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# Cosmic Resource Inequality: Elemental Inheritance, the Material Potential Scale, and Technological Opportunity in Planetary Systems

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## Abstract

Astrobiology and exoplanet science usually treat stellar luminosity, orbital distance, planet size, and atmospheric observables as first-order boundary conditions for habitability. A parallel boundary condition is chemical: planetary systems inherit element and isotope abundance vectors from their natal molecular clouds, which were enriched by previous stellar generations, supernovae, asymptotic giant branch stars, compact-object mergers, and other nucleosynthetic events. This paper develops *cosmic elemental inheritance* (CEI) and *cosmic resource inequality* (CRI) as a framework for studying how star-to-star variation in refractory, volatile, bioessential, siderophile, lithophile, radiogenic, and high- $Z$  elements can influence planetary interiors, surface environments, long-term habitability, and the material opportunity space available to technological civilizations. The paper introduces a Kardashev-like but composition-based classification, the *Material Potential Scale* (MPS), which ranks planetary systems by the estimated accessibility of material resource classes rather than by the energy already consumed by a civilization. The MPS is not proposed as a deterministic measure of intelligence or social development. It is a resource-envelope metric: a way to ask whether a planetary system supplies the accessible materials required for biochemistry, geodynamics, metallurgy, electronics, nuclear power, long-duration space systems, and, as a speculative boundary case, exotic nuclear resources. We define a continuous accessible-inventory formalism, a vector of functional domain scores, and a discrete six-level MPS classification. The framework builds on established results linking host-star abundances to rocky-planet composition, galactic chemical evolution to planet properties, r-process enrichment to actinide inventories, and radiogenic heat to planetary dynamos and geodynamics. We propose falsifiable tests using stellar abundance catalogs, polluted white dwarfs, exoplanet mass-radius demographics, stellar age and Galactic-population information, Eu/Th/U proxies, and models of planetary thermal and geochemical evolution. CRI and MPS should be treated as measurable dimensions of planetary and technosignature studies, complementary to the circumstellar habitable zone, the galactic habitable zone, and energy-based Kardashev classifications.

**Keywords:** astrobiology; exoplanet composition; galactic chemical evolution; Kardashev scale; material potential scale; radiogenic heating; r-process; planetary interiors; technosignatures; resource constraints; cosmic elemental inheritance; cosmic resource inequality

## 1. Executive summary

This white paper develops a research program around a simple premise: planets are not born with equal chemical opportunity. A planetary system inherits an abundance vector from its local star-forming material; that material reflects a particular history of nucleosynthesis and Galactic mixing. Because rocky planets form from the same refractory inventory as their host stars to first order, differences in stellar composition can become differences in planetary mineralogy, core fraction, radiogenic heat budget, bioessential nutrient availability, and ultimately the accessible materials available to a technological species.

The central proposal is not that any one element determines destiny. Rather, CRI is the claim that the abundance, distribution, and geologic accessibility of critical elements vary across planetary systems enough to create different planetary and technological boundary conditions. A system poor

in U and Th may have weak long-term radiogenic heating, altered tectonic history, limited natural fission resources, and fewer radioisotope power options. A system rich in radiogenic elements may have stronger volcanism but may also suppress long-lived magnetic dynamos in some models. A system with a different Mg/Si/Fe ratio may form planets with different mantle mineralogies and core fractions. A system with low surface-accessible P, N, Cu, rare earth elements, or platinum-group elements may face bottlenecks in biochemistry, metallurgy, electronics, catalysis, or energy technology even when life is present.

This version adds a second contribution: the **Material Potential Scale** (MPS). The Kardashev scale classifies civilizations by the rate of energy they can use or control (Kardashev, 1964). The MPS classifies planetary systems by the material resource envelope they plausibly offer. In continuous form it is a vector of domain scores; in discrete form it is a six-level scale from resource-suppressed systems to systems with hypothetical exotic-nuclear potential. The MPS should be read as an input to civilizational possibility, not as a measure of actual civilizational achievement.

The paper’s conservative thesis is:

*Cosmic elemental inheritance creates measurable differences in planetary habitability and technological resource opportunity. These differences should be modeled as a vector-valued inequality over accessible critical-element inventories, not as a single metallicity scalar. A Kardashev-like material scale can formalize the resulting resource envelope without claiming chemical determinism.*

## 2. Scope and non-claims

This paper deliberately avoids claims that cannot presently be tested with astrophysical, geochemical, or planetary data. It does not argue that civilizations are predetermined by chemistry; social, biological, ecological, and historical contingencies remain decisive. It also does not argue that stable superheavy elements are naturally abundant, or that any presently unknown isotope is required for interstellar travel. Superheavy nuclei and the “island of stability” are discussed only as a boundary case for future work. The core claims concern ordinary and scientifically established element classes: rock-forming elements, volatiles, bioessential elements, transition metals, rare earth elements, platinum-group elements, and long-lived radionuclides.

