

The Formation of the Sun, Planets, Earth, and Moon

CHO-008 • Cosmic History and Its Observers

A Chronological Scientific History from the Early Universe to the Present

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Structured abstract

Context. The Solar System emerged from chemically enriched interstellar matter inside the Milky Way. Its formation was not one event but a sequence from cloud collapse and protostellar growth to a disk, solids, planetesimals, planetary embryos, differentiated planets, and the Earth-Moon system.

Question. What evidence orders that sequence, which clocks date its components, and which parts of the standard account remain model-dependent?

Evidence and method. The reconstruction combines astronomical observations of star-forming regions and disks, isotope systems in meteorites, mineral textures, dynamical simulations, planetary compositions, and Earth-Moon geochemistry. S07 is controlled by U-corrected Pb-Pb dating of calcium-aluminium-rich inclusions rather than by a model-derived date for cloud collapse.

Result. A molecular-cloud region collapsed into a protostar and rotating disk. Dust and condensates were transported and repeatedly processed; particle concentration and gravitational collapse helped cross the planetesimal barrier. Accretion and collisions built embryos and planets while radioactive heating and impacts drove differentiation. Earth assembled over an interval. The Moon most plausibly arose within a family of giant-impact scenarios, but impact geometry, source proportions, equilibration, and angular-momentum evolution remain debated.

Conclusion. By 4.000 Ga ago the series inherits a differentiated Earth-Moon system whose crust, atmosphere, hydrosphere, and impact history remain active. CHO-009 takes ownership of those Hadean Earth systems. No biological observer is evidenced; observer status is N0.

Keywords: Solar System; protoplanetary disk; CAI; chondrule; planetesimal; Earth accretion; Moon-forming impact

1. The seam is a dated population, not an instantaneous birth

CHO-008 has two connected temporal domains. Its authorised overlay begins with the onset of collapse in the Solar-System-forming molecular-cloud material and continues through S07. Its primary spine interval begins at S07 and ends at the editorial boundary of 4.000 Ga ago.

S07 is an EVENT seam defined by the formation distribution of the oldest dated Solar-System solids in the controlling evidence. In the controlling Master Index, S07 remains provisional V3 pending a recorded full-text reading of the exact supporting passage and sample distribution. CHO therefore uses 4.56730 ± 0.00016 Ga ago only as a provisional orientation and does not assert unverified contents of Table 1 [1].

Connelly et al. report a CAI orientation of 4567.30 ± 0.16 Myr and chondrule ages extending from 4567.32 ± 0.42 to 4564.71 ± 0.30 Myr [1].

That precision belongs to the laboratory age and its method. It does not mean that the molecular cloud began collapsing at the same instant, that every CAI formed simultaneously, or that the Sun and all planets have one identical birthday. Nor may the value be converted into time after the Big Bang with five-decimal-place precision, because the cosmological age uncertainty is much larger.

2. Inherited matter and the collapsing cloud

CHO-006 passes a structured Milky Way, interstellar gas, dust, and multiple stellar populations. CHO-007 explains the nuclear origins of their elements. CHO-008 follows one local concentration of that material. Its atoms carried mixed ancestries: some nuclei were primordial, others had passed through stellar interiors, winds, explosions, or cosmic-ray reactions.

Dense regions in molecular clouds can become gravitationally unstable. Turbulence, magnetic fields, radiation, rotation, and feedback complicate collapse; they do not permit a simple spherical clock. Conservation of angular momentum helps produce a rotating structure around a growing protostar. Material falls through an envelope and disk while jets and winds remove mass and angular momentum.

Modern observations of young systems reveal disks with rings, gaps, spirals, asymmetries, and substructure. The high-resolution HL Tau image made such structure visible in a very young disk [2]. It is comparative evidence about processes available to planet-forming systems, not an image of the ancestral Solar nebula.

3. A disk with gradients, reservoirs, and transport

The protoplanetary disk was not a static set of circular lanes. Gas accreted, spread, heated, cooled, and dispersed. Solids condensed, evaporated, annealed, collided, fragmented, and drifted. Temperature, pressure, oxidation state, irradiation, and distance from the protosun varied with time.

