Tension and systematics in the Gold06 SnIa data set

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Abstract. The Gold06 SnIa data set recently released in astro-ph/0611572 consists of five distinct subsets defined by the group or instrument that discovered and analysed the corresponding data. These subsets are: the SNLS subset (47 SnIa), the HST subset (30 SnIa), the HZSST subset (41 SnIa), the SCP subset (26 SnIa) and the low redshift (LR) subset (38 SnIa). These subsets sum up to the 182 SnIa of the Gold06 data set. We use Monte Carlo simulations to study the statistical consistency of each one of the above subsets with the full Gold06 data set. In particular, we compare the best fit $w(z)$ parameters ($w_0, w_1$) obtained by subtracting each one of the above subsets from the Gold06 data set (subset truncation), with the corresponding best fit parameters ($w^r_0, w^r_1$) obtained by subtracting the same number of randomly selected SnIa from the same redshift range of the Gold06 data set (random truncation). We find that the probability for $(w^r_0, w^r_1) = (w_0, w_1)$ is large for the Gold06 minus SCP (Gold06-SCP) truncation but is less than 5% for the Gold06-SNLS, Gold06-HZSST and Gold06-HST truncations. This result implies that the Gold06 data set is not statistically homogeneous. By comparing the values of the best fit $(w_0, w_1)$ for each subset truncation we find that the tension among subsets is such that the SNLS and HST subsets are statistically consistent with each other and ‘pull’ towards ΛCDM ($w_0 = -1, w_1 = 0$) while the HZSST subset is statistically distinct and strongly ‘pulls’ towards a varying $w(z)$ crossing the line $w = -1$ from below ($w_0 < -1, w_1 > 0$). We also isolate six SnIa that are mostly responsible for this behaviour of the HZSST subset.

Keywords: cosmological constant experiments, cosmology of theories beyond the SM

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1. Introduction

Current cosmological observations show strong evidence that we live in a spatially flat universe [1] with low matter density [2] that is currently undergoing accelerated cosmic expansion. The most direct indication for the current accelerating expansion comes from the accumulating type Ia supernovae (SnIa) data [3]–[5], [7]–[10] which provide a detailed form of the recent expansion history of the universe.

This accelerating expansion has been attributed to a dark energy component with negative pressure which can induce repulsive gravity and thus cause accelerated expansion (for recent reviews see [11]–[17]). The simplest and most obvious candidate for this dark energy is the cosmological constant $\Lambda$ [18] with equation of state $w = p/\rho = -1$. This model however raises theoretical problems related to the fine tuned value required for the cosmological constant. These difficulties have lead to a large variety of proposed models where the dark energy component evolves with time usually due to an evolving scalar field (quintessence) which may be minimally [19] or non-minimally [20] coupled to gravity. Alternatively, more general modified gravity theories [21] have also been proposed based on $f(R)$ theories [22]–[24] (for a debate on the issue see [25]), braneworlds [26]–[29], Gauss–Bonnet dark energy [30], holographic dark energy [31] etc. The main prediction of the dynamical models is the evolution of the dark energy density parameter $\Omega_X(z)$. Combining this prediction with the prior assumption for the matter density parameter $\Omega_{0m}$, the predicted expansion history $H(z)$ is obtained as

$$H(z)^2 = H_0^2[\Omega_{0m}(1 + z)^3 + \Omega_X(z)]. \quad (1.1)$$

The dark energy density parameter is usually expressed as

$$\Omega_X(z) = \Omega_{0X} \exp\left(3 \int_0^z \frac{dz'}{1 + z'}(1 + w(z'))\right) \quad (1.2)$$

where $w(z)$ is related to $H(z)$ by [32]–[34]

$$w(z) = \frac{\frac{d}{dz}(1 + z)(d \ln H)/dz - 1}{1 - (H_0/H)^2 \Omega_{0m}(1 + z)^3}. \quad (1.3)$$
Table 1. The subsets of the Gold06 data set (see also [35]).

| Subsets | Total | Redshift range | Years of discovery | References |
|---------|-------|----------------|--------------------|------------|
| SNLS    | 47    | 0.25 \( \leq \) \( z \) \( \leq \) 0.96 | 2003–2004          | [8]        |
| HST     | 30    | 0.46 \( \leq \) \( z \) \( \leq \) 1.76 | 1997–2005          | [10]       |
| HZSST   | 41    | 0.28 \( \leq \) \( z \) \( \leq \) 1.20 | 1995–2001          | [3]        |
| SCP     | 26    | 0.17 \( \leq \) \( z \) \( \leq \) 0.86 | 1995–2000          | [4]        |
| LR      | 38    | 0.024 \( \leq \) \( z \) \( \leq \) 0.12 | 1990–2000          | [5, 6]     |

If the dark energy can be described as an ideal fluid with conserved energy momentum tensor \( T^{\mu\nu} = \text{diag}(\rho, p, p, p) \) then the above parameter \( w(z) \) is identical with the equation of state parameter of dark energy

\[
w(z) = \frac{p(z)}{\rho(z)}. \quad (1.4)
\]

Independently of its physical origin, the parameter \( w(z) \) is an observable derived from \( H(z) \) (with prior knowledge of \( \Omega_m \)) and is usually used to compare theoretical model predictions with observations.

