Scale-invariant Cosmology and CMB Temperatures as a Function of Redshifts

Andre Maeder
Geneva Observatory, University of Geneva CH-1290 Sauverny, Switzerland; andre.maeder@unige.ch
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Abstract
Cosmological models assuming the scale invariance of the macroscopic empty space show an accelerated expansion, without calling for some unknown particles. Several comparisons between models and observations (tests on distances, \(m−z\) diagram, \(\Omega_L\) versus \(\Omega_m\) plot, age versus \(H_0\), \(H(z)\) versus \(z\), transition braking-acceleration) have indicated an impressive agreement. We pursue the tests with the CMB temperatures \(T_{\text{CMB}}\) as a function of redshifts \(z\). CO molecules in DLA systems provide the most accurate excitation temperatures \(T_{\text{exc}}\) up to \(z \approx 2.7\). Such data need corrections for local effects like particle collisions, optical depths, UV radiation, etc., We estimate these corrections as a function of the \((\text{CO}/H_\alpha)\) ratios from far-UV observations of CO molecules in the Galaxy. The results show that it is not sufficient to apply theoretical collisional corrections to get the proper values of \(T_{\text{CMB}}\) versus \(z\). Thus, the agreement often found with the standard model may be questioned. The \(T_{\text{CMB}}(z)\) relation needs further careful attention and the same for the scale-invariant cosmology in view of its positive tests.

Key words: cosmic background radiation – cosmology: theory – dark energy

1. Introduction

Unlike theories with modified gravity, the scale-invariant models further explore the invariance properties of spacetime, which, as emphasized by Dirac (1973), play a fundamental role in physics. It is well known that the presence of matter in a system tends to kill the scale invariance of the physical laws (Feynman 1963). However, the empty space at large scales may have the property of scale invariance, a property present in Maxwell equations in the absence of charge and current. Weyl (1923), Eddington (1923), Dirac (1973), and Canuto et al. (1977) developed a theory which, in addition to the general covariance of general relativity (GR), also permits (but does not demand) the invariance to a scale transformation \(ds' = \lambda(t)ds\). In this most general framework, the assumption of scale invariance of the macroscopic empty space leads to two differential equations between the cosmological constant \(\Lambda\) and the scale factor \(\lambda(t)\). Adopting the postulate of GR that gravitation universally couples to all energy and momentum contributions (Carroll et al. 1992), we account for the contribution from the \(\lambda\)-derivatives and obtain new basic cosmological equations (Maeder 2017). After an initial braking phase, they lead to a general acceleration of the cosmic expansion for models with a density parameter \(\Omega_m < 1\).

The properties of these models have been studied, and detailed tests have been performed (Maeder 2017), in particular on the distances; the magnitude–redshift \(m−z\) relation; the \(\Omega_L\) versus \(\Omega_m\) plot; the relation between \(H_0\) and the age of the universe; the expansion rates \(H(z)\) versus redshifts \(z\); and the transition from braking to accelerated expansion. All of these tests were very well satisfied without calling for some dark energy. This is why further exploration is necessary.

The \(T_{\text{CMB}}(z)\) relation of the temperatures of the cosmic microwave background (CMB) as a function of redshifts \(z\) is a fundamental cosmological test (Peebles 1993). Deviations from the laws, if they exist, may appear at large enough redshifts. The Sunyaev–Zeld’ovich (SZ) effect provides some tests (Luzzi et al. 2015) for low \(z\). At such low \(z\), different models predict only small differences within the error bars. Chluba (2014) consider these tests to have a limited applicability. The situation is better for the tests based on molecular absorption in the diffuse intergalactic gas, particularly from CO lines by Srianand et al. (2008), Noterdaeme et al. (2010, 2011, 2017). The observations of the rotational excitation of the CO molecules in Damped Ly\(\alpha\) (DLA) systems up to \(z \approx 2.7\) have recently been possible (Srianand et al. 2008). Remarkably, at present, six absorption-line systems produced by clouds of diffuse gas have been detected on the sight lines of more than 40,000 quasars investigated. The CO molecules emit a spectrum with spectral lines in radio, infrared, and far ultraviolet from rotational, vibrational, and electronic transitions. There are several lines observable in the near-UV and visible spectral domains (due to the redshift). Their simultaneous fitting leads to improved determinations of the excitation temperatures. These objects, despite their rareness, appear extraordinarily interesting in view of their higher accuracy and the redshifts they concern.

In Section 2, we study the heating and cooling processes intervening in the excitation of the CO molecules and try to estimate the global amplitude of these effects from Galactic data. In Section 3, the excitation temperatures in DLA systems are discussed and corrections are applied to get the temperatures of the CMB at different \(z\). Comparisons of models and observations are performed in Section 4. Section 5 gives a conclusion.

