N-body/SPH and galaxy evolution

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Outline

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N-Body

The concept behind N-Body simulations

Simulations of dynamical system of particles

- Particles are under the influence of physical forces such as gravity
- Force exerted on each particle arises from its interaction with all the other particles

Two parts are essential to any N-Body code:

- The **force calculator routine**, which computes forces
- The **integrator**, which integrates the equations of motion

Force routine methods

Overview of force calculator methods

Compute forces from physical quantities (mass, charge, etc.)

- PP (Particle-Particle)
- PM (Particle-Mesh)
- Tree
- P^3M (Particle-Particle/Particle-Mesh)
- Fourier

Particle-Particle

Force routine methods

The force acting on particle i is computed using all the other particles.

$$\vec{F}_i = m_i \vec{a}_i = -\sum_{j \neq i} \frac{G m_i m_j}{r_{ij}^3} \vec{r_{ij}}$$

- Very straightforward
- Computationaly inefficient $\sim O(n^2)$
- Unappropiate to simulate large systems
- Cool enough for clusters and simulations of close-range dynamics

Particle-Mesh

Force routine methods

Space is divided up with a mesh of density values

- Particles no longer interact with other particles
- Potential energy of each point in the mesh calculated through FFT (Fast Fourier Transform) techniques

$$\nabla^2 \Phi = 4\pi G\rho$$

- Forces applied to particles based on the cell they're in
- More efficient than PP, usually $\sim$O(n+$n_g$log (n_g))
- Does not handle particle interactions
- Thus, it is obsolete to P^3M

Force superposition concept

- $F = F_{external} + F_{nearest\_neighbours} + F_{far\_field}$
- QuadTree in 2D, OctalTree in 3D
- Each node contains mass and position of subsquare CM
- $\sim$O(n log(n))

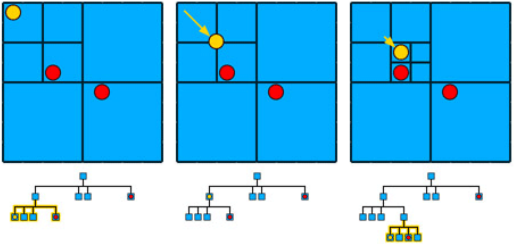

Figure: Quadtree evolution with time

Integrator methods

Overview of integrator methods

Various methods for integrating differential equations from forces to find out $x_i, \dot{x}_i, \ddot{x}_i$

- **Euler**, 1st order - Calculate all values at each time step
- **Leapfrog**, 2d order - Calculate velocities and positions interleaved in time
- **Runge-Kutta methods**
- **Symplectic integrators**, based on canonical transformations

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SPH
Smoothed-Particle Hydrodynamics

SPH is a computational method used to simulate fluid flows.

- Fluid is divided into a set of discrete elements, referred to as particles, from which continuous properties are derived
- Particles have a *smoothing length*, h, over which physical properties are smoothed by a kernel function, W
- Contribution of particle to a property weighted according to distance and density

$$F(r_i) = \sum_{j=1}^{n} F_j \frac{m_j}{\rho_j} W(|r_{ij}|, h_i)$$

W: Gaussian function, cubic spline, etc.

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Starting point
GADGET-2

The starting point is the GADGET-2 code for cosmological N-body/SPH simulations

- Collisionless fluid (stars, DM) computed with a **TreePM** n-body algorithm
  - **Tree** scheme used for short-range forces
  - **FFT-based PM** scheme used for long-range forces
- The collisional component (gas) is described using SPH

Outline

Modelling the galaxy evolution

Galactic evolution ingredients to add to our barebones code

- Radiative cooling
- Star formation
- Gas restitution
- Supernova energy feedback
- Chemical enrichment
- White Dwarf population
- AGN outflow

Radiative Cooling

Mechanism responsible (among others) for galaxy and star formation: collapse through internal energy decrease

- Variation of u due to expansions and contractions of gas and viscosity process (already in GADGET-2)
- Decrease of u due to radiative non conservative process of cooling

$$\left(\frac{du}{dt}\right) = \left(\frac{du}{dt}\right)_{vis} + \left(\frac{du}{dt}\right)_{rad}$$

$$\left(\frac{du}{dt}\right)_{vis} = -\frac{P}{\rho}\nabla \cdot v$$

$$\left(\frac{du}{dt}\right)_{rad} = -\frac{\Lambda(u,\rho)}{\rho}$$

Star formation (1/2)

Step 1 - Election of candidate particles

SF $\rightarrow$ convert gas particle to stellar particle. Conditions:

1. Gas particle must be shrinking

$$\nabla \cdot v_i < 0$$

2. Jeans criterion must be met locally: Gravity force larger than force due to pressure gradient

$$\frac{h_i}{c_i} > 1/\sqrt{4\pi G \rho_i}$$

3. When collapsing, the gas particle must not gain heat

Star formation (2/2)

Step 2 - Convert fluid element into stars

Particle i elegible to star formation if it satisfies conditions. Then, convert selected fluid particles into stars according to SF rate

$$\frac{d\rho_*}{dt} = -\frac{d\rho_g}{dt} = c_* \frac{\rho_g}{\tau_{ff}}$$

$$f = P(SF) = 1 - exp(-c_* \frac{\Delta t}{\tau_{ff}})$$

Gas restitution

How to model the return of enriched material from evolved stars to ISM

- $P[gas \rightarrow star] = SFR, \quad P[star \rightarrow gas] = ?$
- Stochastic algorithm, no instantaneous recycling of material
- Baryonic particle: Gas, Star, Remnant
- Considering $T = T_H - t_0$,

$$1 = \int_{m(T)}^{m_{max}} \Phi(m)dm + \int_{m_{min}}^{m(T)} \Phi(m)dm$$

- Divide SSP in $E_{SSP}(T)$, $R_{SSP}(T)$ and $LM_{SSP}(T)$. Draw $R_{and} in[0, 1]$

Supernova energy feedback

Energy released by SNe decreases SF efficiency (c_*) by means of:

- Destroying star forming clouds
- Generating supersonic turbulence
- Blow gas out of disc
- Number of SN produced in SSP of age t

$$N_{SN}(t) = \int_{max(m(t),m_{SN})}^{m_{max}} \frac{\Phi(m)}{m} dm$$

AGN outflow

SMBH may play an important role to outflow from galaxies that pollute IGM

- SNe not energetic enough to account for outflow
- Start simulation with BH seed that will accrete mass at a rate

$$\dot{M}_{BH} = \frac{4\pi\alpha G^2 M_{BH}^2 \rho}{(c_s^2 + v^2)^{3/2}}$$

- To compute this, a gas particle i around BH will be accreted with a probability

$$p_i = \frac{\omega_i \dot{M}_{BH} \Delta t}{\rho}$$

Conclusions

- N-Body simulations are more that just gravitational evolution of systems
- **N-Body/SPH GADGET-2** proved a worthy sandbox to test models of galactic evolution
- Current steady growth in computer power → increase in spatial & temporal resolution leading to more accurate simulations

References

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