

31. Highly Redshifted Neutral Hydrogen: Observation, Interpretation and Cosmological Inference

The proposed CosmoCube observatory as a prospective test of cosmological interpretation

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Abstract

The 1420.4 MHz hyperfine transition of neutral hydrogen provides a prospective means of probing highly redshifted matter through low-frequency radio observations. Such measurements are commonly described as observations of the cosmic “Dark Ages”, but this description already incorporates a cosmological interpretation. The directly accessible quantities are radio brightness and frequency; identification of a spectral component with neutral hydrogen supplies a spectroscopic redshift, while its conversion into a particular thermal, gravitational and chronological history requires additional assumptions.

This paper separates these observational and interpretative steps and examines the widely proposed 21-cm spectral consistency relations predicted by Λ CDM. These relations are unusually insensitive to variation of the standard cosmological parameters and therefore offer a potentially stringent test of the predicted spectral shape. Their agreement with observation would not, however, uniquely establish the particulate cold-dark-matter ontology used in their derivation. Conversely,

disagreement would challenge the standard consistency relation without selecting any particular alternative explanation.

The Time-Symmetric Parity Constraint (TSPC) provides a useful counter-model with which to expose this distinction. Examination of the 21-cm consistency relations shows that their overall matter-dependent normalisation can substantially cancel, whereas their spectral shape depends upon the evolution of quantities whose high-redshift behaviour has not yet been derived within TSPC. The presently undeveloped TSPC mapping between spectroscopic redshift and the relevant geometrical evolution therefore prevents a unique TSPC 21-cm prediction and does not, in general, cancel from the observable ratios. Highly redshifted neutral-hydrogen measurements can consequently provide a stringent prospective test of Λ CDM, but cannot yet discriminate between Λ CDM and TSPC. The analysis identifies precisely what further TSPC development would be required before such observations could become a genuine model discriminator.

1. Introduction

The proposed CosmoCube observatory offers an unusual opportunity to examine a region of the radio spectrum that is exceptionally difficult to observe from Earth.¹ By placing a small radio instrument in lunar orbit, observations made while the spacecraft is shielded from terrestrial radio-frequency interference by the Moon could extend measurements to frequencies at which the Earth's ionosphere and human transmissions

¹ Artuc K., de Lera Acedo E. (2025), *The spectrometer development of CosmoCube, lunar orbiting satellite to detect 21-cm hydrogen signal from cosmic dark ages*, RAS Techniques and Instruments, 4, 1–13. DOI: 10.1093/rasti/rzae061. Describes the design and development of the CosmoCube lunar-orbiting spectrometer; intended to measure the redshifted neutral-hydrogen 21-cm signal over 10–100 MHz (conventionally interpreted as $13 < z < 150$).

severely restrict ground-based observations. A principal objective is to search for the highly redshifted 21-cm hyperfine signature of neutral hydrogen.

The prospective measurement is commonly described in terms of observing the cosmic “Dark Ages”, the period conventionally placed between recombination and the appearance of the first luminous objects. That description is convenient, but it contains more interpretation than observation. The instrument will measure radio brightness as a function of observed frequency. If a component of that spectrum can reliably be identified with the precisely known 1420.4 MHz hyperfine transition of neutral hydrogen, its frequency displacement provides a spectroscopic redshift. It does not, by itself, establish the age of the hydrogen, the expansion history through which the signal has propagated, the composition of the gravitating matter, or the thermal and structural history conventionally associated with that redshift.

This distinction is important because the standard Λ CDM cosmology makes comparatively precise predictions for the global 21-cm spectrum at very high redshift. In particular, combinations of brightness temperatures measured at selected frequencies have been shown to be remarkably insensitive to variation of the usual Λ CDM parameters. Future low-frequency measurements may therefore provide an unusually stringent prospective test of a prediction made within the standard cosmological framework.

Agreement between observation and such a prediction must nevertheless be distinguished from confirmation of every physical proposition used in deriving it. A measured spectral relation may agree with Λ CDM because the relevant physical evolution is correctly represented by the model; it does not follow without further argument that each component of the model, including particulate cold dark matter, has thereby been independently observed. Conversely, departure from the predicted relation would establish a problem for the assumptions from which it was derived, but would not by itself identify the alternative explanation.

The Time-Symmetric Parity Constraint (TSPC) provides a useful counter-model against which to examine this distinction. TSPC does not introduce an alternative dark-matter particle. It restricts the admissible spacetime geometry and asks whether phenomena conventionally attributed to additional matter content may instead arise, wholly or partly, from that geometrical constraint. Highly redshifted neutral hydrogen therefore presents an interesting question: can its observed radio spectrum distinguish a cosmology containing particulate cold dark matter from one in which the corresponding gravitational phenomena have a geometrical origin?