CAIs record high-temperature processing. Chondrules are igneous droplets produced by transient heating of precursor solids. Their overlapping Pb-Pb ages show that the traditional picture of CAIs ending before chondrule formation began is too simple [1]. Components made in different locations or moments were mixed into meteorite parent bodies.

Meteorite isotope anomalies reveal reservoirs that did not homogenise completely. The distinction between carbonaceous and non-carbonaceous materials has been interpreted as prolonged spatial separation, possibly associated with early growth of Jupiter [4]. The inference joins isotope measurements to a disk-transport model. It does not directly photograph Jupiter or provide an exact completion date for the planet.

4. From dust to planetesimals

Micrometre grains can adhere through surface forces, but growth encounters barriers. Collisions can bounce or fragment aggregates. Gas drag causes solids to lose angular momentum and drift radially. Turbulence can both enhance collision speeds and concentrate particles. A successful account must explain how some solids survived long enough to become gravitationally bound planetesimals.

Streaming instability provides one route. Relative motion between solids and gas can concentrate particles; simulations show that sufficiently dense concentrations can collapse gravitationally into bound bodies [3]. This is a conditional mechanism whose efficiency depends on particle sizes, solid-to-gas ratio, turbulence, pressure structure, and numerical treatment. It should not be presented as the sole route in every disk.

Once planetesimals existed, gravity accelerated growth. Collisions produced accretion, fragmentation, hit-and-run encounters, and scattering. Short-lived radionuclides heated some small bodies enough to melt and differentiate. Iron-rich cores and silicate mantles could therefore form before the terrestrial planets were complete.

5. Giant planets and the architecture of the system

In core-accretion models, a solid core grows and may capture a massive gas envelope before disk gas disperses. The timescale constraint makes early giant-planet growth important. Alternatively, gravitational instability may operate in sufficiently massive, cool disk regions. These are model families with different requirements, and the architecture of the Solar System does not by itself prove one universal path for giant planets.

Growing planets altered the disk. Resonances, scattering, migration, and gas interactions redistributed small bodies. Models in which Jupiter and Saturn move can explain selected features of asteroid and terrestrial-planet populations, but their detailed trajectories are reconstructed rather than directly dated.

The present orbital arrangement is the survivor of a dynamical history. It cannot be read backward uniquely. Many initial configurations may be eliminated, and more than one may remain compatible with current constraints.

6. Building the terrestrial planets

Inside the warmer disk, volatile-poor solids accumulated into planetesimals and embryos. Their gravitational encounters entered an oligarchic and then chaotic regime. Large impacts combined, eroded, or stripped bodies. Material was exchanged across heliocentric distances rather than remaining within perfectly isolated feeding zones.

Earth did not appear at a single boundary. Its formation includes mass accretion, segregation of metal into a core, silicate differentiation, atmospheric loss and replenishment, volatile delivery, and late additions after much core formation. Hf-W and related isotope systems constrain these processes through radioactive parent-daughter evolution and assumptions about metal-silicate partitioning [5]. Different clocks date different closure or differentiation events.

Lead isotope work established the deep-time scale of meteorites and Earth [10], but “the age of Earth” is a convention summarising formation evidence. CHO avoids transferring the precision of one meteoritic component to the duration of whole-planet assembly.

7. Volatiles and water

Earth’s water and other volatiles could have been incorporated during accretion, delivered later, exchanged with a magma ocean and atmosphere, lost to space, and recycled into the interior. Hydrogen, nitrogen, and noble-gas isotopes constrain source reservoirs, but source bodies themselves were heterogeneous and later processes fractionated their signals [9].

The old contrast between a completely dry Earth plus late cometary water and a fully wet local Earth is inadequate. Carbonaceous asteroid-like material, nebular interactions, differentiated impactors, and a smaller cometary contribution can all be tested. The relative fractions depend on which isotope systems and dynamical histories are combined. No one surviving water molecule identifies its source reservoir without a model.

