Few-Body Problem: Theory and Computer Simulations
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Strong three-body interactions in centers of galaxies - Arp 5, 87, 240, 335 and NGC 4314

Joanna Anosova

University of Texas

Abstract. Many violent and/or complicated phenomena take place on many scales in the Universe. Many of these phenomena may be caused by multiple centers of gravitational attraction: planetary rings, accretion discs of various scales, peculiar structures of single galaxies and interacting galaxies. We show that various features of celestial objects can be understood by assuming the existence of two dominating gravitational centers of attraction.

1. Introduction

This review presents results of numerical studies of strong Newtonian interactions of bodies in the centers of stellar systems. In the frame of the general three-body problem, Professor T. A. Agekian, J. Anosova, V. Orlov, and N. Zavalov obtain these results in the St. Petersburg University over many years (see Anosova, 1986 and references therein). Anosova and Anandarao (1994), Anosova and Tanikawa (1995) and Anosova and Benedict (2000) apply these results to numerical studies of structures in galaxies.

We study numerically the dynamical evolution of models of stellar systems which contain two dominant centers of gravity and extended shells inside and around the orbits of these binaries. Initially the binary components are surrounded by numerous low-mass particles with small initial velocities. It is shown that at some point collapse of these particles on to the heavier components of the binary takes place, at which time we see strong interactions of the bodies. Frequently, the 'gravitational slingshot' effect occurs. Further along in time, some part of the particles, which initially were outside the binary orbit, escape from the system. Other particles are captured by binary components, forming in the center a 'dumb-bell' type bar. During the evolution of our models, different types of structure emerge, often very similar to the observed structures of galaxies: be they spiral and elliptical galaxies, interacting galaxies, or different types of flows and jets. Globally, the systems are expanding. The formation of different kinds of structure in galaxies depends on the motions of low-mass particles with respect to the line of apses of the heavy nuclear binary:

- in the case of almost orthogonal motion (the gravitational slingshot effect), these particles escape from systems and before an escape, form open expanding spirals;

- in the alternative case, these particles are captured by the binary components;
- in intermediate cases, particles form different kinds of flows, jets, rings, and close spirals.

2. Dynamical studies

About 50% of disk galaxies have a central bar in the disk plane. Bars can be found in all types of disk galaxies, from the earliest to the latest stages of the Hubble sequence. A barred galaxy may also contain a spheroidal bulge at its centre, spirals in the outer and inner disc and other features, including multiple nuclei, inner and outer rings and lenses. Symmetry and asymmetry in both the light and kinematics are quite common. The velocities in the barred region manifest strong non-circular streaming motions, with the major axes of the orbits elongated along the bar.

Most dynamical studies via computer simulations of these complicated systems have been in the fields of hydrodynamics, gravitational potential theory, the theory of stellar orbits, as well as the gravitational N-body problem for large N (see Binney and Tremaine 1987 and references therein). Many of these dynamical studies have assumed collisionless systems. But we are still far from a complete understanding of the dynamical structure and the kinematics of barred galaxies and their features.

Anosova and Tanikawa (1995) and Anosova and Benedict (2000) showed that various structures observed in celestial objects can be generated by simply assuming the existence of two dominating centers of attraction rather than one. In these works we have studied the dynamical evolution of a model, which can be seen as representing galaxies with central massive binaries (black holes) surrounded by relatively low-mass particles, which could be star clusters or gas and dust complexes. We carried out computer simulations in the framework of the N-body problem, taking into account strong interactions of the bodies: we studied the dynamics of these models, considering several tens of thousands of initial conditions for the general three-body problem and compiling them.

This model can be compared with that used by Murai and Fujimoto (1980) and Lin and Lynden-Bell (1982). Valtonen (1984a,b; 1985), Valtonen and Byrd (1976, 1986), Toomre and Toomre (1972), Lin and Saslaw (1972), Basi et al. (1993) and Yoshida and Keiichi (1996) — see Anosova and Benedict (2000), Valtonen (2005) and references therein.

3. Description of the present model — method

Valtonen (1984, 1985), Valtonen and Byrd (1979, 1986) and Toomre and Toomre (1972) had considered only a single approach by the two massive bodies because their relative motions were parabolic, hyperbolic or highly elliptic. The massless tracer particles also could have one approach with each massive body.

