Expansion of the Universe and Spacetime Ontology*

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The theory of the expanding universe is
in some respects so preposterous that
we naturally hesitate to commit ourselves to it.
It contains elements apparently so incredible that
I feel almost an indignation
that anyone should believe in it
– except myself.
Arthur Eddington[1]

ABSTRACT

The debate on the ontological status of spacetime in General Relativity has historically seen two principal philosophical contenders: substantivalism, roughly the view that holds that spacetime exists apart from the material contents of the universe, and relationism, the doctrine that spacetime does not exist, i.e., it is a mere abstract web of spatiotemporal relations among bodies. This dispute, however, has rarely been fought on a cosmological battlefield. In this paper an attempt in this direction is made. The question at issue is the following: is there any feature of our universe that requires or is best explained in terms of a substantival space? I claim that there is indeed: the expansion of the universe, perhaps the most important phenomenon in cosmology, can play such a role.

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[1] Eddington 1933, p. 124.

The expansion of the universe appears as a simple idea: it means that «the proper physical distance between a [typical] pair of well-separated galaxies is increasing with time, that is, the galaxies are receding from each other» (Peebles 1993, p. 71) with velocities proportional to their distances. The systematic redshifts of radiation emitted by distant galaxies are the primary piece of evidence regarding expansion we can gather from direct observations.[2] General-relativistic interpretation of these *cosmological redshifts* is widely accepted, though often challenged and sometimes misinterpreted; in any case, it is still not an exaggeration to say that cosmological redshift is «the most important fact of modern cosmology» (Merleau-Ponty 1965, p. 28). According to this physical interpretation, the wavelength of the emitted radiation from a distant source is stretched during its travel from this source to the observer so that the cosmological redshift is an effect of the large-scale expansion of the universe when regarded as an expansion of space.[3] Hence the global recession of galaxies originates in the dynamical evolution of the universal spacetime metric, and not from the effective motion of galaxies *through* a *static* space, in which case redshift would be interpreted as a classic Doppler shift. However, some authors argue that the expansion of space is a mere coordinate-dependent effect and redshifts are Doppler shifts. Accordingly, the interpretation of the universal expansion is still being debated among cosmologists, especially in these last years in light of new cosmological data.

In this paper I analyse some aspects (confined to classical General Relativity (GR) and to those cosmological models describing homogeneous and isotropic universes) of such a rich debate, favouring those related to the nature of the redshift. I will try to show how its different interpretations, correlated with astronomical observations, might become a crucial discriminating link not only between possible choices of cosmological models but also between ontological commitments on spacetime. I argue that the cosmological interpretation of redshift privileges a substantivalist ontology of spacetime insofar as universal metric field at large scales has an active role in wavelength stretching. On the

[2] However, the expansion of the universe, and the Big Bang theory in which it is mostly codified, is also supported by other phenomena, *in primis* by the interpretation of the cosmic microwave background radiation as the relic radiation from a hot big bang, and by the cosmic abundances of helium and deuterium produced in a primordial hot phase of the universe.

[3] *Distant* objects are those with redshifts of order one or more, for which, as will be clear later, the light-travel distances involved are comparable to the curvature length scale of the universe; thus, at these distances, spacetime cannot be approximated as flat.

contrary, a relationist point of view regarding expansion would be sustainable only in arguing in favour of effective galactic motions through a non-expanding space; in particular, relationists would have to resort to Doppler interpretations and accordingly fall back on cosmologically unfruitful descriptions based on Special Relativity (SR).

The plan of the paper is as follows: in section 1, I review the Doppler and cosmological redshifts with their differences in order to introduce, in section 2, the most common approach to the expansion of the universe, the so-called expanding space paradigm. In section 3, I explain in which sense the expansion of space is regarded as a coordinate-dependent concept. After having expounded, in section 4, the theoretical and observational reasons favouring a cosmological interpretation of distant redshifts, I take a closer glance at the expansion: its simpler physical aspects (section 5) and its effects on local systems (section 6). Starting from section 7, some philosophical analyses of the expansion are pursued, showing how it sustains a substantivalist metaphysics on spacetime (section 8), whereas a relational one is not satisfactory (section 9).

1. A LITTLE BIT OF TECHNICAL BACKGROUND

It is well known that it is possible to recognize the atomic origin of incoming light from the pattern of the received spectral lines, each line being a precise measurable wavelength. Hence it is possible to compare different light spectra of chemical elements whose emitting sources have different status (at rest, moving, large or small distance from the detector) and eventually detect systematic shifts (towards the red or the blue of the spectrum) of their characteristic wavelengths.[4] Two reasons for these systematic displacements are here analysed.

[4] Obviously, these comparisons make sense only if it is assumed that the frequency with which light is emitted by a distant object (then in a remote past) is the same with which light, of the same element at rest in our laboratories, radiates now.

