Internal Propagation Speeds Track Escape Velocities in Self-Gravitating Bodies

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Abstract

Escape velocity and internal propagation speed are generally regarded as independent properties of self-gravitating bodies. Escape velocity is determined by the global gravitational potential, whereas propagation speed depends primarily on local material properties such as density and elastic response. Here we report a previously unrecognized correspondence between these quantities across a range of gravity-shaped bodies. Observational data for Earth, Mars, Venus, the Moon, and the Sun indicate that characteristic internal propagation velocities closely match the corresponding escape velocities despite substantial differences in composition, thermodynamic state, and evolutionary history.

The observed relation spans more than two orders of magnitude in characteristic velocity and appears to hold for both planetary and stellar interiors. For tidally locked bodies such as the Moon, a geometric correction associated with non-radial propagation yields the same scaling behavior. The correspondence is quantified through the dimensionless ratio $R = v_{prop}/v_e$, which remains close to unity across the investigated bodies within observational uncertainty.

The relation was originally identified as a consequence of a broader framework in which gravitational potential is associated with cumulative relativistic interaction delay. Within that framework, equating the relativistic time-dilation factors associated with finite-speed propagation and gravitational potential leads directly to the observed scaling. Although the physical origin of the correspondence remains open, the results suggest an unexpected connection between internal propagation processes and gravitational potential. Future planetary, lunar, and helioseismic observations may provide additional tests of the proposed relation.

1. Introduction

Escape velocity and internal propagation speed are generally regarded as independent properties of self-gravitating bodies. Escape velocity is determined by the global gravitational potential and depends primarily on the body's mass and radius. Internal propagation speed, by contrast, is governed by local material properties such as density, composition, and elastic response. Despite their distinct physical origins, observational data for several planetary and stellar bodies reveal a close numerical correspondence between these quantities.

This apparent correspondence is unexpected. Standard models of planetary and stellar interiors successfully describe seismic and acoustic propagation through the mechanical properties of matter, while escape velocity follows directly from the body's gravitational potential. No general relation between these quantities is normally anticipated. The existence of such a relation therefore raises the possibility that both quantities may reflect a deeper property of self-gravitating systems.

A common feature of coherent physical systems is the requirement that their constituent parts continuously exchange information, momentum, and stress. In solid bodies, this communication occurs through electromagnetic interactions and propagating stress waves. In gravitationally bound systems, coherence is maintained through gravitational coupling among their constituents. Although the physical carriers differ, all such interactions propagate at finite speed.

The importance of finite propagation may be illustrated by the response of an extended body to an external force. When a ball is struck, the opposite side does not respond instantaneously. Information about the applied impulse propagates through the material via internal stress waves, and the body moves coherently only because its constituent parts continuously exchange momentum through finite-speed interactions. A self-gravitating body faces an analogous requirement. Although gravity acts throughout the body, the local gravitational acceleration is not identical at all locations. Neighboring regions therefore experience slightly different accelerations and must continuously exchange momentum and stress in order to maintain structural coherence. The existence of finite propagation speeds implies that a non-zero propagation delay is necessarily associated with this process.

The present work originated from a broader investigation of the hypothesis that gravitational potential may be related to cumulative relativistic interaction delay arising from finite-speed propagation within self-gravitating systems. Within this framework, a simple prediction emerges. Equating the relativistic time-dilation factors associated with finite-speed propagation and gravitational potential leads to a characteristic relation between internal propagation speed and escape velocity. The correspondence reported here was identified while testing this prediction against observational data.

We examine planetary and stellar bodies possessing coherent internal propagation paths, including Earth, Mars, Venus, the Moon, and the Sun. Despite substantial differences in composition, thermodynamic state, and evolutionary history, these bodies exhibit a remarkable convergence between characteristic propagation velocities and escape velocities. The relation spans more than two orders of magnitude in characteristic velocity and appears to remain valid within observational uncertainty.

The purpose of the present work is twofold. First, it documents and quantifies the observed correspondence between internal propagation speeds and escape velocities in self-gravitating bodies. Second, it evaluates whether the relation is consistent with the prediction of a cumulative-delay framework. Although the physical origin of the correspondence remains open, the results suggest an unexpected connection between internal propagation processes and gravitational potential.

The paper is organized as follows. Section 2 derives the expected scaling relation from the equivalence of the associated relativistic time-dilation factors. Section 3 compares the prediction with observational data from planetary and stellar interiors. Section 4 discusses the implications, limitations, and possible extensions of the proposed framework to larger gravitational systems. Conclusions are presented in Section 5.

