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Do type Ia supernovae prove a positive cosmological constant?

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Abstract
Nowadays the only direct evidence for a model Universe with non-zero cosmological constant is the Hubble diagram of the distant Ia type supernovae. Other observations, e.g. the WMAP measurements, do not support the existence of a non-zero cosmological constant without any doubt (see Blanchard et al. (2003)). Therefore there is a growing interest in studying the redshift distance diagram of SN Ia supernovae to verify the existence of $\Lambda \neq 0$ cosmological constant. In this paper we show that (i) there is a correlation between the statistical residuals of SN Ia distance moduli in the Hubble-diagram and the calculated internal extinction values of the host galaxy. It suggests that there is something wrong with the previous estimations of internal extinction. Furthermore, we show that (ii) the correction for these correlation results a Hubble-diagram which does not support models with $\Omega_\Lambda \simeq 0.7$, rather an Einstein-de Sitter Universe.
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1 Introduction

It seems evident that after an alternative explanation of the WMAP results (Blanchard et al., 2003) the Hubble-diagram of the distant Ia type supernovae will become a more fundamental (and maybe the only direct) evidence for a cosmology with *non-zero* cosmological constant. Therefore there is an increasing interest in studying the fine details of this diagram to exclude the possible alternative explanations.

Type Ia supernovae (SNe Ia) have an important role in the chemical evolution of the Universe and the determination of cosmological distance scale. This later application is based on their well defined $M_V = -19.4 \pm .5$ maximum luminosity (Richardson et al., 2002).

It is worth noting that the mean absolute magnitude of SNe Ia is assumed to be a universal standard in the whole Universe. Therefore they are used as standard candles. The paper of Tonry et al. (Tonry et al. (2003) and references therein; "TONRY" in what follows) concluded that $\Omega_\Lambda \simeq 0.7$ and $\Omega_M \simeq 0.3$, where Ω_M is the ratio of the density of the non-relativistic matter in Universe to the critical density and $\Omega_\Lambda = \lambda c^2/(3H_o^2)$, where λ is the cosmological constant, c is the velocity of light, and H_o is the Hubble constant. Previously, both the High-z Supernova Search Team (Schmidt et al. (1998), Riess et al. (2000)) and the Supernova Cosmology Project (Perlmutter et al. (1999)) came to the conclusion that supernovae (SNe) between redshifts of $z \simeq (0.3 - 1.0)$ had in the average $\simeq 0.28$ mag higher distance moduli than expected assuming $\Omega_M \simeq 0.3$ and $\Omega_\Lambda = 0$ (Riess, 2000).

Recently, two independent studies queried the reality of the nonzero cosmological constant deduced from the studies of high-redshift type Ia supernovae in the last years. Rowan-Robinson (2002) argued that the internal extinctions in the host spiral galaxies are underestimated, and he obtained inconclusive evidence for the positive cosmological constant. Mészáros (2002) used pure statistical arguments, and also showed that the introduction of the positive cosmological constant is premature yet.

The paper is organized as follows: After defining some important cosmological quantities and equations related to SNe Ia the statistical studies mentioned above are further extended in this paper. Out of 230 supernovae in TONRY dataset 188 have given extinction values. We separated it into subsamples with respect to their extinction values. Then the whole sample of 188 supernovae and its different subsamples are tested whether the statistical structure of the redshift distance relation depends on the internal extinction. These tests suggested that distances obtained for the high z part of the dataset were not independent from the internal extinction. Therefore any cosmological conclusion drawn from the supernova data should be taken with care. A more extensive sample of supernovae containing much more objects is highly required for a more reliable analysis.

We give the results of these tests. We show that former investigations, for example Choudhoury et al. (2004) failed to recognize the inadequacy of the removal of internal extinction from the data because of the improper definition of the subsamples investigated.

Using the result of statistical tests connected with the internal extinction values of SNe Ia we conclude that the corrected Hubble-diagram does not support models with $\Omega_\Lambda \simeq 0.7$, rather an open Universe with $\Omega_m \simeq 0.1$ matter.

