Thermodynamic Signatures and Information-Theoretic Constraints in SETI: A Multi-Messenger Approach

Abstract

With the deep exploration of exoplanet atmospheres by the James Webb Space Telescope (JWST) and the discovery of anomalous physical properties of interstellar meteors (such as IM1), the Search for Extraterrestrial Intelligence (SETI) is undergoing a paradigm shift from radio detection to the identification of multimodal technosignatures. This paper proposes a comprehensive detection framework integrating thermodynamics, astrophysics, and information theory.

First, based on the high-intensity kinetic parameters and the "BeLaIu"-type chemical abundance pattern of the interstellar meteor CNEOS 2014-01-08 (IM1), this study explores the possibility of high-strength metal components serving as technological probes.

Secondly, combining the latest multi-band observational data of the interstellar object 3I/ATLAS discovered in 2025, and addressing the Radio Silence phenomenon confirmed by the *Breakthrough Listen* project alongside the anomalous chemical non-equilibrium state exhibited in its spectrum, this paper constructs a discriminant model based on High-Albedo and thermodynamic entropy reduction characteristics. It demonstrates the observational criteria for distinguishing natural differentiated fragments from "silent" technological components in the absence of active communication signals.

At the theoretical level, this paper reconstructs the Kardashev scale based on the

Second Law of Thermodynamics, defining technological activity as entropy-reducing behavior at specific spatial scales, and provides quantitative indicators for the infrared excess (IR Excess) and atmospheric chemical non-equilibrium states required to detect Type I, II, and III civilizations.

Finally, addressing the Fermi Paradox, this paper introduces the Manifold Projection theory from information theory, proposing an "Information Collapse" model in cross-dimensional communication, and demonstrating the physical inevitability that low-dimensional observers cannot fully decode high-dimensional semantics. This study aims to provide observational constraints based on physical first principles for next-generation sky survey projects.

Keywords: Technosignatures; Interstellar Objects; Thermodynamic Entropy; Information Collapse; Non-equilibrium Atmosphere

1. Introduction: The Great Silence and "Their" Return

1.1 A Modern Interpretation of the Fermi Paradox

Since Enrico Fermi posed the question "Where is everybody?" in 1950, the Fermi Paradox has been the core logical contradiction in the Search for Extraterrestrial Intelligence (SETI). In the approximately 13.6 billion year history of the Milky Way, even at sub-light navigation speeds, advanced civilizations should have had sufficient time to spread throughout the entire galaxy **(Berezin, 2018)**. However, long-term radio silence has led to the "Great Silence" phenomenon.

Modern astrophysics offers several explanations for this: first, the Great Filter theory suggests that civilizations must encounter some bottleneck leading to extinction before evolving to the interstellar stage; second is the Zoo Hypothesis, where advanced civilizations are in the position of observers, intentionally avoiding direct contact with lower civilizations. This paper proposes a third possibility: signals are not non-existent, but rather human detection technology is currently unable to identify high-dimensional or cross-dimensional information transmission.

1.2 From "Searching for Life" to "Defining Civilization"

Traditional search targets have focused on the microbial level (such as Mars soil sampling), but with precise measurements of the atmospheric spectra of planets like Kepler-22b by JWST, the research focus is shifting toward Technosignatures. This paradigm shift requires us to define "civilization" as technological entities capable of modifying their host star system's environment on a large scale and leaving behind infrared radiation anomalies (such as Dyson Sphere structures) or industrial chemical footprints (such as CFCs).

1.3 Core Arguments

This paper argues that extraterrestrial intelligent life is not an illusory concept far away in the sky. From the engineering miracles of ancient ruins to the non-Newtonian flight characteristics exhibited by modern UAP, various signs indicate that extraterrestrial civilizations may have already become deeply intertwined with human civilization through technological observation or physical intervention.

2. The Biological Blueprint of Extraterrestrial Life

2.1 The "Universal Language" of Life

Although carbon-based life forms are the only currently known life forms due to the extremely strong bonding ability of carbon atoms, non-carbon-based life possesses theoretical plausibility under different physicochemical conditions.

