Directional dependence of the local estimation of $H_0$ and the nonperturbative effects of primordial curvature perturbations

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Abstract – Recent measurements of the cosmic microwave background (CMB) radiation have shown an apparent tension with the present value of the Hubble parameter inferred from local observations of supernovae, which look closer, i.e. brighter, than what is expected in a homogeneous model with a value of $H_0$ equal to the one estimated from CMB observations. We examine the possibility that such a discrepancy is the consequence of the presence of a local inhomogeneity seeded by primordial curvature perturbations, finding that a negative peak of the order of less than two standard deviations could allow to fit low-redshift supernovae observations without the need of using a value of the Hubble parameter different from $H_0^{\text{CMB}}$. The type of inhomogeneity we consider does not modify the distance to the last scattering, making it compatible with the constraints of the PLANCK mission data. The effect on the luminosity distance is in fact localized around the region in space where the transition between different values of the curvature perturbations occurs, producing a local decrease, while the distance outside the inhomogeneity is not affected. Our calculation is fully relativistic and nonperturbative, and for this reason shows important effects which were missed in the previous investigations using relativistic perturbations or Newtonian approximations, because the structures seeded by primordial curvature perturbations can be today highly nonlinear, and relativist Doppler terms cannot be neglected. Because of these effects the correction to the luminosity distance necessary to explain observations is associated to a compensated structure which involves both an underdense central region and an overdense outer shell, ensuring that the distance to the last scattering surface is unaffected. Comparison with studies of local structure based on galaxy surveys analysis reveals that the density profile we find could in fact be compatible with the one obtained for the same region of sky where most of the supernovae used for the local $H_0$ estimation are located, suggesting a possible directional dependence which could be partially attributed to the presence of the Sloan Great Wall and hinting to the need of a more careful investigation, including a wider set of low-redshift supernovae in different regions of the sky.

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Introduction. – Recent observations [1] of the cosmic microwave background (CMB) have pointed to an apparent discrepancy between the value of the Hubble parameter $H_0$ deduced from cosmological data and the value inferred from local astrophysical observations [1–3].

Following [4] we denote with $H_0^{\text{app}}$ the value of the Hubble constant estimated from observational data ignoring the presence of an inhomogeneity and with $H_0^{\text{true}}$ the value obtained taking into account the inhomogeneity. According to this notation, since both the above-mentioned estimations were based on the assumption of homogeneity, the apparent tension can be expressed as $H_0^{\text{app},\text{SN}} \approx 1.09 H_0^{\text{app},\text{CMB}}$, where $H_0^{\text{app},\text{SN}}$ and $H_0^{\text{app},\text{CMB}}$ are the values estimated from fitting respectively low-redshift supernovae and CMB observations. One possible explanation of such a difference could be the effects of local structure on the analysis of cosmological and astrophysical observations, and we will show what kind
of inhomogeneity could resolve the tension, i.e. could give
\[ H_{0, SN}^{\text{true}} = H_{0, \text{CMB}}^{\text{true}}. \]

The effects of a local inhomogeneity on the estimation of cosmological parameters have been studied already in different contexts such as the estimation of the equation of state of dark energy [4], where it has been shown that ignoring the presence of local inhomogeneities in data analysis can lead to the wrong conclusion of an apparent evolving dark energy, while only a cosmological constant is in fact present, or to corrections [5] to the apparent value of the cosmological constant. More recently [6] it was shown that a present-day local inhomogeneity seeded by a peak of primordial curvature perturbations could in fact not only affect the estimation of the value of the cosmological constant, but also of \( H_0 \). In particular it was shown that the effects of such an inhomogeneity on \( H_0 \) depend on the spatial gradient of the inhomogeneity, and could be important independently of the amplitudes of the curvature perturbations. This implies that this kind of inhomogeneities arise naturally from fluctuations of the primordial curvature perturbations, and require a careful investigation. In this letter we will focus on the early-time origin of an inhomogeneity able to solve the apparent tension in the \( H_0 \) estimation, showing how the inflationary scenario can easily explain the formation of such a local structure today.

