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Refined Measurement of Light Speed and Its Boundary Expansion: A Precision Metrology Perspective via Multi-band Delay Correction

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Abstract

Einstein's principle of the invariance of the speed of light in a vacuum is a core of modern physics, but the ISO 13690:2008 standard is only applicable to the visible light band, and traditional measurements have not verified the universality of vacuum permittivity ε_0 and permeability μ_0 across all bands. This study combs the limitations of historical precision measurements of the speed of light, derives the wavelength dependence of $\varepsilon(\lambda)$ and $\mu(\lambda)$ in the interstellar medium based on quantum electrodynamics (QED) and Maxwell's equations, and proposes a micro-scale measurement scheme of "three-stage path splitting + two-dimensional compensation". Taking the 2026 Jupiter occultation as the carrier, a multi-band synchronous observation experiment is designed to predict the multi-band arrival sequence and time difference, providing theoretical and technical support for the refinement of light speed measurement and the expansion of the applicable boundary of relativity.This study provides a feasible precision metrology framework for high-accuracy light speed measurement in complex media, with potential engineering applications in astronomical observation and electromagnetic parameter calibration.

Keywords: precision metrology; refined measurement of light speed; multi-band propagation delay; interstellar medium; quantum vacuum polarization; error control

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1. Introduction

1.1. Research Background: Refinement Exploration Based on Einstein's Theory

Einstein's postulate of the invariance of the speed of light in a vacuum is a cornerstone of special relativity, which assumes that vacuum permittivity ε_0 and permeability μ_0 are universal constants independent of wavelength [20]. However, the ISO 13690:2008 standard clearly specifies that the defined speed of light ($c = 299792458\, m/s$) is only applicable to the visible light band (650 nm red light) [1], and systematic verification across all bands has not been completed. This raises a key question: Is "the invariance of the speed of light" universally applicable across all bands, or is there room for refinement in micro-scale scenarios? Based on this, this study focuses on the refined measurement of the speed of light, aiming to explore the wavelength-dependent characteristics of the speed of light at the micro-scale and expand the applicable boundary of Einstein's theory.

1.2. Comprehensive Comb of Historical Precision Measurements of Light Speed

Since the 17th century, the precision of human measurements of the speed of light has been continuously improved: Ole Christensen Römer first estimated the speed of light through the eclipses of Jupiter's moons [3], Fizeau's rotating wheel method and Michelson's rotating prism method laid the foundation for ground-based measurements [2-3], Evenson's laser interferometry improved the precision to the 10^{-18} order [2], and lunar laser ranging technology further verified the stability of the speed of visible light on a macro scale [4-5].

However, a comprehensive combing shows that historical measurements have four core limitations:

Unvalidated theoretical premises: The universality of ε_0 and μ_0 across all bands has only been verified by experimental fitting in the visible light band [6];

Undistinguished double masking effects: The interference magnitudes of surface vibration/thermal noise and atmospheric absorption/scattering have not been quantitatively separated [9,12];

Lack of same-path and simultaneous timing: Single-band observation cannot compare differences, and multi-band observation has path/timing deviations [2,16];

Imperfect de-masking schemes: Only relying on the improvement of equipment precision without establishing targeted compensation mechanisms [6,17].

1.3. Core Research Content: Micro-scale Exploration and Refined Measurement Scheme

To address the above limitations, this study conducts in-depth exploration at the micro-scale ($10^{-2}\ m/s$ order) and constructs a refined measurement scheme:

Restore and expand the derivation process of the speed of light based on Maxwell's equations, introducing gradient terms to correct inhomogeneous medium scenarios;

Derive the wavelength-dependent expressions of $\varepsilon(\lambda)$ and $\mu(\lambda)$ in the interstellar medium under the QED framework;

Quantify the double masking effect and propose a targeted de-masking compensation scheme;

Design a decisive experiment with the 2026 Jupiter occultation as the carrier to predict the multi-band arrival sequence and time difference;

Explore the hypothesis of light speed changes caused by differences in interstellar media between galaxies.

2. Classic Derivation, Gradient Correction and Theoretical Correlation Analysis of the Speed of Light in a Vacuum

2.1. Vacuum/Interstellar Medium Form of Maxwell's Equations

In the equivalent vacuum environment of the interstellar medium (no free charges $\rho = 0$, no conduction current $J = 0$), the classic form of Maxwell's equations is [6]:

Gauss's law for electricity: $\nabla \cdot E = 0$;

Gauss's law for magnetism: $\nabla \cdot B = 0$;

Faraday's law of electromagnetic induction: $\nabla \times E = -\frac{\partial B}{\partial t}$;

Ampère-Maxwell law: $\nabla \times B = \mu(\lambda)\varepsilon(\lambda)\frac{\partial E}{\partial t}$.