- **Silicon-based life:** Silicon is in the same group as carbon and may form stable polymer chains in high-temperature and high-pressure environments (such as the interior of certain super-Earths).
- **Solvent substitution:** On extremely cold planets (such as Titan), liquid methane or ethane may replace water (H_2O) as the solvent for biochemical reactions.
- **Energy bodies and plasmas:** In extreme magnetic fields or stellar atmospheres, life may exist as ordered electromagnetic field structures.

2.2 The Morphological Evolutionary Logic of Alien Organisms

Based on principles of evolutionary biology, the morphology of alien organisms is strictly limited by the environmental parameters of their home planet.

Table 1 | Morphological Evolutionary Logic.

Environmental Parameter	**Deduced Morphological Features**
High Gravity Environment	Short, multi-limbed structures; extremely high bone density to support self-weight.
High Density Atmosphere	Development of streamlined or inflatable floating mechanisms; enhanced sound sensing capabilities.
Red Dwarf Illumination	Retinal photosensitivity shifts toward the infrared band; skin may possess more efficient radiation-absorbing

	pigments.

2.3 Insights from Extremophiles

Extremophiles on Earth—such as hyperthermophiles living in deep-sea hydrothermal vents and anaerobes under the Antarctic ice sheet—prove the tenacity of life in extreme environments. This provides strong analogical support for the existence of multicellular organisms in the subsurface oceans of Europa or Enceladus. Through in-situ detection technologies like Cryobots, we hope to verify predictions from these "alien simulators" within the next decade.

3. Physical Constraints on Anomalous Atmospheric Kinematics

Before discussing specific kinematic constraints, it is crucial to distinguish between two distinct scales of technosignatures. On one hand, as detailed in Section 5, interstellar objects like 3I/ATLAS exhibit mild, continuous non-gravitational acceleration consistent with passive propulsion systems such as light sails. On the other hand, radar observations of UAP phenomena imply a regime of extreme high-energy kinematics. To establish a comprehensive SETI framework, this section introduces metric engineering within General Relativity as a theoretical exploration. This aims to define the physical upper limits of advanced propulsion technologies, distinct from the observational data of 3I/ATLAS, thereby covering the full spectrum from "mild" to "extreme" technosignatures.

3.1 Instantaneous Acceleration and Material Strength Limits

Based on existing radar observational data (e.g., the 2004 Nimitz incident), some unidentified aerial targets exhibit the capability to accelerate from rest to supersonic speeds within $t < 0.1s$. Their estimated acceleration is 7,000 times the acceleration of gravity. Under the framework of classical mechanics, this overload far exceeds the yield strength of any known aircraft material. If observational errors are excluded, this kinematic characteristic implies that the propulsion mechanism must circumvent inertial mass effects.

3.2 Theoretical Propulsion Model: Metric Engineering

To explain the aforementioned high g-force phenomena without violating General Relativity, and to make General Relativity compatible with such observational data, a possible mathematical solution is to introduce an Alcubierre-like metric **(Alcubierre, 1994).** In this model, the object is in a state of geodesic motion, and its local acceleration within proper time is zero:

$$ds^2 = -c^2 dt^2 + [dx - v_s(t)f(r_s)dt]^2 + dy^2 + dz^2$$

This metric structure requires the existence of a negative energy density field or high-frequency gravitational wave effects within local space. For SETI observations, this implies that the detection of such technosignatures should focus on the high-frequency bands of gravitational wave detectors, rather than traditional optical or radio bands.

4. UAP and Alien Tech: The Unfolding "Contact"

4.1 Kinematic Analysis of UAP Physical Properties and the Challenge of Extreme Acceleration

The most significant feature of Unidentified Anomalous Phenomena (UAP) lies in the "Five Observables" they exhibit, particularly instantaneous acceleration and inertialess turns.

4.1.1 Estimation of Kinematic Parameters

According to multiple radar data sources (such as the 2004 USS Nimitz sighting), observed UAPs can accelerate from rest to approximately $M = 20$ (20 times the speed of sound) within $t < 0.1s$.

The average acceleration a can be estimated as:

$$a = \frac{\Delta v}{\Delta t} \approx \frac{6860 m/s - 0 m/s}{0.1 s} = 68,600 m/s^2 \approx 7000g_0$$

Under the classical mechanics framework, any known human aircraft material would undergo structural collapse when subjected to overloads exceeding $100g$, and due to the lack of aero-heating effects and sonic booms, traditional fluid dynamics (Navier-Stokes equations) can no longer describe their motion process.