The question cannot be answered merely by extrapolating the phenomenological clock-skew treatment developed for TSPC at much lower redshift. No quantitative TSPC mapping between observed redshift and geometrical evolution has yet been derived for the very high redshifts relevant to the proposed measurements. To impose such a

mapping for the purpose of obtaining a result would substitute assumption for prediction.

This paper therefore takes the opposite approach. It begins with the prospective observable and asks what can be inferred from it without first assuming either cosmological interpretation. It then examines the origin of the unusually stable 21-cm spectral relations predicted within Λ CDM, identifies which dependencies cancel and which remain, and asks whether the corresponding quantities can presently be determined within TSPC. The purpose is not to claim a premature TSPC prediction, but to establish whether highly redshifted neutral-hydrogen observations can provide a genuine discriminator between the two frameworks and, if they cannot yet do so, to identify precisely what further theoretical development would be required.

2. What is actually observed?

CosmoCube is intended to measure the brightness of the radio sky over a range of low frequencies. The primary observational product is therefore a spectrum: received radio intensity, conventionally expressed as a brightness temperature, as a function of observed frequency. Neither cosmic time nor the physical state of the early Universe is measured directly.

Neutral hydrogen provides a potentially identifiable feature because its ground state possesses a precisely known hyperfine transition at approximately 1420.4 MHz, corresponding to a rest wavelength of about 21 cm.² A photon emitted at this frequency, or an absorption feature produced against a background radiation field, may subsequently be observed at a lower frequency. Once a spectral feature has been securely identified with this transition, the ratio between its rest and observed frequencies defines its spectroscopic redshift.

Frequency and spectroscopic redshift

The rest frequency of the neutral-hydrogen hyperfine transition is

$$1 + z_{\text{spec}} = \frac{\nu_{21}}{\nu_{\text{obs}}}$$

For an observed frequency (ν_{obs}), the spectroscopic redshift is defined by

$$40 \text{ MHz} \rightarrow z_{\text{spec}} \simeq 34.5$$

$$30 \text{ MHz} \rightarrow z_{\text{spec}} \simeq 46.3$$

and

$$20 \text{ MHz} \rightarrow z_{\text{spec}} \simeq 70.0$$

² Furlanetto S. R., Oh S. P., Briggs F. H. (2006), *Cosmology at low frequencies: The 21 cm transition and the high-redshift Universe*, Physics Reports 433, 181–301. DOI: 10.1016/j.physrep.2006.08.002. Comprehensive review of the atomic physics of the neutral-hydrogen 21-cm transition and its application to high-redshift radio observations.

These values follow from the measured frequency ratio. No assumption concerning the age of the Universe or its matter content is required to calculate them.

The distinction between redshift and chronology is important. Identification of neutral hydrogen observed at 30 MHz would establish a frequency displacement corresponding to ($z_{\text{spec}} \simeq 46.3$). It would not, from that observation alone, establish when the relevant interaction occurred, how long radiation subsequently travelled, what expansion history related that event to the present, or what gravitating components were present at the time.

The amplitude of the 21-cm feature supplies additional information, but here too interpretation must be approached carefully. The observable is a difference in radio brightness associated with neutral hydrogen. Its magnitude depends upon the population of the hydrogen hyperfine states and upon the radiation field against which the transition is observed. These are described through the hydrogen spin temperature and the brightness temperature of the background radiation. Radiative-transfer physics can relate these quantities to an observed absorption or emission signal, but it does not independently specify their cosmological history.³

Nor does the word “absorption” imply that the instrument receives photons emitted at 21 cm by hydrogen at a remote epoch. In the circumstances of principal interest here, neutral hydrogen modifies an existing radiation field. If its spin temperature is lower than the effective temperature of that background, the resulting spectral feature appears in absorption; if it is higher, the feature may appear in emission. What reaches the observer is consequently a frequency-dependent alteration of the radio background rather than a simple beacon transmitted by primordial hydrogen.

The practical difficulty is considerable. The anticipated cosmological component is small compared with much brighter foreground radio emission, principally Galactic synchrotron radiation. Instrumental response and foreground separation therefore form part of the process by which a putative neutral-hydrogen contribution is extracted from the measured spectrum. A claimed detection must establish that the feature is astronomical rather than instrumental or foreground in origin and that its spectral behaviour is consistent with neutral hydrogen.⁴

It is useful, therefore, to distinguish three stages which are sometimes compressed into a single description. The first is observation: radio brightness as a function of frequency. The second is physical identification: attribution of a component of that spectrum to the known neutral-hydrogen hyperfine transition, from which a spectroscopic redshift can

³ Furlanetto S. R. *et al. ibid.*

⁴ Artuc K. *et al., Op cit.*

be obtained. The third is cosmological interpretation: assigning that hydrogen to a particular epoch, thermal history, expansion history and gravitational environment.

