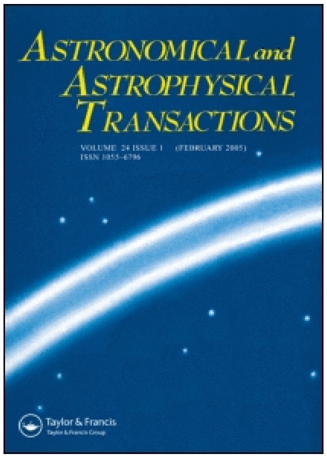

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RESPONSE OF THE GALACTIC GASEOUS DISC TO THE FLIGHT OF GLOBULAR CLUSTERS

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The response of the gaseous galaxy disc to the passage of globular clusters is studied in this paper. The initial Gaussian distribution of gas density in the vertical direction is perturbed by the gravity of the globular cluster. The cooling and heating processes in the gas are neglected. The process is followed through 2D hydrodynamic simulations. Since the globular cluster's velocity is supersonic it is essential to take into account the shock wave in the gas. This wave propagates in the disc up to distances of at least 4–5 times the vertical scales of the disc. The ultimate state of the gas is hot and turbulent in the cylindrical shocked region and has ring-like condensation around the remnant of the shock front. The intensity of response of the galaxy disc depends on the mass, size and velocity of the globular cluster. Thus the cluster–disc collisions may play an important role in star formation and galactic evolution.

KEY WORDS Disk galaxies, star formation, shock waves, galactic morphology

1 INTRODUCTION

It is well known that the star formation rate in disc galaxies is greater in an interacting companion galaxy (Kennicutt *et at.*, 1987; Bushouse, *et al.*, 1988) or developed density waves are present. In the case of an isolated galaxy without powerful spirals, local sites of star formation may be caused by interaction between the gaseous disc and strange objects such as high velocity clouds (HVCs) or globular clusters (GCs).

Both HVCs and GCs have the same masses and velocities on average but the results of their collisions with a galactic disc are very different. Upon collision, a HVC spends all its mass and kinetic energy and creates strong shocks in the galactic gaseous disc (Tenorio-Tagle *et al.*, 1987; Comerón and Torra, 1992; Lépine and Duvert, 1994a). Then the compressed gas collapses into stars in a short time. On the other hand, a GC passes through the gaseous disc without loss of mass and energy (in the zeroth approximation). Nevertheless the gaseous disc is disturbed by dynamical friction due to the gravitational field of the GC and such a mechanism can trigger local star formation nearby (Wallin *et al.*, 1996).

However, an essential fact was omitted in the last paper. The motion of a GC in the gaseous disc is supersonic with Mach numbers about 5–30. In this case the disturbance of the gas necessarily has the form of a shock wave (SW). Hence there will be more effective compression of the interstellar medium than that due to dynamical friction. I believe that the mechanism of shock generation rather than dynamical friction will trigger significant star formation. In this paper I present 2D hydrodynamic calculations of the response of a galactic gaseous disc to the passage of a GC. The morphology and evolution of shock waves are modelled in the simplest case of a non-cooling gas.

2 MODEL PARAMETERS

In order to get a clean effect let us neglect all secondary factors. We assume the GC is a material point moving perpendicular to the disc plane with constant velocity. Then we can use cylindrical coordinates $(r,\, z)$ with axis Oz along the trajectory of the GC. Let us take the gravitational potential of the GC in the form

$$\psi_s(r,z,t) = -\frac{Gm_s}{\sqrt{r^2 + (z - z_s(t))^2 + r_s^2}}, \quad z_s(t) = z_0 + V_s t,$$

where m_s, r_s are the mass and size of the GC and z_0, V_s are its initial location and velocity, respectively. The gas is assumed to be ideal with adiabatic index γ which is equal to 5/3. The initial equilibrium is supported by a stellar disc potential

$$\psi_0(z) = \Omega^2 z^2/2$$

and the distribution of the gas density has Gaussian form

$$\rho(z, t = 0) = \rho_0 \exp(-z^2/h^2)$$

with uniform temperature and sound speed c_0 distributions. It is convenient to adopt the convention that initial parameters of the gas are equal to unity: $h = 1$, $\rho_0 = 1$, $c_0 = 1$ and to imply the typical values $h \sim$ 50–500 pc, $\rho_0 \sim 1\text{–}10 \times 10^{-24}$ g cm^{-3}, $c_0 \sim$ 5–15 km s^{-1}. Then we have three governing dimensionless parameters: $M = V_s/c_0$ (Mach number), $M_s = Gm_s/c_0^2 h$, and $R_s = r_s/h$, which characterize the relative velocity, mass and size of the GC.