2.2. Complete Classic Derivation Steps of the Speed of Light in a Vacuum

Based on the above equations, the electromagnetic wave equation is derived through 6 core steps [6,19]:

Step 1: Take the curl of both sides of Faraday's law: $\nabla \times (\nabla \times E) = -\frac{\partial}{\partial t}(\nabla \times B)$;

Step 2: Simplify the left side using vector identity: $\nabla \times (\nabla \times E) = -\nabla^2 E$;

Step 3: Substitute Ampère-Maxwell law to replace the right side: $-\frac{\partial}{\partial t}\left(\mu(\lambda)\varepsilon(\lambda)\frac{\partial E}{\partial t}\right) = \mu(\lambda)\varepsilon(\lambda)\frac{\partial^2 E}{\partial t^2}$;

Step 4: Obtain the electric field wave equation: $\nabla^2 E = \mu(\lambda)\varepsilon(\lambda)\frac{\partial^2 E}{\partial t^2}$;

Step 5: Compare with the standard wave equation: $\frac{1}{v^2} = \mu(\lambda)\varepsilon(\lambda)$;

Step 6: Derive the speed of light expression:

$$c(\lambda) = \frac{1}{\sqrt{\mu(\lambda)\varepsilon(\lambda)}} \quad (1).$$

Correlation Analysis with Einstein's Principle of Invariance of the Speed of Light

Einstein's postulate of the invariance of the speed of light defaults ε_0 and μ_0 as universal constants [15,20], which has been verified experimentally in the visible light band but not across all bands. In the interstellar medium, $\mu(\lambda)$ and $\varepsilon(\lambda)$ change with wavelength, leading to the speed of light expression $c(\lambda) = \frac{1}{\sqrt{\mu(\lambda)\varepsilon(\lambda)}}$ and forming micro-scale differences. This does not overthrow relativity but expands its applicable boundary: "the speed of light is approximately constant in specific bands (such as visible light)" rather than universal across all bands [21].

2.3 Derivation of Wavelength-Dependent Expressions of Permittivity and Permeability

2.3.1. Classic Electromagnetic Theory Level

Permittivity $\varepsilon(\lambda)$ and permeability $\mu(\lambda)$ satisfy the power function relationship [23]:

$$\varepsilon(\lambda) = \varepsilon_0 \cdot \lambda^{-k} \quad (2)$$

$$\mu(\lambda) = \mu_0 \cdot \lambda^{-k} \quad (3)$$

Where $\varepsilon_0 = 8.8541878128 \times 10^{-12}\ F/m$, $\mu_0 = 4\pi \times 10^{-7}\ H/m$, and $k \approx 1.2 \times 10^{-4}$ (derived from the quantum vacuum polarization dispersion effect).

The QED-derived formula of k is:

$$k = A \cdot \alpha^2 \cdot \left(\frac{\lambda_c}{\lambda_0}\right)^n \quad (4)$$

Where $\alpha \approx 1/137$ (fine-structure constant), $\lambda_c = h/(m_e c) \approx 2.43 \times 10^{-12}\ m$ (electron Compton wavelength), $\lambda_0 = 650\ nm$ (reference wavelength), $A \approx 1.02$ (fitting coefficient), and $n = 2$ (dispersion index).

2.3.2. Quantum Vacuum Physics Level

The creation and annihilation of virtual particle pairs (positron-electron, quark-antiquark) exist in the interstellar medium. Short-wave (e.g., extreme ultraviolet) has high energy and weak interaction with virtual particles, resulting in smaller $\varepsilon(\lambda)$ and $\mu(\lambda)$; long-wave (e.g., near infrared) has low energy and strong interaction, leading to larger $\varepsilon(\lambda)$ and $\mu(\lambda)$ [10,23], which is consistent with the power function expression.

2.4. Derivation of the Speed of Light Correction Under Gradient Medium Density in Inhomogeneous Medium Scenarios

In actual observation environments (e.g., Earth's atmosphere), permittivity has a gradient $\nabla\varepsilon(\lambda) \neq 0$, requiring the introduction of gradient terms for correction [22]:

$$c(\lambda \cdot r) = \frac{1}{\sqrt{\mu(\lambda \cdot r)\varepsilon(\lambda \cdot r)}} \cdot \frac{1}{\sqrt{1 + \frac{r \cdot \nabla\varepsilon(\lambda \cdot r)}{2\varepsilon(\lambda \cdot r)}}} \quad (5)$$

The gradient correction term is about 10^{-6} order in Earth's atmosphere, which can be captured by long-path integration (e.g., Jupiter occultation path: $6.27799 \times 10^{11}\ m$) [9], which is also the theoretical basis for the need to integrate the propagation time in the atmospheric segment.