Some of the previous studies of the effects of inhomogeneities on the expansion rate, such as, for example, [7–9], were based on an implicit assumption of the validity of the Hubble law and on the use of a Newtonian approximation to relate the local velocity field to \( H \). Other approaches are based on the Hubble bubble model [10], which is the basis of the top hat spherical collapse, or on the averaging of the perturbations [11]. All these different attempts to estimate the effects of inhomogeneities are based on a Newtonian or relativistic linear perturbations approximation, and as such are not able to obtain the nonperturbative relativistic effects that the use of an exact solution of Einstein’s equations allows to calculate. In fact, as shown in [12], perturbation theory is not able to fully account for the relativistic effects of an inhomogeneity for the luminosity distance, because gradient terms can have important contributions which are normally ignored in the Newtonian or relativistic perturbative calculations.

The discrepancy between apparent and true values of cosmological parameters is a consequence of the intrinsic limitation of cosmological or astrophysical observations involving redshift measurements, implying an intrinsic uncertainty [13] on the estimation of cosmological parameters. Under the assumption of homogeneity the redshift is explained exclusively as a consequence of the expansion of the Universe, while taking into account spatial inhomogeneity additional contributions to the redshift can come from the spatial variation the gravitational potential. While the effects of these variations are normally considered to be small compared to the contribution associated to the Universe expansion, it is possible that the local structure can actually induce some important corrections with respect to the apparent values, i.e. the ones obtained from observation ignoring the space variation of the metric.

From the relation between the Hubble parameter and the luminosity distance in a spatially flat FLRW Universe,

\[ D_L(z) = (1 + z) \int_0^z \frac{dx}{H(x)}, \]
\[ H^{\Lambda \text{CDM}}(z) = H_0^{\app} \sqrt{\Omega_M (1 + z)^3 + \Omega_{\Lambda}}, \]

we can see that the larger estimated value of \( H_{0, \text{SN}}^{\app} \) compared to \( H_{0, \text{CMB}}^{\app} \) corresponds to the observation of supernovae closer than what is expected in a \( \Lambda \text{CDM} \) model with the Hubble parameter equal to \( H_{0, \text{CMB}}^{\app} \). In the framework of homogenous cosmological models the observed brightness of low-redshift supernovae is interpreted as the result of a faster expansion of the Universe, while if the effects of a local inhomogeneity are properly taken into account there is no need to invoke a value of \( H_0 \) different from \( H_{0, \text{CMB}}^{\app} \). In the particular case of the set of observations we are interested in this letter, we have that an appropriate local inhomogeneity does not affect the distance to the last scattering, and consequently the estimation of \( H_0 \) from CMB data, so that the assumption of homogeneity in analyzing CMB data does not give a different result with respect to the corresponding data analysis taking into account the inhomogeneity, i.e. \( H_{0, \text{CMB}}^{\app} \approx H_{0, \text{CMB}}^{\true} \).

The presence of a local inhomogeneity could instead affect the local estimation of \( H_0 \), so that \( H_{0, \text{SN}}^{\app} > H_{0, \text{SN}}^{\true} \), where \( H_{0, \text{SN}}^{\true} \) is the value of \( H_0 \) which, according to the above definitions, is obtained from the data taking into account the effects of the inhomogeneity. In the presence of an inhomogeneity in fact the determination of \( H_0 \) from \( D_L^{\obs}(z_{\text{SN}}) \), where \( z_{\text{SN}} \approx 0.04 \) is the mean redshift of the supernovae observations used for the local estimation of \( H_0 \) [2], should not be based on the standard \( \Lambda \text{CDM} \) redshift distance relation, but another one which takes into account the local inhomogeneity, and in this way the discrepancy can be solved, i.e. \( H_{0, \text{CMB}}^{\app} \approx H_{0, \text{CMB}}^{\true} = H_{0, \text{SN}}^{\true} \).

**Low-redshift supernovae and the \( H_0 \) estimation.** – We will adopt the following notation for the luminosity distance: \( D_L^{\mathrm{mod}}(z, H_0) \), where we are denoting with a superscript the cosmological model or the observed data, and \( H_0 \) is explicitly treated as an argument to avoid confusion. According to the above notation low-redshift supernovae observations are fitted by a homogeneous cosmological model according to

\[ D_L^{\mathrm{mod}}(z_{\text{SN}}, H_{0, \text{SN}}^{\true}) = D_L^{\obs}(z_{\text{SN}}), \]

with \( H_{0, \text{SN}}^{\true} \approx 1.09 H_{0, \text{CMB}}^{\app} \). We will show that if the effects of primordial curvature perturbations are taken into account, a local inhomogeneity could resolve the apparent discrepancy, i.e.

\[ D_L^{\mathrm{inh}}(z_{\text{SN}}, H_{0, \text{CMB}}^{\true}) = D_L^{\obs}(z_{\text{SN}}). \]
Such an inhomogeneity can arise naturally from primordial curvature perturbations as predicted by inflation and constrained by CMB observations to have a standard deviation of about $5 \times 10^{-5}$, providing a simple mechanism for its origin.

