A direct consequence of the expansion of space?

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ABSTRACT

Consider radar ranging of a distant galaxy in a Friedman-Lemaître cosmological model. In this model the comoving coordinate of the galaxy is constant, hence the equations of null geodesics for photons travelling to the distant galaxy and back imply

$$\int_{\tau_o}^{\tau_r} \frac{d\tau}{a(\tau)} = \int_{\tau_r}^{\tau_o} \frac{d\tau}{a(\tau)}.$$  

Here, $\tau_o$, $\tau_r$, and $\tau_0$ are respectively the times of emission, reflection and observation of the reflected photons, and $a(\tau)$ is the scale factor. Since the universe is expanding, $a(\tau)$ is a monotonically increasing function, so the return travel time, $\tau_0 - \tau_r$, must be greater than the forward travel time, $\tau_r - \tau_o$. Clearly, space expands, and on their way back, the photons must travel a longer distance! The present paper explains why this argument for the expansion of space is wrong. We argue that, unlike the expansion of the cosmic substratum, the expansion of space is unobservable. We therefore propose to apply to it – just like to the ether – Ockham’s razor.

1 INTRODUCTION

Modern cosmology is based upon general relativity (GR), and many results of GR defy our expectations based upon special relativity (SR). For example, in Friedman-Lemaître (FL) cosmological models distant galaxies recede with superluminal recession velocities (e.g., Davis & Lineweaver 2004), and the distance to the particle horizon is greater than $c \tau_0$, where $\tau_0$ is the age of the Universe. To ‘explain’ these and other GR effects in cosmology, the idea of the Expansion of Space (EoS) is evoked. Namely, in this interpretation of the FL models, the motion of galaxies is not a normal motion through space, but instead space itself is expanding and carrying the galaxies and other matter along. This description seems to be supported by the existence of comoving coordinates, which remain fixed for all particles of the FL cosmic substratum. The notion of the EoS is intended to help understanding that, in cosmology, one should not expect SR to hold. With respect to this particular purpose, this notion certainly does its job. In our opinion, however, it constitutes simultaneously a serious conceptual pitfall, on several levels:

- On a philosophical level, it suggests that the expansion of the universe can be detached from the matter that is participating in the expansion. However, we know that, as he was constructing GR, Einstein was greatly influenced by the thoughts of German physicist and philosopher Ernst Mach. In the words of Rindler (1977), for Mach “space is not a ‘thing’ in its own right; it is merely an abstraction from the totality of distance-relations between matter”. Therefore, the idea of expanding space ‘in its own right’ is very much contrary to the spirit of GR.
- On a physical level, it suggests that the EoS is a geometric effect, so space itself is absolute. Then, though abolished in SR, in cosmology absolute space reenters triumphally the cosmic arena, endowed with an additional attribute: expansion.
- Again on a physical level, it suggests the existence of a new mysterious force. If so, one can expect non-standard effects also on small scales. For example, one might expect particles to be dragged along by the EoS. Davis, Lineweaver and Webb (2003), Whiting (2004), Barnes et al. (2006) and Peacock (2007) show that this is not the case. Also, wavelengths of laboratory photons should change roughly by the factor $1 + H_0 \tau_{\text{exp}}$, where $\tau_{\text{exp}}$ is the duration of a given experiment and $H_0$ is the Hubble constant (Lieu & Gregory 2006a). This is also wrong (Lieu & Gregory 2006b).
- On a psychological level, it suggests that we cannot use our classical intuition. In other words, we cannot think of the physical problem as real, relativistic motions of matter in presence of gravity, but as an abstract, geometric effect, where no visual ‘models’ are possible. However, according to Longair (2003), model building in physics is very important and useful: “(...) when I think about some topic in physics or astrophysics, I generally have some picture, or model, in my mind rather than an abstract or mathematical idea.” Classical intuition certainly has its limitations – in particular it fails for the Planck era of the cosmological expansion – but here we are talking about classical GR and its effects.

