АКАДЕМИЯ НАУК АРМЯНСКОЙ ССР

АСТРОФИЗИКА

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# ON THE FORMATION OF GALAXIES BY FRAGMENTATION*

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Observational evidence for the existence of two kinds of elliptical galaxies is discussed. The distribution of galaxies in the mass-radius diagram is interpreted as the result of fragmentation of elliptical galaxies of large mass. A model describing the gross properties of galaxies resulting from explosive events is developed and shown to be in fairly good agreement with observations. The properties of unstable groups of galaxies and clusters are also discussed.

1. *Properties of Elliptical Galaxies*. The most striking characteristic of the elliptical galaxies is the uniformity of their properties. Their brightness distribution has been well studied and shows that they all have the same fundamental photometric profile. This is in contrast with the variety of the observed structures in spirals and irregular galaxies and suggests essentially different conditions of formation. It is difficult to imagine initial conditions in the medium from which galaxies were formed, to account for close pairs of E and S or I galaxies, without very high gradients.

However, not everything is uniform among elliptical galaxies. We shall discuss here evidence which suggests that they do not form a continuous sequence but rather have different properties according to their absolute photographic magnitudes being greater or less than $M_p = -19.5$.

1 — The luminosity function for field galaxies according to S. van den Bergh [1] shows a change of slope at the absolute magnitude —19, both for E and other types of galaxies.

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2 — The cumulative luminosity function in clusters of galaxies shows a change of slope at absolute photographic magnitude —19.5, in the sense that the brighter objects are scarcer, according to G. O. Abell [2, 3]. The population of those clusters studied by Abell is mainly formed by E and S0 galaxies.

3 — W. C. Baum [4] and G. de Vaucouleurs [5] have independently found a luminosity effect in the colour indexes of elliptical galaxies. Galaxies brighter than $M_p = -19.5$ have approximately a colour index $B - V = 0.9$, whereas those with smaller luminosities show a blue excess which is larger for fainter luminosities. G. de Vaucouleurs has noticed that elliptical galaxies with larger colour excess (and therefore low luminosity) have the tendency to be associated with other galaxies, usually with spirals.

4 — According to A. Fish [6], elliptical galaxies of smaller mass have low ratios of mass to luminosity ($M/L$ of the order of 10) and are associated with spiral galaxies (e. g. NGC 221, 2300, 3379, 4649). He also points out that the companions are usually of Sb or Sc type, and that the high-luminosity ellipticals are isolated.

5 — A. Poveda [7] and also Yu. Pskovsky [8] have proposed a $M/L$ ratio increasing with mass for elliptical galaxies. Both results are essentially in agreement and the relation found is

$$\log (M/L) = -0.1\, M_p - 0.4$$

from which the following typical values may be deduced:

| | | | |
|---|---|---|---|
| $M_p$: | $-15$ | $-18$ | $-21$ |
| $M/L$: | 13 | 25 | 50 |

On the other hand T. L. Page [9] in a recent discussion of the masses and luminosities of galaxies finds a mean value $(M/L) = 30$ for elliptical galaxies (9 individual cases with values of $M/L$ ranging from 11 to 60) while in the case of pairs he found $M/L = 90$.

6 — Fig. 1 shows a diagram relating to absolute magnitude of elliptical galaxies to $\log R_e$ (where $R_e$ is the effective radius in *kpc* as defined by de Vaucouleurs). Table 1 summarizes the data [10]. The diagram shows two parallel sequences with a transition region around $M_p = -19.5$ and $R_e = 2$ *kpc*. Interacting galaxies are only found in this transition region and on the brighter sequence.

7 — H. Spinrad [11] has classified elliptical galaxies by luminosity according to their integrated spectra on type D (stellar population dominated by G and K dwarfs) or type G (stellar population dominated by G and K giants). He also notes a relation between his luminosity classes D and G and the total mass or luminosity. Massive ellipticals

