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Abstract

In order to explain the Hubble diagram for quasars, an alternative to ΛCDM is proposed, namely, a simple Newtonian cosmological model where the loss of photons along the line-of-sight mimics the cosmic distance-duality relation, up to $z \approx 0.2$. According to this model, after ≈ 3 Gyr of travel, half of the photons emitted by a galaxy have been lost.

Keywords: distance modulus, distance duality.

Introduction

According to ΛCDM, the nowadays standard cosmological model, the dimming of supernovae of type Ia is due to an accelerated expansion of the space-time metric [1, 2]. However, the redshift of the farthest observed type Ia supernova is ≈ 1.4 [3] and it has recently been shown that, at higher redshifts, the Hubble diagram for quasars can not be handled by ΛCDM, with a statistical significance of 4σ [4]. Of course, these latter data can be accommodated by extended versions of the model, through the adjustment of additional free parameters, like the equation of state parameter w [4].

Hereafter, it is shown that the loss of photons along the line-of-sight is a possible alternative for explaining the Hubble diagram for quasars, at least in the context of a pair of Newtonian cosmological models. It is then shown that the cosmic distance duality relation [5] can be used to single out one of them.

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Cosmological model

Let us assume that $\tau(z)$, the age of the Universe at redshift z, is approximately given by:

$$\tau(z) = \frac{1}{H_0(1+z)} \tag{1}$$

where H_0 is the Hubble constant. Eqn 1, which is for instance a consequence of the linear-coasting cosmological model [6, 7, 8], has noteworthy proved able to cope with the age of objects that, according to ΛCDM, seem significantly older than the Universe itself [9, 10, 11].

Let us also assume that, during its travel, a photon ages as the Universe does, namely:

$$\Delta t = \tau(0) - \tau(z) \tag{2}$$

where Δt is the time taken by the photon to fly from a source at redshift z to an observer on Earth. Since the speed of light, c_0, is constant, with eqn 1 and 2, D_c, the light-travel distance, is so that [12]:

$$D_c = \frac{c_0}{H_0}\frac{z}{1+z} \tag{3}$$

Moreover, let us assume that D_L, the luminosity distance, has the following, rather general form:

$$D_L = D_c(1+z)^n e^{\frac{1}{2}\frac{\Delta t}{\tau_p}} \tag{4}$$

where n is a half-integer, τ_p being the photon lifetime along the line-of-sight.

In the context of Newtonian cosmological models, as a consequence of the energy loss of photons during their travel, $n = \frac{1}{2}$. However, if, as predicted by metric theories of gravity like ΛCDM, time-dilation of remote events is a general phenomenon [13, 14, 15], then $n = 1$. Both cases are considered hereafter.

Observables

Distance modulus

With eqn 2, 3 and 4, μ, the distance modulus:

$$\mu = 5\log_{10}(D_L) + 25$$

becomes:

$$\mu = 5\log_{10} z(1+z)^{n-1} + \alpha\frac{T_H}{\tau_p}\frac{z}{1+z} + \mu_0 \qquad (5)$$

where $T_H = H_0^{-1}$ is the Hubble time, with $\mu_0 = 5\log_{10}(c_0 T_H) + 25$ and $\alpha = 2.5\log_{10} e$.

Distance duality

If there is no photon loss along the path between a source at redshift z and an observer on Earth, metric theories of gravity predict that [5, 16]:

$$D_L = D_A(1+z)^2$$

where D_A is the angular distance. Deviations from this so-called cosmic distance duality relation can be quantified using the following quantity [17]:

$$\eta(z) = \frac{D_L}{D_A(1+z)^2} \qquad (6)$$

In practice, such deviations have been measured using single-parameter functional forms [16, 17] like, as considered herein:

$$\eta(z) = 1 + \eta_0 z \qquad (7)$$

In the context of Newtonian cosmological models, $D_A = D_c$. Thus, with eqn 1, 2 and 4, eqn 6 becomes:

$$\eta(z) = (1+z)^{n-2} e^{\frac{1}{2}\frac{T_H}{\tau_p}\frac{z}{1+z}} \qquad (8)$$

Datasets

Quasars

A homogeneous sample of 1598 quasars [4] with luminosity-distances determined using their rest-frame X-ray and UV fluxes [18, 19] was considered. Since such luminosity-distances are rather noisy, the dataset was sorted by increasing values of the redshift and 16 subsamples of 101 quasars[1] were analyzed, using the median redshift and luminosity-distance of each subsample.

Galaxy clusters

η_0 (eqn 7) has been determined by several groups, using various datasets [20]. The following two measures are considered hereafter:

- $\eta_0 = -0.15 \pm 0.07$ [21]. This measure was obtained with a cosmological model-independent approach, using the gas mass fraction, from the Sunyaev-Zeldovich effect, and X-ray surface brightness observations of 38 massive galaxy clusters spanning redshifts between 0.14 and 0.89.

- $\eta_0 = -0.08 \pm 0.10$ [22]. This measure was obtained using the gas mass fraction, from the Sunyaev-Zeldovich effect, of 91 massive galaxy clusters spanning redshifts between 0.1 and 1.4, luminosity distances coming from supernovae of the Union 2.1 compilation [3] with similar redshifts.

Results

Quasars

With eqn 5, when $n = \frac{1}{2}$, a least-square fit of the median distance modulus of the 16 subsamples of quasars yields:

$$\frac{T_H}{\tau_p} = 3.2 \pm 0.4$$

with $\mu_0 = 18.0 \pm 0.2$.