2. Contributions to the Excitation of the CO Rotational Levels

In addition to the CMB radiation, various physical effects in the diffuse gas may influence the absorption profiles of the fine-structure atomic levels and of the rotational levels of molecular lines, and thus the determinations of the the excitation temperature \(T_{\text{exc}}\) of the gas. A thorough review of the heating and cooling processes in the interstellar gas has been given by Lequeux (2005); see also Wolfire et al. (1995). We will concentrate here on the efficient physical effects in molecular regions, with a particular interest on those potentially able to influence the excitation temperature of the CO molecules, which have a ground rotational \(J = 1 → 0\) transition at an energy
corresponding to a temperature of 5.54 K. The significant effects should normally be accounted for to permit a reliable CMB temperatures at different redshifts. However, corrections for local effects influencing the excitation temperatures in DLA systems have in general not been applied to the CO observations (of the six observations, only one (Noterdaeme et al. 2017), has been corrected; see below).

2.1. Molecular Regions: Heating Effects Influencing the CO Excitation

There are many processes contributing to the heating of an interstellar molecular region. The basic effect is the ejection of an electron from an atom (or a molecule) by an incident photon or a particle, the electron heating the gas by further collisions which rapidly ($\lesssim 1$ year) thermalize the gas. The main processes are (1) heating by low-energy by cosmic rays; (2) grain photoelectric emission; (3) chemical energy of H$_2$ formation; (4) photon trapping; (5) grain-gas thermal exchange; and (6) UV pumping by molecules. The heating by low-energy cosmic rays process is always present due the high penetration of cosmic rays, but it is generally insignificant except in the depths of molecular clouds where it can even dominate. A cloud model (Noterdaeme et al. 2017) illustrates the increase of the relative role of cosmic rays with depth in the cloud, where they dominate for relatively low temperatures. The grain photoelectric emission process results from the ambient UV flux that removes electrons from the grains. The electrons carry a large fraction of the energy of the incident UV photon and thermalize the medium by collisions; this process is most efficient in H II and neutral regions, but it may still remain efficient in the photodissociation regions, intermediate between the H II and molecular regions. The above-mentioned cloud model shows that this process is still dominant in a large part of the cloud where CO molecules are present. The chemical energy of H$_2$ formation process is the formation of a H$_2$ molecule from atomic hydrogen is a very exothermic reaction, yielding energy mainly to the excitation of H$_2$ and the kinetic energy of the gas; this process is present in the outer layers of the the molecular region, though about an order of a magnitude lower than the previous mechanism. The photon trapping process occurs in regions of high optical depths, which may largely reduce the effect of spontaneous emission (Lequeux 2005). For example, the de-excitation photons from a CO molecule may be re-absorbed by another CO molecule. This decrease the radiative cooling, so that the interactions with H$_2$ molecules equilibrate at a higher temperature (Burgh et al. 2007). The grain-gas thermal exchange: it intervenes due to the collisions between the dust grains and atoms or molecules in the gas. A high density of the medium favors the process, which is thus generally unimportant in the diffuse gas, (there, the grains being colder than the gas, may provide some minor cooling). However, in the depths of giant molecular clouds, the grains may be heated by the far-IR radiation, which easily penetrate the clouds; this process dominates in molecular clouds with a concentration $n$ higher than $2 \cdot 10^4$ cm$^{-3}$ (Lequeux 2005). However, Wannier et al. (1997) have shown that even in a relatively diffuse gas with $n$ between 100 and 1000 cm$^{-3}$, the millimeter-wave emission from the dust of a nearby cloud may provide a significant specific increase of the CO rotational excitation temperature, (the effect evidently depends on the solid angle presented by the cloud). The UV pumping by molecules process is an efficient mechanism only in regions exposed to a strong UV flux. The molecules are then excited rotationally and vibrationally by the absorption of UV photons and the de-excitation transfers some energy to the gas; this process is often killed by dust extinction (Krotkov et al. 1980). As CO molecules require screening from UV radiation to exist, this process may not be dominant for their excitation.

As to the cooling processes, the cooling by the emission of fine-structure lines is mainly due to C II and O I in neutral regions, while in H II regions and deep molecular clouds it becomes insignificant (Lequeux 2005). The de-excitation of level $n = 2$ of hydrogen, which may be collisionally excited, produces the Ly$\alpha$ line. In molecular regions, the main cooling results from the radiation by the fundamental rotational transition of CO molecules at 2.6 mm. The emission from C I with a first level of excitation at $T = 23.4$ K may also be significant. The recombinations of charged particles on grains, by the inverse process of the above-mentioned grain photoelectric emission, produces a cooling which is rapidly growing with temperature. The grain-gas thermal exchange, as we have seen above, is insignificant in a cold diffuse gas.

Energy losses by induced or stimulated emission do not seem significant processes in the diffuse or translucent interstellar medium. Stimulated emission by OH, H$_2$O, NH$_3$, HCN, or SiO molecules is known to produce the maser effect under certain conditions in dense molecular regions. Even for these relatively easily excited molecules, densities in excess of $10^4$ cm$^{-3}$ are required, i.e., two orders of magnitude higher than in the diffuse or translucent interstellar gas. To be active, the process also requires a high velocity coherence to avoid Doppler shifts, so that extended low-density regions are unfavorable.

