A Strange Detail Concerning the Conceptualization of the Hubble Constant

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An ambiguous mathematical definition of the Hubble constant, which apparently confused two possible redshift approximations of relativistic cosmology from early times on, is fixed and cleared up here. Using a significant Hubble parameter instead of the conventional one, the authors of the Steady-state Theory might have found the line element of a 'Coasting Cosmology', possibly with far reaching implications for the historical development.

Introduction

There is a strange detail concerning a significant Hubble parameter

$$H_{\mathrm{s(significant)}} \equiv \dot{a} \equiv \frac{\mathrm{d}a}{\mathrm{d}t'} \tag{1}$$

in contrast to the conventional one

$$H_{\mathrm{c(conventional)}} \equiv \frac{\dot{a}}{a}, \tag{2}$$

where as usual the dot at $\dot{a}$ means differentiation of the FLRW scale factor $a \equiv a(t')$ with respect to the corresponding time coordinate, here t', where $t'=0$ means today {that time coordinate is used without prime by Friedman(n) 1922/24 [1], Lemaître 1927/31 [2], Robertson 1935/ 36 [3], Walker 1936 [4]}. At first a deduction of both parameters (1) and (2) is given together with the clarification of the discrepancy between them in the following section.

As a fundamental feature, it is commonly accepted from the beginning of relativistic cosmology, that there is a coordinate system where, with respect to sufficiently large scales, galaxies are statistically at rest. Therefore a natural question is: How does the redshift of the 'fixed' galaxies depend on those coordinates?

In contrast to proper length l (where $\Delta l = r$ with respect to an individual observer), any difference of such coordinates may be briefly denoted here as the 'universal' (coordinate) distance l^* with $\Delta l^* = r^*$ (temporarily without any interpretation anticipating the concept of a 'comoving' frame). The parameter H_{s} of equation (1) is called 'significant', because it will be shown here that it is directly related to the 'comoving' distance r^* which itself is directly significant for any individual galaxy or cluster by the presupposition of constant respective values except for peculiar motions.

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Tacitly about such a distinction of 'proper' and 'comoving' distances, in Hubble's 1929 paper [5] there was given the famous figure showing the "velocity-distance relation among extra-galactic nebulae". The actual historical development to that discovery of 'Hubble's law' by originally Lemaître [2] in 1927 has been pointed out in Luminet's note [6] as well as in e.g. a 2011 letter of Way & Nussbaumer [7] with references therein. These authors highlight that in addition also the concept of an expanding universe has been explicitly developed by Lemaître, in contrast to later Hubble again.

Thus the historical first findings of both the "roughly linear" velocity-distance correlation, independently rediscovered and illustrated by Hubble, as well as that of a 'universal expansion' – closely related to one another – seem clear after all. But this insight may not yet be the final word on the advance to the actual theoretical basis of today's concordance cosmology.

It is particularly an interesting question to consider possible consequences for the historical development in the middle of the last century, if then the focus had been on the significant Hubble parameter H_{s} but not on the conventional one H_{c} instead.

Confrontation of two rivaling parameters

To directly deduce both Hubble parameters (1) and (2) above, it is sufficient to use the traditional FLRW form presupposing spatial flatness in this section (spatial flatness is included in Lemaître's seminal treatment as a special case). Correspondingly, the FLRW line element may be written in the form

$$\mathrm{d}\sigma'^2_{\mathrm{FLRW}} = c^2\mathrm{d}t'^2 - a^2\mathrm{d}l^{*2}, \tag{3}$$

where $a \equiv a(t')$ is the dimensionless scale factor with $a(t'{=}0) \equiv 1$ today. If in the valid local approximation

$$\mathrm{d}l \approx a\,\mathrm{d}l^* \tag{4}$$

an equal-sign '=' was used instead of the approximate-sign '≈', then the whole relation (3) would be nothing but the line element of Special Relativity Theory (SRT) itself – whose Riemann, Ricci, Einstein tensors and therefore the entire universal mass energy density would vanish to zero.

