Available online at www.sciencedirect.com

ScienceDirect

Nuclear Physics B 905 (2016) 45–72

NUCLEAR PHYSICS B

www.elsevier.com/locate/nuclphysb

Hydrodynamics of ultra-relativistic bubble walls

Leonardo Leitao, Ariel Mégevand [*,1]

IFIMAR (CONICET-UNMdP), Departamento de Física, Facultad de Ciencias Exactas y Naturales, UNMdP, Deán Funes 3350, (7600) Mar del Plata, Argentina

Received 17 November 2015; received in revised form 6 January 2016; accepted 10 February 2016

Available online 11 February 2016

Editor: Hong-Jian He

Abstract

In cosmological first-order phase transitions, gravitational waves are generated by the collisions of bubble walls and by the bulk motions caused in the fluid. A sizeable signal may result from fast-moving walls. In this work we study the hydrodynamics associated to the fastest propagation modes, namely, ultra-relativistic detonations and runaway solutions. We compute the energy injected by the phase transition into the fluid and the energy which accumulates in the bubble walls. We provide analytic approximations and fits as functions of the net force acting on the wall, which can be readily evaluated for specific models. We also study the back-reaction of hydrodynamics on the wall motion, and we discuss the extrapolation of the friction force away from the ultra-relativistic limit. We use these results to estimate the gravitational wave signal from detonations and runaway walls.

1. Introduction

A first-order phase transition of the universe proceeds by nucleation and expansion of bubbles, and may have different cosmological consequences, depending on the velocity of bubble growth. For instance, the generation of the baryon asymmetry of the universe in the electroweak phase transition is most efficient for non-relativistic bubble walls, and is suppressed as the bub-

* Corresponding author.
E-mail addresses: lleitao@mdp.edu.ar (L. Leitao), megevand@mdp.edu.ar (A. Mégevand).

1 Member of CONICET, Argentina.

http://dx.doi.org/10.1016/j.nuclphysb.2016.02.009
0550-3213/

ble wall velocity approaches the speed of sound in the plasma [1]. In contrast, the formation of gravitational waves may be sizeable if the wall velocity is supersonic [2]. These cosmological consequences generally depend not only on the wall velocity but also on the bulk motions of the plasma caused by the wall. For instance, gravitational waves are generated by bubble collisions [2–4] as well as by turbulence [5–7] and sound waves [8].

The propagation of the phase transition fronts (bubble walls) is affected by hydrodynamics in a non-trivial manner (see, e.g., [9–13]). The wall motion is driven essentially by the difference of pressure between the two phases. This force grows with the amount of supercooling, i.e., the further down the temperature descends below the critical temperature, the larger the pressure difference between phases. As a consequence, the driving force is very sensitive to the (inhomogeneous) reheating which occurs due to the release of latent heat.

Besides, the microscopic interactions of the particles of the plasma with the wall cause a friction force on the latter (see, e.g., [15]). Computing the friction force is a difficult task, and for many years only the non-relativistic (NR) case was studied [16]. In this approximation, a wall velocity $v_w \ll 1$ is assumed, and the friction force scales as v_w. Beyond the NR regime, a dependence $v_w \gamma_w$ was usually assumed, where $\gamma_w = 1/\sqrt{1-v_w^2}$. As a consequence of this scaling, the wall would always reach a terminal velocity. More recently, the *total* force acting on the wall was calculated in the ultra-relativistic (UR) limit, $\gamma_w \gg 1$ [17]. The result does not allow to discriminate the friction or the hydrodynamic effects. Nevertheless, the net force F_{net} is independent of v_w, which means that the friction saturates as a function of $v_w \gamma_w$. As a consequence, the wall may run away. For intermediate velocities, microscopic calculations of the friction were hardly attempted [18,19]. To compute the wall velocity, phenomenological interpolations between the NR and the UR limits have been considered in Refs. [20,21].

Leaving aside the determination of the wall velocity, the perturbations caused in the plasma by the moving wall have been extensively studied for the case of a stationary solution [22–25]. Different hydrodynamic regimes can be established, depending on the wall velocity. For a subsonic wall the hydrodynamic solution is a weak deflagration, in which the wall is preceded by a shock wave. For a supersonic wall, we have a Jouguet deflagration if the wall velocity is smaller than the Jouguet velocity. In this case, the fluid is disturbed both in front and behind the wall. For higher wall velocities, the solution is a weak detonation. For the detonation, the velocity is so high that the fluid in front of the wall is unaffected. In this case, the wall is followed by a rarefaction wave.

The steady-state hydrodynamics can be investigated as a function of thermodynamic parameters (such as the latent heat) and of the wall velocity (i.e., considering v_w as a free parameter). Thus, in particular, the kinetic energy in bulk motions of the plasma, which is relevant for the generation of gravitational waves, was computed in Refs. [20,24] for the whole velocity range $0 < v_w < 1$. These results are useful for applications, as they do not depend on a particular calculation of the wall velocity for a specific model.

For the runaway case, the hydrodynamics was considered in Ref. [20]. However, the results rely on the decomposition of the total force into driving and friction forces, and are sensitive to approximations. The decomposition of the UR force was discussed also in Ref. [21]. Since the net force is known [17], it is actually not necessary, in the UR limit, to determine the friction component in order to study the wall motion. However, identifying the forces acting on the wall is useful, in the first place, to understand the hydrodynamics, and, in the second place, to construct a phenomenological model for the friction, which allows to compute the wall velocity away from the UR limit.