Only the first two are required to speak of a highly redshifted neutral-hydrogen signal. Description of the same measurement as a signal “from the cosmic Dark Ages” belongs to the third. It may prove to be an exceptionally successful interpretation, but it should not be incorporated into the statement of what has actually been observed.

3. The standard cosmological interpretation

Within the standard cosmological model, sufficiently highly redshifted neutral hydrogen is assigned to the period following recombination and preceding the formation of the first luminous objects. During recombination, the expanding plasma is calculated to have cooled sufficiently for protons and electrons to combine predominantly into neutral hydrogen, greatly reducing the interaction of ordinary matter with the background radiation. The cosmic microwave background is interpreted as radiation released from this transition to transparency. The subsequent interval, before stars supplied significant additional radiation, is conventionally described as the cosmic Dark Ages.⁵

This reconstruction combines well-established atomic and radiative physics with a particular cosmological history. Recombination physics determines how hydrogen ionisation responds to temperature and density, but the temperatures, densities and elapsed times assigned to particular redshifts depend upon the assumed cosmological evolution. The existence of the neutral-hydrogen transition is not model-dependent; the statement that hydrogen observed at a specified redshift occupied a particular stage of a calculated post-recombination history is.

In Λ CDM, the radiation temperature increases with redshift as $(T_\gamma \propto (1 + z))$. At sufficiently early stages the temperature of the ordinary gas remains coupled to the radiation field principally through residual free electrons and Compton scattering. As that coupling becomes ineffective, the gas is calculated to cool more rapidly than the radiation. In the approximately adiabatic regime its kinetic temperature falls roughly as $(T_k \propto (1 + z)^2)$, while the background radiation continues to follow the shallower $(T_\gamma \propto (1 + z))$ relation. The gas consequently becomes colder than the radiation background.

The observable 21-cm contrast does not depend directly upon the kinetic temperature alone. It depends upon the relative populations of the two hyperfine states, conventionally represented by the spin temperature (T_s) . Collisions between hydrogen atoms and other particles can couple (T_s) towards the kinetic temperature of the gas. Where that coupling is effective and $(T_s < T_\gamma)$, neutral hydrogen is predicted to produce

⁵ Furlanetto S. R., *et al.*, *Op cit.*

an absorption feature against the background radiation. As the density falls, collisional coupling weakens and (T_s) tends back towards the radiation temperature, reducing the absorption signal.⁶

The resulting global spectrum is therefore not simply a redshifted atomic line. Its predicted shape represents the combined evolution of the hydrogen density, kinetic temperature, spin temperature, radiation temperature and cosmological expansion. Under Λ CDM these quantities are related through the assumed expansion history and matter content. The observed frequency provides the redshift coordinate against which the prediction is plotted; the physical history assigned to that coordinate comes from the model.

Cold dark matter enters this reconstruction principally through gravitation rather than through the atomic transition itself. In the standard account, non-baryonic matter dominates the gravitating matter density and begins developing structure without the radiative interactions experienced by ordinary matter. Baryonic matter subsequently responds to the resulting gravitational potentials. At sufficiently high redshift the global 21-cm signal is dominated by comparatively homogeneous thermal evolution, while departures produced by the growth of structure can modify the predicted spectrum. Such effects provide one proposed route by which low-frequency neutral-hydrogen observations might constrain the assumed matter model.⁷

None of this makes the Λ CDM interpretation arbitrary. It combines independently developed physical theory with a cosmological framework that has achieved extensive observational success. The distinction required here is narrower: a successful theoretical reconstruction is not the same thing as a direct observation of each element employed in that reconstruction. In particular, the attribution of a highly redshifted neutral-hydrogen feature to a specified chronological epoch, and the role assigned to cold dark matter in producing its detailed evolution, remain conclusions drawn within the cosmological model.

The expression “Dark-Ages 21-cm signal” will therefore be used in this paper only when referring specifically to the signal predicted under that interpretation. Where the observational quantity itself is meant, the more neutral expression “highly redshifted neutral-hydrogen 21-cm signal” will be retained. This distinction becomes important when the standard prediction is compared with a cosmology in which the relationship between observed redshift, gravitational evolution and matter content is not assumed to be the same.

