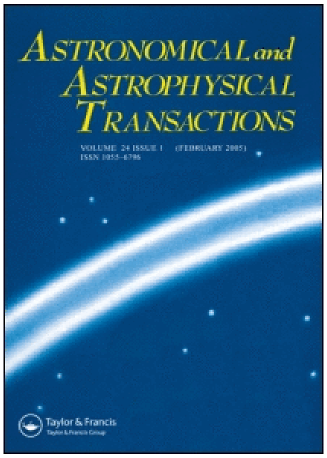

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SHOCK-SHOCK COLLISIONS IN THE INTERSTELLAR MEDIUM

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We show that the nonlinear structure produced by the collision of two spherical shock fronts develops into binary self-collimating outflows behind the accelerating reflected shocks. Computer simulations describing this evolution are presented and possible astrophysical applications are discussed.

KEY WORDS Cosmical gas-dynamics, shock-wave interaction, self-collimating outflows

1 INTRODUCTION

Shock waves and other supersonic effects are common in the gas dynamics of the interstellar medium. A nonlinear collision of two shock fronts is the subject of this paper. In our gas dynamics study we follow Courant and Friedrichs (1948) who demonstrated a dynamics structure that could be expected when two shock fronts came into collision. The fronts were assumed to be spherical with equal radii. When they met, the symmetric flow stopped at the point of the first contact of the surfaces of the fronts. Since than a nonlinear interaction of the shocks began, and at the later stages of the process, a symmetric structure formed which included a ring of the Mach front, two surfaces of tangential discontinuities and two reflected shocks that propagated backward in the opposite directions (Figure 1). Similar (topologically) structures can also form in flows that do not have symmetry of this kind.

Basic features of further nonlinear dynamical behaviour of the Courant–Friedrichs structure are studied here with computer simulations which reproduce this structure and describe the formation of large-scale vortices in the zone of the initial interaction of the shock fronts and collimated binary outflows behind the reflected shocks. We focus on the outflows and consider possible astrophysical applications of this process for supersonic phenomena in the interstellar medium.

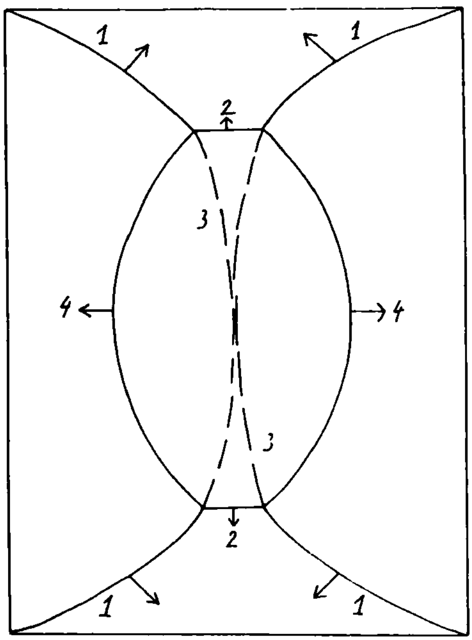

Figure 1 Sketch of the shock-shock interaction zone in projection on a plane containing the axis of symmetry of the flow (after Courant and Friedrichs, 1948); *1*, initial shock fronts; *2*, the ring of the Mach shock; *3*, the contact jumps; *4*, reflected shocks.

2 FLOWS BEHIND THE REFLECTED SHOCKS

Let us follow the evolution of the reflected shocks in the Courant–Fridrichs configuration and consider the gas flow forming behind them. The whole dynamics of the fronts as well as the geometry of their surface are critically affected by the character of the matter distribution in the area where the fronts propagate. This matter distribution is mainly due to the initial shocks that compress the major portion of the gas into two spherical shells behind their fronts. For each of the reflected shocks propagating into such cavities, it is crucial that it moves in the medium of decreasing density along the direction of the shock propagation.

