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The cosmic microwave background in an inhomogeneous universe

M. Regis

Dipartimento di Fisica Teorica, Università di Torino, Istituto Nazionale di Fisica Nucleare,
Sezione di Torino via P. Giuria 1, I–10125 Torino, Italy, e-mail: `regis@to.infn.it`

Abstract. The dimming of Type Ia supernovae could be the result of Hubble-scale inhomogeneity in the matter and spatial curvature, rather than signaling the presence of a dark energy component. We show that such models can account for the lithium problem of standard Big bang nucleosynthesis and fit the detailed spectrum of the cosmic microwave background (CMB). A full treatment of the radiation in inhomogeneous models is necessary if we are to understand the full constraints from the CMB, as well as other observations which rely on it, such as spectral distortions of the black body spectrum, the kinematic Sunyaev-Zeldovich effect or the Baryon Acoustic Oscillations. Although still in the context of toy cases, the agreement of inhomogeneous models with observed background dynamics of the universe suggests they deserve further investigation.

Key words. Cosmology: Dark energy, Cosmic microwave background, Big bang nucleosynthesis

1. Introduction

What is dark energy really about? The answer to this question might sound rather obvious to most cosmologists. However, to non-experts (and general public) is very often taught that Supernovae Type Ia (SN) data implies an accelerating universe. This statement is not, strictly speaking, completely correct. Indeed, the problem is rather that distances in a homogeneous universe filled by matter and radiation only are too short. If one, by hand, would increase distances to SN and to the last scattering surface (LSS) of the cosmic microwave background (CMB), all cosmological observables could be fitted without introducing an accelerating phase of the universe (and a fluid that causes it).

So, how to stretch cosmological distances? To compute distances we need equations of motion for photons (which are what we measure). They are given by Einstein field equations:

$$G_{\mu\nu} = R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = -8\,\pi\, G\, T_{\mu\nu}\ . \tag{1}$$

The key ingredients are the energy-momentum tensor $T_{\mu\nu}$ and the metric $g_{\mu\nu}$. If we consider $g_{\mu\nu}$ for a homogeneous and isotropic universe (the FLRW metric) and $T_{\mu\nu}$ given by matter and radiation only, the resulting distances are incompatible with SN and CMB data as mentioned above. Possible solutions include:

Send offprint requests to: Marco Regis

- $\tilde{T}_{\mu\nu}$: a new (exotic) fluid component in the right-hand-side of Eq. 1 (e.g., cosmological constant, quintessence, k-essence, etc..)
- $\tilde{G}_{\mu\nu}$: a theory of modified gravity (i.e., some change in the left-hand-side of Eq. 1). Note that this solution is analogous to the above one for what concerns the acceleration of the universe (but not for evolution of perturbations) since one can always recast Eq. 1 in its original form redefining $T_{\mu\nu}$.
- Small scale inhomogeneities: effects beyond the linear level described by Eq. 1, given by the so called 'back-reaction' of structures. Although an interesting solution of the coincidence problem as well, the size of such effect is currently strongly debated.
- Large scale inhomogeneities: an inhomogeneous universe with metric $\tilde{g}_{\mu\nu}$. This is the case I'm going to discuss in more details in the next Sections.

2. Voids and supernovae data

An inhomogeneous, spherically symmetric Universe can be described by the Lemaitre metric (Lemaitre 1933):

$$ds^2 = -e^{2\phi(t,r)}dt^2 + \frac{a_{\|}^2(t,r)}{1-k(t,r)r^2}dr^2 + a_{\perp}^2(t,r)\,r^2 d\Omega^2 \qquad (2)$$

where $a_{\|}$ and $a_{\perp}$ are the parallel and perpendicular scale factor, respectively. $\phi(t,r) \neq 0$ if two non-comoving fluid are present (e.g., matter and radiation) since, in this case, there is no 'absolutely' comoving frame.

So let us assume we live at the center of a spherically symmetric Universe with a few-Gpc underdensity (a large 'void') around us. As it has been shown in many works (see, e.g., February et al. 2009) this scenario can easily fit SN data and it is indistinguishable from a ΛCDM scenario whichever information criterion is considered. To simply understand the reason, consider Fig. 1. Spatial homogeneity cannot be directly observed since effectively our observations only access the past lightcone of here-and-now (see, e.g., review in Clarkson & Maartens 2010). In other words, an increase of the expansion rate along our past-lightcone can be due to either an increase in the temporal direction (acceleration) or an increase in the radial direction (inhomogeneity). In fact, in void models, the expansion rate in the underdense region (close to us) is larger than in the overdense region (far from us) and so it mimics an expansion rate in a homogeneous accelerating universe that evolves with time down the past lightcone. (i.e., direct observation cannot distinguish between a homogeneous distribution of matter that evolves with time down the past lightcone, and inhomogeneity with a different time evolution).

