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No obvious change in the number density of galaxies up to $z \approx 3.5$

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Abstract

The analysis of the cumulative count of sources of gamma-ray bursts as a function of their redshift strongly suggests that the number density of star-forming galaxies is roughly constant, up to $z \approx 3.5$. The analysis of the cumulative count of galaxies in the Hubble Ultra Deep Field further shows that the overall number density of galaxies is constant as well, up to $z \approx 2$ at least. Since Λ CDM does not seem able to cope with the age of old objects, both analyses were performed using a non-standard redshift-distance relationship.

Keywords: Age problem, Milne model, Gamma-ray bursts, Hubble Ultra Deep Field, Galaxy mergers, Splitting events.

Introduction

Λ CDM, the nowadays standard cosmological model, has proved able to rationalize numerous observations, of various kinds. However, although the reintroduction of a cosmological constant, twenty years ago, did help a lot [1, 2], it is still suffering from an age problem [3, 4, 5, 6]. And though this problem has been around since the earliest version of the model [7], the level of accuracy reached during the last decade for the measurements of cosmological parameters [8, 9, 10, 11, 12] leaves little room for future major changes of the predicted age of the Universe.

So, either the methods used for estimating ages of objects like stars or galaxies require significant improvements, or Λ CDM has to be replaced by another model.

Since Λ CDM is built with still mysterious dominant components like dark energy [13] or non-baryonic dark matter [14], and since it requires additional strong assumptions, like an exponential expansion of space in the early Universe [15, 16], it may prove worth considering the later hypothesis. Hereafter, a non-standard redshift-distance relationship is thus preferred. Note that it may serve as an anchor for the development of the next generation of cosmological models.

The age problem

Within the frame of a Friedmann-Lemaître-Robertson-Walker cosmology for the case of an homogeneous and isotropic Universe, $\tau(z)$, the age of the Universe at a given redshift, is so that [13]:

$$\tau(z) = \int_z^\infty \frac{dz'}{(1+z')H(z')} \quad (1)$$

with:

$$H(z) = H_0(\Omega_m(1+z)^3 + \Omega_k(1+z)^2 + \Omega_\Lambda)^{\frac{1}{2}} \quad (2)$$

where H_0 is the Hubble constant and where the contribution of Ω_r , the radiation term, has been omitted, the radiation-dominated era being much shorter than $\tau(z)$ for redshifts considered in the present study.

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Table 1: Estimated age and incubation time of two old, well characterized, objects. The incubation time is defined as the time elapsed between the birth of the Universe, according to Λ CDM or to the Milne cosmological model (with $H_0=67.4$ km s $^{-1}$ Mpc $^{-1}$ [12]), and the birth of the object. Negative incubation times are underlined. HD 140283 is an extremely metal-deficient subgiant; APM 08279+5255 is an exceptionally luminous, gravitationally lensed, quasar.

Object	Redshift	Age (Gyr)	Ref.	Age of Universe		Incubation time	
				(Λ CDM)	(Milne)	(Λ CDM)	(Milne)
HD 140283	0	14.5 ± 0.8	[17]	13.8	14.5	<u>-0.7</u>	0
		14.3 ± 0.8	[18]			<u>-0.5</u>	0.2
		13.7 ± 0.7	[19]			0.1	0.8
		12.2 ± 0.6^a	[19]			1.6	2.3
APM 08279+5255	3.9	3	[20, 21]	1.6	3.0	<u>-1.4</u>	0
		2.1^b	[22]			<u>-0.5</u>	0.9

^aWith $A_V=0.1$ mag [19].

^bThe lowest limit being 1.8 Gyr [22].

Λ CDM

Analyses of Planck measurements of the CMB anisotropies are consistent with a flat ($\Omega_k=0$) Λ CDM cosmological model, with $H_0=67.4 \pm 0.5$ km s $^{-1}$ Mpc $^{-1}$ and a matter density parameter $\Omega_m=0.315 \pm 0.007$ [12].

But with such parameters, according to eqn (1), Λ CDM can hardly explain how a quasar as old as APM 08279+5255 can be observed at $z=3.9$ [20]. Indeed, within the frame of the Λ CDM model, this quasar should be at least 0.2 [22] and up to 1.4 Gyr [21] older than the Universe itself (Table 1).

Other objects have been claimed to be older than the age of the Universe predicted by Λ CDM like, in our neighborhood, the metal-deficient subgiant HD 140283 [17, 18]. It has recently been shown that, by assuming an extinction value of 0.1 mag, the estimated age of this star can become comfortably lower (12.2 ± 0.6 Gyr [19]; Table 1). However, for stars as close as HD 140283, interstellar extinction is usually assumed to be non-existent [19].

Note that the value of the Hubble constant obtained by the Planck collaboration [12] is significantly lower than values recently obtained using local measurements [9, 10, 11] meaning that, according to Λ CDM, the age of the Universe could be as low as 12.7 Gyr [11] (1.4 Gyr at $z=3.9$).

