Confirmation of Inflaton-like Oscillations in the Scale Factor from the Pantheon Compilation of 1048 SNe1a

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We have confirmed the presence of damped temporal oscillations in the scale factor at a frequency of ~ 7 cycles/Hubble-time in the Pantheon Compilation of 1048 SNe. This closely matches our initial observation [Ringermacher and Mead, AJ 149, 137 (2015)] from earlier SNe data [dominated by SNLS3 of Conley et al., ApJS, 192, 1 (2011)] at 2-sigma confidence. The nearly identical shapes in amplitude, frequency, phase and damping constant makes it highly likely the signal is real. Furthermore, 75% of the Pantheon SNe cover different portions of the sky compared with SNLS3 strengthening this conclusion. We have also merged these two data sets creating a set of approximately 1200 independent SNe, doubling the S/N for z > 0.7. The merger permitted the observation of an additional full-cycle of oscillation. Our model describing the oscillation, presented in the AJ paper above, is the simple scalar field Chaotic Inflation model carried into the present epoch. The observed oscillation follows the model in frequency, phase and damping rate but is two to three times greater in amplitude. The scalar field energy density in our model substitutes for the dark matter energy density in Lambda-CDM cosmology, fits well on average, and matches the present dark matter density suggesting this oscillation may be a signature of dark matter.

I. INTRODUCTION

In earlier work [1] we demonstrated a novel method of transforming a standard Hubble diagram of distance modulus vs. redshift into a scale factor vs. cosmological time plot for a data set of type 1a supernovae (SNe) together with radio galaxy beacons. We refer to this data as “CDR” (Conley, et al [2], Daly and Djorgovski [3], Riess et al. [4]). The transformation depends only on the knowledge of spatial curvature and no other properties of a universe model. We showed that the ΛCDM model for zero spatial curvature in the scale factor plot was the best fit at 98% confidence to the merged data set thus confirming the technique. In a second follow-up paper [5] we analyzed the scale factor plot seeking an inflection point, which would define the “transition-time” when the universe changes from a decelerating expansion to accelerating. We observed relative minima, apparently arising from damped oscillations in the scale factor at a dominant frequency of ~ 7 cycles/Hubble-time (7 Hubble-Hertz, or 7HHz from [5]), thus accounting for the large variation of transition redshifts in the literature. The oscillations were analyzed using a variety of methods including Gaussian smoothing, Fourier analysis, auto-correlation and a careful noise study of 5000 trials generating random noise with the same temporal distribution as the data. The noise study showed that the likelihood of generating a specific sharp (1 HHz width) frequency from smoothing
random noise was 1/20. We also proposed a simple “Chaotic Inflation” scalar field harmonic oscillator model to explain the oscillations. The scalar field is coupled to the scale factor through the $\Lambda$CDM Friedmann equations. The scalar field energy density, $\rho_\phi$, was simply substituted for the usual dark matter density term. We showed that the scalar field solution for the scale factor closely fit the $\Lambda$CDM scale factor as an average through the oscillations. The observed oscillations followed the model oscillations in frequency, phase and damping rate, however, the observed amplitude was two to three times higher.

New SNe data [6], the “Pantheon Compilation” was recently made public. Three quarters of the Pantheon SNe cover different portions of the sky compared with SNLS3. In the present paper we present the Pantheon data in a standard Hubble diagram, then transform the modulus vs. redshift plot to a scale factor vs. cosmological time plot following the procedure detailed in [1]. The Pantheon time domain data are then analyzed for oscillations and compared to an identical reanalysis of the previous CDR data.

II. PANTHEON SNe DATA ANALYSIS

Figure 1a displays the Pantheon Compilation as a standard Hubble diagram of distance modulus vs. redshift for a best-fit Hubble constant of 68.7 km/s/Mpc and SN1a $M_0 = -19.36$. Redshift, $z$, is directly transformed to scale factor using $a(t) = 1/(1+z)$.

