N91-16859

A HOMOGENEOUS SAMPLE OF BINARY GALAXIES: BASIC OBSERVATIONAL PROPERTIES

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ABSTRACT

A survey of optical characteristics for 585 binary systems, satisfying a condition of apparent isolation on the sky, is presented. Influences of various selection effects distorting the average parameters of the sample are noted. The pair components display mutual similarity over all the global properties: luminosity, diameter, morphological type, mass-to-luminosity ratio, angular momentum etc., which is not due only to selection effects. The observed correlations must be caused by common origin of pair members. Some features (nuclear activity, color index) could acquire similarity during synchronous evolution of double galaxies.

Despite the observed isolation, the sample of double systems is seriously contaminated by accidental pairs, and also by members of groups and clusters. After removing false pairs estimates of orbital mass-to-luminosity ratio range from 0 to 30 $f_\odot$, with the mean value (7.8 ± 0.7) $f_\odot$. Binary galaxies possess nearly circular orbits with a typical eccentricity $e = 0.25$, probably resulting from evolutionary selection driven by component mergers under dynamical friction. The double-galaxy population with space abundance 0.12 ± 0.02 and characteristic merger timescale 0.2 H^{-1} may significantly influence the rate of dynamical evolution of galaxies.

1. INTRODUCTION

Every year interest increases in investigating the structure and dynamics of systems of galaxies. The main stimulus here is the search for "missing" virial mass in these systems, which gives this problem somewhat of a detective nature. In the wide range of hidden mass searches pairs occupy an important place, as the simplest of galactic systems. Investigation of pairs allows us to approach the hidden mass problem at an elementary, "cellular", level. Binary galaxies are also especially interesting because of the accelerated rates of evolution as compared to solitary ones. Because of galaxies' mutually proximity in pairs, gravitational tides play a major part in their fate, star-formation bursts and dynamical friction effects. There are grounds to think that pairs significantly influence the dynamical evolution of galactic systems in general.

The first systematic studies of double galaxies were carried out by the Swedish astronomers Lundmark (1927) and Holmberg (1937, 1954), who suggested quantitative definitions of binary systems. Further progress in this study was achieved by Page. He made the first systematic measurements of radial velocities in binaries and worked out mass cal-

culation methods with different assumptions on the kind of orbital motions in pairs (Page 1952, 1960, 1967).

Zwicky *et al.* (1961-1968) and Vorontsov-Velyaminov *et al.* (1962-1968) compiled extensive galaxy catalogs, in which among others numerous examples of close binary systems are marked. Impressive collections of peculiar and interacting pairs are represented in the atlases by Arp (1966) and Vorontsov-Velyaminov (1959,1977). But in these catalogs, the binary galaxies do not form homogeneous samples because quantitative criteria had not been used in their selection. The pairs were selected according to strong signs of interaction as by-products of the main program. In time, the necessity of having a new double-galaxy catalog became apparent. It should be characterized by homogeneous observational data and be based on strict selection criteria of isolated pairs. Such a task was set by the author and realized in the form of the "Catalogue of isolated pairs of galaxies in the northern hemisphere" (Karachentsev, 1972). When preparing the catalogue, including 603 pairs, we kept a rule to inspect in detail the neighborhoods of all galaxies brighter than a fixed photometric limit, using the POSS prints. The search and selection of isolated binary systems was based on quantitative criteria for measuring mutual distances and angular diameters of the galaxies. A similar approach was used later by Turner (1976), Peterson (1979) and Schweizer (1987). According to our criterion, two galaxies with apparent magnitudes

$$m_1, m_2 < 15.7,$$

angular diameters a_1, a_2, and angular separation X are isolated relative to neighboring (in projection) galaxies, when the conditions

$$X_{1i}/X_{12} > 5a_i/a_1,$$

$$X_{2i}/X_{12} > 5a_i/a_2,$$

are satisfied ; i denotes any "significant" neighbouring galaxy, whose angular diameter a_i lies in the interval

$$4a_1 > a_i > a_1/2,$$

$$4a_2 > a_i > a_2/2,$$

Without going into detail, we may say that this criterion selects double systems with local density contrast on the sky more than 25.

Mass radial velocity measurements in isolated pairs aiming to study the kinematics and dynamics of double galaxies were undertaken (Karachentsev, 1980, Tifft, 1982). As a result of the combined efforts of several observers the program of radial velocity determination had been completed by 1983. Compared to previous episodic observations of galaxies in pairs, higher accuracy of radial velocity measurements was achieved, which allowed determination of masses of double systems with greater reliability.

After reduction of apparent magnitudes and angular diameters of galaxies to a standard system, specifying morphological and spectral types (and also excluding 18 single objects) the final version of the catalog was published in the book "Binary galaxies" (Karachentsev, 1987).

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The present report contains the main conclusions drawn when analysing the above-mentioned sample of 585 isolated pairs. In the interest of brevity, we must omit arguments for most of the statements.

2. OBSERVATIONAL PROPERTIES OF THE SAMPLE AND SELECTIVITY

Using the objective isolation criterion allowed us to account for various selection effects, badly affecting binary system sample characteristics. We investigated the efficiency and selectivity of the pair criterion with the help of Monte Carlo numerical experiments. Simulation of the apparent distribution of galaxies was carried out, accounting for their spatial clustering in systems of various scale and population. Approaching this simulated galaxy distribution by the same double system selection criterion as that used in the real catalogue, we obtained the following result. Among the catalogue objects 11% are optical pairs, caused by accidental projection in the line of sight of galaxies that are not in spatial proximity. About 32% the of catalog pairs are false double systems, formed by projection of two members of one group or cluster on the line of sight. Earlier the role of false pairs (system members) was much underestimated, which gave anomalously high values of average orbital mass for binary galaxies. The low efficiency of any pair criterion is associated with the large luminosity dispersion of galaxies, because of which apparent magnitude or angular diameter of a galaxy are unreliable indicators of its distance.

