ON THE NUCLEI OF GALAXIES AND THEIR ACTIVITY[1]

Introductory remarks

The present paper is my second report at the Solvay Conferences. The previous report of 1958 concerned the eruptive activity of the nuclei of galaxies, the ejection of large masses from those nuclei and other processes connected with the quick release of large quantities of energy in nuclei. The present communication will be devoted to the same subject: activity of nuclei.

The position of the speaker on this topic in 1958 was much more difficult than it is at present. At that time one had to argue, contrary to general opinion, that radio galaxies do not result from the collisions of pairs of galaxies but constitute stellar systems, in the nuclei of which giant explosions had taken place with the formation of large clouds of relativistic electrons. At that time only indirect evidence existed concerning ejections of large masses of *conventional matter*[2] from the nuclei of galaxies. But now the recent fine work of Sandage and Lynds relating to M 82 galaxy has left no doubt on that issue.

Now the available information on the galaxies of different morphological and physical types is much richer. It paves the way for a disclosure of the nature of these basic formations of the Universe.

As in 1958, I will try again to proceed not from preconceived notions, but to rely on observational data. Preconceived notions often hinder the reaching of right conclusions. In my first Solvay report, as well as in my 1961 Berkeley Invited Discourse, data were demonstrated evidencing the active and perhaps even basic role of the nuclei in the evolution of galaxies. Disregarding these facts, we still have attempts to explain the unusual

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[2]By "conventional matter," Ambartsumian means "nonrelativistic plasma."

phenomena that we observe in the nuclei in terms of concepts of gradual concentration of the surrounding matter toward the nucleus. I think that the earlier we give up this idea, the sooner we arrive at the true explanations.

While new observations increasingly point to the outflow of matter from the center, to explosions, jet and ejections, some theoreticians speak in favor of condensation, implosions and collapses. In the meantime, no convincing and regular facts have been adduced to support condensation of large masses of the surrounding matter towards the nucleus of the galaxy.

Contrary to this, the problem of impact of the observed large-scale explosions and ejections from the nuclei on the life of the surrounding galaxy has not, so far, properly deserved attention of theoreticians.

It seems to us that an astronomer dedicated to the study and analysis of facts has to concentrate on two objectives:

(1) The study of the nature of nuclei and processes going on there;

(2) The influence of those processes on the evolution of the galaxy as a whole.

As to the theoretical explanation of the unusual phenomena occurring in the nuclei, we can think about two stages. The right interpretation of observations marks the first stage. When observational data are scanty, it is essential, first of all, to form a clear idea about the physical nature of the observed phenomenon. Next comes the second stage: after forming a general idea of what is going on, we try to find out the cause of the phenomenon.

Unfortunately, there is at times a tendency to skip the first stage. Particularly, such haste can be noticed in the problem of explosive processes in the nuclei of galaxies. I think, however, that at present we have to concentrate mainly on the first stage of the work leaving the explanations of the observed phenomena for the future.

Forms of activity of nuclei

Observations show that the nuclei of galaxies are not isolated systems. In addition to radiation they also emit conventional matter into the surrounding space. This process may occur in various ways, and there is reason to speak of the various forms or types of activity of nuclei. We list below some observed forms of activity including those that might be regarded as controversial.

(a) The quiet outflow of conventional gaseous matter from the area of the nucleus at the rate of tens or hundreds of kilometers per second. The best illustration of such an outflow is M 31 at $\lambda 3727$. Similar outflow occurs in our own Galaxy and in the Small Magellanic Cloud.

(b) Continuous outflow of relativistic particles or other agents which produce high-energy electrons resulting in radio halos around the nucleus in the meter and decimeter wavelengths. Such a phenomenon is seen around the nucleus of our Galaxy. According to Mathewson and Rome, the radio frequency radiation in Sc galaxies in the decimeter range is concentrated in the area around the nucleus, and the diameter of the radio image is several times less than the diameter of the optical image (NGC 253, 4945, 5236 and also Sb galaxy 1068).

(c) Eruptive ejection of gaseous matter (examples: M 82 and possibly NGC 2685). The same phenomena are probably present in the radio galaxy NGC 1275 as well, where a gaseous cloud is observed moving at the speed of 3000 km/sec from the center of the galaxy.