**Modeling the local Universe.** – We will model the local structure with a LTB solution of Einstein’s equation with a cosmological constant term, assuming to be located around its center. This is a pressureless spherically symmetric solution which allows to take into account the nonperturbative effects due to the inhomogeneity. The central location assumption can be interpreted [14] as calculating perturbative effects due to the inhomogeneity. The central structure, it can be used to find what primordial curvature perturbation could have originated it. Normally the first approach is adopted [4,6], but in this letter we will adopt the second one, since it is more convenient to define the model of the inhomogeneity in terms of $k(r)$. In this way we can find a natural explanation for the origin of the present-day highly nonlinear structure whose effect cannot be captured by the perturbations theory, while the use of the LTB solution gives the nonperturbative evolution of the structure.

**Effects on the luminosity distance.** – To compute $D_L^{LTB}(z)$ we need to solve the radial null geodesics

$$\frac{\text{d}r}{\text{d}z} = \frac{\sqrt{1+2E(r(z))}}{(1+z)R'[T(r(z)),r(z)]}, \tag{10}$$

$$\frac{\text{d}t}{\text{d}z} = -\frac{2}{(1+z)R'[T(r(z)),r(z)]}, \tag{11}$$

and then we substitute in the formula for the luminosity distance in a LTB space,

$$D_L^{inh}(z, H_0^{true}) = D_L^{LTB}(z) = (1+z)^2 R(t(z), r(z)), \tag{12}$$

where we set the parameters of the LTB solution so that

$$H_0^{LTB} = \frac{2}{3} \frac{R(t_0,0)}{R(t_0,0)} + \frac{1}{3} \frac{R(t_0,0)}{R(t_0,0)} = H_0^{true}. \tag{13}$$

For homogeneous cosmological models we assume a flat $\Lambda$CDM solution according to

$$H(z) = H_0^{app} \sqrt{\Omega_M (1+z)^3 + \Omega_\Lambda}, \tag{14}$$

$$D_L^{hom}(z, H_0^{app}) = (1+z)^2 \int_0^z \frac{\text{d}x}{H(x)}. \tag{15}$$

The above definitions are very important since they give an explicit mathematical definition of $H_0^{app}$ and $H_0^{true}$, which is coherent with the notion of apparent observable adopted in this paper and which can be expressed as

$$D_L^{hom}(z, H_0^{app}) = D_L^{inh}(z, H_0^{true}) = D_L^{bs}(z). \tag{16}$$

We consider solutions with the function $k(r)$ given by a Gaussian

$$k(r) = Ae^{-(\frac{r-r_0}{\sigma})^2}, \tag{16}$$

where $R$ is a function of the time coordinate $t$ and the radial coordinate $r$, $E(r)$ is an arbitrary function of $r$, and $R_r = \partial_t R(t, r)$. The Einstein’s equations with a cosmological constant give

$$\left(\frac{\dot{R}}{R}\right)^2 = \frac{2E(r)}{R^2} + \frac{2M(r)}{R^3} + \frac{\Lambda}{3}, \tag{6}$$

$$\rho(t,r) = \frac{2M_r}{R^2 R_r}, \tag{7}$$

where $M(r)$ is an arbitrary function of $r$, $\dot{R} = \partial_t R(t,r)$ and $c = 8\pi G = 1$ is assumed in the rest of the paper. We will also adopt, without loss of generality, the coordinate system in which $M(r) \propto r^3$, fix the geometry of the solution by using a function $k(r)$ according to $2E(r) = -k(r)r^2$, and consider models with a vanishing bang function, i.e. $t_0(r) = 0$.

