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Formation of Triaxial Galaxy*

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Abstract

Results of N-body simulation of dissipationless cold collapse of spherical gravitating system are presented. We compared the results with properties of elliptical galxies. The system gradually evolved to triaxial system. The projected density profile is in good agreement with the de Vaucouleurs' r¼ law and the velocity dispersion profile is consistent with observations. In addition to triaxial instability, it seems that there is another instability.

I. Introduction

Radial changes of ellipticity and isophote twistes in some elliptical galaxies have been reported by a number of authors (Cater 1978; Strom and Strom 1978; King 1978; Bertola and Galletta 1979; Williams and Schwartzschild 1979). These phenomena are important because they contain information about the three dimensional shapes of the galaxies. It can be easily shown that if any galaxy is triaxial, then the observed isophote will have radial changes of ellipticity and twisting of the axes at most viewing angles. Many theoretical arguments suggest that such systems can have triaxial forms in the most general cass (Binney and de Vaucouleurs 1981; Binggeli 1980; Noerdlinger 1979).

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Previous numerical models of elliptical galxies (Gott 1975; Larson 1975) predicted good fits to several properties of elliptical galaxies. Those models are based on the assumption that flattening of elliptical galaxies is due to rotation. Naturally, these models predict high rotation velocity that is against observations (Bertola and Capaccioli 1975; Illingworth 1977). On the other hand, there are some alternatives in which its flattening do not depend on rotation (Binney 1976; Aarseth and Binney 1978).

Equilibrium models describing elliptical galaxies are often found to be unstable. Especially, any model in which radial orbits are dominant is imposed upon triaxial type instability (Merritt and Aguilar 1985; Barnes et al. 1986). So, it is natural to think that radial collapse would have such a type of instability and to wonder at what point during the formation of such a galaxy the instability would take an active role in determining its shape. A promising line of such an inquiry is suggested by the results of Merritt and Aguilar (1985). However, they did not compare their results with observations. The possibility that the instability would determine the shapes of elliptical galaxies is not fully answered until now.

The purpose of the present paper is to investigate the possibility that realistic elliptical galaxies can be formed by the instability. We will present simple qualitative comparisons with observations. In section II, we will address numerical techniques and initial conditions, and in section III, results and comparisions with observations followed by discussion and conclusions.

II. Numerical techniques and Initial conditions

We have converted a plasma physics electrostatic code to a gravitational N-body code for our purpose. The code has particle mesh scheme and incorporates finite-size particles of Gaussian shapes with scale a length which is usually the order of Debye length in plasma physics, but is merely a softning parameter in gravitating systems. The use of finite-size particles eliminates the singular behavior of the point particles in the short range interactions. The fast Fourier transformation (FFT) and linear interpolation algolithm have been used to evaluate the potential, and the leap-frog scheme has been employed to integrate the equation of motion.

We have assumed initially very cold spherical stellar system which is presumed to develope some kinds of dynamical instability because of the predominance of radial orbits during the collapse. We have used 8000 particles in a 3-dimensional (32x32x32) cartesian grid. The particles have been seeded uniformly within a radius 7 (in units of grid size) and have a Maxwellian velocity distribution with $|2T/W| \simeq 0.03$, where T and W is the total kinetic and potential energy, respectively. The time step for the integration is fixed at $\Delta t=0.002t_0$ throughout the calculation. The time unit t_0 here is defined by $t_0=(4\pi G\rho_0)^{-1/2}$ in order of 10^8 years where ρ_0 is the initial mean density of the system. The energy conservation per integration time step was better than 0.01% during the rapid collapse phase and become better than 0.001% afterwards.

We haveadopted very simple initial condition because our purpose is to investigate another possibility of formation of triaxial type galaxy via cold collapse. Effects of another assumptions (expanding boundary, cosmic infall, initial clumpiness, angular momentum, etc.) are elsewhere. The currently popular theories for the formation of galaxies predict that galaxies would be formed from the amalgation of smaller lumps rather than uniform cloud and that most protogalactic pertubation would presumably be non-spherical. On the other hand, we can not exclude galaxy formation discussed here.