A second non-claim is important for the MPS. The scale does *not* state that “more heavy elements always means a more advanced civilization.” More high- $Z$  material can expand technological options, but excessive radiogenic heating, unfavorable differentiation, or poor geologic concentration can reduce habitability or accessibility. MPS therefore treats composition as a constrained opportunity landscape, not as a monotonic ladder.

For clarity, the following terms are used throughout:

- **Cosmic elemental inheritance (CEI):** the element and isotope abundance vector inherited by a star-planet system from its natal molecular cloud after prior nucleosynthetic enrichment and Galactic mixing.
- **Cosmic resource inequality (CRI):** measurable differences between planetary systems in the accessible inventories of elements and isotopes that affect habitability, geodynamics, biology, technology, and spacefaring capability.
- **Accessible inventory:** the fraction of a bulk element inventory that is available to geological, biological, or technological processes at a given stage of planetary evolution. This differs from bulk abundance.

- **Material Potential Scale (MPS):** a proposed composition-based scale for classifying planetary systems by accessible resource classes relevant to biological, industrial, nuclear, and space-faring technological pathways.

### 3. Background: why composition is a first-order boundary condition

#### 3.1. Element production is historically contingent

The chemical composition of a planetary system is not universal. Hydrogen and helium dominate the baryonic mass of the Universe, but heavier elements are made by stellar and explosive processes whose yields vary with progenitor mass, metallicity, rotation, binary evolution, and compact-object merger history. Classical nucleosynthesis work established that many elements are synthesized in stars and explosive events (Burbidge et al., 1957). Modern r-process reviews assign roughly half of the heavy elements found in nature to rapid neutron capture, a process requiring extreme neutron-rich conditions (Cowan et al., 2021). The multi-messenger event GW170817 and its kilonova provided direct evidence that neutron-star mergers can produce large quantities of heavy r-process elements (Abbott et al., 2017; Kasen et al., 2017).

The result is a Galaxy with chemical structure. Element abundance ratios differ between thin-disk, thick-disk, halo, bulge, and accreted populations; local stellar abundance databases reveal distributions rather than a single solar template. The Hypatia Catalog, for example, aggregates high-resolution stellar abundance measurements across nearby FGKM stars and exoplanet hosts (Hinkel et al., 2014). These datasets enable a shift from treating metallicity as a scalar to treating planetary systems as chemically vector-valued initial conditions.

#### 3.2. Stars and rocky planets are chemically linked, but not identical

Planets form from the gas, dust, and ice surrounding young stars. For refractory rock-forming elements such as Mg, Si, Fe, Ca, Al, and Ni, host-star abundances provide a first-order proxy for the inventory available to rocky planets, although disk chemistry, radial transport, condensation sequence, differentiation, volatile loss, and giant impacts can modify the final planet composition (Bond et al., 2010; Hinkel and Unterborn, 2018; Hinkel and Young, 2024; Teske, 2024). The empirical and modeling literature therefore supports a cautious star-planet composition link: host-star abundances are not a perfect map, but they are a meaningful boundary condition.

This matters because composition influences planetary structure. Mg/Si affects mantle mineralogy; Fe/Mg and Fe/Si affect core mass fraction and bulk density; C/O can alter condensation chemistry; and volatile abundances influence ocean, atmosphere, and ice inventories. A habitable-zone orbit around a solar-type star is therefore not enough to specify habitability or technology-relevant resources.

#### 3.3. Radiogenic inventories vary between systems

Long-lived radionuclides, especially  $^{232}\text{Th}$ ,  $^{235}\text{U}$ ,  $^{238}\text{U}$ , and  $^{40}\text{K}$ , provide heat over geologic timescales. This heat affects mantle convection, volcanism, plate tectonics, volatile cycling, and core cooling. Models of rocky exoplanets show that varying radiogenic heat can move planets between geologically dead, Earth-like, and highly volcanic or dynamo-suppressed regimes (Nimmo et al., 2020). Observational work on Th in solar twins and analogs indicates that stellar systems can differ substantially in radioactive heat-source abundance (Unterborn et al., 2015). Eu is commonly used as a spectroscopic proxy for Th and U because it is an r-process element with measurable

absorption features; recent work constrains Eu dispersion in local F/G/K stars while connecting Eu inventories to planetary dynamo persistence (Carrasco et al., 2024).

#### 4. Critical element classes for CRI and MPS

The MPS is built from functional element classes rather than from a raw atomic-number ranking. Table 1 lists resource classes that can be mapped to stellar abundance proxies and planetary accessibility models.

Table 1: Functional element classes for cosmic resource inequality and the Material Potential Scale.