(d) The eruptive ejection of dense relativistic plasma. Examples: NGC 4486, 5128 and many other radio galaxies.

(e) The ejection of rather dense blue concentrations having m_{pg} ranging from $-14^m.0$ to $-17^m.0$. These concentrations may be taken to be newly-born galaxies. Examples: NGC 3561 and IC 1182. The possible cases of the division of nuclei into two or more comparable components with a subsequent formation of double or multiple galaxies may also be classed with these phenomena.

(f) The outflow of matter from which the spiral arms are subsequently formed (a hypothetical form of activity).

(g) The ejection of the matter of bars in SB galaxies (hypothetical form of activity).

(h) The ejection of matter from which the stellar population of spherical subsystems is formed (hypothetical form).

It is quite possible that some of those processes represent different aspects of the same active process. Take, for instance, radio galaxy Hydra A in the immediate vicinity of which a very interesting blue object can be observed. It is rather likely that ejections of the radio-emitting cloud and of the blue object have taken place simultaneously. Though these phenomena are interrelated, it is also possible that they have occurred in some succession. All these forms of activity may also be supplemented by explosions that lead to the formation of quasi-stellar sources of the 3C 273 type. These phenomena exceed other forms of activity in scale. Such explosions may possibly mark the birth of a new galaxy or even of a whole cluster of galaxies.

On the nature of nuclei

From the point of view of the power of nuclei the observed galaxies may be grouped into five classes:

(1) Galaxies without any noticeable nuclei with no considerable condensation in the center. Many irregular galaxies belong to this class. The elliptic dwarf galaxies of the Sculptor type should also be included here.

(2) Galaxies having quiet nuclei of relatively low luminosity. This class may include cases where the nucleus is more than four magnitudes fainter than the integral luminosity of the galaxy. M 31, NGC 5194, M 33 and, possibly, our Galaxy fall into this class.

(3) Galaxies with quiet nuclei of high luminosity when the nucleus is fainter than the whole galaxy by 1.5–4 magnitudes. The spectra of nuclei in classes 2 and 3 are continuous. Emission lines 3727 and others may be present. Although these lines sometimes may attain a considerable degree of intensity, they show neither marked broadening nor division into components. Examples: NGC 4303, NGC 3162.

(4) The Seyfert galaxies with bright nuclei comprising a considerable portion of the luminosity of the entire galaxy. Numerous emission lines are present. The latter show either widening or splitting produced by the great speed of motion of the gaseous clouds inherent in the nucleus.

(5) Compact galaxies which may comprise the starlike radio galaxies as well as many other compact objects detected by optical means (Zwicky). In this case we can assume that the luminosity as a whole is concentrated in the nucleus of the galaxy.

Nuclei of class 2 are of small dimensions. Their diameters are several parsec or several tens of parsec. In classes 3, 4 and 5 we have nuclei of larger dimensions with diameters measured in hundreds of parsec. For instance, the nucleus of the galaxy of the SBb type NGC 3504 has a diameter of the order of 10 parsec, with some intensification of brightness toward the center. Other nuclei often show a more regular distribution of energy over the disk. However, this intricate problem of distribution of brightness over the disks of the nuclei requires higher resolving power of telescopes and remains completely unstudied.

The continuous spectrum of the nuclei of the galaxies of classes 2 and 3 indicates that the source of luminosity is the stellar population which differs but little from the stellar population of the central regions of such galaxies as M 31 and M 81. But the gaseous component is already present in these nuclei. Data relating to the lines $\lambda 3727$ in the area of the nucleus M 31 point to a comparatively quiet and continuous outflow of matter from such nuclei. Although the yield is poor, still a mass up to 10^8 $M_\odot$ may flow out over a long period of time. Hence the question of sources of the gaseous outflows arises.

We stress that the nuclei of Seyfert type (class 4) contain, apart from the stellar, a gas component too. The isolated discrete clouds of the latter escape from the nucleus at the speed of thousands of kilometers per second. Such great velocities leave no room for doubt that those discrete gas clouds were born within the nucleus. This invariably leads us to the conclusion that they were ejected from denser bodies, only a few tens of thousands of years ago. This means that such nuclei contain bodies that, at the present stage of evolution of nuclei, manifest a tremendous eruptive activity. Therefore, the Seyfert type nuclei of galaxies should be properly called excited nuclei. At the same time there is no reason to believe that the clouds have been ejected by the members of a common stellar population of the nucleus, particularly because the masses of certain clouds should be of the order of hundreds of $M_\odot$ and more. We inevitably come to the conclusion that such a nucleus contains one or more supermassive nonstellar bodies which eject the gaseous clouds.