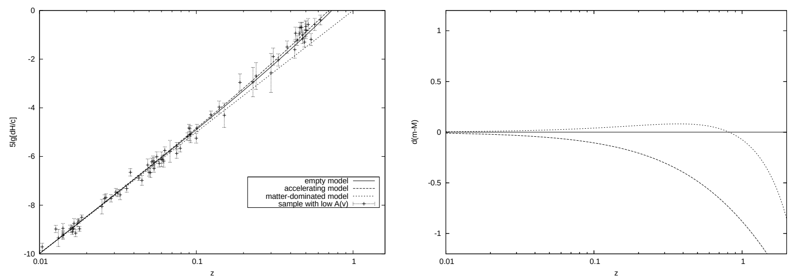

Figure 1: *Left: The distance modulus-redshift relation of SNe Ia. The data-set is form Tonry et al. 2003. There are three cosmological models marked in the figure. The "empty model" is dominated by only the cosmological constant, there is no matter density:* $\Omega_m = 0, \Omega_\Lambda = 1$. *The "accelerating model" is the today mostly accepted flat model, with cosmological constant, or dark energy:* $\Omega_m = 0.3, \Omega_\Lambda = 0.7$. *The "matter-dominated model" is a flat model without cosmological constant:* $\Omega_m = 1, \Omega_\Lambda = 0$. *Right: The deviation of the measured distance moduli from the calculated ones of the empty Universe. The uppermost curve represents the acceelrating model, the zero line belongs to the empty model, the lower curve is the Einstein-de Sitter Universe.*

2 Observational cosmology with SNe Ia

The luminosity distance (D_L) of cosmological objects depends on some cosmological parameters. These parameters determine the structure of the space-time. In the practice we measure some appropriate quantities of celestial objects from which we can calculate their luminosity distances. If we have the value of luminosity distance, we are in the position to compare these data with the predictions of theoretical models. SNe Ia are especially good objects for measurements like this because they are standard candles, i.e. their absolute luminosities (after corrections) are the same everywhere in the Universe. We can measure the redshift, and the apparent brightness of an individual supernova and one can calculate from these data the luminosity distance. The latest extensive data-set (Tonry et al. 2003) lists the logarithm of the redshift, multiplied by the speed of light c, and the logarithm of the luminosity distance multiplied by the present value of the Hubble constant, H_0. In this case there is no need for the accurate value of H_0. If we draw the distance modulus-redshift relations of different models we obtain the left side of Fig. 1.

The following equation specifies the relationship between the apparent magnitude and the redshift of an object:

$$m = M + 5 \log_{10} Q(z, \Omega) \tag{1}$$

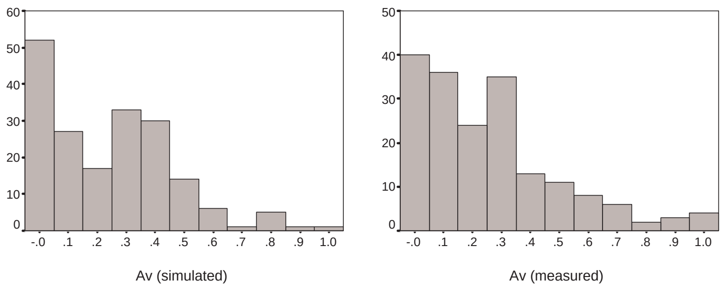

Figure 2: *Histogram of simulated SNe extinctions (left), and the real sample (right). The extinction is in magnitude on the horizontal axis. There is a well pronounced peak at $A_V = 0$ due to the objects at the front side of the host galaxy. The second smaller peak can be accounted for objects at the opposite side.*

where

$$Q(z, \Omega) = \frac{D_L H_0}{c} \tag{2}$$

As it was noticed at the beginning of this section the D_L luminosity distance strongly depends on some cosmological parameters. By definition the distance modulus is the difference between the apparent and the absolute magnitude: $\mu = m - M$ so Eq. 1 can be written in the following form using this definition:

$$\mu = 5 \log_{10} Q(z, \Omega) \tag{3}$$

In the redshift range investigated there are only small differences between the different models: we displayed in the left panel of Fig. 1 the deviation of the distance moduli obtained from different models and the distance modulus calculated from the empty Universe $\Delta\mu = \mu_i - \mu_{empty}$ (Fig. 1, right)

3 Data and statistical methods

Before putting the supernova data into a scatter plot, let us cast a glance on the sample! The extinction values scatter between 0 and 4.1 magnitudes with a median of 0.2 magnitude. Except a few outliers the data are concentrated in the 0-1 magnitude range. The distribution of the extinction values can be well understood if we compare it with a simple model. Assuming that the Ia type supernovae belong to the old disc population with a scale height of 340 pc and the interstellar dust concentrate to the plane of the host galaxy within a layer of 100 pc FWHM the observed distribution