The simulation results were used to recover true (space) characteristics of double system using their catalogued characteristics, distorted both by projection effects and by presence of non-isolated pairs in the catalog. If we exclude 98 pairs with orbital mass-to-luminosity ratio $f> 100\ f_{\odot}$ as being false, then for the remaining 487 systems the distribution according to radial velocity difference is shown by a histogram in Figure 1. After correction for velocity measurement errors the distribution has a form close to the exponential one with the average $<y>= 120$ km/s.

Unlike radial velocities, angular separations between galaxies are directly included in the isolation criterion. As a result of this, double galaxies' distribution in projected linear separation, X, is subjected to strong selection. Thus, when $X > 100$ Kpc, about 90% of pairs are omitted by the isolation criterion. This circumstance together with the increasing contribution of false pairs with increasing X does not let us determine the true number of wide double systems in a unit volume of space. The distribution of 487 isolated pairs according to their linear separations is shown in Figure 2. It is well represented by a gamma function, $n(X) \sim X^{1/2} \exp(-X/C)$, with mean value 33.2 kpc,the Hubble constant being taken as $H_0=75$ km/s Mpc. About 70% of the catalog objects are rather tight systems where the mutual distance of components does not exceed their combined diameters. After correction for the selection criterion the mean spatial separation for galaxies in isolated pairs is $<r_{12}> = 83$ kpc.
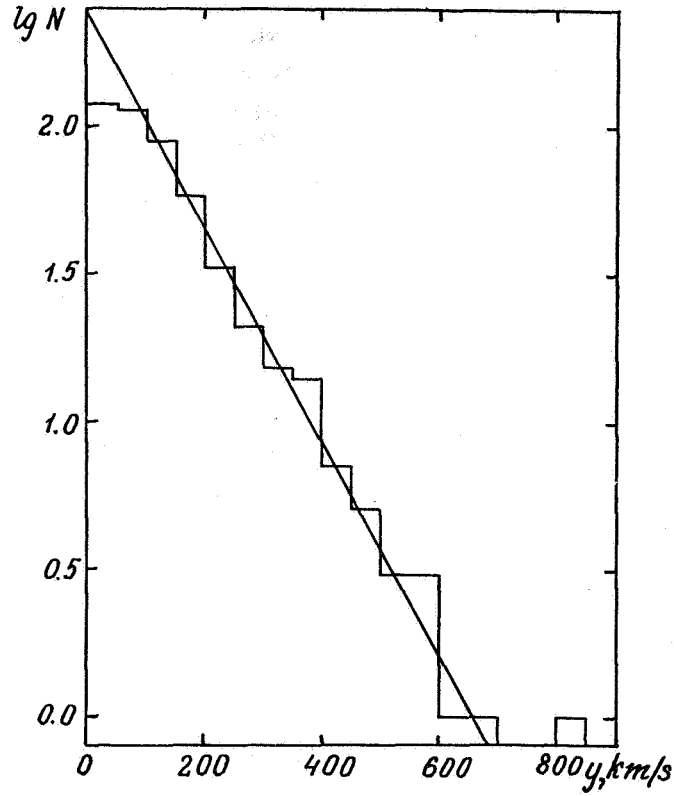
Fig. 1. Distribution of radial velocity difference (km/s) for components of 487 pairs.
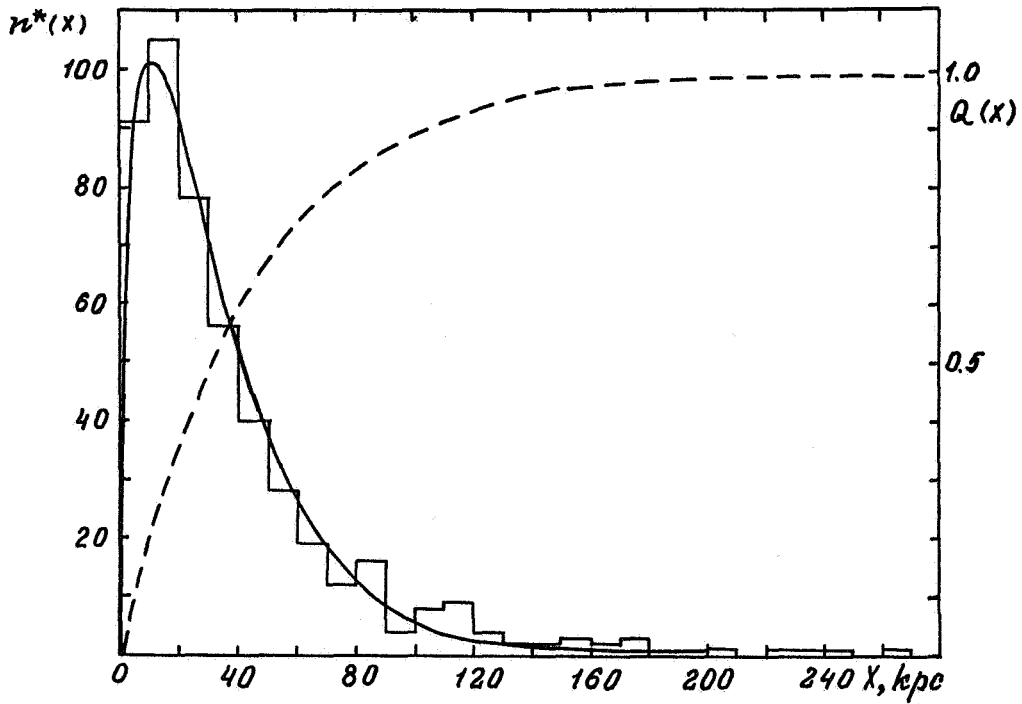

Fig. 2. Distribution of 487 isolated binary systems according to projected separation of their components. Dashed curve shows selectivity function for the criterion (right scale).