Now, with regard to the FLRW-form (3) the redshift parameter z is

$$z \equiv \frac{a(t'_{\mathrm{A}})}{a(t'_{\mathrm{E}})} - 1 \equiv \frac{\Delta a_{\mathrm{AE}}}{a(t'_{\mathrm{E}})} \approx \frac{\dot{a}}{a}\Delta t', \tag{5}$$

where the indices E/A, stand for emission/absorption. Since light propagates according to $\mathrm{d}\sigma'_{\mathrm{FLRW}} = 0$, it follows for comparably infinitesimal intervals $\Delta t'$ of time

$$\Delta t' = \frac{a\Delta l^*}{c} \tag{6}$$

or

$$\Delta t' \approx \frac{\Delta l}{c} \tag{7}$$

because according to (4) the numerator $a\Delta l^*$ of (6) is assumed to be approximately the local element Δl of proper length. Inserting both quantities either (6) or (7) into (5), it results at first Hubble's law in its *significant* form

$$cz \approx \dot{a}\,\Delta l^* \equiv H_s\,\Delta l^* \tag{8}$$

as well as, on the other hand, approximately the corresponding law in its *conventional* form

$$cz \approx \frac{\dot{a}}{a}\Delta l \equiv H_c\,\Delta l\,, \tag{9}$$

where according to (7) the quantity $\Delta l \approx c\,\Delta t'$ is usually regarded the proper distance to the light source again.

Even in view of traditional cosmology and without any restriction to spatial flatness, however, the conventional assignment of the Hubble parameter H_c in (2) is misleading because: not the proper distance $\Delta l = r$, but the universal ('comoving') distance $\Delta l^* = r^*$ is *actually presupposed to be constant* for galaxies without peculiar motion, thus confirming expression (1) instead of (2). Independently of the respective scale factor, this clearly means the significant assignment $H_s \equiv \dot{a}$.

In view of these simple results, some characteristic steps in the development of relativistic cosmology may be reviewed here in chronological order.

A brief mathematical review

At the beginning of the last century, the extra-galactic redshifts of nebulae as observed by Slipher [8] and others have at first been assumed probably to arise due to solar motion. Thus the phenomenon of a *cosmological* redshift – definitely recognized only later – has been associated to a Doppler effect from the start.

After de Sitter in his 1917 papers [9] had introduced such a cosmological redshift to be a consequence of his model "B", as early as in 1921 Wirtz [10] using measurements of various authors in the literature came up with the suggestion of an "approximately linear relation … as if … distant [spiral nebulae] show [the tendency of] receding from our Milky Way system." 1)

Then it has been Lemaître [2], who – according to tables of Strömberg and Hubble (the first mostly relying on data of Slipher again) – expressed today's redshift parameter z approximately in terms of v/c with regard to an "apparent Doppler effect", where "v is that velocity *of the observer* which would produce the same effect" (emphasis by present author). He found 2)

L(23)
$$\frac{\dot{a}}{a} = \frac{v}{r} \tag{10}$$

where according to the unnumbered relation between his expressions L(22) and L(23) the "distance" r is implicitly introduced in the approximate form $r \approx c\Delta t'$ [he wrote d instead of Δ, R instead of a, and used a prime operator (') instead of $1/c$ times a dot (because his t equals identically ct' in the notation of the note at hand)]. – Correspondingly in Hubble's paper [5] it reads

H(unnumbered)
$$rK + \ldots = v\,, \tag{11}$$

where the constant "K represents the velocity at unit distance due to this effect" indicated in form of "a roughly linear relation".

In contrast to Lemaître who, two years before, had concluded an expansion of space, Hubble interpreted the data at least in parts as an ordinary Doppler effect due to a real radial motion ('scattering') of galaxies in a static de Sitter universe [9], which assumption, however, had already been shown by Lemaître to unacceptably "introduce a center".

Since according to Hubble [5] the residual " + …" is only accounting for peculiarities of solar motion, his relation (11) is approximately the same as Lemaître's, here (10), by identifying the conventional Hubble parameter (2) with his constant

$$K \equiv H_c\,. \tag{12}$$

About two decades after that, in the midst of last century, there appeared the 'Steady-state Theory' (SST) of Bondi & Gold [11], Hoyle [12], becoming a prominent alternative to Lemaître's 'primeval atom' concept developed from his original expanding-space model to what has been called the 'big bang' later by Hoyle.