4.1.2 Inertial Mass Elimination Hypothesis

To explain the above phenomena, this paper introduces local spacetime distortion theories related to the "Alcubierre Metric". It is assumed that UAPs achieve local gravitational shielding by generating high-frequency gravitational waves or strong electromagnetic fields:

$$ds^2 = -c^2 dt^2 + [dx - v_s(t)f(r_s)dt]^2 + dy^2 + dz^2$$

In this model, the object does not "move" through spacetime but "drifts" with a local spacetime bubble, thereby circumventing the acceleration resistance caused by inertial mass.

4.2 Physical Algorithms of Anomalous Technical Features: Reverse Derivation of

Potential Extraterrestrial Technosignatures

Based on the observation of non-Newtonian mechanical characteristics exhibited by Unidentified Anomalous Phenomena (UAP), this section attempts a "reverse engineering" derivation from the perspective of theoretical physics. The focus is on analyzing how to achieve kinetic energy conversion by manipulating local spacetime or electromagnetic fields, and discussing the physical bottlenecks of current materials science (such as anisotropic metamaterials) in mimicking such features.

- **Application of Metamaterials:** In analyzing possible wreckage samples, it was found that their atomic arrangement possesses unnatural anisotropy, capable of achieving perfect electromagnetic wave absorption or deflection at specific frequencies; this is viewed as a conceptual technical source for flight platforms like the B-2 stealth bomber or TR-3B.
- **Reverse Conversion of Propulsion Systems:** Research focuses on how to efficiently convert nuclear energy or vacuum zero-point energy (ZPE) into kinetic energy. Compared to human chemical rockets (specific impulse $I_{sp} \approx 450s$), alien spacecraft may employ Magnetohydrodynamic (MHD) propulsion, eliminating shockwave drag by ionizing the surrounding medium.

5. Three Interstellar Objects Discovered by Humanity

Since 2017, humanity has possessed the ability to directly observe "uninvited guests" traversing the solar system for the first time.

5.1 October 2017: 1I/ ‘Oumuamua

As the first interstellar object discovered by humanity, ‘Oumuamua exhibited extreme elongation ratios and non-gravitational acceleration. Harvard astronomer Avi Loeb proposed that due to the anomalous propulsion it exhibited while leaving the sun, the possibility of it being some form of "solar sail" artificial component cannot be ruled out **(Bialy and Loeb, 2018)**.

5.2 August 2019: 2I/Borisov

Unlike ‘Oumuamua, Borisov exhibited typical cometary features, possessing a distinct coma and tail. It represents pure natural interstellar matter, providing a direct sample for studying the chemical abundances of other star systems **(Guzik et al., 2020)**.

5.3 July 2025: Multi-Messenger Observational Analysis of 3I/ATLAS (C/2025 N1)

5.3.1 Discovery and Anomalous Orbital Characteristics

On July 1, 2025, the ATLAS survey system at the Chile station captured the third interstellar visitor for the first time, subsequently designated by the International Astronomical Union (IAU) as 3I/ATLAS (C/2025 N1) **(ATLAS Collaboration, 2025; NASA/JPL, 2025)**. The object entered the inner solar system at a hyperbolic excess speed of approximately 60 km/s, with an orbital eccentricity $e \approx 1.2$, and passed perihelion ($q \approx 1.4 \text{ AU}$) on October 29, 2025.

Similar to 1I/ ‘Oumuamua, 3I/ATLAS exhibited extremely significant non-gravitational acceleration, which could not be explained solely by its weak coma outgassing model **(Loeb, 2025)**. Dynamic inversion showed that the radiation pressure effect it experienced far exceeded that of ordinary rock or icy core bodies, suggesting it possesses an extremely high Area-to-Mass Ratio.

5.3.2 Empirical Evidence of the "Great Silence": Radio Silence and Spectral Enigmas

Targeting the close flyby of this object (passing Earth at a distance of 1.8 AU on December 19, 2025), the Breakthrough Listen project conducted a full-band listening campaign using the Green Bank Telescope (GBT). The latest report released in January 2026 confirmed that no narrowband artificial signals were detected in the 1-110 GHz range **(Breakthrough Listen Team et al., 2026)**. This "Null Result" ruled out the possibility of it being an active broadcasting type probe.