The variety of selection factors for binary galaxies makes determining their spatial luminosity function $\Phi(M_1,M_2)$ rather complicated. As compared to field galaxies, pair components show a luminosity excess by 1.7 times on average. The observed positive correlation for absolute magnitudes of double galaxies is not only due to selection effects in the sample, but is caused by real physical similarity of objects inside one system. As with the luminosity correlation, so its excess, evidently, reflects the special conditions under which common formation of double galaxies took place.

3. ORBITAL MASSES

The hidden mass problem certainly should be placed first in the study of double systems. It had been repeatedly supposed that pairs of galaxies are surrounded by invisible massive coronae, and therefore Keplerian description of their dynamics is not appropriate. To motivate such a statement some indirect arguments are drawn 'from below' (flat rotation curves for individual galaxies) and 'from above' (a virial mass excess for X-ray clusters). Besides such indirect considerations, direct evidence of mass excess in double systems has been inferred from their high mean orbital mass-to-luminosity ratio ($\approx 60 \; f_\odot$), obtained by Page (1952), Turner (1976) and Peterson (1979). The "anatomy" of this excess was discussed at length in the book "Binary Galaxies" (Karachentsev, 1987). Those data allow us to affirm that the paramount reason for high estimates of orbital mass is that a large number of false pairs is present in the catalog samples. The histogram in Figure 3 shows the distribution of 585 binary systems according to their orbital mass-to-luminosity ratio,

$$ f = \frac{32 X_{12} \; y^2{}_{12}}{3\pi G(L_1 + L_2)}, $$

where G is the gravitational constant and $(32/3\pi)$ the average projection factor for circular motions. Regions occupied by true pairs, optical pairs and non-isolated pseudo-pairs, i.e. group and cluster members, are indicated. After a correct accounting for fictitious double systems, and also radial velocity measurement errors, the average orbital mass-to-luminosity ratio corresponds well with individual values obtained from galaxy rotation curves. We will stress here, that we are dealing with more than a coincidence of average values. Corrected for projection effects, pair members' orbital mass-to-total luminosity ratio appears distributed in a narrow range of values [0, 30] $f_\odot$ with average (7.8 ± 0.7) $f_\odot$ and standard deviation 6.5 $f_\odot$. Nearly this distribution law is characteristic for field galaxies' individual mass-to-luminosity ratios. An important circumstance here is also the good correspondence of orbital and individual f-values for various types of galaxies along the Hubble sequence (Figure 4). Comparison of binary galaxies' orbital mass with their sum of individual masses determined from internal motions shows that the main part of their mass is concentrated inside the standard optical radius R_{25} . Though the most of the catalog objects are close (contact) systems, broad pairs with X> 100 Kpc also possess a low average ratio of orbital mass-to-luminosity which would not agree with the hypothesis of massive invisible coronae.
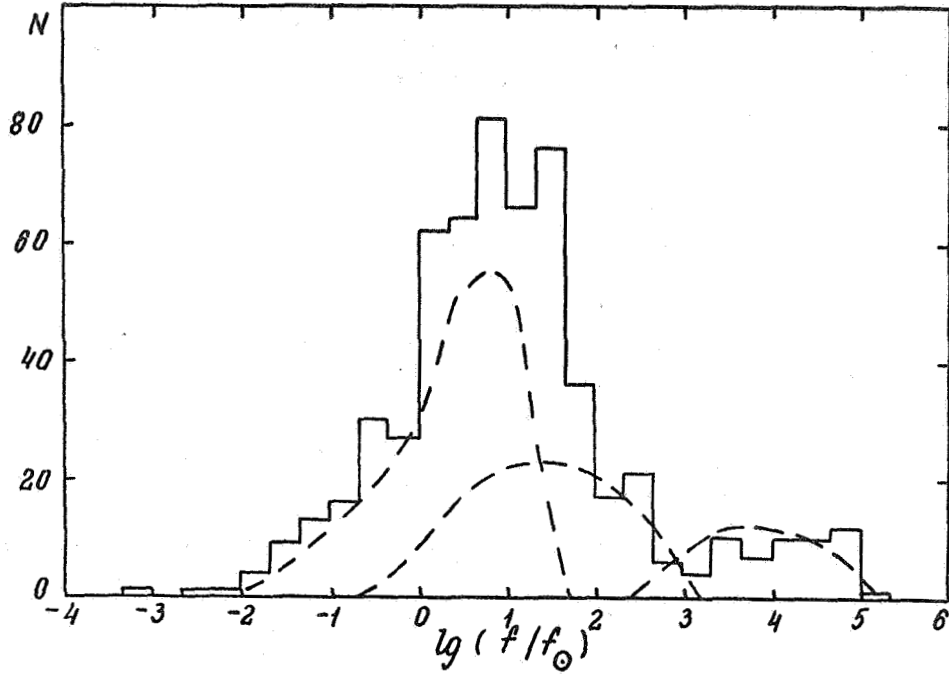
Fig. 3. Distribution of 585 catalogued pairs according to their orbital mass-to-luminosity ratio in solar units (histogram). The dashed curves show the simulated distributions for true binaries (left), members of groups (middle), and optical pairs (right).
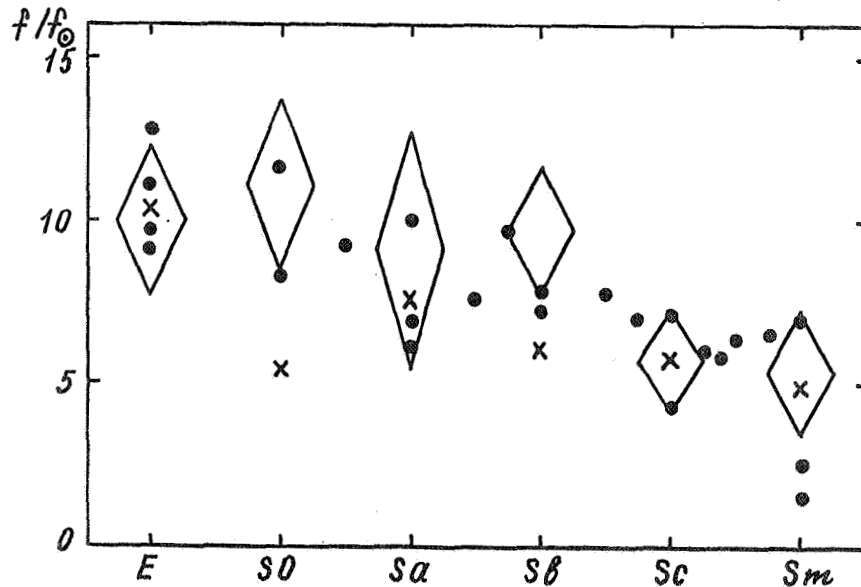

