple systems, it has to be admitted that the ratio $f=M/L$ must be about one order of magnitude larger than follows from other data. Thus it is pointed out in the following paper by Kalloghjan that the multiple system comprising NGC 68, 69, 71, 72 and one anonymous galaxy, if it has negative total energy, would lead to a value of f greater than 300. For the double galaxy NGC 7385-7386, he finds f greater than 600.

The sign of the total energy of Stephan's Quintet has been determined by us and by G. and E. M. Burbidge (1959) in detail, resulting in positive total energy. Later, Limber and Mathews (1960) indicated that, under certain assumptions, when the mass of the components is supposed to be very high, the Quintet can have a negative total energy.

The sign of the total energy in a number of clusters of galaxies is elucidated in several recent investigations in detail. A number of difficulties are caused by uncertainty in the exact value of f for giant elliptical galaxies. This value is believed to lie in the range $30<f<70$. However, greater values ($f\sim100$), although rare, are not excluded, particularly for the brightest supergiants ($M\sim-21.5$). No straightforward data exist that would enable us to estimate the value of f for these brightest supergiants. It is natural, therefore, to believe that the sign of the total energy is determined with greater reliability in those clusters and systems in which there are no supergiant elliptical galaxies. The case will be even better for systems with no giant elliptical galaxies either, and that is why the positive total energy of the nearby system of galaxies in Sculptor, as established by de Vaucouleurs (1959) is of paramount importance.

Of no lesser value is the result obtained by van den Bergh (1960) in respect to the cluster of galaxies in Canis Venatici, although studies toward determining the borders and identifying the members of this cluster should continue.

The Hercules cluster, investigated by G. and E. M. Burbidge (1959), contains but a small percentage of bright elliptical galaxies. To admit negative total energy of this cluster we have to ascribe the value of f_E of the order of 300, which seems to be improbable. The contrast becomes still sharper in the case of the cluster in Virgo. Assuming the stability of this system we should have to acknowledge that $f_E>1000$, as shown by de Vaucouleurs (1960).

It might be conjectured that perhaps the Coma cluster could have negative total energy if the modern distance scale of Sandage could be further changed by further diminution of the redshift constant. On the other hand, many members of this cluster are elliptical galaxies of moderate luminosity. The value f cannot be very high for them, so that a particularly high value of f must be ascribed to the remaining supergiant galaxies if the cluster has negative total energy.

Naturally, the sharp discrepancy between the summed luminosities of the clusters of galaxies and the masses found by applying the virial theorem has compelled some authors to favor the hypothesis of supplementary masses in the clusters which do not form part of member galaxies, i.e., intergalactic matter. Yet the data available on the upper limit of opacity in the clusters of galaxies, as well as the data on the 21-cm radiation, are not favorable.

There remains the assumption of a comparatively rich intergalactic *stellar* population in the clusters. Such a possibility has been contemplated in detail by de Vaucouleurs with reference to the Coma cluster. The result is negative if we refrain from an improbably large value of f for this intergalactic stellar population. This result apparently refers to other clusters as well.

Thus there is only one natural assumption left relating to the clusters cited above—they have positive total energies. It should be stressed that no *a priori* arguments can be advanced against this assumption.

A study of the structure of the irregular clusters of galaxies leads one to the conclusion that often they are made up of several superimposed groupings. An interesting example of such a grouping was pointed out by Markarian a few years ago: the chain of bright galaxies in the Virgo cluster containing NGC 4374, 4406, 4438 and others. This wonderful arc of eight bright galaxies is presumed to represent a physical grouping within the Virgo cluster. On the other hand, facts about the radial velocities of the members of this group undoubtedly establish its positive total energy.

Recently I looked through the abstract of van den Bergh's latest paper, in which the assumption of irregular clusters being made up of separate subsystems and subclusters is made in the most general form. It is difficult to overestimate the importance of this phenomenon in comprehending the evolution of clusters of galaxies. In this case we apparently have consecutive formation of relatively independent subsystems (subclusters), the superposition of which brings about irregular clusters. It is probable that many of these subsystems have a positive total internal energy.

Of considerable interest are the results of determination of the average value of f from the differences of radial velocities in double galaxies as obtained by Page (1961), who obtained for spiral and irregular galaxies $f=\frac{1}{3}$; for ellipticals and lenticulars $f=94$. These values are derived on the assumption that in double galaxies the motion takes place in circular orbits. That the value of f for spiral and irregular galaxies is even less than the one derived from rotations of single galaxies means that all or almost all of the observable narrow pairs of such galaxies constitute negative-energy systems. Let us compare this with the unusually large values of f obtained on the basis of the virial theorem for clusters composed of spiral and irregular galaxies. Such a comparison leads to two inevitable conclusions:

(a) All explanations allowing for the negative total energy of clusters and groups made up of spirals and irregular galaxies become still more highly improbable, since the arguments adduced in similar cases are likewise applicable to the double galaxies.