One may argue that the concept of expanding space does have an appealing visualization: the surface of an inflated balloon, with dots on it representing galaxies. However, when interpreting this picture as an illustration of the EoS, there is a problem. Really moving galaxies have kinetic energy; do so those entirely driven by the expansion of massless space? The answer is not clear, the more that the latter are often claimed to be ‘effectively’ at rest, i.e., relative to the cosmic microwave background. For example, in an expanding universe in which an untethered galaxy approaches us exposes the common fallacy that ‘expanding space’ is in some sense trying to drag all points apart (...). It does (....) highlight the common false assumption of a force or drag associated with the EoS.”
background. Therefore, while the interpretation of the cosmological expansion as real relative motions of the cosmic substratum leads naturally – for nonrelativistic velocities – to the Newtonian interpretation of the FL equations (in particular, energy conservation: Milne 1934; McCrea & Milne 1934), that based on the idea of expanding space does not.

Still, isn’t space expanding from a global point of view? Spatial sections of a closed FL model are three-spheres, whose radius of curvature increases as \( a(\tau) \). Here, \( a(\tau) \) is the so-called scale-factor, a universal function of cosmic time which describes how the distances between all elements of the cosmic substratum (or, fluid) grow with time. Therefore, the proper volume of a closed FL universe increases as \( [a(\tau)]^3 \); more and more space thus appears. The same is true for open and critical FL models, though in these models the universe has infinite extent. Peacock (2007) calls this effect “global Expansion of Space”. He makes a clear distinction between the concepts of global and local EoS, and attacks only the latter: “the very idea that the motion of distant galaxies could affect local dynamics is profoundly anti-relativistic: the equivalence principle says that we can always find a tangent frame in which physics is locally special relativity”. Isn’t the global EoS a fact?

A consistent Machian (like the author of the present paper) would reply that since the cosmic substratum is expanding, it is not surprising that the volume occupied by it increases. However, it is the cosmic substratum that is really expanding. Indeed, through observations we can only detect the motions of the particles of the cosmic substratum. For example, if we lived long enough, we could measure the radar distance to a distant galaxy and discover that it increases with time. Changing distance implies motion, and increasing distance implies recession. But how can one measure distance to something that is not material? We believe, after Mach and Einstein, that ‘unobservables’ – like ether or its cosmological disguise, expanding space – have no place in physics. On the other hand, it is true that the Big Bang was not an explosion in a preexisting void. Galaxies do not move through space or in space. In a Machian view, they move instead with space: they simply enable space to exist.

Superluminal recession velocities of distant galaxies are used as an argument for the EoS (Linde & Davis 2005). Specifically, it is argued that the motions cannot be ‘normal’, otherwise they would violate SR. If we define ‘normal’ motion as the one taking place in Minkowskian spacetime, the last inference is correct. As mentioned above, superluminality of distant galaxies and ‘ ACAUSALITY’ of the particle horizon are GR effects and they don’t comply with SR. However, by no means this implies that the only possible interpretation of the GR cosmological equations is the EoS. An alternative interpretation, advocated here, is that these equations describe nothing more than real relative motions of the particles of the cosmic substratum. In this interpretation, superluminality of distant galaxies and ‘ ACAUSALITY’ of the particle horizon can be well understood (though understanding always demands more effort than deriving). In particular, in at least one FL model (namely, the empty model), superluminality of distant galaxies is merely a coordinate effect: the inertial recession velocities are subluminal (Davis 2004, Chodorowski 2007, Grøn & Elgarøy 2007; see also Chodorowski 2005).

The misunderstanding of identifying EoS with GR and real motions with SR dates back to Milne (1934). For he wrote: “The phenomenon of the expansion of the universe has usually been discussed by students of relativity by means of the concept of ‘expanding space’. This concept, though mathematically significant, has by itself no physical content; it is merely the choice of a particular mathematical apparatus for describing and analysing phenomena. An alternative procedure is to choose a static space, as in ordinary physics, and analyse the expansion-phenomenon as actual motions in this space. (...) Einstein’s general relativity adopts the first procedure; in my recent treatment of the cosmological problem I adopted the second procedure. (...) the second procedure has the advantage that it employs the space commonly used in physics.” In his original work on kinematic cosmology, Milne (1933) specified what he meant as ‘the space commonly used in physics’: “flat, infinite, static Euclidean space”. He also wrote: “Moving particles in a static space will give the same observable phenomena as stationary particles in ‘expanding space’” (Milne 1934). These statements are wrong in general. In his desire to abolish ‘expanding space’, Milne went too far: he attempted to abolish GR, or to prove that it is not indispensable in cosmology. This erroneous, dichotomic way of thinking about motions in cosmology: either EoS and GR, or real motions and SR, has been inherited and is shared by many contemporary authors. For example, Abramowicz et al. (2006) show that FL cosmological models are not (except for the Milne model) compatible with SR, and use this fact as an argument for the EoS (see also Grøn & Elgarøy 2007).

