Windowing Artifacts Likely Account for Recent Claimed Detection of Oscillating Cosmic Scale Factor

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Accepted XXX. Received YYY; in original form ZZZ

ABSTRACT

Using the Pantheon data set of Type Ia supernovae, Ringermacher and Mead (2020) (R20 henceforth) report a 2σ detection of oscillations in the expansion history of the universe. Applying the R20 methodology to simulated Pantheon data, we determine that these oscillations likely arise from analysis artifacts. The uneven spacing of Type Ia supernovae in redshift space and the complicated analysis method of R20 impose a structured throughput function. When analyzed with the R20 prescription, about 11% of artificial ΛCDM data sets produce a stronger oscillatory signal than the actual Pantheon data. The study conducted by R20 is a wholly worthwhile endeavor. However, we believe that the detected oscillations are not due to an oscillating cosmic scale factor and are instead artifacts of the data processing. Our results underscore the importance of understanding the false ‘signals’ that can be introduced by complicated data analyses.

1 INTRODUCTION AND BACKGROUND

Since the initial discovery of dark energy (DE) by Riess et al. (1998); Perlmutter et al. (1999), observations of Type Ia supernovae (SNe Ia) have been integral in establishing the canonical ΛCDM cosmological model. In the ΛCDM model, the present energy density of our flat universe is dominated by cosmologically constant DE (Λ) and non-relativistic, collisionless (‘cold’) dark matter (CDM). Though some tensions between predictions and observations exist (Weinberg et al. 2015; Verde et al. 2019), this simple model has successfully predicted many cosmological and astrophysical signals (Peter 2012; Mortonson et al. 2013).

However, despite the success of the ΛCDM model, the physical identities of Λ and CDM remain unsettled. Researchers continue to search for deviations from the predictions of ΛCDM in many data sets, including an ever-increasing archive of SNe Ia. In particular, some non-canonical cosmological models, such as those discussed by Barenboim et al. (2005); Xia et al. (2005); Feng and Li (2006); Lazkoz et al. (2010); Wang et al. (2017), predict that the true expansion of the universe might oscillate around the predictions of ΛCDM. Respectively using the Gold (Riess et al. 2007), Union (Kowalski et al. 2008), Constitution (Hicken et al. 2009) and Pantheon (Scolnic et al. 2018) data sets of SNe Ia, Jain et al. (2007), Liu and Li (2009), Lazkoz et al. (2010), and Brownsberger et al. (2019) search for evidence of such oscillations in cosmic expansion. Though they utilize a diversity of data sets and statistical methodologies, those analyses universally report no evidence of oscillations in the rate of cosmic expansion.

Contrary to those previous findings, Ringermacher and Mead (2015) and Ringermacher and Mead (2020) (R15 and R20 henceforth) claim to identify damped oscillations in the universe’s recent expansion history. Combining data of radio galaxies and SNe Ia (Conley et al. 2011; Daly and Djorgovski 2004; Riess et al. 2004) into a ‘CDR’ data set, R15 claim to detect cosmic oscillations in the universe’s scale factor. Using the Pantheon data set of type Ia supernovae, R20 build on R15 to claim a detection of an oscillating scale factor with a total statistical significance of at least 2σ.

Such a detection of oscillatory cosmic expansion would mark an enormous paradigm shift in our understanding of the physics of the universe, changing the canonical model that has held since the first identification of DE. The work of R20 is entirely worthwhile. Their results should be seriously considered and appropriately scrutinized.

Replicating the analysis method of R20 and applying it to simulated data, we find that there is an 11% chance that the Pantheon data observed in a ΛCDM universe would produce a stronger oscillatory signal than that which R20 detect. Our measurement does not include a statistical ‘trials factor’ penalization for the various tunable parameters in the R20 analysis, and the significance of the detected oscillations is therefore less than our reported metric. The oscillations noted by R20 are likely data analysis artifacts - the signature of a throughput function that consists of the uneven spacing of the Pantheon SNe in redshift and their sequencing of filtering and differentiation analysis steps.

In Section 2 below, we describe our replication of the R20 analysis. In Section 3, we describe our generation of the artificial data and the assessment of the consistency of the
real data with ΛCDM. We detail our conclusions in Section 4.

2 REPLICATING THE R20 RESULTS

In this Section, we describe our replication of the R20 analysis and the R20 results.

2.1 Inferring Cosmic Time and Residual Scale Factor Derivative for SNe Ia

R20 search for oscillations by transforming the standard Hubble diagram (brightness vs. redshift) into plots of scale factor vs time. They claim that such a plot enables a model-independent study of the universe’s expansion history.

The Pantheon data set of Type Ia supernovae consists of measured redshifts, \( z_i \), distance moduli, \( \mu_i \), and distance modulus uncertainties, \( \sigma_\mu_i \). The subscripts identify each SNe in order of increasing \( z_i \). These are the directly measured quantities from which cosmologists infer cosmic expansion.

From these measured quantities, R20 note oscillations in non-standard inferred quantities: the normalized cosmic expansion.