As for the class 5 of compact objects, at least part of them contain supermassive bodies of nonstellar nature. Of course, we mean quasi-stellar radio galaxies. It is essential, however, that most of the radiation comes in this case directly from such a body. Judging by the spectral distribution of energy, the radiation that reaches us is nonthermal and is characterized by an ultraviolet excess.

The presence of an ultraviolet excess is also typical for the nuclei of the majority of the Seyfert galaxies (class 4). Moreover, Markarian has shown that many galaxies which should be classified in categories 2 and 3 also have an ultraviolet excess presumably of nonthermal origin. All this gives full reason to believe that nonstellar bodies exist also in the nuclei of these categories of galaxies although direct indications for this are by far less prominent than in categories 4 and 5. Particularly, the luminosity of the supermassive bodies in the visible part of the spectrum is faint as compared to the luminosity of the stellar component. The outflow of the gases is less powerful and is of a more quiet nature.

Therefore, an analysis of observational data brings us to the following conclusion: every nucleus contains a supermassive body which may be either in the state of eruption (quasi-stellar galaxies) or in an excited, active state (the Seyfert galaxies), or still in a state of weak activity (galaxies 2 and 3).

This signifies that the nucleus is made up of three components: *stellar population, gas and a supermassive body.* Dynamically, the nucleus evolves independently of the rest of the galaxy.

On the nature of the relationship between the nucleus and the galaxy

The assumption that every nucleus contains, as a rule, a supermassive nonstellar body is in full harmony with the view expressed in our report in Berkeley, according to which the nucleus plays an essential if not a dominant role in the evolution of each galaxy. Actually, there is no more arguing the idea that the origin and evolution of at least some of the subsystems forming the galaxy are due to the nucleus itself (for instance, the subsystem consisting of relativistic plasma so prominent in radio galaxies). The case of the M 82-type galaxies shows that in the evolution of the common (nonrelativistic) gas component, the nucleus can play a decisive part. However, assumptions made in the Berkeley report that both the spiral arms and the second type population originate from the matter ejected out of the nucleus remain unproved.

Two extreme points of view seem possible:

(1) Development of a nucleus is conditioned by the evolution of the galaxy itself. The subsequent evolution of the outer parts of the galaxy is practically independent of the nucleus.

(2) The formation of the various components of the galaxy is conditioned by the activity of the nucleus. The subsystems of stars once formed evolve henceforth loosely, depending on the nucleus as well as on other subsystems according to the laws of stellar dynamics.

Now the question arises: what would be the expected relation between the parameters characterizing the nucleus and the galaxy.

If the first hypothesis is true, the state of the galaxy should account for the state of the nucleus. In the case of the second hypothesis, the state of the nucleus should be, to a certain extent, independent of the state of the galaxy. To be more precise, in the latter case the state of a galaxy is to be explained in terms of the entire activity of the nucleus over the preceding period, that is the whole history of the nucleus. This means that the state of the galaxy should correlate with the present state of the nucleus, to the extent its history may be judged by the given state of the nucleus.

Our information concerning the nuclei is always very scanty. Nevertheless, in a number of cases where nearby galaxies contain relatively bright nuclei, we can roughly estimate some of their integral parameters especially luminosity and color index. Evaluation of the diameters of the nuclei is rarely possible. Therefore, we should look for a correlation of the state of the galaxies with values of those two nuclear integral parameters alone. But the values of these two parameters may not completely determine the whole history of the nucleus. We can expect no correlation between the state of the galaxies and the above-mentioned integral parameters of the nuclei.

During the past year, several hundred pictures of galaxies were taken in the Byurakan Observatory, with the aim of determining the characteristics of their nuclei. A scale has been applied to estimate the degree of prominence of a nucleus; it is now explained in Table 1.

