

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.

О формировании галактик дроблением. Обсуждается доказательство, полученное из наблюдений, существования двух сортов эллиптических галактик. Распределение галактик в диаграмме масса-радиус интерпретируется как результат дробления эллиптических галактик большой массы. Разрабатывается модель, описывающая грубые свойства галактик, исходя из случаев взрыва и показывается, что она находится в хорошем согласии с наблюдениями. Также обсуждаются свойства неустойчивых групп галактик и скоплений.

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 (1961) shows a change of slope at the absolute magnitude -19 , both for E and other types of galaxies.

(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 (1962, 1964). The population of those clusters studied by Abell is mainly formed by E and S0 galaxies.

(3) W. C. Baum (1959) and G. de Vaucouleurs (1961) have independently found a luminosity effect in the colour indices 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 (1963), 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 (1961) and also Ju. Pskovskij (1965) have proposed a M/L ratio increasing with mass for elliptical galaxies. Both results are essentially in agreement and the relation found is

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

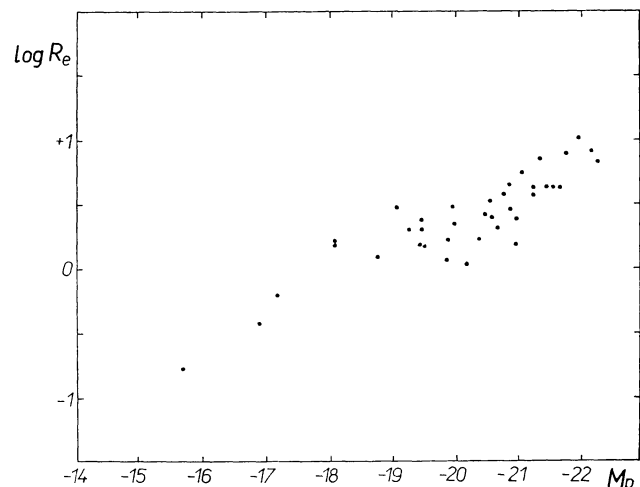


Fig. 1. Relationship between absolute magnitude and effective radius for elliptical galaxies.

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from which the following typical values may be deduced:

$$\begin{array}{rcc} M_p: & -15 & -18 & -21 \\ M/L: & 13 & 25 & 50 \end{array}$$

On the other hand, T. L. Page (1965) 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) Figure 1 shows a diagram relating the absolute magnitude of elliptical galaxies to $\log R_e$ (where R_e is the

effective radius in kpc as defined by de Vaucouleurs). Table I summarizes the data (Fish 1964). 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 (1962) 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

Table I*)
Data for elliptical galaxies (A. Fish, 1964)

NGC	Type	$\log N_e$	$-M_p$	\log	$\log D$	Dates
221	d E2	0.77	15.7	9.46	2.05	
741	E0	1.01	22.0	12.00	0.45	
750	Ep	0.64	21.6	12.04	0.50	
751	Ep	0.64	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 NGC 1888
2300	E+2	0.31	20.7	11.66	1.66	
3158	E3	0.92	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()0*	0.06	19.9	11.36	1.54	
4472	g E2	0.64	21.5	12.00	0.46	Associated radiosource
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 NGC 4647
4697		0.35	20.0	11.40	0.73	
4889	E4	0.84	22.3	12.32	0.18	
4782		0.38	21.0	≥ 11.49	> 0.73	Interac. pair (Burbidge's 1964)
4783		0.40	20.6	≥ 11.34	≥ 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	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.

or luminosity. Massive ellipticals 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 $M_p = -19.5$.

(8) The radio emission of elliptical 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 $M_p = -20.5 \pm 0.8$ (B. Hanbury Brown and G. Hazard, 1961; R. J. Long and D. R. Marks, 1961; P. Maltby, T. A. Matthews and A. J. Moffet, 1963; R. C. Roeder and G. C. McVittie, 1963.)