(b) There are almost no systems with positive energy among the isolated double galaxies, for such systems can represent a *narrow* pair only for a very short duration of time (of the order of 10^8 years).

If this is so, then the double elliptical systems are also to be regarded as systems possessing, for the most part, negative energies, and Page's value $f=94$ can be taken as close to the real value. This brings us nearer to the conclusion according to which the Coma cluster can have negative total energy.

It is interesting to note that when we pass from double galaxies to multiple configurations of the trapezium type the differences of the velocities of the components become much greater. Assuming negative total energies of these configurations leads to the too large values of f_E.

Speaking of instability in systems of galaxies, we should also touch upon the *radio galaxies* which, as a rule, occur in clusters of galaxies. Apparently the radio galaxies are always among the few brightest members of the corresponding clusters. The best example is furnished by the source Perseus A (NGC 1275), which is the brightest member of the cluster in Perseus.

In the radio galaxy NGC 4486, a jet is being ejected from the central nucleus with separate condensations, the luminosities of which resemble those of dwarf galaxies. Apparently these condensations contain an enormous amount of relativistic electrons. However, it is difficult to refute the suggestion that these condensations include also a substantial amount of common matter in addition to the relativistic plasma. In particular they are likely to contain, especially, *sources* of relativistic electrons.

A strong argument in support of this view is provided by the two galaxies (NGC 3651 and IC 1182) out of the nuclei of which jets are ejected containing blue condensations. These galaxies with blue jets are also among the brightest members in the corresponding clusters. Finally, there are cases when blue components occur in the vicinity of other giant elliptical galaxies, which evidently represent a later stage in the evolution of the above blue condensations.

In all probability, the condensations in NGC 4486 represent an earlier stage of evolution of the same objects. In such cases the intensity of radio emission of the blue condensations and the blue companions is believed to have already weakened.

From this point of view it is interesting to note that, as revealed in Burakan, a blue object of photographic magnitude $18^{m}.5$ is situated very close to the remote radio galaxy in Hydra. The color index of this object is about $-0^{m}.5$. It is starlike on our plates (as expected at such a distance, assuming that its diameter is less than 2000 parsecs.) If it can be shown that this object is in fact a physical companion of Hydra A, then a close connection is indicated between the two types of eruptive activities of the nuclei of supergiant galaxies: the ejection of plasma condensations and that of blue condensations. One way or another, all the data indicate that this activity is of great import in the origin of galaxies.

Thus we conclude that there exist clusters which are in a particularly active phase of evolution when new galaxies originate within them. The existence of a radio galaxy is an indicator of this phase. It is possible that even in such a phase the radio emission erupts only now and then, and with varying intensity at that.

In the radio galaxy Perseus A it is well known that large relative velocities are observed, up to 3000 km/sec. Such velocities exceed the velocity of escape from the cluster and thus speak for themselves of instability.

It seems, therefore, that a study of the radio galaxies as systems from the nuclei of which large masses are ejected or which are in the process of division must throw a new light upon the phenomena of instability in the clusters of galaxies.

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DISCUSSION

LEMAITRE asked whether "positive total energy" necessarily means that clusters are flying apart, or whether it might include the case (covered in his paper below) of a continuous exchange of galaxies between clusters and the field. AMBARTSUMIAN answered that positive total energy is a matter of observation, and could include both possibilities. However, if the galaxies in a cluster had a *common origin*, as most astronomers agree, then the concept of exchange is ruled out, and clusters with positive total energy must simply be expanding, or losing members to the general field. PAGE added that it would seem improbable that field galaxies could gather into a cluster with positive energy, but LEMAITRE argued that such a concept of probability is based on preconceived notions of the processes and earlier states of the galaxies.

POVEDA referred to the Local Group of galaxies, where the center of mass may be taken as that of M31 and the Galaxy (neglecting the masses of other members). Six of the eight members for which radial velocities are available, omitting the close companions of M31 and the Magellanic Clouds, are found to be approaching the center of mass. Only NGC 598 and 6822 are receding, at 14 and 110 km/sec, respectively. The stability of the Local Group is covered more completely by LIMBER in another paper, below.

In answer to JUST, who pointed out that "expansion of a cluster" could mean merely that its dimensions increase relative to the sizes of galaxies in it, AMBARTSUMIAN said that the dimensions of an expanding cluster are generally increasing faster than the Hubble expansion, $V=HD$. He also emphasized that he does not propose that *all* clusters and groups of galaxies are unstable.

HECKMANN referred to numerical studies of VON HOERNER showing that a system of mass points can eject members even though it has negative total energy, and PAGE made the point that, unlike the quasi-stable groups of negative total energy, the groups and clusters of postulated *positive* total energy require further explanation of the source of the positive energy. AMBARTSUMIAN replied that he wished first to establish the existence of cases of positive total energy, and to investigate the circumstances where this occurs, before seeking a physical explanation of the original source.