1.1 DOPPLER SHIFT

Doppler shift is the fractional shift of the spectral lines of an object due to a decreasing or increasing radial distance between the emitting object and the observer. For a received wavelength λ_{rec} and an emitted wavelength λ_{em}, Doppler shift *z* is defined as:

$$z \equiv \frac{\lambda_{rec} - \lambda_{em}}{\lambda_{em}}.$$

If the object is receding, the spectral lines are shifted toward longer wavelengths (*redshifts*), whereas if it is approaching, spectral lines are shifted toward shorter wavelengths (*blueshifts*). Doppler shift is the result of the relative motion of objects moving *through* space: it depends upon the relative velocity between the source and the receiver and it is caused by *peculiar* velocities *v* (i.e., *physical* motions in space) of objects. If $v \ll c$ (where *c* is the speed of light in a vacuum), *z* is expressed by the *Fizeau-Doppler formula*: $z = v/c$.[5]

1.2 COSMOLOGICAL SHIFT

Cosmological redshift is usually drawn from the most common cosmological model of our universe whose metric, describing the large-scale structure of the universe, is the so-called *Friedmann-Lemaître-Robertson-Walker* (FLRW) *spacetime*[6], which can be written as[7]:

$$ds^2 = -c^2dt^2 + R^2(t)\left[dc\chi^2 + S^2(\chi)\left(dc\vartheta^2 + \sin^2\vartheta d\varphi^2\right)\right],$$

where *t* is the synchronous *cosmic time* coordinate; χ, ϑ and φ are the comoving space coordinates; the function $S_k(\chi) = \sin\chi, \chi\ or \sinh\chi$ for closed, flat, or open spatial sections, respectively; and the scale factor *R*(*t*), with dimensions of distance, characterizes the relative size of the space

[5] This formula is an approximation of the *relativistic Doppler effect* (with $v \approx c$) given by (for a source moving at an angle ϑ to the observer) $1 + z = (1 + v\cos\vartheta/c)/\sqrt{1 - v^2/c^2}$ (for small v, indeed, it reduces to $v \approx cz$).

[6] The currently adopted basis for the interpretations of astrophysical observations is a model $< M, g_{ab}, T_{ab} >$ in which *M* is the spacetime manifold, g_{ab} is the following FLRW metric (representing the gravitational field and the geometric structure of spacetime), and T_{ab} is the stress-energy tensor (representing the material contents of the universe) taking a perfect fluid form with zero pressure (dust). In this idealization, valid only at large scales, clusters of galaxies may be regarded as the particles – the so-called *fundamental particles* – out of which this fluid is made.

[7] See Cook and Burns 2008, p. 3; Davis and Lineweaver 2003, p. 18; Peacock 1999, p. 69.

sections (each one having constant curvature) as a function of cosmic time and hence describes – is the "essence" of – the expansion of the universe when regarded as the expansion of space. Indeed, speaking of an "expanding space" makes sense in these particular highly symmetric cosmological models[8] in which it is possible to decompose in an unique way the spacetime into space and time, namely, into spatial hypersurfaces of simultaneity expanding over time.[9] The idealized fluid of fundamental particles is always at rest relative to the space coordinates (and for this reason are called "comoving"). Thus the constant spatial coordinates mark the position of the fundamental particles whose worldlines are geodesics of the metric. Fundamental particles, when regarded as mere geometric points, constitute the kinematic *substratum*. At every point of such a substratum, a locally inertial reference frame, along with its own *fundamental observer*, can be defined. Along their worldlines, fundamental observers measure the same cosmic time and see the universe spatially isotropic and homogeneous.

From the radial null-geodesic $(ds = d\vartheta = d\varphi = 0)$ of the FLRW line element, we may obtain the *cosmological redshift z* from the *Lemaître's equation*:

$$1 + z = \frac{\lambda_{rec}}{\lambda_{em}} = \frac{R\,(t_{rec})}{R\,(t_{em})},$$

where λ_{rec} (λ_{em}) is the wavelength *received* (*emitted*) at t_{rec} (t_{em}) when the factor scale of the universe was $R(t_{rec})$ ($R(t_{em})$). In an expanding universe such as ours, $R(t_{rec}) > R(t_{em})$, so wavelengths increase in time and z is always positive, while in a contracting one wavelengths decrease and z is negative. This equation contains no velocity terms, and hence z cannot be measuring any sort of *kinematic* redshift: z here depends on the increase of distance between emitter and receiver during the time of propagation, not from their actual movements in space. How then to interpret the cosmological redshift? Rindler is clear:

[8] The FLRW spacetime is the most general metric compatible with an isotropic and spatially homogeneous distribution of dust (such a requirement is named *Cosmological Principle*). The form of this metric is derived from these symmetries alone, and not from the assumptions of GR (Rindler 2006, p. 368). The Einstein field equations intervene only afterwards to determine (by the so-called *Friedmann equations*) how $R(t)$ changes with time for a given universe with specified matter and radiation contents.

[9] In other words, in FLRW models there are invariant quantities that we can think of as indicating in some clear sense that space is expanding, whereas, in more general (less symmetric) models, where that decomposition is not even possible, it is not evident what the term "space" means.

> What is remarkable about this formula is that the frequency shift depends only on the values of $R(t)$ at emission and reception. What $R(t)$ does in between is irrelevant. Regarded in this way, the cosmological redshift is really an *expansion* effect rather than a velocity effect. (Rindler 2006, p. 375)

In other words, cosmological redshift cannot be a Doppler velocity effect because the increase of wavelength does not depend on the rate of change of $R(t)$ at emission or reception, but «on the increase of $[R(t)]$ *in the whole period* from emission to absorption» (Weinberg 2008, p. 11, *my emphasis*).[10]

2. THE EXPANDING SPACE PARADIGM

Although Doppler and cosmological effects cannot be distinguished from one another by observing their spectra, the interpretative difference, as deduced from their mathematical expressions (quite similar at small distances, but significantly different at large ones), is very important: the latter effect does not contain any relative velocity, but only a relative distance, namely the ratio $R(t_{rec})/R(t_{em})$. This relative distance tells us how much the universe has expanded during the time the light has been travelling. Due to the fact that the difference between these two redshifts is evident only at large scales, historically the cosmological nature of high redshifts was recognized only when observations of the distant universe became more accurate. For this reason, some authors[11] speak of a paradigm change between an expanding universe *in* space (in which galaxies are hurled through a static space) and a universe *consisting of* expanding space (in which a continual expansion of space is "pulling along" galaxies fixed to it).[12] Thus in the *expanding space paradigm*,

[10] This cosmological interpretation is adopted by most cosmology textbooks. In particular, some authors, for example MTW (1973, p. 776) and Peebles (1993, p. 96) describe cosmological redshift as an effect of standing waves (generated, for instance, between comoving points in the universe) independent of: 1) why expansion came about; 2) the rate – uniform or nonuniform – at which it came about; 3) the source-receptor distance at emission, at reception, or at any time in between.