III. Results and Comparisons with Observations

The evolution of this system is shown in Fig. 1, which is the projected shapes of particles on x-y plane or y-z, z-x plane in order to see 3-dimensional shapes of the system. The bar shape begins to develope at $t \simeq 2.6$ and becomes prominant at $t \simeq 4.2$. We have continued this calculation up to t=8.0, but the shapes do not significantly vary except slight development of triaxiality.

At first, the system experiences overall contraction, then center is highly condensed continuing contraction, but as a counter part expanding outer halo is formed. After this stage, core collapse and expansion are repeated until $t \simeq 2.0$. This process is reminiscent of gravothermal instability (Bettwieser and Sugimoto 1984) occuring in core of globular clusters at post collapse stage. It is, however, uncertain wheather this phenomena is numerical effect or intrinsic properties of collisionless gravitating system. Then, bar is formed abruptly and gradually developed, and finally fixed in triaxial shape. Overall evolution of this system is very similar to that of Merritt and Aguilar's results (1985).

Radial density profile (Fig. 2) is more or less steeper than r^{-3} profile and in outer parts density decreases rapidly. Radial velocity dispersion profile is presented in Fig. 3. In order to compare our results with observations we have projected density and velocity dispersion profile into each plane. Each projected density profile (Fig. 4) is well approximated to $r^{1/4}$ law in the intermediate parts. It is shown that projected density profile has one form regardless of projected direction. Velocity dispersion profile (Fig. 5) is similar to Binney's calculations (1980) using tensor virial theorem. The value in each projected plane is different in the sense that the longest axis has the largest value. This fact indicates that triaxial shape of the system is retained by anisotropy and that heating ratio of each axis is different.

We represent the $r\text{-}v_r$ phase diagram in Fig. 6 and Fig. 7. Fig. 6 is very similar to self-similar solution of gravitational collapse in an expanding universe (Fillmore and Goldreich 1984). Fig. 7 shows that there is a kind of instability even though in these stages, the system is very stable in its forms, and it is unlikely that this instability has numerical origin.