The two most reliable and robust SnIa data sets existing at present are the Gold data set [10] (hereafter Gold06) and the Supernova Legacy Survey (SNLS) [8] data set. The Gold data set compiled by Riess et al is a set of 182 supernova data from various sources analysed in a consistent and robust manner with reduced calibration errors arising from systematics. It contains 119 points from previously published data [9] (hereafter Gold04) plus 16 points with \( 0.46 < z < 1.39 \) discovered recently by the Hubble Space Telescope (HST). It also incorporates 47 points (\( 0.25 < z < 1 \)) from the first year release of the SNLS data set [8] out of a total of 73 distant SnIa. Some supernovae were excluded [10] due to highly uncertain colour measurements, high extinction \( A_V > 0.5 \) and a redshift cut \( cz < 7000 \text{ km s}^{-1} \) or \( z < 0.0233 \), to avoid the influence of a possible local ‘Hubble bubble’, so as to define a high confidence subsample. In addition, a single algorithm (MLCS2k2) was applied to estimate all the SnIa distances except of those originating from SCP and SNLS (see [10] footnotes 14 and 15), thus attempting to minimize the non-uniformities of the data set.

The total of 182 SnIa included in the Gold06 data set can be grouped into five subsets according to the search teams/instruments that discovered them. These subsets are shown in Table 1. A detailed table of all the data used in our analysis and their subset origin is shown in the appendix. Notice that the early data of the Gold06 data set were obtained mainly in the 1990s and consist of the High \( z \) Supernova Search Team (HZSST) subset, the Supernova Cosmology Project (SCP) subset and the low redshift (LR) subset.

The above observations provide the apparent magnitude \( m(z) \) of the supernovae at peak brightness after implementing correction for galactic extinction, \( K \)-correction and light curve width–luminosity correction. The resulting apparent magnitude \( m(z) \) is related to the luminosity distance \( d_L(z) \) through

\[
m_{\text{th}}(z) = \bar{M}(M, H_0) + 5 \log_{10}(D_L(z)) \quad (1.5)
\]
where in a flat cosmological model

\[ D_L(z) = (1 + z) \int_0^z \frac{dz'}{H(z'; a_1, \ldots, a_n)} \]  

(1.6)

is the Hubble free luminosity distance \((H_0 d_L/c)\), \(a_1, \ldots, a_n\) are theoretical model parameters and \(\bar{M}\) is the magnitude zero point offset and depends on the absolute magnitude \(M\) and on the present Hubble parameter \(H_0\) as

\[ \bar{M} = M + 5 \log_{10} \left( \frac{c H_0^{-1}}{\text{Mpc}} \right) + 25 = M - 5 \log_{10} h + 42.38. \]  

(1.7)

The parameter \(M\) is the absolute magnitude which is assumed to be constant after the above mentioned corrections have been implemented in \(m(z)\).

The data points of the Gold06 data set are given after the corrections have been implemented, in terms of the distance modulus

\[ \mu_{\text{obs}}(z_i) = m_{\text{obs}}(z_i) - M. \]  

(1.8)

The theoretical model parameters are determined by minimizing the quantity

\[ \chi^2(a_1, \ldots, a_n) = \sum_{i=1}^{N} \frac{(\mu_{\text{obs}}(z_i) - \mu_{\text{th}}(z_i))^2}{\sigma_{\mu i}^2 + \sigma_{v i}^2}. \]  

(1.9)

where \(\sigma_{\mu i}^2\) and \(\sigma_{v i}^2\) are the errors due to flux uncertainties and peculiar velocity dispersion respectively. These errors are assumed to be Gaussian and uncorrelated. The theoretical distance modulus is defined as

\[ \mu_{\text{th}}(z_i) \equiv m_{\text{th}}(z_i) - M = 5 \log_{10}(D_L(z)) + \mu_0 \]  

(1.10)

where

\[ \mu_0 = 42.38 - 5 \log_{10} h \]  

(1.11)

and \(\mu_{\text{th}}(z_i)\) also depends on the parameters \(a_1, \ldots, a_n\) used in the parametrization of \(H(z)\) in equation (1.6).

The parametrization used in our analysis is the CPL parametrization \([36,37]\)

\[ w(z) = w_0 + w_1 \frac{z}{1 + z}, \]  

(1.12)

\[ H^2(z) = H_0^2[\Omega_{0m}(1 + z)^3 + (1 - \Omega_{0m})(1 + z)^3(1 + w_0 + w_1) e^{3w_1[1/(1+z)-1]}], \]  

(1.13)

with a prior of the matter density parameter \(\Omega_{0m} = 0.28\) (as in \([10]\)), assuming flatness, according to the methods described in detail in \([38,39]\).