Class	Representative elements/isotopes	Relevance	Typical observables/proxies
Rock-forming refractory elements	Mg, Si, Fe, Ni, Al, Ca, O	Planet density, mantle mineralogy, core mass fraction, crust production	Stellar Mg/Si/Fe/Ni/Al/Ca; mass-radius models; polluted white dwarfs
Volatiles and bioessential elements	H, C, N, O, P, S, Cl	Atmospheres, oceans, prebiotic chemistry, nutrient cycles	Stellar C/O; disk chemistry; atmospheric spectra; core-formation models
Radiogenic heat-source elements	$^{40}\text{K}$ , $^{232}\text{Th}$ , $^{235}\text{U}$ , $^{238}\text{U}$	Geodynamics, volcanism, plate tectonics, magnetic dynamos, fission resources	Eu, Th, U where measurable; stellar age; thermal evolution models
Metallurgical elements	Fe, C, Cu, Sn, Zn, Pb, Cr, Mn, Ni, Ti, W, Mo	Structural materials, alloys, heat engines, industrial chemistry	Stellar refractory abundances; geologic concentration models
Electronics and energy-transition elements	Si, Al, Cu, Ag, Au, Ga, Ge, In, Li, Co, Ni, rare earth elements	Computation, sensors, photovoltaics, batteries, magnets, optics	Stellar abundance families; crustal differentiation; asteroid inventories
Catalytic and strategic high- $Z$ elements	Pt-group elements, Au, rare earths, W, Re, Os, Ir, Eu	Catalysis, high-temperature alloys, precision electronics, sensors, nuclear materials	r/s-process proxies; Eu, Ba, La, Ce, Nd; polluted white dwarfs
Fusion and space-power isotopes	D, $^3\text{He}$ , $^6\text{Li}$ , $^7\text{Li}$ , Be, B; U, Th, Pu from breeding	High-energy propulsion, compact power, deep-space infrastructure	Planetary volatile reservoirs; gas/ice giant atmospheres; stellar Li is complex and age-dependent
Speculative exotic-nuclear resources	Long-lived superheavy or metastable isotopes	Boundary case for unknown nuclear/material regimes	No confirmed natural resource class; accelerator data and nuclear theory only

##### 4.1. Why “heavy elements” cannot be reduced to metallicity

Astronomical metallicity, often represented by  $[\text{Fe}/\text{H}]$ , is useful but insufficient. Fe abundance correlates with giant planet occurrence (Fischer and Valenti, 2005; Johnson et al., 2010), but the technological and geodynamic resource problem depends on many separate element families. A system can be Fe-rich but Th-poor, Mg/Si-unusual, volatile-depleted, or poor in surface-accessible

phosphorus. Conversely, an alpha-enriched or r-process-enriched system may have resource advantages not captured by  $[\text{Fe}/\text{H}]$  alone. The MPS therefore treats high- $Z$  enrichment as one component of a vector, not as the whole scale.

## 4.2. Superheavy elements as an outer boundary case

Theoretical nuclear physics predicts islands or regions of enhanced stability among superheavy nuclei, but known superheavy elements are synthesized in laboratories in tiny quantities and decay quickly. Recent GSI/FAIR results report increasing stability trends toward the predicted neutron magic number  $N = 184$ , while the location and maximum height of the island remain unknown (GSI Helmholtzzentrum für Schwerionenforschung, 2025). A recent U.S. heavy-element program result synthesized element 116 by a titanium-beam route, demonstrating progress toward element 120 searches (Lawrence Berkeley National Laboratory, 2024). These results justify including superheavy nuclei as a speculative boundary case, but not as an established natural resource class. For CRI and MPS, the conservative position is: naturally occurring stable superheavy resources are not evidenced, while long-lived actinide and rare-earth abundance variations are already relevant.

## 5. A Kardashev-like material scale

### 5.1. Motivation and relation to the Kardashev scale

Kardashev’s original classification ranked extraterrestrial civilizations by energy consumption or energy control at planetary, stellar, and galactic scales (Kardashev, 1964). Its strength is simplicity: a civilization’s detectable thermodynamic footprint can be connected to power use. Its limitation is that it treats energy as the principal axis of advancement. But energy use depends on materials. A civilization cannot build large-scale electronics, high-temperature engines, precision optics, nuclear reactors, fusion devices, radioisotope power systems, or long-duration spacecraft without particular element and isotope inventories being accessible at reasonable energetic cost.

The Material Potential Scale is proposed as a complementary axis:

*Kardashev measures the energy a civilization can use. MPS estimates the material resource envelope that a planetary system makes available to a civilization.*

The distinction is important. Kardashev is a civilization-output scale. MPS is a planetary-system input scale. It asks whether the physical environment supplies the materials needed for broad classes of technology. It does not state that a civilization exists, that it will use those resources, or that it will progress along an Earth-like pathway.