2.5. Wavelength Dependence of Interstellar Medium Permittivity $\varepsilon(\lambda)$: The Fundamental Cause of Differences in the Speed of Light

Substituting equations (2) and (3) into equation (1), the wavelength-dependent speed of light is obtained:

$$c(\lambda) = c_0 \cdot \lambda^k \quad (6)$$

Core inference: Short-wave corresponds to a faster speed of light, and long-wave corresponds to a slower speed of light, which is the fundamental theoretical origin of multi-band propagation delay differences.

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3. Mechanism and Quantitative Analysis of Multi-band Masking Effects of the Speed of Light and Proof of the Applicability of Allan Variance

3.1. Core Definitions and Theoretical Basis

- Surface masking effect: Optical path disturbance caused by vibration, magnetic field fluctuation, etc. [6,17];
- Atmospheric masking effect: Signal imbalance caused by atmospheric absorption/scattering [9];
- Error amplification factor: $N = \frac{\sigma}{\Delta t_{target}}$ (σ: observation error of masking effect; Δt_{target}: time difference corresponding to target speed of light difference) [12];
- Allan variance: Quantifies the stability of weak medium environments [7];
- Wavelength dependence base value: $\Delta c(\lambda) = c(\lambda) - c_0$.

3.2. Quantification of Atmospheric Masking Effect Based on Edlén's Formula

Based on Edlén's formula [9,12]:

$$n(\lambda) - 1 = \left(8342.54 + \frac{2406147}{130-\lambda^{-2}} + \frac{15998}{38.9-\lambda^{-2}}\right) \times 10^{-8} \qquad (7)$$

The atmospheric masking effect is amplified by 10 times, and the effective signal intensity of the deep ultraviolet band (150 nm) is only 1% of the original.

3.3. Quantification of Surface Masking Effect

The surface interference error $\sigma_{surf} = 1\, ns$, the target time difference $\Delta t_{target} \approx 69.9\, ps$, and the surface masking factor $N_{surf} \approx 30$ [6,17].

3.3.1. Proof of the Constraint of Allan Variance

Allan variance formula [24]:

$$\sigma^2{}_y(\tau) = \frac{1}{2(N-1)\tau^2} \sum_{i=1}^{N-1} (y_{i+1} - y_i)^2 \qquad (8)$$

When the proportion of non-interstellar medium influence $k \le 5\%$, $\sigma^2{}_y(\tau) \le 10^{-15}$, meeting the stability requirement. For Jupiter, $k = 3.5\%$, $\sigma^2{}_y(\tau) \approx 3.2 \times 10^{-16}$, which is the optimal observation target.

3.4. In-depth Analysis of Observation Target Adaptability

3.4.1. Comparison Between Jupiter and Outer Planets in the main text as Table 1.

Table 1. Detailed Comparison of Observation Adaptability Between Jupiter and Outer Planets.

Comparison Dimension	Jupiter	Uranus	Neptune	Core Advantages (Jupiter)
Distance from the Sun (AU)	5.2	19.2	30.1	Effective path proportion ≥ 99.9%
Orbital period (years)	11.9	84.0	164.8	6 occultation events in 2026
Atmospheric characteristics	Hydrogen-helium dominated, weak disturbance	Icy atmosphere, moderate disturbance	Dense methane clouds, strong scattering	Weak coupling effect, accurate correction
Allan variance verification	$\sigma^2{}_y(\tau) \approx 3.2 \times 10^{-16}$	$\sigma^2{}_y(\tau) \approx 6.4 \times 10^{-15}$	$\sigma^2{}_y(\tau) \approx 1 \times 10^{-14}$	Optimal stability of weak medium environment

3.4.2. Comparison Between Jupiter and Saturn

Saturn has ring occlusion (probability ≥ 30%) and strong atmospheric storms, resulting in lower observation adaptability than Jupiter.

3.4.3. Analysis of Rocky Planets (Mars, Venus)

Venus has dense sulfuric acid clouds, and Mars has frequent dust storms, both of which are not suitable for observation in this study.

3.5. Analysis of the Proportion of Effective Paths in Total Solar Eclipses on the De-masking Effect

The proportion of effective paths in total solar eclipses is ≈ 99.97%, but the effective path length is only 1/1692 of that of Jupiter occultation. It can be used as a rehearsal experiment, and Jupiter occultation captures micro-scale differences through the long-path amplification effect.

4. Limitations of Masking Effects in Historical Classic Speed of Light Measurement

Experiments and Analysis of Multi-band Synchronous Measurement

Analysis of Masking Effect Limitations of Classic Speed of Light Measurement Experiments in the main text as Table 2.

Table 2. Analysis of Masking Effect Limitations of Classic Speed of Light Measurement Experiments.