Hydrodynamical equations are solved by the simplest first-order upwind conservative code. Calculations were performed with a uniform $\Delta r = \Delta z = 0.05$ grid which covers the region $r < 10$, $|z| < 6$ (in dimensionless units). The initial conditions are a non-moving gas and location of the GC far from the disc. The boundary conditions are at $r = 10$ and $|z| = 6$ were chosen to be a solid surface. Such conditions allow stable calculations but lead to the appearance of reflected waves. To avoid the influence of boundary reflections on the numerical solution we (1) restrict the time of calculations and (2) show the solution only for the inner region $r < 5$, $|z| < 3$ before it is covered by the reflected shock waves.

3 RESULTS

Let us assume the basic set of parameters are $M = 5$, $M_s = 1$, and $R_s = 0.1$ which correspond to average values of $V_s \sim 50$–100 km s^{-1} $m_s \sim 1$–$2 \times 10^6 M_\odot$, and $r_s \sim 5$–10 pc.

The process has three apparent stages. In the first one, when the GC approaches the disc, we don't see any significant response in the gas except in the case of an extremely high mass of the GC. If $M_s \sim 10$ ($m_s \sim 10^7 M_\odot$) the gaseous disc slightly bends toward the GC before it enters the gas (Figure 5(a)).

At the second stage, when the GC moves inside the gaseous disc, the shock wave (SW) appears in the form of Mach's cone (Figures 1, 2). The upper point of the cone moves with the GC until it exits from the disc. However, if the velocity of the GC is low enough ($M \sim 2$) the apex of the cone may move ahead of the GC. In this case after the SW crosses the middle plane $z = 0$ it self-accelerates due to the motion in the descending density distribution (Figure 3).

At the last stage, when the GC moves away from the gaseous disc, the evolution of the gas is determined by the SW behaviour alone. The front of the SW propagates in the radial direction and changes its form. In the cross-section Qrz we can see in series "linear"-like ($r \sim z$, Figures 1(a), 2(b)), "hyperbola"-like ($r^2 - z^2 = \text{const}$, Figures 3(c), 5(c)) and "parabola"-like ($r - z^2 = \text{const}$, Figures 3(d), 5(d)) forms of the SW at different times. This effect is due to the slower motion of the SW in the middle plane because of the maximal unperturbed density of the gas. In the case of a low-velocity and/or massive GC it is possible that the GC captures gaseous masses and flies away with a gaseous "atmosphere" (Figures 3(d), 5(c)).

The perturbed motion of the gas is presented in Figure 4 for radial V_r and vertical V_z components. Alternating regions of positive and negative values correspond to complicated and vortex motion. The contrast of density in the SW depends on the parameters and was 2–30 in the different runs. If we take into account cooling and heating processes this result will be much greater due to additional compression of the shock layer.

In these calculations the SW reaches a distance of up to $r \sim 4$–5 before dissipation (or being covered by reflected waves). Thus a round region with diameter at least 8–10 of the vertical scales of the initial disc containing hot turbulent gas remains after SW dissipation. The remaining density distribution has a ring-like condensation around this hot "hole".

In general we will obtain the same evolution of the gaseous disc with practically any reasonable values of the governing parameters. The difference mainly consists in the intensity of response which grows with decreasing velocity M and size R_s and with increasing mass M_s of the GC. Note that all the above properties are relative values. Assuming the massive GC passes through a molecular cloud or another dense region of the galactic disc we obtain more serious consequences.