The previous version of the Gold sample \([9]\) (Gold04) had been shown to be in mild (2\(\sigma\)) tension with the SNLS data set \([39,40]\). While the Gold04 mildly favoured an evolving dark energy equation of state parameter \(w(z)\) (crossing the phantom divide line \(w = -1\)) over the cosmological constant (ΛCDM) at almost 2\(\sigma\) level \([38,41]-[45]\), the SNLS data had shown no such trend and provided \([39]\) a best fit \(w(z)\) very close to \(w = -1\) (ΛCDM). The trend towards phantom divide crossing cannot be explained in the context of minimally coupled quintessence and could be viewed as an indication for more exotic models \([46]-[53]\). This mild tension could have been attributed to systematic errors.
Tension and systematics in the Gold06 SnIa data set

Figure 1. Maximum likelihood fits of the CPL parametrization \((1.12)\) to the SNLS (a) Gold04 (b) and Gold06 (c) data sets. The \(2\sigma\) tension between the Gold and SNLS remains with the new Gold06 data set despite the improved filtering, calibration and data extension.

due e.g. to the different algorithm used in the analysis of the two data sets. The new version of the Gold sample however, (Gold06) involves an improved uniform analysis and incorporates a large part of the SNLS sample. Thus there could have been an anticipation that the mild tension with SNLS would be ameliorated or even disappear. As shown in figure 1 however, this anticipation has not been fulfilled (see also [54, 55]).

The mild (almost \(2\sigma\)) tension between the Gold04 and the SNLS samples (figures 1(a) and (b)) has not decreased by using the Gold06 sample (figure 1(c))! The investigation of the origin of this tension and the statistical uniformity of the Gold06 data set consist the main focus of the present paper.

2. Tension in the Gold06 data set

The 182 SnIa included in the Gold06 data set originate mainly from the search teams/instruments shown in table 1. The low redshift (LR) subset is a mixture of various early SnIa by different groups and instruments but we consider it as a single subset because otherwise we would have to increase the number of subsets beyond a reasonable number.

In order to investigate the statistical uniformity of the Gold06 data set and also the origin of the tension with the SNLS, we have decomposed the Gold06 data set into the subsamples of table 1 and constructed new data sets by subtracting each one (or two) of the subsets from the full Gold06 data set. We thus obtained the following six subset truncations:

\begin{enumerate}
\item \(182_{\text{G06}} - 47_{\text{SNLS}} - 30_{\text{HST}}\)
\item \(182_{\text{G06}} - 47_{\text{SNLS}}\)
\item \(182_{\text{G06}} - 30_{\text{HST}}\)
\item \(182_{\text{G06}} - 26_{\text{SCP}}\)
\end{enumerate}
Tension and systematics in the Gold06 SNeIa data set

Figure 2. The $1\sigma$–$2\sigma\chi^2$ confidence region ellipses in the $w_0$–$w_1$ plane based on parametrization (1.12) for the Gold06 data set and $\Omega_{0m} = 0.28$. Superposed are the best fit parameter values for each one of the truncations 1–6 of the Gold06 data set.

1. 182G06–41HZSST
2. 182G06–47SNLS–30HST
3. 182G06–30HST
4. 182G06–41HZSST+26SCP
5. 182G06–41HZSST
6. 182G06–47SNLS–30HST

We did not consider the subset 182G06–38LR with low redshift truncation because the LR subset is not uniform and also because subtracting it cannot be associated with a corresponding random truncation in the same low redshift range (the range $z < 0.124$ is spanned completely by the LR subset). We then addressed the following two questions:

- How do the best fit $(w_0, w_1)$ values for each of the six truncations compare with the corresponding best fit value of the full Gold06 data set?
- How do the best fit $(w_0, w_1)$ values for each of the six truncations compare with the corresponding best fit value of a random truncation of the full Gold06 data set made in the same redshift range as that of the subtracted subset?

The answer to the first question is provided in figure 2 where we show the best fit values $(w_0, w_1)$ for each one of the above six truncations. Notice that the two multiple truncations: 182G06–41HZSST–26SCP (point 1) and 182G06–47SNLS–30HST (point 6) correspond to more extreme best fit values of $(w_0, w_1)$. The best fit $(w_0, w_1)$ of the Gold06 data set along with its $1\sigma$ and $2\sigma$ contours is also shown in figure 2 (point 0).

The following comments can be made on the basis of figure 2:

- The truncation 182G06–26SCP leaves the best fit $(w_0, w_1)$ of the Gold06 data set practically unchanged
- No single subset truncation is able to shift the best fit $(w_0, w_1)$ values beyond the $1\sigma$ contours of the Gold06 data set.
- All the subset truncations (except 182G06–26SCP) systematically shift the best fit $(w_0, w_1)$ along the major axis of the $\chi^2$ ellipse. In particular for 182G06–30HST and 182G06–47SNLS the best fit is left mainly under the influence of HZSST and is shifted along the major axis, away from $\Lambda$CDM towards an evolving $w(z)$ crossing the line $w = -1$ ($w_0 < -1$, $w_1 > 0$). On the other hand for 182G06–41HZSST the best fit
(w₀, w₁) is left under the influence of HST and SNLS and is shifted towards ΛCDM. This implies that the subsets HST and SNLS favour ΛCDM while the subset HZSST favours an evolving w(z) crossing the phantom divide w = −1. This result is further amplified by the behaviour of the multiple truncations $182_{\text{G06}}–41_{\text{HZSST}}–26_{\text{SCP}}$ (further shifted towards ΛCDM) and $182_{\text{G06}}–47_{\text{SNLS}}–30_{\text{HST}}$ (strongly shifted towards a varying w(z) crossing the phantom divide w = −1 at a level more than 2σ (see figure 2)).