Fig. 4. Average mass-to-luminosity ratio for various structural type galaxies from different sources (points). Oblique crosses are used to distinguish mean values for components of pairs. Rhombs mark mean values of orbital mass-to-luminosity ratio for pairs with similar types of galaxies.

Thus, pairs of galaxies seem a missing link in the chain of various scales of systems in a hierarchy, others of which show virial mass excess. The strange character of this situation should be specially stressed.

Observational data place limits on the possible kinds of orbital motions of galaxies in pairs. Using different methods, we came to the conclusion that binary galaxy orbits are close to circular. The best agreement with observational data is obtained with orbital eccentrity $e = 0.25$.

4. MORPHOLOGY AND ACTIVITY.

Rich opportunities for testing scenarios of origin and evolution of galaxies are given by analysis of the population of binary galaxies according to their morphological and spectral types, signs of interaction, color indices etc. In this problem only "the upper cultural layer" has been taken up.

Binary systems, as compared to single ones, contain a higher percentage of earlier structural type objects. Besides, the relative number of elliptical galaxies is falling with increasing separation of pair components. It is necessary to note here, that the observed frequency of binary systems with similar Hubble type components is considerably higher than that expected for accidental combinations of these features. The correlation function of pairs according to their morphological types is presented in Figure 5.
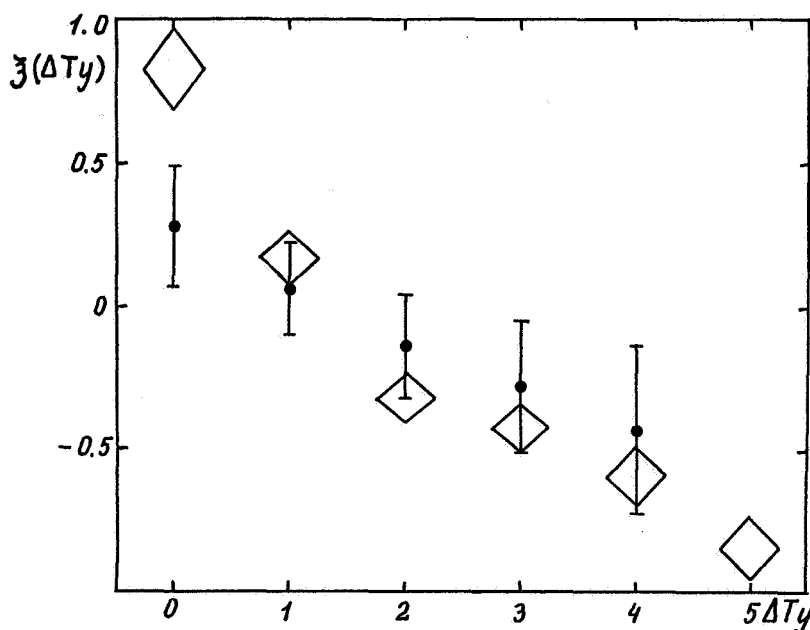

Fig. 5. Correlation function of binary systems according to a structural type of their components. Rhomboids are data for the whole 487 pair sample, points - for 118 wide pairs with X> 50 Kpc.

About 60% of the catalogued pairs show traces of tidal interaction. As analysis shows, all structural types of galaxies are present among the interacting ones in equal proportion. But their distribution according to interaction types is highly inhomogeneous.

Such linear structures as tails and bridges (see Figure 6) are characteristic of ob-

jects with dominant stellar populations of the disk with almost circular velocities. In elliptical binary galaxies, with significantly elongated stellar orbits, amorphous symmetric atmospheres are usually observed. The relation between interaction signs and character of stellar motions in pairs members usually agrees with results of numerical experiment (Clutton-Brock , 1972).

Considering spectral and morphological types of binary galaxies together with their interaction types shows that tidal interaction is favourable for galaxies to have strong emission features. Activity of galactic nuclei is apparently intensified by the flow of gas to it as a result of collision and loss of momentum of gas clouds caused by tidal perturbation. Another mechanism - gas exchange between pair components - does not take any significant part, judging by the absence of emission in spectra of elliptical galaxies in contact with a spiral partner.
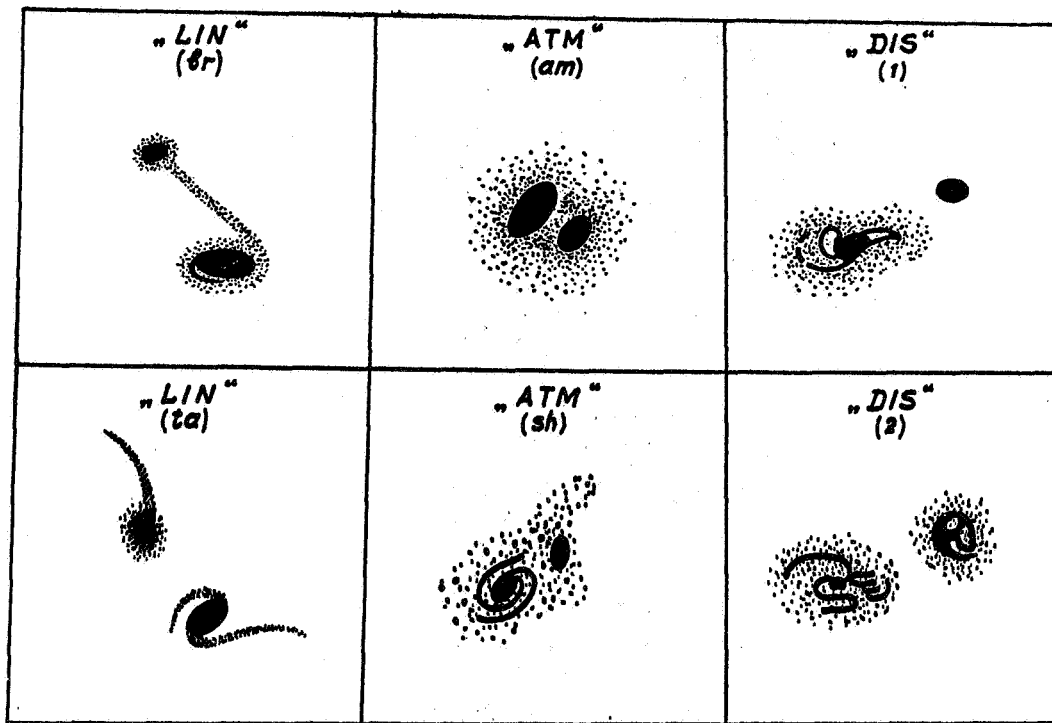

