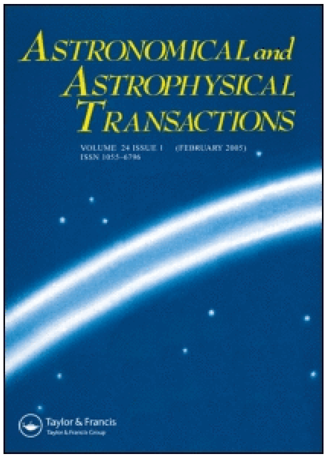

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V. V. Korol'ov [a]; V. V. Levy [a]
[a] Volgograd State University,

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A VERTICAL STRUCTURE OF A GALACTIC SHOCK WAVE

V. V. KOROL'OV and V. V. LEVY

Volgograd State University

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We carry out a 2D numerical simulation for the interaction of interstellar gas flow with the potential well of the spiral arm within a vertical cross-section. Unexpected results were obtained. First, the arising shock wave does not settle down to steady state and always passes through the arm and away. Second, the shock wave changes the vertical gas density scale – the scale decreases in front of the arm and increases behind the arm. Third, the interaction of the flow with the well has a resonant dependence on the initial flow speed and reaches its maximum at $M \sim 2$–3.

KEY WORDS Hydrodynamics, shock wave, numerical simulation

1 INTRODUCTION

The problem of interaction of supersonic gas flow with a gravitatioal potential well arises by the consideration of effects, occurring in a galactic gaseous disk, when a spiral density wave appears. The presence of a large-scale shock wave (SW) in the gas, as the response to the density wave, was demonstrated by Fujimoto (1968a,b). The problem was investigated numerically and analytically in a series of papers, for example (Baker and Barker, 1974; Tubbs, 1980; Kovalenko and Levy, 1992; Mishurov, 1992). In particular, it was shown in the one-dimensional approximation (Kovalenko and Levy, 1992) that the SW is formed on the rear side of the potential well, and then it disperses on the front side of the well. The vertical structure of the galactic SW was considered by Tubbs (1980) with curvilinear spiral coordinates and taking account of inertial forces; the numerical experiments were performed with low spatial resolution on a grid with 50×25 cells. It was found that the shock front (SF) is located on the front side of the spiral arm and almost perpendicular to the disk plane. We have tried to determine the vertical structure of the interstellar gas flow through the spiral arm in detail, using a simplified model, but fine spatial resolution. Therefore, the gas motion along the spiral arm, inertial forces, the influence of self-gravity and magnetic fields were neglected. In this paper we have also neglected thermal processes in the interstellar gas; we propose to take this effect into account later. Thus, the purpose of this paper is a study of the hydrodynamical features of inhomogeneous (with respect to the z-coordinate) flow under the influence of the additional gravitational field of the spiral arm. Consideration of this problem should serve as a background (the zero approximation) on which to display the effects pointed out above (and which are neglected).†

2 MODEL AND MAIN EQUATIONS

The gas within the framework of our model was assumed ideal with adiabatic index $\gamma = 5/3$. In the initial state the gas moves in the external gravitational field of the stellar disk, which was simulated by an infinite homogeneous layer of half-thickness H_* with density ρ_* and quadratic potential in the z-direction. It was assumed that thermal and hydrostatic balance in the gas was established in the absence of the spiral arm, and movement of the gas was stationary:

$$\begin{aligned}
\varepsilon(x, z, t, = 0) &= \varepsilon_0 = \text{const}, \\
v_x(x, z, t = 0) &= v_0 = \text{const}, \\
v_z(x, z, t = 0) &= 0, \\
\rho(x, z, t = 0) &= \rho_0 \exp(-z^2/h_0^2),
\end{aligned}$$

where ε is the internal energy per mass unit, v_x, v_z are the velocity components along and across the plane of the disk respectively, ρ is the density of the gas, ρ_0 is the initial density in the symmetry plane ($z = 0$), and h_0 is the characteristic scale of the thickness of the gaseous disk.