[11] *In primis* Harrison 1993; Harrison 2000. See also Baryshev 2005.

[12] This paradigm change is evident in the laws stating the expansion of the universe. Indeed, whereas the so-called *velocity-distance law* $v = Hd$ (H is the Hubble constant) is a linear *theoretic* law (derived from the FLRW metric) valid for all distances, the *redshift-distance law* $cz = Hd$ is an *empirical* approximate relation that can be used only in the limit of small (when compared with the *Hubble distance* $D_H = c/H(t)$) distances. The former is often called *Hubble law*, but it is only the latter that was really discovered by Hubble; they are theoretically equivalent only in small redshift domains (Harrison 1993, Harrison 2000).

the universal expansion, incorporated within a spacetime metric through the use of a scale factor, manifests itself as a geometric effect.

The sense in which the universe is experiencing a metric expansion can be seen in mathematical terms by analysing the comoving coordinate separation χ of the FLRW metric. The proper radial ($d\vartheta = d\varphi = 0$) distance *D*, at time *t*, between two fundamental reference frames increases with time as does the scale factor *R*(*t*). Consider, indeed, the proper distance (defined to be along a surface of constant time, $dt = 0$ between an observer at $\chi = 0$ and a distant cluster whose local frame is at $\chi = const$. The FLRW metric is thus reduced to $ds = Rd\chi$, which, upon integration, becomes $D(t) = R(t)\chi$. Differentiating with respect to time, one obtains: ($\dot{D} = (\dot{R}\chi + R\dot{\chi}$), that is to say, the total velocity $v_{tot} = \dot{D}$ has two components: the *recession velocity* $v_{rec} = \dot{R}\chi$ and the *peculiar velocity* $v_{pec} = R\dot{\chi}$, so that $v_{tot} = v_{rec} + v_{pec}$.

The peculiar velocity is the normal physical velocity of a cluster in space: it expresses the *local* movement "through" comoving coordinates. The recession velocity, instead, is the rate of increase of the metric distance *D* as a function of time: it expresses the *global* "movement", as it were, *of* comoving coordinates, so that the increasing separation of the inertial frames of the fundamental observers is referred to as the *expansion of space*.[13] It is the peculiar velocity – *not* the total one – that must always be less than (or, for light, equal to) *c* (as SR claims) because that is the velocity of a material object with respect to its local reference frame. The total velocity, on the other hand, governed by the rules of GR (we are generally in curved spacetimes), is given also by the additional "stretching" of distances between observers as codified in the recession velocity, so it can increase without bounds.[14] It goes without saying that

[13] The different nature of recession and peculiar velocities is evident in their mathematical expressions given respectively, in GR and SR, by: $v_{rec}(t,z) = c(R_0)^{-1}R(t)\int_0^z[(z')]^{-1}\,dz'$, and $v_{pec}(z) = c[(1 = z)^2 - 1][(1+z)^2+1]^{-1}$ (see Davis and Lineweaver 2003, p. 5). These formulae give the same results only in the first order of *v/c*.

[14] When $\dot{\chi} = 0$, i.e., for fundamental particles (defined as those for which $\chi =$ const.), the total velocity is given only by the term referred to the expansion of space. In this case, the *exact relativistic* theoretical form of the "Hubble law" (recall footnote 12) is yielded. Indeed, $\dot{D} = \dot{R}\chi$ implies $v_{rec} = \dot{R}(t)\chi(z)$, and from $D(t) = R(t)\chi$ one has $v_{rec} = H(t)D(t)$. Thus, whereas in the Minkowski space of SR, or in other non-expanding solutions, for *any* spatial separation of objects their relative peculiar velocity is necessarily less than *c*, in expanding universes, at distances greater than the Hubble distance, recession velocities exceed *c*: if, for instance, $v_{pec} = c$, then $v_{tot} = H(t)D(t) + c > c$.

Doppler and cosmological shifts are evidence, respectively, of peculiar and recession velocities.

3. THE EXPANSION OF SPACE AS A COORDINATE-DEPENDENT CONCEPT

Some authors[15] counter the expanding space paradigm by arguing that the observed redshifts are not consequences of some sort of "stretching of space" but are classic kinematic Doppler (or, at most, gravitational) shifts due to the outward *effective* radial motion of clusters in static space. They maintain that the interpretation of the expansion of the universe as an expansion of space itself results from and is merely an artefact of choosing certain particular coordinatizations of spacetime. Indeed, one can reasonably describe the redshift as due to the expansion of space only when standard comoving coordinates are used, namely only when one has decided to establish a correspondence between fixed spatial coordinates and fundamental observers (so that the latter can be *thought* to be at rest). But *since* using noncomoving reference frames, observers do not necessarily correspond to constant coordinates, they argue that we thus have at least two different coordinate systems, and two equally valid descriptions along with them. One of them (the former) is surely more convenient than the other (and thus mainly used) but this does not make the other one (the latter) less true. The profound reason for this equality resides in that fundamental principle on which GR is based, *general covariance*, which roughly states that the form of physical laws under arbitrary coordinate transformations is invariant, that is to say, all spacetime coordinate systems are physically equivalent for the description of nature. In the light of general covariance, many arguments are nothing more than interpretations of the same physical fact in different mathematical forms. Accordingly, if the characteristics (for example, the spatial curvature) pertaining to a given spacetime are non-invariant, i.e., they "disappear" when that *same* spacetime is described by a different coordinate system, then those