On the other hand, when $n = 1$, $\frac{T_H}{\tau_p} = 1.0 \pm 0.4$, $\mu_0 = 18.4 \pm 0.2$. As illustrated in Figure 1, in both cases, the fit matches the data nicely, with a root-mean-square of the residuals of 0.2. Note that several other simple cosmological models have already proven able to pass this test [23].

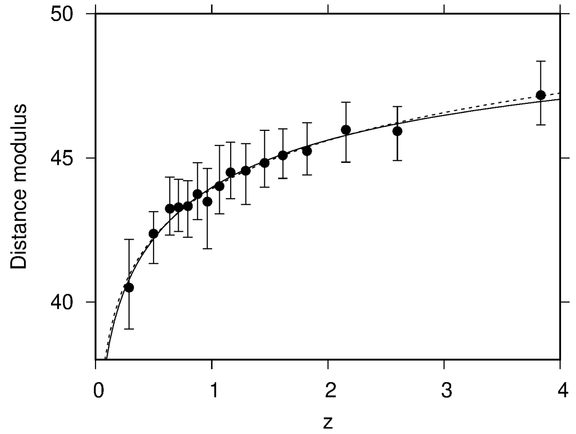

Figure 1: The distance modulus of quasars, as a function of redshift. Each point (filled circle) is the median of 101 values, the error bars showing the corresponding interquartiles. Plain line: least-square fit of these 16 median values, when $n = \frac{1}{2}$. Dashed line: when $n = 1$.

Distance duality

With the $\frac{T_H}{\tau_p}$ values determined above, eqn 8 can be plotted as a function of redshift. As shown in Figure 2, $n = 1$ is *not* found consistent with observational data, since it yields values more than 2σ away from both measurements, on the whole redshift range considered.

On the other hand, $n = \frac{1}{2}$ matches the data comfortably. Interestingly, while ΛCDM predicts $\eta(z) \geq 1$ [5], it has been noticed that measurements of $\eta(z)$ tend to yield values below one [17, 20, 21, 24], like when $n = \frac{1}{2}$.

Discussion

How are photons lost ?

$\frac{T_H}{\tau_p} = 3.2$ means that half of the photons are lost after ≈ 3 Gyr of travel (assuming $T_H = 13.3$ Gyr [25]). As briefly detailed below, their loss along the line-of-sight can for instance be due to absorption. It could also have a less mundane origin.

Absorbers

Photons can be absorbed along the line-of-sight. Indeed, it has been suggested that gray intergalactic dust could account for the dimming of type Ia supernovae [26]. However, in particular because the luminosity-distances of quasars considered herein have been determined by comparing their X-ray and UV fluxes [4], to be relevant, such absorption would have to exhibit little dependence upon photon frequency.

[1]With only 83 quasars in the highest-redshift subsample.

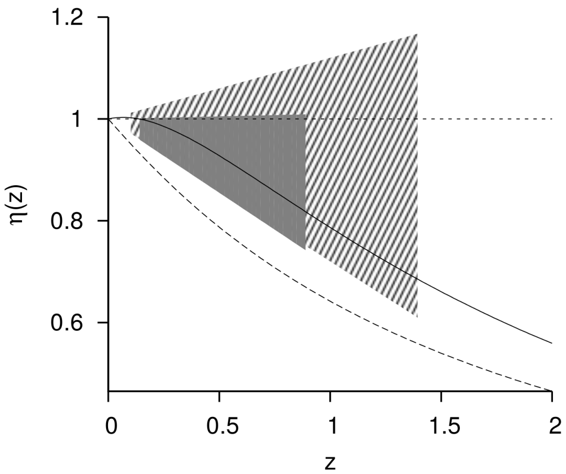

Figure 2: Compatibility with the cosmic distance duality relation, as a function of redshift. Grey and hatched sectors: measurements obtained using the gas mass fraction of 38 or 91 globular clusters, respectively, the lower and upper limits of each sector being 2σ away from the average value. Horizontal dotted line: minimum value expected within the frame of metric theories of gravity like ΛCDM. Plain and dashed lines: values expected if photons are lost along the line-of-sight, when $n = \frac{1}{2}$ or $n = 1$, respectively.

Photon decay

It has also been suggested that photons could have a finite lifetime [27, 28], *e.g.* by decaying into lighter particles like massive neutrinos [29], thus reducing their flux along the line-of-sight.

Is time-dilation universal ?

In the context of the Newtonian cosmological models considered herein, the fact that observations support $n = \frac{1}{2}$ likely means that X-ray and UV fluxes from quasars have not experienced time-dilation. As a matter of fact, while it has been found that light-curves of type Ia supernovae are dilated by a $(1+z)$ factor [30, 31, 32], no such time-dilation was observed in the light curves of quasars [33, 34].

Conclusion

As shown in Figure 2, when a loss of photons along the line-of-sight is taken into account, $\eta(z) \approx 1$ is also expected within the frame of a simple Newtonian cosmological model ($n = \frac{1}{2}$), up to $z \approx 0.2$. However, above this value, $\eta(z)$ is predicted to be significantly lower than one, while metric theories of gravity like ΛCDM predict $\eta(z) \geq 1$ [5].

In any case, the present study shows that the combination of the Hubble diagram for quasars with the cosmic distance duality relation is a powerful test for cosmological models.

Nevertheless, as Figure 2 suggests, more accurate data, over a wider range of redshifts, would be welcome. They could for instance be obtained using the Sunyaev-Zeldovich effect for galaxy clusters and luminosity-distances of samples of quasars with similar redshifts.

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