

Plasma, Atoms, and the Release of the Cosmic Microwave Background

CHO-004 · Cosmic History and Its Observers

A Chronological Scientific History from the Early Universe to the Present

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Structured abstract

Context. After primordial nucleosynthesis, the Universe remained a hot, expanding plasma. Its nuclei, electrons, photons, neutrinos, and non-baryonic matter did not form a featureless equilibrium bath: gravity amplified inherited density perturbations while photons and charged baryons remained tightly coupled.

Question. How did that plasma become predominantly neutral gas, and why can present observers detect a microwave record of the transition?

Evidence and method. The reconstruction combines atomic and radiative-transfer calculations, general-relativistic cosmological perturbation theory, measurements of the cosmic microwave background spectrum, and statistical fits to its temperature and polarisation anisotropies. Times quoted in years are conversions within a specified cosmological model; redshift and the photon visibility function are closer to the observables.

Result. Matter-radiation equality altered the growth of perturbations. Acoustic competition between gravity and photon pressure imprinted scale-dependent correlations. As expansion lowered the temperature, helium and hydrogen recombined through non-equilibrium pathways. The falling free-electron abundance increased the photon mean free path, producing an extended last-scattering distribution rather than one instantaneous release at exactly 380,000 years. The photons subsequently redshifted into the cosmic microwave background.

Conclusion. CHO-004 passes to CHO-005 a mainly neutral gas with inherited density structure, freely propagating relic photons, and no evidenced biological observer. The microwave sky is a physical trace later measured by observers, not evidence that awareness caused decoupling.

Keywords: recombination; photon decoupling; cosmic microwave background; matter-radiation equality; acoustic oscillations; visibility function; cosmological parameters

1. Chronological orientation

CHO-004 occupies the BOOK interval from twenty minutes to 0.5 million years after the formal hot-Big-Bang coordinate boundary. The lower seam begins after the effective freeze-out of primordial light-element production. The upper seam is deliberately later than the peak of photon last scattering so that the article contains the full transition to the neutral, optically thin conditions inherited by CHO-005.

Several clocks coexist. Cosmic time tBB is computed from an expansion model. Redshift, z , describes the stretching of wavelengths between emission and observation. Temperature is a dynamical coordinate for the thermal plasma. None is a universal wall clock independent of assumptions. A statement such as “the CMB was released 380,000 years after the Big Bang” is a useful orientation under baseline cosmological parameters, but it compresses a finite visibility distribution and a multi-stage atomic history into one number.

The controlled order is:

Phase	Principal change	Evidential character
Post-BBN plasma	Ionised H/He nuclei, electrons and photons continue cooling	Calculated from inherited composition and expansion
Equality	Non-relativistic matter overtakes radiation in the background density budget	Parameter inferred through cosmological fits
Acoustic evolution	Coupled photons and baryons oscillate in gravitational potentials	Encoded statistically in CMB anisotropies
Recombination	Neutral helium and hydrogen become abundant through non-equilibrium pathways	Atomic calculation constrained by CMB data
Decoupling	Thomson scattering becomes inefficient and photons free-stream	Reconstructed as a visibility function

2. Initial state inherited from CHO-003

CHO-003 passes forward a composition dominated by hydrogen and helium nuclei, with trace deuterium, helium-3, and lithium-related nuclei. Electrons maintain charge neutrality. Photons dominate the electromagnetic thermal bath, while neutrinos have already ceased to share full thermal equilibrium with it. Non-baryonic dark matter, if the baseline model is correct, contributes gravitationally without participating in Thomson scattering.

The plasma is extremely uniform but not perfectly so. Inflationary models in CHO-001 supplied a candidate origin for primordial perturbations; CHO-004 does not re-own that origin. It asks how those initial conditions evolve when different components respond differently to pressure, gravity, and scattering.

3. Expansion, cooling, and matter-radiation equality

Radiation density falls more rapidly with expansion than non-relativistic matter density. Photons lose energy as their wavelengths stretch, in addition to being diluted by volume, whereas conserved non-relativistic rest mass is principally diluted by volume. The two background densities therefore cross. In the baseline Planck analysis, equality lies near redshift 3400, but this is not a directly photographed event. It is inferred from a model connecting the primordial spectrum, matter content, expansion, and observed correlations [1].