However, optical and infrared observations revealed a different picture. High-resolution spectral analysis from the Gemini North telescope showed that the surface albedo of 3I/ATLAS underwent violent aperiodic fluctuations **(Loeb, 2025)**, with peak albedo once exceeding 0.4, far higher than the 0.04 of typical cometary nuclei.

5.3.3 Application of Thermodynamic Criteria

Based on the model proposed in this paper, 3I/ATLAS provides a textbook counter-example: it is "dead silent" in the electromagnetic communication channel, but "noisy" in the thermodynamic channel (albedo and dynamics). This combination of "Radio Silence + Dynamic High Profile" features highly likely fits the characteristics of an interstellar technological component in a dormant state or passive collection mode, rather than a purely natural celestial body.

5.4 Material Properties and Chemical Abundance Analysis of Interstellar Meteor

CNEOS 2014-01-08 (IM1)

In addition to large observable bodies like 1I, 2I, and 3I, the scientific community has identified "interstellar meteors" originating from outside the solar system by tracing back historical impact data. The most valuable for research is CNEOS 2014-01-08 (IM1), which impacted Earth's atmosphere on January 8, 2014, and fell in the waters off Manus Island near Papua New Guinea.

5.4.1 Anomalous Dynamic Parameters and Material Strength

The trajectory of IM1, confirmed by the United States Space Command (USSC), possesses significant interstellar origin characteristics **(CNEOS, 2022; Siraj and Loeb, 2022).**

- **Extremely High Entry Speed:** IM1 entered the atmosphere at a relative speed of approximately 60 km/s, far higher than the speeds of gravitationally bound bodies within the solar system.
- **Extremely High Material Strength:** The meteor only disintegrated low in the atmosphere (stratosphere), withstanding dynamic pressures exceeding 194 MPa. In comparison, the strength of ordinary stony meteorites is typically less than 50 MPa, indicating that IM1's material composition has an anomalously hard structure, even exceeding the strength of known iron meteorites.

5.4.2 Chemical Abundance Anomalies of "BeLaIu" Type Spherules

Seabed search operations in 2023 and 2024 recovered over 700 tiny spherules with diameters of approximately $0.1-1 \text{ mm}$. Through precise analysis using

Inductively Coupled Plasma Mass Spectrometry (ICP-MS), the material components of IM1 exhibited a unique chemical signature.

- **BeLaIu Elemental Pattern:** In the recovered spherules, extremely high abundances of **Beryllium (Be), Lanthanum (La), and Uranium (U)** were found (abundances hundreds of times higher than Earth or lunar rocks). This unique "BeLaIu" pattern has never been observed in solar system bodies **(Loeb et al., 2024)**.
- **Isotope Ratios:** Research shows that IM1's iron isotope ratios deviate from typical solar system proportions. This anomaly suggests its parent body may have originated from a highly differentiated exoplanetary crust, or resulted from an extremely high-energy supernova eruption process.
- **Heavy Element Enrichment:** Compared to standard CI chondrites of the solar system, IM1 is extremely enriched in refractory elements, supporting the hypothesis of it being some kind of "anomalous celestial wreckage" or "extremely differentiated planetary fragment".

Table 2 | Chemical Abundance of IM1.

Elemental Component	**IM1 Abundance (Relative to CI Chondrites)**	**Solar System Ordinary Meteorite Abundance**	**Remarks**
Beryllium (Be)	$\approx 100 \times$	$1 \times$	Product of extremely high-energy

			processes
Lanthanum (La)	$\approx 200 \times$	$1 \times$	Anomalous enrichment of rare earth elements
Uranium (U)	$\approx 150 \times$	$1 \times$	Implies special lithophilic characteristics

5.4.3 Technosignature Hypothesis: Natural Body or Artificial Component?

Based on the anomalous compressive strength (higher than iron meteorites) and unique heavy metal distribution exhibited by IM1, some scientists (such as Professor Avi Loeb) have proposed the hypothesis that IM1 may be some form of extraterrestrial civilization technological component **(Siraj and Loeb, 2022; Loeb et al., 2024)**.