The spiral arm was modelled as an infinite homogeneous cylinder of radius R_S with quadratic potential inside the arm and logarithmic potential outside the arm. We assume that the spiral arm is absent at the initial time and then the stellar density in the arm grows as

$$\rho_S(x, z, t) = \begin{cases} \rho_{0S}(x, z) \sin^2(\pi t/(2\tau)), & t < \tau, \\ \rho_{0S}(x, z), & t > \tau, \end{cases}$$

where τ is the characteristic time of growth of the spiral structure, and $\rho_{0S}(x, z)$ is the density of additional stars in the arm after the spirals have formed. The complete stellar density in the arm area is

$$\rho_{\text{full}}(x, z, t) = \rho_S(x, z, t) + \rho_*.$$

We use dimensionless values, assuming that the three basic dimensional parameters – the half-thickness of the gaseous disk $h_0 \sim 100$ pc, the initial sonic speed in the gas $c_{s0} \sim 10$ km s^{-1} and initial gas density in the mid-plane of disk ρ_0 –

†In fact taking account of several factors simultaneously can give essentially different results from the sum of the results of accomodating separate factors due to the non-linearity of the problem.

are equal to unity. The characteristic dimensionless parameters of the problem are $H_* \sim 5$, $v_0 \sim 2$–4, $\tau \sim 50$ ($\sim 5 \times 10^8$ years), $R_S \sim 1$–6, $\rho_S/\rho_* \sim 0.2$–5.

We use the large particle method (Belotserkovskij, 1982) to solve the standard 2D hydrodynamic equations. The computational grid (500 $\times$ 50 square cells) was placed perpendicular to the spiral arm and was rigidly fixed relative to it. The symmetry of the problem allowed us to locate the grid in the top half-plane $z \geq 0$, displaying the results by reflection on to the bottom half-plane.

The boundary conditions were chosen as follows. On the left-hand border ($x = x_{\min}$) the flow parameters are equal to the initial one. Along the symmetry plane ($z = 0$) we use "a solid wall" (non-passing) condition. The conditions of "a translucent wall" were used on the right-hand ($x = x_{\max}$) and top ($z = z_{\max}$) borders. The translucent wall becomes a solid wall if the local flow direction is an inflow and it becomes a transparent wall if the local flow direction is an outflow. Such boundary conditions allow us to avoid the creation of self-supporting inflows from outside into the calculating area without visible physical reasons.

As long as the force from the spiral arm is $\sim x^{-1}$, it is large enough close to the left and right boundarie of the grid. Therefore we define buffer areas near $x = x_{\min}$ and $x = x_{\max}$ where we assume that the perturbing force is equal to zero.

3 RESULTS

The results of our calculations are similar to the results of analogous 1D experiments in the plane $z = 0$. The assumption of a gravitational potential well leads to the formation of SW on the rear side of the well at time $t \simeq 15$–20. Then the SF gradually moves to the front side of the well.

However, the behaviour of the flow essentially varies far from the symmetry plane. As long as the field of the spiral arm is weak, the density of the gas is practically undisturbed and quickly decreases with the growth of $|z|$ at early times. Therefore the created SF moves in the *inhomogeneous* gas flow and the speed of the SF elements, remote in the z-direction (in the areas with low density) is greater than the speed of the elements close to the symmetry plane. This effect leads to inversion of the SF shape. The SF is initially convex opposite to the flow direction (having a "<"-like shape). Then it straightens (a "|"-like shape) and becomes convex to the flow direction (a ">"-like shape). The SW dynamics is presented in Figure 1, the SF location is displayed by concentrations of the isolines. The SF almost stays on the front side of the well in the symmetry plane, but the SW wings move away outside the symmetry plane.

