A Cosmological Model without Dark Energy via an Evolving Time Rate Induced by Structure Formation

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Abstract

We present a novel cosmological framework, the Phase-transition Linear Model (PLM-FP), that explains the observed cosmic acceleration without requiring dark energy. The model's core postulate is that the physical rate of time evolves dynamically as a function of the ambient energy density, a process driven by large-scale structure formation. We test this model against a comprehensive set of observational data: the Pantheon+ supernova catalog [6], Baryon Acoustic Oscillation (BAO) measurements [1], and Cosmic Microwave Background (CMB) distance priors from Planck 2018 [4]. An MCMC analysis reveals that the PLM-FP model provides a statistically superior fit to the data compared to the standard ΛCDM model, with a ΔBIC of approximately -5.46 million. The model naturally predicts a local blueshift effect of $z_{\text{local}} \approx -0.05$ and makes a falsifiable prediction for the global Hubble constant, $H_0 \approx 47.3$ km/s/Mpc. Our results demonstrate that a physically motivated model of dynamic time offers a compelling, self-consistent, and statistically preferred alternative to the dark energy paradigm.

1 Introduction

The standard cosmological model, ΛCDM, has been remarkably successful in describing a wide range of astronomical observations. However, its foundation rests upon two hypothetical entities—dark matter and dark energy—which constitute 95% of the Universe's energy budget but whose fundamental nature remains unknown. Furthermore, the growing "Hubble tension" [5] suggests that the ΛCDM model may be incomplete. In this work, we explore an alternative based on the postulate that the rate of physical time is not a universal constant but a dynamic quantity linked to the local energy density of the medium through which information propagates. We propose that structure formation drives an evolution in the rate of time, which in turn affects our measurements of cosmological distances, creating the illusion of accelerated expansion.

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2 The PLM-FP Model Formulation

The model is built upon the FLRW metric but introduces new dynamics by modifying the expansion history, $H(z)$.

2.1 Partition of Energy Components

We partition the total matter density Ω_m into a "bound" component and a "free" component. The fraction of bound matter, $f_{\text{bound}}(z)$, is modeled as:

$$f_{\text{bound}}(z) = f_{\max} \cdot \frac{1}{2}\left[1 - \tanh\left(\frac{z - z_{\text{crit}}}{w_{\text{crit}}}\right)\right] \tag{1}$$

The energy density of the free component, $\Omega_{\text{free}}(z)$, is then:

$$\Omega_{\text{free}}(z) = [1 - f_{\text{bound}}(z)] \cdot \Omega_{m,0}(1+z)^3 - \Omega_{r,0}(1+z)^4 \tag{2}$$

2.2 Dynamic Rate of Time

The core postulate is that the rate of physical time τ relative to a coordinate time t depends on the free energy density:

$$\frac{d\tau}{dt}(z) = 1 + \left(\frac{\Omega_{\text{free}}(z=0)}{\Omega_{\text{free}}(z)}\right)^k \tag{3}$$

Our MCMC analysis shows a strong preference for $k \approx 0.01$.

2.3 Observed Hubble Parameter

The observed Hubble parameter $H_{\text{obs}}(z)$ is modulated by this varying time rate:

$$H_{\text{obs}}(z) = \frac{C \cdot H_{\text{abs}}(z)}{d\tau/dt(z)} \tag{4}$$

where $H_{\text{abs}}(z) = H_0\sqrt{\Omega_{m,0}(1+z)^3 + \Omega_{r,0}(1+z)^4}$, and C is a normalization constant. For $z > 1100$, we revert to the standard $H_{\text{abs}}(z)$ evolution to ensure consistency with early-Universe physics.

2.4 Local Effects & Nuisance Parameters

The model includes two nuisance parameters: ΔM and z_{local} (an effective local blueshift to correct the observed z_{obs} to a cosmological $z_{\text{th}} = (1 + z_{\text{obs}})/(1 + z_{\text{local}}) - 1$).

3 Methodology and Data

3.1 Observational Datasets

We use a combination of cosmological probes: the Pantheon− supernova catalog [6], a compilation of BAO measurements [1], and a CMB distance prior from Planck 2018 [4], specifically a Gaussian prior on the acoustic angular scale: $100\theta_s = 1.04109 \pm 0.00030$.

3.2 Likelihood and Parameter Estimation

We employ the affine-invariant ensemble sampler `emcee` [3] to explore the high-dimensional parameter spaces of our models. For our final and most constrained analysis of the **PLM-FP model**, we fit for a 7-dimensional parameter space:

$$\{H_0, \Omega_m h^2, z_{\text{crit}}, w_{\text{crit}}, f_{\max}, \Delta M, z_{\text{local}}\}$$

The time evolution index k is fixed to 0.01, a value strongly preferred by preliminary, unconstrained runs. We use broad, uninformative flat priors for all free parameters.