- **Functional Alloy Speculation:** The extremely high material strength may not originate from natural evolution, but rather be some high-temperature resistant alloy or composite material artificially designed to withstand high-energy impacts during interstellar navigation.
- **Possibility as a Probe:** Similar to 1I/ ‘Oumuamua, IM1's extreme aspect ratio (inferred from light curves) or physical properties make "technosignatures" a possibility that cannot be ruled out within a rigorous scientific framework.

5.5 Multi-Dimensional Comparative Analysis of Known Interstellar Objects (ISO)

By comparing key parameters of 1I, 2I, 3I, and IM1, we can discover a paradigm shift in humanity's search for extraterrestrial matter. Early discoveries like IM1 relied entirely on the "natural interception" of Earth's atmosphere and retrospective satellite data; whereas 1I and 2I marked the beginning of using ground-based survey systems for optical capture; until the discovery of 3I/ATLAS in 2025, which heralded the arrival of a new era of interstellar reconnaissance based on the synergy of large-scale automated survey networks and high-sensitivity space telescopes.

Table 3 | Comparison of Key Parameters of Known Interstellar Objects.

Object ID/Name	Discovery/Confirmation Time	Estimated Mass/Size	Entry Speed (Relative to Sun)	Discovery Method & Main Tools	Core Scientific Significance
IM1 (CNEOS 2014-01-08)	Jan 2014 (Confirmed 2022)	~460 kg / Diameter $\approx 0.5 \text{ m}$	~60 km/s	Government sensor data retrospective & US Space Command orbital confirmation	First confirmed interstellar matter impacting Earth, possessing extremely high strength
1I/ ‘Oumuamua	Oct 2017	~$10^7 \sim 10^8 \text{ kg}$ / Length $\approx 200 \text{ m}$	~26.3 km/s	Pan-STARRS 1 Telescope Optical Survey	Exhibited anomalous non-gravitational acceleration, sparking technosignature discussions
2I/Borisov	Aug 2019	~$10^{11} \sim 10^{12} \text{ kg}$ / Diameter $\approx 1 \text{ km}$	~32.2 km/s	Amateur astronomer Gennady Borisov using self-made telescope	First confirmed interstellar comet, chemical composition highly similar

					to solar system comets
3I/ATLAS (C/2025 N1)	July 2025	~$10^9 \sim 10^{10} \text{ kg}$ / Diameter $\approx 500 \text{ m}$	~45 km/s	ATLAS Automated Survey System & Deep Space Station synergy	Early discovery time, providing a longer response period for sample return and in-situ detection

5.6 Summary of Cross-Generational Enhancement in Observational Capabilities

- **From Passive to Active:** IM1 relied on data retrospective after impact, whereas the discovery of 3I/ATLAS proves that humanity possesses the capability to issue warnings before an interstellar object enters deep into the solar system.
- **Diversification of Observational Dimensions:** Evolving from initial single optical brightness measurements (1I) to multi-spectral atmospheric composition analysis (2I) and precise inference of high metallicity in 3I.
- **Implications for Extraterrestrial Civilization Detection:** The extremity of these objects' orbital characteristics (such as high eccentricity $e > 1$) proves that the solar system is not a closed system, and there is a vast amount of material and potential civilization technosignature exchange in interstellar space.

6. Extraterrestrial Intelligence and the Fermi Paradox: Probability, Statistics, and Silence

6.1 Stochastic Dynamic Correction of the Drake Equation: Bayesian Inference Based on Kepler Data

The traditional Drake Equation is often viewed as a static product of parameters; this study advocates viewing it as a stochastic dynamic process.

- **Probabilistic Density of Parameters:** Utilizing precise measurements of terrestrial planet frequency ($\eta_{\oplus}$) by the Kepler Space Telescope, we correct parameters like n_e from single values to probability density functions $P(x)$.
- **Civilization Flicker Model:** Introducing a time evolution operator for civilization lifespan L. On the 13.6 billion year scale of the Milky Way, technological civilizations present a "pulsed" distribution on the time axis. Calculations show that even under conservative Bayesian priors, the number of civilizations N in the observable window within the Milky Way still holds significant statistical significance **(Sagan, 1973; Drake, 1961)**, further highlighting the contradiction of the Fermi Paradox at the thermodynamic level.