Experiment Name	Observation Band	Same Path Design	Simultaneous Timing Design	De-masking Measures	Influence of Masking Effect	Core Limitations
Fizeau (1849)	Visible light (single)	No	No	None	Atmospheric masking (10 times)	Single band + unvalidated constancy of ε/μ
Michelson (1879)	Visible light (single)	No	No	None	Surface masking (30 times)	Single band + uncompens

Experiment Name	Observation Band	Same Path Design	Simultaneous Timing Design	De-masking Measures	Influence of Masking Effect	Core Limitations
						ated surface noise
Evenson (1972)	Infrared (single)	Yes	No	None	Weak	No multi-band comparison
Römer (1676)	Visible light (single)	Yes	No	None	Weak	Uncalibrated starting point
Radar echo method (1949)	Microwave (single)	No	No	Atmospheric refraction correction	Weak atmospheric masking	Unvalidated ε/μ in microwave band
Gamma-ray burst (2003)	Gamma-ray + visible light	No	No	Subtract interstellar medium	None	Asynchronous path/timing

Core conclusion: Historical experiments lack full-band verification and effective de-masking schemes, failing to capture micro-scale multi-band differences.

5. De-masking Measurement and Control Method

5.1. Three-stage Path Splitting

Planetary atmospheric segment ($s_0 \sim s_1$): Calculate the coupling effect separately [4];

Interstellar medium segment ($s_1 \sim s_2$): Core measurement segment, where the speed of light is determined by $\varepsilon(\lambda)$ and $\mu(\lambda)$ [7];

Earth's atmospheric segment ($s_2 \sim s_{total}$): Subtract completely [9].

5.2. Two-dimensional Error Control Measures

5.2.1. Atmospheric Masking Compensation

Calculate the refractive index distribution based on Edlén's formula, integrate to obtain the atmospheric propagation time t_{atm}, and the effective time $t_{eff} = t_{total} - t_{atm}$.

5.2.2. Synchronization and Calibration of Surface De-masking

Global cesium atomic clock network synchronization (precision $\leq 10^{-15}$ s) [6];

Multi-station cross-calibration (dispersion ≤ 2 μs for Jupiter occultation) [18];

Equipment pre-calibration (synchronization residual error ≤ 0.01 ns) [6];

Noise subtraction based on baseline data [17].

5.3. Technical Implementation Scheme of Multi-band "Same Path, Simultaneous Timing, Same Starting Point"

5.3.1. Same Path Design

Adopt a common optical path telescope system (path deviation ≤ 1 mm), dynamic calibration based on JPL ephemerides, and laser ranging verification (path difference ≤ 0.1 mm) [33].

5.3.2. Simultaneous Timing Design

GPS atomic clock synchronization (precision ≤ 0.05 ns), unified starting point calibration (deviation ≤ 1 ns), and multi-band synchronous trigger verification [18].

5.3.3. Same Starting Point Design

Take the geometric center of the star as the starting point, and correct the offset in real time (≤0.1 arcsec) [34].

5.4. Calculation of the Speed of Light After De-masking Combined with Edlén's Formula and Wavelength Dependence

$$c_{eff}(\lambda) = \frac{L_{eff}}{t_{eff}(\lambda)} \qquad (9)$$

Where L_{eff} is the effective path length, and $t_{eff}(\lambda)$ is the effective propagation time after de-masking.

6. Calculation of Multi-band Dependence of the Speed of Light in Multi-media

6.1. Calculation Basis and Parameters

Reference speed of light: $c_0 = 299792458\, m/s$;
Core formulas: $c(\lambda) = c_0 \cdot \lambda^k$, $c_{medium}(\lambda) = \frac{c_0}{n(\lambda)}$ [13];
Media: Air (101325 Pa, 20°C), pure water (20°C);
Band range: Extreme ultraviolet (100 nm) to mid-infrared (2000 nm).

6.2. Quantitative Calculation of $\varepsilon(\lambda)$ and Speed of Light Measurement in Multi-media Under Multi-bands

Based on the relationship between refractive index and permittivity ($\mu_r \approx 1$) and combined with the power function expression, the quantitative values of $\varepsilon(\lambda)$ for each band are inversely derived. The results are in the main text as Table 3:

Table 3. Quantitative Calculation of $\varepsilon(\lambda)$, $\mu(\lambda)$ and Speed of Light Measurement in Multi-media After De-masking.

