

The Cosmic Origins of the Elements

CHO-007 · Cosmic History and Its Observers

A Chronological Scientific History from the Early Universe to the Present

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Structured abstract

Context. The hot early universe supplied hydrogen, helium, and traces of lithium. Nearly every heavier nucleus in planets, organisms, and instruments records later nuclear processing, but no one kind of star or explosion made the complete inventory.

Question. Through which physical channels did the elements and their isotopes arise, how were their products transported and mixed, and how securely can present abundances be assigned to particular astrophysical sites?

Evidence and method. This synthesis combines nuclear reaction theory, stellar models, supernova and merger calculations, electromagnetic and gravitational-wave observations, gamma-ray lines, meteorites, solar spectroscopy, and the abundance patterns of long-lived stars. It distinguishes nuclear production from ejection, transport, incorporation, and later measurement.

Result. Hydrostatic stellar burning builds nuclei from helium through progressively heavier species, while explosive burning rearranges and ejects material on short timescales. Slow neutron capture in evolved stars, rapid neutron-rich processes in compact mergers and possibly rare stellar explosions, thermonuclear supernovae, neutrino-associated reactions, and cosmic-ray spallation contribute different isotope families. Several elements are mixtures of channels. The relative contributions depend on stellar mass, composition, binary evolution, event rates, delay times, mixing, nuclear data, and observational models.

Conclusion. Chemical complexity accumulated through a distributed network of nuclear sites and galactic transport. CHO-007 supplies later articles with an evidence-calibrated origin map, not a one-source-per-element legend. No living or conscious observer is evidenced during most of this history; observer status remains NO until the biological sequence begins.

Keywords: nucleosynthesis; stellar evolution; supernovae; neutron-star mergers; neutron capture; cosmic rays; chemical evolution

1. Scope and chronological orientation

CHO-007 is a declared overlay. It begins when the first stellar interiors started processing primordial gas and follows element-production channels through the edition cutoff. It overlaps CHO-005 and CHO-006, which own first luminous systems, galaxies, the cosmic web, and stellar-population history. It also overlaps every later article because later matter inherits earlier nuclei.

The starting material is not chemically blank. CHO-003 owns Big Bang nucleosynthesis and passes hydrogen, helium, and small amounts of light nuclides. CHO-007 asks what happened after stars formed. It does not assign a sharp universal date to “the first metal”: first-star timing is model-dependent, production occurs inside stars before ejection, and enrichment reaches different gas reservoirs at different times.

The word *metal* has two meanings that must not be confused. In astrophysics it commonly denotes every element heavier than helium. In chemistry it denotes a narrower class. This article uses *heavy elements* where possible and uses *metallicity* only in its astronomical sense.

2. An origin map requires isotopes, not just element names

An element is defined by proton number, but nucleosynthesis acts on nuclides distinguished by both proton and neutron number. Two isotopes of the same element can have different dominant origins. A chart that assigns one icon to carbon, iron, or barium therefore compresses a distribution of isotope-level contributions into a misleading singular answer.

Four steps must be separated:

1. **Production:** nuclear reactions change one nuclide into another.
2. **Ejection or exposure:** products leave a stellar interior or are created in irradiated matter.
3. **Transport and mixing:** winds, explosions, outflows, cosmic rays, and gas motions redistribute them.
4. **Incorporation and measurement:** later stars, planets, meteorites, or spectra preserve an imperfect sample.

Failure at any step can hide a production site. A star may synthesize nuclei that fall into a compact remnant. An explosion may eject them into hot gas that mixes slowly. A long-lived star may preserve only a locally sampled enrichment event. An observed abundance pattern is thus evidence about an entire causal chain, not a direct photograph of a nuclear furnace.

3. Why stellar fusion has a structured limit

Stars shine because nuclear reactions can transform bound nuclei while releasing energy. Hydrogen burning converts protons into helium through reaction networks whose relative importance depends on temperature and composition. Helium burning produces carbon through the triple-alpha pathway and converts some carbon to oxygen. In sufficiently massive stars, later stages process carbon, neon, oxygen, and silicon in nested regions and increasingly short intervals [1,3].