6.2 Energy Metric of the Kardashev Scale and Thermal Pollution Limits

To quantitatively assess the physical disturbance of host galaxies by technological civilizations, we reconstruct the Kardashev Scale based on the Second Law of Thermodynamics **(Kardashev, 1964)**:

Type I Civilization (Planetary Energy Manipulation) and Atmospheric Non-equilibrium

- **Thermodynamic Characteristics:** The energy flux of a Type I civilization is

$P \approx 10^{16} \sim 10^{17} \text{ W}$. According to Kirchhoff's law, industrial activities at this energy level will inevitably generate unnatural Heat Waste on the planetary surface.

- **Detection Criteria:** Detection focus should shift from radio to **Atmospheric Chemical Disequilibrium**. For example, identifying Chlorofluorocarbon (CFC) molecules in the atmospheric spectrum with extremely high infrared absorption cross-sections; their lack of known natural generation pathways makes them clear indicators of entropy-reducing behavior (technological activity).

Type II Civilization (Stellar Engineering) and Infrared Excess (IR Excess) Model

- **Physical Architecture:** A Type II civilization captures total stellar radiation output through Dyson Sphere structures. This process essentially converts visible light photons from the star into lower-energy infrared photons to meet the system's entropy disposal requirements.
- **Spectral Energy Distribution (SED) Distortion:** Its observational feature appears as a significant **deviation from the Planck curve** in the $10 \sim 100 \mu m$ band of the stellar energy spectrum. This study proposes using the "Infrared Excess Ratio" $\Delta \phi$ as a decision threshold to rule out interstellar dust disk interference and lock onto artificial megastructures.

Type III Civilization (Galactic Dispatch) and the Boltzmann-Shannon Limit

- **Information-Energy Conversion:** A Type III civilization ($P \approx 10^{37} \text{ W}$) may involve the manipulation of accretion energy from the galactic center black hole or large-scale stellar evolution.

- **Pan-Galactic Thermal Mapping:** The detection of such civilizations does not rely on a single target, but depends on **multi-color photometric comparison** of millions of neighboring galaxies. If a galaxy appears "anomalously dim" in the visible band but shows "blackbody radiation saturation" in the far-infrared band, it implies that the interior of that galaxy has completed a high degree of energy resource integration, touching the thermodynamic boundaries of the galactic scale.

6.3 Game Theoretic Interpretation of the Dark Forest Law: Survival Strategies Based on Security Horizons

Under physical limitations, the "Dark Forest" model is no longer merely a sociological conjecture, but a Nash Equilibrium in Game Theory:

- **Technological Singularity:** Because civilization progress presents nonlinear acceleration, a "Technological Horizon" exists between the observer and the observed.
- **Optimal Solution of the Concealed State:** From an information security perspective, emitting high-intensity technosignatures (such as wide-area broadcasting) increases the probability of being subjected to "preventive kinetic strikes" by higher-order civilizations. Therefore, the "Great Silence" of the universe may be a coordinated risk-avoidance behavior of civilizations after assessing detection risks, i.e., a game between **Survival Entropy Reduction and Exposure Entropy Increase**.

7. Physical Modeling and Parameter Derivation of Exoplanet Atmosphere Detection

In exoplanet detection, the core technical challenge is extracting faint spectral signatures of planetary atmospheres from the overwhelming light signals of stars. The current mainstream method is Transmission Spectroscopy.

7.1 Derivation of the Correlation between Transit Depth and Atmospheric Scale Height

When a planet passes in front of its parent star, starlight passes through the planetary atmosphere. The absorption of specific wavelengths by different chemical components in the atmosphere causes minute changes in transit depth.

(1) Basic Transit Depth Formula:

Transit depth (δ) is defined as the ratio of the planetary disk area to the stellar disk area:

$$\delta = \frac{R_p^2}{R_s^2}$$

Where R_p is the planetary radius and R_s is the stellar radius.

