A simple Hubble-like law in lieu of dark energy

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Abstract

Context. Within the frame of the \(\Lambda\) cold dark matter paradigm, a dark energy component of unknown origin is expected to represent nearly 75% of the energy of the Universe. Aims. To provide new grounds on which alternative cosmologies could be developed. Methods. A new form is proposed for Hubble’s law. Its consistency with observational data of various origin is checked. Results. This Hubble-like law yields an age-redshift relationship which is consistent with available data. Together with a non-standard distance-duality relationship, it provides an alternative interpretation for both angular-diameter and luminosity distance data. Conclusions. Along this line of thought, there is no need for a dominant energy component of unknown origin.

I. INTRODUCTION

Over the last twenty years, as a consequence of its numerous successes, the \(\Lambda\) cold dark matter (\(\Lambda\)CDM) paradigm has reached the status of a ”concordance” cosmology [1, 15, 31]. However, several clouds are still obscuring the brilliance of this paradigm, one of the most notable being that it relies on a new kind of so-called ”dark energy”, of unknown origin but accounting for nearly 75% of the energy of the Universe [2, 15, 16]. As long as this dominant component remains mysterious [25], alternative cosmologies [8, 30] need to be developed.

The purpose of this Letter is to provide new grounds on which such cosmologies could be established.

II. MAIN HYPOTHESIS

In the late 1920’s, Edwin Hubble discovered a proportionality between \(z\), the redshift of nearby galaxies, and \(D_{\text{mes}}\), their distance estimates [21]. He wrote his law as follows:

\[
z = \frac{\lambda_0 - \lambda}{\lambda_0} = \frac{H_0 D_{\text{mes}}}{c_0}
\]

where \(\lambda_0\) is the wavelength of the light received from the galaxy, \(\lambda_0\) the wavelength measured for the same kind of source sitting on Earth, \(c_0\), the speed of light, \(H_0\) being nowadays known as the Hubble constant.

In the late 1990’s, using type-Ia supernovae as standard candles, it was shown that, for large values of the distance, Hubble’s law is not linear any more [34, 57]. Within the frame of \(\Lambda\)CDM, this deviation from linearity is noteworthy due to a non-zero, although very small [38], value of \(\Lambda\), the cosmological constant.

Hereafter, it is instead assumed that, as advocated by Hubble, the law he discovered is indeed linear. However, it is also posited that, when Hubble defined the redshift, he made the wrong choice. Specifically, herein, the physically relevant form of Hubble’s law is assumed to be:

\[
z = \frac{\nu_0 - \nu_{\text{obs}}}{\nu_0} = H_0 \Delta t
\]

where \(\nu_{\text{obs}}\) is the frequency of the light received from a remote source, \(\Delta t\), the photon time-of-flight between the source and the observer, with \(H_0\) being an actual constant. Note that, as long as:

\[
D_{\text{mes}} = c_0 \Delta t
\]

when \(z \ll 1\), (2) can indeed be approximated by (1) since:

\[
z = \frac{z_\Delta}{1 + z_\Delta}
\]

III. THE AGE-REDSHIFn T RELATIONSHIP

A. The age of the oldest stars

Considering the case of early-type stars or galaxies born \(T_{\text{early}}\) Gyr ago, \(T_{\text{obs}}\), their age estimate for an Earth-based observer is:

\[
T_{\text{obs}} = T_{\text{early}} - \Delta t
\]

that is, with (2):

\[
T_{\text{obs}} = T_{\text{early}} - T_H z
\]

or, with (3):

\[
T_{\text{obs}} = T_{\text{early}} - T_H \frac{z_\Delta}{1 + z_\Delta}
\]

where \(T_H\), the Hubble time, is the inverse of \(H_0\). Table I shows the age estimates of what could be the two oldest objects presently known. Being in our neighborhood, HD140283 may provide a fair estimate for \(T_{\text{early}}\) while, according to (4) and under the hypothesis that APM 08279+5255 was born nearly
TABLE I: The two oldest objects presently known. HD140283 is an extremely metal-deficient subgiant while APM 08279+5255 is a quasar. At the same time as HD140283, the age and the redshift of the former allow to determine the Hubble time, namely:

\[ T_H = \frac{T_{\text{early}} - T_{\text{obs}}}{z_{\nu}} = 15.6 \text{ Gyr} \]

that is, a value in good agreement with recent estimates \[39\].