[15] For instance: Chodorowski 2007, Bunn and Hogg 2008, Cook and Burns 2008.

characteristics do not exist – are not real[16] – in the physical world correspondent to that spacetime.[17]

One example of this way to proceed is given by Cook and Burns (2008). They consider a particular instance of an expanding FLRW metric (an empty universe, $T_{\mu v} = 0$, with negative spatial curvature and $R(t) = ct$ for which a coordinate transformation leads to a Minkowskian metric which is no longer expanding (its spatial part does not depend on time), and thus shows that many of the conclusions usually derived from the initial FLRW expanding metric – the Hubble law, the expansion of space itself, the recession of distant objects faster than light, the observed redshifts considered as cosmological, the impossibility to apply SR at large scales, the negative spatial curvature – are not invariant properties but coordinate-dependent effects. Therefore, according to Cook and Burns, the expansion could also be interpreted as given by peculiar motions in a static flat space (as in the Milne kinematic model[18]).

The same line of reasoning, but mainly focused on the redshift interpretation, is pursued by Bunn and Hogg (2008). In a few words, their idea (based also on Peacock 1999, p. 87; Peacock 2008, p. 4) is that the "most natural interpretation" of the redshifts of any cosmic object is as a Doppler shift. But, since redshifts of distant objects cannot be thought of as *global* Doppler shifts[19], their effects are supposed to be given by the integration of many *infinitesimal* Doppler shifts caused by photons passing, along their

[16] This view obviously endorses the claim that invariance is at least a necessary condition for existence.

[17] Think about black holes: the *Schwarzschild singularity*, the radius that makes singular the Schwarzschild metric (describing the spacetime outside a spherical, non-rotating body), is not a real singularity of spacetime, but it is a *coordinate singularity* as it occurs only in some coordinate systems.

[18] This universe was proposed by Edward Milne in 1932 to be a Minkowski spacetime described from an expanding reference frame. He did not agree with the GR dictate that matter and space (geometry) are linked together. His model of the expansion, based on the so-called *kinematic relativity*, is built without the presence of gravity as an initial assumption and is not a dynamical model: it lives in Minkowski spacetime and may be treated by SR. For Milne, indeed, the big bang is like a real physical explosion of matter (that does not affect the universe's geometry): an infinite number of test (no mass, no volume) particles shot out radially with all possible speeds (less than *c*) in all directions, at a particular unique creation event, into previously empty infinite Minkowski space. Thus he rejected the expansion of space, insisting instead on expansion through space, hence redshifts are Doppler. His model, however, suffers many fatal flaws (Rindler 2006, p. 360) and today is used only as a "pedagogical" tool.

[19] Indeed SR would be violated. Recall that such a redshift is due to the relative peculiar velocity of emitter and receiver, so that for large distances, the redshift would be given by superluminal velocities.

paths, between fundamental observers separated by small distances (each observer, placed on the photon's path, measures her infinitesimal Doppler shift in her local inertial frame in which SR hold). Bunn and Hogg also address the question of whether it makes any physical sense to interpret the redshift as one big Doppler shift, rather than the sum of many small ones. Technical details apart[20], the major difficulty in this kind of argument – as admitted by Bunn and Hogg themselves – regards the necessity, when one wants to read the redshift of a distant object as a Doppler shift, of taking into account the velocity of that object (at the instant in which light is emitted) relative to the present of the observer. This is because relative velocity in curved spacetime is undefined for widely separated objects.[21] Accordingly, it is not correct to call their relative motion a motion of one of the objects relative to the other (at most their relative velocity can be considered a mere "coordinate velocity" and not an "actual velocity"). The only meaningful thing to say is that they are increasing their separation. Consequently, it seems to me that such a procedure based on partitioning large redshifts into infinitesimal Doppler ones is only a *mathematical* way to relate the special-relativistic Doppler redshift, holding locally, to the global cosmological redshift; however, this does not imply that the nature of the cosmological redshift is a Doppler one.[22]

About Cook and Burns' conclusions regarding, in particular, the nature of the expansion of space as a reference frame-dependent concept, I have some criticisms. It is in general true that observations carried out in different reference frames can lead to very different, but equally correct and physically equivalent, descriptions of phenomena. However, the SR and the GR descriptions of universal expansion can be equivalent descriptions *at most* in the particular case of a flat spacetime, whereas in curved spacetimes they coincide only locally. Thus, the only FLRW metric – as Cook and Burns themselves admit – for which measurements in an expanding universe can be

[20] And noting previously that this interpretation holds mathematically even for $z \gg 1$ (Peacock 2008, p. 4).

[21] Indeed velocities can only be compared at the same spacetime point, and the only way to compare velocities of separated objects is by "parallel transporting" one velocity four-vector to the spacetime location of the other, but the result of such parallel transport is path-dependent.