In contrast, Anosova et al. (1995, 2000) consider a central massive binary with a circular orbit. This is a long-living binary system. Low-mass particles may interact with this binary nucleus many times during the dynamical evolution of the entire system. In such models the 'gravitational slingshot' effect occurs many times, especially under total collapse of the system of low-mass particles.

The basic aim of the present work is to construct dynamical models for identification of possible processes that lead to the formation of structures observed in real galaxies. Our model permits us to inspect structures in the models in 6-dimensional coordinate and velocity space. We studied the dynamical evolution of all spherical shells together and separately. Using our method, we take into account the close double and triple approaches of the bodies and are able to consider their individual trajectories. Multiple runs of the model allow us to classify the numerous strong triple interactions of bodies (the binary components with small-mass particles) resulting in various structures of models.

The parameters of the model are as follows:

- The binary system has components with masses M_1 and M_2; the orbit is circular; the semi-major axis is a. The ratio of masses $k = M_2/M_1$ is varied in $[0.1, 1.0]$.
- Dynamical system of units : the unit of distance is $a = 1$; unit of time is the period $P = 1$ of the binary; the gravitational constant $G = 1$.
- The model of shells: low mass M_i particles are distributed randomly with uniform density on shells with initial radius R_0, on each shell the number of particles $N = 1000$.
- The initial velocities of particles $V_0 = S_0 \times V_{\rm esc}$ where $V_{\rm esc}$ is the critical velocity of the bodies. The critical velocity $V_{\rm esc} = [2G(M_1 + M_2)/R_0]^{1/2}$. We consider values of S_0 in the interval $[0.0, 1.0)$.
- We carry out numerical integration of the regularized equations of motion of the bodies in the three-body problem, using the code due to Aarseth and Zare (1974) during the time $T_{ev} = 40P$ of the dynamical evolution of our models. Altogether, we considered 19 shells (separately and together) with radii R_0 in the interval $[0.25, 50.00]$ with different combinations of k and S_0; the total number of particles $N = 1000000$.
- Our models contain N low-mass M_i particles, which do not interact with each other; and this number N is large. Therefore, to approximate self-consistant models, we need to consider a sufficiently small value of the ratio $q = M_i/M_1$. We carried out the trial calculations with the values of q : 0.000001, 0.0001, 0.001, 0.01.

For these values of q we obtained almost the same results, but the CPU-time increases crucially with decreasing q. For basic calculations we use the ratio $q = M_i/M_1 = 0.01$.

4. Results — comparison with observed galaxies

We follow the time-dependent evolution of these models (for each individual shell and for the ensemble of all shells) and compare the resulting structures with several such structures as observed in the galaxies Arp 5, 87, 240, 335 and NGC 4314. We find some combination of the initial conditions and model parameters that produces at some time T_c similar structure and velocity fields (for NGC 4314-see Anosova, Benedict 2000) as that found in these galaxies.

Figs. 1a-5a present the dynamical evolution of models with given initial parameters $R_0 = R$, $V_0 = V$, M_2, $M_i = M_3$, N, $T_{ev} = P_f$ during the time of the system evolution P_f, where P is a period of rotation of the massive nuclear binary black hole; $t_0 = 0.00$ is the initial time of the evolution, dt is the time span when a model structure is fixed. These figures present 10 snapshots of the evolution of the structure of the model over this time span. Fig.1b-5b show the photographs of observed galaxies Arp 5, 87, 240, 335 and NGC 4314. Comparison of the structures of our models shows that, at some time, the modeled and observed structures are similar.

5. Dynamical explanations

The detail investigation of trajectories of low mass particles shows that in our models we often observe nearly simultaneous approaches of low mass bodies to the center of mass of the binary. Basic results of such approaches are as follows:

- as a consequence, numerous low-mass particles escape from the system; before escaping, these particles form flows like open spirals.
- particles with lower velocities return to the center of the system; then, flows with the appearance of jets, rings and closed spirals form.
- particles which initially were inside the binary orbit, form a stable central dumbbell bar.
- symmetrical structures appear in models with equal mass bodies of the central binary.

6. Conclusion

We conclude that the evolution of a simple model of the N-body system containing a massive nuclear binary can generate structure similar to that observed in the galaxies Arp 5, 87, 240, 335, NGC 4314. We have determined initial conditions in such models. We show the past and future evolution of these models.