Fig. 6. Scheme of interaction signs for the pair members. "LIN" - linear structures of bridge type (br) or the tail, one (ta). "ATM" - amorphous (am) or shredded (sh) atmosphere. "DIS" - structure distortion in one (1) or both (2) components.

Recently much evidence has been gathered in favor of the fact that star-formation processes in binary systems go more actively, than in field galaxies or members of rich clusters. This is indicated by: the observed infrared and radio emission excess in binary galaxies (Stocke, 1978, Lonsdale et al. , 1984; Sulentic, 1989), increased frequency of supernova outbursts (Smirnov, Tsvetkov, 1981), and a high percentage of double systems among Seyfert objects and quasars (Heckman et al. , 1984; Dahari, 1984). In pairs with small radial-velocity difference and small separation of their components, i.e. where tidal

interaction is most effective, blue Markarian galaxies are met especially often.

According to photoelectric data (Demin *et al.* , 1984), binary system components show a relationship in color indices (Holmberg effect). For spiral galaxies in pairs their bluish color and correlation of color indexes may, probably, be explained by simultaneous star-formation bursts, periodically repeated because of mutual tidal perturbation. In pairs with elliptical components, where gas resources for such bursts are not large, the observed color correlation might result from similar chemical abundances of components at the epoch of their mutual origin.

5. PAIRS AS A POPULATION

Considering binary galaxies as a metagalactic population, we may note the following properties of their distribution.

a) The relative number of galaxies in the sample brighter than $m = 15.7$ is 0.042, and their abundance per unit volume is rather higher : 0.12 ± 0.02.

b) The spatial distribution of pairs obeys a common law of hierarchical clustering. About 90 per cent of nearby pairs are members of known nearby galaxy groups. Not less than half of binary systems with radial velocities $V_0 < 2400$ km/s form part of the Local Supercluster.

c) The two-point correlation function for pair centers has a shallower slope in the interval 1-10 Mpc, than the standard Peebles function (1980). This means that binary galaxies usually avoid dense supercluster regions. Such a tendency is seen in Figure 7, where the overall distribution of pair centers in the sky is shown in equatorial coordinates.
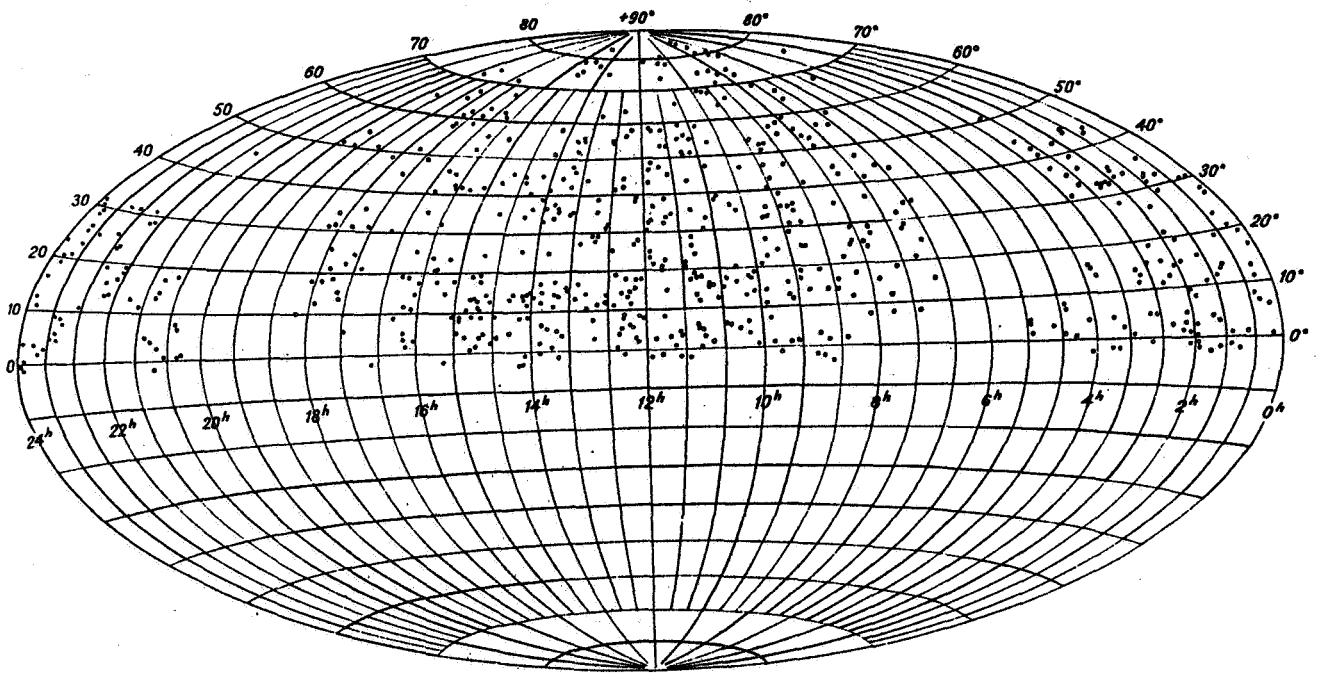