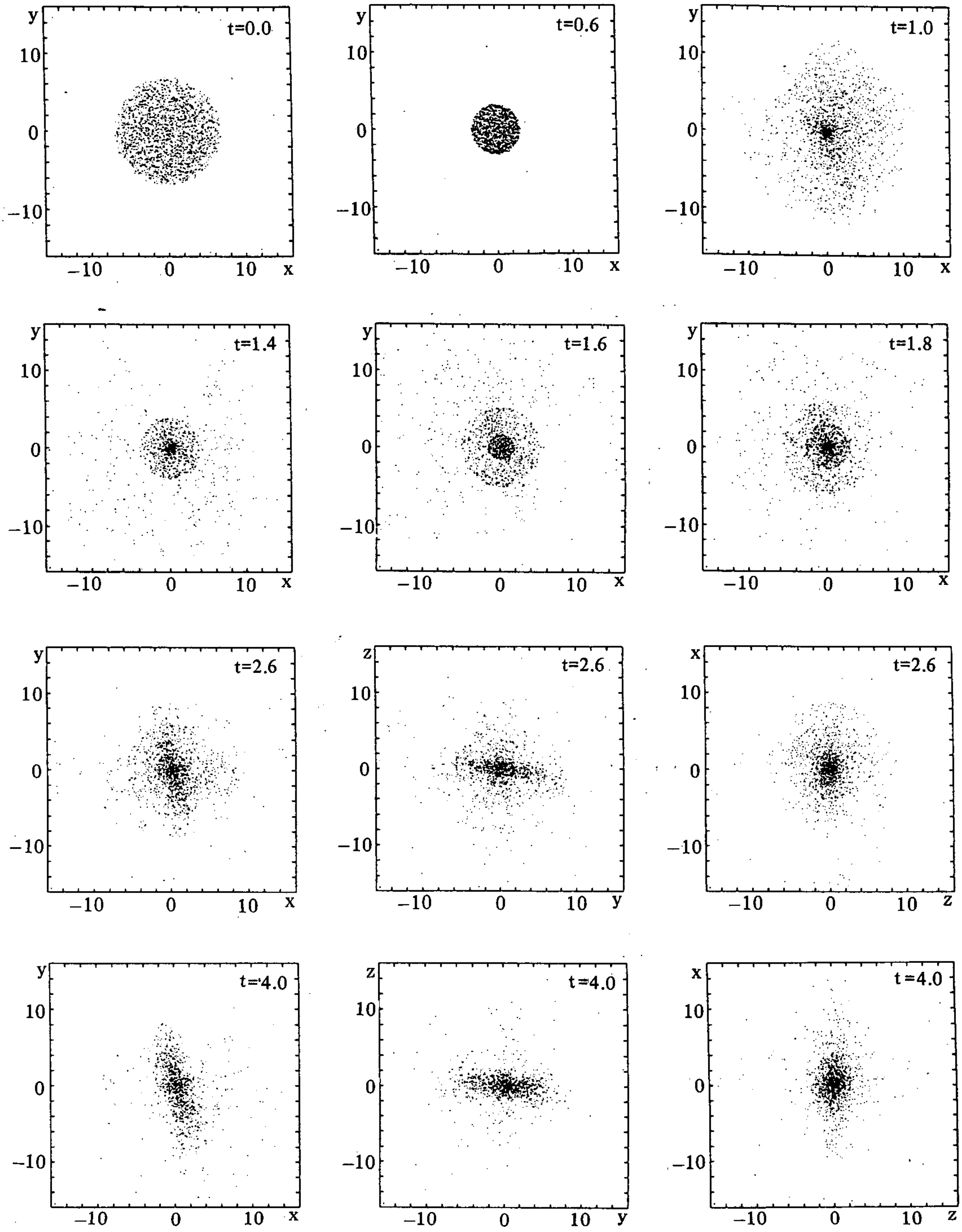
Another diagnostics are needed in order to fully describe the system. More extensive and comprehensive analyses, however, are postponed to following papers.

IV. Discussion

If initial temperature is very low, N-body simulation of collapising protogalaxy yield density distribution in good agreement with the de Vaucouleurs' $r^{1/4}$ law (van Albada 1982), and Merritt and Aguilar (1985) argued that the instability criterion is $|2T/W| \quad 0.2$. We have chosen the initial condition satisfying this criterion. van Albada (1982) treated this instability in a simple fashion and Merritt and Aguilar did not compare their results with observations. Our results indicates that the instability occurs and thus formed galaxy is in good agreement with $r^{1/4}$ law. It is noted that regardless of projected direction, the projected density profile have generality. This fact shows why observed ellipticals have such general forms of density profiles and that violent relaxation process is very effective in forming general characteristics.

Velocity dispersion profile is decreasing outward, but there is no unique behavior in variation of velocity dispersion profile and observations are restricted within one effective radius. Our results are flat or increasing to one effective radius, then decreasing in outer parts, and it seems to be rather increasing in far out side similar to very anisotropic model of Efstathiou *et al.*(1982).