⁶ Furlanetto S. R. *et al. ibid.*

⁷ Park H., Barkana R., Yoshida N., Sikder S., Mondal R. et al. (2025), *The signature of subgalactic dark matter clumping in the global 21-cm signal of hydrogen*, Nature Astronomy 9, 1723–1731. DOI: 10.1038/s41550-025-02637-0. Calculates the predicted effect of nonlinear dark-matter structure formation on the global 21-cm spectrum and examines its potential sensitivity to dark-matter properties and non-standard cosmologies.

4. A remarkably precise Λ CDM prediction

The usefulness of the highly redshifted 21-cm spectrum does not depend solely upon predicting its absolute brightness.⁸ Okamatsu et al. have identified a spectral consistency relation which is substantially less sensitive to the usual Λ CDM parameter uncertainties. Instead of asking whether the predicted brightness temperature at one frequency is correct, brightness temperatures at several frequencies are compared with that at a reference frequency. Much of the dependence upon the assumed cosmological parameters then cancels.

This is important because the absolute 21-cm brightness temperature depends upon several quantities simultaneously. Within the standard calculation these include the neutral-hydrogen abundance, baryon density, total matter density, radiation temperature and spin temperature. During the redshift interval considered by Okamatsu et al., however, the standard model predicts a comparatively simple matter-dominated evolution. Over much of this interval the dependence upon the principal cosmological density parameters acts predominantly upon the overall amplitude of the spectrum rather than upon its shape.

The result is a prediction considerably sharper than might be expected from the number of physical quantities entering the calculation. Okamatsu et al. find that ratios of the predicted brightness temperature at selected frequencies to that at 30 MHz vary by less than one per cent over broad ranges of the standard cosmological parameters. The relative shape of the spectrum therefore constitutes a consistency test of the physical assumptions from which it is derived.

The Λ CDM 21-cm spectral consistency relation

For small 21-cm optical depth, the differential brightness temperature may be written schematically as

$$T_b(z) \simeq \frac{T_s - T_\gamma}{1 + z} \tau_{21}$$

where (T_s) is the hydrogen spin temperature, (T_γ) is the radiation temperature and the optical depth contains the neutral-hydrogen density and the expansion rate:

$$\tau_{21} \propto \frac{n_{\text{HI}}}{T_s H(z)}$$

Under the matter-dominated approximation used for the standard calculation,

$$H(z) \propto \sqrt{\omega_m} (1 + z)^{3/2}$$

⁸ Okamatsu T., Sekiguchi T., Takahashi T. (2023), *Probing the existence of the dark ages: novel consistency test of the Λ CDM model at the global 21-cm signal*, Physical Review D 108, 083526. DOI: 10.1103/PhysRevD.108.083526. Develops ratios of global 21-cm brightness temperatures at selected frequencies as a consistency test of Λ CDM, showing that the predicted spectral ratios are unusually insensitive to variation of the standard cosmological parameters.

while

$$n_{\text{HI}} \propto \omega_b (1 - Y_p) (1 + z)^3$$

The resulting brightness temperature can therefore be expressed approximately as

$$T_b \simeq 85 \text{ mK} \left(\frac{T_s - T_\gamma}{T_s} \right) \left(\frac{\omega_b}{0.02237} \right) \left(\frac{0.144}{\omega_m} \right)^{1/2} \left(\frac{1 - Y_p}{1 - 0.24} \right) \left(\frac{1 + z}{100} \right)^{1/2} x_{\text{HI}}$$

Much of the parameter dependence is common to the brightness temperatures at different frequencies. Defining

$$R_{\nu/30} = \frac{T_b(\nu)}{T_b(30 \text{ MHz})}$$

therefore removes much of this common normalisation.

Okamatsu et al. obtain, for their standard calculation,

$$R_{40/30} = 0.3873 \pm 0.0029$$

$$R_{35/30} = 0.6401 \pm 0.0016$$

$$R_{20/30} = 1.8487 \pm 0.0126$$

$$R_{20/30} = 1.8487 \pm 0.0126$$

The corresponding frequency ratios refer to spectroscopic redshifts of approximately 34.5, 39.6, 55.8 and 70.0 respectively, with 30 MHz corresponding to ($z_{\text{spec}} \simeq 46.3$).

The narrow ranges of these ratios are the relevant prediction. They express the expected shape of the highly redshifted 21-cm spectrum rather than simply its absolute amplitude.⁹

The cancellation should not be misunderstood. The consistency relation is not model-independent merely because it is relatively insensitive to variation of parameters within Λ CDM. Its stability arises because the calculations being compared share a set of physical assumptions. Okamatsu et al. identify these as including matter domination, the absence of significant $Ly - (\alpha)$ radiation from early luminous sources, standard Compton coupling between matter and radiation, and the CMB as the relevant radio background. Altering those assumptions can alter the predicted ratios.

