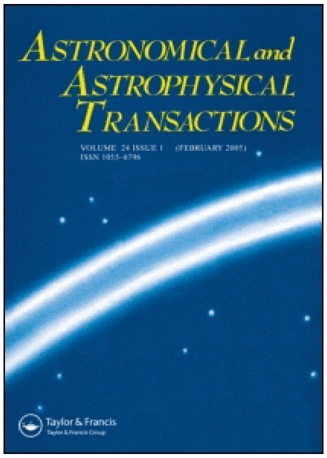

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3D STRUCTURE OF THE GALACTIC SHOCK WAVES

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3D STRUCTURE OF THE GALACTIC SHOCK WAVES

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We present the results of 2- and 3-dimensional simulations of the vertical structure of the galactic shock wave. The aim of our study is to clarify whether galactic shocks may establish connection between disk and gaseous galactic halo. We find some curious properties of the structure of the steady state flow: multiple shocks formation and the effect of sharp bend of the shock front. We believe that galactic shock waves may serve as an effective mechanism for extended halo support.

Keywords: Spiral galaxies; Galactic halo; Interstellar medium; Hydrodynamics

Extended gaseous halos are clearly seen in our Galaxy and some external spiral galaxies (Howk and Savage, 1997; 1999; Dahlem, 1997; Lee *et al.*, 2001). There is a strong correlation between the type of spirals and the extension of halos (Dahlem, 1997). In the early-type spirals (SO) with depressed star formation (SF) halos are not detectable, while in the late-type spirals – starburst galaxies with rate $\dot{M} \sim$ few $10M_{\odot}/\mathrm{yr}$ halos are the most prominent.

It is accepted that SF processes constitute the basic mechanism able on the one hand to provide a certain minimal amount of energy to support extended halos, and on the other hand able to establish disk-halo connection via dynamical processes such as galactic fountains (Shapiro and Field, 1976) or chimneys (Norman and Ikeuchi, 1989).

Meantime in the correlation 'types of galaxies – star formation rate – halos' the interagent 'star formation' seems to be not an essential element. Indeed, there exists another possible mechanism able to transfer matter and energy into halo – the galactic shock waves (GSW) (Walters and Cox, 2001). Simple estimates show that the galactic shocks in a typical 2-arm spiral galaxy with the characteristic radius of 10 kpc produce 1.6×10^{48} $(\rho/10^{-24}\,\mathrm{g\,cm^{-3}})$ $(h/300\,\mathrm{pc})$ $(v/100\,\mathrm{km\,s^{-3}})^3$ erg/yr converting kinetic energy of gas revolution in a disk into thermal energy and energy of vertical motion. Here ρ is the gas density on the equatorial plane, h is the half-thickness of the gaseous disk, and v is the velocity at which interstellar gas encounters spiral arms. This is comparable with the integral radiative losses $L \sim 3 \times 10^{48}\,\mathrm{erg\,yr^{-1}}$ for a normal galaxy.

Though the typical energy output by stellar winds and supernovae (SNe) can be one or two orders of magnitude higher, several facts favor the GSW mechanism. (1) GSW is a global and

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long-term mechanism whereas SF is a transient process. (2) GSWs realize the direct connection of disk with halo, so that the efficiency of GSWs may be quite high while the efficiency of SNe energy transfer to interstellar medium (ISM) is disputable (Thornton *et al.*, 1998). (3) In terms of GSW mechanism it is easy to explain large-scale vertical structures, particularly because such extended vertical dust structures are often identified as emanating from spiral arms (Sofue, 1987).

In this paper we study the efficiency of mass and energy transfer into halo by a GSW through 2- and 3-dimensional calculations. We study steady state configurations of the flow which are established through integration of hydrodynamic equations.

We employed an explicit version of Versatile Advection Code on the uniform Cartesian grid that consisted of 480×320 in 2-d and $125 \times 100 \times 50$ in 3-d calculations. Grid cells were taken as squares (cubes) with the sizes equal to 0.2 (0.4) pc.

We limited our consideration by adiabatic flow. A more sophisticated model with non-adiabatic processes will be described elsewhere.

First consider 2-dimensional experiments.

Figure 1 illustrates the sketch of the flow. We actually considered the vertical slice of the disk neglecting the effects of curvature of the real flow, Coriolis and centrifugal forces as well as self-gravity, magnetic fields and thermal conduction.