This behaviour of the SW causes strong compression of the gaseous disk in front of the arm, which is expressed by a reduction of its effective thickness in this area by about 2–3 times and by an appropriate increase of the gas density. Moreover the passage of the SW wings is accompanied by condensation of the gas behind the SF and growth of the scale of the gas density in the vicinity of the spiral arm.

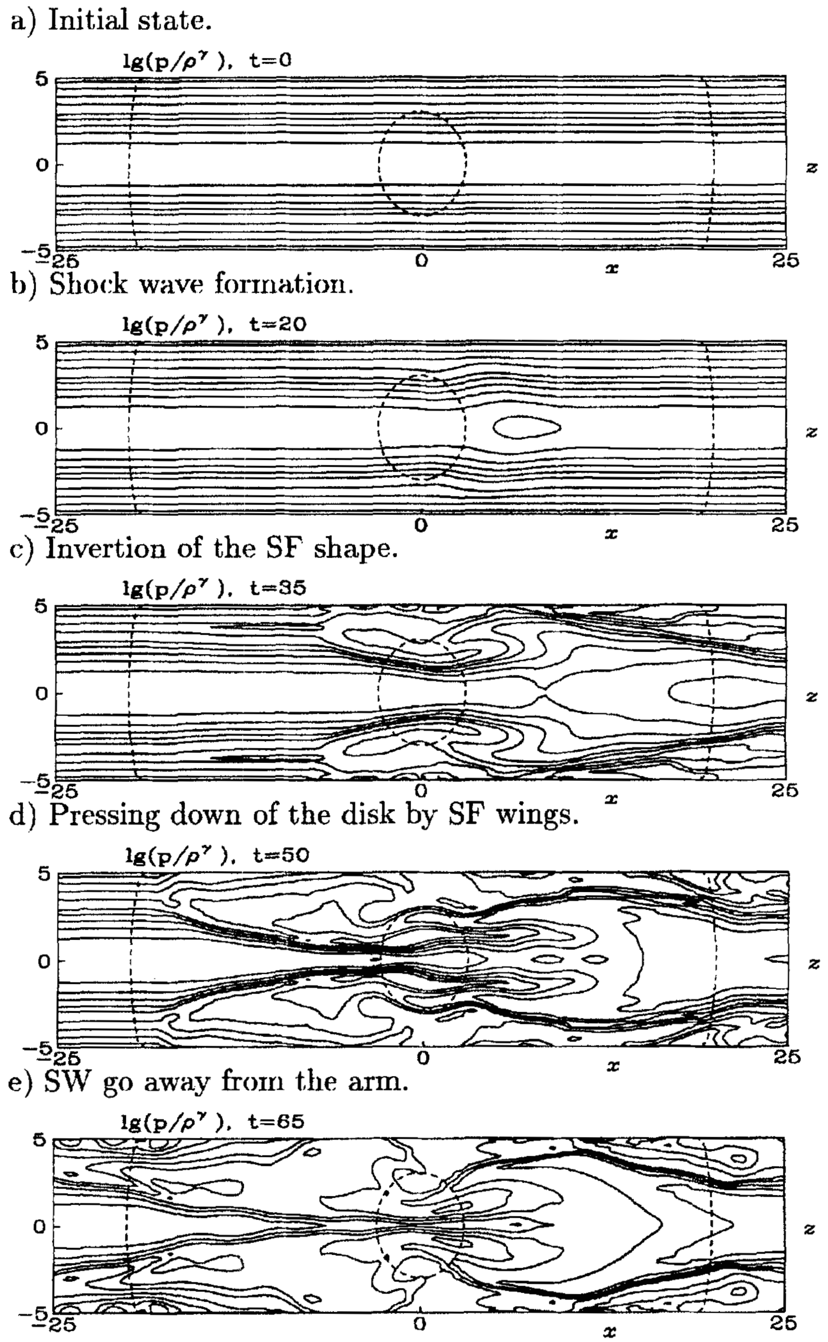

Figure 1 Isolines of the gas-specific entropy at consecutive moments of time. The dashed circle in the centre indicates the location of the spiral arm (the scale on the z-axis is changed). The dashed lines near the borders show the buffer zone bounds.

