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Jeans instability in the linearized Burnett regime

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Abstract

Jeans instability is derived for the case of a low-density self-gravitating gas beyond the Navier–Stokes equations. The Jeans instability criterium is shown to depend on a Burnett coefficient if the formalism is taken up to fourth order in the wave number. It is also shown that previously known viscosity corrections to the Jeans wave-number are enhanced if the full fourth-order formalism is applied to the stability analysis.

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Keywords: Hydrodynamics; Burnett regime; Gravitational instability

1. Introduction

The physics of low-density systems is relevant in the description of thermodynamic processes which presumably occurred in the universe some time between its age of 10^6 s, temperature $k_B T = 1\,\text{keV}$ and the stage after matter decoupled from radiation

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when the matter density reached values of $\sim 10^{-18}\,\mathrm{g/cm^3}$ and $k_B T = 1\,\mathrm{eV}$. It is also known that these types of regimes prevail in many other astrophysical systems [1]. Since a hydrodynamical, Navier–Stokes, description of a low-density fluid breaks down for small Knudsen numbers, it is desirable to go beyond this regime and analyze the fluid with the tools that statistical physics provide as the particle collision frequency decreases. One simple tool useful for this purpose is, on the one hand, the phenomenological formalism now known as linear irreversible thermodynamics (LIT), which provides a good grasp about how non-equilibrium processes evolve in time [2]. On the other hand, kinetic theory provides a solid mesoscopic foundation for this theory, specially if we want to deal with hydrodynamics beyond the Navier–Stokes regime [3,4].

The relevance of transport coefficients in cosmological and astrophysical problems has already been widely recognized [1,5,6]. Nevertheless, the Burnett equations [3,4] have rarely been applied to structure formation problems in a phenomenological context, although the Burnett regime itself has been addressed in the context of transport theory in special relativity [7–9]. One possible motivation for the study of the Burnett regime in cosmological situations is the well-known relation between wave scattering processes, density fluctuations and dissipative effects [10–12]. Dynamic structure factors, possibly relevant for describing CMB distortions, can be derived from the hydrodynamical Burnett approach, as it has already been done for collisionless plasmas [13]. The use of these structure factors has appeared to be useful in the study of scattering laws to describe the Sunyaev–Zel'dovich effect and can, in principle, be applied to study density–density correlation functions to deal with hydrodynamical instabilities [14] or temperature–temperature correlation functions, a problem that remains to be studied via a thermodynamical approach. For the background microwave radiation, this is done at present carried out using the well-known multipole expansion. In this work we analyze the solutions to the phenomenological linearized Burnett equations in the context of Jeans instability theory, generalizing previous work [15,16]. The main reason for doing this is that the introduction of the Burnett regime allows to take into account all k^4 order terms in the dispersion relation. Furthermore, the general tenets behind this formalism are worth emphasizing in view of its wide range of applicability [17]. To accomplish this task, the paper is divided as follows: Section 2 reviews the basic phenomenological equations governing the Burnett regime. Section 3 is dedicated to the analysis of the dispersion relation obtained form the linearized formalism. Final remarks about the implications of the Burnett regime in structure formation are included in the last section.

2. Basic formalism

The starting point for our calculation concerns the method whereby for a simple fluid which is not in equilibrium we can apply the adequate information to transform the well-known conservation equations for mass, momentum and energy into a complete set. For this purpose, we assume that the fluid is isothermal and, therefore,