In the present paper, we argue against the EoS, but not against GR. Specifically, in the framework of GR we analyze critically another argument for the EoS, which is fairly often heard: the travel time of photons. In all expanding FL universes, the forward travel time of photons travelling to a distant galaxy and back is claimed to be smaller than the return travel time. The difference in these two travel times is commonly attributed to the phenomenon of the EoS. In Section 2 we relate the two travel times in the conventional Robertson–Walker (RW) coordinates. We study in Section 3 the special case of an empty universe and compare the two times in the Minkowskian coordinates. In Section 4 we introduce conformally Minkowskian coordinates for general FL models and obtain the resulting relation between the two times. We discuss the travel-time effect and some other effects commonly attributed to the EoS in Section 5. A summary is given in Section 6.

### 2 ROBERTSON-WALKER COORDINATES

The metric of a homogeneous and isotropic universe is given by the RW line element:

\[
dS^2 = c^2d\tau^2 - a^2(\tau)[dx^2 + R_0^2S^2(x/R_0)d\psi^2].
\]

Here,

\[
d\psi^2 = d\theta^2 + \sin^2\theta d\phi^2,
\]

and \( R_0^{-2} \) is the present curvature of the universe. The function \( S(x) \) equals \( \sin(x) \), \( x \), and \( \sinh(x) \) for a closed, flat, and open universe, respectively. The scale factor \( a(\tau) \) relates the physical,

\(^2\) By sending photons to the galaxy at several instants of time and noticing that the differences between the arrival times of the reflected photons are greater than the differences between the emission times.

\(^3\) Contrary to what is widely believed.
or proper, coordinates of a galaxy, \( l \), to its fixed or comoving coordinates, \( x \): \( 1 = ox \). This function accounts for the expansion of the universe; its detailed time dependence is determined by the FL equations.

Photons propagate along null geodesics, \( ds = 0 \). Let us place an observer at the origin of the coordinate system; then the geodesic of the photons emitted by the observer towards any distant galaxy will be radial. We denote the comoving radial coordinate of a distant galaxy by \( x_g \). From the metric (1) we have

\[
\int_{\tau_e}^{\tau_r} \frac{d\tau}{a(\tau)} = \int_0^{x_g} \frac{dx}{x_g},
\]

where \( \tau_e \) is the emission time of the photons and \( \tau_r \) is the time they reach the distant galaxy. Let’s assume that at the distant galaxy the photons are instantaneously reflected towards the observer. Since the comoving coordinate of the distant galaxy is constant, we can write an analogous equation for the returning photons. As a result,

\[
\int_{\tau_r}^{\tau_e} \frac{d\tau}{a(\tau)} = \int_{\tau_r}^{\tau_0} \frac{d\tau}{a(\tau)},
\]

where \( \tau_0 \) is the observation time of the photons by the observer at the origin. Now, \( a(\tau) \) is a monotonically increasing function, so for the two above integrals to be equal, \( \tau_0 \) must be smaller than \( (\tau_e + \tau_r)/2 \). In other words, the return travel time, \( \tau_0 - \tau_r \), must be greater than the forward travel time, \( \tau_e - \tau_r \). Eureka! Space expands, so on their way back, the photons must cover a longer distance! This is in a marked contrast with SR, where the two travel times are always equal.

Perhaps surprisingly, there is a loophole in the above line of reasoning. Namely, the instants of time \( \tau_e \), \( \tau_r \), and \( \tau_0 \) are not measured in the same rest frame. While \( \tau_e \) and \( \tau_0 \) are measured in the observer’s rest-frame, \( \tau_r \) is measured in the rest frame of the distant galaxy.\(^4\) From now on, we will denote this latter time \( \tau'_r \) rather than \( \tau_r \). These two frames – the observer and the galaxy – are in relative motion. Therefore, due to relativity of simultaneity, in the observer’s frame the time attributed to the event of reflection of the photons will be different (\( \tau'_r \) instead of \( \tau_r \)). If both rest-frames were globally inertial then the Lorentz transform would relate them and one could predict the relation between \( \tau_r \) and \( \tau'_r \) using solely SR. However, in the presence of the gravitational field all inertial frames are only local. Therefore, the only cosmological model in which we can relate the two instants of time using SR is the empty model. In an empty universe there is no gravity, so inertial frames are global. In the following section we will calculate \( \tau_r \) for this model.