The sum of all the heating and cooling processes leads to a certain equilibrium state in the interstellar medium dominated by H atoms and H$_2$ molecules. In this medium, the particular excitation temperature of the CO molecules depends on all the above-mentioned mechanisms and on their collisional interactions with the main gas components. Sobolev et al. (2015) recently studied the population distribution of the rotational states of the CO molecules ($^{12}$C$^{16}$O), taking into account the CMB radiation and the collisional excitation by H, H$_2$, and He. Their results are based on experimentally measured probabilities of collisional transitions. They provide the corrections to be applied to $T_{\text{exc}}$ of CO molecules to get the CMB temperatures. These corrections essentially depend on the following four physical factors in the intervening cloud on the sight line of quasars: (1) the total concentration $n$ of particles in the gas; (2) the hydrogen molecular fraction $f = 2 n(H_2)/(n(H_2) + n(H))$, where $n(H)$ and $n(H_2)$ are the concentrations of the atomic and molecular hydrogen; (3) the kinetic temperature $T_{\text{kin}}$ of the gas; and (4) the observed excitation temperature $T_{\text{exc}}$ of the CO molecules. Figure 1 illustrates the corrections $\Delta T$ derived from the analytical expressions by Sobolev et al. (2015) as a function of $T_{\text{exc}}$ due to particle collisions for some typical conditions. These corrections are to be subtracted from the excitation temperatures $T_{\text{exc}}$ to get the CMB temperatures $T_{\text{CMB}}$. The values of $\Delta T$ depend linearly on the concentration $n$ and are given for different values of $f$ and $T_{\text{kin}}$. We see that they show little variations with the excitation temperatures, while they are more sensitive to the three other parameters.
higher by 1.37 K than the local CMB temperature. Burgh et al. (2007) also point out that, for CO column densities from $10^{15} \text{ cm}^{-2}$ and above, the average $T_{\text{exc}}$ from CO lines reaches $5.2 \pm 1 \text{ K}$ (5.43 K for the weighted mean), i.e., 2.50 K (2.7 K) higher than $T_{\text{CMB}}$. For CO column densities inferior to $10^{15} \text{ cm}^{-2}$, Burgh et al. (2007) find an average $T_{\text{exc}} = 3.6 \pm 0.5 \text{ K}$, (the weighted average $T_{\text{exc}}$ is 3.69 K, i.e., about 0.96 K higher than $T_{\text{CMB}}$). They note that the increase of $T_{\text{exc}}$ for high CO (see also Figure 3) may result from “photon trapping” in regions with a higher optical depth, with photons being absorbed by more than one CO molecule so that the radiative cooling is reduced. Burgh et al. (2007) also find some relations between the molecular (CO/H$_2$) ratios and the extinction properties (color excess $E(B-V)$ and absorption rate $A_V/d$ in mag/kpc) for the various diffuse and translucent regions studied.

Referring to Section 2.1, we may remark that for the above average values of $T_{\text{kin}}, f$, and $n$ from 20 to 200 cm$^{-3}$, we have a collisional correction between 0.069 K (for $n = 20$) and 0.69 K (for $n = 200$). For a mean value value of the space density $n = 100 \text{ cm}^{-3}$, the typical collisional correction would be 0.35 K. This is much smaller than what is suggested by the above observations in Figure 2. It means that if we account only for the collisional broadening of the lines according to Sobolev et al. (2015), we may underestimate by a large amount the total number of corrections to be applied to the observed $T_{\text{exc}}$ of the CO lines ($^{12}$C$^{16}$O).

The above-mentioned results by Burgh et al. (2007) indicate an effect of the optical thickness of the intervening interstellar gas on the determination of the $T_{\text{exc}}$ of CO lines. In a cloud model by Bolatto et al. (2013), the CO is optically thin for column densities of the CO gas less than about $10^{-15} \text{ cm}^2$. For this limit, the CO gas in DLAs with a low log $N$(CO) value would appear to be generally optically thin. We note this is not the case for the translucent molecular cloud along the sight line of J0000+0048 (Table 1), which has received a collisional correction according to the developments by Sobolev et al. (2015).

2.2. The Excitation Temperatures in the Milky Way and the Estimates of the Corrections

CO molecules produce absorption bands in the UV, which permits their detection. On the basis of far-UV data from the Space Telescope Imaging Spectrograph (STIS) onboard the Hubble Space Telescope (HST), and the Far Ultraviolet Spectroscopic Explorer (FUSE), Burgh et al. (2007) have studied the interrelations between the physical properties of CO and H$_2$ molecules in diffuse and translucent regions toward 23 OB stars in the Milky Way. The average $T_{\text{kin}}$ of CO molecules ($^{12}$C$^{16}$O) is $74 \pm 24 \text{ K}$, with space densities between 20 and 200 cm$^{-3}$ and an average $f = 0.22$. (There are six sight lines, where $^{13}$CO could be observed and specific excitation temperature could be determined, but in most cases (and even more for DLAs), the observation of $^{13}$CO is not achievable at present time). The above ranges covered by the parameters $n, f$, and $T_{\text{kin}}$, as well as the abundance pattern, are rather similar in the diffuse gas of the Milky Way and in DLA systems with CO lines. We note, however, that the ambient UV flux generally appears higher or equal in DLA systems compared with the Milky Way (Ge et al. 1997; Lima et al. 2000; Srianand et al. 2000, 2005, 2008; Molaro et al. 2002; Noterdaeme et al. 2010). As shown in Figure 2, the distribution of the CO excitation temperatures $T_{\text{exc}}$ obtained by Burgh et al. (2007) spans a large range of values above the local CMB temperature $T_{\text{CMB}} = 2.726 \text{ K}$ (Fixsen 2009). The average of these $T_{\text{exc}}$-values is $4.095 \pm 1.01 \text{ K}$,
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Table 1
Physical Parameters in the DLA Systems with CO Absorption Lines and Determinations of the Excitation Temperatures