This distinction is particularly important for dark matter. The total matter density enters the standard brightness-temperature calculation through the expansion history, but much of its effect is an overall normalisation which is suppressed when ratios are formed. The consistency relation should therefore not be regarded as a direct detector of particulate cold dark matter. Its strength lies elsewhere: it tests whether the observed

⁹ Okamatsu T., *et al.*, *ibid.*

spectral shape follows the tightly constrained relation produced by the standard combination of expansion, thermal and radiative assumptions.

Future observations capable of measuring the global spectrum at these frequencies could therefore confront Λ CDM with a genuinely prospective prediction. Agreement close to the quoted ratios would be non-trivial evidence that the predicted physical relations are being reproduced in nature. A substantial and well-established departure would demonstrate that at least one of the assumptions responsible for the consistency relation is incomplete or incorrect.

Neither outcome, however, determines by itself why the relation succeeds or fails. Agreement with a prediction made within Λ CDM is not logically identical to separate observational confirmation of each constituent of Λ CDM. It is this distinction that makes the consistency relation particularly useful for examining TSPC: before asking whether TSPC predicts different numbers, it is necessary to determine which parts of the Λ CDM prediction actually distinguish the two frameworks.

5. What would the observation establish?

The precision of the Λ CDM consistency relation makes the prospective observation unusually informative, but it also creates a risk of attributing more significance to agreement than the measurement can support. A successful prediction may confirm a relationship between observable quantities without independently confirming every element of the theoretical framework from which that relationship was derived.

Suppose, for example, that future observations recover a highly redshifted neutral-hydrogen spectrum whose brightness-temperature ratios agree with the values predicted by Okamoto et al. Such a result would be important. The agreement would extend across measurements made at different observed frequencies and would reproduce a spectral shape predicted in advance to comparatively high precision. It would therefore provide evidence that the combination of physical relations responsible for that shape gives a good description of the observed phenomenon.

It would not follow, however, that particulate cold dark matter had thereby been detected. Cold dark matter enters the Λ CDM calculation as part of a wider description of gravitational and cosmological evolution. As shown in the preceding section, much of the dependence upon total matter density affects the normalisation of the global 21-cm brightness and is substantially suppressed in the spectral ratios. The observation would test the resulting relation; it would not separately identify the physical origin of every contribution used to derive it.

The distinction can be stated more generally. A theoretical prediction has the logical form

$$A + B + C + \dots \Rightarrow P$$

where (P) is an observable prediction and (A), (B) and (C) represent assumptions or physical propositions entering its derivation. Observation of (P) establishes that the prediction has succeeded. It does not, without additional discriminatory evidence, establish individually that (A), (B) and (C) are uniquely responsible for that success. A different physical construction may, in principle, produce the same observable relation.

The converse requires equal care. If a securely measured spectrum were inconsistent with the predicted ratios, the observation would establish that the set of assumptions used to derive the consistency relation was incomplete or incorrect within the relevant regime. It would not identify which assumption had failed. A departure might arise from the expansion history, the thermal evolution of the gas, the assumed radiation background, additional interactions, unexpectedly early luminous sources, or other physics not included in the standard calculation. Nor would disagreement constitute evidence for TSPC unless TSPC had independently predicted the observed departure.

This asymmetry is important. Agreement can strengthen confidence in a model without uniquely establishing its ontology; disagreement can falsify a particular prediction without identifying which of the assumptions responsible for it has failed. The evidential value of the observation therefore depends upon whether competing frameworks make genuinely different predictions for the same measured quantities.

This is especially relevant to the interpretation of highly redshifted neutral hydrogen. The spectrometer measures brightness as a function of frequency. The Λ CDM consistency relation converts part of that spectrum into a stringent test because Λ CDM supplies the physical evolution connecting the measurements. To distinguish Λ CDM from another cosmology, however, it is necessary for the alternative framework either to predict a different relation or to demonstrate that the same relation follows without one or more of the physical assumptions conventionally used to explain it.

The question for TSPC is therefore narrower than whether it can provide an alternative narrative for the proposed observations. It is whether the geometrical constraint changes any quantity controlling the spectral ratios in a way that is both calculable and observationally distinguishable. If it does, the highly redshifted 21-cm spectrum could become a genuine discriminator. If it does not, agreement with the standard prediction would leave the two descriptions observationally degenerate for this particular test. If the relevant TSPC quantities cannot yet be calculated, the observation may test Λ CDM while remaining unable, for the present, to test Λ CDM against TSPC.