Fig. 7. Distribution of pairs on the sky in equatorial coordinates.

d) Pairs of galaxies in groups and clusters are distinguished by small values of mutual distance between their components. Pairs, compared to single members of a system, reveal a distinct tendency to be located mainly in the less dense peripheral regions of groups and clusters. The hypothesis of tidal destruction of wide pairs in systems gives us an estimate of the system mass, which satisfactorily agrees with the virial mass.

e) The RMS difference of radial velocities for catalogued binary galaxies is 170 km/s. Nearly the same value (194 km/s) was obtained by Davis and Peebles (1983) from the CfA survey data. Using a relation between distance modulus and average velocity for nearby pairs we estimated the value of peculiar motions of their centers: $\sigma(v_p) < 80$ km/s. In the picture of galaxian gravitational clustering (Turner $et\ al.$, 1979), this estimate corresponds to an open cosmological model with density parameter $\Omega_0 < 0.1$.

6. ANGULAR MOMENTA

To understand the conditions of formation and dynamical evolution of binary systems, data on the magnitudes and mutual orientations of angular momenta of galaxies in pairs have principle significance. Until recently, this question did not attract proper attention. Because of the almost circular character of their motions, double galaxies possess large orbital momentum. In 75% of catalogued pairs the orbital momentum exceeds the value of total rotational momentum for our Galaxy.

The relation $\mu_{12} = |K_{12}|/[|K_1| + |K_2|]$ between a pair's orbital momentum value and the sum of spins of pair components essentially depends on galaxy structural type (see Figure 8). Double systems of spiral galaxies possess relative momentum $\mu_{12} \approx 1.3 - 2.5$, pairs with galaxies of Sm type occupy the region $\mu_{12} \approx 1$, and for double elliptical galaxies the main part of angular momentum is caused by orbital motions ($\mu_{12} \approx 10$).

In almost all scenarios of galaxy formation some preferred orientation of orbital and spin momenta is predicted for binary galaxies. Attempts to find such tendencies were not successful. The distribution of pair components in position angle of major axes and inclination angle testifies to a chaotic orientation of rotation vectors. Some authors' indications of excess numbers of pairs with antiparallel spins (Helou, 1984) should be further tested in observations. An initial ordering of spins in binary galaxies might be destroyed due to loss of mass and angular momentum during a stage of violent dynamic evolution. A notable part might be played by precession and nutation processes. Thus, for spiral galaxies in contact pairs a typical precession period is only 2×10^9 years.

7. ON THE RATE OF DYNAMICAL EVOLUTION

Galaxies in double systems reveal mutual correlation in almost all their integral properties : luminosity, linear diameter, structural type, mass-to-luminosity ratio, angular momentum etc.. Relationship of components according to these parameters is not due only to observational selection, but has a physical basis. As the above-mentioned features characterize the global structure of a galaxy, it seems improbable that such resemblance might appear in pair components during the process of their common evolution. Without risk of serious error, we may suppose that the structural similarity of binary galaxies is

caused by similar conditions in which the system components were being formed.
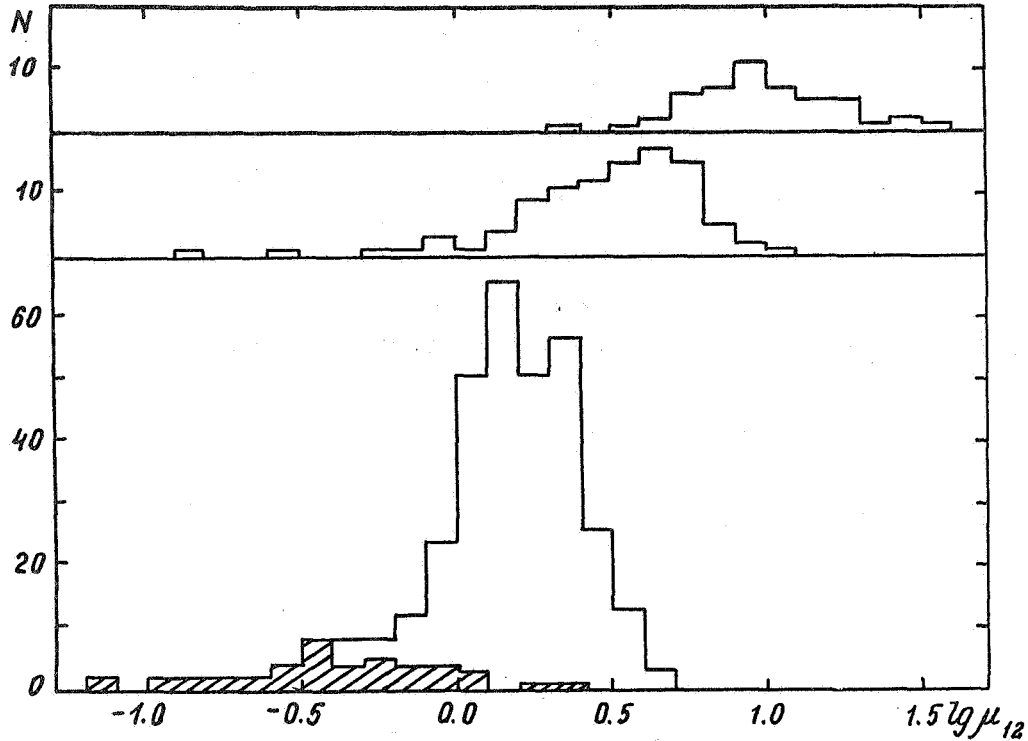

Fig. 8. Distribution of binary systems according to the ratio of their orbital momentum to sum of spins . From bottom to top, pairs with SS, SE and EE components, relatively, are shown. Pairs consisting of one or two Sm galaxies are hatched.