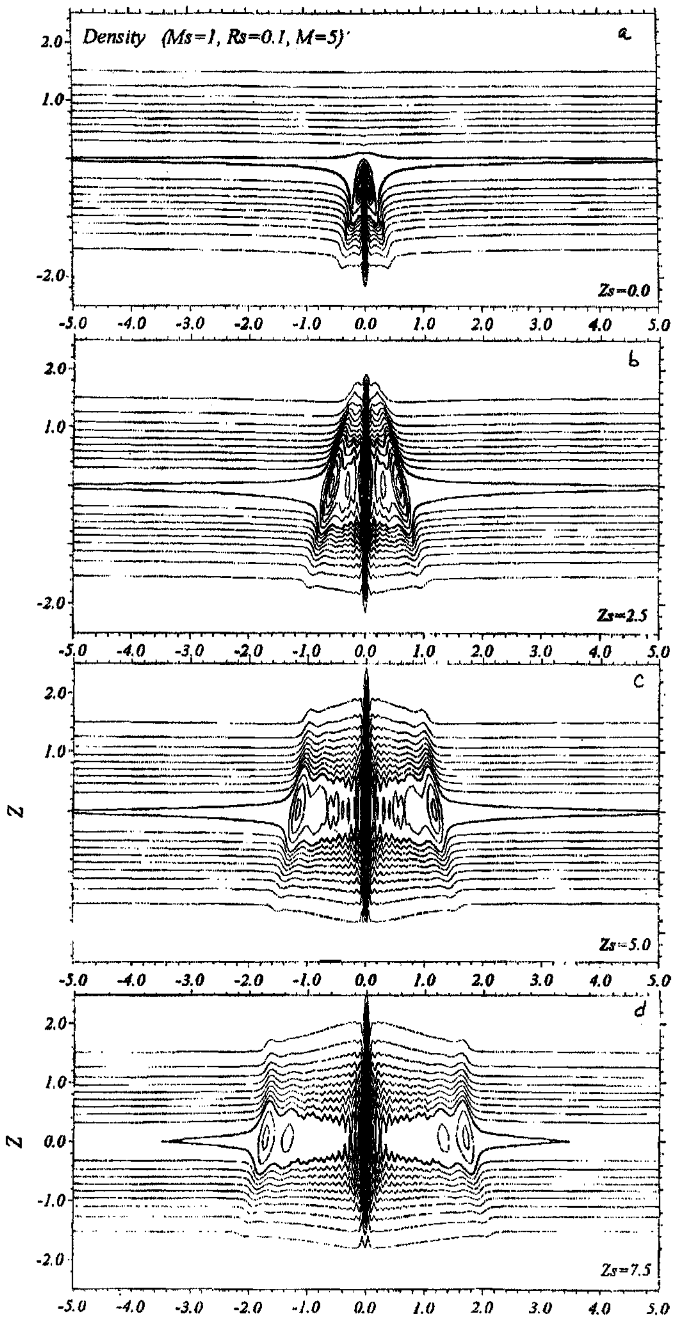

Figure 1 Evolution of gaseous density in the basic model with $M = 5$, $M_s = 1$ and $R_s = 0.1$. The level $\rho = 1$ is denoted by bold lines. The levels below are plotted with an interval 0.1, the levels above with an interval 0.5. The evolutionary time is shown in the lower right corner of each frame in terms of the current globular cluster's coordinate Z_s.