Initially, the flow was set up as steady state. Equilibrium along the vertical z-axis was maintained by the balance of pressure and gravitational forces. We used a simple approximation for the gravitational potential fitting quadratic function below and constant function above $z \sim 5h$. The scale height h of unperturbed gas was taken as $h = 300$ pc. The contrast in density between the equatorial plane values and values far from the disk was 3.5 orders of magnitude. We shifted the upper boundary to $z = 20h$ far from the disk plane to avoid numerical effects of interaction of the flow with boundaries. This particularly allowed us to reach the final steady state while some earlier works encountered problems to converge to equilibrium (Martos and Cox, 1998; Martos *et al.*, 1999; Korol'ov and Levy, 1999). For simplicity we considered only the upper half-plane of the disk thus ruling out in our consideration bending modes of the flow.

We considered three families of models: (a) the flows with isothermal initial vertical distribution, (b) isentropic distribution, and (c) the model with linear growth of temperature with z. In all cases gas was assumed to be polytropic with adiabatic index $\gamma = 5/3$ and the sound speed on the plane of symmetry was equal to $10\,\mathrm{km\,s^{-1}}$.

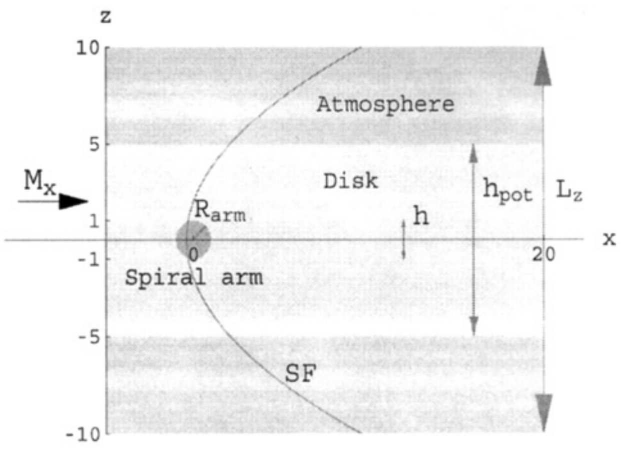

FIGURE 1 The sketch of the vertical structure of the galactic shock wave.

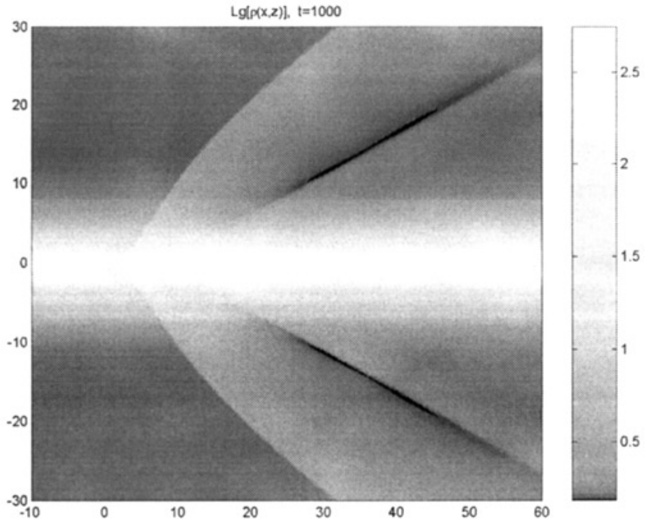

FIGURE 2 The vertical structure of the galactic shock wave in an initially isothermal disk. The inflow Mach number is $M = 3$.

Formation of the galactic shock wave within the gravitational well required special care. Within the first 20 dynamical times the circular potential well was formed with the center at $x = 0$, $z = 0$, radius $a = h$ and depth $\psi_0 = -6 \div -7$ (in terms of square of sound speed). This leads to formation of a shock. After few hundreds of dynamical times the flow relaxed to a steady state.

We distinguish four key results.

1. The galactic shock wave extends far from the plane of the disk into the halo.
2. The gaseous disk unbalanced behind the shock front oscillates in vertical direction. The amplitude of oscillations is maximum immediately behind the shock front and slowly damps downstream.
3. The secondary shock front may form behind the primary front at the distance of approximately one half length of oscillations (Fig. 2). The position of the secondary shock shifts away from the primary shock as M increases. At low Mach numbers the tertiary shock may be detected. The shock waves play the role of strong dissipative factor forcing disk to relax to hydrostatic equilibrium within two or three oscillations. As a consequence, the higher order shocks have never been discovered in the experiments.
4. The pitch angle and the intensity of the primary shock *decrease* with the Mach number (Tab. I). This fact points out the necessity of taking into account vertical

TABLE I The Galactic Shock Front (SF) Parameters in the Isothermal Disk.