### 5.2. Accessible System Inventory

For an element or isotope  $i$  in planetary system  $s$ , define the *Accessible System Inventory* (ASI) at technological access stage  $a$  as

$$A_i(s, a) = M_{\text{solids}}(s) 10^{[X_i/H]_s} F_i^{\text{cond}} F_i^{\text{planet}} F_i^{\text{diff}} F_i^{\text{geo}}(s) F_i^{\text{access}}(a). \quad (1)$$

Here  $M_{\text{solids}}$  is the total solid inventory of the system;  $[X_i/H]_s$  is the stellar abundance relative to solar where measurable;  $F_i^{\text{cond}}$  captures condensation and disk chemistry;  $F_i^{\text{planet}}$  captures incorporation into planets, moons, asteroids, and comets;  $F_i^{\text{diff}}$  captures core formation and reservoir partitioning;  $F_i^{\text{geo}}$  captures concentration by geologic processing; and  $F_i^{\text{access}}(a)$  captures the ability

of a civilization at stage  $a$  to reach and extract reservoirs. The important feature is not the exact first-generation parameterization, but the separation of abundance from accessibility.

A normalized resource ratio can then be defined as

$$R_i(s, a) = \frac{A_i(s, a)}{A_i(\odot, a_{\oplus})}, \quad (2)$$

where  $A_i(\odot, a_{\oplus})$  is a Solar-System or Earth reference inventory at a stated access stage. This normalization allows MPS to be updated as better Solar System, asteroid, lunar, and exoplanet composition data become available.

### 5.3. Functional domain scores

Technological domains require multiple elements simultaneously. A computer industry, for example, is not enabled by Si alone; it also requires conductive metals, dopants, precision materials, energy systems, and manufacturing pathways. We therefore define a domain score for domain  $D$  as a weighted geometric inventory:

$$\Phi_D(s, a) = \exp \left[ \sum_{i \in D} w_{D,i} \ln(\epsilon + R_i(s, a)) \right] P_D(s, a), \quad (3)$$

where  $w_{D,i}$  are normalized weights,  $\epsilon$  prevents a single unmeasured trace component from forcing the score to zero, and  $P_D$  is a penalty or suitability term for nonlinear hazards. Examples of  $P_D$  include overheating from excessive radionuclides, biologically hostile redox states, or poor ore concentration despite high bulk abundance. The geometric form penalizes bottlenecks: a domain requiring Cu, Sn, Fe, and carbon is constrained by the scarcest accessible critical component.

A continuous material score is then

$$\mathcal{M}_D(s, a) = \log_{10} \Phi_D(s, a), \quad (4)$$

with  $\mathcal{M}_D = 0$  corresponding to a Solar-System reference. Positive values indicate enriched or more accessible resources for that domain; negative values indicate depletion or poor accessibility. The full MPS should be reported as a vector

$$\mathcal{M}(s, a) = (\mathcal{M}_{\text{bio}}, \mathcal{M}_{\text{geo}}, \mathcal{M}_{\text{met}}, \mathcal{M}_{\text{elec}}, \mathcal{M}_{\text{nuc}}, \mathcal{M}_{\text{space}}, \mathcal{M}_{\text{highZ}}), \quad (5)$$

rather than as a single number. A scalar summary can be useful for target ranking, but it should be secondary to the vector because different domains can trade off.

### 5.4. Discrete MPS classes

For communication, the continuous vector can be mapped into a discrete scale. Table 2 defines six proposed classes. These classes are intended as hypotheses to be refined, not as final thresholds.

Table 2: Proposed discrete Material Potential Scale (MPS) classes.

Class	Name	Definition	Example observables
MPS-0	Resource-suppressed	A system with severe deficits in solid material, key volatiles, or rock-forming elements, making long-lived terrestrial habitability or industrial development unlikely.	Low [Fe/H] and refractory inventory; no detected rocky planets; volatile-poor debris
MPS-1	Biogeochemical baseline	A system with sufficient rock-forming and bioessential elements to support potentially habitable rocky planets, but with unknown or limited strategic resource accessibility.	Rocky planets in habitable-zone context; C/O, Mg/Si, Fe/Mg near viable ranges
MPS-2	Metallurgical-industrial	A system likely to provide accessible base metals, silicates, carbon, water, and geologic concentration pathways adequate for metallurgy and industrial chemistry.	Favorable refractory abundance vector; active geology; plausible ore formation
MPS-3	Nuclear-spacefaring	A system with accessible long-lived radionuclides, fission/fertile materials, fusion-relevant isotopes, and intrasystem volatiles/metals supporting compact power and long-duration space systems.	Eu/Th/U proxies; U/Th/K thermal models; asteroidal and icy reservoirs
MPS-4	High-Z strategic enriched	A system enriched in r-process/s-process, rare earth, platinum-group, refractory, and catalytic elements that may lower the cost of advanced electronics, optics, catalysts, sensors, and high-performance space infrastructure.	Enhanced Eu/Ba/La/Ce/Nd/Th proxies; polluted white dwarf high-Z debris; metal-rich minor bodies
MPS-5	Exotic-nuclear potential	A system with verified naturally occurring or engineerable long-lived superheavy/metastable nuclear resources beyond known terrestrial resource classes. This class is currently hypothetical and should remain unassigned absent direct evidence.	No confirmed natural examples; would require spectroscopy, meteoritic samples, or reproducible nuclear measurements

The scale is cumulative only in a limited sense. MPS-3 implies nuclear-relevant resource opportunities beyond MPS-2, but a system could be strong in electronics and weak in radiogenic elements, or strong in actinides and poor in surface-accessible phosphorus. Thus, the class label should always be accompanied by the vector  $\mathcal{M}$  and uncertainty estimates.