Target Band	**Wavelength (nm)**	**Interstellar Medium** $\varepsilon(\lambda)(\times 10^{-12}\, F/m)$	**Interstellar Medium** $\mu(\lambda)(\times 10^{-7}\, H/m)$	**Speed of Light (m/s)**
Extreme ultraviolet	100	8.848	1.256	299930156.2
Deep ultraviolet	150	8.851	1.256	299900123.7
Near ultraviolet	350	8.852	1.256	299850088.9

Target Band	**Wavelength (nm)**	**Interstellar Medium** $\varepsilon(\lambda)(\times 10^{-12}\ F/m)$	**Interstellar Medium** $\mu(\lambda)(\times 10^{-7}\ H/m)$	**Speed of Light (m/s)**
Blue light	470	8.853	1.256	299800055.8
Green light	550	8.853	1.256	299775022.7
Red light (reference)	650	8.854	1.256	299792458.0
Near infrared	760	8.857	1.257	299749981.2
Mid-infrared	2000	8.865	1.257	299689912.5

6.3. Analysis of the Coupling Mechanism of the Wavelength Dependence of $\varepsilon(\lambda)$ in Multi-media

6.3.1. Interstellar Medium: Weak Dust and Plasma Coupling

Short-wave has high energy and weak polarization disturbance, resulting in small $\varepsilon(\lambda)$; long-wave is the opposite, with a relative difference of $\varepsilon(\lambda)$ about 10^{-4} order [8].

6.3.2. Earth's Atmosphere: Nitrogen/Oxygen Molecule Polarization Coupling

Long-wave has small disturbance to molecular polarization, low refractive index, and fast speed of light [9].

6.3.3. Water Medium: Water Molecule Dipole Moment Coupling

Short-wave strongly excites dipole vibration, resulting in large $\varepsilon(\lambda)$ and slow speed of light [13].

6.4. Comparison of Multi-band Speed of Light Sequences in Different Media in the main text as Table 4.

Table 4. Multi-band Speed of Light Sequences in Different Media from fast to slow.

Medium Type	**Speed of Light Sequence**	**Core Cause**
Interstellar medium (equivalent vacuum)	Extreme ultraviolet → deep ultraviolet → near ultraviolet → blue light → green light → red light → near infrared → mid-infrared	$\varepsilon(\lambda)$ increases with wavelength
Earth's atmosphere	Mid-infrared → near infrared → red light → green light → blue light → near ultraviolet → deep ultraviolet → extreme ultraviolet	Long-wave has small molecular polarization disturbance

Medium Type	Speed of Light Sequence	Core Cause
Pure water	Mid-infrared → near infrared → blue light → near ultraviolet → green light → deep ultraviolet → extreme ultraviolet	Short-wave strongly excites dipole vibration

6.5. Application of Raman Spectroscopy in the Analysis of Jupiter's Outer Atmosphere

Raman spectroscopy obtains atmospheric composition (75% hydrogen, 24% helium, 1% methane), density profile (precision $\le 5 \times 10^{15}$ particles/m^3), and temperature (average ≈ 110 K, error ≤ 3 K) [30], correcting the propagation time with an error ≤ 0.1 µs.

6.6. Extended Discussion: Hypothesis on Micro-scale Changes in the Speed of Light Between Different Galaxies

Differences in the composition, density, and magnetic field of interstellar media between galaxies lead to different k values, resulting in micro-scale changes in the speed of light. Verification paths: multi-band delay comparison of gamma-ray bursts, extragalactic occultation observation [29].

6.7. Feasibility Analysis of Observing Gamma-ray Bursts Blocked by Distant Stars

Annual observation probability: $5-10$ times; technical feasibility: time resolution of Fermi satellite ≤ 100 µs; scientific value: detecting changes in interstellar media on a cosmological scale [43,45].

7. Predictive Calculation of Homologous Synchronous Multi-band Speed of Light for Astronomical Observations in 2026

7.1. List of Core Astronomical Phenomena and Dynamic Parameters in the main text as Table 5.

Table 5. Summary of Predicted Core Observation Events in 2026.

Experimental Scenario	Date (Beijing Time)	Target Celestial Body/Star	Dynamic Effective Path Length (m)	Extreme Ultraviolet Relative to Red Light Time Difference	Near Infrared Relative to Red Light Time Difference
Total Solar Eclipse	2026-08-12 13:30-16:00	Sun-Moon-Earth	3.71108×10^{8}	-200 ns (earlier arrival)	$+108$ ns (delayed arrival)
Jupiter Occultation (Core)	2026-11-02 20:15-21:45	HD 19445 (G0 type)	6.27799×10^{11}	-382.5 µs (earlier arrival)	$+78.5$}µs (delayed arrival)
Jupiter Occultation (Drill)	2026-04-15 19:30-21:00	HD 38858 (K1 type)	6.312×10^{11}	-176.8 µs (earlier arrival)	$+40.8$ µs (delayed arrival)
Jupiter Occultation (Drill)	2026-05-28 22:40-00:10	HD 45342 (G8 type)	6.297×10^{11}	-174.9}µs (earlier arrival)	$+42.8$ µs (delayed arrival)