*Table 1*

DATA FOR ELLIPTICAL GALAXIES

| NGC | Type | Log $R_e$ | $-M_p$ | Log M | Log $D$ | Dates |
|---|---|---|---|---|---|---|
| 221 | d E2 | —0.77 | 15.7 | 9.46 | 2.05 | |
| 741 | E0 | 1.01 | 22.0 | 12.20 | 0.45 | |
| 750 | Ep | 0.64 | 21.6 | 12.04 | 0.50 | |
| 751 | Ep | 0.60 | 21.3 | 11.88 | 0.34 | VV 189=Interacting galaxy |
| 1316 | Ep | 0.90 | 21.8 | 12.12 | 0.20 | Fornax A |
| 1395 | E2 | 0.57 | 20.8 | 11.74 | 0.41 | |
| 1889 | E0 | 0.31 | 19.3 | 11.11 | 0.56 | Interacting with NGC1888 |
| 2300 | E+2 | 0.31 | 20.7 | 11.66 | 1.66 | |
| 3158 | E3 | 0.97 | 22.2 | 12.28 | 0.10 | |
| 3193 | E2 | 0.22 | 19.9 | 11.23 | 0.95 | |
| 3348 | E0 | 0.64 | 21.7 | 12.08 | 0.54 | |
| 3379 | E+1 | 0.17 | 19.5 | 10.98 | 0.85 | |
| 3605 | E4—5 | —0.43 | 16.9 | 10.18 | 1.85 | |
| 3608 | E2 | 0.10 | 18.8 | 10.93 | 1.01 | |
| 4278 | E1—2 | —0.17 | 19.5 | 11.20 | 1.07 | |
| 4283 | E0 | —0.21 | 17.2 | 10.32 | 1.33 | |
| 4350 | | 0.18 | 18.1 | 10.64 | 0.48 | |
| 4365 | E3 | 0.42 | 20.5 | 11.61 | 0.73 | |
| 4374 | E+1 | 0.46 | 20.9 | 11.76 | 0.76 | |
| 4406 | E+3p | 0.53 | 20.6 | 11.98 | 0.77 | |
| 4417 | | 0.21 | 18.0 | 10.60 | 1.60 | |
| 4459 | SA(r)0* | 0.06 | 19.9 | 11.36 | 1.54 | |
| 4472 | g E2 | 0.64 | 21.5 | 12.00 | 0.46 | Associated Radio source |
| 4473 | E5 | 0.03 | 20.2 | 11.45 | 1.74 | |
| 4486 | g E0—1p | 0.75 | 21.1 | 12.42 | 0.55 | Virgo A |
| 4494 | E1—2 | 0.32 | 19.5 | 11.20 | 0.62 | |
| 4552 | E0 | 0.23 | 20.4 | 11.57 | 1.26 | |
| 4564 | | 0.21 | 18.1 | 10.77 | 0.39 | |
| 4621 | E | 0.48 | 19.1 | 11.57 | 0.51 | |
| 4649 | E2 | 0.65 | 20.9 | 11.78 | 0.21 | Interacting with NGC4647 |
| 4697 | | 0.35 | 20.0 | 11.40 | 0.73 | |
| 4889 | E4 | 0.84 | 22.3 | 12.32 | 0.18 | |
| 4782 | | 0.38 | 21.0 | $\geqslant$11.49 | $\geqslant$0.73 | Interacting pair [24] |
| 4783 | | 0.40 | 20.6 | $\geqslant$11.34 | $\geqslant$0.52 | |
| 5128 | S0p | 0.58 | 21.3 | 11.81 | 0.45 | Centaurus A |
| 5557 | E1 | 0.86 | 21.4 | 11.97 | 0.23 | |
| 6438 A | S0p | 0.49 | 20.0 | 11.53 | 0.45 | Interacting galaxy |
| VV 117 A | | 0.38 | 19.5 | 11.40 | 0.64 | Interacting galaxy |

* According to de Vaucouleurs

of high luminosity are of type D, while less massive (and then less luminous) ones are of type G. The transition occurs at $M = 10^{11}$ solar masses or at absolute magnitude $M_p = -19.5$.

