Some Thoughts on Dynamical Evolution of Galaxies

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Ways of dynamical evolution of galaxies as systems of gravitating point masses are qualitively discussed. The equations of gross-dynamics (generalizing the Lagrange—Jacobi equation) are suggested for describing large-scale evolution. Under an additional condition of quasi-homologicity a system exerts undamping oscillations. Possible stochasticity of such oscillations may be one of mechanisms of violent relaxation.

1. We shall consider galaxies as statistical ensembles of N gravitating point masses. Their dynamical evolution is governed by smoothed or regular forces, and random or irregular forces due to close stellar encounters. It is known that the timescale of regular forces is the so-called crossing time, equal to the typical period of star motions in the system (e. g. Ogorodnikov 1965). It is more important that the crossing time of a gravitating system has an order of a period of its collective oscillations relative an equilibrium (e. g. Lynden-Bell 1967, Chandrasekhar & Elbert 1972).

According to the classical theory of irregular forces developed by Jeans, Chandrasekhar and others, the timescale of irregular forces (the relaxation time) has an order of N (or $N/\ \ln N$) times of the crossing time for non-rotating systems, i.e. it is practically infinite. So, galaxies are considered as collisionless systems, and irregular forces are not taken into account.

There were many attempts to shorten the effective timescale of irregular forces. An interesting approach was developed by Gurzadyan & Savvidy (1986) who tried to combine the statistical consideration by Chandrasekhar & von Neumann with ideas of the ergodic theory. Following it, Rastorguev & Sementsov (2006) and Ossipkov (2008) has shown that an effective stochastization time in non-rotating systems is of the same order as the crossing time. That coincides with results of numerical simulations by Kandrup (1990) and others. The smoothed field can accelerate the relaxation process. An effective relaxation time was found by Genkin (1969) (and also by Kurth (1972)) but it is not confirmed yet by direct simulations.

We can conclude that we cannot ignore irregular forces when we discuss the secular evolution of galaxies. But it seems that the large-scale structure of galaxies is due to collisionless evolution mainly.

2. Gross-dynamic equations for gravitating systems can serve for studying the large-scale evolution of galaxies (Ossipkov 2004a). For spherical systems it is enough to restrict ourselves with the well-known Lagrange-Jacobi equation combined with the energy conservation. Let a be an inertia radius and R be a gravitational radius (the equilibrium velocity dispersion is equal to GM/R). We suppose that a/R is constant. That means that the evolution is quasi-homological and the “halo-core structure” does not appear. Then the Lagrange-Jacobi equation can be qualitevely analyzed and solved (Chandrasekhar & Elbert 1972, Ferronsky *et al.* 1979, Ossipkov 1981, David & Theuns 1989). Negative energy systems will oscillate without any damping. A period of oscillations depends on energy of the system. So, the large-scale evolution of such systems seems to be deterministic without violent relaxation (Ossipkov 1985b). Such evolution was found in simulations by David & Theuns (1989) and Miller & Smith (1994). It is not difficult to construct series of mass distribution models along which a/R is constant (Garcia Lambas *et al*. 1985, Ossipkov 2004b).

The only possibility for irreversibility lies in formation of the "halo-core" structure when *a/R* is not constant. Intuitively we can expect that amplitude of oscillations will decrease, and at last the system will be almost steady. To study this process it is possible to represent a spherical system as a set of concentric shells (Campbell 1962, Henon 1964, Bisnovatyi-Kogan & Yangurazova 1984, Barkov *et al*. 2002, Bisnovatyi-Kogan 2002). It is interesting that vibrations of shells were found to be chaotic under some conditions (Barkov *et al*. 2002). An alternative method is to consider a system as an ensemble of concentric spheres (Danilov 1983, Ossipkov & Shoshin 2004). Interaction of spheres (or shells) can be considered as one of realizations of Lynden-Bell's (1967) idea of violent relaxation. Such evolution is a kind of compulsive mixing (Antonov *et al*. 1973, 1995).

Actually, when a potential energy changes periodically, a potential of regular forces is not constant, of course, and its time dependence is close to periodic, too. (Antonov & Nuritdinov (1975) found an exact model of a homogeneous pulsating sphere.) So, any star exerts almost periodic pushes in course of its travel in the galaxy. Its motion can become chaotic (e. g. Zaslavsky 1998) that provides irreversible changes in velocity distribution (Terzic, Kandrup 2004). But details of such process were not studied yet, as I can judge.

3. Let us discuss axisymmetric galaxies. Then the problem is reduced to studying a dynamical system with two degrees of freedom. Various ways of closing the gross-dynamic equations were discussed by Ossipkov (1985a) and Fu & Sun (1999). An analysis of linearized equations has shown a stability of equilibrium (when the virial theorem is fulfilled) (Fu & Sun 1999, Ossipkov 2000). What will be with non-linear oscillations? Unfortunately, the problem is not studied yet. But chaotic non-linear oscillations were found for some special cases (Som Sunder & Kochnar 1985, 1987, Malkov 2001, Omarov & Malkov 2004). In general, dynamical systems with two degrees of freedom are not integrable, and chaotic orbits exist. The latter means that chaotic large-scale oscillations of axisymmetric galaxies are possible. Probably, damping such oscillations will be a result of non-linear interaction of modes of oscillations. They will not be quasi-homological. At last, the system will reach a steady state.

We can expect that evolutionary history of triaxial galaxies will be similar. Maybe, oscillations of such galaxies will be more chaotic.

4. If the above considerations are correct, we can suggested the following qualitive picture of dynamical evolution of *isolated(!)* galaxies (taking into account ideas by Eddington 1921, Kurth 1949, Kuzmin 1957, Agekian 1960, Henon 1964, Pucacco 1992 and others). Probably, at first a galaxy will collapse, as it was discussed by many authors. Then it will expand, collapse again etc. Such oscillations will become quasi-homological. If a galaxy was gaseous, it will loose some part of its energy, and amplitude of its oscillations will decrease (Ossipkov & Starkov 1986). Star formation will be the most intensive when the sizes of the galaxy will be minimal. So, we can expect several peaks in age distribution of stars (Ossipkov 1985c). Star orbits will be chaotic under action of the time-dependent potential of regular forces. Some stars will be thrown out of the pulsating system and form a halo (Chernin's idea, see Antonov *et al.* (1975), Theuns & David (1990)). At the same time some irreversible changes will appear at the microscopic level as results of far encounters. When oscillations of the potential become chaotic (for non-spherical galaxies) the equations of star motion will be stochastic. That means the fast stochastization of the galaxy and irreversibility at the microscopic level. At last oscillations will stop, and the further evolution is reduced to the collisional relaxation in the regular field.

We did not discuss the stability problem for galaxies. It is known that relaxation on density waves is possible, and it will accelerate the irreversible evolution.

Of course, galaxy interaction is one the most important factors of their dynamical evolution. It is believed that elliptical galaxies formed as results of merging. But even relatively weak but chaotic interactions of three or more galaxies will provide their stochastization as it was qualitively discussed by Chernin *et al.* (2002) (see also Kandrup 2001). Equations of star motion in a galaxy under joint action of its own pulsating potential and random external forces will be stochastic equations. Unfortunately, such equations were used very rarely in galactic dynamics and mainly in the simplest form of the Langevin equations (e. g. Saslaw 1987).

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