2. Delay Framework and Predicted Scaling

2.1 Finite-Speed Communication in Self-Gravitating Systems

The delay framework is motivated by a simple physical observation: coherent systems require finite-speed communication among their constituent parts. In solid bodies, information, momentum, and stress are transmitted through electromagnetic interactions and propagating mechanical disturbances. In gravitationally bound systems, coherence is maintained through gravitational coupling among constituent elements. In all cases, interactions require finite propagation time.

The present framework explores the possibility that the cumulative effect of these finite propagation times may be related to the quantity conventionally described as gravitational potential. The framework does not modify the mathematical structure of General Relativity [1]. Instead, it seeks a physical interpretation of the observed connection between gravitational potential and relativistic time dilation.

2.2 Gravitational and Propagation Time Dilation

In the weak-field limit of General Relativity, gravitational time dilation may be written as

$$\frac{\Delta t'}{\Delta t} \approx 1 - \frac{GM}{Rc^2} \tag{1}$$

Using the definition of escape velocity,

$$v_e = \sqrt{\frac{2GM}{R}} \tag{2}$$

the same expression becomes

$$\frac{\Delta t'}{\Delta t} \approx 1 - \frac{v_e^2}{2c^2}. \tag{3}$$

A propagation process characterized by velocity v_{prop} is associated with the leading-order kinematic time-dilation factor

$$\frac{\Delta t'}{\Delta t} \approx 1 - \frac{v_{prop}^2}{2c^2} \tag{4}$$

Equations (3) and (4) show that both gravitational potential and propagation speed may be expressed through equivalent relativistic delay factors.

2.3 Predicted Relation Between Propagation Speed and Escape Velocity

If gravitational potential reflects cumulative interaction delay, the dominant propagation process within a coherent self-gravitating body should be characterized by the same delay scale appearing in gravitational time dilation.

Equating the leading-order delay terms in Eqs. (3) and (4) gives

$$\frac{v_{prop}^2}{2c^2} = \frac{v_e^2}{2c^2}, \tag{5}$$

and therefore

$$v_{\ prop} = v_{\ e} \tag{6}$$

The predicted correspondence does not arise from matching velocities directly. Instead, it follows from the equivalence of the associated relativistic time-dilation factors.

Eq. (6) therefore provides a direct empirical test of the delay framework. The following section compares this prediction with observational data from planetary and stellar interiors.

2.4 Scope and Limitations

The derivation above does not establish a causal relation between propagation speed and escape velocity. Rather, it identifies a specific observational consequence of the delay framework. The prediction is expected to be most relevant for self-gravitating bodies possessing coherent internal propagation paths and approximately continuous material structure.

Whether analogous delay tracers exist in larger gravitational systems such as galaxies and galaxy clusters remains an open question and is discussed only briefly in Section 4.

3. Observational Test of the Predicted Scaling

3.1 Earth

For Earth, the average compressional-wave velocity in the inner core is approximately 11.2 km s^{-1} [2], while the escape velocity is 11.2 km s^{-1}. The resulting ratio $R = v_{prop}/v_e$ is therefore approximately unity.

3.2 Mars

Independent seismic observations from the InSight mission [3,4,5] yield characteristic core propagation velocities near 5 km s^{-1}, closely matching the Martian escape velocity of 5.0 km s^{-1}.