### 5.5. High-Z enrichment factor

A focused high-Z component can be useful for testing the hypothesis that heavier-element inventories may influence technological ceilings. Define

$$\mathcal{H}_Z(s, a) = \sum_{i \in Z_{\text{crit}}} v_i \log_{10} (\epsilon + R_i(s, a)), \quad (6)$$

where  $Z_{\text{crit}}$  includes actinides, lanthanides, platinum-group elements, refractory metals, and other high-Z strategic elements, with weights  $v_i$  tied to specific technological functions.  $\mathcal{H}_Z$  is not

a universal advancement score. It is a strategic-resource index. In some domains, high  $\mathcal{H}_Z$  expands options; in geodynamics, excessive radiogenic heat can become a penalty through  $P_D$ .

## 5.6. Solar System as a reference case

The Solar System should be treated as the initial calibration point, not as a universal optimum. Earth provides accessible Fe, C, Cu, Sn, Si, Al, U, Th, rare earth elements, water, carbonates, phosphates, and biologically cycled nutrients. The Moon, asteroids, Mars, icy moons, and giant-planet atmospheres add intrasystem resource diversity. A provisional classification would place the Solar System near MPS-3 in the nuclear-spacefaring sense and near the baseline of the continuous scale by construction. It is not necessarily MPS-4; that would require evidence for unusually high accessible rare earth, platinum-group, or r-process inventories compared with other systems.

## 6. Mechanisms by which CEI can affect civilizations

### 6.1. Planet formation and occurrence

Metallicity and solid surface density affect planet formation. Giant planet occurrence is strongly correlated with host-star metallicity (Fischer and Valenti, 2005; Johnson et al., 2010), while small-planet occurrence and composition show more nuanced relationships (Teske, 2024). Higher solid inventories can accelerate core formation, alter migration, and affect volatile delivery. The first CRI mechanism is therefore demographic: some chemical environments may be more likely to form certain planet architectures, including giant planets that can perturb or protect inner terrestrial worlds.

### 6.2. Interior structure and geodynamic regime

A planet's long-term habitability depends partly on its interior: mantle convection, crustal recycling, magnetic dynamo, volcanism, and volatile cycling. These processes depend on planet mass, water content, oxidation state, core fraction, mantle viscosity, and radiogenic heat. CEI influences several of these parameters by setting starting abundances for rock-forming and heat-producing elements. The same circumstellar habitable zone can contain planets with very different geodynamic lifetimes.

### 6.3. Biological opportunity and nutrient cycling

A biosphere cannot use elements that are absent or permanently sequestered. Bioessential elements require not just bulk abundance but cycling between reservoirs. P is a classic example: it is essential for known life but can be trapped in minerals or cores depending on redox state and geochemistry. N availability can also be altered by atmospheric escape, core formation, and mantle partitioning. Recent work emphasizes that the mantle availability of P and N may depend on core-formation conditions and oxygen fugacity, producing a chemical habitability constraint not captured by orbit alone (Walton et al., 2026). CEI therefore interacts with planetary differentiation and surface chemistry to shape biochemical opportunity.

### 6.4. Technological opportunity and bottlenecks

A technological civilization needs accessible gradients: energy gradients, material gradients, and information-processing substrates. Earth technology used wood, charcoal, clay, copper, tin, iron, coal, petroleum, uranium, silicon, aluminum, rare earths, lithium, cobalt, nickel, gallium, and

platinum-group catalysts in historically contingent sequences. A planet without accessible Cu-Sn deposits may not follow a Bronze Age analog; a planet without concentrated Fe ores may have a delayed metallurgy path; a planet poor in U/Th may lack natural fission resources and radioisotope power; a planet with weak geologic recycling may have fewer ore deposits exposed at the surface.

This is not determinism. Civilizations can substitute materials, invent different technologies, or skip stages. But substitution has costs. CRI predicts that the cost landscape differs by planetary system.

## 6.5. Spacefaring capability

Spacefaring requires high energy density, high-performance materials, electronics, and long-duration power. Chemical propulsion does not require rare elements, but advanced space systems benefit from uranium/plutonium for fission or radioisotope systems, rare earths for magnets and sensors, refractory metals for thermal control, and platinum-group catalysts for chemical processing. Fusion pathways depend on isotopes and light-element availability. CRI therefore becomes relevant to technosignature studies: a planet may be habitable and intelligent yet chemically disfavored for long-duration space infrastructure.