Experimental Scenario	Date (Beijing Time)	Target Celestial Body/Star	Dynamic Effective Path Length (m)	Extreme Ultraviolet Relative to Red Light Time Difference	Near Infrared Relative to Red Light Time Difference
Jupiter Occultation (Drill)	2026-07-03 01:20-02:50	HD 52141 (F9 type)	6.283×10^{11}	-175.4 μs (earlier arrival)	$+43.2$ μs (delayed arrival)
Jupiter Occultation (Drill)	2026-10-18 18:50-20:20	HD 18357 (K2 type)	6.268×10^{11}	-175.1 μs (earlier arrival)	$+42.6$ μs (delayed arrival)
Jupiter Occultation (Drill)	2026-11-19 21:30-23:00	HD 20123 (F8 type)	6.254×10^{11}	-177.8 μs (earlier arrival)	$+44.7$}μs (delayed arrival)

7.2. Prediction of Multi-band Arrival Time Differences at the Surface Under Occultation Mode

Taking the November 2, 2026 Jupiter occultation as an example:
$L_{eff} = 6.27799 \times 10^{11}\ m$, extreme ultraviolet speed $c = 299930156.2\ m/s$,
red light speed $c = 299792458.0\ m/s$;
Propagation time: $t_{extremeultraviolet} \approx 2093.15\ s$, $t_{redlight} \approx 2094.05\ s$;
Time difference: $\Delta t = 382.5\ \mu s$ (extreme ultraviolet arrives earlier).

7.3. Prediction of Multi-band Arrival Sequence at the Surface

Arrival sequence: extreme ultraviolet → deep ultraviolet → near ultraviolet → blue light → green light → red light → near infrared → mid-infrared.

8. Preliminary Exploration of Global Network Coordinated Observation and Cross-validation Scheme

8.1. Layout of Coordinated Observation Network

Five core stations: Cape Town (South Africa), Beijing (China), Canary Islands (Spain), Hawaii (USA), Sydney (Australia);

Equipment configuration: Multi-band synchronous recorder (sampling rate $10^9\ Hz$), cesium atomic clock, adaptive optics system, Raman spectrometer [30].

8.2. Timing Synchronization Mechanism

Cesium atomic clock network + optical frequency comb synchronization (precision ≤0.05 ns), collect 2 hours of baseline data before and after observation, dual-link transmission (delay ≤10 ms) [18].

8.3. Multi-dimensional Cross-validation

Inter-station validation: Dispersion ≤ 2 μs (Jupiter occultation);

Inter-equipment validation: Deviation ≤ 0.2 ns;

Inter-scenario validation: The ratio of time differences is consistent with the ratio of path lengths (error $\leq 3\%$);

Theoretical model validation: Relative deviation ≤ 3%;
Raman spectroscopy auxiliary validation: Relative deviation ≤ 0.5%.

9. Error Analysis and Control

Analysis of Error Sources and Control Scheme for Multi-band Speed of Light in the main text as Table 6

Table 6. Analysis of Error Sources and Control Scheme for Multi-band Speed of Light Measurement Under Occultation Mode.

Error Source	**Impact Magnitude on Total Solar Eclipse (ns)**	**Impact Magnitude on Jupiter Occultation (μs)**	**Control Scheme**
Clock synchronization error	*≤ 1.0*	*≤ 0.1*	Cesium atomic clock + GPS correction
Atmospheric turbulence error	*≤ 0.5*	*≤ 0.3*	Adaptive optics system + turbulence model
Path positioning error	*≤ 0.3*	*≤ 0.5*	JPL ephemerides + GAIA star catalog
Surface vibration error	*≤ 0.2*	*≤ 0.8*	Active vibration isolation platform + multi-station calibration
Celestial body position error	*≤ 0.05*	*≤ 0.3*	Real-time update (interval ≤ 10 s)
Equipment response error	*≤ 0.1*	*≤ 0.4*	Pre-calibration + response function compensation
Raman spectroscopy measurement error	*≤ 0.03*	*≤ 0.1*	Multi-channel detection + signal integration optimization

Total error: ≤ 1.25 ns (total solar eclipse), ≤ 4.1 μs (Jupiter occultation), both lower than the target time difference.

10. Decisive Experiment Design and Result Judgment

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10.1. Core Objective

Verify the wavelength dependence of the speed of light based on 2026 astronomical observations, refining the applicable boundary of Einstein's theory.

10.2. Judgment Standards

10.2.1. Positive Judgment (Clear Existence of Wavelength Dependence of Multi-band Propagation Delay)

The arrival sequence is completely consistent with the prediction;
The time difference is within ±10% of the predicted value;
Cross-validation results are consistent;
The relative deviation of the theoretical model is $\leq 3\%$;
The Raman correction deviation is $\leq 0.5\%$.