Along with signs of "genetic", relic relationship, binary galaxies show positive correlations of spectral types (emission features) and color indexes. An approach to common values of these properties should apparently take place under active coevolution subject to mutual tidal perturbation (the gaseous component of a galaxy is dynamically more active than the stellar one).

Numerical experiments conducted by Toomre and Toomre (1972), White (1978), and other authors, pointed out the important role of dynamical friction in double galaxies' evolution. After approaching to a distance equal to the sum of their diameters, pair members manage to perform only 2-3 damping revolutions and merge into a single system.

Ostriker and Turner (1979) drew attention to the fact that pairs with large massive components merge fastest. For reason, a lack of giant galaxies among tight binary systems should be observed. As is seen from Figure 9 such an effect for the catalogued pairs is really present, but is hard to distinguish from a result of the selection criterion.

The process of dynamical friction may lead to a specific evolutionaary selection of pairs acording to their orbital eccentrity. If an elongated orbit and small perigalaxian distance favour a merging, then only binary systems with mainly circular orbits survive to the present epoch.

According to the data of Figure 10, the median orbital period for the pair members is $\tau_m = 0.06$ in units of cosmological age H^{-1} . As the merging time exceeds the orbital
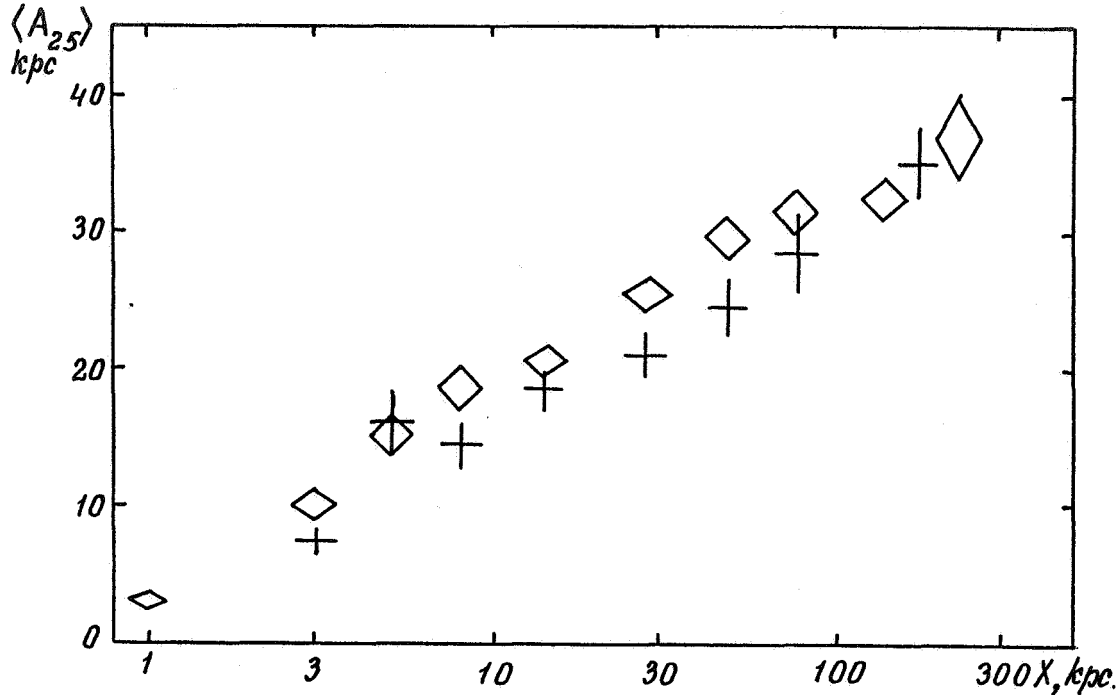
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Fig. 9. Dependence of average linear diameter of pair components on their projected separation. Rhomboids show catalogued pairs, crosses simulated pairs. For the simulated pairs the "diameter versus separation" correlation is caused exclusively by selection effects.

period by only 2-3 times, during $\tau_m = 0.1 - 0.3$ most of the catalogued pairs should become single objects. Such a short scale for merging of double galaxies is argued thus: during $\tau = 1$ the merging process would lead to an irreversible accumulation of single galaxies in numbers significantly exceeding the observed relative number $\delta_1 < 0.05$ of isolated galaxies. However, this is only an apparent contradiction, as binary systems' distribution is subject to a general law of hierarchical clustering. Having experienced merging, pairs in groups and clusters do not become isolated objects of a metagalactic field.

With the relative abundance of binary galaxies $\delta_2 = 0.12$ and characteristic merging scale $\tau_m = 0.2$ the expected number of merging acts per galaxy is $< m > \approx 0.6$ during the cosmological time $\tau = 1$. If in earlier epochs the pair merging rate was higher, by the present time many galaxies should be considered to have experienced several mergers. Indirect affirmation may be provided by the increased number of blue objects among faint remote galaxies (Zepf and Koo, 1989). During their merging, double galaxies experienced bursts of star formation, becoming bluer and thereby more notable at large distances.

If many galaxies possess extended massive coronae, their presence should accelerate a merging process. As a result, a peculiar evolutionary selection might appear: we observe binary systems without coronae now, because their merging rate is not so high as in the rest of galaxies.