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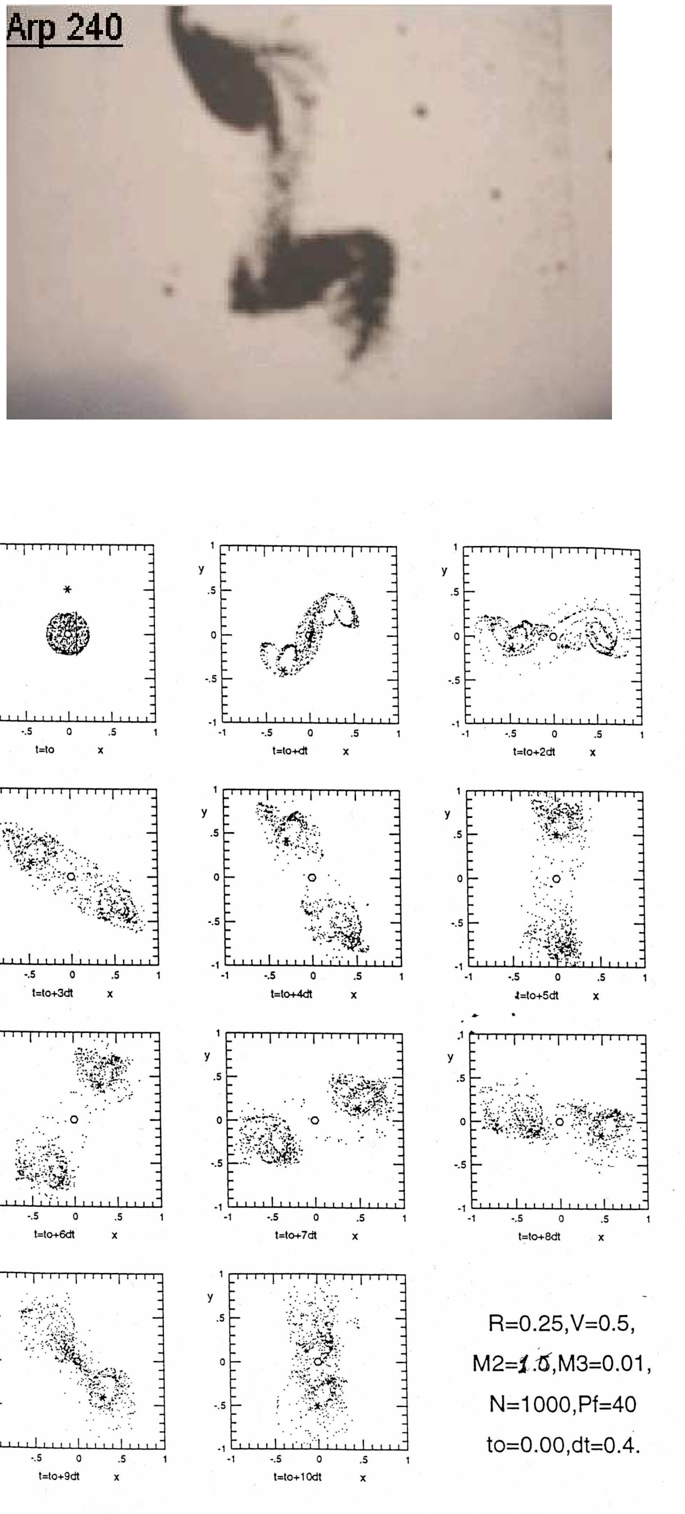

Figure 1. The galaxy Arp 240, and the dynamical evolution of a model with the parameters: $R = 0.25, V = 0.5, M_2 = 2.0, M_3 = 0.01, N = 1000, P_f = 40, t_0 = 0.00, dt = 0.4$.