Barnes *et al.*(1986) reported the instability that they called as first kind of non-radial instability i.e. triaxial instability, which is evolved from radial orbit dominated equilibrium model. They analysed this instability analytically using periodic universe. According to their results, there is an unstable mode with wave number k if $\sigma_T < \sqrt{4\pi G\rho_0}/k$, and the system is stable against all modes if $\sigma_T{}^2 > G\rho_0 L^2/\pi$, where σ_T is the traverse velocity dispersion, ρ_0 is initial density, and L is the length of the system. Also, Polyachenko (1981) has reported a numerical simulation of this instability in a system of 300 softening particles.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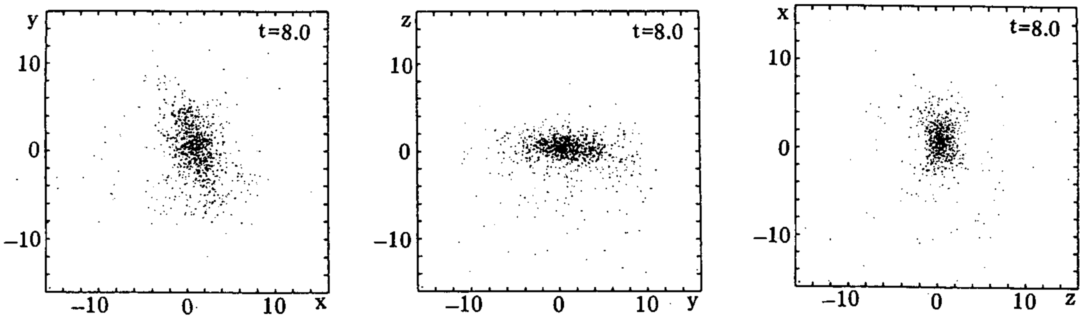

Fig. 1. Overall time evolution of the system. At t=2.6, 4.0 and 8.0, the system is projected in three directions in order to see its 3-dimensional shapes.

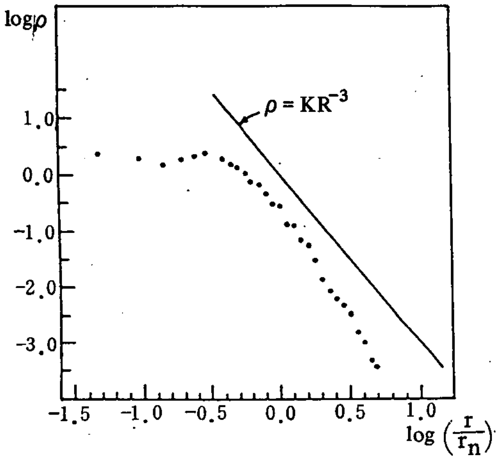

Fig. 2. Radial density distribution at t=8.0. R_h is a half-mass radius. We have drawn a line which is in proportion to r^{-3} for the comparison.

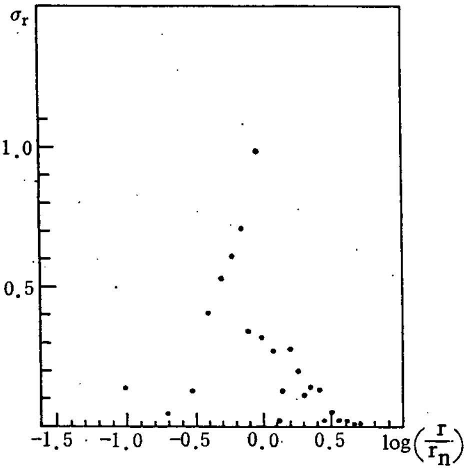

Fig. 3. Radial velocity dispersion distribution at t=8.0.