2. The mass-radius diagram

Using the data of Table I with $M/L = 30$ for all ellipticals, we may compute the masses and plot in the $\log M - \log R_e$ plane, where we obtain again, as expected, the two parallel sequences and the transition region of Fig. 1. The slope of both sequences is sensitive to the M/L ratio in the sense that Poveda's or Pskovskij'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 sequences) 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 is still meagre, we adopt the mean value $M/L = 30$ as Fish did in his paper (1964).

To incorporate the irregulars (IrI), spirals (S), and S0 galaxies in the same diagram we have to convert total dimensions (A), as defined by Holmberg, to effective radii (R_e). We proceed as follows: de Vaucouleurs (1959) work on diameters of galaxies gives

Table II
Data for average types of galaxies

Type	$\log M$	$\log A$ (pc)	$\log R_e$ (kpc)
IrI	9.0	4.03	0.31
Sc+	9.7	4.20	0.50
Sc-	10.4	4.45	0.75
Sb+	11.1	4.58	0.88
Sb-	11.2	4.47	0.77
Sa	11.2	4.45	0.75

$\log R_e = \log A - 3.70$ if A is Holmberg's microphotometric diameter in parsec and R_e is the effective radius in kpc. From Holmberg's data (1964) given in Table II, we deduce the average $\log R_e$ for each nebular type; the last column in that table has been calculated in that way.

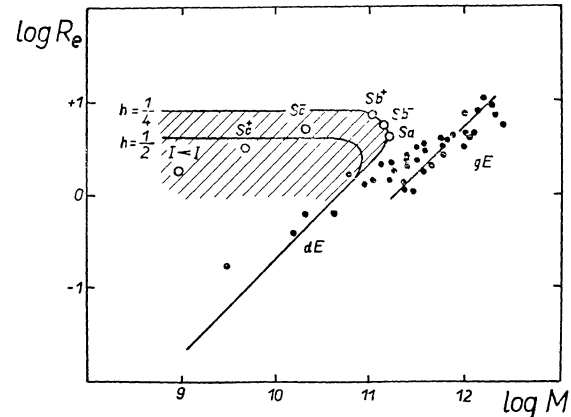


Fig. 2. Mass-radius diagram for galaxies.

Figure 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 brightness affects only the region of large R_e and small masses, just where IrI 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 sequences 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 over-represented.

3. Fragmentation of galaxies

The announcement by H. Arp (1966) that interacting galaxies are associated with radiosources raises again the problem of the explosive origin of galaxies as postulated by V. A. Ambarcumjan (1958).

According to Arp's findings the radiosources

associated with the interacting galaxies are farther away than those associated with typical radiogalaxies, as we have previously suggested (1961, 1966). That would mean that the interacting galaxies result from galactic explosions observed as intense radiosources. The morphology of such pairs and groups described by Voroncov-Vel'jaminov (1962) and Arp (1966) strongly suggests that matter is being ejected from giant elliptical galaxies, as has been observed spectroscopically in some cases.

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 $i = 1, 2, \dots, n$. Moreover, let E_1^B and T_1 be 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 (1938)

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

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

$$E_0^B = \Sigma E_i^B + E_1^B + \mu c^2 - \frac{1}{2}(d^2J/dt^2),$$

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

$$T_0 = \Sigma T_i + T_1 + \mu c^2 - (d^2J/dt^2),$$

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

$$\frac{1}{2}(d^2J/dt^2) = T_1 = E_1^B$$

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. Ambarcumjan (1958)) 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 μc^2 is smaller than $E_0^B - \Sigma E_i^B$ or not. This condition readily follows if we notice that E_1^B is negative and d^2J/dt^2 positive for unstable configurations, whilst E_1^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 will the assumption of steady state for each fragment be true. Let μ_0 be now the value of μ at that time; then we have

$$T_0 = \Sigma T_i + \mu_0 c^2 + T_1; \quad T_0 - \Sigma T_i > \mu_0 c^2$$

for stable configurations, and

$$T_0 = \Sigma T_i + \mu_0 c^2 - 3T_1; \quad T_0 - \Sigma T_i < \mu_0 c^2$$

for unstable groups of fragments. $\mu_0 c^2$ 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

$$nT = \Sigma T_i; \quad nM = \Sigma M_i = M_0,$$

the preceding Eqs. become

$$(1a) \quad T_0/M_0 = T/M + (\mu_0/M_0) c^2 + T_1/M_0$$

$$(1b) \quad T_0/M_0 = T/M + (\mu_0/M_0) c^2 - 3T_1/M_0$$

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 conclusion 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 k now 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