The shocks in the medium of decreasing density are known to move with an increasing velocity (Chisnell, 1955; Whithem, 1958). Thus, the reflected shocks should be accelerating. It gives rise to a number of dynamical effects; the most important of them seems to be the formation of collimating currents behind the fronts of the reflected shocks.

Collimation is possible or even inevitable because the acceleration of the front as a whole and the accelerating of each particular area on it depend on the local density gradient. As a result the acceleration proves to be non-uniform, and different areas of the front start to move at different velocities.

Indeed, the central head area of the reflected front moves along the axis of symmetry of the structure. This is the direction of the steepest density decrease for the front. Because of this, the velocity of the front head increases at the largest rate. As for as the side areas of the front, they are accelerated at a slower rate or even decelerated. It is obvious, in particular that due to the spherical geometry of the cavities the density does not decrease, but rather increases in the directions which are perpendicular to the axis of symmetry of the structure.

Such an anisotropy of the density distribution for the reflected shock propagation in this picture is stronger initially than in the case of another geometry when, say, the gas is plane-stratified.

The difference in velocities of the head and areas of the front increases with time and leads to an overall transformation of the velocity field and the shape of the outflow behind the shock front. Each of the reflected shocks has a front with a convex surface (with respect to the direction of its motion). The simulations show that the curvature of this surface (in the head area of the front) increases with time because of non-uniform acceleration of the shock front. The changing shape of the front surface is the major physical factor that controls the dynamical structure of the outflows. In the course of this nonlinear evolution, the gas flow behind the reflected shock tends to trasform into a directed current along the axis of symmetry.

It is of special interest that the flow of this origin behaves as a self-collimating dynamical structure: while the density of the medium keeps decreasing, the flow becomes more and more directed.

Our computer models based on the methods of Fursenko *et al.*, 1993) agree completely with these considerations (Barausov *et al.*, 1988; 1992; Chernin and Voinovich, 1995); they give a clear picture of the space-time structure of the binary outflows produced by the reflected shocks. They obviously show that the flow as a whole transforms into two directed outflow currents along its axis of symmetry (Figure 2). This figure demonstrates the state of the flow at an advanced stage of its evolution (about one hundred time units since the first contact of the initial fronts, where the time units is the time interval between the "explosion" and the first contact of the fronts).

Note that the evolution of the reflected shocks has common features with similar processes studied earlier. First of all, we would like to mention that many years ago an effect of the "breaking through" of a strong blast wave propagating into a plane stratifield atmosphere was studied by Zel'dovich and Raizer (1967) (actually much earlier than in 1967). An analogous process called the "champagne effect" was analyzed later in cosmic gas dynamics by Bodenheimer *et al.* (1979) in the context of embedded HII regions. Königl (1982) not only developed similar ideas (with a reference to Zel'dovich and Raizer), but also quantified the conditions under which the effect might occur in dense molecular clouds.

Figure 2 shows also an interesting dynamic structure formed in the central region around the zone of the initial shock-shock contact: this is a system of two major annular eddies. The evolving tangential discontinuities of the Courant–Friedrichs configuration make their contribution to the eddy generation in the interaction zone.