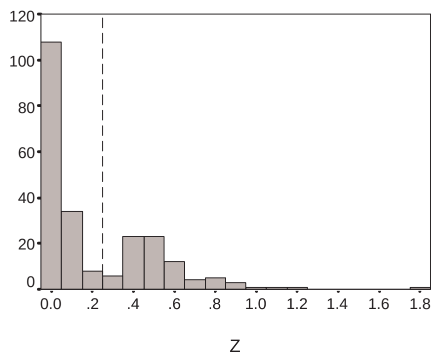

Figure 3: *Histogram of z distribution in the TONRY sample. The vertical dashed line indicates a cut between the low and high redshift part of the sample.*

of internal extinction is simply a projection effect. The peak near to zero extinction comes from supernovae in front of the host galaxy. Fig. 2 shows a comparison of the simulated distribution of the observed internal extinction along with that of TONRY data. In both samples there is a peak at $A_V = 0$ corresponding to the objects at the front side of the host galaxy. Both samples have another peak at $A_V \simeq 0.3$, which can be accounted for objects at the opposite side of the host. Despite of these similarities the peaks of the real sample are less pronounced probably due to observational errors.

The distribution of redshifts in the TONRY sample is bimodal. There is a dip at around $z = 0.25$. Having a cut at this point we defined two different subsamples. The high z subsample is interesting from at least two point of views. First, the calculated distance moduli from different cosmological models depart from each other exceeding the error of direct measurements obtained from SN Ia supernovae. Second, as we demonstrate below the estimated internal extinction in the high redshift part has some interrelation with the distance modulus which is not the case at $z < 0.25$.

The calculated distance moduli obtained from the observation of SN Ia events assumed to be independent from the internal extincion listed in the TONRY sample. It is easy to infer from the low redshift subsample that this is really the case. In the $z > 0.25$ range, however, at the low extinction part the majority of the SN Ia distance moduli exceeds those obtained from an empty Universe. Distance moduli from an empty Universe can be treated as an upper bound for those obtained from models without cosmological constant. Only in models of non zero cosmological constant can be exceeded this bound. The excess of SN Ia distances exceeding the empty case is considered as a firm evidence favoring the non zero cosmological constant.

The difference between distance moduli obtained from the observation of SN Ia

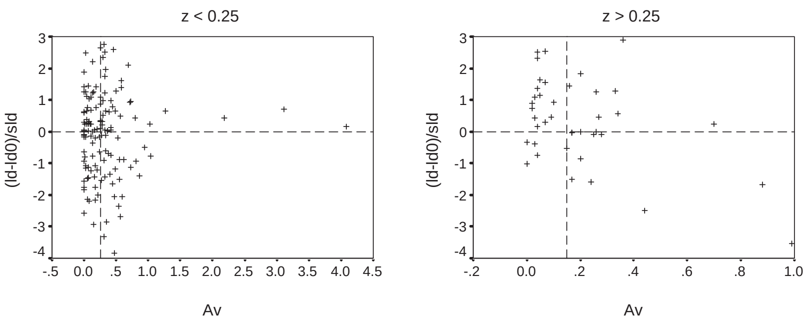

Figure 4: *The absorption-luminosity distance relation of the low (left) and high-z (right) subset (data source: TONRY). On the vertical axis the standardized deviation from distance moduli calculated in an empty Universe is given. Vertical dashed line mark the median of the extinction data. Horizontal dashed line marks the reference level of an empty Universe. Note the difference between the left and the right panel. In the* $z < 0.25$ *case the distribution of residuals is symmetric to the reference level of an empty Universe, independently from the extinction. On the contrary, the low exinction part (left from the median line) of the* $z > 0.25$ *panel clearly has an excees of the points above the reference line but it disappears at higher extinction values displaying a pronounced negative trend.*

events and calculated from an empty cosmological model assumed to be independent from the internal extinction of the host galaxy. As we demonstrated in the right panel of Figure 4 it is not the case in the $z > 0.25$ range. While the absorption values right from the median are symmetrical to the line representing the empty model, left from it, however, there is a remarkable asymmetry because there are more points above the line of the empty model than below it. If there was no interrelation between the distance moduli residuals and the internal extinction this trend would not be present. (The detailed calculation of the statistical significance of this trend will be published in a forthcoming paper). [1]

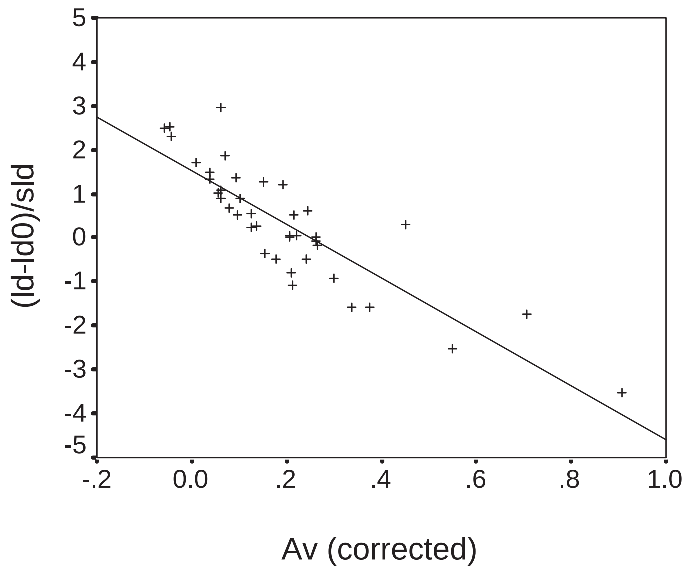

Figure 5: *Dependence of the uncorrected standardized residual on the corrected extinction represented by the f background variable. Full line displays the obtained relationship between the uncorrected residual and internal extinction.*