Based on the above comments we conclude that the answer to the first question stated above can be summarized as follows: the best fit (w₀, w₁) values for each of the four single set truncations 2–5 do not differ more than 1σ from the best fit corresponding values of the Gold06 data set but they show distinct trends which are characteristic for each one of the truncations.

A separate question (related to the second question stated above) is the question of statistical consistency between each subset truncation and the full Gold06 data set. To address this question we compare the best fit value of (w₀, w₁) for each subset truncation with a large number (500) of corresponding random truncations of the Gold06 data set. The random truncations involve random subtractions of the same number of SnIa and in the same redshift range as the subset truncation. These random truncations can be used to obtain the 1σ range for the expected values of the best fit (w₀, w₁) of the randomly truncated Gold06 data set. If the best fit values (w₀, w₁) of the subset truncation is within the 1σ range of the best fit values (w₀, w₁) of the random truncation then the considered subset truncation is a typical truncation representative of the Gold06 data set and statistically consistent with it. If on the other hand (w₀, w₁) differs by 2σ or more from the mean best fit values ($\bar{w}_0$, $\bar{w}_1$) of the random truncation then the considered subset truncation is not a typical truncation and is systematically different from the full data set. We have implemented the above comparison for the six subset truncations referred above and the results are shown in table 2 and in figure 3. Notice that the mean best fit values ($\bar{w}_0$, $\bar{w}_1$) of the random truncations in table 2 scatter between the various truncations by an amount larger than the expected value $\sim \sigma/\sqrt{N}$. This is justified because the truncation classes are not equivalent with each other. They differ in the redshift range where the data points are truncated. Each redshift range of random truncation is selected to be the same as the redshift range of the original subset truncation.

### Table 2. The six subset truncations of figure 3.

| Data set               | $w_0$ | $w_1$ | $w_0^\text{MC}$ | $w_1^\text{MC}$ | ($w - \bar{w}$)/σ₀ | ($w - \bar{w}$)/σ₀ |
|------------------------|-------|-------|-----------------|-----------------|-------------------|-------------------|
| 182–47SNLS–30HST       | 2.21  | 7.53  | 2.35            | 2.63            | −3.7σ             | −3.7σ             |
| 182–47SNLS             | 1.62  | 3.95  | 2.67            | 2.79            | −2.2σ             | −2.2σ             |
| 182–30HST              | 1.60  | 4.05  | 2.60            | 2.60            | −2.4σ             | −2.4σ             |
| 182–26SCP              | 1.39  | 2.75  | 2.79            | 2.79            | +0.2σ             | +0.2σ             |
| 182–41HZSST            | 1.12  | 1.34  | 2.80            | 2.80            | +2.7σ             | +2.7σ             |
| 182–41HZSST–26SCP      | 1.01  | 0.81  | 2.75            | 2.75            | +2.6σ             | +2.6σ             |
The following comments can be made on the basis of table 2 and figure 3:

- The SCP is a typical, statistically consistent subset of the Gold06 data set because its truncation does not significantly alter the statistical properties of the Gold06 data set. In particular the best fit \((w_0, w_1)\) value of the 182\text{G06}–26\text{SCP} truncation differs only by 0.2\(\sigma\) from the corresponding mean random truncation best fit \((\bar{w}_0^r, \bar{w}_1^r)\) which involves random subtraction of the same number of SnIa from the same redshift range as the SCP subset.

- The other five subsets considered in figure 3 are not typical subsets of the Gold06 data set. The best fit \((w_0, w_1)\) values of the truncations considered in figure 3 differ by more than 2\(\sigma\) from the mean best fit values \((\bar{w}_0^r, \bar{w}_1^r)\) of the corresponding random truncations.

- An extreme case is the truncation 182\text{G06}–47\text{SNLS}–30\text{HST} whose best fit values are 3.7\(\sigma\) away from the corresponding mean best fit values of a random truncation! This implies that the combination of the 38\text{LR} + 41\text{HZSST} + 26\text{SCP} which is left over from the truncation 182\text{G06}–47\text{SNLS}–30\text{HST} strongly favours an evolving \(w(z)\) and is statistically inconsistent with the Gold06 data set. This result is consistent with figure 2 which also shows that best fit \((w_0, w_1)\) of the truncation 182\text{G06}–47\text{SNLS}–30\text{HST} is about 3\(\sigma\) away from the Gold06 best fit!

- The SNLS and HST subsets are statistically very similar to each other (with a trend towards \(\Lambda\)CDM) even though they are both significantly different (more than 2\(\sigma\)) from the corresponding random truncations of Gold06 (see also figure 2).

- Both figures 2 and 3 indicate that the trend towards \(\Lambda\)CDM increases for more recent (HST and SNLS) data while earlier data (HZSST and SCP) seem to favour an evolving \(w(z)\).
Figure 4. The $1\sigma$–$2\sigma\chi^2$ confidence region ellipses in the $w_0$–$w_1$ plane based on parametrization (1.12) for the Gold06p data set and $\Omega_{0m} = 0.28$. Superposed are the best fit parameter values for each one of four truncations of the Gold06p data set. The best fit parameters for the truncation 135–41HST–26SCP are shifted by about $3\sigma$ from corresponding Gold06p best fit values in the direction of $\Lambda$CDM.

