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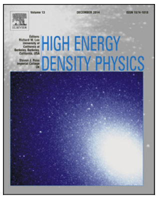

Vorticity deposition, structure generation and the approach to self-similarity in colliding blast wave experiments

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ABSTRACT

When strong shocks interact with transverse density gradients, it is well known that vorticity deposition occurs. When two non-planar blast waves interact, a strong shock will propagate through the internal structure of each blast wave where the shock encounters such density gradients. There is therefore the potential for the resulting vorticity to produce pronounced density structures long after the passage of these shocks. If the two blast waves have evolved to the self-similar (Sedov) phase this is not a likely prospect, but for blast waves at a relatively early stage of their evolution this remains possible. We show, using 2D numerical simulations, that the interactions of two 'marginally young' blast waves can lead to strong vorticity deposition which leads to the generation of a strong protrusion and vortex ring as mass is driven into the internal structure of the weaker blast wave.

1. Introduction

The generation of vorticity and multi-scale structure in fluids subjected to multiple shocks is an important problem in a number of areas in astrophysics, high-energy density physics, and inertial fusion. It is important in the study of star formation as this is dependent on the development of fine structure in the interstellar gas [1,2]. Certain theories [3,4] aimed at accounting for the intergalactic magnetic field depend on a seed magnetic field that in turn arises from vorticity generated in shock interactions in the pregalactic medium. Supernova remnants are blast-driven systems that are well-known for their complex structure and morphologies [5]. In both the astrophysical context of supernova ejecta and inertial fusion, shock-deposited vorticity can drive mixing [6] which is important to both areas of study [7].

The development of high-powered laser technology has allowed researchers to study energetic, compressible hydrodynamical systems, including blast waves [8]. Vorticity generation and magnetic field generation (via the Biermann battery effect) has been studied for laser-driven blast waves [9]. There are a range of different methods for launching blast waves in laser-driven experiments. Some of these allow for considerable control, e.g. cluster targets [10], which has greatly expanded the range of experimental possibilities. Experiments which might produce supersonic turbulence are currently being considered [11].

The flexibility of blast wave experiments based on cluster media has made it relatively easy to pursue studies of blast wave collisions [12,10]. The production of multiple, interacting blast waves is, of course, possible with other laser-target configurations and other HEDP drivers. It is well known that the interaction of strong shocks with density inhomogeneities leads to copious vorticity deposition and thus the formation of corresponding density structures (e.g. shock–bubble interactions [13]). The implication of this is that studies of shock-deposition of vorticity could be pursued experimentally with systems in which two strong explosions interact.

In this paper we consider a hypothetical experiment in which two moderately asymmetric blast waves are launched and interact. This leads to a situation where shocks cross the interior region of each blast wave (which we refer to as the 'cavity'). The inhomogeneities in the density and sound speed of the unshocked material might be thought to lead to significant shock-deposition of vorticity which can then lead to complex density structure being produced. However there are also good reasons to doubt that significant vorticity can be generated, e.g. weak density gradients in the central region of a Sedov–Taylor solution. We suggest that if the blast waves are relatively 'young', and have not evolved to the self-similar state, then strong vorticity deposition is still possible. We demonstrate this using 2D numerical simulations. The deposition of vorticity and development of density structure depends heavily on the blast waves not having evolved fully to a self-similar state.

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This hypothetical experiment therefore examines not only the important issues of shock-deposition of vorticity and shock propagation in non-uniform flows, but it also examines the approach of flows towards self-similar states.

Note that throughout this paper we use the term 'blast wave' to refer to strong explosions that are produced by rapid, localized energy deposition in the most general sense, and not in the more limited sense where the solution has evolved far from its initial conditions. Throughout the paper we discuss the physics using the viewpoint of vorticity deposition and evolution [14], and we work solely in the framework of ideal hydrodynamics. We will also only consider the case of 2D Cartesian geometry in which uniformity is supposed in the ignored coordinate. This means that, prior to interaction, the two blast waves will be cylindrical, axisymmetric blast waves. This minimal problem is particularly relevant to experiments with cluster media where the laser propagates through the cluster medium to produce long 'rods' of strongly heated matter that subsequently produce quasi-cylindrical blast waves. This problem has only indirect relevance to astrophysical problems, since, along with the chosen geometry, precise synchronization of blast waves generation is unlikely in an astrophysical context.

2. Theory

The central idea in this paper is that a binary blast–blast interaction which is asymmetric (in the sense that the explosions are launched from hot spots with somewhat different energy) will experience vorticity deposition (e.g. from inhomogeneous density) when the two blast waves interact and reflected shocks propagate back through the 'cavities' of each blast wave. An illustrative schematic of this interaction is shown in Fig. 1. The deposition of vorticity can then lead to the generation of complex density structure. The asymmetry is not necessary for vorticity deposition (this also occurs in the symmetric case), but it is relevant to the subsequent development of density structure. Despite the clear combination of shock propagation and density inhomogeneity, the occurrence of strong shock-deposition of vorticity and structure generation is not necessarily obvious.