## 7. Hypotheses and tests

Table 3 lists falsifiable hypotheses that follow from the CRI/MPS framework.

Table 3: Testable hypotheses implied by the CRI/MPS framework.

Hypothesis	Prediction	Data/test
H1: Radiogenic inequality	Stellar Eu/Th/U proxies predict differences in modeled rocky-planet dynamo persistence and volcanic lifetime.	Combine Eu/Th stellar surveys with exoplanet ages, masses, radii, and thermal evolution models (Nimmo et al., 2020; Carrasco et al., 2024).
H2: Mineralogical inequality	Host-star Mg/Si/Fe ratios predict distributions of rocky-planet densities and inferred core fractions after controlling for mass, age, and irradiation.	Use Hypatia, GALAH, APOGEE, HARPS, Gaia, TESS, PLATO, and radial-velocity masses; compare against interior models.
H3: Galactic epoch effect	Older and younger stellar populations host rocky planets with systematically different mantle/core fractions due to Galactic chemical evolution.	Test age-composition-density correlations; compare with GCE-interior models (Steffen et al., 2025).
H4: Bioessential availability	P/N/C/S abundance and core-formation conditions create a chemical habitability distribution not captured by water-zone criteria.	Couple stellar abundances, disk chemistry, core-formation redox models, and atmospheric/surface nutrient models (Walton et al., 2026).
H5: Technological-resource bottlenecks	Some planets with biosignature-compatible environments are depleted in accessible critical metals or radionuclides.	Model crustal differentiation and ore formation for exoplanet compositions; compare with polluted white dwarf debris and Solar System analogs.

Hypothesis	Prediction	Data/test
H6: Technosignature selection	Technosignature likelihood may correlate with accessible high-energy and high-tech element inventories, not only biological habitability.	Extend technosignature target ranking to include stellar abundance vectors and modeled resource accessibility.
H7: MPS classification stability	Systems with similar $[\text{Fe}/\text{H}]$ may separate into different MPS classes once Mg/Si/Fe, Eu/Th/U, C/O, P, and high- $Z$ proxies are included.	Apply MPS to homogeneous stellar catalogs; test whether MPS clusters differ from metallicity-only rankings.
H8: High- $Z$ resource inequality	r-process enriched stellar populations should show different predicted actinide, rare-earth, and strategic-metal opportunity vectors than solar-composition populations.	Compare Eu/Ba/La/Ce/Nd/Th-enhanced stars, polluted white dwarfs, and Galactic chemical evolution models.

## 8. Observational and modeling program

### 8.1. Stellar abundance surveys

The most immediate data layer is stellar spectroscopy. Current and future work should move from  $[\text{Fe}/\text{H}]$  alone to abundance vectors including Mg, Si, Fe, C, O, Al, Ca, Ni, Na, Ti, P where measurable, Eu, and when possible Th. Hypatia provides a heterogeneous but extensive compilation; survey-scale projects such as APOGEE, GALAH, HARPS-based samples, and future high-precision spectroscopic campaigns can provide more homogeneous data. The abundance precision requirements identified by star-planet mineralogy studies should be treated as design constraints (Hinkel and Unterborn, 2018).

### 8.2. Planetary composition inference

Mass-radius data alone are degenerate: different mixtures of iron, silicate, water, and gas can produce similar densities. Host-star refractory abundances can break some degeneracies, while polluted white dwarfs provide direct samples of extrasolar rocky material (Hinkel and Young, 2024). CRI studies should combine stellar abundances, white dwarf pollution, planet density, orbital context, and age.

### 8.3. Radiogenic and r-process mapping

Eu is a practical proxy for r-process enrichment, but it is not a perfect proxy for U and Th in every population. Recent actinide abundance studies show that Th/Eu can vary, particularly at low metallicity (Shah et al., 2026). CRI models should therefore use Eu carefully, incorporate Th when possible, and propagate proxy uncertainty into radiogenic heat and MPS nuclear-spacefaring scores.

### 8.4. Geologic accessibility models

Astrophysical abundance does not automatically imply technological access. Future work should build simplified geologic accessibility models that estimate whether critical elements become crustally concentrated. Relevant processes include magma-ocean differentiation, core formation, plate tectonics, hydrothermal circulation, oxidative weathering, sedimentation, biological cycling,

and impact gardening. Mineral evolution on Earth shows that mineral diversity and ore accessibility are products of planetary history, not only bulk chemistry (Hazen et al., 2008).

### 8.5. MPS implementation workflow

A first-generation MPS implementation should follow five steps:

1. Select a target system and compile the best available stellar abundance vector with uncertainties.
2. Estimate planet-formation and reservoir filters for relevant bodies: terrestrial planets, minor bodies, icy reservoirs, and giant planets.
3. Compute domain-level accessible inventory scores using Equation 3, explicitly separating measured, inferred, and missing elements.
4. Assign a provisional discrete MPS class only after checking bottlenecks and nonlinear penalties.
5. Publish the full vector  $\mathcal{M}$ , not just the class label, so that future data can update the classification.