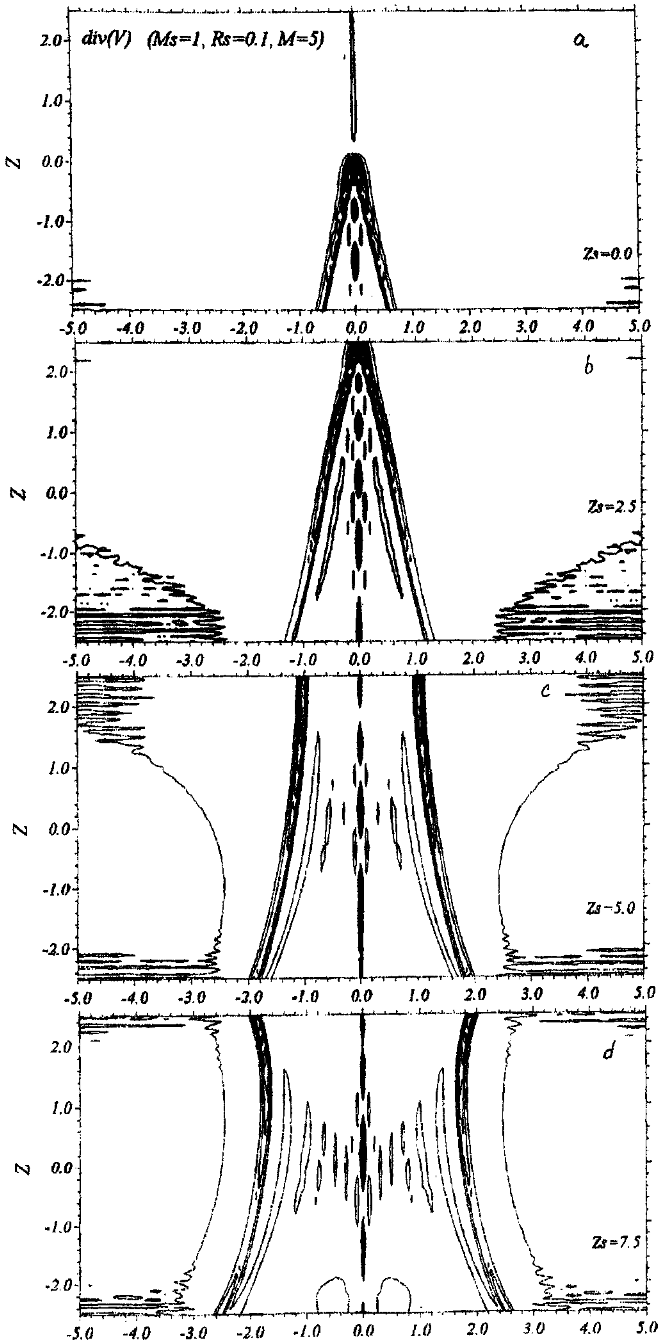

Figure 2 Same as Figure 1 for the quantity $\mathrm{div}(\boldsymbol{V}) = \partial(rV_r)/r\partial r + \partial V_z/dz$. Only non-positive levels are plotted with unity intervals to indicate the regions of most kinematic compression in the shock waves.

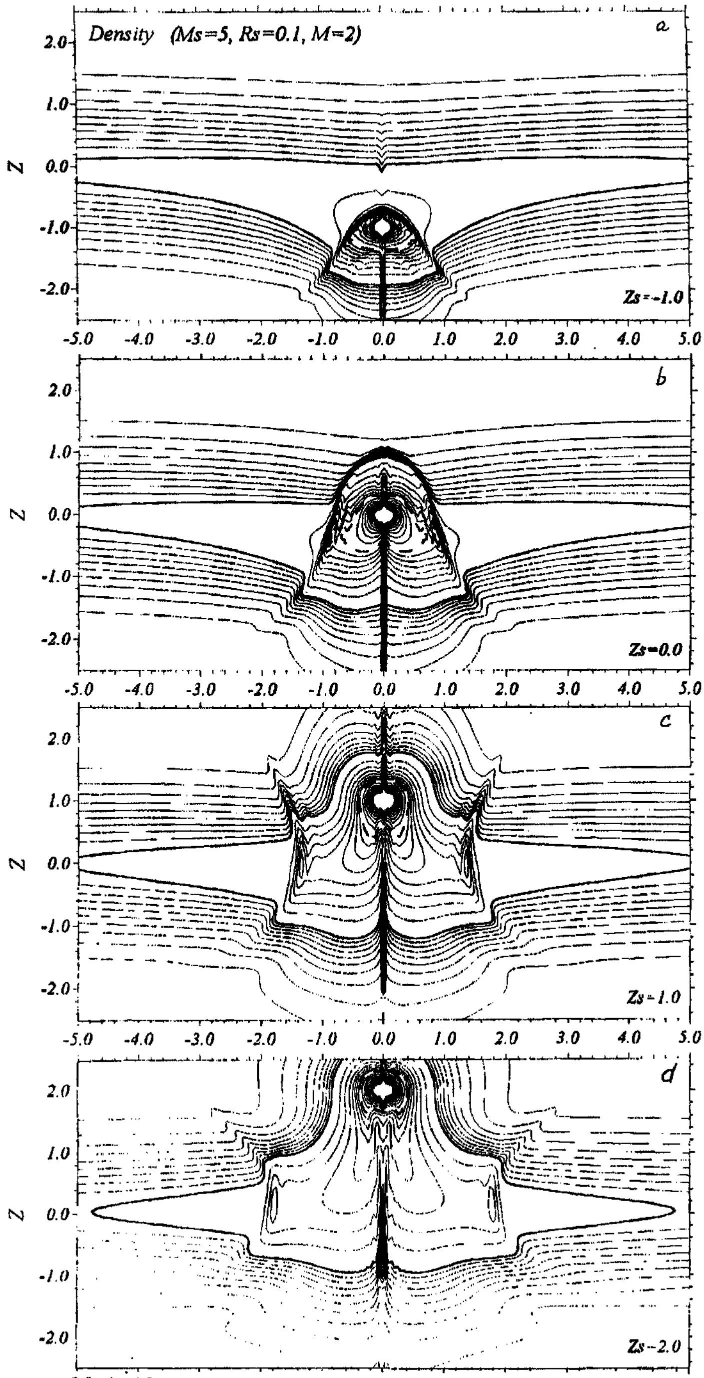

Figure 3 Same as Figure 1 for massive and low-velocity globular cluster.