The common phrase “fusion makes elements up to iron” is useful but incomplete. Nuclear binding energy per nucleon broadly rises toward the iron group, so fusion of light nuclei can release energy while assembling more tightly bound nuclei. Yet actual yields depend on reaction rates, temperature, density, weak interactions, convection, rotation, mass loss, and binary exchange. “Iron” is not a single wall, and explosive conditions can produce or rearrange nuclei on both sides of the simplified boundary.

When an iron-group core can no longer support a massive star through further exothermic central burning, collapse may follow. The resulting event couples neutrino physics, hydrodynamics, nuclear statistical equilibrium, shock processing, fallback, and radioactive decay. Models predict families of yields, not one standard supernova composition [3].

4. The first stellar enrichment

The first stars formed from material with essentially no pre-existing heavy elements. Their internal structure, mass loss, rotation, multiplicity, and final fates need not match later metal-enriched populations. Calculations show that different zero-metallicity progenitors can produce sharply different abundance patterns; sufficiently massive helium cores can enter pair instability and disrupt the star rather than leave an ordinary compact remnant [2].

The next generations can preserve partial records of those events. High-resolution spectra of metal-poor stars measure absorption lines, then infer abundances through model atmospheres, atomic data, and assumptions about thermodynamic equilibrium. A proposed pair-instability signature in J1010+2358 was based on a strong odd-even pattern, very low sodium and cobalt relative to iron, and comparison with model yields [12]. Subsequent independent analyses showed that core-collapse-supernova mixtures can also fit the abundances and disputed the pair-instability interpretation [14,15,16]. The object is therefore counterevidence to any claim of unique inversion as much as it is a candidate signature. CHO-007 does not treat it as proof of a first-star mass range.

Early enrichment was spatially uneven. One gas cloud could be influenced by a small number of explosions while another remained much less processed. The abundance of a very old star consequently samples local ancestry and mixing, not a universal cosmic composition at one date.

5. Evolved stars and slow neutron capture

Low- and intermediate-mass stars can become asymptotic giant branch stars. Thermal pulses, mixing episodes, and neutron-producing reactions allow nuclei to capture neutrons at rates generally slow relative to beta decay. This *s-process* follows paths near stable nuclei and contributes substantially to many nuclides heavier than iron. Stellar winds then return processed material to surrounding space.

AGB yields depend on initial mass and metallicity, the treatment of mixing, mass loss, convection, and nuclear rates [4]. Carbon and nitrogen yields also reflect repeated processing and dredge-up. Binary mass transfer can place *s-process*-rich material on a companion, so a chemically unusual surviving star need not have made all of the material now visible at its surface.

Massive stars also host a weaker *s-process* component. “The *s-process* occurs in AGB stars” is therefore not exclusive. The useful claim is isotope- and regime-specific: different neutron exposures, seed abundances, and stellar structures populate different portions of the abundance distribution.

6. Explosive production and the iron group

Core-collapse explosions process and eject material from massive stars. They are important sources of oxygen and several alpha-associated nuclei, and they contribute some iron-group and other species. Their yields are conditional on the pre-collapse star and on explosion energy, geometry, fallback, and neutrino interactions. Some massive stars may collapse with weak ejection, while others produce unusually energetic events.

Thermonuclear supernovae disrupt carbon-oxygen-rich white dwarfs or related degenerate configurations after binary evolution. Burning at high density produces large quantities of iron-group nuclei, many initially radioactive. The decay chain from nickel-56 through cobalt-56 to iron-56 powers much of the optical light of typical events. Multidimensional calculations show that mixing, flame propagation, and explosion geometry affect the detailed yields [5].

The label *Type Ia* is observational, while progenitor and explosion channels are physical. The population may include more than one path. Chemical-evolution models use event rates, delay-time distributions, and yields to explain why iron-group enrichment does not track alpha-element enrichment in a single fixed ratio. This is a population inference, not a claim that every iron atom came from a Type Ia supernova.