In classes 3, 4, and 5 we regard the existence of a nucleus as definite, but photometric evaluations are possible only in 4 and 5. For the classes in the upper rows, it is possible to estimate only the upper limit of the luminosity of the nucleus that forms a part of the observed central condensation. The importance of the nucleus in galaxies of SB type is not very closely correlated with the morphological subtype of the galaxy. For instance, such subtypes as SBa, SBb often belong to classes 4 or 5, while for subtypes SBO and SBc this almost never occurs. As a rule, the SBc galaxies are apparently deprived of any bright nuclei.

Table 1
Prominence of Nuclei on the images of Galaxies

Class	Pattern	Interpretation
1	No appreciable condensation at the center	No nucleus present
2	Weak condensation at the center	Probably a nucleus exists
3	Strong concentration at the center, but no starlike image	A nucleus definitely exists but cannot be distinguished from the background
4	Starlike nuclear image at short exposures, but nebulous at long exposures	A nucleus is seen surounded by the dense part of the background
5	Starlike nuclear image even at moderate exposures	A bright nucleus clearly distinguished against the background

We have tried to detect a correlation between the absolute integral magnitude of the nucleus and the absolute magnitude of the galaxy for the entire group of galaxies SB and for galaxies Sc with nuclei belonging to classes 4 and 5 of Table 1. No significant correlation has been found in either case. This testifies to the relative independence of the state of the nucleus from the parameters that characterize the galaxy. The independence of the state of the nucleus from the luminosity of the galaxy is something which deserves particular mention. On the other hand, we have seen above that an explicit correlation of the nuclei with the morphological subtype exists in the SB class. Finally, in the case of giant elliptical galaxies, nuclei with low luminosity predominate, providing an example of a closer correlation. On the contrary, we can find nuclei of different luminosities, or even no nucleus at all in the elliptical galaxies of low luminosity (cf. M 32, NGC 205, 185, 147). The presence of close or loose correlation as conditioned by the class of the galaxies in question strongly supports the second hypothesis.

Let us assume that the giant galaxies begin their lives as elliptical systems in which the nuclei are also young and do not yet possess a significant stellar population. The greater the activity of the nuclei, the brighter their luminosity. At the same time, new subsystems are formed in the galaxy. Therefore, within the galaxies Sa, Sb, SBa and SBb nuclei of high luminosity are probable. Finally, galaxies Sc, SBc and those irregulars that contain population I (Magellanic Clouds and others) seem to be the oldest systems. Nuclei of high luminosity are rarely encountered in galaxies of the Sc type, while no nuclei are seen in SBc's and irregulars. At the last stage we have reduction of luminosity and disappearance of the nuclei.

Most astronomers engaged in the study of the evolution of galaxies proceed from the opposite end and consider the objects of the Magellanic Clouds type the youngest. They argue that the latter systems contain numerous young stars of high luminosity. It seems to me that those who hold this view ignore the fact that one should not confuse the youth of a galaxy with the youth of a certain part of its population. We know cities with histories dating back thousands of years, but the average age of their inhabitants is young. On the other hand think about a modern health resort with a population of patients of advanced age. In the course of time some industry may develop in this modern health resort and may attract a great number of young inhabitants.

Of course, this is only a rough comparison: I do not have much trust in the concept of formation of several consecutive generations of stars out of the same matter.

Thus, our starting point is the assumption that at its initial stage of development the stellar population is something like what we conventionally call population II, a young variety of population II. The formation of population I should be attributed to later stages when spiral arms form out of the matter ejected from the nuclei.

The initial stages of the evolution of galaxies

Now the question comes up as to whether there are galaxies consisting of population II with relatively direct evidence of their being young. At the 1958 Solvay Conference we mentioned that galaxy M 82 from the group M 81 displays a velocity probably greater than the escape velocity from the gravity center of this group. It naturally follows that the age of the galaxy must be of the order of 10^8 years (or 2×10^8 years). The well-known work of Sandage and Lynds drew attention to the galaxies of this type and I will dwell on this point in more detail.

De Vaucouleurs' list, comprising the new classification of 1500 bright galaxies, includes 12 objects of the M 82 type. Of these one galaxy has a southernmost position, and we do not have its photograph at our disposal. Instead, I have added galaxy NGC 520 which, no doubt, is of the same type. Three of these twelve galaxies, NGC 972, 3955 and 4753, are isolated objects. There is no galaxy of comparable luminosity or diameter in their surroundings. As to galaxies NGC 972 and NGC 4753, the radial velocities of which are known, it can be stated with confidence that no galaxy occurs over a surrounding area closer than 500,000 parsec in diameter that would be fainter than the one under consideration by four magnitudes or less. They seem to be, in fact, isolated objects of a fairly high absolute magnitude ($-20^m.0$).

