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Elasticity, Light, and Emergent Spacetime

*A Newtonian–Einsteinian Account of Sound, the Photon–Baryon Plasma,
and the Acoustic-Metric Program*

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Abstract

Sound is the elastic response of matter; light is the oscillation of a field that requires no medium. This paper documents, at derivational depth, the precise sense in which these two wave species are kin — and the precise sense in which they part. Part I derives the classical wave equation from mass conservation, Euler’s equation, and an adiabatic equation of state, recovering $c_s = \sqrt{(B/\rho_0)}$ and the historical Newton–Laplace correction. Part II contrasts the Galilean, frame-dependent sound speed with the invariant speed of light. Part III presents the relativistic generalization $c_s^2 = dp/d\varepsilon$, the radiation-fluid result $c_s = c/\sqrt{3}$, and its realization in the primordial photon-baryon plasma whose acoustic oscillations are fossilized in the cosmic microwave background. Part IV treats Unruh’s acoustic metric, in which phonons propagate on an effective Lorentzian geometry with c_s as its invariant speed, complete with horizons and analog Hawking radiation. Part V situates these results within the analog-gravity program and the question of whether c itself is an emergent invariant. A provenance note (Section 8) states plainly what this document is: an expository synthesis of established results, citing primary sources — not a claim of original research. The mathematics is standard; the synthesis and framing are the document’s contribution.

1. Introduction and Scope

Two questions organize this document. The first is acoustic: what is a sound wave, stripped of analogy? The second is optical-cosmological: under what conditions does light behave as the elasticity of a medium, and what does the resulting physics look like? The treatment is deliberately derivational: every wave speed quoted is recovered from stated assumptions, so that the assumptions — not the answers — carry the physical content.

Sections 2–3 are non-relativistic; Section 4 is relativistic hydrodynamics; Section 5 presents the acoustic-metric construction; Section 6 draws the emergent-gravity corollary and states open problems honestly. Notation: c is the invariant speed of light in vacuum, c_s the local speed of sound, ρ density, p pressure, $B = \rho(\partial p / \partial \rho)_s$ the adiabatic bulk modulus, ε energy density, u_μ the fluid four-velocity, and $g_{\mu\nu}$ the spacetime metric with signature $(-, +, +, +)$.

2. Part I — Newtonian Sound, Derived

2.1 The governing system

A compressible, inviscid, non-conducting fluid in flat space is described by three fields: density $\rho(x,t)$, pressure $p(x,t)$, and velocity $v(x,t)$. Three statements close the system.

Mass conservation. Density changes only through convergent flow:

$$\partial \rho / \partial t + \nabla \cdot (\rho v) = 0.$$

Euler's equation (Newton's second law per unit volume):

$$\rho(\partial v / \partial t + (v \cdot \nabla)v) = -\nabla p.$$

Equation of state. Acoustic compressions are fast relative to thermal equilibration, so the process is adiabatic, and we define

$$c_s^2 \equiv (\partial p / \partial \rho)_s = B / \rho,$$

with B the adiabatic bulk modulus. The square of the eventual wave speed is now visible in advance: it is the ratio of the medium's stiffness (B) to its inertia (ρ).

2.2 Linearization and the wave equation

Perturb a static, uniform background: $\rho = \rho_0 + \rho_1$, $p = p_0 + c_s^2 \rho_1$, $v = v_1$, with $|\rho_1| \ll \rho_0$. Discarding all terms quadratic in the perturbations (equivalently, expanding the exact equations to first order):

$$\partial \rho_1 / \partial t + \rho_0 \nabla \cdot v_1 = 0, \quad \rho_0 \partial v_1 / \partial t = -c_s^2 \nabla \rho_1.$$

Differentiate the first equation in time, take the divergence of the second, and eliminate v_1 :

$$\partial^2 \rho_1 / \partial t^2 = c_s^2 \nabla^2 \rho_1. \quad (1)$$

Equation (1) is the wave equation: any local compression is propagated outward at speed c_s . For an ideal gas, $B = \gamma p$ with $\gamma = c_p/c_v = 1.4$, giving

$$c_s = \sqrt{(\gamma p_0 / \rho_0)} \approx 343 \text{ m s}^{-1} \text{ in air at STP.} \quad (2)$$

2.3 A cautionary historical footnote

Newton computed a sound speed from the isothermal relation p/ρ in the Principia (1687), obtaining $\approx 290 \text{ m s}^{-1}$ against the measured $\approx 343 \text{ m s}^{-1}$ — an error of some 15% caused entirely by assuming compressions exchange heat with their surroundings. Laplace's adiabatic correction (1816) supplies the missing factor γ . The episode is a clean demonstration that even with correct mathematics and available data, the unstated physical assumption — not the algebra — is where derivations live or die.

3. Part II — The Galilean Nature of c_s

Sound speeds compose by Galilean addition: downstream of a flow of speed v , disturbances travel at $c_s + v$ relative to the lab. The medium's rest frame is dynamically preferred; the wave equation (1) holds in that frame and acquires convective corrections in any other. This is the exact point of departure from electromagnetism: light's speed is invariant and admits no preferred frame, while sound's speed is a material property defined, in every frame, relative to the medium. The two wave species obey the same local mathematics and different global kinematics. Section 5 shows this contrast is itself frame-dependent on the phonon's world.