| Quasar       | z      | \(T_{\text{kin}}\) (K) | \(f\) | \(n\) (cm\(^{-3}\)) | \(T_{\text{exc}}\) (CO) (K) | \(\log N(\text{CO})\) | \(\log N(\text{H}_2)\) | \(\log \frac{N(\text{CO})}{N(\text{H}_2)}\) | References |
|-------------|--------|-------------------------|------|----------------------|---------------------------|----------------|----------------|---------------------|------------|
| J0000+0048  | 2.5255 | 50                      | 0.46 \(^{+0.07}_{-0.07}\) | 80                   | 9.9 \(^{+0.7}_{-0.6}\)    | 14.95 \(\pm\) 0.05 | 20.43 \(\pm\) 0.02 | \(-5.48 \pm 0.05\) | 4          |
| J085726+185524 | 1.7293 | ...                     | ...  | ...                  | 7.5 \(^{+0.6}_{-0.6}\)    | ...            | ...            | ...                 | 3          |
| J104705+205734 | 1.7738 | ...                     | ...  | ...                  | 7.8 \(^{+0.7}_{-0.6}\)    | 14.74 \(\pm\) 0.07 | ...            | ...                 | 3          |
| J123714+064759 | 2.6896 | 108 \(^{+0.6}_{-1.0}\) | 0.24 (1.0) | 50-60            | 10.5 \(^{+0.8}_{-0.6}\)  | 14.17 \(\pm\) 0.09 | 19.21 \(^{+0.13}_{-0.12}\) | \(-5.04 \pm 0.16\) | 2          |
| J143912+111740 | 2.4184 | 105                     | 0.27 \(^{+0.04}_{-0.06}\) | 45-62            | 9.15 \(^{+0.7}_{-0.7}\)  | 13.89 \(\pm\) 0.02 | 19.38 \(\pm\) 0.10 | \(-5.49 \pm 0.10\) | 1          |
| J170542+354340 | 2.0377 | ...                     | ...  | ...                  | 8.6 \(^{+1.0}_{-1.0}\)    | ...            | ...            | ...                 | 3          |

References.
(1) Srianand et al. 2008; (2) Noterdaeme et al. 2010; (3) Noterdaeme et al. 2011; (4) Noterdaeme et al. 2017.

![Figure 2](image-url)

**Figure 2.** Excitation vs. kinetic temperatures for CO molecules in the diffuse gas on the sight lines of 23 OB stars in the Milky Way from Burgh et al. (2007); see also Srianand et al. (2008). The CMB temperature is indicated, as well as the global average of the excitation temperatures.

![Figure 3](image-url)

**Figure 3.** Excitation temperature \(T_{\text{exc}}\) of CO molecules vs. \(\log \frac{N(\text{CO})}{N(\text{H}_2)}\) for diffuse Galactic regions from the data by Burgh et al. (2007). A weighted average of \(T_{\text{exc}} = 3.69 \pm 0.33\) K is found for regions with \(\log \frac{N(\text{CO})}{N(\text{H}_2)} < -5.5\).

between the excitation temperatures of the CO molecules and the (CO/H\(_2\)) ratios for the Galactic sample. The six regions with \(\log N(\text{CO}) > 15\) are also the six regions with \(\log \frac{N(\text{CO})}{N(\text{H}_2)} < -5.5\) in Figure 3. For them, we notice a relatively well defined relation with a steep increase of \(T_{\text{exc}}\) with \(\log \frac{N(\text{CO})}{N(\text{H}_2)}\). This corresponds to the transition region towards the optically thick region, and this enables us to perform individual corrections in the transition domain. For the flat part of the curve corresponding to the optically thin region below about \(\log \frac{N(\text{CO})}{N(\text{H}_2)} = -5.5\), the mean temperature \(T_{\text{exc}}\) is 3.69 \(\pm\) 0.33 K, leading to a correction of (3.69–2.73) = 0.96 \(\pm\) 0.33 K, when compared with the Wilkinson Microwave Anisotropy Probe (WMAP) determination of the CMB temperature of 2.726 K (Fixsen 2009). For the steep region, the corrections will depend on the observed (CO/H\(_2\)) ratios. The question now is to what extent can we apply these last corrections to the DLA sample? The answer essentially depends on whether the physical parameters are similar to those in the Galactic gas.