Table 3. The four subset truncations of figure 5.

| Data set               | $w_0$  | $w_0^0$ (MC) | $(w - \bar{w})/\sigma_{w}$ |
|------------------------|--------|--------------|-----------------------------|
| 135–30HST              | $w_0^0$=−2.21 | $w_0^0$=−1.63±0.17 | $-3.6\sigma$                |
| 135–26SCP              | $w_0^0$=−1.75 | $w_0^0$=−1.63±0.17 | $-0.8\sigma$                |
| 135–41HST              | $w_0^0$=−1.20 | $w_0^0$=−1.60±0.21 | $+1.9\sigma$                |
| 135–41HST–26SCP        | $w_0^0$=−0.42 | $w_0^0$=−1.67±0.37 | $+3.7\sigma$                |

The above results can also be verified by considering the ‘pure’ Gold06 data set which does not include the 47 SnIa of SNLS. This data set (Gold06p) consists of 135 SnIa and is essentially a filtered version of the Gold04 data set with the addition of the 16 SnIa with $0.46 < z < 1.39$ discovered recently by the HST. The best fit parameter values for the Gold06p data set are somewhat shifted in the direction of varying $w(z)$ compared to the full Gold06 (compare figures 2 and 4) as expected since SNLS favours $\Lambda$CDM. As shown in figure 4 and table 3, the effect of each subset truncation in this case is more prominent due to the smaller number of points in the Gold06p data set.

For example, the 135G06p–41HST–26SCP truncation shifts the best fit parameter values of the Gold06p by about $3\sigma$ in the direction of $\Lambda$CDM (and beyond it) while the shift with respect to the random truncations of Gold06p is $3.7\sigma$ (figure 5). The corresponding shifts with respect to the Gold06 data set were about $1\sigma$ and $2.6\sigma$ respectively (figures 2 and 3).

3. Discussion and conclusion

The fact that more recent SnIa data (HST and SNLS) seem to favour $\Lambda$CDM significantly more than earlier data (HZSST) makes it possible that earlier data may be more prone...
Figure 5. Comparison of the best fit parameters to the subsample truncations shown in table 3 with corresponding random truncations of the Gold06p data set. In all truncation cases (except of the SCP truncation) the best fit parameter values are shifted (in different directions) by more than 2σ from the mean random truncation values. The best fit parameter shift of the 135G06p–41HZSST–26SCP is 3.7σ compared to the corresponding random truncation. The point corresponding to ΛCDM (w_0 = -1, w_1 = 0) is also shown.

It is therefore interesting to identify a small subset of SnIa from the HZSST data that is mostly responsible for the trend of HZSST towards an evolving w(z). We have isolated the group of SnIa in the HZSST subset whose distance modulus differs by more than 1.8σ from the ΛCDM predictions (Ω_m = 0.28). The group which consists of just six SnIa is also significantly responsible for the trend of the HZSST subset towards an evolving w(z). These SnIa are: (SN99Q2, SN00ee, SN00ec, SN99S, SN01fo, SN99fv). The shifted best fit parameter values (w_0, w_1) due to these six SnIa data truncation are shown in figure 6(a) superposed on a Monte Carlo simulation of corresponding random 6 point truncations to the HZSST subset. We anticipate that the possible systematic errors that lead to the distinct behaviour of the HZSST subset are maximal for these six SnIa and it may be easier to identify them and correct them in this set of six SnIa. There has been independent evidence [56] that one of the above SnIa (SN99Q2) is an outlier and may not be reliably used in the Hubble diagram. In fact, according to [56], measurements of optical and IR light curves of SN99Q2 indicate that this object may not be a SnIa, or at least may not be a ‘normal’ one. Alternatively the above six SnIa could be discarded from the Gold06 data set as outliers in an
effort to improve its statistical uniformity and bring it to line with the more recent data.

A visual display of the six data points (points in red) compared to other data points is shown in figure 6(b) where we show the distance modulus relative to ΛCDM ($\Omega_{0m} = 0.28$) of the Gold06 data in the redshift range of the HZSST subset. In the same plot we show (thick dashed line) the distance modulus corresponding to the best fit values ($w_0 = -1.62, w_1 = 3.95$) obtained from the Gold06p data (dashed line) indicating that all of the six red data points strongly favour the best fit $w(z)$ over ΛCDM.

In conclusion we have demonstrated that despite the careful filtering and the improved calibration, the Gold06 data set is plagued with statistical inhomogeneities which are possibly due to systematic errors. Given the fact that the more recent data (SNLS and HST) are statistically consistent with each other and homogeneous, it is highly probable that the possible source of systematic errors lies within the earlier data and in particular in the HZSST subset.

**Numerical analysis:** The Mathematica files and the datafile used in the numerical analysis of this work may be found at [http://leandros.physics.uoi.gr/gold06/gold06.htm](http://leandros.physics.uoi.gr/gold06/gold06.htm) or may be sent by e-mail upon request.