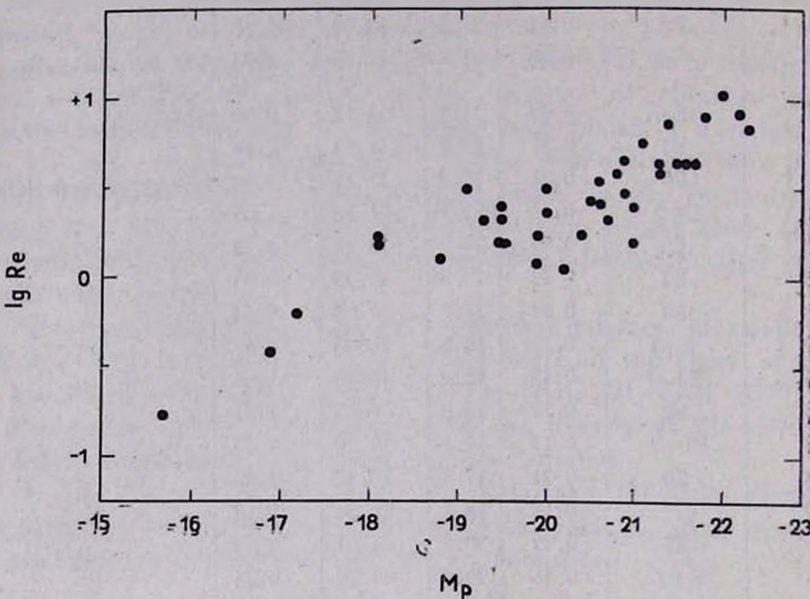


Fig. 1.

8 — The radio emission of elliptic galaxies also shows the existence of two groups. In fact, the radio index for E galaxies of high luminosity has values ranging from —5 to —15, while those of less luminous ones are close to zero, if there is any radio emission at all. It is well established that the luminosity of radio galaxies is very high, corresponding to $M_p = -20.5 \pm 0.8$ [12—15].

2. *The mass-radius diagram.* Using the data of Table 1 with $M/L = 30$ for all ellipticals, we may compute the masses and plot in the $\log M$-$\log R_e$ plane, where we recover again, as expected, the two parallel sequences and the transition region of Fig. 1. The slope of both sequences is sensible to the $M/L$ ratio in the sense that Poveda's or Pskovsky's relationship will give a slope smaller than one, whilst different $M/L$ ratios for each sequence keep the slopes equal to one but change the width of the transition region. We think that this second possibility ($M/L = 10$ or 50 for each sequence) is more in accordance with the apparent discontinuity of properties of elliptical galaxies discussed in the preceding section. Although, as the present evidence

on $M/L$ ratios still is meagre we adopt the mean value $M/L = 30$ as Fish did in his paper [10].

To incorporate the irregulars (Ir I), spirals (S), and SO galaxies in the same diagram we have to convert total dimensions (A), as defined by Holmberg, to effective radi ($R_e$). We proceed as follows: de

*Table 2*

DATA FOR AVERAGE TYPES OF GALAXIES

| Type | log $M$ | log $A$ ($pc$) | log $R_e$ ($kpc$) |
|---|---|---|---|
| IrI | 9.0 | 4.03 | .31 |
| Sc+ | 9.7 | 4.20 | .50 |
| Sc— | 10.4 | 4.45 | .75 |
| Sb+ | 11.1 | 4.58 | .88 |
| Sb— | 11.2 | 4.47 | .77 |
| Sa | 11.2 | 4.45 | .75 |

Vaucouleurs work on diameters of galaxies [16] gives $\log R_e = \log A - 3.70$ if $A$ is Holmberg's microphotometric diameter in parsec and $R_e$ is the effective radius in $kpc$. From Holmberg's data [17] given in Table 2, we deduce the average $\log R_e$ for each nebular type; the last column in that table has been calculated in that way.

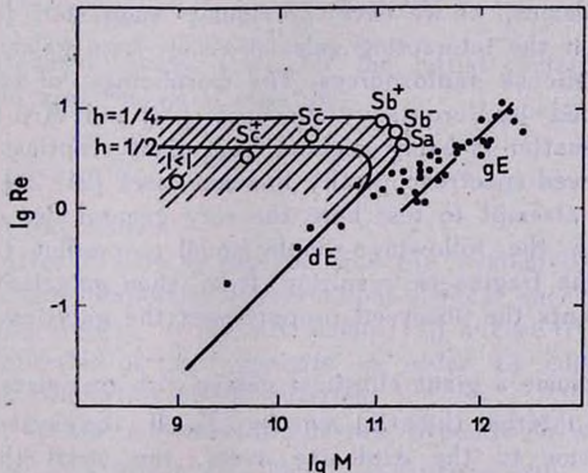


Fig. 2.