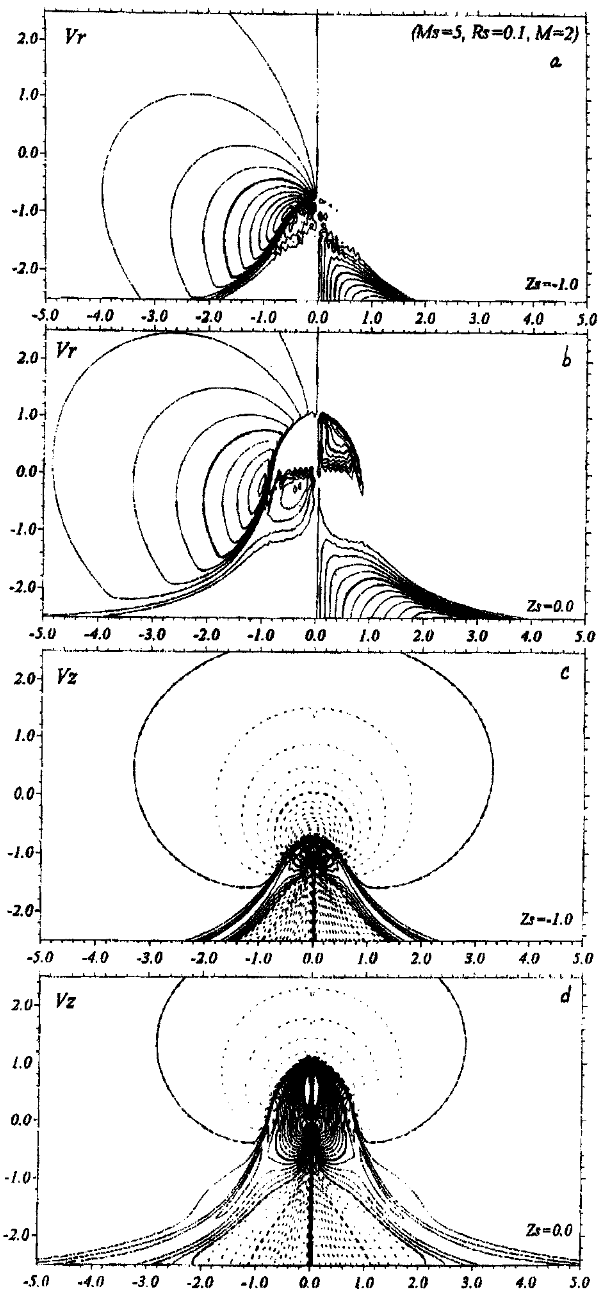

Figure 4 Distributions of radial V_r (a,b) and vertical V_z (c,d) components of the perturbed gas motion for the same model as Figure 3. The lines are plotted with an interval of 0.2 in units of the initial sound speed. Bold lines denote unity levels. Only positive levels (motion from left to right) are plotted for the radial velocity $(a,\ b)$ because of antisymmetry. The dashed lines denote the negative levels for the vertical velocity $(c,\ d)$.