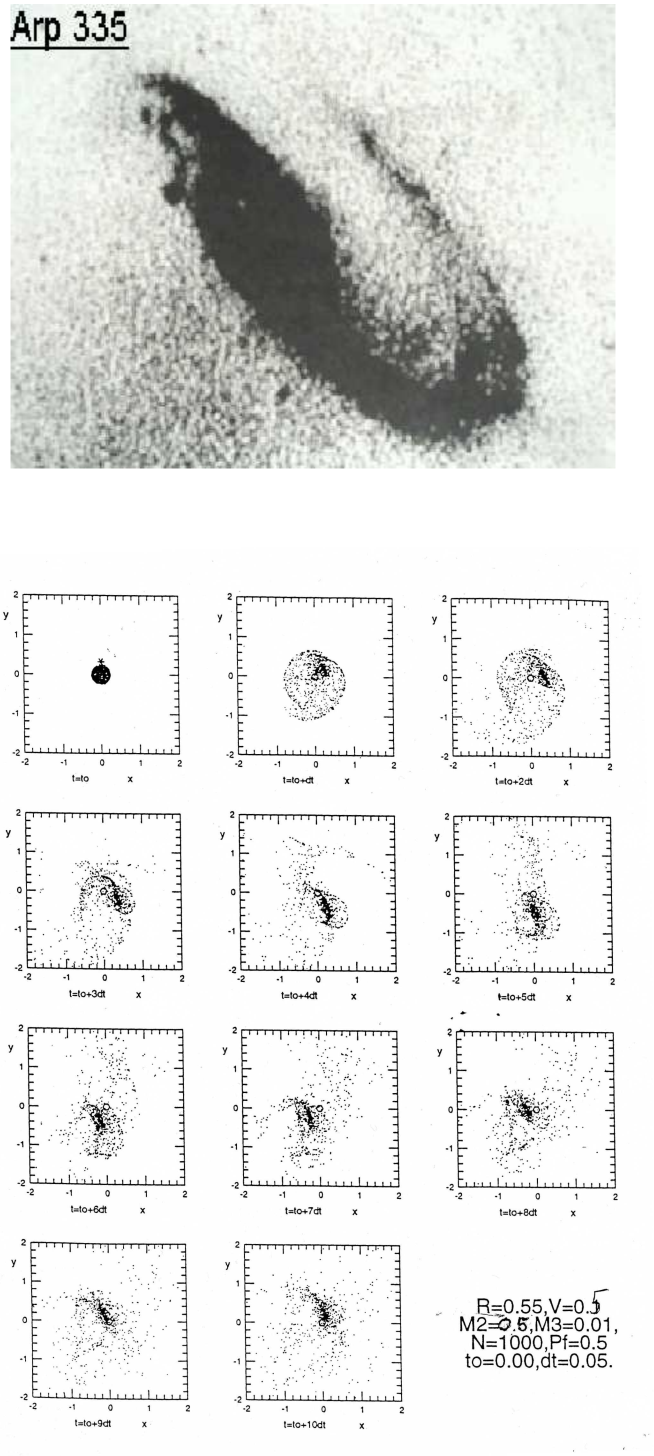

Figure 2. The galaxy Arp 335, and the dynamical evolution of a model with the parameters: $R = 0.55, V = 0.5, M_2 = 0.5, M_3 = 0.01, N = 1000, P_f = 0.5, t_0 = 0.00, dt = 0.05$.