The distinction is consequential for any claim made from future CosmoCube data. A measured spectrum may confirm a precise Λ CDM prediction, challenge it, or prove insufficiently precise to do either. None of those outcomes should be described as evidence for or against particulate dark matter, or for or against a geometrical alternative, unless the additional inference required for that conclusion has itself been demonstrated.

6. The TSPC counter-model

TSPC approaches the same observational problem from a different starting point. It does not seek to replace cold dark matter with another particulate component. Instead, it restricts the admissible spacetime geometry through a fixed parity constraint and asks whether gravitational phenomena conventionally attributed to additional matter content can arise from the resulting geometry. The question raised by a highly redshifted neutral-hydrogen spectrum is therefore whether the Λ CDM consistency relation depends upon the particulate nature of dark matter, or upon more general features of the cosmological evolution that a TSPC-compliant geometry might also reproduce.¹⁰

At first sight the consistency ratios appear promising. The standard brightness-temperature expression contains the total matter density through the expansion rate. Removing the cold-dark-matter contribution might therefore be expected to produce a substantially different result. But much of this dependence contributes only to the overall amplitude of the predicted spectrum. If the expansion rate retains the same redshift dependence,

$$H(z) = A(1 + z)^{(3/2)}$$

with a different coefficient (A), that coefficient enters the 21-cm optical depth as a common normalisation. Forming brightness-temperature ratios at different frequencies substantially removes it. The absence of a particulate cold-dark-matter component does not, by itself, imply a different consistency ratio.¹¹

The more important dependence lies in the shape of the spectrum. This is determined by the evolution of the hydrogen kinetic and spin temperatures, the radiation temperature, collisional coupling, neutral-hydrogen density and the geometrical rate of evolution. These quantities are evaluated at different observed redshifts when a spectral ratio is formed. A TSPC prediction therefore requires more than an alternative value for the total gravitating matter density.

Does the unknown TSPC mapping cancel?

Let (z_{obs}) denote the spectroscopic redshift obtained directly from the observed frequency:

$$1 + z_{\text{obs}} = \frac{\nu_{21}}{\nu_{\text{obs}}}$$

¹⁰ Salisbury I. (2025), *The Time-Symmetric Parity Constraint: On the loss and recovery of constraint in modern cosmology*, TSPC-1, Paper 3. Introduces TSPC as a fixed algebraic admissibility constraint on the spacetime metric, implemented through the non-dynamical involutive tensor Π and a Lagrange multiplier, without introducing additional propagating fields.

¹¹ Okamatsu T., *et al*, *Op cit.*,

Let (Z) denote the variable describing the corresponding stage of geometrical and physical evolution in a TSPC cosmology. Until the high-redshift TSPC solution is derived, allow the relation between them to remain unspecified:

$$Z = F(z_{\text{obs}})$$

The predicted TSPC brightness temperature may then be represented schematically as

$$T_b^{\text{TSPC}}(z_{\text{obs}}) = \mathcal{T}[F(z_{\text{obs}}), H_{\text{TSPC}}, T_k, T_s, T_\gamma, x_{\text{HI}}, \dots]$$

A spectral ratio measured at two observed frequencies therefore becomes

$$R_{i/j}^{\text{TSPC}} = \frac{\mathcal{T}[F(z_i), H_i, T_{k,i}, T_{s,i}, \dots]}{\mathcal{T}[F(z_j), H_j, T_{k,j}, T_{s,j}, \dots]}$$

An overall multiplicative factor common to numerator and denominator will cancel. A non-trivial function $(F(z_{\text{obs}}))$, however, is evaluated at two different observed redshifts:

$$F(z_i) \neq F(z_j)$$

It therefore changes the relative evolution sampled at the two frequencies and does not, in general, cancel from the ratio.

The consistency ratio becomes independently calculable within TSPC only if the relevant high-redshift mapping and resulting thermal evolution are specified, or if a derivation can demonstrate that the mapping leaves the ratio invariant.

This result imposes an important limit upon the present comparison. TSPC has not yet derived a quantitative relation between spectroscopic redshift and the relevant geometrical evolution over the range represented by approximately 20–40 MHz. The phenomenological clock-skew treatment developed elsewhere for much lower redshift cannot simply be extrapolated into this regime. Doing so would introduce an assumed high-redshift function for the purpose of obtaining a prediction and would therefore remove the prospective character of the test.¹²

It follows that no numerical TSPC counterpart to the Okamatsu ratios can presently be justified. This is not because the standard calculation is intrinsically dependent upon particulate cold dark matter. Indeed, the substantial cancellation of the total-matter normalisation demonstrates the opposite: a TSPC-compliant cosmology could, in principle, reproduce similar spectral ratios without containing the same matter content.