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

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

$$(2) \quad m/r + h^2r^2 = 1 - q_c,$$

after introducing the non-dimensional variables

$$\begin{aligned} m &= M/M_0, \quad r = R/R_0, \quad h^2 = w_0^2R_0^3/pGM_0, \\ r_1 &= R_1/R_0, \quad q = 2(\mu_0/M_0)c^2R_0/pGM_0, \\ s^2 &= 2T_1R_0/pGM_0^2 \end{aligned}$$

and defining

$$(3) \quad \begin{aligned} q_c &= q + 1/r_1 \quad (\text{stable system}) \quad \text{or} \\ q_c &= q - 3s^2 \quad (\text{unstable system}). \end{aligned}$$

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

Equation (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 $m = (1 - q_c)r$ 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 radii (which also means small angular momenta per unit of mass hr^2) and appear on a line $M/R = C$ in Figure 2. Moreover, as $M/R = C_0$ for giant ellipticals, we have from the same figure $C = 0.25C_0$, from which $q_c = 0.75$. 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

$$\sigma_0^2 = GM_0/3 \cdot 11R_0 = GC_0/3 \cdot 11 = (522 \text{ km/sec})^2,$$

as $p = 1/3 \cdot 11$ according to Poveda (1958). The critical value of μ_c/M_0 , which separates stable from unstable configurations of fragments, is given by

$$\mu_c/M_0 = \frac{1}{2}q_c(\sigma_0/c)^2 = 10^{-6},$$

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 results 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 Zeldovič and Novikov (1965). 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 configuration.

Figure 2 shows that the curves (2) with $h = \frac{1}{2}, \frac{1}{4}$ approximate reasonably 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 (1960).

We now notice that (2) does not represent points with masses larger than $(0.24/h)(1 - q_c)^{3/2}$ 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

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

while the mean square velocity in the radial direction amounts to

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

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

$$\sigma_1^2 < \sigma_0^2/10 = (170 \text{ km/sec})^2$$

and
$$\sigma_r^2 \quad (100 \text{ km/sec})^2$$

for loose groups and otherwise for the tight ones.

The preceding figures suggests 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 (1938) and also is coincident with the value derived by G. de Vaucouleurs 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 said to be stable 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 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 throw some light about the origin of the instability of loose groups of galaxies.

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THE ECLIPSING BINARY SYSTEM SW LYNCIS

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Two-colour light curves based on photoelectric measurements have been determined for the system SW Lyncis. The period is discussed and a provisional solution of the elements based on an annular primary eclipse is given.

Система затменной переменной SW Lyncis. В работе определены кривые блеска затменной переменной SW Лун в желтом и синем цветах. Дискутируется период переменной и определяются предварительные элементы системы.

1. Introduction

SW Lyncis is the little known star number 346 in the Finding List of Eclipsing Variables (Koch, Sobieski, and Wood 1963). Its variability was first discovered by Hoffmeister (1949). It was observed by Kippenhahn who derived five times its minimum light, and by Mauder who published eleven other ones. The most extensive search for the determination of the

light elements of this star was performed by Huth. This author compiled an extensive list of the minima observed, derived new light elements, and classified SW Lyncis as a β Lyrae type variable (Huth 1958). This was contrary to all other preceding observations from which the star was classified as an eclipsing binary of the Algol-type. The amplitude of the light changes was given between 0.5 and 0.8 magnitude, the secondary minimum was hard to detect.