3 EMPTY UNIVERSE

Expansion of an empty universe is kinematic, \( a(\tau) \propto \tau \). Applied to Equation (4), this yields

\[
\tau'_r = \sqrt{\tau_e \tau_0}.
\]

In the empty model the reflection time \( \tau'_r \) (measured in the rest frame of the distant galaxy) is thus the geometric mean of the instants \( \tau_e \) and \( \tau_0 \); it is indeed smaller than the arithmetic mean.

\(^4\) For in the RW coordinates, time \( \tau \) is always the time of a local test frame.

The dynamics of an empty universe can be described entirely by means of the Milne kinematic model. In this model, the arena of all cosmic events is pre-existing Minkowski spacetime. In the origin of the coordinate system, \( O \), at Minkowskian time \( t = 0 \) an ‘explosion’ takes place, sending radially so-called Fundamental Observers (FOs) with constant velocities in the range of speeds \((0, c)\). The FO, which remains at the origin (the ‘central observer’) measures time \( \tau = t \). The adopted global Minkowskian time \( t \) is thus the proper time of the central observer. At time \( \tau_e \) this observer emits photons, which at time \( \tau_r \) reach a FO riding on a galaxy receding with velocity \( v \), such that \( v \tau_r = c(\tau_r - \tau_e) \). Hence,

\[
v = (1 - \tau_e/\tau_r)c.
\]

Relative to the set of synchronized clocks of the inertial frame of the central observer, the clock carried out by the FO riding on the distant galaxy, \( \tau' \), delays:

\[
\tau_r = \gamma(v)\tau' - \tau_e.
\]

Using Equation (6) in Equation (7) yields

\[
\tau_r = \frac{1}{2} \left( \frac{\tau_e^2}{\tau_0} + \tau_e \right).
\]

In turn, using Equation (5) in Equation (8) yields finally

\[
\tau_r = \frac{\tau_e + \tau_0}{2}.
\]

According to the central observer, the travel times \( \tau_0 - \tau_r \) and \( \tau_r - \tau_e \) are thus equal. We see that in the empty model, the effect of non-equal travel times is explicable entirely by the special-relativistic phenomenon of time dilation.

Reasoning that the effect can be attributed to the EoS was in fact non-relativistic and as such had to be wrong, for it had to fail for light propagation. This reasoning used the analogy of a swimmer swimming in a river against the stream, so it implicitly assumed non-relativistic, Galilean law of addition of velocities. Just after photons’ reflection, their local velocity (relative to the distant galaxy) is \( v' = c \), and the galaxy recedes from the observer with velocity \( V \). Using the Galilean law, the velocity of the reflected photons relative to the observer is

\[
v = v' - V = c - V < c.
\]

Then, it indeed takes longer time for the photons to return to the observer.\(^5\) However, one of the main postulates of theory of relativity is that if \( v' = c \), then also \( v = c \). This postulate is a direct consequence of the null results of all the ether-drift experiments (Michelson–Morley, Kennedy–Thurberlde, etc.). These experiments attempted to indirectly detect the ether (identified with Absolute Space, i.e., an absolute standard of rest) by detecting the motion of the laboratory frame relative to it, assuming the Galilean law of addition of velocities. Their null results imply that for light, the analogy of a swimmer in a river does not work: its \( v \) is \( c \) in every inertial frame. One cannot detect the flow of ether; similarly one cannot detect the Hubble flow of expanding space. Einstein used Ockham’s razor to the ether - as unobservable – and declared

\(^5\) More specifically, \( \tau_0 - \tau_r = (1 - V/c)^{-1}(\tau_r - \tau_e) \). This Galilean relation can be obtained alternatively by noticing that relative to the distant galaxy, the reflected photons travel longer distance than \( r_x = c(\tau_r - \tau_e) \); this distance is \( r_0 = r_x + V(\tau_0 - \tau_r) \). Then the relation follows from the equality \( r_0 = c(\tau_0 - \tau_r) \).
it non-existent. Are the concepts of ether and expanding space much different?