Note that (5) gives an upper-bound for the age of early-type stars at any redshift. For instance, it has been claimed that two galaxies found at \( z_{\lambda} = 6.027 \) and \( z_{\lambda} = 9.6 \) could be 0.8 \[36\] and 0.2 \[48\] Gyr old, respectively. According to (5), and as illustrated in Fig. 1, the corresponding upper-bounds at these redshifts are indeed higher, namely, 1.2 and 0.3 Gyr, respectively.

Fig. 1 also shows that (5) yields upper bounds that are well over current estimates for the ages of 3C65 \[41\], LBDS 53W069 \[53\], LBDS 53W091 \[11\], QSO B1422+231 \[47\] and GNS-zD1 \[17\], at \( z_{\lambda} = 1.175, 1.43, 1.55, 3.62 \) and 7.2, respectively.

B. A corollary

As a consequence of (4), \( T_{\text{obs}} > 0 \) if:

\[ z_{\nu} < \frac{T_{\text{early}}}{T_H} = 0.93 \] (6)

C. Another corollary

More generally, (3) implies that \( z_{\nu} \leq 1 \). Thus, (6) yields:

\[ T_{\text{early}} \leq T_H \]

which means that no early-type object older than 15.6 Gyr should be observed.

D. Another prediction

On the other hand, as a consequence of (2):

\[ \frac{\partial z_{\nu}}{\partial (\Delta t)} = H_0 \]

With \( \Delta t = t_0 - t \), taking (3) into account yields:

\[ \frac{\partial z_{\nu}}{\partial \Delta t} = -\frac{1}{(1 + z_{\lambda})^2} \frac{\partial z_{\lambda}}{\partial t} = H_0 \] (7)

where \( t_0 \) and \( t \) are the observer and cosmic times, respectively. Measurements of \( \frac{\partial z_{\lambda}}{\partial t} \), obtained through studies of the age redshift (\( z_{\lambda} \)). The dashed line corresponds to \( T_H = 15.6 \text{ Gyr} \), i.e., \( H_0 = 63 \text{ km.s}^{-1}.\text{Mpc}^{-1} \). \( H(z_{\lambda}) \) data come from \[29\].

So, according to (5), and under the assumption that no object significantly older than HD140283 and APM 08279+5255 can be observed nowadays from Earth, it should not be possible to observe any galaxy at a redshift larger than 13.

This is consistent with current knowledge, since the highest redshifts known so far are around 10 \[8, 48\].

FIG. 1: Age-redshift (\( z_{\lambda} \)) relationship. Filled circles: Ages of nine early-type stars, galaxies and quasars (see text). Plain line: upper bound expected with \( T_{\text{early}} = 14.5 \) and \( T_H = 15.6 \text{ Gyr} \), according to the Hubble-like law introduced herein.

FIG. 2: \( \frac{H(z_{\lambda})}{1+z_{\lambda}} \) as a function of redshift (\( z_{\lambda} \)). The dashed line corresponds to \( T_H = 15.6 \text{ Gyr} \), i.e., \( H_0 = 63 \text{ km.s}^{-1}.\text{Mpc}^{-1} \). \( H(z_{\lambda}) \) data come from \[29\].
of passively evolving galaxies, are usually provided through $H(z_{i})$ [29], which is defined as follows [23]:

$$H(z_{i}) = -\frac{1}{1 + z_{i}} \frac{\partial z_{i}}{\partial t}$$

that is, with (7):

$$H(z_{i}) = H_{0}(1 + z_{i})$$

While the corresponding relationship expected within the frame of $\Lambda$CDM is far from being that simple [12 23], as shown in Fig. 2, currently available data are consistent with $H(z_{i}) \propto 1 + z_{i}$. In other words, they are in good agreement with [3].

IV. DISTANCE-REDSHIFT RELATIONSHIPS

A. Luminosity distance

Without any explicit cosmology, going further requires additional hypotheses. So, let us assume that:

$$D_{L} = D_{C}(1 + z_{i})^{n}$$

where $D_{L}$ is the luminosity-distance, $D_{C}$, the light-travel distance ($D_{C} = c_{0}\Delta t$), $n$ being an unknown parameter, likely to be a rational number (see below).