Two of the nine nonisolated objects belong to double systems (NGC 5195 and NGC 3448). In both cases the other component is an Sc galaxy, the spiral arm of which stretches out to the object itself. Seven galaxies of the M 82 type enter into poor groups made up of four or five objects, apart from possible objects of very low luminosity. M 82, and NGC 3077 from M 81 group may serve as examples. These features are so outstanding that they may serve as a touchstone for hypotheses accounting for the origin of these galaxies.

We may suppose that at the earliest stage of evolution a galaxy has very low luminosity and an active nucleus. In the course of time the luminosity increases. If the groups of young galaxies have positive total energies, we will have younger objects among the groups of smaller linear size. Considering the M 82-type galaxies as such young objects, these galaxies will have lower luminosity in groups of smaller size, and higher luminosity in groups of larger linear size. After dispersion of the group we will have isolated M 82 galaxies of the highest possible luminosities. But this is what we actually observe. All M 82 objects of low luminosity enter into compact groups. Of the three galaxies with large luminosities, one (the NGC 520) is a member of a group very large in dimensions, and the two others are isolated objects.

On the nonthermal radiation of the nuclei

It is well known that objects of the 3C 273 type possess a spectrum that sharply deviates from the Planck curve. Apparently the distribution of energy in the spectrum of these objects can be better explained in terms of synchrotron radiation. Yet, one can believe that many other nuclei also exhibit a nonthermal component in their radiation. According to Minkowski, the nucleus of the radio galaxy NGC 6166 is particularly distinct in the ultraviolet. On the basis of an analysis of the colors of the central parts of the galaxies, in which the morphological features and the spectrum are incongruous, the conclusion is made (Markarian) that there is a blue excess of radiation of the nuclei of such galaxies. Using photographs of the blue jet from the galaxy NGC 3561, Zwicky has shown that the continuous spectrum extends far into the ultraviolet. In all these cases we can hardly expect to have blue stars in any considerable number in the nuclei of the galaxies. Therefore, the ultraviolet or blue excess should be ascribed to nonthermal radiation.

As established at Byurakan, a number of the SB-type galaxies with high luminosity nuclei are substantially redder than their nuclei. Sometimes the color index of the nuclei is +0.2. Galaxy NGC 3504 is an example. All this makes us believe that nonthermal radiation in the nuclei is a relatively frequent phenomenon. On the other hand, the occurrence of nonthermal radiation speaks for the activity of nonstellar bodies included in the nucleus.

Although it is difficult at present to judge the nature of the nonthermal radiation manifesting mainly in the form of an ultraviolet excess, I would like to make two remarks.

(1) We do not assume that this nonthermal radiation proceeds directly from a nonstellar massive body. On the contrary, it probably emanates directly from the diffuse matter within the nucleus. However, the source

of energy radiated by the diffuse matter can be the nonstellar body. This energy may be transferred to the diffuse matter, say, through the high energy particles, or, as in the case of the mechanism of relativistic electrons, it may radiate directly from those particles.

(2) The occurrence of a powerful nonthermal excess in the far ultraviolet may sometimes lead to the appearance of emission lines connected with fluorescence. Our astronomers have called attention to this fact in connection with the occurrence of H emission in a number of areas of M 82. One can imagine even more striking consequences of this phenomenon.

Conclusion

In conclusion I would like to say a few words about the theoretical explanation of the unusual phenomena that are connected with the nuclei of the galaxies. It is clear that very rapid transformations of energy play a substantial role in this case. Such rapid processes of transformation and release of energy originate in systems that are characterized by the instability of possible states. The relativistic theory of gravitation seems, from this point of view, to be most suitable. The first attempt at drawing up relativistic models that contain such local explosions was made by Novikov, who works with Prof. Zeldovitch.

Such models are, of course, very useful and they deserve more detailed study. But since work on interpreting the observed phenomena is not yet complete, it is hard to draw a line of comparison between the various models constructed and the reality.

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