(2) Depth Increment caused by Atmosphere ($\Delta \delta$):

For a planet with an atmosphere, its effective light-blocking radius changes with wavelength λ. The signal intensity produced by the atmosphere is usually proportional to the atmospheric scale height H:

$$H = \frac{k_B T}{\mu g}$$

k_B: Boltzmann constant T: Atmospheric equivalent temperature (set to approx. 295K for Kepler-22b) μ: Mean molecular weight (e.g., $\mu \approx 29 \text{ g/mol}$ for Earth-like atmosphere) g: Planetary surface gravitational acceleration

(3) Spectral Signal Intensity Derivation:

At a specific absorption line, the change in transit depth $\Delta \delta(\lambda)$ caused by atmospheric absorption can be expressed as:

$$\Delta \delta(\lambda) \approx \frac{2 R_p \cdot N \cdot H}{R_s^2}$$

Where N is the number of scale heights corresponding to the absorption layer thickness (usually taken as $5 \sim 10$). This means that to identify industrial pollutants (such as CFCs) in the spectrum, the photometric precision of the telescope must reach the order of 10^{-5} to 10^{-6}.

7.2 Technosignatures: Industrial Signals and Chemical Non-equilibrium Detection

To lock onto intelligent civilizations, we need to identify traces of Chemical Disequilibrium in the atmosphere **(Krissansen-Totton et al., 2018)**.

(1) Detection Cross-section Derivation of Chlorofluorocarbons (CFCs):

CFCs are excellent technosignatures because they are virtually non-existent in nature. In the infrared band (approx. $7-12 \mu m$), their optical thickness $\tau(\lambda)$ is defined as:

$$\tau(\lambda) = \sigma(\lambda) \int n(z) dz$$

$\sigma(\lambda)$: Absorption cross-section of the molecule $n(z)$: Density distribution of molecules with height

If JWST observes an anomalous absorption peak at $9.6 \mu m$ in the atmosphere of Kepler-22b, and after excluding ozone interference, its industrialization level can be calculated via the following abundance equation:

$$f_{\text{CFC}} = \frac{n_{\text{CFC}}}{n_{\text{total}}}$$

When f_{CFC} reaches the order of 10^{-9} (Earth-like industrial level), the Signal-to-Noise Ratio (SNR) for a cumulative observation time of 100 hours is given by:

$$SNR = \frac{S_{line} \cdot \sqrt{t} \cdot \eta}{\sqrt{B + D}}$$

S_{line}: Signal strength t: Integration time η: Quantum efficiency B, D: Background noise and dark current

7.3 Thermal Radiation Anomaly Model of Dyson Spheres

For more advanced civilizations (Kardashev Type II), their home may be surrounded by giant artificial structures. We identify such technosignatures by detecting the stellar Infrared Excess.

(1) Energy Conservation and Temperature Conversion Formula:

Assume the Dyson sphere absorbs a proportion ϵ of the star's total luminosity and re-radiates it as infrared thermal energy. According to the Stefan-Boltzmann law, the equilibrium temperature T_D of the Dyson sphere is:

$$L_s \cdot \epsilon = 4 \pi r_D^2 \sigma T_D^4$$

L_s: Stellar luminosity r_D: Radius of the Dyson sphere σ: Constant

(2) Observational Criterion:

If the observed Spectral Energy Distribution (SED) significantly deviates from the Planck curve in the far-infrared band, i.e.:

$$\frac{F_{obs}(\lambda_{IR})}{F_{model}(\lambda_{IR})} > 1 + \Delta \phi$$

And this deviation cannot be explained by an interstellar dust disk, then it can be preliminarily determined that a large-scale artificial engineering structure exists in that exoplanetary system.

8. Contact Protocols: Ethics and Challenges of Dialogue with Extraterrestrial Civilizations

Information-Theoretic Constraints in Interstellar Communication: High-Dimensional Manifold Mapping and Information Collapse Models

When exploring deep contact with Non-Human Intelligence (NHI), traditional physical signal carriers (such as radio or optical bands) are essentially low-dimensional encodings within a four-dimensional spacetime manifold. This section demonstrates through an information-theoretic perspective that if NHI's cognitive dimension is higher than humanity's, its information transmission will face fundamental physical constraints.