Fig. 2 displays the location of all main types in the mass-radius diagram. Irregular and late type spirals seem to follow an approximately constant $R_e$ sequence. The shaded area suggests qualitatively the dispersion of individual points.

Although the observational evidence for Fig. 2 is scarce, it seems difficult to deny the existence of the sequence of irregulars and spirals joining that of the ellipticals in the transition region. The mass-radius diagram may be affected by selection. However, observational selection by surface brigthness affects only the region of large $R_e$ and small masses, just where Irl and Sc+ galaxies lie below the horizontal line $\log R_e = 0.6$, suggesting that the representative points of those galaxies are artificially lowered in the diagram. On the other hand, the intersection of the three sequances is located in the region of the best observed galaxies (high intrinsic luminosity, high surface brightness), not affected by selection effects of this type. The relative number of galaxies on each sequence is strongly affected by selection because the samples are not homogeneous. In particular peculiar galaxies, interacting pairs and radiogalaxies are overrepresented.

3. *Fragmentation of galaxies.* The announcement by H. Arp [18] that interacting galaxies are associated with radio sources raises again the problem of the explosive origin of galaxies as postulated by V. A. Ambartsumian [19].

According to Arp's findings the radio sources associated with the interacting galaxies are farther away than those associated with typical radiogalaxies, as we have previously suggested [20, 21]. That would mean that the interacting galaxies result from galactic explosions observed as intense radiosources. The morphology of such pairs and groups described by Vorontsov-Veliaminov [22] and Arp [23] strongly suggests that matter is being ejected from giant elliptical galaxies, as has been observed spectroscopically in some cases [21, 24].

We shall attempt to test here the very general idea of explosions in galaxies with the following simple model to predict the statistical properties of the fragments resulting from such galactic „mitosis". It roughly represents the observed properties of the galaxies in the mass-radius diagram.

Let us assume a giant elliptical galaxy with rest mass $M_0$, binding energy $E_0^B$ and internal (kinetic) energy $T_0$. If the system lies in a steady state prior to the explosive event, the virial theorem gives $T_0 = E_0^B$. After the explosion we assume the system breaks in $n$ fragments with masses $M_i$, binding energies $E_i^B$ and internal (kinetic) energies $T_i$, where $i = 1, 2, \cdots n$. Moreover, let be $E_I^B$ and $T_I$ the interaction and kinetic energies of the system of fragments. After a long enough time, each fragment becomes dynamically stable and we may assume that the virial theorem applies again, $E_i^B = T_i$.

With the foregoing premises we recall the expression for the gravitational mass $M$ of a system not necessarily steady, given by Eddington and Clark [25].

$$Mc^2 = M_0c^2 - E^B + \frac{1}{2}(d^2J/dt^2),$$

where $M_0$ is the rest mass of the system, $c$ the speed of light and $J$ the momentum of inertia of the configuration relative to the baricentre. Now, as the new configuration after the explosive event is more dispersed than the initial one, the gravitational mass will increase to $M + \mu$ and we shall have

$$E_0^B = \sum E_i^B + E_I^B + \mu c^2 - \frac{1}{2}(d^2J/dt^2)$$

a relationship between the binding energies, the increase of gravitational mass $\mu > 0$, and the second derivative of the momentum of inertia $J$ of the system of fragments. On the other hand, it is possible to write an analogous relationship for kinetic energies, namely

$$T_0 = \sum T_i + T_I + \mu c^2 - (d^2J/dt^2)$$

because of the assumed steady state for the initial configuration and the fragments, and also the virial equation.

$$\frac{1}{2}(d^2J/dt^2) = T_I - E_I^B$$

for the system of fragments.

We do not attempt here to explain why the system prefers fragmentation to complete dispersion (observations suggest such fragmentation processes according to V. Ambartsumian [19]) but we try to predict the statistical properties of the fragments in order to compare them with the observed properties of the galaxies.

The stability of the system of fragments depends on whether $\mu c^2$ is smaller than $E_0^B - \sum E_i^B$ or not. This condition readily follows if we notice that $E_I^B$ is negative and $d^2J/dt^2$ positive for unstable configurations, whilst $E_I^B$ is positive and $d^2J/dt^2$ is zero for stable configurations.