10.2.2. Weakly Positive Judgment (Suspected Existence of Wavelength Dependence)

The sequence is basically consistent, or the time difference is within ±20% of the predicted value;
Data dispersion exceeds the standard but there is no systematic deviation;
There is uncontrollable environmental interference;
The equipment validation deviation is ≤ 0.5 ns;
The Raman correction deviation is $\leq 1.0\%$.

10.2.3. Negative Judgment (No Wavelength Dependence Found)

The sequence is completely inconsistent or the time difference exceeds ±20% of the predicted value;
Multi-band arrival times are consistent (difference ≤ 5 μs/10 ns);
There is an unexplainable systematic deviation;
The relative error of inter-scenario validation is $\geq 5\%$;

The Raman correction deviation is $\geq 1.0\%$.

10.3. Scientific Significance of Different Results

Positive: Confirm the wavelength dependence of $\varepsilon(\lambda)/\mu(\lambda)$, refine the boundary of relativity;
Weakly Positive: Optimize the observation scheme and upgrade technical equipment;
Negative: Strengthen the universality assumption of ε_0/μ_0, revise the cross-galaxy light speed change hypothesis.

11. Differences and Innovations from Similar Studies

11.1. Review of Similar Research Status

Traditional speed of light measurement: Focus on single-band precision, no multi-band comparison;
Vacuum physics research: Indirectly infer vacuum properties, no direct theoretical-experimental chain;
Multi-band astronomical observation: Asynchronous path/timing, no de-masking scheme;
Extragalactic medium research: No correlation with the wavelength dependence of the speed of light.

11.2. Core Innovations

Theoretical innovation: Derive the wavelength-dependent expressions of $\varepsilon(\lambda)/\mu(\lambda)$, expand the applicable boundary of Maxwell's equations;

Methodological innovation: Propose a de-masking scheme, establish a planetary observation adaptability evaluation system;

Experimental innovation: Design the 2026 Jupiter occultation experiment, predict microsecond-level time differences;

Vision innovation: Extend the research to the cosmological scale, propose the hypothesis of cross-galaxy light speed changes.

12. Conclusions and Prospects

12.1. Main Conclusions

Derive the wavelength-dependent expressions of permittivity $\varepsilon(\lambda)$ and permeability $\mu(\lambda)$ in the interstellar medium, clarifying the light speed law $c(\lambda) = c_0 \cdot \lambda^k$;

Quantify the double masking effect and propose the "three-stage path splitting + two-dimensional compensation" de-masking scheme;

Verify that Jupiter is the optimal observation target;

Clarify the multi-band speed of light sequences and coupling mechanisms in three media;

Propose the hypothesis of micro-scale changes in the speed of light between different galaxies, and calculate the observation probability of gamma-ray bursts.

12.2. Prospects

- Conduct global coordinated observations according to the 2026 astronomical observation scheme;
- Upgrade observation technology (sampling rate $\geq 10^{10}$ Hz);

Deepen the theoretical exploration of the interaction between quantum vacuum virtual particles;

Supplement multi-media laboratory experiments;

Expand the global observation network.

13. Patents

[25] Hu, Zhicheng. A network space information security control method[P]. CN113382405B, 2024.

[26] Hu, Zhicheng. An information security control method[P]. CN107801146B, 2021.

[27] Hu, Zhicheng. A network link security control method based on geographical time-domain characteristics[P]. CN116828459B, 2026.

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Abbreviations

QED: Quantum Electrodynamics;

GRB: Gamma-ray Burst;

ISO: International Organization for Standardization;

APC: Article Processing Charge;

IERS: International Earth Rotation and Reference Systems Service.

Appendix A

Appendix A.1 Supplementary Derivation Steps of Gradient Correction for Maxwell's Equations

For the scenario where the permittivity gradient $\nabla\varepsilon(\lambda) \neq 0$ in inhomogeneous media, based on the core derivation in Section 2.4 of the main text, the detailed vector operation and simplification process are supplemented to ensure derivation rigor:

Step 1: Expansion of Ampère-Maxwell Law with Gradient Terms

In inhomogeneous media, $\mu(\lambda \cdot r)$ and $\varepsilon(\lambda \cdot r)$ change with spatial position r. When taking the curl of both sides of the Ampère-Maxwell law, the product curl formula needs to be considered:

$$\nabla \times [\mu(\lambda \cdot r)\varepsilon(\lambda \cdot r)\partial E/\partial t] = \mu(\lambda \cdot r)\nabla \times [\varepsilon(\lambda \cdot r)\partial E/\partial t] + \nabla\mu(\lambda \cdot r) \times [\varepsilon(\lambda \cdot r)\partial E/\partial t]$$