3. The Excitation and CMB Temperatures in DLA Systems

As mentioned above, from the 40,000 quasars investigated, six CO absorption-line systems produced by clouds of diffuse or translucent gas on their sight line have yet been detected. In general, in the interstellar medium carbon is found in different forms from the external to the inner parts of the clouds: ionized, atomic, and molecular CO in central regions where the shielding from ambient UV radiation is larger. The difficulty is that at the same time, the dust extinction is generally larger, making the observations of CO absorption lines more difficult or preventing them. The noticeable successful observations of CO were performed with the Ultraviolet and Visual Echelle Spectrograph (UVES) on the Very Large Telescope (VLT) (Srianand et al. 2008; Noterdaeme et al. 2010, 2011, 2017).

3.1. CO Observations and Properties in DLA Systems

These major findings are mentioned by order of discovery. Their specific data are given in Table 1, where we collect, when available, the physical parameters of the diffuse gas in the six DLA absorbers where CO has been observed. The first detection of CO absorption lines in a DLA system was made by Srianand et al. (2008) with UVES at \(z = 2.418\) towards the quasar J143912+111740. The physical parameters given in Table 1 indicate a similarity of the physical conditions with those of the diffuse Galactic interstellar material. No collisional correction was applied. Thus, the derived value of \(T_{\text{CMB}}\) was taken equal to the observed \(T_{\text{exc}}\), which is 0.17 K lower than the theoretically predicted \(T_{\text{CMB}}(z)\).

The sub-damped Ly\(_\alpha\) system at \(z \approx 2.69\) toward J123714+064759 was studied by Noterdaeme et al. (2010) with the VLT/UVES and X-shooter spectrographs. The mean molecular...
fraction $f$-value is 0.24, but in some component of the cloud it
could be close to 1.0. This absorption region with both atomic
and molecular carbon classifies as a translucent one. From
the electronic density they derived, those authors deduced that the
local UV flux in this DLA system is similar to that in the Milky
Way. No correction was applied to $T_{\text{exc}}$ to get $T_{\text{CMB}}$, despite
the fact that this translucent region is unlikely optically thin.

Three new CO absorption-line systems were observed by
Noterdaeme et al. (2011) with the same instrument and
reduction process as before. A system at $z = 1.774$ was
observed on the sight line of J104705+205734. Two systems
were also observed: one at $z = 1.729$ toward J085726 +185524,
and another one at $z = 2.038$ towards J170542 +354430. These two systems are hardly resolved, but best-fit
models nevertheless provide the excitation temperatures. No
corrections were applied to these three systems.

A molecular cloud classified as a DLA at $z \approx 2.53$ along the
sight line of J0000+0048 has recently been studied in great
details by Noterdaeme et al. (2017). The derived molecular
fraction is $f = 0.46 \pm 0.07$, which is the highest average $f$
observed in a high-$z$ intervening system. The properties of this
translucent region compare well with those of the Galactic
Perseus complex (Noterdaeme et al. 2017). The collisional
correction derived by the authors amounts to 0.3 K on the basis
of the data by Sobolev et al. (2015). Applied to the observed
$T_{\text{exc}} = 9.9 \text{ K} \ (\pm 0.7, -0.6)$, it leads to a value $T_{\text{CMB}}$
in agreement with the standard value for this redshift.

### 3.2. Applications of the Galactic Temperature Corrections

There is evidently a great variety of physical conditions in DLA systems. Some also have an UV radiation field up to 10-100 times
the Galactic one; in that case, the molecular fraction is very low
(Reimers et al. 2003), and such systems show no CO molecular
absorption. However, the systems with C and CO molecules
typically show physical conditions and UV radiation fields close
to those of the Galactic diffuse gas. To some extent, the presence
of CO molecules imposes a limited domain in the space of the
physical parameters. Molaro et al. (2002) detect a Galactic type
UV radiation field in a DLA system at $z = 3.025$ with various C
absorption lines. Srianand et al. (2008) conclude that the physical
conditions in the object at $z = 2.418$ (with the first-discovered CO
lines) are similar to those in the diffuse Galactic clouds. For the
second discovery, Noterdaeme et al. (2010) find a molecular
fraction $f$, typical of the Galactic conditions. They also point out
the similarity of the abundance patterns. Noterdaeme et al. (2017)
also find physical properties (density, molecular fraction, UV
radiation, ...) in the Perseus-like system at $z = 2.5255$, very
similar to the conditions observed in the Milky Way. All these
comparisons support the application of the temperature corrections
based on the Galactic diffuse gas to the excitation temperature of
CO molecules in DLA systems.

