Apparent Superluminal Observational Emergence in Cosmology:

Detectability Transitions in an Expanding Universe

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Abstract

This article examines how large-scale transitions in observational detectability within standard ΛCDM cosmology can create the appearance of abrupt emergence of previously inaccessible structure without implying superluminal physical propagation. Using the Tolman surface brightness dimming relation and opacity evolution of the intergalactic medium, a quantitative detectability threshold is formulated for cosmological sources. Two representative cases are examined: recombination, when photon decoupling rendered the universe transparent, and reionisation, when ionisation of the intergalactic medium enabled observational access to high-redshift structure. In both cases, the presently inferred spatial scales exceed the Hubble scale associated with the relevant epochs, creating an observational impression of emergence across superluminal recession distances. This interpretation remains fully consistent with general relativity and standard cosmology, while clarifying the distinction between physical existence and observational accessibility in cosmological observations.

Keywords: cosmological horizons; observational detectability; superluminal recession; Tolman surface brightness dimming; recombination; reionisation; high-redshift cosmology; observational cosmology

1 Introduction

It is well established within the framework of general relativity that regions of the universe sufficiently distant from any observer recede at effective speeds exceeding that of light [1, 2]. This apparent superluminal recession is a consequence of the global evolution of the spacetime metric rather than local motion, and it does not violate relativistic causality. Davis and Lineweaver [2] have shown rigorously that, in all viable ΛCDM models, objects at redshifts $z \gtrsim 1.5$ are currently receding at speeds greater than c, and that these objects are nevertheless observable. The Hubble sphere—the surface at which recession velocity equals c—is neither a limit of observability nor a causal boundary in the standard cosmological sense [2, 3].

A distinct but related question concerns not the recession of already-detected sources, but the apparent *emergence* of newly detectable structure. When physical conditions in the universe undergo a large-scale transition, previously undetectable matter or radiation may suddenly become observable. If such a transition occurs across a spatial region that spans superluminal recession distances, the resulting appearance of structure may seem to emerge simultaneously across scales exceeding the speed of light. We refer to this as *apparent superluminal emergence* (ASE), and we argue that it is a natural consequence of cosmological detectability thresholds rather than a violation of any physical principle.

This article does not propose a modification to the standard cosmological model. Rather, it provides a conceptual and quantitative clarification of how observational detectability thresholds interact with the causal and geometric structure of an expanding universe. Section 2 reviews the Tolman surface brightness effect and derives the relevant detection threshold condition. Section 3 identifies two representative physical examples of large-scale detectability transitions: the epoch of recombination and the epoch of reionisation. Section 4 formalises the connection between these transitions and apparent superluminal emergence. Section 5 discusses the broader implications.

2 Cosmological Detectability and the Tolman Factor

For an extended source at cosmological redshift z, the bolometric surface brightness I_{obs} observed today is related to the intrinsic emitted surface brightness I_{em} by the Tolman relation [4, 5]:

$$I_{\text{obs}} \;=\; \frac{I_{\text{em}}}{(1+z)^4}. \tag{1}$$

This suppression receives two independent contributions: a factor of $(1+z)^{-1}$ from the loss of photon energy to cosmological redshift, and a factor of $(1+z)^{-3}$ from the combined reduction in photon flux due to time dilation and the expansion of the solid angle subtended by the source [4, 6]. The Tolman signal has been confirmed observationally through surface photometry of distant galaxy clusters [6, 7].

Consider an observer equipped with an instrument whose minimum detectable surface brightness is I_{min}. A source with intrinsic surface brightness I_{em} falls below the detection threshold when

$$\frac{I_{\text{em}}}{(1+z)^4} \;<\; I_{\text{min}}, \tag{2}$$

or equivalently, when the source redshift exceeds the critical detectability threshold

$$z \;>\; z_{\text{det}} \;\equiv\; \left(\frac{I_{\text{em}}}{I_{\text{min}}}\right)^{1/4} -\; 1. \tag{3}$$

For typical astrophysical sources and realistic instrumental sensitivity limits, z_{det} falls well within the observable universe. Equation (3) formalises the central epistemological point: a source physically present at $z > z_{\text{det}}$ makes no detectable contribution to an observed signal, even though its electromagnetic emission and gravitational influence are real. The absence of a detected signal from a given region does not imply the absence of energy in that region.

Beyond the individual-source detection limit, opacity effects can further suppress detectability. If the intervening medium is optically thick at the relevant wavelengths, radiation cannot propagate to the observer regardless of its intrinsic brightness. This introduces a second class of detectability limitation, governed not by Tolman dimming alone but by the evolving optical depth of the intergalactic medium.