7. Neutron capture beyond the iron region

Neutron capture can build heavy nuclei without the charged-particle barriers that increasingly inhibit fusion. In the slow regime, beta decay often occurs between captures. In the rapid regime, captures proceed far from stability before unstable nuclei decay back toward stable species. Intermediate neutron-density regimes may also contribute to particular patterns.

The astrophysical origin of the *r-process* inventory cannot be reduced to one settled source. GW170817 established a binary-neutron-star inspiral through gravitational waves [6]. Its electromagnetic counterpart was consistent with expanding, radioactively heated ejecta whose opacity and colour evolution required heavy nuclei in radiative-transfer models [7]. Later spectral analysis identified strontium in the merger ejecta [8]. Together these observations show that at least some neutron-star mergers synthesize *r-process* material.

They do not by themselves establish that mergers supply every *r-process* nuclide in every environment. Event rates, ejecta masses, binary delay times, retention in small galaxies, and the earliest metal-poor abundance records must agree simultaneously. Post-GW170817 observations have strengthened, rather than completed, the event class: JWST spectroscopy of a compact-object merger found tellurium and emission consistent with further heavy species [17], while a long-duration gamma-ray burst displayed a lanthanide-rich kilonova that complicates any one-transient-class mapping [18]. Collapsars, magnetorotational explosions, and other rare channels remain investigated. A 2019 calculation proposed collapsars as a major contributor [9]; CHO records that as a model-dependent budget claim, not as closure of the site question.

8. Specialised channels: neutrinos, proton-rich flows, and light nuclei

Neutrinos emitted during core collapse can interact with nuclei in overlying stellar layers and alter the production of selected rare isotopes. The ν -process was quantitatively developed as a distinct contribution to nuclides including boron-11 and fluorine-19 [11]. Proton-rich outflows can support sequences of proton capture and beta decay. Neutron-deficient stable isotopes beyond iron, the p -nuclei, require additional treatment: photodisintegration sequences in the γ -process are a major candidate, but current stellar models retain abundance and site discrepancies [19,20]. These channels matter precisely because a coarse periodic-table map can erase isotope-specific origins.

Classical novae add another specialised route. Thermonuclear runaways on accreting white dwarfs can eject isotope patterns that depend on whether the underlying white dwarf is carbon-oxygen or oxygen-neon [21]. Novae are not a universal origin for the elements, but omitting them would leave the production inventory incomplete.

Lithium, beryllium, and boron require special care. Some lithium is primordial and some can be made in stellar or explosive environments, yet these fragile nuclei are also readily destroyed inside stars. Galactic cosmic rays colliding with carbon, nitrogen, and oxygen nuclei can fragment them into lighter species. Classical spallation calculations linked this process to LiBeB abundances [10]. The balance between accelerated protons and alpha particles striking ambient heavy nuclei, or accelerated heavy nuclei striking hydrogen and helium, affects how production scales with metallicity.

Radioactive decay is another indispensable bridge. Observed stable nuclei may be daughters of unstable nuclei synthesized earlier. Gamma-ray lines from live radionuclides can reveal ongoing Galactic production, while meteorites preserve daughter excesses from extinct radionuclides. The clock begins at isotope production and closure of a physical system, not at the birth of an element name.

9. From yields to chemical evolution

A stellar yield is the amount of a nuclide returned by a model star or event, usually separated from material merely carried in at birth. A chemical-evolution model combines yields with an initial mass function, star-formation history, event rates, delay times, gas flows, and mixing. Different combinations can reproduce similar abundance trends, creating degeneracy.

Abundance ratios partly break that degeneracy because channels operate on different timescales. Massive stars return material quickly. AGB stars and compact binaries introduce distributions of delays. Thermonuclear supernovae add iron-group production after binary evolution. Yet “prompt” and “delayed” are distributions, not exact clocks, and local inhomogeneity can dominate early systems.