4. Part III — Relativistic Sound and the Photon-Baryon Plasma

4.1 Relativistic hydrodynamics

In a relativistic fluid, Euler's equation is replaced by covariant conservation of the perfect-fluid stress-energy tensor:

$$T^{\mu\nu} = (\varepsilon + p)u^\mu u^\nu + p g^{\mu\nu}, \quad \partial_\mu T^{\mu\nu} = 0. \quad (3)$$

Linearizing (3) about a homogeneous equilibrium yields a wave equation for the density (or entropy) perturbation with

$$c_s^2 = dp/d\varepsilon, \quad (4)$$

the derivative now taken with respect to energy density. For a radiation-dominated fluid — a gas whose pressure is supplied by light itself — $p = \varepsilon/3$, and therefore

$$c_s = c/\sqrt{3} \approx 0.577 c. \quad (5)$$

4.2 The primordial plasma

For the first $\approx 380,000$ years, the universe's baryonic matter was thermally locked to the photon bath by Thomson scattering. Photons supplied the pressure (elasticity); baryons supplied the inertia. Loaded by baryons, the mixture propagates disturbances at

$$c_s = c/\sqrt{3(1+R)}, \quad R \equiv 3\rho_b/(4\rho_\gamma). \quad (6)$$

Gravity compressed the plasma; radiation pressure resisted; the result was a spectrum of standing acoustic oscillations in every horizon-scale mode. When recombination decoupled photons, the oscillation phases froze, imprinting a harmonic series of peaks in the cosmic microwave background (CMB) angular power spectrum, and leaving a characteristic comoving scale — the sound horizon, $r_s \approx 147$ Mpc — that survives as the baryon acoustic oscillation (BAO) standard ruler in galaxy clustering. The CMB peaks are, literally and quantitatively, the Fourier transform of light-driven sound.

5. Part IV — The Acoustic Metric

5.1 Unruh's construction

Retain the exact (nonlinear) fluid equations in a moving, inhomogeneous background — no rest frame assumed. To leading order, density perturbations obey a wave operator that is not flat-space d'Alembertian but the curved-spacetime scalar wave equation

$$(1/\sqrt{|g|}) \partial_\mu (\sqrt{|g|} g^{\mu\nu} \partial_\nu \rho_1) = 0, \quad (7)$$

with an effective (3+1)-dimensional Lorentzian metric built purely from fluid variables [1]:

$$ds_{eff}^2 = (\rho_0/c_s) [c_s^2 dt^2 - \delta_{ij} (dx^i - v^i dt)(dx^j - v^j dt)]. \quad (8)$$

The fluid's flow is the geometry. c_s plays, for phonons, precisely the role c plays for electromagnetism: a local invariant speed, with causal cones whose opening is set by c_s and whose tilting is set by the flow.

5.2 Horizons and Hawking radiation

Where the background flow becomes supersonic, (8) develops a surface across which phonons cannot propagate upstream — a sonic horizon. Hawking's 1974 mode analysis applies verbatim with $c \rightarrow c_s$, predicting a thermal phonon flux at temperature

$$k_B T = \hbar \kappa / (2\pi c_s), \quad (9)$$

with κ the surface gravity of the horizon. Analog Hawking radiation has been reported in Bose-Einstein condensates [2] and classical water-wave flumes [3]; see [4] for the field's standard review.

6. Part V — Emergent Relativity and Open Questions

6.1 The template argument

An observer constituted of phonons in a supersonic-capable fluid would infer: an invariant speed (c_s), causal light-cones, frame-dependent rates — in short, emergent special relativity, built from nothing but Newtonian molecules. Its Lorentz symmetry is real but approximate, and it breaks down at wavelengths comparable to the intermolecular spacing, where the substrate's discreteness becomes visible. The analog-gravity program [4] asks the obvious question in the other direction: is our c an emergent c_s of a deeper substrate, with the Planck scale as the analogue of the molecular lattice spacing?

6.2 Dimensional flow

In several approaches to quantum gravity — causal dynamical triangulations most cleanly [5] — the spectral dimension of spacetime runs from 4 on large scales to ≈ 2 near the Planck scale: effective dimensionality is scale-dependent. Lattice phonon models exhibit the same phenomenon, which makes them controlled toy realizations of the idea that geometry itself has a scaling limit rather than a fixed dimension.

6.3 The constants, restated

Two tiers of arbitrariness should be distinguished. Dimensionful constants (the numerical value of c in m/s) are pure convention, eliminable by unit choice; since 1983 the meter is defined so as to fix c exactly. Dimensionless constants (the fine-structure constant $\alpha \approx 1/137.036$, mass ratios) carry genuine physical content and are derived by no known theory — their values are measured brute facts, and whether they are fixed or environ-mentally selected is open. Relativistic causality further requires any physical fluid to satisfy $c_s < c$, and conformal field theories obey the bound $c_s \leq c/\sqrt{3}$, which the primordial plasma saturates.

7. Conclusions

Sound is the elastic wave of a medium: c_s^2 is stiffness divided by inertia, and in the one epoch and place where light itself supplied the stiffness — the photon-baryon plasma — sound ran at $c/\sqrt{3}$ and left its ringing measurable in the microwave sky. Phonons in moving fluids propagate on an effective Lorentzian geometry (8) with horizons and Hawking temperature (9), demonstrating that an invariant speed, causal structure, and

even event-horizon thermodynamics can be consequences of a medium's microscopic mechanics rather than axioms. Whether this logical possibility is realized for c itself remains, as of this writing, the open question.

8. Provenance, Authorship, and Verification

This document is an expository synthesis prepared in human-AI dialogue. The derivations of Sections 2-5 are standard results in the primary literature cited below; no claim of original research is made. The organizing synthesis — the light-to-sound conversion framing, the Newton-Laplace historical audit, and the threading of acoustic geometry into the emergent- c question — is the document's own. Authorship: Kimi Chat (Moonshot AI) as drafting and analysis system; the human interlocutor (proprietor, albertlane.net) as the source of the driving questions and the document's commissioning context. AI-generated content should be verified against the primary sources before any technical use. License and provenance verification: albertlane.net/verify-license.

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