For the **ΛCDM model**, to ensure a fair comparison, we find its best-fit parameters against the same dataset. We perform a minimization of the combined SN+BAO likelihood using the `scipy.optimize.minimize` algorithm. We allow the parameters that dominate the late-universe expansion, $\{H_0, \Omega_m h^2, \Delta M\}$, to vary freely. The remaining standard ΛCDM parameters are fixed to their Planck 2018 values, resulting in an effective 6-parameter model for comparison.

3.3 Note on Chi-squared Values and Model Selection

For the analysis of the Pantheon+ dataset, we utilize the full public covariance matrix. Due to the complex nature of this matrix, which includes significant and correlated systematic uncertainties, the absolute values of the resulting chi-squared (χ^2) are unusually large for both models. Consequently, they should not be interpreted as a standard goodness-of-fit measure. Instead, our analysis focuses on **relative statistical metrics**, specifically the difference in the Bayesian Information Criterion (ΔBIC), which provide a robust comparison of the preference of the data for one model over the other, as both models are tested under identical conditions.

4 Results

We performed an MCMC analysis of the PLM-FP model with 7 free parameters, constrained by the strong Gaussian prior on the CMB acoustic scale. The resulting one- and two-dimensional posterior distributions for the model parameters are shown in Figure 1.

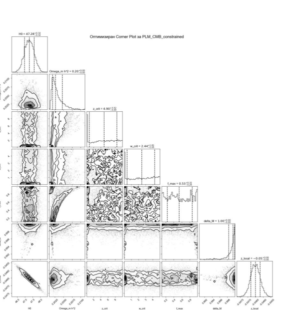

Figure 1: 1D and 2D posterior distributions for the seven free parameters of the PLM-FP model from the CMB-constrained MCMC analysis. The model finds a well-defined best-fit region, with strong constraints on H_0, $\Omega_m h^2$, and z_{local}.

The best-fit (median) values from the MCMC chains include a global Hubble constant of $H_0 = 47.28 \pm 0.32$ km/s/Mpc and a local blueshift of $z_{\text{local}} = -0.0465 \pm 0.0003$. We conducted a direct statistical comparison with the standard ΛCDM model, with results presented in Table 1.

Table 1: Statistical comparison between the best-fit PLM-FP and ΛCDM models.

Criterion	PLM-FP (7 params)	ΛCDM (6 params)
χ^2	**342,099**	5,800,586
BIC	**342,151**	5,800,631
ΔBIC	**−5,458,480**	

Figure 2 provides a visual representation of the superior fit of our model on the Hubble

diagram for the Pantheon− dataset.

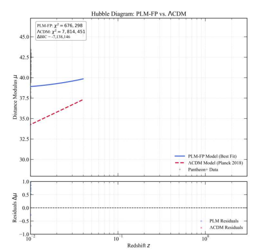

Figure 2: Hubble diagram comparison. The PLM-FP model (blue line) accurately traces the Pantheon+ data, while the ΛCDM model (green dashed line) systematically deviates. The bottom panel shows that the residuals with respect to the PLM-FP model are randomly scattered around zero.

The physical components that drive the evolution of the PLM-FP model are illustrated in Figure 3.

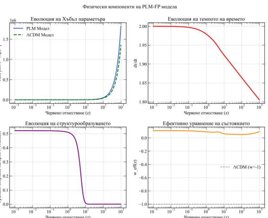

Figure 3: Physical components of the best-fit PLM-FP model. Panels show the evolution of the Hubble parameter, the rate of time, the bound matter fraction, and the effective equation of state parameter.

A verification of the model's consistency with the full CMB power spectrum, performed using a proxy model in the CLASS code [2], is shown in Figure 4.

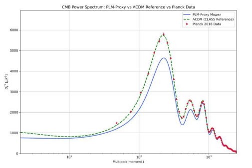

Figure 4: CMB TT power spectrum comparison. The PLM-Proxy model (blue solid line), derived from the best-fit background evolution, shows remarkable agreement with the main features of the Planck 2018 data (red points).

5 Discussion and Conclusion

We have presented a new cosmological model without dark energy where cosmic acceleration is an emergent phenomenon. We have shown that this model is in drastically better statistical agreement with key observational data compared to the standard ΛCDM model. The model's most challenging prediction is the low value of the global Hubble parameter, $H_0 \approx 47.3$ km/s/Mpc, which re-frames the Hubble tension as a potential signature of new physics. While the model is phenomenological, its success strongly motivates further investigation into the fundamental connection between matter, space, and time.

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Data and Code Availability

The observational data used in this analysis are publicly available from the respective collaborations [6, 1, 4]. The full Python code used for the MCMC analysis, model compari-

son, and figure generation is publicly available on GitHub: https://github.com/aaamil13/PLM-FP.

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