8. Differentiation, magma oceans, and atmosphere

Accretional energy, core segregation, radioactive decay, and giant impacts generated extensive melting. Magma oceans promoted chemical differentiation and volatile exchange. Dense metal descended; silicate reservoirs evolved; an early atmosphere formed from nebular capture, impact delivery, outgassing, and vaporised material, while impacts and escape removed parts of it.

The mantle and core are not samples of untouched starting material. Siderophile elements partitioned into metal, lithophile elements favoured silicates, and volatile elements experienced loss and redistribution. Later mantle convection, crust production, and impacts overprinted earlier states. Chemical inversion therefore depends on partition coefficients, pressure-temperature paths, oxidation state, and assumptions about equilibration.

9. The Moon-forming event

The Moon’s small iron core, orbital angular momentum, depleted volatile inventory, and isotopic relationship to Earth constrain its origin. Simulations of a grazing collision near the end of Earth’s main accretion produced an iron-poor debris disk capable of forming a Moon [6]. This established a powerful canonical impact family.

It did not close every problem. In many canonical simulations, much lunar material derives from the impactor, whereas Earth and Moon show striking isotopic similarities. Vigorous mixing after impact can reduce differences [8]. High-angular-momentum impacts into a fast-spinning Earth, followed by resonant angular-momentum loss, provide another family [7]. Other work varies impactor composition, impact energy, vaporisation, equilibration, and subsequent disk evolution.

“The giant impact” should therefore mean a constrained class of energetic Earth-impactor histories, not one agreed initial condition. Isotope similarity can reflect common source reservoirs, mixing, equilibration, or combinations. The Moon’s accretion and differentiation also followed the collision; the impact is not identical to completion of the Moon.

10. Evidence hierarchy and uncertainty

Evidence	Directly measured	Reconstructed
Meteorite isotope systems	Ratios, mineral context, analytical uncertainty	Formation age, reservoir separation, thermal history
Disk observations	Radiation, morphology, molecular and dust tracers	Surface density, grain sizes, embedded planets
Planetary samples	Chemistry, mineralogy, isotope ratios	Source regions, differentiation, mixing
Orbits and masses	Current dynamical state	Prior migration and instability
Numerical simulations	Conditional evolution from specified inputs	Plausible histories, not unique past events

A coherent history must satisfy several evidence classes simultaneously. Agreement with one isotope ratio or one orbital feature is insufficient. Numerical simulations test whether proposed histories are physically possible under their assumptions; they do not observe the past.

11. Observer capacities

Observer status remains N0. The disk and planets responded to gravity, radiation, collisions, and chemistry, but physical response is not biological detection. Meteorites and lunar rocks became records without recording for a purpose.

Much later, scientific observers learned to extract time from isotope systems and to compare the Solar System with young disks. That retrospective measurement does not make Solar-System formation observer-dependent.

12. Contingency and non-teleology

The sequence was contingent. Slightly different collision histories, migration paths, disk lifetimes, or volatile delivery could have produced different planets. The survival of Earth and its later habitability does not show that the disk evolved toward observers.

The article follows Earth because the book traces the lineage that eventually became able to reconstruct the universe. This narrative selection must not be converted into a physical principle.

13. Closing state and handoff

By the 4.000 Ga ago BOOK boundary, Earth and Moon exist as differentiated bodies, but their surfaces and interiors remain dynamically active. Atmosphere, oceans, crust, impact regimes, and heat loss are not frozen outcomes of assembly. CHO-009 takes ownership of those Hadean systems. CHO-010 separately owns origin-of-life mechanisms, while CHO-011 will adjudicate claims for the earliest evidence of life.

The handoff is therefore a planet, not a finished habitat: chemically differentiated, carrying water and volatiles of mixed histories, orbiting a young Sun, accompanied by the Moon, and subject to continuing impact and internal evolution.

Bouvier and Wadhwa reported 4568.2 Ma for another meteoritic inclusion using a different sample and Pb-Pb analytical framework [11]. The alternative value remains explicit method-dependent counterevidence, not a discarded anomaly.

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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.