**FIG.1a** Distance modulus vs. redshift for Pantheon SN1a data. SN abs. mag. $M_0 = -19.36$. 
Modulus is transformed to cosmological time carefully following the definitions and procedure described in [1]. Dominant error is in the time direction since redshift error is negligible. The resultant scale factor data plot for a flat 3-space FRW metric is shown in Figure 1b. The solid curve is the best fit ΛCDM model for $\Omega_\Lambda = 0.73$ and $\Omega_m = 0.27$.

A. Methodology

The data of Figure 1b are first binned into 128 bins on the scale of 0 to 1.0 – time bins fine enough to faithfully resolve waveforms at frequencies less than 200Hz. The error bars then become vertical. We seek residual oscillations on the $\dot{a}(t)$ curve to compare with the results of [5]. This can be derived in three ways: (1) One can fit a polynomial to the binned data and then subtract the fit function (a quadratic) leaving the residuals or, (2) one can subtract the ΛCDM model leaving residuals. The residuals are then processed using a wide-baseline derivative to reduce noise (described in Appendix A of [5]) followed by Gaussian smoothing to further reduce noise, or (3) Apply a long-baseline derivative directly to the binned $a(t)$ curve followed by the same Gaussian smoothing.

All methods were applied and produced the same results. An 8-bin derivative was used. This is a “two-point” derivative separated by 8 time bins that results in exceptional noise reduction. A Gaussian smoothing function with a moving 0.05 time window ("ksmooth")
from Mathcad™ was applied following differentiation. This reduced noise significantly narrowed the frequency spectrum to < 14 HHz (-12 db point). Frequencies less than 2 HHz are also unreliable and can be induced by data filtering end-effects and imperfect fits. Frequencies less than 4 HHz were minimized by heavy low-pass filtering with a Gaussian smoothing window of 0.13 and then subtracting the resulting waveform from the 0.05-smoothed waveform. This left a signal with frequency bandwidth from 4 – 10 HHz, the -6 dB cutoffs, with dominant frequency, 7 HHz. The identical procedure was then applied to the earlier CDR data of [5]. The reanalysis of the earlier set is crucial because that data was not binned prior to smoothing possibly resulting in some spectral distortion where the low-z data was bunched. Any concern that the differentiation procedure could produce such a signal was mitigated by processing the \( a(t) \) curve directly using the same binning and smoothing. The same oscillations were found.

B. Results

Figure 2 compares the \( \dot{a}(t) \) oscillations seen in the CDR and Pantheon data. The raw scale factor vs. time data is available [7]. The time scales for both data sets are normalized for unit Hubble constant. Since the CDR Hubble constant is 66 and Pantheon is 68.75, in order to compare data, we multiplied the Pantheon time scale by 1.04, the ratio of the two Hubble constants, resulting in a correct phase match. The amplitudes, shape, phase, frequency and damping are nearly identical. The RMS S/N is ~2.

![Residual oscillations observed in \( \dot{a}(t) \) for CDR and Pantheon data are compared.](http://example.com/figure2.png)

FIG.2. Residual oscillations observed in \( \dot{a}(t) \) for CDR and Pantheon data are compared.
We performed a $\chi^2$ analysis comparing the two data sets based on a Z-score so as to express a direct estimate of goodness of data match. The Z-score is given by

$$Z = (\chi^2 - df) / \sqrt{2df},$$

where $df$ is degrees of freedom. We are comparing all 68 points in common between the two sets from $t = 0.461$ to $t = 0.984$ with no adjustable parameters. We find $\chi^2 = 65.95$ giving $Z = -0.176$. This corresponds to a 2-tailed probability of 86% goodness of match. An $R^2$ test gives 80% goodness of match. The Fourier analysis of the waveforms is shown in Figure 3. The dominant frequency is $7.34 \pm 1.5$ HHZ in CDR and $7.66 \pm 1.5$ HHZ in Pantheon. Lower and higher frequencies are evident, but have been suppressed.

The probability of measuring the same frequency (~7 HHZ) in two independent data sets is estimated at 1/400 based on the afore-mentioned noise study. The damping was modeled as an exponential decay, $e^{-\alpha t}$, from time 0.4 to 1.0. The average least-squares decay constant is $\alpha = 3.7 \pm 0.3$ which matches our theoretical model decay constant for $\dot{a}(t)$ oscillations, $\alpha = 3.5 \pm 0.2$, thus significantly strengthening the reality of the observations. It is also important to note that the oscillations are not at a single frequency but include higher and lower frequency components, at lower amplitudes, that modulate the shape reproducibly, for example the “kinks” at time 0.52.