Methodological limitations. The detectability criterion of Eq. (3) is a schematic heuristic formulated for bolometric surface brightness. In practice, observational detectability depends on bandpass selection, K-corrections, source morphology, instrumental noise models, and wavelength-dependent opacity of the intergalactic medium. Selection effects further complicate the comparison between a theoretical threshold redshift and the observed detection limits of real surveys. The treatment presented here is therefore intentionally illustrative: it captures the dominant scaling with redshift but does not replace a full radiative-transfer or survey-selection analysis. Predictive applications to specific observational programmes would require a more realistic treatment incorporating these factors.

3 Representative Examples of Large-Scale Detectability Transitions

3.1 The Epoch of Recombination

Prior to the epoch of recombination at $z \approx 1100$, the universe consisted of a tightly coupled plasma of photons, electrons, and protons with a photon mean free path far smaller than the Hubble radius [8]. In this regime the universe was effectively opaque: electromagnetic radiation could not propagate freely, and no information about the state of the plasma was accessible to a distant observer in the form of free-streaming photons. At recombination, as the temperature fell to approximately 3000 K, protons and electrons combined to form neutral hydrogen on a timescale short compared to the Hubble time. The photon mean free path increased by many orders of magnitude, and radiation decoupled from matter, propagating freely thereafter as the cosmic microwave background (CMB) [9].

The comoving radius of the last scattering surface is approximately $D_C \approx 14{,}000$ Mpc, vastly exceeding the comoving Hubble radius at recombination, $c/H(z_{\rm rec}) \approx 90$ Mpc [2, 8]. The present-day recession velocity of this surface is

$$v_{\rm rec} \;=\; H_0\, D_C \;\approx\; 3.2\, c, \tag{4}$$

for standard ΛCDM parameters ($H_0 = 67.4\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$, $\Omega_m = 0.315$, $\Omega_\Lambda = 0.685$) [12]. The Tolman dimming at this epoch amounts to

$$(1 + z_{\rm rec})^4 \;\approx\; (1101)^4 \;\approx\; 1.5 \times 10^{12}, \tag{5}$$

a suppression so extreme that radiation originating from behind the last scattering surface is undetectable in practice, irrespective of instrumental sensitivity. The recombination transition therefore represents the paradigmatic example of an observational detectability transition: within an interval short relative to cosmological timescales, the entire observable universe transitioned from opaque to transparent. From the perspective of a subsequent observer, the CMB constitutes matter and radiation that became observationally accessible simultaneously across a spatial region at superluminal recession distances. No physical velocity exceeded c; the transition was one of detectability.

3.2 The Epoch of Reionisation

Following recombination, the universe entered the cosmic dark ages, during which the intergalactic medium (IGM) consisted predominantly of neutral hydrogen and helium. Neutral hydrogen is highly opaque to photons at frequencies above the Lyman limit ($\nu > 3.3 \times 10^{15}$ Hz, $\lambda < 912$ Å) and in the Lyman-α line, effectively rendering the high-redshift universe opaque to ultraviolet and optical radiation from background sources [10, 11].

The formation of the first stars and galaxies produced ionising radiation that progressively reionised the IGM. Observations of the Gunn–Peterson trough in high-redshift quasar spectra indicate that reionisation was largely complete by $z \approx 6$, with the transition spanning

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approximately $6 \lesssim z \lesssim 11$ [10, 15]. Following reionisation, galaxies and other structures that had formed and evolved during the dark ages became accessible to optical and near-infrared observation for the first time.

The comoving distance to $z = 6$ is approximately $D_C \approx 8{,}800$ Mpc, exceeding twice the Hubble radius $c/H_0 \approx 4{,}300$ Mpc. Objects at this redshift therefore have a present-day recession velocity of approximately

$$v_{\rm rec}(z = 6) \;\approx\; 2.0\, c. \tag{6}$$

Structure that existed throughout the dark ages at these distances was, by the combined criterion of Tolman dimming and IGM opacity, entirely undetectable. The clearing of the IGM through reionisation constituted a large-scale detectability transition, after which pre-existing but previously invisible structure became observable. The appearance of a high-redshift galaxy population in deep surveys such as those conducted by the *Hubble Space Telescope* and the *James Webb Space Telescope* reflects, in part, this detectability transition rather than the instantaneous formation of those galaxies at the moment of their first observation [13, 14].

4 Apparent Superluminal Emergence as a Detectability Effect

The central argument may now be stated precisely. Consider an observer in a ΛCDM universe who monitors a comoving volume of space. Suppose that at cosmic time t_1, corresponding to redshift z_1, a large-scale physical transition occurs that changes the detectability of matter or radiation across that volume. Prior to t_1, the volume appears observationally empty; after t_1, the same matter becomes detectable.

