SIMULATIONS OF LARGE-SCALE GASEOUS STRUCTURES WITH SPH

N.Ya. Sotnikova
Astronomical Institute of St.Petersburg State University,
St.Petersburg, Russia

ABSTRACT. A computer programme based on the 3D SPH approach is described. Some numerical results are presented: the formation of gaseous ring around an S0 galaxy due to the stripping of a gas-rich donor system. It is found that the ring structure strongly depends on the detailed structure of the recipient object. With the same impact parameters, rings forming around galaxies with a strong concentration of mass to the center should be less extended (on the average) than that around galaxies with a more gently sloping density profile. This inference explains in a quite natural manner the absence of extended polar rings around elliptical galaxies.

Key words: galaxies: general, interactions, kinematics and dynamics, peculiar

Method.

Many stellar systems contain a substantial amount of gas and gas dynamical processes play an important role in the evolution of these systems. Studying interacting galaxies we come across nonaxisymmetric and nonlinear phenomena and need to use complicated 3D gas dynamics models. One of the most fit tools to construct such models is the numerical technique. There are two main numerical approaches to solve the hydrodynamical equations. The first is based on finite-difference methods and uses a rigid grid. There is an alternate scheme, smoothed particle hydrodynamics (SPH), which has been introduced to avoid the limitations of grid-based codes. Originally proposed in (Lucy, 1977) and (Gingold and Monaghan, 1977), it has been considerably developed in the late eighties (e.g. (Hernquist and Katz, 1989), see also (Monaghan, 1992; Steinmetz and Muller, 1993).

The SPH algorithm is fully three-dimensional, flexible regarding the geometry of the gas distribution and consequently well-suited to modelling both the interacting galaxies and the empty extended space between them. It is based on an interpolation method which allows any gas dynamical value, $f(\vec{r})$, to be substituted for its smoothed value, $< f(\vec{r}) >$, which is expressed as

$$\langle f(\vec{r})\rangle = \int f(\vec{x}) W(\vec{r}-\vec{x};h) d\vec{x} . \qquad (1)$$

The smoothing kernel, $W(\vec{r})$, is normalized to 1, is sharply peaked about $\vec{r}=0$ in order to resemble a delta-function as $h \to 0$ and has a spherical geometry. The smoothing length, h, specifies the extent of the averaging volume.

The next step is the evaluation of the integral (1) by the Monte-Carlo method. If the values of $f(\vec{r})$ are known for N discrete points, distributed with number density $n(\vec{r})$, then $< f >$ for $\vec{r}_i$ can be evaluated as

$$\langle f(\vec{r}_i)\rangle = \sum_{j=1}^{N} \frac{f(\vec{r}_j)}{< n(\vec{r}_j) >} W(\vec{r}_i-\vec{r}_j;h) . \qquad (2)$$

The SPH method is a particle method. Nevertheless it treats the gas as a continuous medium. This medium is modeled as an ensemble of fluid elements - particles of the finite size. Each particle moves according the momentum equation, its velocity is the local fluid velocity and the particle mass density is proportional to the mass density of the fluid. Then, keeping in mind the properties of function $W(\vec{r})$, one can treated the procedure (2) as a local average of $f(\vec{r})$ performed over particle ensemble in the volume of $2h$ extent and h can be attributed as the particle size.

The smoothing formalism leads to the estimation of gradients of the local fluid properties by means of integral interpolant of $f(\vec{r})$ with the kernel $\nabla W(\vec{r}-\vec{x};h)$. Thus the equations of momentum and energy become sets of ordinary differential equations which are easy to solve.

There are some variants of SPH-equations. Our computer code is rather standard and is based on the numerical algorithm described in (Sotnikova, 1996). The motion of N particles, which represent elements of the continous gaseous medium, can be traced by means of the following equations

$$\rho_i = m \sum_j W(\vec{r}_i-\vec{r}_j;h) , \qquad (3)$$

$$\frac{d\vec{r}_i}{dt} = \vec{v}_i , \qquad (4)$$

$$\frac{d\vec{v}_i}{dt} = -m \sum_j \left(\frac{2\,c^2}{\sqrt{\rho_i \rho_j}} + Q_{ij} \right) \nabla_i W(\vec{r}_i-\vec{r}_j;h) - \nabla\Phi(\vec{r}_i) , \qquad (5)$$

where ρ_i is the local gas density, $\vec{r}_i$ and $\vec{v}_i$ are the spatial coordinate and velocity of i-th particle, m is the particle mass, $c = const$ is the isothermal speed of sound (we assume an isothermal equation of state) and Φ is the gravitational potential. The term Q_{ij} is the viscous contribution to the pressure gradient depending on the velocity field. For more detailed description of the adopted numerical scheme see (Sotnikova, 1996). The code was tested by applying to the shock and rarefaction wave propagation problem (for the case of the adiabatic gas). The test runs have satisfactory reproduced the exact solutions.

Numerical example. Polar ring formation.

Many S0 galaxies possess rings of gas-rich material that appear to be kinematically distinct from the galaxy properties. In these galaxies the material is located in a plane perpendicular to the main disk in a polar configuration (Whitemore et.al., 1990). It is generally assumed that they are of external origin. Two possible scenarios for such an acquisition process are: capture of gas-rich dwarfs and accretion of material during an encounter with a neighbouring galaxy (Schweizer et.al., 1983).

We have considered a distant parabolic encounter of equal-mass galaxies ($10^{11} M_\odot$), one of which is rich of gas. In the case of a distant encounter the effect of self-gravity may be ignored.

For simplicity the potential of the gas-rich galaxy was taken as that of a softened point mass with the softening scale length, a_1, to be equal to 1.5 kpc. $N = 10\,000$ particles are used to represent the gaseous medium. They are initially gathered in a thin disk with a $1/r$ distribution from a center of the donor galaxy up to outward radius 15 kpc and are placed in dynamically cold circular orbits. The total gas mass is $10^{10} M_\odot$. The used value of the gaseous particle size, h, which determines a numerical spatial resolution, is 300 pc.

The host-ring galaxy was represented by a second softened point mass. We have considered 2 models of a galaxy - with the softening scale length, a_2, 1.5 kpc and 3 kpc. So the first model imitates rather E galaxy with a strong mass concentration.

Two interacting galaxies are initially separated by a rather large distance (75 kpc) for tidal effects to be negligible. The host-ring galaxy passes in a zero-inclination (regarding the plane of a gaseous disk of the donor galaxy), prograde orbit (that is, the orbital angular momentum is parallel to the spin of the donor galaxy) with a pericenter distance 24 kpc.

During the encounter the galaxy strips the outskirts of the donor object and a narrow ring, rotating in the direction of the orbital motion, eventually forms around the galaxy in the encounter plane. The timescale of the ring formation is a few 10^8 years. The marked difference in the ring structure for two used models is the difference in the ring size which ranges from 6 kpc in diameter for $a_2 = 1.5$ kpc to 10 kpc for $a_2 = 3$ kpc.

This implies that under the same conditions rings forming around elliptical galaxies with a strong concentration of mass to the center should be less extended (on the average) – rather internal – than that around galaxies with a more gently sloping density profile. This inference explains in a quite natural manner the absence of extended polar rings around elliptical galaxies.

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