**FIG.3.** Fourier power spectrum of Fig. 2 showing peaks for both data sets at ~ 7HHZ.
III. MERGER OF CDR AND PANTHEON SNe DATA

We merged CDR and Pantheon SNe data comprising 1200 independent points, significantly increasing the S/N of the oscillations first observed, particularly for $z > 0.7$. The merger of the distance modulus data was achieved by adjusting the SN1a absolute magnitudes, $M_0$, so as to obtain a match of the mean modulus for data between $z = 0.25$ and $z = 0.5$ and also between $z = 0.5$ and $z = 1.0$. Pantheon data with $M_0 = -19.36$ (Hubble constant 68.7) was not adjusted. Rather, the CDR data with $M_0 = -19.24$ (Hubble constant 66) was adjusted to $M_0 = -19.04$. The resulting modulus means at low-$z$ were 41.273 and 41.257 for CDR and Pantheon, respectively, and 43.184 for both CDR and Pantheon at high-$z$. The best-fit Hubble constant for the combined modulus data is 69.7. The merged Hubble diagram was then transformed to a scale factor plot and processed precisely the same as the Pantheon data described above. The resulting $\dot{a}(t)$ residual oscillation is shown in Figure 4. The doubling of S/N at high $z$ permitted the extraction of an additional wavelength at earlier times. The same waveform shape as Figure 2 is discerned in the merged data. We include our single-frequency scalar field model oscillations for comparison only. The model amplitude has been multiplied by a factor of 2.7 to better match the data. Otherwise, it aligns well considering there are no adjustable parameters [5] in the model. We also calculated $a(t)$ for the merged data and found it precisely follows the correct phase and amplitude required compared to $\dot{a}(t)$.

![Graph](image_url)  

**FIG.4.** $\dot{a}(t)$ oscillation amplitude for the merger of CDR and Pantheon data (solid). The augmented scalar field model oscillations are compared (dashed).
Figure 5 shows the power spectrum of the merged data oscillations. The sharp dominant peak is at $7.15 \pm 1.0$ HHz. There is a significant secondary peak at 10.5 HHz, which is the main cause of the slight aperiodicity and modulation in the waveform.

![Fourier power spectrum of the merged data in Figure 4.](image)

**FIG.5.** Fourier power spectrum of the merged data in Figure 4.

**IV. CONCLUSIONS**

We have confirmed the presence of temporal oscillations in the scale factor from the Pantheon Compilation of SNe1a matching our earlier observations from an independent data set. 75% of Pantheon SNe cover new sky. The oscillations were observed by converting the standard Hubble diagram of modulus vs. redshift to scale factor vs. cosmological time. The dominant frequency is approximately 7 cycles/Hubble-time, or 7 HHz (Hubble-Hertz), in both sets. We reanalyzed our previous CDR data for this comparison in an identical fashion. We also merged the two data sets, significantly improving S/N overall and doubling the S/N for $z>0.7$. This permitted the analysis of a full 4 cycles of signal which was consistent with the individual data set analyses, including damping. Systematic error producing identical temporal effects in 2 independent data sets seems unlikely. We have shown from previous noise studies that the probability of getting the same sharp frequency signal from 2 independent data sets is $\sim 1/400$. In [5], we proposed a simple harmonic oscillator model similar to “Chaotic Inflation” [8] but coupled to the Friedmann equations and penetrating into the present epoch to explain the oscillations. The damping constant of the observed oscillations...
matches that of our model thus strengthening our conclusions. Though the model follows the observations fairly well in frequency, phase and damping, it is short a factor of two to three in amplitude and so is incomplete. The scalar field energy density in our model substitutes for the dark matter energy density in ΛCDM cosmology, fits well as an oscillating average, and matches the present dark matter density suggesting this oscillation may be a signature of dark matter.

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