Mach number	*SF pitch angle, deg*
3	49
5	22
7	13
10	8

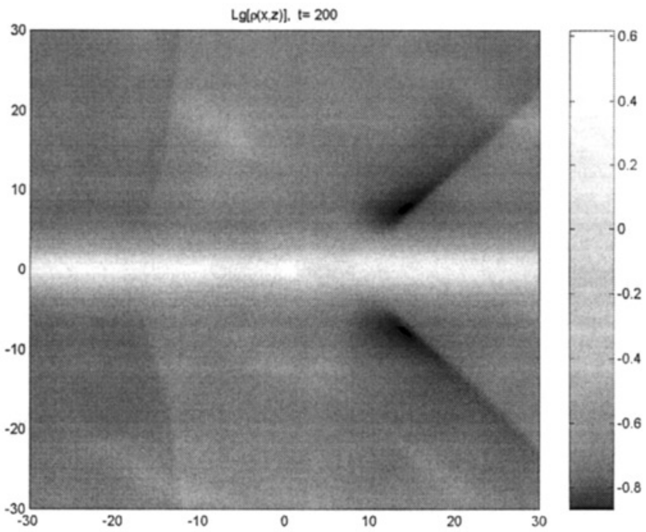

FIGURE 3 The same as in Figure 2, but for the disk with increasing temperature with height.

direction in simulations of thin gaseous disks. Flattening of the shock front is observed in the models with increasing temperature $T_0(z)$ (Fig. 3) and in the isentropic atmosphere. Thus we expect higher efficiency of the disk heating by GSW in non-isothermal models.

In 3-dimensional experiments we studied the effects of curvature of the spiral arm gravitational well in the plane of the disk. We considered a fragment of the arm with length 6 kpc and curvature radius 10 kpc and higher. The shape of the well is plotted in Figure 4. We found that

1. The vertical structure changes insignificantly compared to the 2-dimensional models.
2. The flow in the equatorial plane forms 4-shock wave configuration.

Summarizing we may conclude that the galactic shock waves may serve as a complementary mechanism for extended halo support competitive with star forming processes.

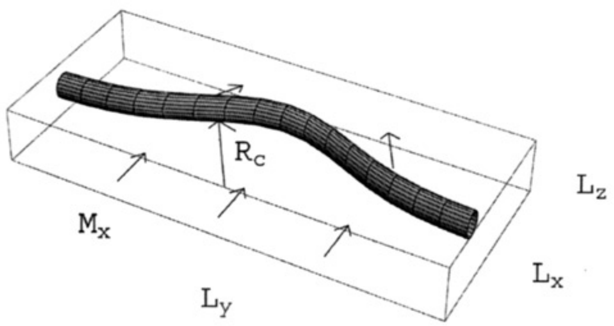

FIGURE 4 The sketch of the 3-dimensional structure of the flow. The cylinder represents a fragment of a spiral arm.

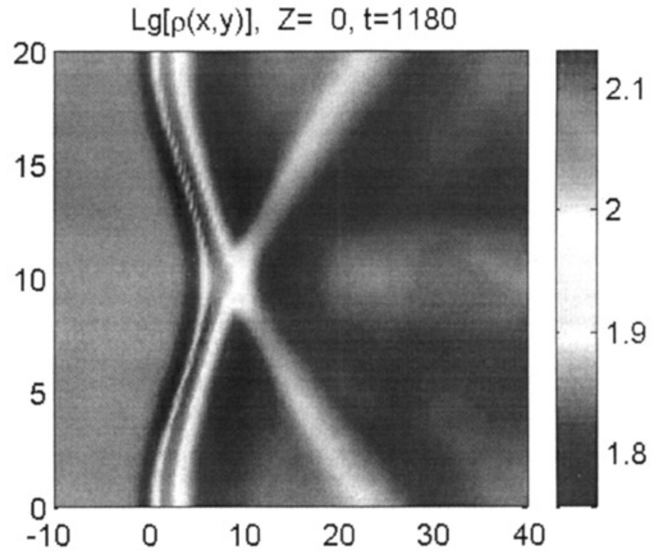

FIGURE 5 The horizontal structure ($x - y$ plane) of the galactic shock wave in an initially isothermal disk in 3-d calculations. The inflow Mach number is $M = 3$.

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