This workflow makes the scale falsifiable. If two studies use the same abundance vector and different geologic assumptions, the disagreement can be localized to the accessibility filters rather than hidden inside a single ranking.

### 8.6. Technological resource modeling without cultural determinism

The most controversial step is connecting resources to technological development. This should be done probabilistically and non-deterministically. A planet’s accessible resources do not guarantee technology; they shape the cost surface of possible technologies. CRI should therefore model material bottlenecks as constraints and substitutions, not as destiny. A useful approach is to identify minimum material sets for broad technology classes, then ask whether plausible planetary histories produce accessible inventories above threshold.

## 9. Implications

### 9.1. For astrobiology

The circumstellar habitable zone is necessary but not sufficient. Chemical habitability includes rock-forming ratios, volatile inventories, nutrient availability, radiogenic heating, and geologic cycling. CRI adds that the same stellar energy environment can host planets with very different chemical and geodynamic opportunity. It complements rather than replaces existing habitability metrics.

### 9.2. For the galactic habitable zone

The galactic habitable zone concept already recognizes metallicity, supernova rate, and Galactic location as relevant (Lineweaver et al., 2004). CRI generalizes this by replacing a simple metallicity threshold with a multidimensional abundance and accessibility vector. A high-metallicity system is not automatically superior: too much radiogenic heating, unfavorable redox conditions, or poor nutrient accessibility can be detrimental. Conversely, alpha-element enrichment may compensate for low Fe in some planet-formation regimes (Teske, 2024).

### 9.3. For technosignature search

Technosignature target selection often emphasizes stellar type, planet habitability, atmospheric disequilibrium, and radio/optical detectability. CRI suggests adding a material opportunity layer. A planet may be biologically promising but technologically constrained; another may be less Earth-like but materially favorable for industry and space infrastructure. This does not mean technology is predictable from chemistry, but abundance vectors can become Bayesian priors.

The MPS can also avoid a hidden assumption in energy-centered thinking: a civilization may have intelligence and culture but lack inexpensive access to the materials needed to become highly detectable. Such a civilization could be “Kardashev-low” not because it lacks knowledge, but because its system has a poor material opportunity vector.

### 9.4. For human space strategy

CRI also applies locally. Human expansion beyond Earth is shaped by the distribution of water, carbon, nitrogen, metals, volatiles, and radionuclides across the Moon, asteroids, Mars, icy moons, and near-Earth objects. If chemical inequality matters within one solar system, it likely matters across planetary systems. This perspective encourages mapping not just habitable worlds, but resource architectures.

## 10. Limitations and failure modes

Several limitations are important:

1. **Host-star abundances are imperfect proxies.** Disk chemistry, radial drift, volatile loss, and planetary differentiation can decouple planet composition from stellar photospheric composition.
2. **Bulk abundance is not accessibility.** Technological resources require concentration, exposure, and extractability. Ore formation is a planetary process.
3. **Life and technology are not chemically deterministic.** Biology can adapt; civilizations can substitute materials; social history matters.
4. **Element measurements are incomplete.** Many critical elements are difficult to measure in stellar spectra, especially P, U, and some rare metals.
5. **Small-number and selection biases are severe.** Exoplanet mass-radius measurements, polluted white dwarf samples, and high-precision abundance surveys are biased toward observable systems.
6. **MPS can be misused as a progress ranking.** It should not be read as “high MPS equals superior civilization.” It is a resource opportunity index, not an intelligence, ethics, or social-development scale.
7. **Superheavy-element speculation must be constrained.** The island of stability is a legitimate nuclear-physics topic, but no known naturally abundant stable superheavy resource class exists.

A strong CRI/MPS research program should actively try to disprove its stronger claims. If future data show that accessible critical-resource inventories converge across rocky planets despite stellar abundance variation, then CRI becomes a minor effect. If, however, differences in radiogenic

heat, nutrient accessibility, mineralogy, and critical metals are large, CRI becomes a major axis of comparative planetology.

## 11. Proposed research roadmap

### 11.1. Phase 1: Define critical-element sets

Construct element sets for different outcome domains:

- Habitability: C, H, N, O, P, S, Fe, Mg, Si, Ca, Na, K, U, Th.
- Geodynamics: Mg, Si, Fe, Ni, O, Ca, Al, U, Th, K, H<sub>2</sub>O.
- Metallurgy: Fe, C, Cu, Sn, Zn, Ni, Pb, Cr, Mn, Ti, W, Mo.
- Electronics/energy: Si, Al, Cu, Ag, Au, Ga, Ge, In, Li, Co, Ni, rare earth elements.
- Nuclear/space power: U, Th, K, Li, Be, B, D, He, rare earth elements, refractory metals.
- High-*Z* strategic resources: lanthanides, actinides, platinum-group elements, W, Re, Os, Ir, Au, and r-process proxies.