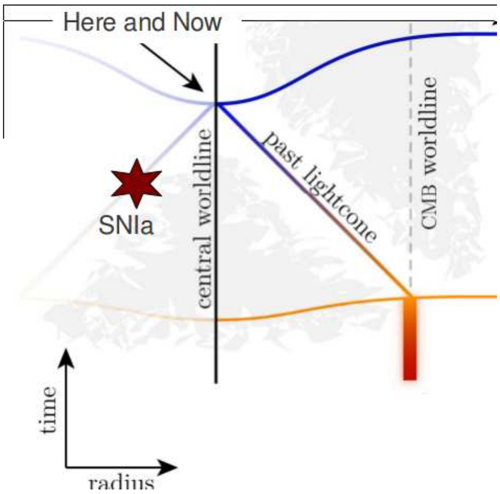

Fig. 1. A schematic space-time picture showing that spatial and temporal effects are hardly separable since our observations only access the past lightcone of here-and-now. Therefore, spatial homogeneity cannot be directly observed.

3. Big Bang nucleosynthesis

A further important dilemma in the standard model is the lithium problem, which is the substantial mismatch between the theoretical prediction for ^{7}Li from Big Bang Nucleosynthesis and the value that we observe today. The baryon-to-photon ratio η derived from ^{7}Li (at $z = 0$) disagrees with η derived from CMB and D (at $z \sim 3$) by up to 5-σ (Cyburt, Fields & Olive 2008). There are potential astrophysical

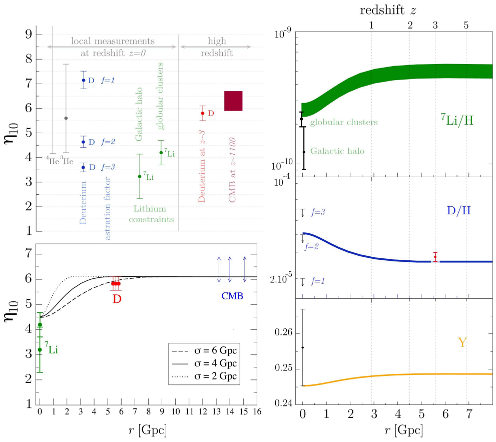

Fig. 2. Constraints on η. Top left we estimate current constraints on $\eta_{10} = 10^{10}\eta$ from different observations. Bottom left we show how a varying radial profile for η_{10} (from $\sim$ 4.5 at the center to $\sim$ 6 asymptotically) can fit all the observational constraints, for differing inhomogeneity scales. (The D and CMB constraints are in redshift, so move when given in terms of comoving distance r, since $r(z)$ is dependent on inhomogeneity profile.) On the right we show the nuclei abundances as a function of z in a typical void model. Filling in points on this graph will test this theory. References to all shown datapoints can be found in Regis & Clarkson (2010).

solutions (e.g., Korn et al. 2006) but it is still an open problem.

This observation is one of the very few we have from along our past worldline as opposed to our past lightcone (so possibly probing inhomogeneity). By introducing a spatially varying η, as naturally predicted in void models, the disagreement can be solved as shown in Fig. 2 (Regis & Clarkson 2010). Therefore, by releasing the untested assumption that the universe is homogeneous on very large scales, both apparent acceleration and the lithium problem can be easily accounted for as different aspects of cosmic inhomogeneity.

4. Cosmic microwave background

We focus on the small-scale CMB since the largest scales depends on the integrated Sachs-Wolfe effect, namely, on the detailed evolution of perturbations during the curvature era which are not yet understood in the context of inhomogeneous models. The comoving scale of the voids which closely mimic the ΛCDM distance modulus are typically O(Gpc). The physical size of the sound horizon, which sets the largest scale seen in the pre-decoupling part of the power spectrum, is around 150 Mpc in comoving units. This implies that in any causally connected patch of the Universe prior to decoupling, the density gradient is very small, and we can model the universe in disconnected FLRW shells at different radii, with the one of interest located at the distance where we see the CMB. This can be calculated using standard FLRW codes, but with the line-of-sight parts corrected for.

It is know that three parameters are sufficient to characterize the key features of the first three peaks of the CMB (e.g., Hu & Dodelson 2002). On can choose, for example, to fit the baryon fraction $f_b = \Omega_b/\Omega_m$, the baryon-to-photon ratio η, and the area distance d_A. Moreover, a viable void model has also to reproduce the correct CMB temperature today (i.e., $T_0 = 2.725$ K), or in other words the redshift from decoupling. Three papers came out around July 20th, 2010, with three different conclusions: voids can fit CMB although they need low H_0 value (i.e., $H_0 < 60$ km/s/Mpc) in Biswas, Notari & Valkenburg (2010), voids are ruled out by CMB because they need low H_0 value in Moss, Zibin & Scott (2011), and voids can easily fit the CMB even for large H_0 in Clarkson & Regis (2011). The first two analyses obtained similar results and the conclusions differ because of different interpretations of H_0 data. However, both disregarded radiation (or better, inadvertently fine tuneed its spatial profile), while its contribution is found to be crucial in Clarkson & Regis (2011).

f_b and η are local to the LSS and can be freely chose (since the CMB worldline is in outer part of the void, far away from us). d_A and the redshift depend instead on the void profiles. Using the degree of freedom of the matter profile only, as in Biswas, Notari & Valkenburg (2010), and Moss, Zibin & Scott (2011), one needs to adjust H_0 to get compatible values. However, considering also the degree of freedom of the radiation profile, both can be easily fitted, as shown in the example of Fig. 3 (Clarkson & Regis 2011).