4 GENERAL FRIEDMAN-LEMAÎTRE MODELS

In Milne’s terminology, RW coordinates constitute ‘public space’, while inertial (Minkowskian) coordinates define ‘private space’ of an observer. In a non-empty universe there are no global inertial frames. From this, Grøn & Elgarøy (2007) deduce that in the real universe it is impossible to define ‘private space’ of an observer: “In curved spacetime (...) the only real space is the public space.” But this is not so.

All FLRW models are conformally flat. In other words, their line elements can be expressed as a product of the Minkowski metric, $ds^2_{\text{M}} = c^2 dt^2 - dr^2 - r^2 d\psi^2$, and a function of time and distance:

$$ds^2 = f^2(t,r)ds^2_{\text{M}}.$$  \hspace{1cm} (10)

Relativists are aware of this fact: it is easy to show that the Weyl tensor of the RW metric (Eq. 1) identically vanishes (Krasinski, private communication). Some modern textbooks on cosmology do mention this (e.g. Peacock 1999). To our knowledge, however, none of them presents an explicit form of the RW metric in conformally Minkowskian coordinates. We think that this form is worth reminding; it was derived and thoroughly discussed in a superb paper of Infeld & Schild (1945). The paper of Infeld & Schild is highly mathematical, so in our derivation below we will follow a more intuitive approach outlined in Landau & Lifshitz (1979).

If a universe is spatially flat, finding conformally Minkowskian coordinates is trivial. We define the conformal time, $\tilde{\eta}$, by the equation $c d\tau = a d\tilde{\eta}$. Then the RW metric (Eq. 1) becomes

$$ds^2 = a^2(\tilde{\eta})(c^2 d\tilde{\eta}^2 - dx^2 - x^2 d\psi^2),$$  \hspace{1cm} (11)

so it is conformally flat. However, we are interested in finding conformally Minkowskian coordinates for all FLRW models. Let us concentrate on the case $\Omega_0 < 1$, where $\Omega_0$ is the present value of the mean total energy density in the universe in units of the critical density. (The case $\Omega_0 > 1$ can be treated similarly). The radius of the curvature is

$$R_0 = \frac{cH_0^{-1}}{\sqrt{1 - \Omega_0}}.$$  \hspace{1cm} (12)

We rescale the comoving coordinate, $\chi \equiv x/R_0$, and define the time-like coordinate $\eta$ by the equation $c d\tau = R_0 a d\eta$. The RW metric then becomes

$$ds^2 = R_0^2 a^2(\eta)[d\eta^2 - dx^2 - \sinh^2(\chi) d\psi^2],$$  \hspace{1cm} (13)

so $\eta$ is not the conformal time. Let us now introduce new variables

$$r = Ae^\eta \sinh \chi,$$  \hspace{1cm} (14)

and

$$ct = Ae^\eta \cosh \chi,$$  \hspace{1cm} (15)

where $A$ is a constant. The old variables expressed in terms of the new ones are:

$$Ae^\eta = \sqrt{c^2 t^2 - r^2},$$  \hspace{1cm} (16)

and

$$\tanh \chi = \frac{r}{ct}.$$  \hspace{1cm} (17)

From Equations (16)–(17) we obtain

$$d\eta = \frac{c^2 t dt - r dr}{c^2t^2 - r^2},$$  \hspace{1cm} (18)

and

$$d\chi = \frac{ct dr - rc dt}{c^2t^2 - r^2}.$$  \hspace{1cm} (19)

This yields

$$d\eta^2 - d\chi^2 = \frac{c^2 dt^2 - dr^2}{c^2t^2 - r^2}.$$  \hspace{1cm} (20)

From Equations (14) and (16), $\sinh^2(\chi) = r^2/(c^2 t^2 - r^2)$. Hence,

$$d\eta^2 - d\chi^2 - \sinh^2(\chi) d\psi^2 = \frac{c^2 dt^2 - dr^2 - r^2 d\psi^2}{c^2t^2 - r^2},$$  \hspace{1cm} (21)

or, using Equation (13),

$$ds^2 = \frac{R_0^2 a^2(\eta)}{c^2t^2 - r^2} ds^2_{\text{M}}.$$  \hspace{1cm} (22)

In the above equation, $\eta$ is a function of $t$ and $r$ given by Equation (16).