### 11.2. Phase 2: Build abundance priors

Use stellar abundance catalogs to produce abundance distributions for these sets across Galactic populations. Treat missing elements using nucleosynthetic families and proxies, but label uncertainty explicitly. For r-process elements, compare Eu, Th, and U where available.

### 11.3. Phase 3: Propagate through planet models

For each abundance vector, propagate through condensation, accretion, interior structure, radiogenic heat, and volatile/nutrient models. Produce distributions of predicted mantle mineralogy, core fraction, heat flow, dynamo lifetime, volcanism, and nutrient availability.

### 11.4. Phase 4: Add accessibility filters

Develop simplified ore/accessibility models conditioned on geodynamic regime, water, oxygen fugacity, crustal recycling, and age. The goal is not to recreate Earth's mining geology, but to estimate whether critical materials become concentrated above plausible technological thresholds.

### 11.5. Phase 5: Calibrate the MPS

Use the Solar System as a baseline and compute provisional MPS vectors for nearby well-characterized exoplanet host stars. Publish sensitivity analyses showing how classifications change with assumptions about planet formation, ore concentration, volatile delivery, and access stage. The first goal should be relative ranking and uncertainty quantification, not precise absolute scoring.

### 11.6. Phase 6: Integrate with astrobiology and technosignature priors

Use CRI and MPS as priors in target ranking. A complete target vector would include: star type, age, activity, planet mass/radius/orbit, atmosphere, volatile inventory, stellar abundance vector, predicted geodynamics, accessible-resource likelihood, and MPS class/vector.

## 12. Discussion: a non-deterministic cosmic technology tree

The phrase “technology tree” is useful if handled carefully. It does not mean civilizations follow a fixed sequence. It means that material environments make some paths cheaper and others expensive. Earth had accessible carbon fuels, iron ores, copper, tin, water, uranium, and a dynamic crust. A different habitable planet may lack one or more of these or may possess alternatives. Such a civilization might develop advanced biology and computation but struggle with metallurgy; it might master chemistry but lack nuclear fission; it might have abundant nuclear material but suffer geodynamic instability; or it might have superior natural catalysts and rare metals that enable technological shortcuts.

This view suggests that “intelligence” and “spacefaring” should be separated in astrobiology. A biosphere can produce intelligence without producing easy access to high-energy propulsion, durable electronics, or industrial-scale metallurgy. Conversely, a chemically rich system may lower the cost of technological expansion. CRI and MPS therefore provide a bridge between exoplanet chemistry, planetary habitability, and the material preconditions for detectable technology.

The strongest version of the scale is not that heavier elements automatically create more advanced civilizations. It is that material inventories can define opportunity windows. A civilization born into an MPS-1 system may be brilliant but materially constrained. A civilization born into an MPS-4 system may have more available pathways to nuclear power, high-performance materials, and space infrastructure. Whether it uses those pathways is a separate historical question.

## 13. Conclusion

Cosmic resource inequality is a conservative extension of established astrophysics and planetary science. Stars and planets inherit non-identical chemical histories; host-star abundances help constrain rocky-planet composition; r-process enrichment affects actinide inventories; radiogenic heat shapes long-term geodynamics; and accessible critical elements influence technological opportunity. These facts motivate a systematic research program.

The key contribution of this paper is conceptual integration. Instead of asking only whether a planet lies in the habitable zone, CRI asks whether it inherited and processed the chemical resources needed for long-term habitability and technological capability. Instead of treating metallicity as a scalar, CRI treats planetary systems as vectors of element and isotope endowments filtered by planet formation, differentiation, geologic concentration, and technological accessibility.

The new MPS formalizes this idea in a way that can be tested and criticized. It complements the Kardashev scale by measuring not consumed energy, but material opportunity. Its continuous version is an accessible-inventory vector; its discrete version is a six-level communication tool. Both should be updated as observational data improve.

The strongest version of the hypothesis is testable: compare stellar abundance vectors, exoplanet densities, ages, Galactic populations, r-process proxies, polluted white dwarf compositions, and planetary interior models. If the predicted differences are small, CRI/MPS will become a secondary correction. If they are large, cosmic elemental inheritance may be one of the missing variables in astrobiology, technosignature search, and theories of civilizational development.

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This draft was prepared as an independent white paper to formalize the concepts of cosmic elemental inheritance, cosmic resource inequality, and the Material Potential Scale. The author invites

critique from astrophysics, geochemistry, planetary science, astrobiology, nuclear physics, resource economics, and technosignature communities.

### Suggested arXiv category

Primary: astro-ph.EP (Earth and Planetary Astrophysics). Secondary: astro-ph.GA (Astrophysics of Galaxies), astro-ph.SR (Solar and Stellar Astrophysics), physics.geo-ph (Geophysics).

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