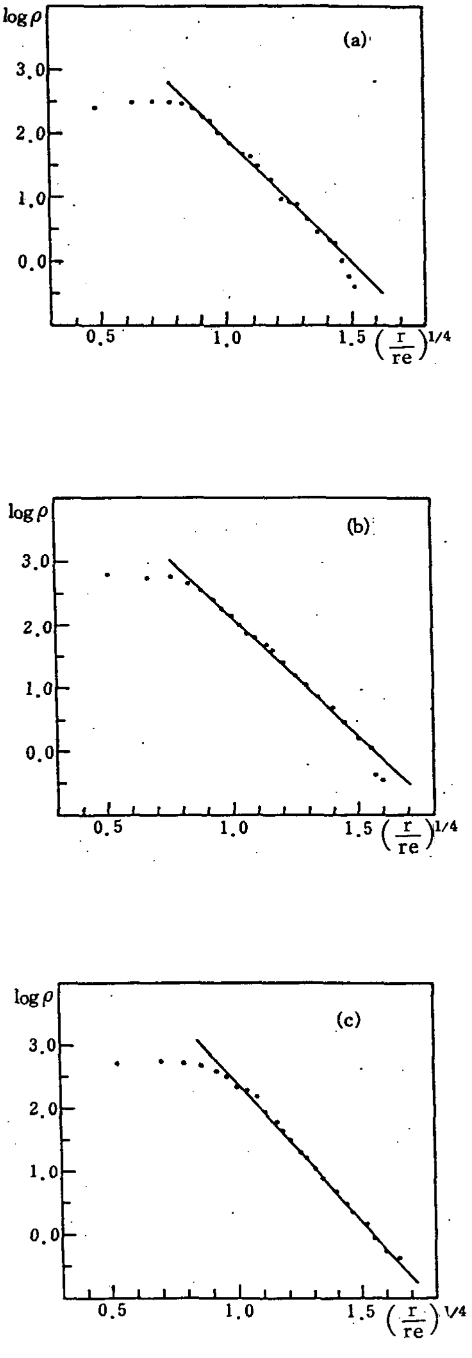

Fig. 4. Projected density distribution. A strsight line is in proportion to $r.^{1/4}$ (a) x-y plane (b) y-z plane (c) z-x plane at t=8.0.

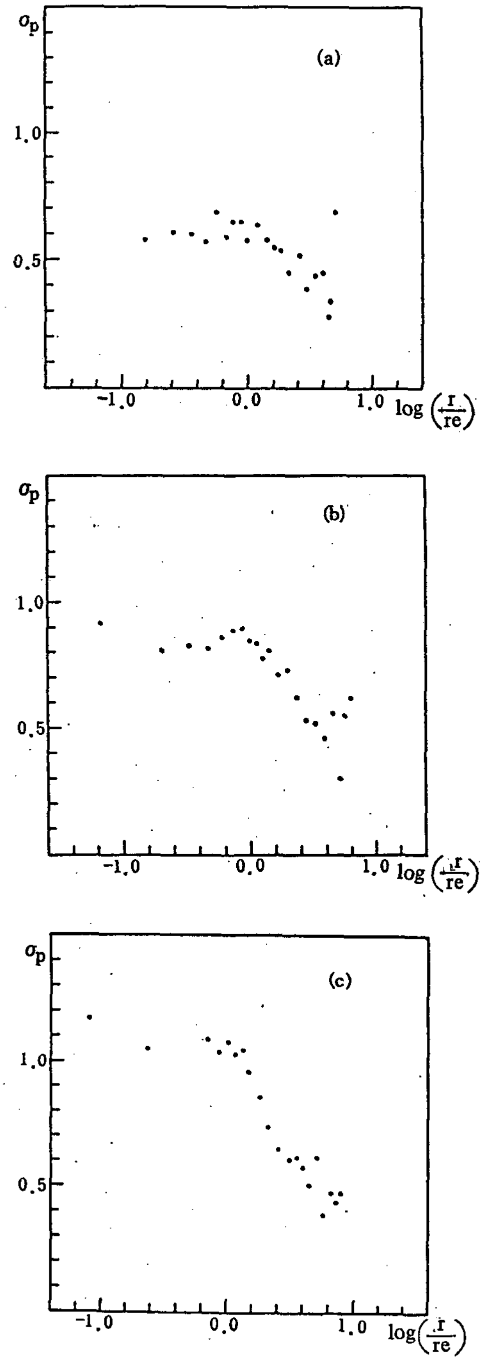

Fig. 5. Projected velocity dispersion distribution. (a) along z direction (b) along x direction (c) along y direction at t=8.0.