The effects of primordial curvature perturbations. – The metric after inflation near a peak of the primordial curvature perturbation [4,6] can be written as

$$\text{d}s^2 = -\text{d}t^2 + a_P^2(t)\text{d}x^2(r^2 + r^2 \text{d} \Omega^2), \tag{8}$$

where $\zeta(r)$ is the primordial curvature perturbation. The spherical symmetry approximation is justified by the property of a Gaussian random field [18] according to which large peaks of a stochastic function tend to have a spherical shape. At a sufficiently early time when both the LTB and the metric in eq. (8) are valid, they can be matched [4] leading to the following relation:

$$k(r) = -\frac{1}{r^2} [(1 + r \zeta)^2 - 1]. \tag{9}$$

The use of the LTB solution allows to study exactly the formation of the structure seeded by $\zeta(r)$, and in particular to go beyond the limitations of the perturbation theory. It turns out in fact that such early-time tiny curvature perturbations of the order of $10^{-5}$ can lead to a highly nonlinear structure today whose effects cannot be neglected.

Equation (9) is very important because it gives the connection between the early and the present Universe, and it can be used in two ways: given an early-Universe curvature perturbations it allows to find the present-day structure seeded by it, or vice versa, given a present-day structure, it can be used to find what primordial curvature perturbation could have originated it. Normally the first approach is adopted [4,6], but in this letter we will adopt the second one, since it is more convenient to define the model of the inhomogeneity in terms of $k(r)$. In this way we can find a natural explanation for the origin of the present-day highly nonlinear structure whose effect cannot be captured by the perturbations theory, while the use of the LTB solution gives the nonperturbative evolution of the structure.
The luminosity distance is approximately the same outside the region affected by it as shown in fig. 2. This shows how, contrary to the linear theory approximation, when nonperturbative effects are taken into account, not only low-density regions but also overdense regions can be associated to the decrease of the luminosity distance necessary to explain observations. Bottom: we plot in units of $(H_{0, CMB}^*)^{-1}$, the luminosity distance for a ΛCDM model and an inhomogeneous model. In both the top and bottom plot the value of the Hubble parameter is the same for the homogeneous and inhomogeneous models, $H_0 = H_{0, CMB}$. The dashed line is the plot of $D_{hom}(H_{0, CMB}^{true}, z)$ while the solid line is for $D_{inh}(H_{0, CMB}^{true}, z)$. The luminosity distance is approximately the same outside the inhomogeneity, for $z > z_{SN}$, implying that the distance to the last scattering is not affected by the inhomogeneity, and, consequently, $H_{0, CMB}^{true} \approx H_{0, CMB}^{app}$. This shows that the analysis of the CMB data performed under the assumption of homogeneity is not introducing any misestimation for $H_0$, contrary to its local estimation, which is based on luminosity distance observations affected by it as shown in fig. 2.

We will adopt a system of units in which $H_{0, CMB}^{true} = 1$, and use the fiducial value $\Omega_A = 0.692$. The time used as initial condition at the center for the geodesics equations is obtained by integrating the Einstein equation in the scale factor from the Big Bang till today.

As shown in fig. 1, since the type of inhomogeneity we have considered is compensated, it has no effect on the luminosity distance outside it, i.e.

$$D_{hom}(H_{0, CMB}^{true}, z_{LS}) \approx D_{inh}(H_{0, CMB}^{true}, z_{LS}),$$

where $z_{LS}$ is the redshift of the last scattering surface, or any redshift sufficiently larger than $z_{SN}$. This is due to the fact that the central and the asymptotic value of the curvature function are approximately the same. According to our definitions of apparent observable, fitting CMB data with a homogeneous or inhomogeneous model is consequently giving the same estimate for $H_{0, CMB}^{true} \approx H_{0, CMB}^{app}$.

For the case of low-redshift supernovae instead it can be seen in fig. 2 that

$$D_{inh}(H_{0, CMB}^{true}, z_{SN}) \approx D_{hom}(H_{0, CMB}^{app}, z_{SN}) = D_{obs}^{true},$$

which implies that

$$H_{0, SN}^{app} > H_{0, SN}^{true} = H_{0, CMB}^{true}.$$  

This shows how the effects of the inhomogeneity are able to resolve the apparent disagreement between cosmological and local estimations of $H_0$, since the luminosity distance is modified only around $z_{SN}$.

As seen in figs. 1, 2 the effect of the structure seeded by this primordial curvature perturbation profile corresponds to an underdense central region followed by an overdense shell, which is what we expect for a compensated inhomogeneity, due to the fact that the function $k(r)$ is asymptotically zero. The luminosity distance is decreased with increasing redshift.