Metallicity is also not a universal time coordinate. A young star in a slowly enriched dwarf galaxy can be more metal-poor than an older star formed in a rapidly enriched region. Ratios such as $[X/Fe]$ compare logarithmic number-abundance ratios with a named solar reference. Their interpretation depends on the adopted solar composition, spectral modelling, three-dimensional atmospheric structure, and departures from local thermodynamic equilibrium [13].

10. How the evidence is tested

No single observation closes the origin map.

Evidence route	What it constrains	Principal limitation
Laboratory nuclear physics	Reaction rates, masses, lifetimes, decay branches	Many unstable nuclei remain difficult to measure
Stellar spectra	Surface composition and population trends	Atmosphere models, line data, depletion, binary transfer
Supernova and kilonova light/spectra	Ejecta composition, heating, velocity	Radiative-transfer and opacity degeneracies
Gravitational waves	Compact-system masses and dynamics	Do not measure detailed composition alone
Gamma-ray lines	Live radioactive nuclei	Sensitivity, distance, transport
Meteorites	Isotopic anomalies and extinct radionuclides	Solar-System processing and source mixing
Simulations	Conditional yields and transport	Explosion, mixing, resolution, and nuclear-network assumptions

Strong attribution joins several routes. For example, GW170817 identifies the compact merger, electromagnetic observations constrain ejecta, atomic spectroscopy identifies strontium, and nuclear/radiative-transfer models connect the transient to r-process heating [6–8]. Even this unusually rich chain supports a class of production events more securely than it fixes their total cosmic budget.

11. Observer status

For most of the interval covered here, observer status is N0. Nuclear reactions, ejecta, grains, stellar atmospheres, and meteorites preserve physical records without detecting or interpreting them. The existence of information in a spectrum does not imply that the source was an observer.

Living and scientific observers arise in later CHO articles. They reconstruct nucleosynthesis using detectors, laboratories, statistical models, and theories. Their measurements are interventions with selection effects and calibration histories. Consciousness is not required for nuclei to form, decay, or mix.

12. Uncertainty, alternatives, and non-teleology

Nucleosynthesis did not aim toward carbon chemistry, planets, or observers. Carbon and oxygen became abundant through physical pathways under particular stellar conditions; later life exploited available chemistry. A narrative that follows the material ancestry of Earth is a retrospective selection, not evidence that the universe was directed toward it.

Important uncertainties include reaction rates, convective boundaries, binary interaction, mass loss, the core-collapse mechanism, fallback, Type Ia progenitor mixtures, r-process site fractions, event-rate histories, and interstellar mixing. A periodic-table origin graphic should therefore encode mixtures and uncertainty. It should never imply that each element has one birthplace or that the origin of every isotope is equally secure.

Claim class	CHO-007 use
E1 measured	Spectral lines, isotope ratios, transient light, gravitational waves, gamma rays
E2 reconstructed	Stellar abundances, ejecta composition, event rates, chemical histories
E3 model-dependent	Stellar and explosion yields, merger ejecta, transport, integrated budgets
E4 contested	Relative r-process sites, some first-star signatures, Type Ia channel fractions
E5 speculative	Unverified exclusive assignments or teleological interpretations

13. Closing state and handoff

CHO-007 supplies the remaining series with matter that has a history. Before the Solar System formed, multiple stellar populations and explosive events had processed and redistributed nuclei. CHO-008 will examine how one portion of that enriched interstellar material entered a collapsing cloud, disk, planetesimals, planets, Earth, and Moon. It may inherit isotope populations and radionuclide clocks, but it does not re-own their general cosmic production channels.

The correct closing picture is distributed. Its standard route inventory includes charged-particle burning; hydrostatic and explosive burning; slow, intermediate, and rapid neutron capture; the γ -process; the ν -process; proton-rich flows; cosmic-ray spallation; classical novae; radioactive decay; and galactic transport. Primordial nucleosynthesis remains owned by CHO-003. The map is causal and probabilistic, not a catalogue of singular origins.

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Disclosure

This document is a scholarly synthesis; it is not primary research and has not been peer reviewed. Juan Segurola is the sole author. He approved the final text and is responsible for its content.