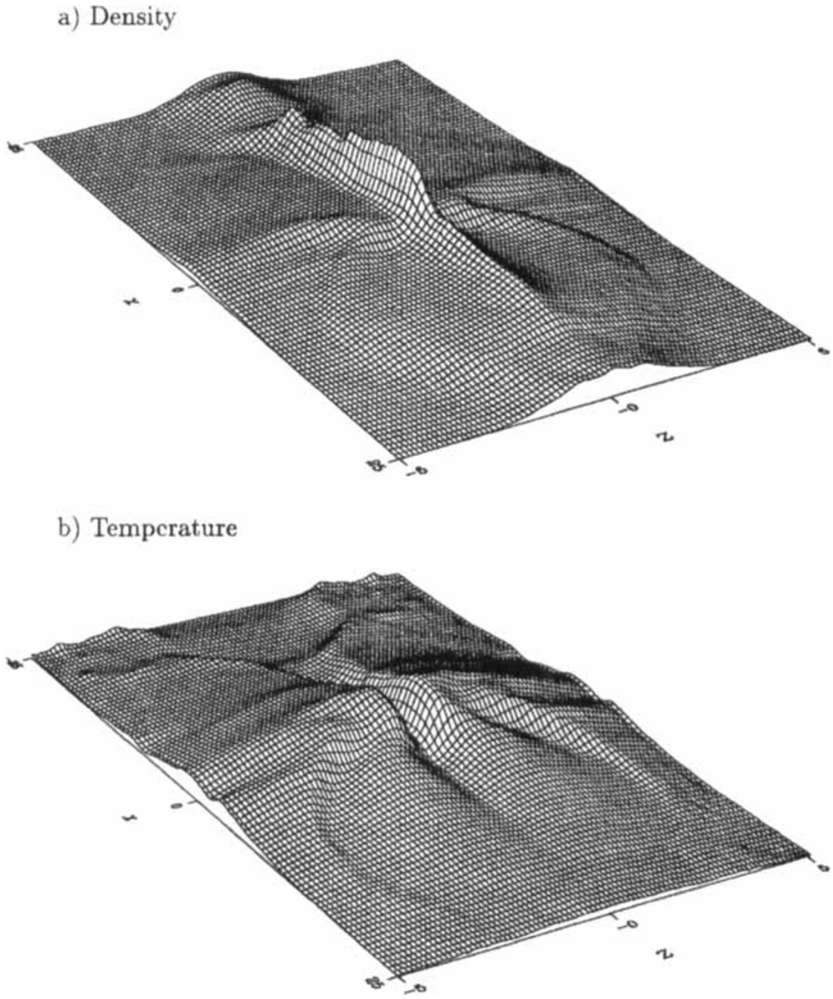

Figure 2 Distributions of density (a) and temperature (b) of the gas near the arm after the shock wave passed. The effect of layer compression at the inflow and ring-like ejections at the outflow relatively to the arm are clearly shown.

While the stellar density in the arm is increased, there is a redistribution of matter in the flow passing through the well. A high density area appears at the formation of the SW inside the arm, where the density exceeds the initial density by 1.5–2.5 times. At times $t \sim$ 25–30 ejections arise, which carry the gas away from the symmetry plane. As a result the profile of the density is expanded in the z-direction: at time $t \sim 40$ the density grows in comparison with the initial condition by about 10 times. Further development of ejections results in the formation of characteristic dense arc-shaped structures above and below the symmetry plane. It is intresting to note that the gas condensation temperature is appreciably below the temperature of the environmental gas (Figure 2(b)), though thermal processes were not taken into account. It is possible that taking account of heating and cooling will strengthen the contrast of the densities and the temperatures between the gas in the condensation and the environmental gas.