A study of of the physical conditions in 33 DLA systems
with significant molecular absorption lines of H$_2$ and lines of
carbon in various excitation states has been performed by
Srianand et al. (2005) on the basis of a sample collected by
Ledoux et al. (2003). The mean kinetic temperature is 153
($\pm 78$) K, significantly higher than the Galactic one (74
($\pm 24$) K. The mean H$_2$ molecular fraction $f$ found by Ledoux
et al. (2003) is smaller than 0.1. This value is in fact an average
over the whole line of sight; the actual $f$ in the individual DLA
components may be much larger, as emphasized by Srianand
et al. (2005). The mean particle concentration is $n = 78 \text{ cm}^{-3}$,
quite within the observed Galactic range of $20$–$200 \text{ cm}^{-3}$. As to
the ambient UV radiation field, Srianand et al. (2005) conclude
that it is of the order or slightly higher than the mean UV
radiation field in the Galactic interstellar material. These results
also suggest that the local excitation processes of molecular
lines are equal or slightly higher in DLA clouds than in the
Galactic interstellar medium.

Table 2 gives the various determinations of the CMB
temperatures. The $T_{\text{CMB}}$ given by the different authors are given
in column 3. Except for J0000+0048, they are identical to the
determined excitation temperatures (see Table 1). The corrections
determined from the Galactic data in Figure 3 are given in
column 4. The corrections amounts to 0.96 $\pm 0.33$ K for objects
belonging to the flat part of the curve below log(CO/H$_2$) = $-5.5$. For objects with log(CO/H$_2$) above this
last value, the corrections are determined individually from the
red curve in Figure 3 with the same error bar of $\pm 0.33$ K,
despite that there the scatter may appear lower. The $f_{\text{CMB}}$-values obtained with these corrections are given in
column 5 of the Table 2. To enable further comparisons, the
theoretical values corresponding to the observed redshifts are
given in columns 6 and 7 for the standard and scale-invariant
cosmology respectively according to Section 4.

There is another concern, related to the slightly higher values of
$T_{\text{exc}}$ in the DLA sample, from 7.5 to 10.5 K (Table 1),
compared with 2.8 to 6.4 K in the Galaxy (Figure 2). The values of $T_{\text{exc}}$
are determined by assuming a Boltzmann distribution of the populations $N(\text{CO}, J)$ of the $J$ rotational
levels, which are fitted by a single value, $T_{\text{exc}}$. This value is
given by the slope of a plot, log($N$(CO), $J$)/$g_J$, versus the
energy $E_J$ of the $J$-level considered ($g_J$ being the statistical
weight). At least four values of $E_J$ have been considered by the
authors referenced in Table 1 up to a value corresponding to
33 K. For J0000+0048, even a value at about 55 K has been
used. In view of the broad ranges of level energies involved in
the plot, a difference between $T_{\text{exc}} = 4$ and 9 K only has a very
limited effect on the $T$-corrections. Moreover, Figure 1 shows
that the collisional corrections slightly increase with $T_{\text{exc}}$. These
facts tend to indicate that the corrections that we apply are not
overestimated, especially more than the UV flux is equal or
higher in DLA systems than in the Milky Way.

### 4. Comparisons with Cosmological Models

#### 4.1. The Classical Model

Because matter and radiation are decoupled in the present era
of the universe, energy conservation implies for the radiation
energy density $\rho_r$, $R^2 = \text{const}$. In turn, as $\rho_r \sim T^4$, we have
$T = \text{const}$. With $R_0/R = 1 + z$, this gives the classical
relation for the CMB temperature, $T_{\text{CMB}}(z)$, law; see, for
example, Peebles (1993),

$$T_{\text{CMB}}(z) = T_{\text{CMB}}(0) (1 + z).$$

(1)

The blue line in Figure 4 illustrates the past variations of $T(z)$,
as well as of the matter and radiation densities $\rho_m(z)$ and $\rho_r(z)$,
respectively. These relations are not sensitive to the shape $R(t)$
of the expansion function (only for the classical case), as are the
tests based on distances such as the $m - z$ diagram (Riess
et al. 1998; Perlmutter et al. 1999), or as the past expansion rates
$H(z)$ versus redshifts (Faroq & Ratra 2013).
4.2. The Scale-invariant Model

Several basic properties of the scale-invariant cosmology, which accounts for the scale invariance of the empty space, were studied recently (Maeder 2017). The numerical solutions of the cosmological models were presented. Comparisons with observations were performed for several major tests, with positive results. From the cosmological equations, we got the following equation of conservation:

\[ \frac{d (\rho R^3)}{dR} + 3 p R^2 + (\rho + 3 p) \frac{R^3}{\lambda} \frac{d \lambda}{dR} = 0, \]

which for a constant \( \lambda \) evidently gives the classical expression. From the equation of state in the general form \( P = w \rho \) with \( c^2 = 1 \) (\( w \) being taken here as a constant) and after integration, we obtained

\[ \rho R^{3(w+1)} \lambda^{(3w+1)} = \text{const}. \]

This implies that the curvature of space associated to a distribution of mass-energy has some dependence on \( \lambda \) and thus on time, as the scale factor \( \lambda \) is equal to \( t_0/t \) (Maeder 2017). For radiation density \( \rho_r \), we have \( w = 1/3 \), thus \( \rho_r R^4 \lambda^2 = \text{const}. \) This leads to \( T R \lambda^{1/2} = \text{const.} \), and the temperature of the CMB radiation behaves like

\[ T_{\text{CMB}}(z) = T_{\text{CMB}}(0) (1 + z)(t_0/t_0)^{1/2}, \]

For high separations amounts to 0.087 dex for \( z < 0.174 \) dex for \( \lambda \), and to 0.174 dex for \( \lambda \) in column 6 of Table 1. Column 4 shows the temperature corrections based on the Galactic data by Burgh et al. (2007) (Section 2.2). Column 5 gives the values of \( T_{\text{CMB}} \) obtained with the corrections of column 4. Columns 6 and 7 give the predicted \( T_{\text{CMB}} \) for the standard and scale-invariant theory respectively (see Section 4).