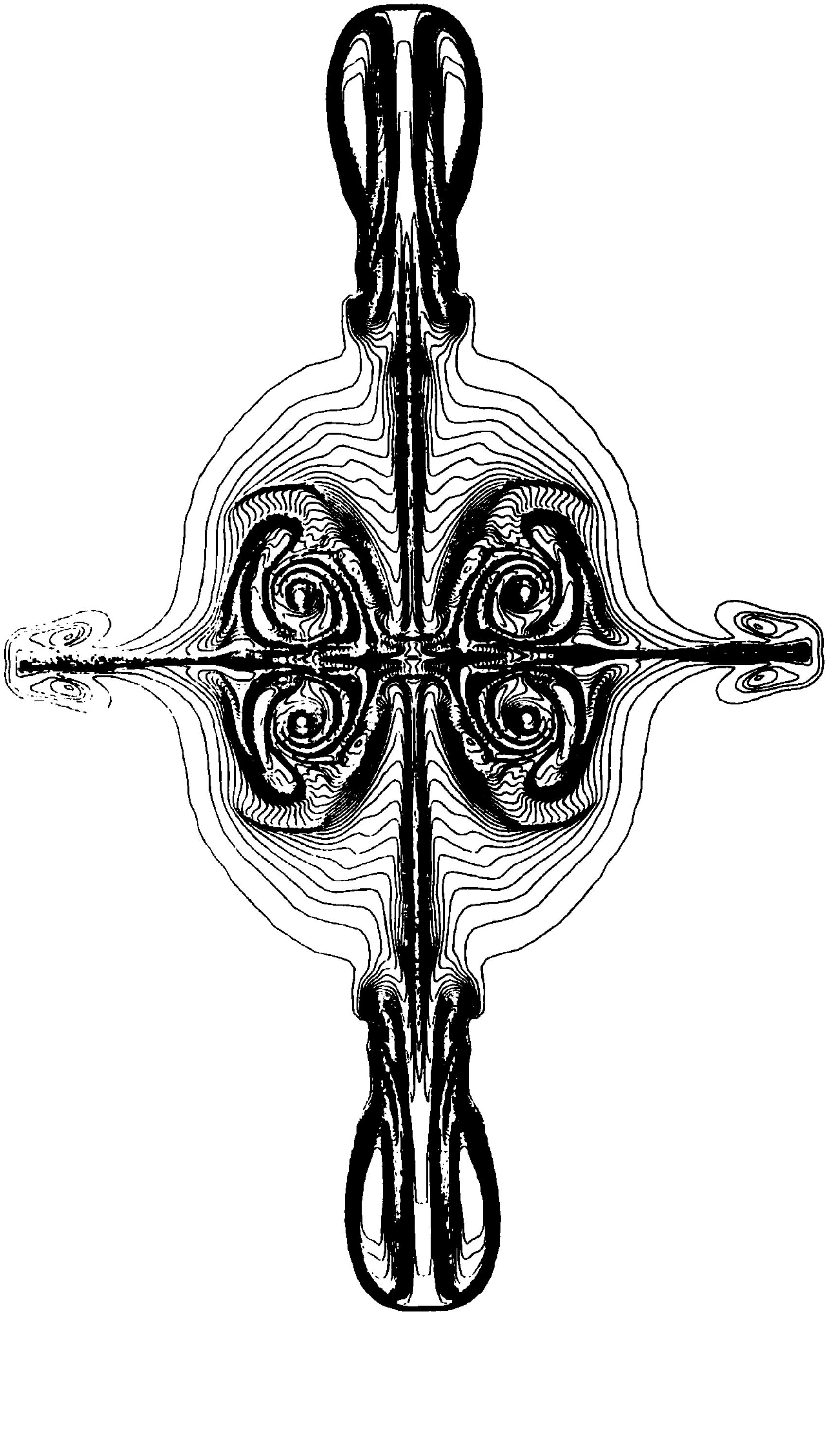

Figure 2 Computer simulation of the evolving Courant-Friedrichs configuration: the collimated outflows behind the reflected shocks and the large-scale vorticity in the central interaction zone.

Another and more important eddy contribution is due to the vorticity generation at the fronts of the reflected shocks.

3 BINARY OUTFLOWS, MOLECULAR BULLETS, H–H OBJECTS, etc.

One can assume that there may be a variety of gas dynamic phenomena which are due to interactions of shock fronts in the interstellar medium. Perhaps star formation is the most interesting among them. When two interstellar shocks meet, they produce region of shocked gas in the central zone of their interaction. The dense gas may then fragment to form a star or a group of stars in this region. Physical conditions in such zones seem to be quite similar to what is usually assumed for star-forming regions. If so, we can expect that a by-product of star formation should be supersonic gas outflows from these regions produced in the way discussed above.