The Milne model

Let us now consider an open model where $\Omega_m=\Omega_\Lambda=0$ ($\Omega_k=1$). Thus, eqn (2) becomes:

$$H(z) = H_0(1+z)$$

and eqn (1) yields:

$$\tau(z) = \frac{T_H}{1+z} \quad (3)$$

where $T_H = H_0^{-1}$ is the Hubble time.

This simple, one-parameter model, which is reminiscent of the Milne cosmology [23], belongs to the family of power-law cosmological models [24, 25, 26, 27, 28, 29]. Interestingly, it has been shown that, at least as far as $H(z)$ and $\tau(z)$ are concerned, the predictions of this model are in good agreement with observational data [25, 26, 27, 30, 31, 32, 33]. Noteworthy, as illustrated in Table 1, it seems able to handle the age problem better than Λ CDM. As a matter of fact, the Milne model would be seriously challenged only if the upper estimates of the ages of HD 140283 and APM 08279+5255 were confirmed.

Although a $\Omega_m=0$ model is not supported by observational data, note that within the frame of the Dirac-Milne cosmology it is expected to be a fair approximation on large scales [28, 34].

Main hypotheses

Hereafter, it is assumed that:

- I. Eqn (3) yields accurate enough predictions for $\Delta\tau = \tau(0) - \tau(z)$, that is:

$$\Delta\tau = T_H \frac{z}{1+z} \quad (4)$$

- II. During its travel, a photon ages as the Universe does, namely:

$$\Delta t = \Delta\tau \quad (5)$$

where Δt is the time taken by a photon to fly from a source at redshift z to an observer on Earth.

- III. The speed of light, c_0 , is constant.

Main consequences

Hypothesis III yields:

$$D_c = c_0 \Delta t \quad (6)$$

where D_c is the light-travel distance while, with eqn (5), eqn (4) becomes:

$$\Delta t = T_H \frac{z}{1+z} \quad (7)$$

Note that this later relationship has been obtained in various contexts [32, 35].

Counts of galaxies

$n(D_c)$, the cumulative count of galaxies as a function of the light-travel distance, is such that:

$$n(D_c) = \int_0^{D_c} 4\pi\rho(r)r^2 dr \quad (8)$$

where $\rho(r)$ is the number density of galaxies at distance r .

Let us assume that $\rho(\Delta t)$, the number density of galaxies as a function of the photon time-of-flight, evolves slowly enough, so that:

$$\rho(\Delta t) \approx \rho_0 + \dot{\rho}\Delta t \quad (9)$$

where $\dot{\rho}$ is the time derivative of $\rho(\Delta t)$. With eqn (6) and (9), eqn (8) yields:

$$n(D_c) = \frac{4}{3}\pi D_c^3 \rho_0 \left(1 + \frac{3}{4} \frac{\dot{\rho}}{\rho_0} \frac{D_c}{c_0} \right)$$

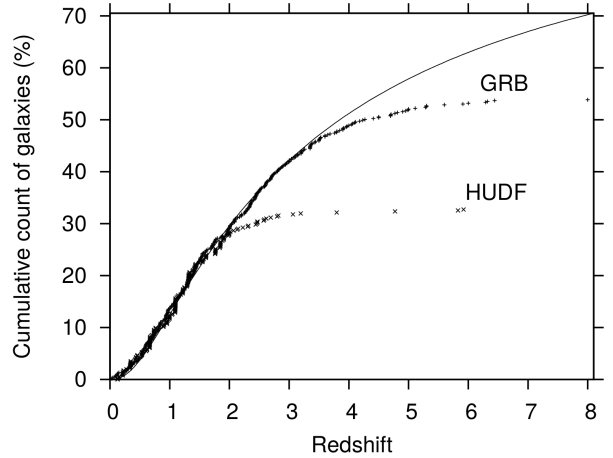


Figure 1: Cumulative count of galaxies in the Hubble Ultra Deep Field (HUDF) and of sources of long gamma-ray bursts (GRB) detected by *Swift*, as a function of redshift. Both counts were normalized using the value expected when $z \rightarrow \infty$, according to a one-parameter function (plain line), as explained in the text.

which becomes, with eqn (6) and (7):

$$n(z) = n_{st} \frac{z^3}{(1+z)^3} \left(1 + \epsilon_\rho \frac{z}{1+z} \right) \quad (10)$$

where:

$$n_{st} = \frac{4}{3}\pi D_H^3 \rho_0$$

and:

$$\epsilon_\rho = \frac{3}{4} \frac{\dot{\rho}}{\rho_0} T_H \quad (11)$$

$D_H = c_0 H_0^{-1}$ being the Hubble length.

Datasets

Studying $n(z)$, that is, a cumulative count of objects as a function of redshift, requires a fair sampling of these objects, for a range of redshifts as large as possible. For this purpose, sources of gamma-ray bursts (GRB) are attractive candidates since their redshifts have been determined up to $z=8.23$ [36], while major efforts have been undertaken by follow-up telescopes for determining the redshift of each of them as accurately as possible [37].