#### Table 2

| Quasar          | \( z \) | Obs. \( T_{\text{CMB}} \) (Ref. 1, 2, 3, 4) | T-corrections from Section 2.2 | Obs. \( T_{\text{CMB}} \) Corrected | \( T_{\text{CMB}}(z) \) Std. Th. | \( T_{\text{CMB}}(z) \) Sc. Inv. |
|-----------------|--------|---------------------------------|-------------------------------|---------------------------------|-------------------------------|-------------------------------|
| J0000+0048      | 2.5255 | 9.6^0.7_0.6                    | 2.57 ± 0.33                    | 7.33^0.77_0.68                  | 9.61                          | 8.27                          |
| J085726+185524  | 1.7293 | 7.5^1.2_1.0                    | 0.96 ± 0.33                    | 6.54^1.2_1.24                   | 7.44                          | 6.53                          |
| J104705+205734  | 1.7738 | 7.8^0.7_0.6                    | 0.96 ± 0.33                    | 6.84^0.77_0.68                  | 7.56                          | 6.62                          |
| J123714+064759  | 2.6896 | 10^0.6_0.6                    | 1.32 ± 0.33                    | 9.18^0.68_0.67                  | 10.06                         | 8.63                          |
| J140912+111740  | 2.4184 | 9.1^0.7_0.3                    | 1.30 ± 0.33                    | 7.85^0.77_0.67                  | 9.32                          | 8.03                          |
| J170542+354340  | 2.0577 | 8.6^1.1_1.0                    | 0.96 ± 0.33                    | 7.64^1.15_1.03                  | 8.28                          | 7.20                          |

Note. Column 3 gives \( T_{\text{CMB}} \) derived by the various authors quoted in Table 1 (no correction was applied except for J0000+0048); the error bars are the same as for \( T_{\text{CMB}}(z) \) in column 6 of Table 1. Column 4 shows the temperature corrections based on the Galactic data by Burgh et al. (2007) (Section 2.2). Column 5 gives the values of \( T_{\text{CMB}} \) obtained with the corrections of column 4. Columns 6 and 7 give the predicted \( T_{\text{CMB}} \) for the standard and scale-invariant theory respectively (see Section 4).

#### Table 3

| \( z \) | \( t \) | \( T_{\text{CMB}}(z) \) Standard | \( \lambda^{1/2} \) | \( T_{\text{CMB}}(z) \) Scale Invariant |
|--------|--------|-------------------------------|-------------------|-------------------------------|
| 0      | 1      | 2.726                         | 1                 | 2.726                         |
| 0.2    | 0.94073| 3.271                         | 0.96991           | 3.173                         |
| 0.4    | 0.89735| 3.816                         | 0.94728           | 3.615                         |
| 0.6    | 0.86441| 4.362                         | 0.92973           | 4.055                         |
| 1.0    | 0.81807| 5.452                         | 0.90447           | 4.931                         |
| 1.5    | 0.78138| 6.815                         | 0.88396           | 6.024                         |
| 2.0    | 0.75753| 8.178                         | 0.87035           | 7.118                         |
| 2.5    | 0.74102| 9.541                         | 0.86082           | 8.213                         |
| 3.0    | 0.72905| 10.904                        | 0.85384           | 9.310                         |
| 4.0    | 0.71309| 13.630                        | 0.84444           | 11.510                        |
| 10.0   | 0.68341| 29.986                        | 0.82669           | 24.789                        |
| \( 10^3 \) | 0.66945| 2.728 \( 10^3 \)             | 0.81820           | 2.232 \( 10^3 \)             |

Note. Column 1 gives the time \( t \) in a scale where \( t_0 = 1 \). Column 4 gives \( \lambda^{1/2} \).
of z. The temperature in the scale-invariant model is lower by about 1 K at z = 2 than in the standard case, corresponding to −0.060 dex. This shows that a relatively high accuracy of the observations is necessary for a significant analysis.

4.3. Comparison of Models and Observations

Figure 5 shows the variations of $T_{\text{CMB}}$ for both the standard and scale-invariant cosmological models as a function of redshift z. The theoretical data are compared with the temperatures derived from the CO molecules as given in Table 2. The blue points represent the values of $T_{\text{CMB}}$ from CO molecular lines in DLA systems as given by the authors (see Table 1). The values $T_{\text{CMB}}$ were taken identical to $T_{\text{exc}}$ (the point at $z \approx 2.53$ has been corrected for collisions). These blue points are supporting the standard case. The red points in Figure 5 give the values of $T_{\text{CMB}}$ obtained with the Galactic corrections as established in Section 2.2; see Table 2. These last results appear to favor the scale-invariant cosmological models. However, one must still be careful in the interpretation of the results in view of the small number of CO observations, which already represent a most remarkable achievement. Coming instrumental developments of high-resolution spectrographs will certainly enlarge the sample of these key observations.