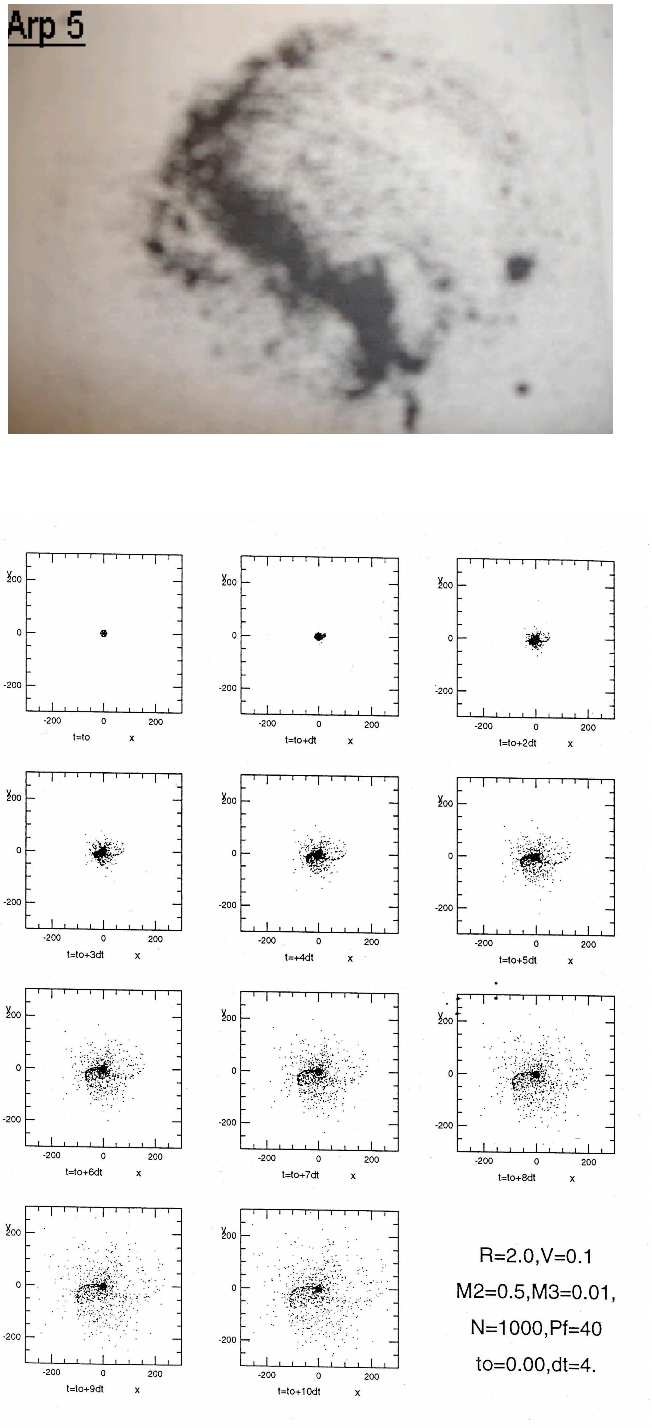

Figure 3. The galaxy Arp 5, and the dynamical evolution of a model with the parameters: $R = 2.0, V = 0.1, M_2 = 0.5, M_3 = 0.01, N = 1000, P_f = 40, t_0 = 0.00, dt = 4.0$.