Fig. 1: (Colour on-line) Top: the percentage density contrast $\delta \rho = 100(1 - \frac{\rho^{true}}{\rho^{true}})$ is plotted as a function of the redshift, showing how, contrary to the linear theory approximation, when nonperturbative effects are taken into account, not only underdense regions but also overdense regions can be associated to the decrease of the luminosity distance necessary to explain observations. Bottom: we plot in units of $(H_{0, CMB}^*)^{-1}$, the luminosity distance for a ΛCDM model and an inhomogeneous model. In both the top and bottom plot the value of the Hubble parameter is the same for the homogeneous and inhomogeneous models, $H_0 = H_{0, CMB}$. The dashed line is the plot of $D_{hom}(H_{0, CMB}^{true}, z)$ while the solid line is for $D_{inh}(H_{0, CMB}^{true}, z)$. The luminosity distance is approximately the same outside the inhomogeneity, for $z > z_{SN}$, implying that the distance to the last scattering is not affected by the inhomogeneity, and, consequently, $H_{0, CMB}^{true} \approx H_{0, CMB}^{app}$. This shows that the analysis of the CMB data performed under the assumption of homogeneity is not introducing any misestimation for $H_0$, contrary to its local estimation, which is based on luminosity distance observations affected by it as shown in fig. 2.
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respect to the homogeneous case both in the under- and overdense regions, a relativistic effect associated to large gradient terms which are normally neglected in Newtonian or perturbative calculations as shown, for example, in [12]. This inhomogeneity is seeded by a curvature perturbation of less than two standard deviations as shown in fig. 3, and the effect on the luminosity distance corresponds to the region of transition between different values of the curvature perturbation.

The density profile shown in fig. 1 is compatible with the results of the analysis of galaxy surveys [19]. Quite remarkably the supernovae used for the local estimation of $H_0$ in [2] are inside the region with the largest overdensity (Subregion 2 in [19]) with a density profile compatible with our model in the region of available data, suggesting a possible directional dependence\(^1\) of the local structure effects on the $H_0$ estimation which could be partially attributed to the presence in the region of the Sloan Great Wall [20].

A careful investigation of such a directional dependence goes beyond the scope of this paper, so we will not pursue it here, but we expect our calculations to provide a good estimation of the effects due to the density profile along that particular direction. It would be interesting though to check carefully if using supernovae in different directions away from the Sloan Great Wall the $H_0$ estimation could change significantly from the one obtained by [2].

Conclusions. – We have shown how the apparent value of $H_{0,SN}^{app}$ obtained from analyzing the supernovae low-redshift luminosity distance data under the assumption of homogeneity can receive an important correction when the local structure is taken into proper account. The apparent disagreement is due to the different way in which the $H_0$ estimation is affected by the presence of the local inhomogeneity we have considered. In the case of CMB, the inhomogeneity does not affect the distance to the last scattering surface, implying that analyzing CMB data under the assumption of homogeneity does not introduce any misestimations. For low-redshift luminosity distance instead there can be an important impact which could resolve the discrepancy, or at least could be able to account for part of the difference. The type of inhomogeneity able to explain the difference can be seeded by a primordial curvature perturbation of the order of less than two standard deviations, and, as such, can arise quite naturally according to the inflationary scenario. This shows the importance of nonperturbative effects for any local observation in order to avoid this kind of apparent tension with other measurements less affected by local structure.

Quite remarkably the comparison with galaxies redshift surveys suggests that the supernovae used for local estimation of $H_0$ are in a region of sky associated to a particularly high overdensity and with an inhomogeneity profile compatible with the one we have studied, which could be partially attributed to the presence in that region of the Sloan Great Wall. It would be interesting in the future to go beyond the monopole contribution and extend the study to the possible directional dependence of the local $H_0$ estimation. In this way it would be possible to determine indirectly the higher multipoles of the local structure which causes the apparent angular dependence of $H_{0,SN}^{app}$. The same type of analysis could be extended to other cosmological parameters, such as, for example, the effective equation of state of dark energy, which have already been shown to be affected by local inhomogeneities, but are normally analyzed under the assumption of isotropy.

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\(^1\)Supernovae are in the same right ascension range of Subregion 2, but span a wider declination range, so here we are assuming that a similar density profile would be obtained if the galaxy survey analysis was extended to the same declination range of the supernovae, or alternatively if $H_0$ was estimated only using the supernovae within the same declination range of Subregion 2.
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