Together with (2) and (3), (9) allows to write $\mu$, the distance modulus:

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

as follows:

$$\mu = 5 \log_{10}(c_{0}T_{H}) + \mu_{0} + 25$$

where $\mu_{0} = 5 \log_{10}(c_{0}T_{H})$.

Nowadays, distance moduli have been measured for hundreds of supernovae of type Ia. As shown in Fig. 3 for the 580 cases of the Union 2.1 compilation [43], an accurate least-square fit of the data can be obtained with (10), which yields:

$$n = 1.65 \pm 0.02$$

However, setting $n = \frac{3}{2}$ also provides fair estimates for these data (Fig. 3).

B. Angular diameter distance

Furthermore, let us assume that $D_{A}$, the angular diameter distance, is so that:

$$D_{A} = D_{C} = c_{0}\Delta t$$

that is, with (2) and (3):

$$D_{A} = D_{H} \frac{z_{i}}{1 + z_{i}}$$

where $D_{H} = c_{0}T_{H}$ is the Hubble length. As a consequence, $\theta$, the angular size:

$$\theta = \frac{s}{D_{A}}$$

$s$ being the actual size of the considered standard rod, is so that:

$$\theta = \frac{s}{D_{H}(1 + \frac{1}{z_{i}})}$$

Interestingly, although this may not be the case for ultra-compact [22] or double-lobed radio sources [7], it has indeed been observed that the average angular size of galaxies seems proportional to $z_{i}^{-1}$, and this, over a wide range of redshifts, namely, for $z_{i} = 0.2 - 3.2$ [26].

C. The distance-duality relation

As a consequence of (9) and (11):

$$D_{L} = D_{A}(1 + z_{i})^{n}$$

Within the frame of $\Lambda$CDM, like in most cosmologies based on a metric theory of gravity, $n = 2$ [45]. But if, for instance, the number of photons is not conserved during their flight towards the observer, $n$ can be lower than that [5]. This would also be the case if the energy of the photon does not change during its flight, that is, if, for instance as a consequence of its quantum nature, the photon wavelength does not follow the expansion of the Universe.

On the other hand, (11) is typical of an euclidean static Universe, where $n = \frac{1}{2}$, as a consequence of the photon energy loss associated to the redshift [26]. But since, at least in the case of supernovae Ia [19 20], an apparent dilation of the timescale of remote events has been observed [13 18 24], $n = 1$ seems more likely in this context.

Note that $n = \frac{1}{2}$ is already expected within the frame of a couple of alternative cosmologies [6 28].
As shown in Fig. 4 as far as distance moduli are concerned, the difference between values predicted with \( \Lambda \)CDM or (10) becomes significant for \( z_\lambda > 2 \), if \( n = 1.65 \), or for \( z_\lambda > 4 \), if \( n = \frac{1}{2} \). Interestingly, although the fit of the supernovae data of the Union 2.1 compilation looks less convincing with \( n = \frac{1}{2} \) (Fig. 3), it matches the values predicted by \( \Lambda \)CDM over a wider range of redshifts (Fig. 4).

\[ \frac{v_{\text{obs}}}{v_0} = 1 - \frac{\Delta t}{t_0} \]

where \( v_{\text{obs}} \) is the measured length, \( D_0 \) being the length obtained when a method in which no clock relying on an atomic or a molecular spectrum is used.

For instance, in the case of the Earth-Moon semi-major axis, an apparent increase of 2.4 cm per year should be observed. As a matter of fact, an increase of \( 3.82 \pm 0.07 \) cm per year has been measured \([10]\). On the other hand, although an actual increase of the Earth-Moon distance is expected as a consequence of tidal friction \([9]\), the measured value is indeed significantly higher than current estimates for the Paleozoic Era \([40]\), namely, about 2 cm per year \([27, 46]\).

VI. CONCLUSION

A new form of Hubble’s law, where the frequency-redshift is proportional to the photon time-of-flight (eqn 2), yields an age-redshift relationship which is consistent with currently available data (Figs 1 and 2). Together with a non-standard distance-duality relationship (eqn 12), it provides a new explanation for the angular-diameter and luminosity distance data (Fig. 3). As such, it could become a fruitful anchor for the development of alternative cosmologies.

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