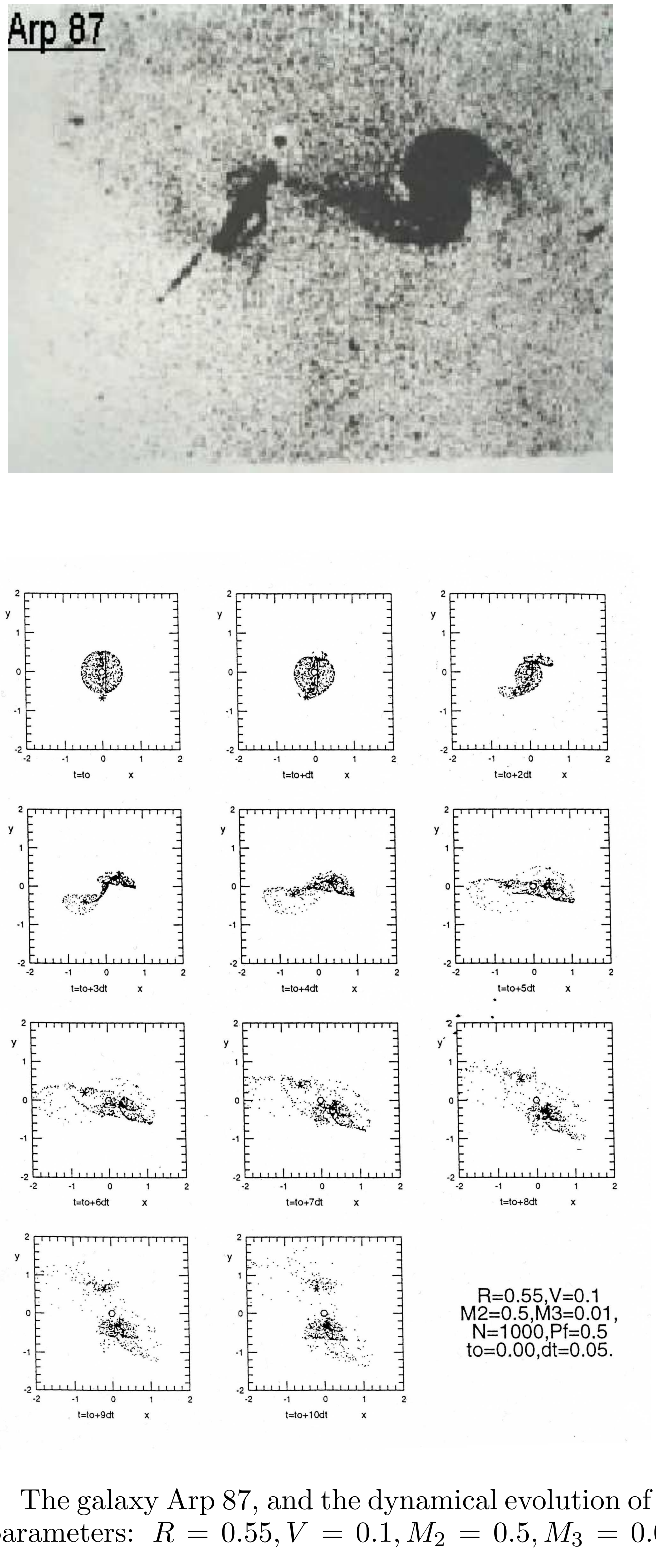

Figure 4. The galaxy Arp 87, and the dynamical evolution of a model with the parameters: $R = 0.55, V = 0.1, M_2 = 0.5, M_3 = 0.01, N = 1000, P_f = 0.5, t_0 = 0.00, dt = 0.05$.

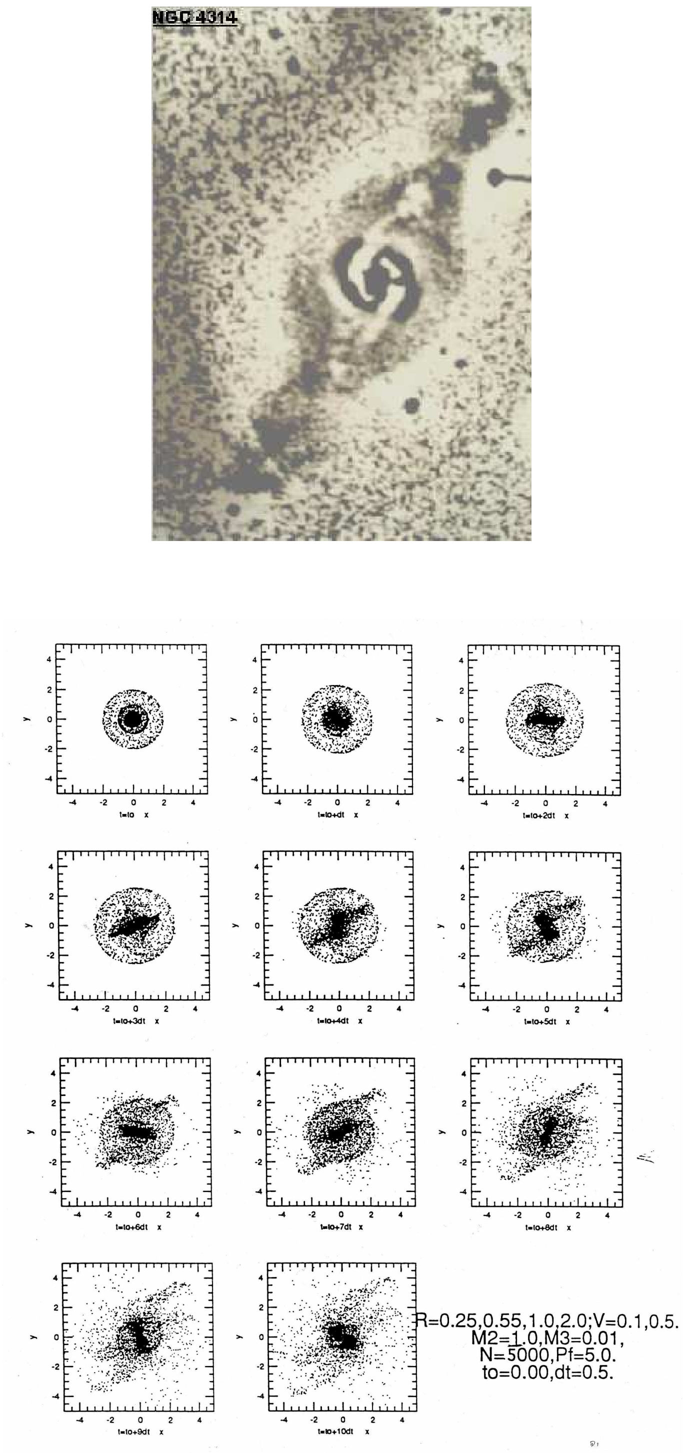

Figure 5. The galaxy NGC 4314, and the dynamical evolution of a model with the parameters: $R = 0.25, 0.55, 1.0, 2.0; V = 0.1, 0.5; M_2 = 1.0, M_3 = 0.01, N = 5000, P_f = 5.0, t_0 = 0.00, dt = 0.5$.