¹² Salisbury I. (2025), *Cosmic Chronometers and Differential Ageing*, TSPC-1, Paper 16. Develops the possibility that observer proper time and the global temporal parameter of a parity-constrained cosmology need not coincide exactly, producing a small accumulated geometric clock skew. Importantly, it does not derive the high-redshift mapping required for the 20–40 MHz neutral-hydrogen calculation considered here.

Whether it actually does so depends upon its high-redshift geometrical and thermal evolution.

This also clarifies what an eventual agreement between CosmoCube observations and the Λ CDM ratios would mean for TSPC. Such agreement would not automatically contradict a geometrical alternative. If a TSPC solution reproduced the relevant matter-dominated scaling and the same hydrogen thermal evolution over the observed interval, it could reproduce substantially the same spectral shape. The two explanations would then remain observationally degenerate under this test despite differing in their underlying interpretation of the gravitational source.

A measured departure from the Λ CDM consistency relation would likewise not constitute evidence for TSPC. It would establish that the standard set of assumptions had failed to reproduce the observed spectral shape. Unless TSPC had independently predicted the departure before the measurement, attributing the discrepancy to its geometrical constraint would be retrospective accommodation rather than prediction.

The present result is therefore restrictive but useful. The highly redshifted 21-cm consistency relation is a prospective test of Λ CDM, but it is not yet a prospective test of Λ CDM against TSPC. The calculation identifies the obstacle precisely: the unknown high-redshift TSPC evolution affects the relative spectral shape and cannot be removed merely by taking ratios.

7. What would make the observation discriminatory?

The present inability to calculate a TSPC counterpart to the Λ CDM consistency ratios does not mean that highly redshifted neutral-hydrogen observations are intrinsically incapable of distinguishing the two frameworks. It means that the required TSPC prediction has not yet been derived. The calculation in the preceding section identifies what is missing and therefore allows the requirements for a genuine prospective test to be stated more precisely.

A complete TSPC cosmology of the early Universe would plainly be sufficient, but it may not be necessary. CosmoCube does not measure cosmic time directly. It measures radio brightness as a function of observed frequency. The minimum theoretical requirement is therefore a TSPC prediction of the physical quantities controlling the 21-cm brightness as functions of that observable frequency, or equivalently of spectroscopic redshift.

The first requirement is a relation between spectroscopic redshift and the geometrical evolution relevant to the hydrogen. In the notation of the preceding section, this is the presently unspecified function

$$Z = F(z_{(obs)})$$

It need not necessarily be expressed as a conventional age-redshift relation. What matters is that the theory determines which physical state of the TSPC cosmology corresponds to hydrogen identified at each observed frequency.

The second requirement is the corresponding geometrical expansion or velocity gradient entering the 21-cm optical depth. In the standard homogeneous treatment this role is represented by $(H(z))$. TSPC must either supply its own equivalent quantity as a function of the observational coordinate or demonstrate that the standard relation remains applicable in the relevant regime.

The third requirement is the thermal evolution of ordinary matter. Once the geometrical evolution is specified, the kinetic temperature of the hydrogen must be determined sufficiently well to calculate its coupling to the radiation field. This includes the period during which residual free electrons maintain Compton coupling and the subsequent cooling of the gas. Unless TSPC modifies the underlying atomic or electromagnetic physics, those microphysical processes need not be reinvented; what must be established is the cosmological evolution within which they operate.

The fourth requirement is the spin temperature. The observable 21-cm contrast depends upon the relative populations of the hyperfine states rather than directly upon the kinetic temperature. The relevant collisional coupling rates are ordinary atomic physics, but the densities and temperatures upon which they depend must be supplied by the TSPC cosmological solution.¹³

These requirements can be summarised without specifying a complete early-Universe model.

Minimum ingredients for a TSPC 21-cm prediction

A prospective TSPC calculation of the global highly redshifted 21-cm spectrum requires sufficient information to determine

$$Z = F(z_{obs})$$

$$H_{(TSPC)}[F(z_{obs})]$$

$$T_k[F(z_{obs})]$$

and

$$T_s[F(z_{obs})]$$

together with the neutral-hydrogen abundance and the relevant radiation temperature.

These quantities would permit calculation of

$$T_b^{(TSPC)}(v_{obs})$$

and hence of directly comparable spectral ratios

¹³ Furlanetto *et al.*, *Op cit.*

$$R_{(v_i/v_j)}^{(TSPC)}$$

A genuine prospective discriminator would then exist wherever

$$R_{(v_i/v_j)}^{(TSPC)} \neq R_{(v_i/v_j)}^{(\Lambda\text{CDM})}$$

by an amount exceeding the combined theoretical and observational uncertainties.