We are interested in the conditions of the system of fragments a long time after the explosive event, because only then the assumption of steady state for each fragment will be true. Let $\mu_0$ be now the value of $\mu$ at that time then we have

$$T_0 = \sum T_i + \mu_0 c^2 + T_1 \qquad T_0 - \sum T_i > \mu_0 c^2$$

for stable configurations, and

$$T_0 = \sum T_i + \mu_0 c^2 - 3T_1 \qquad T_0 - \sum T_i < \mu_0 c^2$$

for unstable groups of fragments $\mu c^2$ is the energy radiated when the core of the giant elliptical galaxy collapses causing the other parts to explode.

If we introduce the average values of $T_i$ and $M_i$ through

$$nT = \sum T_i \qquad nM = \sum M_i = M_0$$

the preceding Eqs. become

$$T_0/M_0 = T/M + (\mu_0/M_0)\, c^2 + T_1/M_0 \tag{1a}$$

$$T_0/M_0 = T/M + (\mu_0/M_0)\, c^2 - 3T_1M_0 \tag{1b}$$

and we arrive at the following picture: a massive elliptical galaxy becomes unstable when its core implodes radiating a large pulse of energy and the decrease of binding energy causes (by hypothesis) the breaking of the parent galaxy in several fragments. The system formed by these fragments may be stable or not, depending on the intensity of the process. In both cases there exists a relationship between the parameters characteristic of the initial and final configurations (1) and several conclusions can be drawn from it, as we shall see in the following section.

4. *Interpretation of the mass-radius diagram.* Some fragments resulting from the explosion will be endowed with rotational besides random motions, and the kinetic energy $T$ will contain contributions from both kind of motions. Let now $k$ be the probability a fragment has to be endowed with only random motions in the fragmentation process, the average kinetic energy will be roughly given by

$$2\,(T/M) = pGM/R + (1 - k)\, w^2 R^2$$

where $M$, $R$, $w$, are the mass, effective radius and angular velocity of the average fragment, $p$ is a number of the order of unity. We think $k$ is a statistical property of the fragmentation process and consequently a constant for a large sample, so we may define an effective angular velocity through $w_0^2 = (1 - k)\, w^2$ for the average fragment. As we have assumed the parent galaxy to be a giant elliptical, we have $2T_0 = pGM_0^2/R_0$ and (1) becomes

$$m/r + h^2 r^2 = 1 - q_c \tag{2}$$

after introducing the non-dimensional variables

$$m = M/M_0, \quad r = R/R_0, \quad h^2 = w_0^2 R_0^3/pGM, \quad r_1 = R_1/R_0,$$
$$q = 2\,(\mu_0/M_0)\, c^2 R_0/pGM_0, \quad s^2 = 2T_1 R_0/pGM_0^2$$

and defining

(3) $q_c = q + 1/r_1$ (stable system) or $q_c = q - 3s^2$ (unstable systems).

$R_1$ is the mean radius of the system of fragments in the stable case.

Eq. (2) allows us to give an interpretation of the mass-radius diagram. In fact, when $r$ is smaller than unity we get a family of straight lines $m = (1 - q_c) \cdot r$ depending on $q_c$ as a parameter, whilst for small $m$ and large $r$ we have $r^2 = (1 - q_c)/h^2$ and the effective radius is independent of the mass. We think the two cases just considered correspond to the dwarf elliptical and spiral sequences respectively. Dwarf ellipticals have small radiae (which also means small angular momenta per unit of mass $h.r^2$) and appear on a line $M/R = C$ in Fig. 2. Moreover, as $M/R = C_0$ for giant ellipticals, we have from the same figure $C = 0.25\, C_0$, from where results $q_c = 0.75$. On the other hand, the irregular and spirals sequence runs roughly at $\log R_e = 0.6$ in Fig. 2, as we would expect for galaxies with large $R_e$ and large angular momentum per unit of mass $hr^2$.

The use of Fig. 2 together with Eqs. (2) and (3) and the preceding interpretation of the mass radius diagram allows us to make some crude estimations of the parameters of the model. According to it, dwarf ellipticals, irregulars and spirals are the result of the fragmentation of giant elliptical galaxies. Each explosive event is not necessarily identical with others, of course, and the distribution of fragments in the mass-radius diagram is a composite of many events.