[22] In fact, if we imagine to decompose the cosmological redshift phenomenon in its three fundamental physical processes we find that only two (emission and reception of light in the emitter and receiver's proper reference frames) are special-relativistic phenomena, whereas one (the propagation of light from emitter to receiver) is a general-relativistic process governed by the law of geodesic motion in curved spacetime (MTW 1973, p. 776).

directly compared with measurements in a static universe is the SR spacetime. Even if in such a case the nature of the redshift, depending on the reference frame, can have an ambiguous status, in the general case (universe *not* empty) the cosmological interpretation globally cannot be avoided insofar as the Doppler one is valid only locally.[23]

Furthermore, Cook and Burns consider only a change of coordinates, but a mere change of coordinates is not enough to obtain a different cosmological model[24]: «To have a cosmological model one has to specify, besides a spacetime (*M*, *g*), a congruence of timelike curves to represent the mean motion of matter» (Ehlers 1990, pp. 29-30). In other words, there is nothing intrinsic to a geometrically defined spacetime which is able to determine which is the family of preferred worldlines representing the average motion of matter at each spacetime point.[25] Coordinate systems and reference frames are not at all equivalent concepts, and general covariance states that all coordinate systems, *not* all reference frames, are equivalent. In general, if a reference frame can be naturally associated with the actual movement of a system of bodies (as happens in FLRW models where the comoving frame is naturally associated to the divergent motions of clusters), the ability to perform a change of coordinates does not necessarily imply that such an association is still possible under the new coordinatization. This difficulty, however, does not imply that we must abandon general covariance; rather, it necessitates a move from general covariance to a «restricted or physical covariance» (Ellis and Matravers 1995, p. 787) in which the coordinates used for physical applications are well-adapted to the system at hand, and despite the restricted coordinate choices, «such physical studies do indeed make sense» (Ellis and Matravers 1995, p. 778).[26] In the FLRW models, it turns out that the *physical*

[23] Even worse, Davis (2004, p. 64) has showed that the SR Doppler shift formula can be used for an object in an empty universe *only* if the velocity in this formula is the velocity in Minkowski space, namely a velocity which *does not* obey Hubble's law. This means that the SR Doppler shift equation does only relate redshift to velocity in the Milne description of the empty universe, but does not relate redshift to the recession velocity appearing in Hubble's law. And indeed, in the Cook and Burns' derivations, Hubble's law of recession does not hold.

[24] At most, the change suggests a different foliation of spacetime into spacelike hypersurfaces, and thus (possibly) different spatial geometries.

[25] The motion of a fundamental particle cannot be deduced directly from the Riemannian metric as the particle moves along geodesic. Indeed, the worldlines of fundamental particles are geodesics, but the contrary is not necessarily true (see Infeld and Schild 1945).

[26] Ellis (2007, p. 1215) highlights another misconception regarding the fact that a preferred FLRW frame would contradict relativity theory according to which all reference frames should be

motion of the substratum corresponds to fixed spatial coordinates, so «the interpretation of the redshift as evidence for the expansion of the universe, is then unique» (Ellis et al. 1978, p. 440).

Moreover, this choice of preferred worldlines – the character of which is described by *Weyl's Principle*[27] – has an ambiguous conceptual status:

> It is neither a *law*, since it is not contained in the equations of GR for which it even presupposes the explicit solutions, nor a general *principle*, since empirically it can at most be realized *on the average*. (Pauri 1991, p. 324; *his italics*)

In a similar way, Cosmological Principle (CP) – which is strictly related to, though is logically independent of, Weyl's Principle (Bergia 1997, p. 187) – has a status that is independent from GR. As already said, indeed, when the CP is adopted (not only on observational bases[28]) the FLRW metric, and the characteristics it contains, is uniquely determined. In this way, FLRW models, relying on these principles, acquire, at least in their foundational aspects, a sort of independence from GR, so that appealing to coordinate changes and to general covariance seems to us not the correct way to remove the supposed spatial nature of the expansion. The expansion of the space, indeed, occurs at those large cosmic scales which are exactly the areas under the "jurisdiction" of both Weyl's Principle and CP. Thus, from this point of view,

> the expansion would be an "effect" of the large-scale homogeneity and isotropy [...]. [It] should be viewed as a *de facto* behaviour of the "substratum" [...] which is merely *compatible* with the equations of GR. (Pauri 1991, p. 323)[29]

In other words, it is only at the largest scales (where special-relativistic descriptions are inadequate) that the expansion of the universe *is*, as it were,

equally valid: «But this equivalence of frames is true for the equations rather than their solutions. Almost all particular solutions will have preferred worldlines and surfaces; this is just a particular example of a *broken symmetry* – the occurrence of solutions of equations with less symmetries than the equations display».

[27] In modern terms it states that the worldlines of clusters form a 3-bundle of non-intersecting diverging geodesics orthogonal to a series of spacelike hypersurfaces. This claim was stressed for the first time by Weyl, in 1923, in the original de Sitter's universe.

[28] See Fano and Macchia 2008, sect. 6.

[29] Actually, Pauri opts for a subtle relational view of the expansion. Indeed, if one lays at the foundations of cosmology Weyl's Principle (even before of the CP), it results – adopting a particular mathematical construction principally due to Ehlers, Pirani and Schild – that the spacetime itself is *relationally* constituted by fundamental particles. However, I will analyse this view on another occasion.

the expansion of space as resulting from the special way in which space and time are combined in FLRW universes, so that the expanding space paradigm is a «legitimate global concept» (Peacock 2008, p. 1) as Peacock sums up, and «this is most clear-cut in the case of closed universes, where the total volume is a well-defined quantity that increases with time, so undoubtedly space is expanding in that case» (Peacock 2008, p.1).