This formulation also identifies a potentially important simplifying case. It is possible that a future derivation will show that TSPC approaches conventional matter-dominated behaviour sufficiently closely at these high redshifts that the relevant mapping becomes effectively standard. If so, TSPC may reproduce the ΛCDM consistency ratios to high accuracy despite dispensing with particulate cold dark matter as the explanation of other gravitational phenomena. The 21-cm spectral shape would then fail to distinguish the two frameworks, but that failure would itself be informative: the agreement would demonstrate that the consistency relation is insensitive to their different underlying ontologies.

Alternatively, the TSPC constraint may require a different relation between spectroscopic redshift and physical evolution, or a different expansion or perturbation history, producing a calculably different spectral shape. In that case the same measurements would become a genuine prospective discriminator. The important condition is that the TSPC prediction must be obtained independently of the observed result. A function adjusted after measurement to reproduce the spectrum would provide accommodation, not a test.

There is a further possibility. A TSPC derivation may establish that the standard spectral relation follows from more general geometrical and atomic conditions than ΛCDM itself. That would not falsify ΛCDM , but it would alter the evidential significance of agreement with its prediction. A successful prediction cannot uniquely support a physical ingredient if the same prediction follows without that ingredient.

The theoretical task exposed by highly redshifted neutral hydrogen is therefore narrower, and potentially more tractable, than constructing an entire alternative history of the early Universe. The immediate requirement is to determine whether the TSPC constraint fixes the relation between observed redshift and the geometrical and thermal quantities entering the 21-cm spectrum over the relevant frequency range. Until that calculation is available, CosmoCube can provide a stringent test of a ΛCDM prediction but not a decisive comparison between ΛCDM and TSPC. Once it is available, the same observational data could provide precisely such a comparison.

8. Conclusion

The proposed observation of highly redshifted neutral hydrogen offers an unusually clean opportunity to test a prediction of modern cosmology. The observable itself is

comparatively simple: radio brightness as a function of frequency. Identification of a component with the known 1420.4 MHz hyperfine transition supplies a spectroscopic redshift. The further description of that signal as originating in the cosmic Dark Ages, and the thermal, chronological and gravitational history assigned to it, belong to its cosmological interpretation.

Within Λ CDM that interpretation leads to a particularly precise prospective prediction. Ratios of the global 21-cm brightness temperature at selected frequencies are expected to follow a tightly constrained spectral relation whose dependence upon the usual cosmological parameters is remarkably small. A future measurement consistent with those ratios would therefore constitute significant confirmation of the predicted spectral behaviour. A secure departure would demonstrate that one or more assumptions responsible for that behaviour require revision.

Neither result would, by itself, establish the physical ontology underlying the prediction. In particular, agreement with the Λ CDM consistency relation would not constitute an independent detection of particulate cold dark matter. Much of the dependence upon total matter density contributes to the overall amplitude of the predicted spectrum and is substantially suppressed when brightness-temperature ratios are formed. Conversely, disagreement with the standard relation would not constitute evidence for TSPC or for any other particular alternative.

TSPC provides a useful counter-model precisely because it separates gravitational explanation from the assumption of additional particulate matter. The calculation undertaken here shows, however, that the presently undeveloped high-redshift TSPC evolution cannot simply be removed from the 21-cm consistency ratios. An overall normalisation may cancel; a non-trivial mapping between spectroscopic redshift and geometrical evolution generally does not. A numerical TSPC counterpart to the Λ CDM ratios therefore cannot presently be derived without introducing assumptions beyond those established by the existing theory.

This limitation defines a specific theoretical task rather than an indefinite deficiency. A complete reconstruction of the early Universe is not necessarily required. What is needed is sufficient TSPC development to determine, over the relevant observational range, the relation between spectroscopic redshift and geometrical evolution, together with the expansion, kinetic-temperature and spin-temperature behaviour required by the neutral-hydrogen calculation. Once those quantities are fixed independently of the observation, the highly redshifted 21-cm spectrum can become a genuine prospective comparison between the two frameworks.

CosmoCube may therefore provide something more useful than a nominal observation of a model-defined epoch. It can confront Λ CDM with a precise prediction in a region of the radio spectrum that has hitherto been exceptionally difficult to observe. Whether the same data can ultimately discriminate between particulate and geometrical explanations of the associated gravitational behaviour depends not upon the

observation alone, but upon whether the competing theories make independently calculable and distinguishable predictions for it.

The methodological distinction is simple but consequential: agreement with a predicted observable tests the prediction; it does not, without further discrimination, uniquely establish the interpretation from which that prediction was obtained.

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