The velocity dispersion for stars in a giant elliptical galaxy is

$$\sigma_0^2 = GM_0/3.11\, R_0 = GC_0/3.11 = (522\ km/sec)^2$$

as $p = 1/3.11$ according to Poveda [26]. The critical value of $\mu_c/M_0$ which separates stable from unstable configurations of fragments is given by

$$\mu_0/M_0 = \frac{1}{2} q_0 (\sigma_0/c)^2 = 10^{-6}$$

as $q_c = 0.75$. For a large giant elliptical galaxy, $M_0 = 2.5 \cdot 10^{12}$ solar masses and the critical mass of the core becomes $\mu_c = 2.5 \cdot 10^6$ suns. This result means that explosive events like those in strong radio-sources lead to unstable systems of galaxies, because the mass-equivalent of the energy released is $10^7 - 10^8$ solar masses, much larger than the stability limit. This kind of event is only possible with a negative mass defect in the final state, the fragmentation being responsible for it, as noticed by Zeldovich and Novikov [27]. Explosions with energy releases smaller than the critical value lead to stable configurations of galaxies, the virial theorem applies, and $s^2 = 1/r_1 = q_0 - q$. The stronger the event is, the larger is the dimension of the stable configurition.

Fig. 2 shows that the curves (2) with $h = \frac{1}{2}, \frac{1}{4}$ approximate reasonable well the sequence of spirals and irregulars. A rough value of the rotation periods may be obtained from $P = 2\pi/w_0 = (R_0/h\sigma_0) = 3 \cdot 10^7 - 3 \cdot 10^8$ years, the spread coming both from the possible range of values of $R_0$ and $h$. The figures we found agree well with the periods of many galaxies of several types given by N. U. Mayall [28].

We now notice that [2] does not represent points with masses larger than $(0.24/h) (1 - q_0)^{3/2}$ so that for values of $M$ larger than about $3 - 8 \cdot 10^{11}$ suns we cannot be sure of the stability of the fragments themselves: it is precisely here, in the transition region, where interacting pairs of galaxies are located, as we saw in sections 1 and 2.

The energy released in strong explosive events is equivalent to $q = 4$ to $40$ so that the velocity dispersion in unstable groups should be of the order of

$$\sigma_1^2 = s^2\sigma_0^2 = (1/3) (q - q_0) \sigma_0^2 = (540 - 1900\ km/sec)^2$$

while the mean square velocity in the radial direction amounts to

$$\sigma_r^2 = (1/3) \sigma_1^2 = (300 - 1100\ km/sec)^2.$$

For stable groups we have to consider separately tight and loose configurations. Let us call loose a group of galaxies with $r_1$ larger than, say, 10; we have

$$\sigma_r^2 < \sigma_0^2/10 = (170\ km/sec)^2 \text{ and } \sigma_r^2 < km/sec)^2$$

for loose groups, and otherwise for the tight ones.

The preceding figures suggest that galaxies in the field were originated in unstable groups, out of explosions not too much larger than the stability threshold $q_c$. In fact, the mean square peculiar radial velocity is of the order 200 *km/sec* after Hubble [29] and also is coincident with the value derived by G. de Vaucouleurs [30] for the velocity dispersion in loose groups in the Metagalaxy. Both figures are over the upper limit given above for loose groups. On the other hand, tight groups of galaxies with their high velocity dispersions cannot be told if stables or not through this procedure.

Summing up, we may say that the fragmentation model for galaxies describes qualitatively well the main features of the mass-radius diagram, allows the estimation of the critical mass of the collapsing core which separates the explosive events leading to unstable configurations of fragments from the stable ones, the velocity dispersion in both cases, the rotation periods of spirals and irregular galaxies, and throws some light about the origin of the unstability of loose groups of galaxies.

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## ОБ ОБРАЗОВАНИИ ГАЛАКТИК ПУТЕМ ФРАГМЕНТАЦИИ

Л. СЕРСИК

Обсуждается наблюдательное свидетельство существования двух видов эллиптических галактик. Распределение галактик на диаграмме масса-радиус интерпретируется как результат фрагментации эллиптических галактик больших масс. Строится модель, описывающая основные свойства галактик образующихся вследствие взрывных процессов и показано, что она находится в довольно хорошем согласии с наблюдениями. Обсуждаются также свойства неустойчивых групп галактик и скоплений.

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