4. HIGH REDSHIFTS ARE NECESSARILY COSMOLOGICAL

Most cosmologists interpret distant redshifts as cosmological redshifts, sustaining, more or less tacitly, the idea that this kind of redshift due to the universal expansion is a physical phenomenon *really* different from the Doppler effect (classical and special-relativistic)[30], or even that the physics of space expansion is different from motion in static space.[31] In this paragraph, I want to analyse briefly the principal arguments promoting the GR interpretation of cosmological redshift.[32]

Firstly, Prokhovnik (1985, p. 25) reminds us that this interpretation is strongly supported by the accepted astronomical and physical evidence regarding the behaviour of light which is affected by gravitational fields. Moreover, as I have already said, general-relativistic expansion of space can explain *superluminal* recession velocities of distant objects and distances to the particle horizon greater than ct (where t is the age of the universe).[33] It is important to remark that these faster than light motions imply no violation of SR in that their relative velocities are not *local* velocity differences, i.e., these

[30] For instance: Harrison 2000, MTW 1976, Rindler 2006.

[31] For instance: Abramowicz 2008, Abramowicz et al. 2007, Baryshev 2005.

[32] It should be noted that other explanations, not operating on Doppler or cosmological premises, have been attempted. Historically, the first one is the so-called *tired-light theory*: it hypothesizes that photons might lose bits and pieces of their energy while traveling across vast regions of extragalactic space. Many physical reasons for this suffering fatigue by light have been proposed, but no one has proved to be satisfactory. Another explanation of distant redshifts, concerning some particular quasars, attributes the cause of their so-called *intrinsic redshifts* to unknown internal mechanisms of quasars themselves. Neither this last hypothesis has never gained significant support in the astronomy community.

[33] The particle horizon marks the size of the observable universe. Since the expansion of space provides an additional stretching of the distances, the size of the entire universe could be bigger than the size of the observable one. This is not possible in SR where the largest distances, since nothing travels faster than light, cannot exceed the observable universe given by the age of the universe multiplied by c.

motions occur *outside* the observers' inertial frames and no information is transferred between them.[34] On the other hand, a kinematical Doppler view, necessarily based on the extension of a Minkowski frame into the expanding universe, is not able to explain the absurdity of light traveling "faster than light" because it does not see any difference between peculiar and recession velocities.

From a theoretical viewpoint, a closer look at Lemaître's equation reveals that the cosmological redshift cannot result from a Doppler shift due to a source receding with the Hubble velocity $v = Hd$. Indeed, if $v(t_{em}) = 0$ and $v(t_{rec}) = 0$, that is, if the universe were not expanding at the times of emission and reception, the Doppler redshift would be null, whereas cosmological redshift would be positive (obviously provided that $R(t_{rec}) > R(t_{em})$, namely, that some expansion had occurred during the intervening time). More specifically, if objects in Minkowski space are at rest with respect to an observer then they have zero redshift, but this does not happen in GR for $v_{tot} = 0$ does not imply $z_{tot} = 0$.[35] Surprisingly, this fact holds also in empty expanding FLRW universes (without cosmological constant), whereas we might have expected (incorrectly) that these universes could have been well-described by SR in flat Minkowski spacetime. Davis et al. (2003), indeed, derive that in such an empty FLRW universe, a galaxy with v_{tot}=0 will be blueshifted, concluding that, in general:

> The fact that approaching galaxies can be redshifted and receding galaxies can be blueshifted is an interesting illustration of the fact that cosmological redshifts are not Doppler shifts. (Davis et al. 2003, p. 362)[36]

This shows that even an empty FLRW universe does not trivially reduce to Minkowski spacetime. All the more, one must use GR in universes with matter and energy because spacetime is curved and there is a cosmic gravitational field.

From an observational viewpoint, these two wavelength shifts reveal noteworthy differences. Cosmological redshift is a global phenomenon: it

[34] See Davis and Lineweaver 2003, pp. 5-6; Ellis 2007, p. 1215.

[35] Zero velocity approximately corresponds to zero redshift only for $v_{rec} \leq 0.3c$ (Davis et al. 2003, p. 362). Note that the total redshift is given by: $1 + z = \lambda_{rec}/\lambda_{em} = (1 + z_c)(1 + z_v)$, with z_c the cosmological redshift, z_v the Doppler shift caused by the local peculiar motion of the object observed (Ellis 2007, p. 1197).

[36] See also Grøn-Elgarøy 2006, pp. 12-13, showing similarly that an object at large distance and at rest relative to the observer has $z \neq 0$.

affects *all* spectral lines alike of a given cluster, and we measure redshifts for *all* clusters whose "movements" are therefore *always* in a radial direction. This cannot be evidence of simple peculiar motions because these motions tend to be in all directions (including towards us) so that their effects should become on average null for a large number of clusters at a certain distance.[37] In addition, peculiar velocities should be smaller than a certain limit (of the order of a few hundred kilometers per second), while those recorded dreadfully increase with distance. Thus, the importance of peculiar motions, whose redshifts or blueshifts contribute to the total redshift of a certain object, decreases with distance: closer objects (like the members of the Local Group) are dominated by peculiar motions[38], but, as distance increases, dilatation of space enormously exceeds peculiar motions. According to Hawley and Holcomb:

> The systematic increase of redshift with distance is the strongest argument that the cosmological redshift is truly cosmological [...]. [It] is due to the properties of *space itself*. (Hawley and Holcomb 2005, p. 294)

Here are three particular pieces of evidence supporting cosmological redshifts and thus the expanding space hypothesis. The first one is exposed by Davis (2004, p. 28), who analyses recent data concerning the Type Ia supernovae magnitude-redshift relation concluding: «SR fails this observational test dramatically» (Davis 2004, p. 33).[39] The second one is about the temperature of the cosmic microwave background measured at redshift z: it is observed (Srianand, Petitjean and Ledoux 2000) that it is given by $(1+z)T_0$ (where T_0 is its present value), just like all GR Friedmann models predict, whereas it would be T_0 if only matter were expanding. The last one, provided by Misner et al. (1973, p. 767), concerns quasar redshifts which are so high that neither a gravitational nor a Doppler origin are acceptable (in the former case, quasars with high gravitational redshifts would be unstable against collapse; in the latter, quasars with high accelerations would be disrupted).