Equality matters because radiation pressure and relativistic free streaming resist clustering on relevant scales, while pressureless matter can build gravitational potentials more effectively. Growth does not begin abruptly at equality, and baryons remain coupled to photons long afterward. Equality is a change in the dominant background term and in the efficiency of structure growth, not the instant when all structure formation switches on.

4. A coupled photon-baryon medium

Free electrons scatter photons by the Thomson process. Coulomb interactions couple electrons to nuclei, so the baryonic component is dragged by the photon field. Gravity attempts to compress overdense regions; photon pressure opposes compression. The result is a family of driven acoustic oscillations whose phase and amplitude depend on scale, composition, expansion, gravitational potentials, and initial conditions.

Calling these features “sound waves” is helpful only if the medium is specified. They are not sound propagating through neutral air. They are perturbations in a relativistic photon-baryon plasma, coupled to the gravitational effects of dark matter and other components. Modes of different wavelength have completed different fractions of an oscillation when photons decouple. Projection onto the sky produces the peak structure of the angular power spectra [5].

Baryons add inertia to the oscillating medium. Dark matter influences gravitational wells. Relativistic species alter expansion and perturbation evolution. Consequently the peak pattern contains information about multiple parameters, but no peak is a single-purpose gauge. Parameter values arise from joint likelihoods, calibration, foreground models, and an assumed cosmological framework.

5. Recombination was not a simple equilibrium switch

The historical name “recombination” is slightly misleading: cosmic protons and electrons had not previously occupied a long-lived neutral phase. Helium recombines through multiple stages before hydrogen becomes predom-

antly neutral. Hydrogen formation is delayed relative to a naive equilibrium estimate because photons trapped near resonant transitions, two-photon decay channels, expansion, and radiative transfer control how rapidly electrons reach the ground state [2,3].

A Saha-equilibrium calculation gives useful orientation when reactions are rapid enough to track equilibrium. Precision CMB work requires non-equilibrium rate equations and radiative-transfer corrections. Codes such as RECFAST, CosmoRec, and HyRec embody successive levels of approximation and accuracy. Their agreement and differences matter because even small changes in the ionisation history can shift predicted anisotropy spectra at the precision reached by modern experiments.

“Atoms formed” therefore names a changing population. There is no observed first hydrogen atom with a timestamp. Transient bound states need not coincide with the epoch when neutral atoms become abundant, and helium follows a distinct sequence. CHO avoids converting a distributed population history into an individual priority claim.

6. Photon decoupling and the visibility function

As the free-electron fraction falls, the mean distance a photon travels between scatterings rises. Decoupling becomes effective when the scattering rate can no longer maintain tight coupling on the expansion timescale. Recombination causes this transparency transition, but the two terms are not synonyms: recombination describes atomic populations, while decoupling describes radiative transport.

For a photon observed today, the visibility function gives the probability density that its last scattering occurred at a given time or redshift. In the standard calculation it peaks around $z \sim 1100$. A Planck-2015-based analysis reported a characteristic conformal thickness of 19 ± 0.065 Mpc and quoted alongside it the standard orientation $\Delta z \sim 90$ [6]. These are statements of different status, not a direct conversion of one into the other, and neither defines a universal boundary. The “surface of last scattering” is therefore a projection of a distribution through an inhomogeneous Universe, not a rigid sphere or an infinitely thin material shell.

Photons did not suddenly start travelling through empty space. They began to free-stream through matter that was becoming neutral, carrying a record of temperature, velocity, gravitational, and polarisation-generating conditions. Later gravitational lensing, reionization scattering, foreground emission, and instrument response alter the maps received today. Reconstruction must model those intervening effects.

7. What the microwave background actually records

COBE/FIRAS measured the all-sky CMB monopole spectrum to be extraordinarily close to a blackbody near 2.725 K [4]. This spectrum is distinct from the much smaller directional temperature differences mapped by COBE, WMAP, Planck, and ground-based experiments. Expansion redshifted the characteristic radiation temperature from thousands of kelvin near decoupling to microwaves today.