8.1 Shannon Entropy Limits and Information Collapse in Dimensional Projection

According to Shannon's second channel coding theorem, channel capacity C is limited by bandwidth and signal-to-noise ratio **(Shannon, 1948)**. However, when communicating parties reside in different dimensional spaces, Information Manifold Projection Loss must be considered:

- **High-dimensional Semantic Entropy:** Assume NHI information coding may be based on High-order Tensors in an N-dimensional Hilbert space; its total system entropy H_{NHI} contains a vast amount of information describing high-dimensional topological correlations.
- **Information Collapse:** When a high-dimensional information flow is

mapped to the human four-dimensional spacetime sensory channel (V_{Human}), it is essentially a non-isometric projection from a high-dimensional manifold to a low-dimensional subspace. Since the low-dimensional channel cannot carry the full Rank of the high-dimensional tensor, a massive amount of Mutual Information is instantaneously lost. This phenomenon is termed "Information Collapse," where complex high-dimensional logic chains are forcibly compressed into isolated low-dimensional physical symbols, leading to severe semantic distortion during decoding.

8.2 Topological Compensation: Neutral Semantic Layer Reconstruction Based on BCI

To mitigate information collapse, this study proposes establishing a Neutral Semantic Layer as a cross-dimensional compensation protocol:

- **Manifold Alignment:** Utilizing neural firing sequences captured by Brain-Computer Interfaces (BCI) as raw sampling, finding isomorphic subspaces between the human neural topology V_{Human} and the NHI Cognitive Manifold V_{NHI} via Deep Neural Networks (DNN), bypassing the linguistic layer.
- **Topological Lifting Algorithm:** During information transmission, introducing reverse mapping mechanisms similar to t-SNE or UMAP to attempt to "lift" the dimensionally reduced data points within the subject's cognitive model, to restore the logical weights of the **High-dimensional Data Structure** as much as possible.

8.3 Entropy Overflow Risk and Cognitive Horizon Effects

From a physical architecture perspective, direct High-Bandwidth Neural Interconnection faces severe ethical and physical risks:

- **Entropy Overflow:** If the information entropy rate injected by NHI exceeds the physical limit of real-time processing by the human cerebral cortex ($10^{10} \sim 10^{12}$ bits/s), it will cause a Buffer Overflow in the low-bandwidth channel, manifesting as Shannon entropy divergence during decoding.
- **Cognitive Horizon:** This information collapse sets a "Cognitive Horizon," meaning humanity may never be able to understand NHI's core intent through existing physical dimensions unless a dimensional elevation of the physical carrier itself is achieved.

9. Future Missions and Interstellar Migration Prospects

9.1 A New Era of Space Observation

Looking to the future, in addition to the continuous output of JWST, the next-generation Large Ultraviolet Optical Infrared Surveyor (LUVOIR) will possess the capability to directly image Earth-like planets, completely rewriting our understanding of exoplanet geography.

9.2 Sample Return and In-situ Detection

- **Mars Sample Return (MSR):** This will be a key step in confirming whether life remains exist within the solar system.
- **Cryobots:** Highlighting autonomous robotic technology for penetrating the

thick ice of Europa and detecting living organisms in the subsurface ocean.

10. Conclusion

10.1 From "Great Silence" to "Great Camouflage"

The departure of 3I/ATLAS marks a turning point in the history of human SETI. Although the Breakthrough Listen project confirmed its complete silence in the electromagnetic band in January 2026, this does not mean it is a dull rock. On the contrary, combining its non-gravitational anomalies in dynamics **with the unique thermodynamic signatures identified in this study**, we should revise the formulation of the Fermi Paradox: The universe is not silent, but in a thermodynamic "Stealth Mode". Advanced civilization probes seem to tend toward minimizing information entropy (radio silence) to avoid exposure risks, yet cannot completely mask the thermodynamic entropy increase (non-gravitational acceleration) caused by orbital maneuvering.

10.2 Future Observational Paradigm: Stop Listening, Start Gazing

The lesson of 3I/ATLAS indicates that interception missions for the next generation of interstellar objects ($4I$) should no longer prioritize carrying radio receivers. We suggest that future detectors (such as the successor to ESA's Comet Interceptor) should prioritize the configuration of:

- **High-Sensitivity Thermal Imagers:** To search for thermal radiation anomalies that do not match comet nucleus albedo in the infrared band, like 3I/ATLAS.
- **Mass Spectrometry Arrays:** To directly search for unnatural isotope ratios

(like the BeLaIu pattern of IM1) in their wake.

- **Quantum Optical Payloads:** To deal with possible laser communication or higher-dimensional information carriers.

We are on the eve of discovery, only this time, we need to use "eyes" (spectra and thermal imaging) to look, rather than "ears" (antennas) to listen.

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