The SST line element corresponds directly to the FLRW form (3) with the scale factor

SST(unnumbered)
$$a_{SST} = e^{H_c^{SST} t'}\,, \tag{13}$$

where H_c^{SST} was assumed to be a universal constant, identical in this case to the conventional Hubble parameter $\dot{a}/a$ as defined in (2). Taking their paper literally, the redshift parameter would be

1) *„Dagegen prägt sich in den mit Vorzeichen gebildeten Mittelwerten ein ungefähr linearer Gang in dem Sinne aus, als ob die uns nahen Spiralnebel die Tendenz der Annäherung, die entfernten die des Zurückweichens von unserm Milchstraßensystem besitzen.“* – Wirtz 1921 (translated by present author, the datings above are given here as those of the respective submissions).

2) Additional equation numbers like L(23) respectively on the left point to those in the original work of e.g. (L)emaître, (H)ubble, (W)einberg and similarly of others.

SST(1) $$z_{\rm SST}^{\rm literally} = \frac{H_{\rm c}^{\rm SST}}{c} r^* , \qquad (14)$$

since Bondi & Gold have written r for r^*, δ for $z_{\rm SST}^{\rm literally}$, and T for c/H with H for $H_{\rm c}^{\rm SST}$. The fact that their r means r^* here, is obvious from the "change from Cartesians (x,y,z) …" as used in their (unnumbered) FLRW line element "… to spherical polars (r, θ, ϕ) in the usual way", where r is one of the coordinates.

The accurately derived redshift parameter from SST's line element, however, would have been in the notation of the note at hand $z = z_0 e^{Ht'}$ instead of (14), with $z_0 = Hr^*/c$ respectively constant. In this case $z = Hr/c$ with $r = r^* e^{Ht'}$ seems to correspond to the *intended* equation (1) of their paper [11], since according to both titles [11], [12] explicitly addressing "*the Expanding Universe*", these authors obviously assumed cosmic proper distances exponentially to increase with time.[3] To keep the impression of a 'steady-state', they claimed an ongoing creation of matter filling the gaps all over the universe[4] (it seems another puzzling question, though, how the new galaxies might find their appropriate positions each sharing the 'Hubble flow' then).

In transfer to the notation used here, later Weinberg's [14] approximate relation W(14.3.7) would *significantly* read

W(14.3.7) $$\upsilon \approx \dot{a}(t'_0)\, r^* , \qquad (15)$$

which follows from his relation W(14.2.21) with $\upsilon = \dot{d}$ by replacing $d_0 :\approx r^*$ – with r^* the constant 'comoving' distance – for "relatively close" galaxies after differentiation with respect to t'. According to the usual understanding of proper length d (in contrast to d_0) without any limitation to local inertial frames, that relation may be written in the form

W(14.2.21) $$d(t') = a(t')\, d_0 . \qquad (16)$$

Then he finds approximately to first order

W(14.6.4) $$z = H_0 \Delta t' + \dots , \qquad (17)$$

after there is defined '*Hubble's constant*'

W(14.6.2) $$H_0 \equiv \frac{\dot{a}(t'_0)}{a(t'_0)} , \qquad (18)$$

which is evidently the present value of the conventional Hubble parameter, $H_0 = H_{\rm c}(t_0')$, at time t_0' for today[5]. Applying this constant (18) to (11), (12), this would obviously read

W(implicit) $$\upsilon \approx \frac{\dot{a}(t'_0)}{a(t'_0)}\, r \qquad (19)$$

according to Lemaître's approximate relation (10) above, what – taking into account that (4) is understood to imply $r \approx a r^*$[6] – consequently reduces to (15) again.

Both expressions (19) and (15), however, obviously allow two almost indistinguishable, but different versions of Hubble's linear law (11). His K may be taken either to equal $H_{\rm c}$ with his r taken the *proper* distance, or else to equal $H_{\rm s}$ with his r taken the *universal* distance r^*. Both possibilities apply as long as this famous relation (11) has only been used as an approximation to first order {in Kr – or correspondingly $K^* r^*$ [where $H_{\rm s} = K^* \equiv aK$ according to (1), (2)]}. But on the other hand, to ignore the difference between 'comoving' and 'proper' quantities is clearly inappropriate in the very phase of conceptualization.