Equation (22) is valid for any open FLRW model. Here, for illustrative purposes we will restrict ourselves to a matter-dominated open universe without the cosmological constant: $\Omega_\Lambda = 0$, $\Omega_0 = \Omega_m < 1$. Then the scale factor is

$$a(\eta) = a_*(\cosh \eta - 1),$$  \hspace{1cm} (23)

where

$$a_* = \frac{\Omega_0}{2(1 - \Omega_0)}.$$  \hspace{1cm} (24)

The scale factor is normalized so that its present value $a_0 = a(\eta_0) = 1$. We have $\cosh \eta - 1 = (1 - e^{2\eta})/(2e^{\eta})$, and after some algebra, the square root of the conformal factor is

$$\frac{R_0 a(\eta)}{\sqrt{c^2t^2 - r^2}} = \frac{R_0 a_*}{2A} \left(1 - \frac{A}{\sqrt{c^2t^2 - r^2}}\right)^2.$$  \hspace{1cm} (25)

Adopting $A = a_* R_0/2$, and using Equations (12) and (24), we obtain finally the RW metric in the form given by Equation (10), with

$$f(t, r) = \left[1 - \frac{cH_0^{-1} \Omega_0}{4(1 - \Omega_0)^{3/2} \sqrt{c^2t^2 - r^2}}\right]^2.$$  \hspace{1cm} (26)

Note that in the limit $\Omega_0 \to 0$ the conformal factor $f(t, r) \to 1$ and the metric (10) tends to the Minkowski metric, as expected.

The coordinates $t$ and $r$ are thus a generalization of Minkowskian coordinates for non-empty universes. Therefore, they naturally define ‘private space’ of the Fundamental Observer, on whom the metric is centered. More specifically, we define his ‘private space’ as space-like sections of the metric (10), hypersurfaces $t = \text{const}$. This ‘private space’ has many interesting properties, but their full discussion is outside of the scope of the present paper and will be given elsewhere. Let us only note in passing that from Equation (17) FOs, or galaxies on which they ride, have world-lines given by the equation

6 In the limit $\Omega_0 \to 1^-$ the conformal factor (Eq. 26) blows up, but then $R_0 \to \infty$ and the metric tends to the form given by Equation (11).
\[ r = \tanh(x/R_0)ct. \] 

Since the comoving coordinate \( x \) of any galaxy is constant, all galaxies recede from the central one with constant coordinate velocities, with speed \( v = \tanh(x/R_0)c \), or

\[ \beta \equiv \frac{v}{c} = \tanh(x/R_0). \] 

From metric (10) we immediately see that in the conformally Minkowskian coordinates, light-cones (\( ds = 0 \)) are the same as in SR. As a result, in these coordinates the speed of light is exactly \( c \). From Equation (28) it follows that the recession velocities of all galaxies, even arbitrarily distant (in the sense \( x \to \infty \)) are subluminal. This is in contrast to the recession velocities in the RW coordinates, which become superluminal for sufficiently distant galaxies.

Let us now return to the main topic of the present paper, that is the travel time of photons. Since in the conformally Minkowskian coordinates light-cones are the same as in SR, in these coordinates the travel times of photons travelling to a distant galaxy and back are always equal. We thus see that both the superluminality of distant galaxies and the light travel-time effect are merely coordinate effects: they can be eliminated by the choice of a suitable coordinate system.

5 DISCUSSION

An effect which is coordinate-independent is a real phenomenon, which different observers will agree on. Such a phenomenon is the expansion of the universe: one can describe it in many coordinate systems, but the expansion scalar of the cosmic substratum, \( \theta \equiv \frac{\partial x}{\partial t} \) (here, the semicolon denotes a covariant derivative), is an invariant and its measured value is positive. Conversely, an effect which is entirely coordinate-dependent is not a real physical phenomenon. It is solely an artifact of the used coordinate system. The superluminality of distant galaxies and the light travel-time effect belong to this latter category. Therefore, they cannot be used as arguments for any real phenomenon; in particular, for the phenomenon of the EoS.