These discussions give us a picture of rather violent dynamical evolution of galaxies and their systems, where the most active role belongs to double galaxies. To understand to what extent this scenario is justified, further observational efforts are needed.
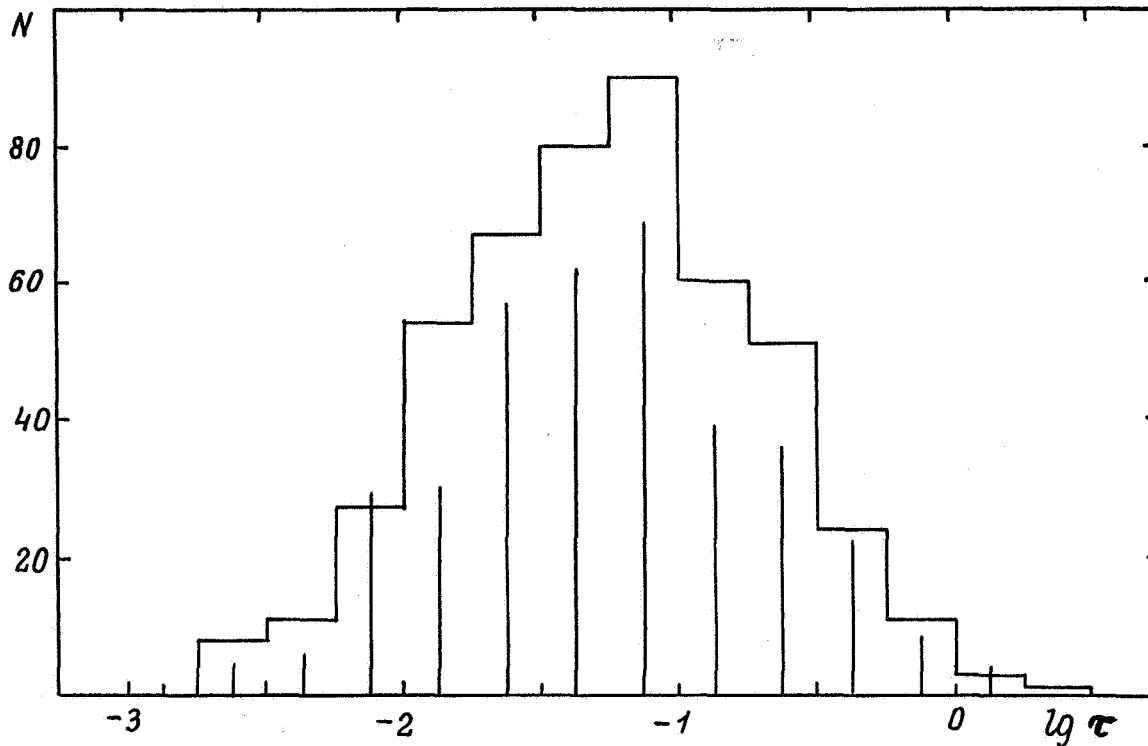
Fig.10. Distribution of isolated pairs according to their dimensionless orbital period, expressed in the units of inverse value of the Hubble constant. Histogram - period estimations based on separations and luminosities of binary galaxies, vertical segments - estimates using separations and radial velocity differences.

8. CONCLUDING REMARKS

Until recently, simulations of dynamical phenomena in pairs of galaxies were limited by rather primitive schemes: single encounter event, a single-component structure of galaxies and ignoring the role of collective processes. There is a pressing need to perform numerical experiments accounting for the kinematic properties of flat and spheroidal components of double galaxies, and also the presence of gas in their disks. Many double galaxies have inner rotation periods close to their orbital period. The characteristic time of a burst of star formation is of the same order, when triggered in galactic disks because of mutual tides. Coincidence of three characteristic times may lead to the intensifying and interweaving of various resonance effects. Therefore, active synchronous evolution of binary galaxies may proceed far from the evolution tracks of single galaxies.

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DISCUSSION

Miller: There are many spiral-spiral pairs in your catalog. A simple observational feature is the number of pairs in which both members have the same sense of spiral pattern as contrasted with the number in which they have the opposite sense of pattern. This relates to the question of whether galaxy rotation might result from gravitational torques.

Karachentsev: Among 54 physical ($\Delta V_{12} < 500$ km/s) SS-pairs with distinct spiral patterns for both components, there are 17 cases with the same sense (9 SS and 8 ZZ) and 37 ones with the opposite senses (17 SZ and 20 ZS).

Xu: While the entire CPG catalog is homogeneous, we found that the E + E subsample is highly inhomogeneous. There is a strong concentration of E + E pairs around $V_r \sim 7000$ km/sec. Could you explain the reason for this effect?

Hickson: Your binaries seem to be very uniformly distributed on the sky, and you mentioned that they avoid clusters. Could this be a result of your isolation criterion?

Karachentsev: Yes, this is one of probable reasons of the effect. Another one may be related to a tidal disruption of wide pairs inside dense regions of clusters. As a matter of fact, tidal mass estimations for the Coma and Virgo clusters are in good agreement with their virial masses.

Roos: Several of your conclusions depend on the orbital angular momentum of the pairs in your catalogue. You found a mean value of the orbital eccentricity of only ~0.25. Could you give us an estimate of the width of the distribution of ellipticities?

Karachentsev: According to my data, for the observed sample of 487 binaries their <u>mean</u> value of orbital eccentricity lies in the interval 0 to 0.55.

Chatterjee: What is the observational value of the frequency of merging galaxies in the present and past epoch?
A comment: most of the mergers take place in 2 to 3 orbital periods. The first orbit affects the circularization.

Karachentsev: Two observational quantities, the relative number of binary galaxies ($\delta_2 = 0.12$) and the typical merger time scale ($t_m \simeq 0.2\ H^{-1}$) , give us a characteristic number of mergers, $\langle m \rangle \simeq \delta_2 / \tau_m \simeq 0.6$, per galaxy during the H^{-1} time. Taking into account the possibility of more favorable conditions for a merger in the past (small mutual separations, much more orbits with high eccentricity), the true cumulative frequency of mergers may be as high as $\langle m \rangle > 1$.