The anisotropies are statistical fields. Their angular power spectra summarise correlations by scale; polarisation adds information about velocity quadrupoles, geometry, lensing, and later scattering. The spectra support a compact baseline cosmological model, but that success does not make every component directly visible. Dark matter density, spectral parameters, and the sound-horizon scale are inferred through their combined influence on predicted correlations [1,5].

This evidential chain is unusually powerful because independent physics converges: atomic transition rates determine the ionisation history; gravity and fluid dynamics determine perturbation evolution; a telescope measures frequency-dependent sky signals; component-separation methods remove Galactic and extragalactic foregrounds; a likelihood compares maps or spectra to predictions. Every stage introduces assumptions and uncertainty.

8. Evidence, dating, and resolution limits

Three distinctions prevent chronological overstatement.

First, a measured redshift is not automatically a model-independent age. Converting the visibility peak to years requires the expansion history. Second, the peak is not the full distribution. Different summaries can quote recombination, last scattering, drag-epoch, or visibility-peak quantities, which need not share the same numerical value.

Third, the CMB observed at Earth is not a pristine image. It has been gravitationally lensed, partly rescattered, contaminated by foregrounds, filtered by beams, and statistically reconstructed.

Precision also creates dependence on convention. Parameters quoted from Planck must specify the data combination and model. The 2021 corrigendum altered early-reionization optical-depth bounds, not the basic recombination sequence used here; its implications are material for CHO-005 [1]. CHO-004 therefore uses rounded values for orientation and reserves exact numbers for source-specific reporting where the evidence supports that precision.

9. Observer capacities present

The article window remains N0: information-bearing physical traces exist, but there is no evidence of a living system detecting or using them. Density perturbations, atomic populations, and photon correlations do not require awareness. They are physical states that later observers can measure.

Present astronomers occupy a radically later causal position. Detectors absorb microwave photons; teams calibrate instruments; statistical models infer parameters. That later epistemic activity explains how the history is known. It did not cause recombination or select the photons’ last scattering events.

10. Contingency and contemporaries

The broad sequence follows from expansion plus the inherited contents, but its detailed outcome depends on those contents. A different baryon density would change acoustic loading and recombination. Different radiation content would change expansion and equality. Energy injection from unstable particles could distort the ionisation history or spectrum. Alternative dark-matter behaviour could alter gravitational growth.

The baseline history is therefore conditional rather than inevitable. Its empirical success constrains alternatives, but it does not show that these parameters were necessary in every possible universe. Nor does later life confer purpose on a plasma transition.

11. Competing interpretations and unresolved questions

The standard recombination calculation is mature, yet precision questions remain: radiative-transfer corrections, atomic rates, helium treatment, energy injection, small spectral distortions, and consistency among CMB datasets. The Hubble-constant tension illustrates a larger methodological point. A CMB-derived present expansion rate is conditional on the cosmological model connecting decoupling to today; disagreement with late-Universe routes is not a direct dispute about a clock at recombination alone.

Proposed extensions can change early expansion, sound horizons, perturbation growth, or recombination. Their value must be judged through global evidence rather than their ability to move one fitted parameter. CHO-004 records the robust thermal and radiative sequence without declaring the baseline model metaphysically final.

12. Claim-class statement

Class	CHO-004 use
E1 measured	CMB frequency spectrum, sky maps, calibrated angular correlations
E2 reconstructed	Ionisation history, equality epoch, visibility distribution
E3 model-dependent	Parameter values and time conversions within a named cosmology
E4 contested	Interpretation of dataset tensions and proposed extensions
E5 speculative	Untested non-standard energy injection or new sectors

13. Boundaries, closing state, and handoff

CHO-004 does not re-derive primordial nucleosynthesis, originate primordial perturbations, or own reionization. It owns the transformation from the post-BBN plasma to predominantly neutral gas and free-streaming relic radiation within [20 min,0.5 Myr).

At the upper seam, photons propagate over cosmological distances; baryons are mainly neutral; dark matter and baryonic perturbations provide seeds for later structure; the Universe has entered the observationally difficult interval called the dark ages. CHO-005 inherits these conditions and asks how gravity, cooling, star formation, galaxies, and ionising radiation ended that darkness.

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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.