A big dilemma: is the Hubble constant really constant?

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1 Introduction

One of the most famous open problems of modern cosmology is the Hubble constant (H_0) tension. This consists in the discrepancy ($> 4\ \sigma$) between the values of H_0 measured with the late universe local probes, namely the Supernovae Ia (SNe Ia), and the early universe observations, the Cosmic Microwave Background (CMB) radiation.

The CMB data provides a map of the residual radiation of the very first photons emitted in the early universe, only 380000 years after the Big Bang, while SNe Ia are violent explosions of stars, which in 1998 brought to the discovery that the universe is in a stage of an accelerated expansion. The most accredited model used to describe the evolution of the universe is the so-called standard cosmological model. The standard cosmology is based on the well-known ΛCDM (cold dark matter) model, which relies on the existence of a cosmological constant Λ with an equation-of-state parameter $w = 1$ and a CDM component. This model is the most widely accepted paradigm to explain the structure and evolution of the late universe. The discovery of the accelerating expansion phase has suggested the presence of a cosmological constant as the most viable scenario to account for the observations of Cepheids, SNe Ia, cosmic chronometer probes for the expansion rate of the parameter H(z), cosmic microwave background (CMB) fluctuations, baryon acoustic oscillations (BAO), weak lensing and other.

Among these probes, Cepheids and SNe Ia are considered the most reliable standard candles: astrophysical objects whose luminosity is known or can be derived from well-established connections between quantities that depend from one hand on the distance and from another hand from a quantity that it is independent from the distance. As a candle gives more light the closer it is, the brightness depends on the luminosity distance, a quantity expressed by a given cosmological model. Thus, knowing the distance will allow us to know the most suitable underlying cosmological model given the current observations.

Despite this being the reference framework, it suffers from two major open problems of theoretical and observational nature, in particular the aforementioned H_0 tension. The so-called fine-tuning problem deals with the discrepancy between the observed vacuum energy and the predicted theoretical expectation from quantum physics. Indeed, the ratio between the two values is 10^{120}. The so-called coincidence problem deals with the still mysterious nature of the constant-energy and dark-matter densities. These are of the same order of magnitude today, while in the past their difference was 10^9 in the CMB epoch. The condition for the late-time acceleration is provided by the equation-of-state parameter of dark energy, w with $w < -1/3$. On the other hand, differently from previous years, it is now possible to precisely constrain w and its evolution to more than 10%, due to improved determinations of cosmological distances. For example, a very well-known and adopted parameterization is given by $w_(z) = w_0 + w_a z/(1 + z)$, according to the Chevallier-Polarski-Linder model, where w_0 and w_a are parameters. The Hubble constant tension could be explained by internal inconsistencies in Planck data or SNe Ia systematics in the local determination of H0 or with a new physics that lies beyond the standard cosmological model.

Thus, an international group lead by Prof. Maria Dainotti (Assistant Professor at NAOJ, at Sokendai University in Japan and affiliated scientist at Space Science Institute in USA) and composed by Biagio De Simone (former master student of Prof. Dainotti and Prof. Lambiase) and Professor Gaetano Lambiase (University of Salerno, Italy), Tiziano Schiavone (PhD student at University of Pisa, Italy), Dr. Giovanni Montani (Senior researcher at ENEA and adjunct faculty at University of Rome La Sapienza, Italy) and Dr. Rinaldi (Senior researcher at University of Michigan, USA) took up on this grand challenge and investigated further this problem.

2 Results

For their analysis, Dainotti et al. used a collection of 1048 spectroscopically confirmed SNe Ia obtained from different surveys (the Pantheon sample) to investigate this problem. They ordered the SNe Ia by the distance by us and they divided this sample in several subsamples. Through a reliable data analysis process they obtained estimates of the Hubble constant in each interval. After the analysis a big surprise came out: the Hubble constant seems to evolve with the distance, thus explaining the observed discrepancy between the independent measurements of CMB and SNe Ia. They assumed two different models ΛCDM and $w_0 w_a$CDM model with the same starting cosmological parameter $H_0 = 73.5\,\mathrm{km\ s^{-1}\ Mpc^{-1}}$. Regarding the ΛCDM model we fix the value of $\Omega_M = 0.298$ and for the case of $w_0 w_a$CDM model we fixed a fiducial value of $\Omega_M = 0.308$ and we used as the equation of state parameter, $w(z) = w_0 + w_a * z/(1+z)$ according to the Chevallier-Polarski-Linder model in which $w_0 = -1.009$ and $w_a = -0.129$. To check if an evolutionary trend is present in the data, they divided the Pantheon sample in 3, 4, 20 and 40 bins (in increasing redshift order), see Fig. 1.

For each bin they performed a Monte Carlo Markov Chain computations to extract the H_0 values, which are then fitted with a function that mimics the dependence on the redshift. Such a redshift evolution is modelled via a parameter, α, of the order of 10^{-2}. Despite α being compatible with zero within 3 σ, this trend may affect cosmological results.

Indeed, by extrapolating the values of H_0 to the redshift of the most distant galaxy ever observed at $z = 11$ and the last scattering surface ($z = 1100$), interestingly they found that H_0 is compatible in 1 σ with the Planck measurements (CMB). The reduction of the H_0 tension ranges from 54% to 72% in both models.

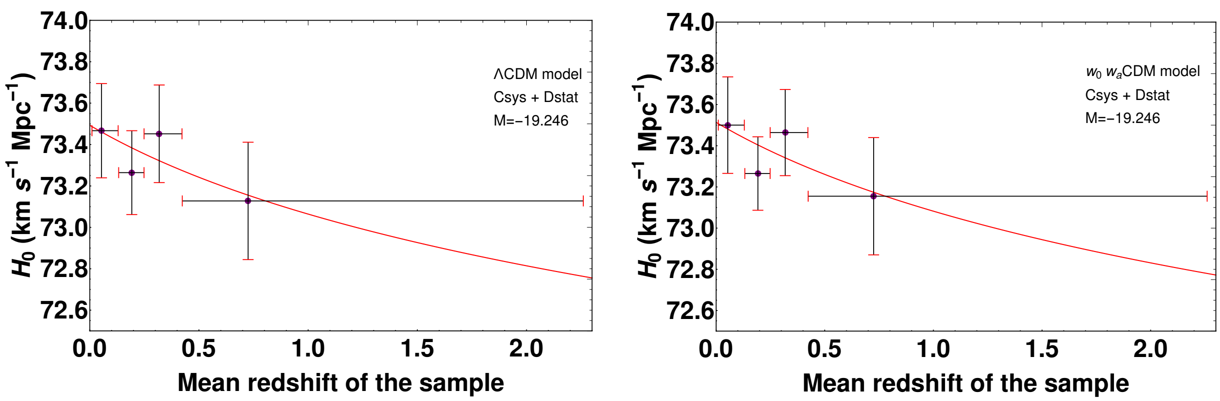

Figure 1: The evolving trend of H_0 in 4 bins with the ΛCDM model (left panel), and the $w_0 w_a$CDM model (right panel).

This discrepancy, if it is confirmed by future observations of the Subaru Telescope, can be due to different factors such as the presence of metallicity in SNe Ia or the residual evolution of the stretch parameter for SNe could induce the evolutionary trend of H_0 with the redshift. If this effect is not due to systematics of SNe Ia, then the decreasing trend of the Hubble constant may reveal an hidden evolutionary effect, the most favored proposal seems the modified theory of gravity. Indeed, our results seems not to reconcile with theories of local under-densities or over-densities. The trend discovered, thus has ushered a new era and new avenues of investigation.