If the spatial extent of this transition—quantified by its comoving radius D_C—exceeds the comoving Hubble radius $c/H(z_1)$ at the time of the transition, then the matter that becomes visible includes material at locations with superluminal recession velocities. The observer will perceive the apparently simultaneous emergence of structure at superluminal scales. This is apparent superluminal emergence: the matter was always present, but the transition from undetectable to detectable—not the matter itself—spans the superluminal region.

This interpretation is consistent with the causal structure of general relativity. The detectability transition propagates as a physical process subject to the standard causal constraints of the spacetime metric. The globally simultaneous nature of transitions such as recombination and reionisation is an approximate description valid in the homogeneous background; in detail, these transitions occur at finite rates and with spatial inhomogeneities. However, the characteristic scale of the transition—governed by the Hubble radius at the relevant epoch and by the speed of ionisation fronts during reionisation—is well within the causal horizon at that time. The large apparent spatial extent of the transition, as observed today, arises from the subsequent evolution of the scale factor and the geometry of the past light cone, not from any acausal propagation.

This stands in direct analogy with the well-understood case of superluminal recession discussed by Davis and Lineweaver [2]: the appearance of superluminality arises from the global properties of the expanding metric, not from local velocities. In the ASE case, the same geometric mechanism—the expansion of the universe stretching a locally sub-luminal transition across apparently superluminal scales—produces an apparent paradox that dissolves upon careful analysis.

5 Discussion

High-redshift survey interpretation. Modern photometric and spectroscopic surveys—including those conducted with the *James Webb Space Telescope*—are detecting galaxy candidates at redshifts as high as $z \approx 13$–16, corresponding to epochs only a few hundred million years after the Big Bang [13, 14]. The detectability transition framework highlights that at least part of this phenomenon reflects the progressive opening of new observational windows through the evolving IGM opacity, the Tolman factor, and improving instrumental sensitivity, rather than the creation of those objects at the moment of their first detection.

Void statistics and detection limits. Surveys of the large-scale distribution of galaxies reveal a network of filaments, sheets, and voids. The observed low-density appearance of cosmic voids is partly a physical reality and partly a detection-limit effect: low-luminosity and low-surface-brightness galaxies, as well as diffuse intergalactic gas below the flux threshold of the relevant survey, may populate apparent void regions without contributing detectable signal. Future surveys with improved sensitivity may reveal structure in currently empty-appearing regions, constituting a local manifestation of the ASE effect described here.

Relation to the horizon problem. The detection of the CMB at nearly uniform temperature across the entire sky—including from regions causally disconnected at the time of recombination—is commonly cited as the horizon problem and as motivation for inflationary cosmology [8]. The ASE framework offers a complementary observational perspective: the apparent simultaneous emergence of the CMB across the last scattering surface, spanning superluminal recession distances, is an extreme case of apparent superluminal emergence driven by the global recombination transition. The horizon problem and the ASE effect share the same geometric origin—the ratio of the observable comoving scale to the Hubble radius at the relevant epoch—though they raise distinct physical questions.

Future observational signatures. The ASE framework suggests that large-scale detectability transitions should produce correlated, spatially extended emergence events in survey data, though quantitative predictions would require detailed modelling beyond the scope of the present analysis. Future 21-cm cosmology experiments probing the neutral hydrogen signal from the dark ages—including the Hydrogen Epoch of Reionization Array (HERA) and the Square Kilometre Array (SKA)—represent a context in which a new detectability transition will be explored, potentially revealing large-scale structure at redshifts $z \approx 20$–30 that is currently undetectable [11, 16].

6 Conclusion

This work has presented a conceptual interpretation of how observational detectability thresholds in standard ΛCDM cosmology can produce the appearance of abrupt emergence of previously inaccessible structure without implying superluminal physical propagation. Using Tolman surface brightness dimming (Eq. 1) and evolving opacity as illustrative mechanisms, recombination and reionisation were discussed as examples of large-scale detectability transitions. The analysis does not introduce new cosmological dynamics, but highlights the observational distinction between physical existence and observational accessibility. A more realistic treatment incorporating wavelength dependence, instrumental selection effects, and detailed radiative transfer would be required for predictive observational applications.

The detection threshold condition

$$z_{\text{det}} = \left(\frac{I_{\text{em}}}{I_{\text{min}}}\right)^{1/4} - 1 \tag{3}$$

(Eq. 3) provides a schematic criterion for when physically present radiation contributes negligibly to observed signals, and the epochs of recombination and reionisation represent instructive examples of such transitions occurring across regions whose comoving extents substantially exceed the Hubble radius. This interpretation requires no modification to general relativity or to the standard ΛCDM cosmological model, and it suggests that the distinction between physical presence and observational visibility should be systematically considered when interpreting the emergence of structure in current and future high-redshift surveys [12, 13, 16].

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