Nevertheless at this stage, though almost two decades later again, there appeared a 'Coasting Cosmology' (CC), what meant "the universe expands with constant velocity" [16]. Consequently, with respect to a strict Doppler approach, a straightforward conclusion would have been that – neglecting peculiar motions – there are constant individual redshift parameters z of each galaxy. In spite of its suggesting title, however, in Kolb's paper [16] any such explicit statement is missing. In view of the note at hand, the reason may lie in the misleading conventional Hubble parameter (2) depending on time, thus concealing the fundamental feature of stationarity there. In present notation, the result has been found

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[3] Though relation (14) might seem plausible at first glance, it shows an inconsistency, because according to the results either (8) or (9), the 'comoving' distance $r^* \equiv \Delta l^*$ cannot appear in a valid relation together with only the *conventional* Hubble parameter as the actual factor there. In contrast to (14), however, the authors apparently have thought of the respective 'proper' distance r instead of the 'comoving' one r^*. Unfortunately such a delicate mistake – thus possibly not only an ordinary typo – is implying a mix-up of both parameters (1), (2) in this context.

[4] Recently in [13] Nussbaumer has revealed that in 1931 Einstein temporarily thought to have found the solution for a "stationary, dynamic universe in expansion" thereby anticipating the SST [11], [12] with regard to an assumed steady particle creation of out the vacuum (governed by his cosmological constant Λ representing an energy reservoir somewhat corresponding to 'dark energy' today). Nussbaumer reports that Einstein's steady-state-model collapsed, after he had found a numerical error in his calculations. – Though there is no such connection with the SUM addressed below, Einstein's meaningful attempt to a "stationary, dynamic universe" seems highly enlightening in this context, because apparently for the first time he clearly realized that 'stationary' does not at all imply 'static' even in case of the universe.

[5] In Misner, Thorne, & Wheeler [15] this same 'constant' H_0 is introduced according to the bold statement: "*Immediately observable* today is the present rate of expansion of the universe …" (the leading words emphasized by these authors). They later proceed in correspondence to Weinberg [14].

[6] According to Weinberg's W(14.2.21) above, the scale-factor assignment below the FLRW line element (3) implies that in case of flat space any comoving distance l^* equals the corresponding proper distance l today.

CC(13) $$H_{c\,(\text{coasting})} \equiv \frac{H_0}{1+H_0 t'} \,, \qquad (20)$$

suggesting a dependence of time where actually no such dependence applies. As another relation of [16] it is given

CC(28) $$H_0 d_L = z + \ldots \,, \qquad (21)$$

where d_L is the *luminosity distance*, which in case of sufficiently small values is approximately equal to both *r or r**.

Only with the development of a speculative stationary toy model [7] SUM [18], these aspects seem to have become clear.[8] That hypothetical model – not claimed to be true, and not even probable in its straight form today – has proved useful to reveal the existence of a significant Hubble parameter in contrast to the conventional one. Although mathematically its FLRW scale factor

SUM(8) $$a_{\text{SUM}} \equiv HT' \equiv 1+Ht' \qquad (22)$$

would also apply within the concept of a 'Coasting Cosmology' if specialized to flat space (hereafter the abbreviation 'CC' will include this restriction), the SUM (additionally considering intrinsic limitations of proper length and time) stands for a different approach.

Since – corresponding to (20) – the conventional Hubble parameter $H_{\text{c-SUM}}(t') \equiv \dot{a}_{\text{SUM}}/a_{\text{SUM}}$ would yield a value $H/(1+Ht')$ decreasing with time again, it seemed an unexpected puzzle to find here a stationary redshift parameter,

SUM(4) $$z = \mathbf{e}^{Hl^*/c} - 1 \,, \qquad (23)$$

in fact independent of time for equally both the CC and the SUM.[9] Just the solution of this puzzle led to the overdue introduction of a significant Hubble parameter, since it is verified at a glance, that in case of the stationary scale factor (22), now $H_s(t') \equiv \dot{a}$ actually means a true Hubble *constant*

$$H_{\text{s-SUM}} \equiv H \,. \qquad (24)$$

According to these results – also directly derivable from the FLRW form (3), (22) above – the stationary redshift (23) has been anticipated by the calculation in universal coordinates[10] based on the original SUM line element given in [18] and references therein.