5. Conclusions

The corrections to be brought to the $T_{\text{exc}}$ of CO molecules seen in absorption on the sight lines of quasars to get $T_{\text{CMB}}(z)$ are a complex problem. Nevertheless, one can safely conclude that the support generally given to the standard model by these CO observations may be questioned. The present results suggest that it is not sufficient to assume that $T_{\text{CMB}}(z) = T_{\text{exc}}(\text{CO})$ at the observed redshifts or to only apply the collisional corrections. The assumption of the scale invariance of the macroscopic empty space is, at least for now, not contradicted by these observations and it deserves further attention.

Figure 5. Temperature of the CMB vs. redshifts. The blue line gives the standard relation (Peekles 1993) and the red line gives the relation for the scale-invariant models with $\Omega_m = 0.30$ (Maeder 2017). These relations are given by Equations (1) and (4), respectively. The blue points show $T_{\text{CMB}}$ (Srianand et al. 2008; Noterdaeme et al. 2010, 2011, 2017), which are identical to $T_{\text{exc}}(\text{CO})$ except for the value at $z \approx 2.526$. The red points give the values $T_{\text{CMB}}$ derived with the empirical corrections from Section 2.2; see Figure 3 based on the data by Burgh et al. (2007). Indicative points below $z = 0.6$ are reproduced from the data on the SZ effect by Luzzi et al. (2015).

References

Andre Maeder © https://orcid.org/0000-0001-8744-0444

Bolatto, A. D., Wolfire, M., & Leroy, A. K. 2013, ARA&A, 51, 207
Burgh, E. B., France, K., & McCandliss, S. R. 2007, ApJ, 658, 446
Canuto, V., Adams, P. J., Hsieh, S.-H., & Tsiang, E. 1977, PhRvD, 16, 1643
Carroll, S. M., Press, W. H., & Turner, E. L. 1992, ARA&A, 30, 499
Chluba, J. 2014, MNRAS, 443, 1881
Dirac, P. A. M. 1973, RSFS, 333, 403
Eddington, A. S. 1923, The Mathematical Theory of Relativity (1st ed.; Cambridge: Cambridge Univ. Press)

Farooq, O., & Ratra, B. 2013, ApJ, 766, L7
Feynman, R. P. 1963, Feynman Lectures on Physics, Vol. 1 (Reading, MA: Addison-Wesley)
Fixsen, D. J. 2009, ApJ, 707, 916
Ge, J., Bechtold, J., & Black, J. H. 1997, ApJ, 474, 67
Krotkov, R., Wang, D., & Scoville, N. Z. 1980, ApJ, 240, 940
Ledoux, C., Petitjean, P., & Srianand, R. 2003, MNRAS, 346, 209
Lequeux, J. 2005, The Interstellar Medium (Berlin: Springer Verlag)
Lima, J. A. S., Silva, A. I., & Viegas, S. M. 2000, MNRAS, 312, 747
Luzzi, G., Genova-Santos, R. T., Martins, C. J. A. P., et al. 2015, JCAP, 09, 011
Maeder, A. 2017, ApJ, 834, 194
Molaro, P., Levshakov, S. A., Dessauges-Zavadsky, M., et al. 2002, A&A, 381, L64
Noterdaeme, P., Petitjean, P., Ledoux, C., et al. 2010, A&A, 523, A80
Noterdaeme, P., Petitjean, P., Srianand, R., et al. 2011, A&A, 526, L7
Noterdaeme, P., Krogauger, J.-K., Blashev, S., et al. 2017, A&A, 597, 82
Perlmutter, S., Aldering, G., Goldhaber, G., et al. 1999, ApJ, 517, 565
Reimers, D., Baade, R., Quast, R., & Levshakov, A. 2003, A&A, 410, 785
Riess, A. G., Filippenko, A. V., Challis, P., et al. 1998, AJ, 116, 1009
Sobolev, A. A., Ivanchev, A. V., Varshalovich, D. A., & Balashev, S. A. 2015, JPhCS, 661, 012015
Srianand, R., Petitjean, P., & Ledoux, C. 2000, Natur, 408, 931
Srianand, R., Petitjean, P., Ledoux, C., et al. 2005, MNRAS, 362, 549
Srianand, R., Noterdaeme, P., Ledoux, C., & Petitjean, P. 2008, A&A, 482, L39
Wannier, P., Penprase, B. E., & Andersson, B.-G. 1997, ApJ, 487, L165
Weyl, H. 1923, Raum, Zeit, Materie, Vorlesungen über allgemeine Relativitätstheorie (Berlin: Springer)
Wolfire, M. G., Hollenbach, D., & McKee, C. F. 1995, ApJ, 443, 152