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Appendix

Table A.1. The Gold06 data set with its subsets. The six outliers of the HZSST subset are denoted by a *.

| SN       | $z$    | $\mu_0$ | $\sigma_{\mu_0}$ | Subsample |
|----------|--------|---------|------------------|-----------|
| SN03D1au | 0.504  | 42.61   | 0.17             | SNLS      |
| SN03D1aw | 0.582  | 43.07   | 0.17             | SNLS      |
| SN03D1ax | 0.496  | 42.36   | 0.17             | SNLS      |
| SN03D1cm | 0.870  | 44.28   | 0.34             | SNLS      |
| SN03D1co | 0.679  | 43.58   | 0.19             | SNLS      |
| SN03D1fc | 0.331  | 41.13   | 0.17             | SNLS      |
| SN03D1fl | 0.688  | 43.23   | 0.17             | SNLS      |
| SN03D1fq | 0.800  | 43.67   | 0.19             | SNLS      |
| SN03D3af | 0.532  | 42.78   | 0.18             | SNLS      |
| SN03D3aw | 0.449  | 42.05   | 0.17             | SNLS      |
| SN03D3ay | 0.371  | 41.67   | 0.17             | SNLS      |
| SN03D3bh | 0.249  | 40.76   | 0.17             | SNLS      |
| SN03D3cc | 0.463  | 42.27   | 0.17             | SNLS      |
| SN03D3cd | 0.461  | 42.22   | 0.17             | SNLS      |
| SN03D4ag | 0.285  | 40.92   | 0.17             | SNLS      |
| SN03D4at | 0.633  | 43.32   | 0.18             | SNLS      |
| SN03D4cx | 0.949  | 43.69   | 0.32             | SNLS      |
| SN03D4cz | 0.695  | 43.21   | 0.19             | SNLS      |
| SN03D4dh | 0.627  | 42.93   | 0.17             | SNLS      |
| SN03D4di | 0.905  | 43.89   | 0.30             | SNLS      |
| SN03D4dy | 0.604  | 42.70   | 0.17             | SNLS      |
| SN03D4fl | 0.791  | 43.54   | 0.18             | SNLS      |
| SN03D4gg | 0.592  | 42.75   | 0.19             | SNLS      |
| SN03D4gl | 0.571  | 42.65   | 0.18             | SNLS      |
| SN04D1ag | 0.557  | 42.70   | 0.17             | SNLS      |
| SN04D2cf | 0.369  | 41.67   | 0.17             | SNLS      |
| SN04D2fp | 0.415  | 41.96   | 0.17             | SNLS      |
| SN04D2fs | 0.357  | 41.63   | 0.17             | SNLS      |
| SN04D2gb | 0.430  | 41.96   | 0.17             | SNLS      |
| SN04D2gp | 0.707  | 43.42   | 0.21             | SNLS      |
| SN04D3co | 0.620  | 43.21   | 0.18             | SNLS      |
| SN04D3cy | 0.643  | 43.21   | 0.18             | SNLS      |
| SN04D3df | 0.470  | 42.45   | 0.17             | SNLS      |
| SN04D3do | 0.610  | 42.98   | 0.17             | SNLS      |
| SN04D3ez | 0.263  | 40.87   | 0.17             | SNLS      |
| SN04D3fk | 0.358  | 41.66   | 0.17             | SNLS      |
| SN04D3fq | 0.730  | 43.47   | 0.18             | SNLS      |
| SN04D3hn | 0.552  | 42.65   | 0.17             | SNLS      |
| SN04D3kr | 0.337  | 41.44   | 0.17             | SNLS      |
| SN04D3ln | 0.822  | 43.73   | 0.27             | SNLS      |
| SN04D3nl | 0.950  | 44.14   | 0.31             | SNLS      |
| SN04D3nh | 0.340  | 41.51   | 0.17             | SNLS      |
| SN04D3oe | 0.756  | 43.64   | 0.17             | SNLS      |
| SN04D4an | 0.613  | 43.15   | 0.18             | SNLS      |
| SN04D4bq | 0.550  | 42.67   | 0.17             | SNLS      |
## Table A.1. (Continued.)