3.3 Extension to Additional Bodies

The comparison may be generalized through the dimensionless ratio

$$R = v_{prop}/v_e. \tag{7}$$

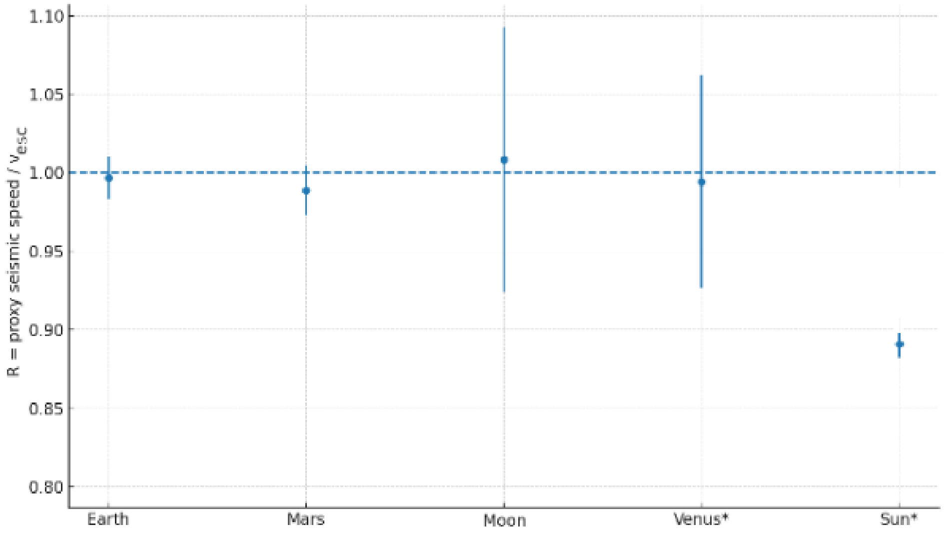

Figure 1. Seismic–escape velocity ratio $R = v^{\mathrm{rad}}_{\mathrm{prop}}/v_e$ for representative gravity-shaped bodies. Earth and Mars use direct seismic constraints; Moon, Venus, and Sun are based on lunar seismology, interior modeling, and helioseismic inversions, respectively. The Moon is corrected for the proposed non-radial propagation geometry associated with tidal locking. Asterisks indicate model- or inversion-based estimates. Error bars represent source-based uncertainty ranges.

Figure 1 summarizes representative values for Earth, Mars, Moon [6,7], Venus [8], and the Sun [9,10]. Despite substantial differences in composition, thermodynamic state, and evolutionary history, all investigated gravity-shaped bodies cluster near $R \approx 1$ within observational uncertainty.

The larger uncertainty associated with the solar value likely reflects the greater complexity of stellar propagation processes compared with planetary interiors.

3.4 Why the Core?

The characteristic propagation velocity is taken from the gravity-dominated interior rather than from crustal or mantle averages.

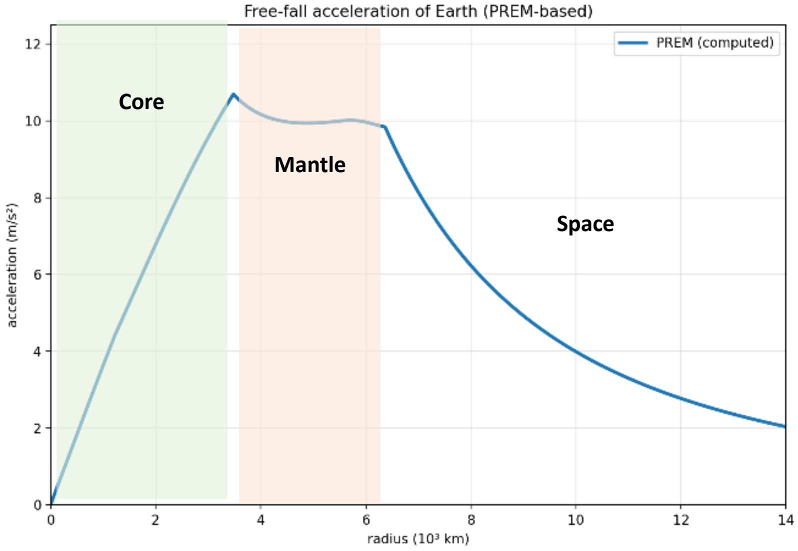

Figure 2: Free-fall acceleration profile derived from PREM, illustrating why the gravity-dominated core is used to define the characteristic propagation velocity.

A key aspect of the core regime is the observed correspondence between internal propagation speeds and escape velocity. This relation can be understood from the fact that, in a self-gravitating body, the elastic properties of the material are not independent of gravity. The bulk modulus K [11-14] governing P-wave propagation is set by the internal pressure, which in turn is determined by gravitational confinement.

$$\bar{v}_{prop}^{rad} \sim \sqrt{\frac{K}{\rho}} \sim \sqrt{\frac{GM}{R}} \sim v_{esc} \tag{8}$$

The free-fall acceleration profile inside a self-gravitating body reveals how gravitational delay may accumulate with radius (Fig.2). The nearly linear increase of g(r) through the core indicates that the gravitational influence accumulates coherently with radius within the gravity-dominated interior Beyond the core, in the mantle and crust, density and rigidity variations introduce discontinuities, and $g(r)$ becomes irregular—signifying interference between partially decoupled delay pathways.

The gravitational acceleration reaches its maximum within the deep interior and remains approximately constant throughout much of the core. Consequently, the core provides the most representative propagation environment for comparison with the global gravitational potential. The core choice is consistent with standard seismological treatments of deep planetary interiors [11–14].

This scaling is consistent with the time-dilation equivalence derived in Section 2, providing both relativistic and material interpretations of the same correspondence.

3.5 Tidally Locked Bodies

The derivation of Eq. (6) implicitly assumes that the dominant source–observer communication path is approximately radial. This assumption is natural for freely rotating gravity-shaped bodies, where no preferred horizontal direction exists over geological timescales.