[37] Obviously, we are not referring to expanding peculiar motions *à la* Milne.

[38] On small scales, indeed, we measure blueshifts Doppler too; for example, the Andromeda Galaxy's one, due to its *peculiar* approaching motion towards Milky Way.

[39] This relation can be used to test the validity of different models concerning the predictions of some cosmological parameters. Roughly, the relation indicates that the model using a special-relativistic redshift does not fit the observational data as well as the model using cosmological redshift.

5. A PHYSICAL GLANCE AT THE EXPANSION

The universe is expanding because it is in a dynamical state determined by its initial conditions. The expansion of space manifests itself at large scales and does not necessarily imply expansion into something; thus it does not occur into a previously existing larger entity (an edge in the universe would be a special location and this is not permitted by CP), but is rather an expansion of the universe *as a whole* and one that takes place without any centre: the universe «is just getting bigger, while always remaining all that is» (Ellis 2007, p. 1214). Hence its volume is increasing[40], and more and more space seems to appear. But what does it mean? Is it an actual incessant *creation* of space, that is a kind of "production" of a larger spatiotemporal container added with vacuum?[41] Is it a sort of stretching of an infinitely elastic substance that "extends" its points? These are very fascinating but "risky" questions: «To speak of the "creation" of space is a bad way of speaking [...]. The right way of speaking is to speak of a dynamic geometry» (Misner et al. 1973, p. 740). This is because we only know that all distances in the 3-dimensional spatial hypersurfaces {*t=const.*} of FLRW universes scale as $R(t)$, all areas as $R^2(t)$, and all volumes as $R^3(t)$ – thus each comoving finite "cosmic box" unceasingly increases its volume – and that the spacetime itself evolves, for its curvature is given by two varying contributions: the curvature of the 3-spaces (which varies as $k/R^2\,(t)$), and their expansion through time which affects the density of matter and consequently part of the curvature of spacetime itself.

To figure out "where" this expansion might take place, if anywhere, is obviously not easy, and may not even be possible: we cannot extrapolate our familiar ideas about the growth of things placed in certain regions of space, because they always expand in a "bigger" spatial container. Even the usual simplifying example of an inflating sphere in a 3-dimensional space is not completely analogous, because the 4-dimensional curved metric of the universe does not necessarily expand in a 5-dimensional flat *physically real* "container".[42] At first sight, it seems plausible think that, if something grows, it must grow in something bigger, so, in order to give a meaning to the

[40] Even if the universe is spatially infinite, the concept of an increasing volume *locally* still makes sense.

[41] For example, Baryshev (2005, p. 5) looks at the "creation of space" as a new cosmological phenomenon.

[42] Even worse, perturbations need spacetimes of still more dimensions (Ellis 2007, p. 1215).

operation of, for instance, doubling the size of space, some higher dimensional space that contains it must be supposed. Such a thesis is sustained by Nerlich (1991), who says: to have a decent syntax, a well-formed description of such an operation (or better, to give it even something stronger: a semantic meaning), we need this further wider spatial "container". However, the latter plays no role in GR, so «we ought to deem the doubling-of-space sentence meaningless, though open to acquiring a meaning» (Nerlich 1991, p. 187). Agazzi couches a similar consideration:

> When one says that the expansion of the universe is not to be conceived like a process that occurs "in space", but it is rather space itself that expands [this expression] is evidently not so much intelligible if one does not refer to a space relative to which it is possible to speak of expansion of space when regarded as a physical magnitude in a given theory. (Agazzi 2006, p. 2362; my translation)

I do not agree with Nerlich and Agazzi on the necessity, at least from a mathematical-physical point of view, of this further wider "container". The reason is simple. For we can distinguish between *intrinsic* and *extrinsic* curvature – namely, a curvature intrinsic to space and not dependent on some higher dimensional containing space, and a curvature "embedded" in a higher dimensional space[43], respectively – the expansion of space can be regarded as intrinsic phenomena too: doubling the radius of curvature, i.e., halving the curvature, or expanding a certain volume of space are possible operations having nothing to do with any higher dimension space.[44] On the other hand, Nerlich himself highlights this objection, judging it meaningful. Therefore, the dynamical spacetime of our cosmos could expand (and shrink and curve) without being embedded in a higher-dimensional one: the universe could be *self-contained*. From this point of view a question like "What does the universe expand into?" does not necessary make sense simply because a bigger spatial container is not an essential requirement to the expansion.[45]

A way to overcome this conceptual impasse is suggested by Schutz (2003). Even if cosmology is the science of the universe as a whole, he invites us to

[43] For instance: a curved line necessitates a plane, a curved plane a volume, and so on.

[44] If some characteristics, as curvature, can *only* exist in conjunction with extrinsic characteristics, or, contrariwise, curved spaces can exist also intrinsically *without* being embedded in higher dimensions, is an issue obviously not solvable by appealing to human imagination. See Ross 1999 on the "ontological axioms" covering the possible spaces that Euclidean and non-Euclidean geometries can describe.