Tension and systematics in the Gold06 SnIa data set

| SN    | $z$  | $\mu_0$ | $\sigma_{\mu_0}$ | Subsample |
|-------|------|---------|------------------|-----------|
| SN04D4dm | 0.811 | 44.13   | 0.31             | SNLS      |
| SN04D4dw | 0.961 | 44.18   | 0.33             | SNLS      |
| 1997ff  | 1.755 | 45.35   | 0.35             | HST       |
| 2002dc  | 0.475 | 42.24   | 0.20             | HST       |
| 2002dd  | 0.950 | 43.98   | 0.34             | HST       |
| 2003eq  | 0.840 | 43.67   | 0.21             | HST       |
| 2003es  | 0.954 | 44.30   | 0.27             | HST       |
| 2003eb  | 0.900 | 43.64   | 0.25             | HST       |
| 2003XX  | 0.935 | 43.97   | 0.29             | HST       |
| 2003bd  | 0.670 | 43.19   | 0.24             | HST       |
| 2002kd  | 0.735 | 43.14   | 0.19             | HST       |
| 2003be  | 0.640 | 43.01   | 0.25             | HST       |
| 2003dy  | 1.340 | 44.92   | 0.31             | HST       |
| 2002ki  | 1.140 | 44.71   | 0.29             | HST       |
| 2002hp  | 1.305 | 45.51   | 0.30             | HST       |
| 2002fw  | 1.300 | 45.06   | 0.20             | HST       |
| HST04Pat | 0.970 | 44.67   | 0.36             | HST       |
| HST04Mcd | 1.370 | 45.23   | 0.25             | HST       |
| HST05Fer | 1.020 | 43.99   | 0.27             | HST       |
| HST05Koe | 1.230 | 45.17   | 0.23             | HST       |
| HST04Gre | 1.140 | 44.44   | 0.31             | HST       |
| HST04Omb | 0.975 | 44.21   | 0.26             | HST       |
| HST05Lam | 1.230 | 44.97   | 0.20             | HST       |
| HST04Tha | 0.954 | 43.85   | 0.27             | HST       |
| HST04Rak | 0.740 | 43.38   | 0.22             | HST       |
| HST04Yow | 0.460 | 42.23   | 0.32             | HST       |
| HST04Man | 0.854 | 43.96   | 0.29             | HST       |
| HST05Spo | 0.839 | 43.45   | 0.20             | HST       |
| HST04Eag | 1.020 | 44.52   | 0.19             | HST       |
| HST05Gab | 1.120 | 44.67   | 0.18             | HST       |
| HST05Str | 1.010 | 44.77   | 0.19             | HST       |
| HST04Sas | 1.390 | 44.90   | 0.19             | HST       |
| SN95K   | 0.478 | 42.48   | 0.23             | HZSST     |
| SN96E   | 0.425 | 41.69   | 0.40             | HZSST     |
| SN96H   | 0.620 | 43.11   | 0.28             | HZSST     |
| SN96I   | 0.570 | 42.80   | 0.25             | HZSST     |
| SN96J   | 0.300 | 41.01   | 0.25             | HZSST     |
| SN96K   | 0.380 | 42.02   | 0.22             | HZSST     |
| SN96U   | 0.430 | 42.33   | 0.34             | HZSST     |
| SN97as  | 0.508 | 42.19   | 0.35             | HZSST     |
| SN97bb  | 0.518 | 42.83   | 0.31             | HZSST     |
| SN97bj  | 0.334 | 40.92   | 0.30             | HZSST     |
| SN97ce  | 0.440 | 42.07   | 0.19             | HZSST     |
| SN97cj  | 0.500 | 42.73   | 0.20             | HZSST     |
| SN98ac  | 0.460 | 41.81   | 0.40             | HZSST     |
| SN98M   | 0.630 | 43.26   | 0.37             | HZSST     |
| SN98J   | 0.828 | 43.59   | 0.61             | HZSST     |
Table A.1. (Continued.)

| SN    | $z$  | $\mu_0$ | $\sigma_{\mu_0}$ | Subsample |
|-------|------|---------|-----------------|-----------|
| SN99Q2$^*$ | 0.459 | 42.67   | 0.22            | HZSST     |
| SN99U2   | 0.511 | 42.83   | 0.21            | HZSST     |
| SN99S$^*$ | 0.474 | 42.81   | 0.22            | HZSST     |
| SN99N    | 0.537 | 42.85   | 0.41            | HZSST     |
| SN99fn   | 0.477 | 42.38   | 0.21            | HZSST     |
| SN99ff   | 0.455 | 42.29   | 0.28            | HZSST     |
| SN99fj   | 0.815 | 43.75   | 0.33            | HZSST     |
| SN99fm   | 0.949 | 44.00   | 0.24            | HZSST     |
| SN99fk   | 1.056 | 44.35   | 0.23            | HZSST     |
| SN99fw   | 0.278 | 41.01   | 0.41            | HZSST     |
| SN99fv$^*$ | 1.199 | 44.19   | 0.34            | HZSST     |
| SN00ec$^*$ | 0.470 | 42.76   | 0.21            | HZSST     |
| SN00dz   | 0.500 | 42.74   | 0.24            | HZSST     |
| SN00eg   | 0.540 | 41.96   | 0.41            | HZSST     |
| SN00ec$^*$ | 0.470 | 42.73   | 0.23            | HZSST     |
| SN00eh   | 0.490 | 42.40   | 0.25            | HZSST     |
| SN01jh   | 0.884 | 44.22   | 0.19            | HZSST     |
| SN01hu   | 0.882 | 43.89   | 0.30            | HZSST     |
| SN01ly   | 0.570 | 42.87   | 0.31            | HZSST     |
| SN01jp   | 0.528 | 42.76   | 0.25            | HZSST     |
| SN01fs$^*$ | 0.771 | 43.12   | 0.17            | HZSST     |
| SN01hs   | 0.832 | 43.55   | 0.29            | HZSST     |
| SN01hx   | 0.798 | 43.88   | 0.31            | HZSST     |
| SN01hy   | 0.811 | 43.97   | 0.35            | HZSST     |
| SN01jf   | 0.815 | 44.09   | 0.28            | HZSST     |
| SN01jm   | 0.977 | 43.91   | 0.26            | HZSST     |
| SN95aw   | 0.400 | 42.04   | 0.19            | SCP       |
| SN95ax   | 0.615 | 42.85   | 0.23            | SCP       |
| SN95ay   | 0.480 | 42.37   | 0.20            | SCP       |
| SN95az   | 0.450 | 42.13   | 0.21            | SCP       |
| SN95ba   | 0.388 | 42.07   | 0.19            | SCP       |
| SN96ci   | 0.495 | 42.25   | 0.19            | SCP       |
| SN96ci   | 0.828 | 43.96   | 0.46            | SCP       |
| SN97eq   | 0.538 | 42.66   | 0.18            | SCP       |
| SN97ek   | 0.860 | 44.03   | 0.30            | SCP       |
| SN97ez   | 0.778 | 43.81   | 0.35            | SCP       |
| SN97F    | 0.580 | 43.04   | 0.21            | SCP       |
| SN97H    | 0.526 | 42.56   | 0.18            | SCP       |
| SN97I    | 0.172 | 39.79   | 0.18            | SCP       |
| SN97N    | 0.180 | 39.98   | 0.18            | SCP       |
| SN97P    | 0.472 | 42.46   | 0.19            | SCP       |
| SN97Q    | 0.430 | 41.99   | 0.18            | SCP       |
| SN97R    | 0.657 | 43.27   | 0.20            | SCP       |
| SN97ac   | 0.320 | 41.45   | 0.18            | SCP       |
| SN97af   | 0.579 | 42.86   | 0.19            | SCP       |
| SN97ai   | 0.450 | 42.10   | 0.23            | SCP       |
| SN97aj   | 0.581 | 42.63   | 0.19            | SCP       |
| SN97am   | 0.416 | 42.10   | 0.19            | SCP       |
Table A.1. (Continued.)