Conclusion

While in apparently all later versions of Hubble's linear approximation the discrepancy between the two parameters H_s and H_c seems largely blurred, the latter quantity H_c has been shown above to be misleading in that it is coupled to the proper-distance concept, while the redshift of galaxies at rest is directly related to universal ('comoving') coordinates *by presupposition*, what is commonly accepted from the beginning until today.

If the redshift of all galaxies – existing wherever – was essentially caused by real motion, then this necessarily implies

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[7] One essential motivation for a tentative hypothetical Stationary Universe Model (SUM) is based on the following question: Given there has been something where a big-bang origin of our evolutionary cosmos took place, what is the relativistic line element describing the energy density and pressure of such a pre-existing universal background? This question is in particular suggesting itself if – allowing for e.g. Linde's chaotic inflation [17] – some physically relevant 'false' vacuum shall be taken into account (which had to be anything but empty space, thus actually requiring a solution in the framework of Einstein's gravitational equations). Unexpectedly, the speculative *Model of a stationary background universe behind our cosmos* (pre-print 2013 at independent-research.org extending [18], with new title the same as arXiv:astro-ph/0312655v6) showed – far from any attempt to declare literal truth – the strange consequence of redshift parameters which, due to a true significant Hubble *constant* here, would be independent of time, as well as it would apparently represent the supernovae type Ia (SNe-Ia) magnitude-redshift data on universal scales. The latter observation, of course, is only one of a plenty which apart from that are uniquely described by the present ΛCDM hot big-bang cosmology. On the other hand, according to the initial motivation above – making a difference between our *evolutionary 'cosmos'* and the *entire 'universe'* – an infinite number of big-bang scenarios might have taken place. Correspondingly, Linde's 'chaotic inflation' concept seems to have effectively established some universal background in the big-bang context before.

[8] In contrast to any thinkable stationary positions of galaxies, Kolb's paper [16] considers mostly "an ever-expanding closed universe" and is focused on "K-matter", while according to the SUM concept [18] there would be a gravitational pressure of –1/3 the critical density, necessarily negative. Furthermore, in [16] particularly the Hubble diagram (luminosity-distance redshift relation) is discussed for various material compositions without pointing out the possibility of those redshift parameters independent of time as underlying the corresponding figures in [18]-a, for example.

[9] Within the usual FLRW framework, it is easily verified, that according to the definition of the redshift parameter $z \equiv \lambda_A/\lambda_E - 1$ [equivalent to (5)] – where the indices E/A, stand for emission/absorption again – the extended non-local Hubble relation (23) results in its time-independent form, too. Taking into account the FLRW coordinate velocity of light $c'_{\text{SUM}} = c/a_{\text{SUM}}$, the covered radial distance $l^* \equiv l_A^* - l_E^*$ between the time of emission t'_E and the time of absorption $t'_A = 0$ today, yields $l^* = -c/H \cdot \ln(1+Ht'_E)$. From this result, calculating the redshift in complete mathematical analogy to the original derivation done by Lemaître [2], or later by e.g. Weinberg [14], the parameter z is found the same as in relation (23) again (the stationarity of the corresponding magnitude-redshift relation is a coordinate-free statement).

[10] With respect to those universal coordinates the redshift of starlight from extragalactic objects might have been interpreted as a particular extension of gravitational redshift only. Independently of whether such a phenomenon was caused by potentials of local inhomogeneities (as commonly accepted), or by a stationarily changing potential of the background universe there, one would have been dealing with formerly unknown effects of gravity, in both cases accordingly derivable from Einstein's relativity theory.

a peculiar past of the entire universe.[11] The associated pure Doppler approach has been questioned by Hubble in [5], though, who referred to de Sitter's 1917 cosmology addressing a "displacements of the spectra (…) from two sources", explicitly including "an apparent slowing down of atomic vibrations" (besides "a general tendency of material particles to scatter").