As it was found a few years ago, young stellar objects have jets associated with them (Mund and Fried, 1984). A remarkable property of high-velocity flows around protostars is their tendency to appear bipolar: they often consist of two spatially separate lobes of emission, and the two lobes are located always more or less symmetrically with respect to the protostar (Lada, 1985).

It is of special interest for the present discussion that:

(1) Some gas currents are highly collimated into a bipolar structure, and the degree of collimation, e.g. the ratio of the observed major axis to the minor axis, ranges from about 1 to over 10.

(2) Many outflows exhibit better collimation with increasing radial velocity as well as a systematic increase in radial velocity along the outflow axis. These features, taken together, suggest that the properties of collimation and acceleration are connected with each other in their physical nature.

According to a recent review (Dyson, 1993), "Curiosly, how stars produce jets is an open question". Our model may give an answer to this question. The jets are produced together with gas compression required for star formation. Our model of binary outflows from the zones of shock-shock collisions demonstrates the major features observed in the jets from protostars (for details see Chernin, 1995). Strong winds from young stellar objects may then use the anisotropic cavities created earlier by these jets, and secondary collimated binary outflows may form this way.

Objects of another kind associated with young stars are the Herbig–Haro (H–H) objects discovered some 40 years ago. The objects come in various shapes and have velocities up to a few hundred km/s. Alen and Burton (1993) observed families of H–H objects in the Orion molecular cloud. They note that molecular hydrogen emission reveals long tail-like structures which project back to a more or less common origin in the vicinity of the well-known stellar residents of the Orion clouds. Alen and Burton (1993) propose that a few thousand years ago, some violent explosive phenomenon occured which hurled numerous bullets (or "shrapnel") into the molecular cloud. The bullets swept up cloud material through the bow shocks on their leading faces, producing iron and oxygen emission behind the shocks. It is assumeed that this process may explain the observed properties of the families of H–H objects. The origin of the bullets remaines, however, obscure in such a picture.

Perhaps the physical mechanism of the formation due to shock-shock collisions may be also applied here. We may assume that the "violent explosive phenomenon" (presumably in the Trapezium star cluster) can form a large-scale expanding shock front. This front can ineract with various smaller-scale shocks propagating in the region. Such an ensemble of shock waves and supersonic plasma motions can reasonably be expected to be present in the Orion complex of molecular clouds and star forming regions where energetic stellar winds and multiple supernova explosions are common. For instance, gamma-ray spectroscopy of the interstellar medium in the Orion complex (Bykov and Bloemen, 1994) supports this view.

The interaction of large-scale shocks with this ensemble of small-scale shocks can lead to the formation of a number of binary outflows with a head-tail structure similar to our Figure 2. In this case, dynamical parameters of the interacting shocks are different; therefore, the lobes of the outflows may be not so symmetric as in our model. But it is important that the axes of the bynary flows should be normal to the surface of the large-scale front and directed back to the center of this front, just as in the observed picture of H–H objects with their tails.

If so, the geometry of this process suggests that the tails of the outflows should, generally, be shorter near the center of the large-scale spherical shock (the direction to the Trapezium stars) because of the projection effect. It seems to be really the case, judging on the observed picture. Only outflows produced by interactions of the small-scale shocks in their ensemble may have arbitrary distributions of the directions and do not reveal this projecton effect.

It is interesting that the Becklin–Neugebauer infrared source is seen very close to the direction of one of the outflows in the Allen–Burton picture. May its formation be due to the same large-scale shock here?

Finally, the largest regions of violent star formation, i.e. superasociations, may also be treated as a result of the collisions of giant shock waves in the interstellar medium (Chernin and Efremov, 1994; Chernin *et al.*, 1995). An impressive example of colliding shells of kiloparsec size was found by Meaburn (1980) in the Large Magellanic Cloud in the area of ongoing star formation near 30 Doradus.

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