Throughout the rest of this Section, we describe how we inferred \( t_i \) and \( \Delta G (d \Delta a_i / dt) \) from \( z_i \) and \( \mu_i \). We measured the cosmological scale factors, \( a_i \), and luminosity distances, \( d_{L,i} \), using the standard relations:

\[
a_i = \frac{1}{1 + z_i},
\]

and

\[
d_{L,i} = 10^{(\mu_i - 25)/5} \text{ Mpc}.
\]

The scaled luminosity distances, \( Y_i \), were defined by

\[
Y_i = a_i \frac{d_{L,i}}{H_0}.
\]

where \( d_H = c/H_0 \), \( c \) is the speed of light, and \( H_0 \) is the Hubble constant. We determined the scaled \( Y \) separations between measured SNe, \( \Delta Y_i \), via the relation:

\[
a_i \Delta Y_i = a_i (Y_i - Y_{i-1}).
\]

We calculated the normalized cosmological times, \( t_{i,\text{raw}} \), by approximating an integral over cosmic time via a discrete sum:

\[
t_{i,\text{raw}} = 1 - \int_0^{z_i} a(t) dY = 1 - \sum_{j=1}^{i} a_j \Delta Y_j.
\]

We corrected the raw cosmological times using the relation:

\[
t_i = a_{\text{Pan} \to \text{CDR}} (t_{i,\text{raw}} - t_{i,\text{corr}}),
\]

where \( t_i \) are the corrected cosmological times. According to R20, \( t_{i,\text{corr}} \) corrects for the fact that the first measurement of \( t \) is at the first SN where \( a \) is not equal to its present day value, and \( a_{\text{Pan} \to \text{CDR}} \) is a scaling to match the Pantheon range to the range of the CDR data set studied in R15. Following R20, we used \( t_{i,\text{corr}} = 0.009579 \) and \( a_{\text{Pan} \to \text{CDR}} = 1.041 \).

We calculated the residual scale factors, \( \Delta a_i \), by subtracting from the measured \( a_i \) values the canonical values of \( a_i \), determined from \( t_i \):

\[
\Delta a_i = a_i - a_{\text{CDM}} (t_i).
\]

We defined the canonical scale factor, \( a_{\text{CDM}} \), for a given cosmic time, \( t \), by the integral relation

\[
t = 1 - \int_0^t a_{\text{CDM}}^{-1} \frac{dz'}{(1 + z'\sqrt{\Omega_M (1 + z')^3 + \Omega_\Lambda})}.
\]

Copying R20, we set \( \Omega_M = 0.27 \) and \( \Omega_\Lambda = 0.73 \). We calculated \( a_{\text{CDM}} (t) \) for each \( t \) by interpolating over an array of \( t \) values calculated at \( N_{\text{interp}} = 1001 \) \( a_{\text{CDM}} \) values evenly distributed over the physically relevant range of \( a_{\text{CDM}} \in [0, 1] \). With \( N_{\text{interp}} = 1001 \), our interpolated values of \( a_{\text{CDM}} (t_i) \) converged to within 0.01% of their true values.

To bin the inferred scale factor residuals, we divided the \( t \) space (0 to 1) into \( N_{\text{bin}} = 128 \) bins of equal size and calculated the mean \( \Delta a_i \) value in each \( t \) bin, \( \overline{\Delta a_i} \). We computed the wide baseline derivative of \( \overline{\Delta a_i} \), \( d \overline{\Delta a_i} / dt \), following Equation (1) of R20:

\[
d \overline{\Delta a_i} / dt = \frac{\Delta a_{i+n/2} - \Delta a_{i-n/2}}{n \Delta t}.
\]

As in R20, \( n = 8 \) and \( \Delta t = 1/128 \). For the first \( \text{[last]} \) \( n/2 \) bins, the lower [upper] \( \Delta a_i \) value was set to the first [last] \( t \) bin and the \( n \) in the denominator was set equal to the number of bins over which the derivative was measured.

We smoothed the \( d \overline{\Delta a_i} / dt \) values using a Gaussian kernel. We denote these smoothed derivatives as \( G_k (d \overline{\Delta a_i} / dt) \) where the \( k \) index denotes the width of the Gaussian kernel in \( t \):

\[
G_k(x) = \frac{\sum_{j=0}^{N_{\text{bin}}} G_k \left( \frac{x - t_j}{k} \right)}{\sum_{j=0}^{N_{\text{bin}}} G_k \left( \frac{x - t_j}{k} \right)},
\]

where

\[
G(a) = \frac{1}{\sqrt{2\pi} \times 0.37} e^{-a^2/(2 \times 0.37^2)}.
\]

We based Equations 10 and 11 on the definition of the \texttt{smooth} function of the \texttt{Mathcad} software, as that is the smoothing function used by R20. We believe the value of 0.37 is an approximation of one e-folding, \( 1/e \).
\[ \Delta \mu = \frac{d \Delta a}{d t} \frac{\Delta}{d \Delta a/dt} \frac{\Delta}{d \Delta a/dt} \frac{\Delta}{d \Delta a/dt} \]
To make this qualitative observation quantitative, we computed power spectra of $\Delta G(d\Delta a/dt)$ in $t_i$. The data were binned in $t_i$ bins of equal size, and the data to be Fourier transformed was thus evenly spaced in time. We measured the Power Spectrum, $P_f$, of $\Delta G(d\Delta a/dt)$ in $t_i$ via a standard discrete Fourier transform:

$$P_f = \frac{1}{N_{bin}} \sum_{j=0}^{N_{bin}-1} |\Delta a_j e^{-i 2\pi f j/N_{bin}}|^2.$$  \hspace{1cm} (13)