Tidally locked bodies may represent a distinct class. Because the same hemisphere continuously faces the primary body, long-term tidal forcing introduces a persistent geometric asymmetry. In such systems, the dominant source–observer communication path may become circumferential rather than radial.

The Moon provides a representative example. The average center-to-surface lunar P-wave velocity is approximately 7.44 km s^{-1}, whereas the lunar escape velocity is 2.38 km s^{-1}. The ratio is therefore close to π. This suggests that the observed propagation speed corresponds to a circumferential source–observer path whose characteristic length is approximately π times the radial distance.

Thus, Eq. (9) may represnt a generalized form of Eq. (6):

$$\bar{v}_{prop}^{rad} \approx v_e \tag{9}$$

Although additional tidally locked bodies with well-constrained interior propagation data are required for a definitive test, the lunar result is consistent with the hypothesis that source–observer geometry influences the observed manifestation of the underlying delay scale..

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3.6 Robustness and Limitations

The present sample is limited by the availability of reliable constraints on deep interior propagation velocities. Earth and Mars provide the strongest direct seismic measurements, whereas Venus, the Moon, and the Sun rely partly on inversion-based interior models.

Future planetary missions, lunar seismology programs, and improved helioseismic inversions will provide additional opportunities to test the robustness and generality of the observed relation.

4. Discussion

4.1 Physical Interpretation

The observed correspondence does not by itself establish a causal relation. However, it suggests that quantities traditionally regarded as independent may be linked through a common relativistic delay scale.

Within the delay framework, the correspondence is interpreted as an indication that gravitational potential and internal propagation dynamics may both reflect cumulative interaction delay.

4.2 Possible Extension to Larger Gravitational Systems

The present analysis is restricted to planetary and stellar bodies possessing coherent internal propagation paths. However, the underlying motivation of the delay framework is not limited to material propagation within continuous media.

A common feature of coherent physical systems is the requirement that their constituent elements remain dynamically coupled through finite-speed interactions. In planetary interiors, this coupling is mediated primarily through electromagnetic interactions and pressure-wave propagation within matter. In larger gravitational systems, such as galaxies and galaxy clusters, coherence is maintained through gravitational coupling among stars and galaxies rather than through a continuous material medium.

From this perspective, the propagation velocities examined in the present study may represent only one manifestation of a more general principle. If gravitational potential is associated with cumulative interaction delay, the dominant observable tracer of that delay need not be the same in all systems. In coherent planetary and stellar interiors, the relevant tracer is expected to be the characteristic propagation velocity within the material medium. In galaxies, where constituents communicate primarily through gravitational interaction, orbital velocities may become the dominant tracer of the underlying delay structure. On still larger scales, galaxy clusters may be characterized by collective velocity dispersion rather than by internal material propagation.

This hierarchy suggests a possible sequence of delay tracers across gravitational scales,

$$v_{prop} \rightarrow v_{rot} \rightarrow \sigma, \tag{10}$$

where v_{prop} denotes characteristic propagation velocity, v_{rot} denotes orbital velocity, and σ denotes velocity dispersion. The communication mechanism changes with scale:

Table 1: Dominant communication mechanism

Regime	**Dominant communication mechanism**	**Observable tracer**
Planetary interiors	Electromagnetic/material stresses	v_{prop}
Galaxies	Gravitational interaction among orbiting constituents	v_{rot}
Clusters	Collective gravitational interaction	σ

If confirmed, such a hierarchy would imply that the correspondence between propagation velocity and escape velocity identified here is not an isolated planetary phenomenon, but rather the smallest-scale manifestation of a more general relationship between gravitational potential and cumulative interaction delay in self-gravitating systems.

The present work tests only the first element of this sequence through planetary and stellar observations. Whether analogous relations exist at galactic and cluster scales remains an open question requiring separate investigation. For systems composed of discrete constituents, such as galaxies and galaxy clusters, reconstruction of the corresponding delay structure may require iterative treatment of the distributed mass configuration. Such extensions lie beyond the scope of the present work.

4.3 Limitations

The present work establishes an empirical correspondence rather than a complete microscopic theory. The physical mechanism linking propagation dynamics and gravitational potential remains to be established.

5. Conclusions

A previously unrecognized correspondence has been identified between characteristic internal propagation speeds and escape velocities in self-gravitating bodies.

The relation emerges naturally from a delay framework in which gravitational potential is associated with cumulative relativistic interaction delay and was identified while testing a prediction of that framework.

Although the physical origin of the correspondence remains open, the observed agreement across planetary and stellar bodies suggests an unexpected connection between internal propagation processes and gravitational potential.

Future planetary, lunar, and helioseismic observations will provide further opportunities to test the robustness and generality of the proposed scaling.

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