| SN    | z    | $\mu_0$ | $\sigma_{\mu_0}$ | Subsample |
|-------|------|---------|------------------|-----------|
| SN97ap| 0.830| 43.85   | 0.19             | SCP       |
| SN98ba| 0.430| 42.36   | 0.25             | SCP       |
| SN98bi| 0.740| 43.35   | 0.30             | SCP       |
| SN00fr| 0.543| 42.67   | 0.19             | SCP       |
| SN92hs| 0.063| 37.67   | 0.19             | LR        |
| SN94M | 0.024| 35.09   | 0.22             | LR        |
| SN94T | 0.036| 36.01   | 0.21             | LR        |
| SN97dg| 0.029| 36.13   | 0.21             | LR        |
| SN00bk| 0.026| 35.35   | 0.23             | LR        |
| SN98cs| 0.032| 36.08   | 0.20             | LR        |
| SN00ef| 0.036| 36.39   | 0.19             | LR        |
| SN98dx| 0.053| 36.95   | 0.19             | LR        |
| SN99gp| 0.026| 35.57   | 0.21             | LR        |
| SN99X | 0.025| 35.40   | 0.22             | LR        |
| SN99cc| 0.031| 35.84   | 0.21             | LR        |
| SN94Q | 0.029| 35.70   | 0.21             | LR        |
| SN95ac| 0.049| 36.55   | 0.20             | LR        |
| SN96bl| 0.034| 36.19   | 0.20             | LR        |
| SN90O | 0.030| 35.90   | 0.21             | LR        |
| SN96C | 0.027| 35.90   | 0.21             | LR        |
| SN96ab| 0.124| 39.19   | 0.22             | LR        |
| SN99ef| 0.038| 36.67   | 0.19             | LR        |
| SN92J | 0.046| 36.35   | 0.21             | LR        |
| SN92bk| 0.058| 37.13   | 0.19             | LR        |
| SN92bp| 0.079| 37.94   | 0.18             | LR        |
| SN92br| 0.088| 38.07   | 0.28             | LR        |
| SN93H | 0.025| 35.09   | 0.22             | LR        |
| SN93ah| 0.028| 35.53   | 0.22             | LR        |
| SN90T | 0.040| 36.38   | 0.20             | LR        |
| SN90af| 0.050| 36.84   | 0.22             | LR        |
| SN91U | 0.033| 35.53   | 0.21             | LR        |
| SN91S | 0.056| 37.31   | 0.19             | LR        |
| SN92P | 0.026| 35.63   | 0.22             | LR        |
| SN92bh| 0.036| 36.17   | 0.20             | LR        |
| SN92bh| 0.043| 36.52   | 0.19             | LR        |
| SN92bh| 0.045| 36.99   | 0.18             | LR        |
| SN92au| 0.061| 37.31   | 0.22             | LR        |
| SN92ae| 0.075| 37.77   | 0.19             | LR        |
| SN92aq| 0.101| 38.70   | 0.20             | LR        |
| SN93ag| 0.050| 37.07   | 0.19             | LR        |
| SN93O | 0.052| 37.16   | 0.18             | LR        |
| SN93B | 0.071| 37.78   | 0.19             | LR        |

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