An ironic background of the further development to the present seems that if a flat-space 'coasting cosmology' had been found instead of the Steady-state Theory – with the objective of a constant H_s instead of a constant H_c [what means (22) instead of (13)] – the Supernovae Type Ia breakthrough [19], [20] of 1998/99 would have apparently confirmed such a model on non-local scales against all rivaling concepts at that time. This is evident from the figures in [18]-a, where – without changing any physical results – the original SUM line element may be replaced[12] by its numerically equivalent FLRW form (22), which together with all relevant relations are equal to those of CC. Obviously such a prediction would have matched the SNe-Ia magnitude-redshift measurements on universal scales z > 0.1 up to recent data directly.[13]

Independently of these conclusions, however, it seems already widely assumed, that only to explain the SNe-Ia magnitude redshift data – 'Hubble diagram'[14] – there had been no need to re-introduce (a strange fraction of) Einstein's cosmological constant Λ (*"größte Eselei"*) accompanied by 'dark energy' now. With hindsight, apart from Lemaître's suggestive concept there even may have been neither any reproducible facts nor any otherwise testable physical reasons which had made a model of receding galaxies mandatory for cosmology at those early times.

In clear contrast, however, today fundamentally based on particularly the recession of galaxies, the commonly accepted Cosmological Concordance Model is uniquely describing the well-known pillars of present cosmology as for example the details of primordial nucleosynthesis with regard to an overdense early state accounting for the relative abundances of the light elements. In addition, it describes other excellently confirmed sets of observations concerning e.g. both kinds of respectively the Sachs-Wolfe or the Sunyaev-Zel(') dovich effect. Most stringently, it reflects in particular all subtle details of the 2.7 K cosmic microwave background radiation including its anisotropies [23], which are clearly the strongest arguments for a hot 'big bang' in the framework of the inflationary ΛCDM model now.[15]

Nevertheless, taken together, there is (a) the fact of an at least partially misleading historical conceptualization of a conventional Hubble parameter instead of the significant one; (b) the feature that there exists a cosmological solution of Einstein's original equations (without Λ) implying stationary redshift parameters independent of time, which model should have been found instead of the so-called 'Steady-state Theory', if only Hoyle and his colleagues had checked the significant Hubble parameter instead of the conventional one; and (c) the point that this solution might have been strongly supported by the completely unexpected supernova data of the past fifteen years, when actually 'dark energy' has been found a necessary component of the inflationary ΛCDM concordance cosmology at last.

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[11] This seems even also assumed for an occasionally supposed initial false vacuum of quantum fluctuations settled 'outside' (literally contradicting the word 'universe', though).

[12] With hindsight, even along straight lines of traditional historical development, all simple SUM results might have been derived independently of any reference to the speculative stationary toy model quoted above (though this is not the way it has been done).

[13] The original talk icra.it/MG/mg12/talks/cot2_ostermann.pdf underlying [18]-a (including the Riess et al. data of [21] as well as those of The Supernova Cosmology Project [22]) shows the figures (together with the relevant relations equal for SUM and CC) in a brief sequence of the historical approach to the concept of accelerated universal expansion (for later data s. footnote 7).

[14] With regard to the usual scale-factor normalization $a(t'=0) \equiv 1$, it is used the luminosity distance $d_L = r^*(1+z)$ here in direct accordance to e.g. the general relation (14.4.14) of Weinberg [14]. This means that – even going far beyond local approximations – the magnitude-redshift plots of reference [18]a for example (or in the 2013 preprint mentioned above) are true 'Hubble diagrams' (in case of the SUM not only for today). In addition, according to e.g. equation (23), one may also plot z vs. l^* directly (s. footnote 6 in this context).

[15] Though "… this is not equivalent to declaring its unvarnished truth" as stated by Martinez & Trimble in [24], these words are expressing what quite a few physicists may feel. Concerning the speculative SUM concept, however, a universe in which the galaxies were not receding from each other might have been a possible model at the times of Hubble's [5] paper or at those of the SST articles [11], [12], while the actual explanation of current data is necessarily based on the recession of galaxies now.

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