ASTRONOMY 506 Spring 2008 Instructor: Anatoly Klypin

Part I : STELLAR DYNAMICS
Part II: HYDRODYNAMICS

Midterm: 11 March. It is a written exam: two questions and two problems to solve
Final : 8 May. It will be an a written exam: short questions and two problems to solve

Project: Study dynamical evolution of a gravitational system of few thousand particles using provided N-body code. Chose one of the following projects:

(1) Dynamical friction: Motion of a massive "satellite" in a halo. Study changes of the orbit (radius, angular momentum, eccentricity) of a massive particle moving in the halo made of 20,000 small particles. Compare results with theoretical predictions. What happens to the halo when the satellites sinks to the center of the system? Where the angular momentum of the satellite is deposited? How energy of halo particles changes? The halo ("galaxy") is a spherically symmetric non-rotating object in equilibrium. Run two models with different initial eccentricities.

(2) Violent relaxation in a simple system ("Formation of a galaxy cluster"). Set initial out-of-equilibrium system and study its subsequent evolution. Analyze the evolution of the distribution of angular momenta of particles. Estimate the time-scale of the violent relaxation and compare it with the dynamical time-scale of the initial system. How many particles become unbound? What is the density profile of the final equilibrium system? Use two initial configurations with 30,000 equal-mass particles.

(3) Collision and merging of two "elliptical galaxies". Prepare two equilibrium systems of 10,000 particles each. Put them in an orbit. Study the merging process. What is the density profile of the final system? How much does it change as compared with the initial profile? What happens with the angular momentum of the system? What fraction of particles and angular momentum escapes? What is the distribution of the angular momentum of the final configuration? Run two models with different orbit parameters.

(4) Testing monolithic collapse scenario. This used to be one of the main scenario for formation of galaxies. According to this scenario bulges and elliptical galaxies were formed in short initial stage when galaxy collapsed from a large quasi-homogeneous initial cloud. Let's test it using n-body simulations. We know how an elliptical galaxy should look like. It should have a mass of about $10^{12}M_{\odot}$. The central velocity dispersion should be about 200 km/s (give an take few dozen km/s). The central region of the galaxy should be relatively compact (2-5kpc) followed by halo where density declines as $\propto r^{-4}$. In the central region the density increased with declining radius as $\propto r^{-1}$. Set initial conditions for 20,000 particles in a homogeneous sphere. Initial velocities of particles are very small. Let the system evolve and relax. Study

the density and rms velocity profile of the relaxed system. Try to find whether there is a way to scale the system so that it matches properties of elliptical galaxies.

(5) Use your n-body code to study evolution of a simplified model of proto-Solar system: 10,000 objects orbiting a massive central object. How orbital parameters of particles change? What are the effects of placing relatively massive objects ("Jupiters") in the system? How orbit of "Jupiter" evolves when placed in relatively massive disk?

(6) Resonances in trans-neptunian objects. It is known that Pluto and a whole family of Kuiper-belt objects are in the resonance with Neptune. How this happens and what is the role of those resonances is the subject of this project. In this case only the large planets of the solar system are important as perturbers. We start by placing the large planets in circular orbits around the Sun. We also place a large number (hundreds) of Kuiper-belt objects outside of the Neptune orbit. Try first with placing the objects on (initial) circle orbits. Note that masses and interactions between the Kuiper-belt objects are negligible. Do not include those into calculations of forces. What will happen with the objects after a long period of time? Will some of the them be ejected? How orbital frequencies of the objects evolve? Accuracy of integration is very important for this project. Energy should be preserved with many digits.

You should use Fortran77, Fortran-90 or C
The project should be written as an article:

- Abstract
- Introduction
- Method and tests
- Analytical estimates
- Results
- Conclusions

You should use TEX or LATEX to format the text. Use supermongo or IDL to make plots.

Project is due 15 April

Homeworks will be given regularly.
Books: Handouts, lecture notes, and
Binney & Tremain "Galactic Dynamics"
Pringle & King "Astrophysical Flows

Grading: for AST506

25% for Homework	25% for Midterm	5% for class activity
25% for Project	25% for Final	

Grading: for AST406

33% for Homework	33% for Midterm	5% for class activity
33% for Final	20% extra credit for a simplified project.	

Part I: STELLAR DYNAMICS

(1) Programming.
(2) N-body problem: numerical methods.
(3) Gravitational potential. General results.
(4) Potentials of spherically symmetric systems.
(5) Potentials of non-spherically systems : general trends and general results.
(6) Motion of particles in a central force: basic equations and properties.
(7) Orbits of stars. Epicycle approximation.
(8) Virial theorem: derivation and limits of application
(9) Two-body relaxation: mechanism, different effects, time-scales.
(10) Two-body relaxation: more formal approach.
(11) Dynamical Friction: basic results and assumptions.
(12) Violent relaxation: basic ideas. Discussion
(13) Boltzman equation: distribution function, phase-space, mean velocity and "pressure".
(14) Boltzman equation: derivation and basic properties.

(15) Midterm
(16) Jeans equations.
(17) Jeans Instability. Toomre instability.

Part II: HYDRODYNAMICS

(1) Elements of Thermodynamics, gas cooling rates.
(2) Hydrodynamics: introduction. Continuity and Euler eqs.
(3) Energy equation.
(4) Lagrangian approach: simple solution for cold flow of gas.
(5) Bernoulli equation. Kelvin theorem.
(6) Propagation of waves: Jeans instability, sound.
(7) Shock waves I.
(8) Shock waves II.
(9) Instabilities
(10) Bondi flow
(11) Discussion