In spite of this, redshifts are known for only 30% of the GRBs detected by *Swift* [38], leaving room

for doubts on the fairness of the sampling [39, 40]. This is why, hereafter, redshifts of galaxies in the Hubble Ultra Deep Field (HUDF) [41] are also considered since, in this small area of the sky, efforts have focused on the accurate determination of the redshift of every single, bright enough galaxy [42].

GRB

The 353 GRB sources observed by *Swift* [37], with a redshift known with fair accuracy¹, were considered for the following analysis. Since they are expected to have a different physical origin [43], the 26 short GRBs ($T_{90} < 0.8$ s) were disregarded².

HUDF

A compilation of 169 robust spectroscopic redshifts of galaxies in the Hubble Ultra Deep Field was also considered³. Half of the galaxies of this sample have at least two redshift measurements, obtained in separate surveys [42].

Results

Least-square fitting of the cumulative count of GRB sources with eqn (10) + δ , for redshifts lower than 3.5, yields a root-mean-square of the residuals of 2.9, with $n_{st} = 650 \pm 12$, $\epsilon_\rho = -0.13 \pm 0.02$ and $\delta = 4.7 \pm 0.6$, that is, noteworthy, a low value of ϵ_ρ , meaning that the evolution of the number density of GRB sources is slow, compared to the Hubble time (eqn 11).

A negative value of ϵ_ρ would mean that the number density of GRB sources was lower in the past, at odds with the popular hypothesis that a merging process drives the evolution of galaxies [44, 45]. However, with $\epsilon_\rho=0$, fitting the cumulative count of GRB sources yields a root-mean-square of the residuals close to previous one, namely, of 3.0, with $n_{st} = 584 \pm 1$ and $\delta = 7.1 \pm 0.4$.

This confirms that, as advocated in previous studies [32, 46], it is not necessary to introduce a time-varying number density for explaining the

¹As provided on the Neil Gehrels Swift Observatory web page (https://swift.gsfc.nasa.gov/archive/grb_table), on October 2018, 27th.

²Ten GRBs with undefined values of T_{90} were considered as being short ones.

³As found in Table 4 of reference [42].

cumulative count of GRB sources as a function of redshift.

On the other hand, fitting the cumulative count of galaxies in the HUDF for redshifts lower than 2.0 yields a root-mean-square of the residuals of 4.5, with $n_{st} = 482 \pm 4$ and $\delta = 5.9 \pm 0.7$. With $\delta=0$, fitting both cumulative counts yield, respectively, $n_{st} = 607 \pm 1$ and $n_{st} = 513 \pm 3$. As shown in Figure 1, when they are normalized with these asymptotical values, both counts match well what is predicted by eqn (10), up to $z \approx 2$.

Discussion

A fair sample of star-forming galaxies

Figure 1 strongly suggests that the sample of GRB sources obtained by *Swift* is a fair one, up to $z \approx 3.5$. If so, it means that when $z > 3.5$, in most cases, follow-up telescopes were not able to determine the redshift of the source. According to Figure 1, this represents $\approx 50\%$ of the GRBs, a number close to the percentage of detected optical afterglows [38]. Indeed, detecting the optical afterglow of a GRB increases chances to pinpoint its host galaxy and, then, to determine its redshift [47]. But since redshifts are known for only 30% of the GRBs detected by *Swift* [38], this also means that in 15% of the cases the redshift of the source was not determined for reasons other than its distance, probably as a consequence of observational constraints or because it occurred in a region highly obscured by dust [48, 49].

Splitting events

Since long GRBs occur in star-forming galaxies [50, 51, 52], the fact that the number density of GRB sources does not vary significantly as a function of redshift ($\epsilon_\rho \approx 0$) means that the number density of star-forming galaxies does not as well. Previous works had indicated that this is indeed the case [53], up to $z \approx 2$ [54]. The present study confirms that this result can be extended up to $z \approx 3.5$ [32, 46].

However, the analysis of counts of galaxies in the HUDF further shows that the overall number density of galaxies does not seem to vary as well (Fig. 1). Since, on the other hand, galaxy mergers [44, 45] are rather frequent, noteworthy in the local

Universe [55, 56], this means that merging events are compensated by the formation of new galaxies, at a similar rate. On the other hand, since young galaxies seem to be rare in the local Universe [57, 58], this suggests that such new galaxies are formed through splitting events, like those observed in cosmological simulations [59]. Interestingly, being pairs of close galaxies with highly similar compositions, identifying recent splitters should prove easy.

Conclusion

A redshift-age relationship (eqn 3) able to handle the ages of the oldest objects known (Table 1) allows to show, based on safe grounds, that the number density of galaxies is roughly constant, up to $z = 2-3.5$.

Previous studies had already shown that the mass density of star-forming galaxies seems constant over a wide range of redshifts [53, 54]. However, though the number density of quiescent galaxies was also found constant over the interval $0.2 < z < 0.8$ [60], and not significantly different at $z = 0.03-0.11$ and $z = 1-2$ [61], a clear evolution was reported for $0.4 < z < 2$ [54]. The present analysis of the count of galaxies in the Hubble Ultra Deep Field supports the former claim.

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