Therefore, at present, the question is not whether or not void models can fit the small-scale CMB, but rather which matter and radiation profiles provide a good fit (i.e., do they need to be fine-tuned?). In the approximate treatment in Clarkson & Regis (2011), a simple $O(1)$ inhomogeneity in both radiation and matter is found to work. However, the final answer requires a fully numerical integration of the Einstein equations for the two fluid system in a spherically symmetric universe (Clarkson, Lim & Regis 2011).

Strong constraints to void models come from CMB dipoles. Direct measurement of the CMB dipole at our location implies we have to live within ~ 80 Mpc of the centre of spherical symmetry (Alnes & Amarzguioui 2006, Foreman et al. 2010) which is a strong violation of the Copernican principle (at the level of $\sim 10^{-7} = (80\ \text{Mpc}/10\ \text{Gpc})^3$).

Dipoles along our past lightcone would induce kSZ-like signatures which rule out adiabatic void models (GarciaBellido & Haugboelle 2008, Zhang & Stebbins 2010, Moss & Zibin, 2011). On the other hand, for isocurvature voids (i.e., with radiation tilted with respect to matter) such constraints can be satisfied. Indeed, the dipole $\Delta T/T \propto v^2$, where v is the velocity between the matter and the radiation frames, which is, in principle, an arbitrary function. Again the question is rather about the fine-tuning of initial conditions that can provide viable scenarios and the answer requires a fully consistent treatment of matter and radiation (Clarkson, Lim & Regis 2011).

5. Conclusions

I showed that large scale inhomogeneities are a viable alternative to an accelerating universe and (isocurvature) void models can fit all 'background' observables. However, they are still in a context of toy models since we need an explanation for the formation mechanism (standard inflation cannot work on such large scale), a computation of evolution of perturbations (some attempts in, e.g., Clarkson, Clifton & February 2009), and to address the Copernican principle (maybe, an inhomogeneous but statistically homogeneous universe?).

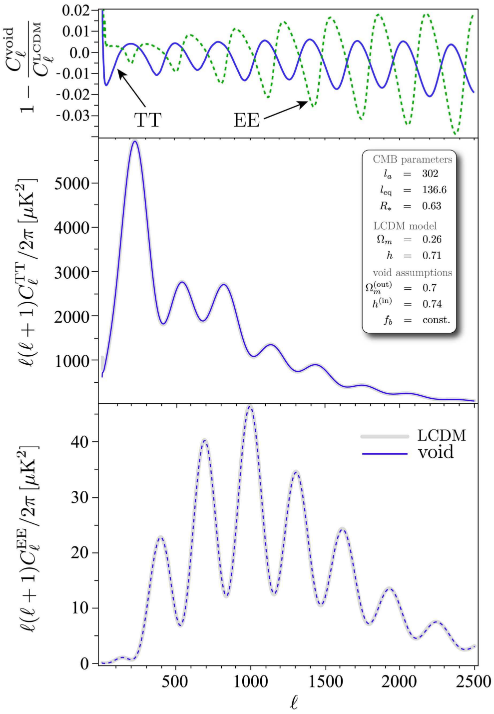

Fig. 3. The TT (middle) and EE (bottom) angular power spectra for a flat ΛCDM model and a void model which give the same f_b, η, and d_A parameters. The difference between the two is just a few percent (top). Although the void is derived with the assumptions indicated, we find similar plots for different types of void which fit the CMB parameters indicated.

Concluding, there is still a long-way before inhomogeneous cosmological models can be considered as viable and realistic alternative to ΛCDM, but the picture is promising.

6. Discussion

GENNADY BISNOVATYI-KOGAN: The CMB temperature in the void (and entropy) is in general different from the surrounding region. The photons coming to the observer are from different temperature Planck spectra, so the resulting spectrum will be not Planckian. Did you check if these discrepancies are consistent with the present measurements of the spectrum?

MARCO REGIS: In a spherically symmetric universe and assuming we live at the center (as in voids), the temperature of photons coming directly from our LSS does not vary with direction, because of the symmetry; so such photons don't give any distortion. On the other hand, a significant distortion to the black-body spectrum may come from photons rescattered towards us by 'mirrors' (as e.g., electrons in clusters or IGM), and this is indeed one of the strongest constraints for voids (analogous to a kinematic SZ as mentioned at the end of the talk). One has to choose an appropriate radiation profile (and tilt with respect to matter profile) such that the inhomogeneity does not lead to a huge dipole in the frame of such mirrors (i.e., for 'observers' along our past light-cone).

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