To explain why, we first consider the shock deposition of vorticity in more detail. The vorticity jump across a shock is a topic with a long history in the scientific literature (see references to Truesdell [15], Lighthill [16], Hayes [17] and Berndt [18]). In relatively recent work, Kevlahan [19] derived an expression for the vorticity jump for the case where the flow is *non-uniform*. Kevlahan's expression is,

$$\delta\omega = \frac{\mu^2}{1+\mu}\frac{\partial C_r}{\partial S} - \frac{\mu}{C_r}\left[\left(\frac{D\mathbf{u}}{Dt}\right)_S + \frac{C_r^2}{1+\mu}\frac{1}{\rho}\frac{\partial \rho}{\partial S}\right] + \mu\omega. \qquad (1)$$

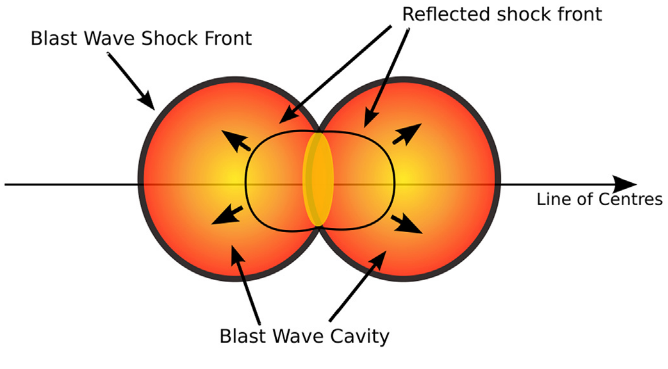

Fig. 1. Schematic of binary blast wave interaction.

In Eq. (1), μ is the density compression factor across the jump, C_r is the shock speed relative to the normal component of the flow ahead of the shock, $\mathbf{u}$ is the velocity vector field of the flow, $\partial/\partial s$ is the tangential part of the directional derivative, and ω denotes the vorticity in the direction $\mathbf{b} = \mathbf{n} \times \mathbf{S}$, where $\mathbf{n}$ is the normal direction to the shock and $\mathbf{S}$ is the aforementioned tangential direction. This equation can be interpreted physically. The first term on the RHS of Eq. (1) is the vorticity jump that arises from shock curvature. The second term is baroclinic vorticity generation arising from non-uniformity in the flow. The third term represents conservation of angular momentum.

Since we are considering a system which is initially static, we are therefore automatically dealing with a problem in which the unshocked fluid is vorticity-free. We therefore do not have to consider the third term in the first instance. Prior to interacting we have $\partial C_r/\partial S = 0$ for each blast wave, so if we neglect the possibility that the first term is important (i.e. shock refraction is assumed to be weak), then we are left with the second term. For the case where the un-shocked fluid is isentropic (as it is in the case we consider), the second term can be shown to depend only on $\partial\rho/\partial S$. One can describe a blast wave as consisting of a thin 'shell' surrounding an interior 'cavity' [20]. There exists a well-known self-similar solution by Sedov [21], however the simplified picture will suffice for this discussion. The strongest density gradients are localized to the thin shell, with weaker variation of density inside the cavity. There are therefore two problems with obtaining significant vorticity deposition. On the one hand one might expect the density gradients in the 'cavity' region to be too weak (based on Sedov's solution). On the other hand, although there are strong density gradients in the shell, this region is moving rapidly which means that C_r may not be large. As can be seen in Fig. 1, once the blast waves interact, the outermost shock front is always moving away from the reflected shock. There is also the issue of shock deceleration on encountering an increasing density gradient which may lead to C_r being small when the reflected shock reaches the shell region. Thus, without detailed calculation, we have good reason to doubt the possibility of significant vorticity deposition.

There is, however, the possibility that if the blast wave has not been able to evolve to the point that it closely matches the Sedov–Taylor state then the density gradients in the cavity may be much stronger than we would anticipate based on Sedov's solution. This would remove the first obstacle suggested above, and could lead to strong vorticity deposition in the cavity region (although not in the shell). The characteristic time for the blast wave evolution is $\tau = R_h^2\sqrt{\frac{\rho}{\mathcal{E}}}$ [22,23] (assuming cylindrical geometry; where R_h the characteristic size of the initial hot spots, ρ the ambient density, and $\mathcal{E}$ is the area-integrated energy deposited in the hot spot). When $t \ll \tau$, the explosion cannot have evolved far from its initial conditions. This can be seen by noting that τ is approximately equal to R_h/c_h. On the other hand when $t \gg \tau$ we expect the blast wave to have reached the Sedov phase. Therefore one expects that, for $\tau \approx 1$ that the blast wave will be 'young' in the sense that strong cavitation will have occurred, but that it will still be far from the self-similar state. The blast wave may still be relatively 'young' even up to ≈10τ. We note that the issue of departure from the self-similar solution has long been noted in astrophysical studies, particularly in the case of supernova remnants [24,23]. Of course, the density profile of the 'young' blast wave does not have an analytic solution as such, and we must therefore resort to numerical simulations to further investigate this matter.

Finally we note that it is vorticity deposition in the cavity region that is potentially the most interesting possibility. As we are considering asymmetric blast waves, the material that builds up at the intersection of the two blast waves will experience a net drive into the cavity of the weaker blast wave. If there has been copious