It is obvious, the distance moduli obtained from SN Ia observations have to be freed from the interrelation with the internal extinction before using it for testing

[1] It is interesting to note that some recent papers (for example Choudhoury et al. (2004)) divided the sample into two parts as follows: They cut off points with high absorption values and fitted some model on the remainder. As one can see on Fig. 4 this remainder subset really shows an excess of points above the zero level of the empty Universe.

cosmological models. To calculate statistically the effect of interrelation we introduced an f stochastic background variable representing the relationship between $\Delta\mu$ distance moduli residuals and the A_V internal extinction:

$$A_V = A_0 f + \varepsilon_A \quad (4)$$

$$s = s_0 f + \varepsilon_s \quad (5)$$

where $s = \Delta\mu/\sigma_\mu$ is the standardized residuals of distance moduli, $A_0, s_0, \varepsilon_A, \varepsilon_s$ are constants and noise terms, respectively. Estimation of f and other quantities in this system of equations can be performed by using factor analysis which is a standard procedure in multivariate statistics (the details will be given elsewhere). Based on this solution we can remove the effect of the background variable responsible for the interrelation between the residual and internal extinction and obtain the correct luminosity distances appropriate for testing cosmological models. Fig. 5 shows the dependence of the uncorrected standardized residual on the corrected extinction represented by the f background variable.

With the procedure outlined above we ceased statistically the interrelation between the distance moduli residuals and internal extinction displayed in Fig 4. It is worth noting that these corrections have also an effect on the data-points of low extinction values which were the firm basis of arguing for the existence of a positive cosmological constant.

4 Cosmological constant revisited

As a result of the corrections mentioned above we obtain a new luminosity distance-redshift diagram. While former results suggested the existence of a hump in the data (Fig 6, left), and the best fit was an accelerating model with $\Omega_m = 0.3, \Omega_\Lambda = 0.7$, after our correction the situation became highly different. Fig. 6, right shows that the modified SNe Ia data prefer a standard solution which seems to be open and contains only matter. It is interesting to note that due to our treatment the scatter of SN Ia distance moduli residuals decreased, as one can infer from comparing the two panels in Fig. 6.

5 Conclusion

Recently, it is commonly accepted that the expansion of the Cosmos is accelerating. However, there are some papers, which argue against the introduction of a cosmological constant with different arguments. Mészáros (2002) used pure statistical arguments to show that the use of the cosmological constant is premature yet. We also have done

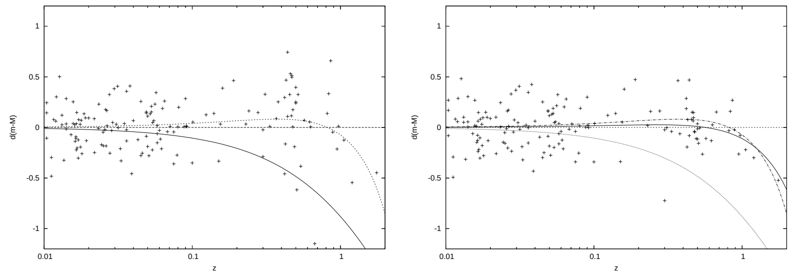

Figure 6: *Previous and new data plotted against z. As old sample favors a flat accelerating model (left) the new (right), statistically corrected one rather fits a matter dominated Universe. The labels are the same as Fig. 1, the new curve on the right panel is the fit.*

statistical study on the newest TONRY dataset. We investigated the absorption-luminosity distance relation statistically on those data which have $z > 0.25$. We found that there is an interrelation between the distance moduli residuals and the internal extinction of host galaxies in this part of the sample. We used statistical methods to calculate quantitatively this interrelation. After correcting for this effect the new residual Hubble-diagram does not fit a flat model with a positive cosmological constant instead, the best fit is an open matter-dominated model.

There is a need to explain the physical nature of the interrelation between distance muduli residuals and internal extinction of host galaxies. Does it have an astrophysical basis or it is only a byproduct of the data reduction?

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