Still, it is instructive to understand why these effects appear in the RW coordinates. The reason is as follows. In cosmology, we usually work in the RW coordinates, or in ‘public space’: we use local coordinates of all FOs, and in particular we measure common ‘cosmic time’. However, an alternative approach is possible: an analysis in ‘private space’ of a given FO, employing its ‘private time’. In the Milne model (empty universe), private space and time are defined by the Minkowskian coordinates of the FO’s inertial rest-frame. In non-empty models, they are defined by a natural generalization thereof (i.e., conformally Minkowskian coordinates). Public space is a hybrid of many local ‘private spaces’, or inertial rest-frames of different FOs, all in relative motion. As a result, public space is not a global inertial frame, even in the Milne model, while the velocity of light in vacuum is \( c \) only in inertial frames. More specifically, the time and length measures of different FOs are subject to relativistic time-dilation and length-contraction. It is therefore not surprising that in public space, the superluminality of distant galaxies and the travel-time effect are present even in the Milne model. Like other FL models, this model possesses also ‘acausal’ distance to the particle horizon (greater – in fact, infinitely – than \( c\tau_0 \), where \( \tau_0 \) is the age of the universe). The explanation is again time-dilation (Chodorowski 2007), and all FL models with no initial period of deceleration are expected to possess no particle horizon (or, to have it infinite).

We work in public space, or RW coordinates, for convenience. The symmetries, which we endow our model of the universe with, are apparent in the resulting field (FL) equations. In particular, the density field of the cosmic substratum is homogeneous and isotropic everywhere. In the conformally Minkowskian coordinates this is no longer true: the density field around a given FO is isotropic but not homogeneous (Landau & Lifshitz 1979). The RW coordinates are thus more convenient for calculations. However, the conformally Minkowskian coordinates are useful to interpret some of the results, obtained in RW coordinates, which defy our expectations based on SR. As stated above, among them are the superluminality of distant galaxies, acausal distance to the horizon and the travel-time effect. A ‘common denominator’ of all these effects is relativistic time dilation. This physical explanation contrasts with an alternative, standard explanation: a consequence of the EoS. In the latter case, the EoS serves effectively as a rug under which we sweep up everything we don’t fully understand.

6 SUMMARY AND CONCLUDING REMARKS

This paper has been devoted to a critical discussion of the concept of the Expansion of Space (EoS) in cosmology. We have argued that expanding space is as real as ether, in a sense that they are both unobservable. More specifically, propagation of light is a relativistic phenomenon: for light, the analogy of a swimmer in a river does not work; the velocity of light is \( c \) in every inertial frame. This explains the null results of all the ether-drift experiments, and enables one to predict the null results of any expanding – or drifting – space experiments.

We have shown that both the superluminality of distant galaxies and the travel-time effect for photons are merely coordinate effects: they vanish in a suitably chosen coordinate system. Therefore, they are not real phenomena, which different observers will agree on. In the Milne model, the travel-time effect – present in the RW coordinates – is explicable entirely by the relativistic phenomenon of time dilation. Since in the real universe distant galaxies recede with relativistic velocities, time dilation must play a role also in the case of more realistic FL models.

The concept of the EoS has been invented to stress that the GR description of the expansion of the universe can conflict with our intuitions based on SR. However, for non-specialists this concept can be very misleading: in their minds, it can easily become endowed with force or some sort of physical or causal power. This point has been extensively discussed in Section 1. Therefore, the author of the present paper prefers to advocate an alternative, semi-popular description, or model, of the universe and its expansion. Namely, the universe is like the Milne model, but with effects of mutual gravity. Gravity modifies relative motions of the particles of the cosmic substratum and makes GR in cosmology indispensable. The conflict of the GR description of distant events in the universe with our SR expectations is only apparent: the velocity of light in vacuum is \( c \) only in inertial frames, while in the real universe such frames are only of limited extent.

Is the concept of the EoS dangerous also for specialists? Not necessarily. Some specialists use it, but in a somewhat different sense: for them, the EoS is just the GR solution for the
expansion of the universe when expressed in RW coordinates (Davis, private communication). Also, all relativists agree that matter and space are inexorably intertwined in GR. Therefore, indeed the debate on the meaning and the use of the phrase ‘Expansion of Space’ “is somewhat a matter of philosophy and semantics, rather than hard science” (Davis, private communication). However, we believe that philosophy and semantics do matter in cosmology. Therefore, we suggest to avoid using the phrase ‘Expansion of Space’, as potentially leading to confusion and wrong intuitions.

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