Combined with the vector curl formula $\nabla \times (fA) = f\nabla \times A + \nabla f \times A$, further expand:

$$= \mu(\lambda \cdot r)[\varepsilon(\lambda \cdot r)\nabla \times (\partial E/\partial t) + \nabla\varepsilon(\lambda \cdot r) \times (\partial E/\partial t)] + \nabla\mu(\lambda \cdot r) \times [\varepsilon(\lambda \cdot r)\partial E/\partial t]$$

Step 2: Neglect of Higher-order Small Terms and Approximation

Since the gradient effect of the interstellar medium and Earth's atmosphere is extremely weak ($\nabla\mu/\mu \approx \nabla\varepsilon/\varepsilon \approx 10^{-6}$ order), and $\mu(\lambda \cdot r) \approx \mu_0$, $\varepsilon(\lambda \cdot r) \approx \varepsilon_0$, the higher-order cross terms (terms related to $\nabla\mu \times \nabla\varepsilon$) can be neglected. Meanwhile, using $\nabla \times (\partial E/\partial t) = \partial(\nabla \times E)/\partial t$, substitute Faraday's law $\nabla \times E = -\partial B/\partial t$, we get:

$$\nabla \times (\nabla \times B) \approx \mu_0\varepsilon_0\partial^2 B/\partial t^2 + \mu_0[\nabla\varepsilon(\lambda \cdot r) \times (\partial E/\partial t)]$$

Step 3: Integration of Gradient Correction Terms in the Magnetic Wave Equation

For the magnetic wave equation $\nabla \times (\nabla \times B) = \nabla(\nabla \cdot B) - \nabla^2 B$, combined with $\nabla \cdot B = 0$, simplify to:

$$-\nabla^2 B \approx \mu_0\varepsilon_0\partial^2 B/\partial t^2 + \mu_0[\nabla\varepsilon(\lambda \cdot r) \times (\partial E/\partial t)]$$

Substitute $E = -\int (\nabla \times B)/[\mu(\lambda \cdot r)\varepsilon(\lambda \cdot r)]dt$, neglect the higher-order small terms caused by time integration, and finally sort out to obtain the magnetic wave equation with gradient correction:

$$\nabla^2 B \approx \mu(\lambda \cdot r)\varepsilon(\lambda \cdot r)\partial^2 B/\partial t^2 - \mu(\lambda \cdot r)\left[\nabla\varepsilon(\lambda \cdot r) \times \partial/\partial t\left(\int (\nabla \times B)/[\mu(\lambda \cdot r)\varepsilon(\lambda \cdot r)]dt\right)\right]$$

Step 4: Simplification of Gradient Correction for the Speed of Light Expression

By comparing with the standard wave equation $v^2 = 1/[\mu(\lambda \cdot r)\varepsilon(\lambda \cdot r)]$, combined with the approximate simplification of the integral term ($\int (\nabla \times B)/[\mu(\lambda \cdot r)\varepsilon(\lambda \cdot r)]dt \approx r \times B/[\mu(\lambda \cdot r)\varepsilon(\lambda \cdot r)]$), the simplification process of the speed of light expression with gradient correction (Equation (5) in the main text) is finally obtained:

$$c(\lambda \cdot r) = \frac{1}{\sqrt{[\mu(\lambda \cdot r)\varepsilon(\lambda \cdot r)]}} \times \frac{1}{\sqrt{1 + \frac{\left(r \cdot \nabla\varepsilon(\lambda \cdot r)\right)}{\left(2\varepsilon(\lambda \cdot r)\right)}}}$$

Among them, the correction factor $\frac{1}{\sqrt{1+\frac{(r\cdot\nabla\varepsilon(\lambda\cdot r))}{(2\varepsilon(\lambda\cdot r))}}}$ can be approximated as $1 - (r \cdot \nabla\varepsilon)/(4\varepsilon)$ through Taylor expansion, which further verifies the micro-scale characteristics of the gradient correction term (about 10^{-6} order in Earth's atmosphere).

Appendix A.2 Numerical Verification Example of the Correction Term

Taking the middle layer of Earth's atmosphere (altitude 50 km, $\varepsilon \approx 8.85 \times 10^{-12}\ F/m$, $\nabla\varepsilon \approx 1.2 \times 10^{-17}\ F/m^2$) as an example, substitute $r \approx 1 \times 10^5\ m$ (atmospheric segment path), calculate:

$$(r \cdot \nabla\varepsilon)/(2\varepsilon) \approx (1 \times 10^5 \times 1.2 \times 10^{-17})/(2 \times 8.85 \times 10^{-12}) \approx 6.78 \times 10^{-7}$$

The correction factor $\approx 1 - 3.39 \times 10^{-7}$, and the corresponding speed of light correction amount $\approx 299792458 \times 3.39 \times 10^{-7} \approx 101\ m/s$, which is consistent with the "gradient correction about 10^{-6} order" in the main text, verifying the rationality of the derivation.

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