To avoid aliased modes, we measured the Fourier power in

**Figure 3.** The power spectrum of the true Pantheon data (black line) and the distribution of power spectra of the randomized Pantheon-like data. The $N_R = 10^5$ randomized Pantheon-like data sets produce, at every frequency, a distribution of $N_R$ measurements of the power spectra that could result from random deviations around the $\Lambda$CDM cosmology. At each frequency, the noted percentage of randomizations lie below the labeled contour. For example, at each frequency, 90% of randomizations have power below the blue contour.

*Figure 4.* The distribution of Fourier power at $f = 7.5\,\text{Hz}$ measured in the artificial Pantheon-like data randomly distributed around $\Lambda$CDM and analyzed according to the methodology described by R20, shows no statistically significant evidence of oscillations in the rate of cosmic expansion.
frequencies, $f$, from $0\text{Hz}$ to $N_{\text{bin}}/4 = 32\text{Hz}$. Replicating R20, $1\text{Hz}$ (‘one Hubble Hertz’) = $0.1023h_{100}\text{Gyr}^{-1}$.

Using Equation 13, we computed the Power Spectrum of $\Delta G(d\Delta a_i/dt)$ in $t_i$ for the true Pantheon data set and for the $N_R$ artificial Pantheon-like data sets. We show the true Pantheon power spectrum and the distribution of artificial Pantheon-like power spectra in Figure 3. At its peak, the power spectrum of the true Pantheon data (black line) lies below the 90% contour of the artificial power spectra (blue shading).

R20 focus primarily on the frequency peak at $f = 7.5\text{Hz}$. In Figure 4, we display a histogram showing the Fourier power at $f = 7.5\text{Hz}$ of the $N_R$ Pantheon-like artificial data sets and show where the power of the real Pantheon data lies in this histogram (black line). About 11% of randomized Pantheon-like $\Lambda$CDM data sets have more power at the chosen frequency than the real Pantheon data.

4 CONCLUSIONS

We replicated the analysis of the Pantheon data set of SNe Ia described by R20 and we found a similar result: the inferred residuals oscillate in the inferred cosmic time. We show these results in Figure 1.

We repeated this analysis on artificial Pantheon-like data sets with unchanged redshifts and with distance moduli randomly drawn from normal distributions centered at the canonical $\Lambda$CDM cosmology. By definition, this randomization erased any cosmic oscillation signature that exists in the true Pantheon data. Many plots of the R20 analysis applied to these randomized distributions (see Figure 2 for a representative subsample) display oscillations similar in amplitude and frequency to those identified in the real Pantheon data.

To make this qualitative observation quantitative, we measured the power spectra of the real Pantheon data and of the artificial Pantheon-like data sets. We showed these power spectra in Figure 3. R20 focus on the power spectrum peak at $f = 7.5\text{Hz}$. In Figure 4, we showed the distribution of the artificial data sets’ powers at this chosen frequency and where the true Pantheon data lies in this histogram. About 11% of the Pantheon-like $\Lambda$CDM data sets have more power at this chosen frequency than the real Pantheon data when analyzed according to the prescription of R20. Our analysis used the same choice of tuned analysis parameters that R20 report, including the widths of the smoothed Gaussian kernels, the chosen frequency, and the number of time bins. A robust measurement of the statistical significance of this $\approx 11\%$ effect would also include a statistical penalization for these adjustable analysis parameters.

There are potential sources of systematic error that neither we nor R20 consider. Particularly, the Pantheon data set is a combination of distinct supernova survey projects, each of which carries its own imperfectly characterized systematic errors. These inter-survey systematics inherit each individual survey’s uneven distributions in redshift and on the sky. If the oscillations noted by R20 appeared to be more than data analysis artifacts, we would analyze the signal’s robustness against these inter-survey systematics.

There is at least a one-in-ten chance that statistical fluctuations around the canonical $\Lambda$CDM cosmology would conspire with the windowing function of the R20 data analysis to produce a larger oscillatory signal than that which R20 report. The apparent oscillatory signal is consistent with data processing artifacts that masquerade as an oscillating signal in a truly $\Lambda$CDM cosmology.

5 ACKNOWLEDGMENTS

We found the work of VanderPlas (2018) particularly helpful in understanding the importance of being cautious about the potential impact of processing artifacts. SB and CS are supported by Harvard University and the US Department of Energy under grant DE-SC0007881. DS is supported by DOE grant DE-SC0010007 and the David and Lucile Packard Foundation. DS is supported in part by NASA under Contract No. NNG17PX03C issued through the WFIRST Science Investigation Teams Programme.
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