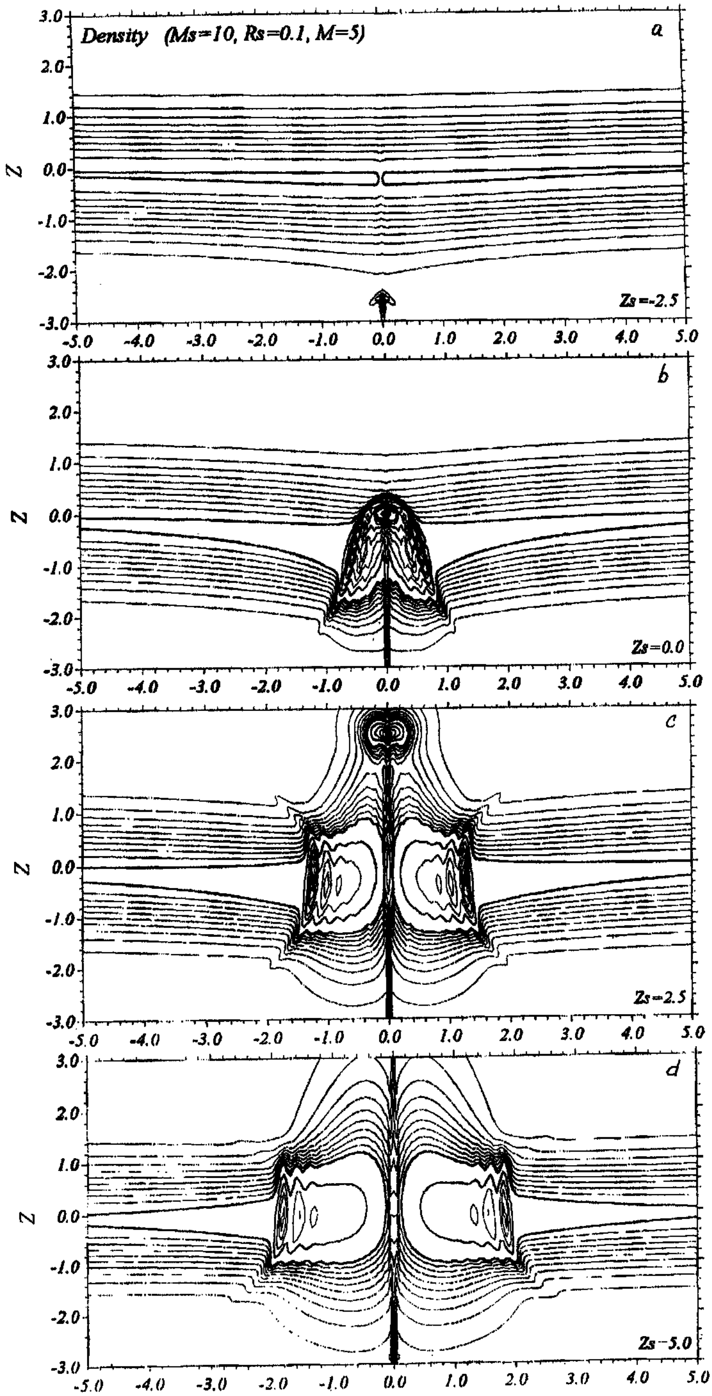

Figure 5 Same as Figure 1 for an extremely massive globular cluster.

4 DISCUSSION

Thus we can see that the response of the gas to the passage of GCs is not so trivial even in the framework of the simplest assumptions. The main features of this process are creation of the SW, heating, turbulence and redistribution of a significant amount of gas. A cylindrical region with perturbed gas remains after the GC's passage. For a typical vertical scale of $h \sim 100$ pc the diameter of this "hole" reaches ~ 1 kpc. Since the GCs pass through the galactic disc approximately every 10^6 yr, all gas in the galaxy will be disturbed at least once in the galaxy's lifetime.

The calculations predict the appearance of ring-like condensation with the same diameter which may be observed especially in the case of a high mass or low velocity of the GC. It is natural to assume that the star formation occurs at first in the high density regions and the star formation rate is proportional to the gas density contrast. This fact leads to the appearance of ring-like morphology in infrared and optical images of a galaxy. However such regular structures cannot exist for a long time because of thermal motion, differential rotation of the galactic disc and the possibility of induced star formation. Moreover, star formation may occur during SW propagation (Lépine and Duvert, 1994b); then the ultimate stellar configuration is unpredictable in the adopted model. Nevertheless the observation of similar morphology in a galactic disc may point to the presence of a massive body (GC) within 1–2 kpc of the centre of the ring.

The density contrast in the SW is definitely greater than that estimated by dynamical friction mechanism because of the different induced velocities. They are less than or comparable to the average thermal velocity for the mechanism of dynamical friction (Wallin *et al.*, 1996) and greater or much greater than the sound speed for the SW mechanism.

On the other hand, the GC is influenced by the wave resistance upon the motion through the galactic disc since it spends its kinetic energy on the excitation of the SW. This resistance is much more effective than dynamical friction and may be essential for the evolution of the entire GC system of the galaxy. Accounting for this effect will increase the GC destruction rate in the analysis (Aguilar *et al.*, 1988; Gnedin and Ostriker, 1997).

It is difficult to judge the exact quantitative estimates in this simplest of simulations but the qualitative response of the gas to the GC's passage seems quite plausible. Thus the GC-disc collisions may play an important role for triggering star formation and for the evolution of an entire galaxy.

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