This effect probably relates to certain observable ring-shaped structures in our Galaxy (Heiles superbubbles), which are now interpreted as the remains of collective explosions of supernovae. In our experiments these structures should have the form of cylinders extending along the spiral arms, and in the condensations gas moves in the opposit direction to the initial gas flow. At a certain orientation relative to the observer these structures can look like a superbubble. In this case, if the superbubbles are formed as a result of explosions, the gas should have a radial motion from the centre of the explosion and the shape of the superbubble will be close to spherical. Measurements of the gas velocity in a superbubble could reveal the mechanism responsible for their formation.

The behaviour of the SW and of the flow passing through the potential well depends on the density of the spiral arm ρ_S, its radius R_S and the initial velocity of the gas v_0. The flow is stronger repelled by the denser arm, creating bright ejections of the gas and ring-shaped structures. The passage of the SW through the undisturbed flow causes more intensive compression of the gaseous disk in the case of a dense spiral arm. With the increase of initial gas velocity the discovered ejections deform along the outflow and are gradually destroyed, and the characteristic condensation is not formed. The effect of disk compression remains quite observable; however, the SW is weakened and its evolution proceeds slowly.

Thus, the interaction intensity of the gas flow with the spiral arm depends non-monotonically on the initial speed. The maximum amplitude of the gas flow response is reached at $M \sim 2$–3 ($M = v_0/c_{s0}$ is the Mach number of the initial flow), whereas at $M \geq 4$ the SW is carried away from the well by the gas outflow, and the inflow remains smooth. The observable effects of such non-monotonicity can be seen in those parts of spiral arms where the effective cross-component of the gas velocity $v_\perp = v_{\rm rot} \sin i$ exceeds the sonic speed by about 2–3 times. If the velocity of gas rotation around the Galactic centre $v_{\rm rot}$ and the spiral pitch angle i depend on the coordinates, favourable conditions for resonant interaction of the flow with the potential well can be created only in short segments of the arms. In this case the cylindrical structures observed as superbubbles should be hard to distinguish from the spherical structure by virtue of their small axial extent.

The reduction of the spiral arm radius R_S at constant arm mass acclerates all dynamical processes and leads to a stretching of the gas condensations along the outflow. The increase of the radius R_S at constant mass of the arm relaxes the response, but the qualitative behaviour of the flow remains the same, as described above.

4 CONCLUSION

We should note that these results specify essentially non-stationary behaviour of the SW in the (x, z) plane, though the initial problem was to search for a stationary state. The final flow condition (almost stationary) obtained in the numerical experiments is actually formed by the interaction of the SW with the boundaries and cannot be considered as a result of natural evolution of the flow. The reason for this non-stationarity is that the undisturbed gas flow is very inhomogeneous in the z-direction, therefore any motion of the SF is accompanied by a sharp change of shape and reorganization of the flow behind the SF as a whole. The SW emitted from the well can move for some time inside the Galaxy, and is gradually decreased. However, the flow behind the SF cannot be stationary, as long as the rotational velocity of the gas passing through the potential well is decreased, and the gas should move to the Galactic centre, obtaining a velocity component along the arm. If the Galactic SW evolves, the trajectories of the gas particles cannot be closed curves, hence it stationary flow with the SW in our 2D-model is unlikely. In the elementary case, the 3D-model should take into account both the heterogeneity of the gaseous disk and the movement of the gas in the third dimension, along the arm. In this model it is possible to obtain the stationary flow, however, it requires global consideration of the galactic disk as a whole and departs far from framework of the present work.

Thus, our attempt to study the vertical structure of a galactic SW has suffered. We have studied the dynamics of the movement of the SW and the result of its passage through the arm in the gaseous disk. It was earlier considered (according to the 1D analysis) that the SW causes a burst of star formation inside the spiral arms and in the gas outflow. Our research admits this situation, when star formation is more intensive in the inflow to the arm and in the ring-shaped arches above and below the symmetry plane behind the spiral arm.

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