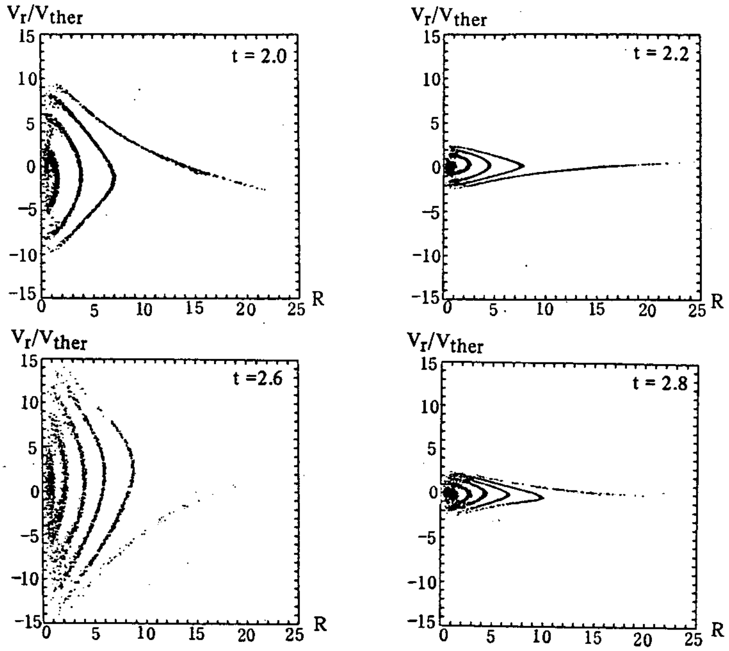

Fig. 6. R-V_r phase diagram at early stages.

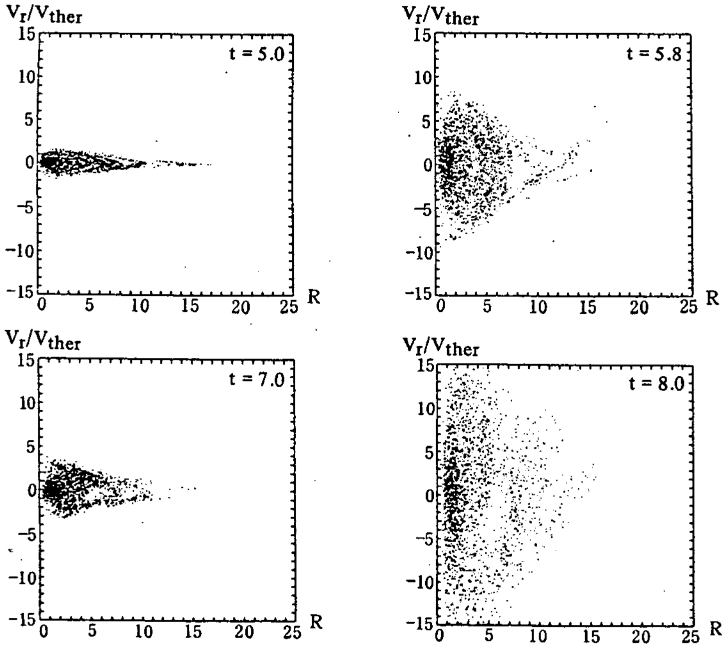

Fig 7 R-V_r phase diagram at late steady stages.

After the system reached to steady state, it seems to exist another dynamical instability which is illustrated in Fig. 7. After t=4.0, it seems that overall shapes of the system do not significantly vary, but its internal dynamics is not completely in stable state. The possibility that this instability has numerical origin exists, but in order to resolve this problem more detailed analysis of our code is needed. If this instability is intrinsic properties of the system, it is very interesting to find its astrophysical meaning. Our following paper will consider this problem in more comprehensive respect.

In summary, our results of N-body simulation about the formation of triaxial type galaxy is in good agreement with the surface density profile and the velocity dispersion profile of real elliptical galaxies, and there is a possibility being another kind of instability although it is not resolved accurately. Initial condition of low temperature is possibly necessary to form a triaxial type galaxy.

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