[45] However, about "where", or better "how", space could grow see Ohanian 2000, p. 690.

regard its expansion as a *local* property (a phenomenon pertaining each of its single parts), not a *global* one: «The Hubble expansion [...] does not define the *global* structure of our rubber-band universe [...]. It only tells us how it stretches, locally» (Schutz 2003, p. 349); in this way,

> if the distance between two typical galaxies doubles over some period of time, then the "size" of the cosmology has effectively doubled. These relative size changes are the important aspects of cosmological expansion, not the overall size of the universe. (Schutz 2003, p. 363)

6. Expansion of the Universe and Dynamics of Local Systems

Rejecting the paradigm of expanding space from the observation that space locally, at small scales (galaxy, solar system, house, atom), shows no sign of expansion, is not pertinent. Cosmology considers only the largest scales, and solutions to the Einstein equations, obtained by assuming some averaged matter-energy distribution, correspond to the behaviour of the overall gravitational field of the universe. At scales smaller than 100 Mpcs, the CP does not hold (even approximately), i.e., the symmetries of the FLRW metric do not match the matter distribution in the universe. The FLRW metric is only a large scale approximation, thus «the expansion of space is global but not universal» (Francis et al. 2007, p. 7).

In fact, the geometry of spacetime inside a galaxy, or near a planet, is dominated by the curvature produced by local masses, so that there is no global expansion for these objects to oppose, since locally the dynamics of spacetime has already been modified (given that the local gravitational field of these masses is stronger than that of the universe). In terms of classical physics, inside a galaxy, «the forces holding atoms and molecules together have decoupled their constituents from the general expansion; the gravity that holds the stars in a galaxy together has decoupled *them* from the expansion» (Rindler 2006, p. 353), so that the local situation in the universe is quite analogous to the case of the Schwarzschild metric rather than to a FLRW one, and the planetary orbits are unaffected, as Birkhoff's theorem states, by the existence of expanding surrounding mass shells.[46]

[46] Remind that Birkhoff's theorem roughly states: in order to calculate the motion of a certain galaxy *A* relative to a given galaxy *B*, it is only necessary to take into account the mass contained within the sphere around *B* passing through *A* (the effects of all matter outside that sphere are negligible).

Accordingly, the space in a house, for instance, does not expand insofar as its walls, held together by electromagnetic forces, do not follow geodesics, and the distribution of matter is not at all uniform but has collapsed so that, as already claimed, the geometry of spacetime is completely different from the FLRW metric. Davis and Lineweaver speak of *coherent objects*: galaxies, cities, atoms are «objects whose size has been set by a compromise among forces» (Davis and Lineweaver 2005, p. 44). On the contrary, photons are not coherent objects, and thus their wavelengths expand with the space. Expansion by itself – they go on to state – regarded as a coasting expansion neither accelerating nor decelerating, produces no forces: it is only a changing rate of the expansion that adds a new force to the cosmic objects, but even this new force does *not* make them expand or contract. In our universe, the accelerating expansion exerts a tiny outward force on bound bodies, thus the equilibrium among forces is reached at a slightly larger size, and consequently they are slightly larger than they would be in a non-accelerating universe. But what happens if the acceleration itself is not constant but increases? Some cosmologists think that an acceleration growing strong enough to tear apart all objects structures could eventually lead to a kind of "big rip", not caused, however, by expansion or acceleration per se, but by an accelerating acceleration.

However, since the Einstein and Straus' pioneering paper on the Solar System (Einstein and Straus 1945), showing that the Solar System is completely immune from the cosmological expansion, the problem regarding the effects of cosmic expansion on local non-comoving systems has been analysed many times without unanimous agreement among scholars: some think that the tendency to expand is merely negligible in practice, others that it is completely non-existent.[47] In any case, the large scale phenomenon of the expanding space is not invalidated by such a "local uncertainty".

However, Cooperstock et al. 1998, p. 3, point out that this analysis holds only for a *spherical* cavity embedded in a FLRW universe, but if spherical symmetry is absent satisfactory *quantitative* calculations are missing in the literature.

[47] For instance, recent supporters of the former view are Cooperstock et al. (1998), Davis et al. (2003), of the latter Peacock (2006). For a rich bibliography see Carrera and Giulini 2006. A classic analysis is the so-called *tethered galaxy problem*, in which a galaxy is imagined to be tethered to the Milky Way so that their distance is constant; the point is to understand what happens when the tether is cut: does the galaxy join up with the Hubble flow, starting to recede with the expansion of the universe? In general, however, it is important to note that many characteristics of this issue do not depend just on the simple expansion of the universe but on its acceleration (or deceleration).

As regards the redshifts, the different interpretations of these at small versus large scales is physically motivated by the different physical states of the emitting objects: in the first case, objects within bound systems are not participating in the universal expansion, so SR applies and their redshifts are Doppler, in the second one, such objects are participating, so FLRW and GR apply, and redshifts are cosmological.

7. A PHILOSOPHICAL GLANCE AT THE EXPANSION

Is it possible to relate, by means of the redshift interpretations, the expansion of the universe to the nature of spacetime? «It seems rather metaphysical to argue whether (on the one hand) two points are actually moving apart, or (on the other) the space between them itself is growing» (Whiting 2004, p. 4). It is true: it seems *rather* metaphysical, *but*, hopefully, *not completely*.[48]

7.1 SUBSTANTIVALISM AND RELATIONISM

The two principal philosophical views concerning the nature of spacetime are *spacetime substantivalism* and *spacetime relationism*. The former roughly maintains that spacetime is a sort of "thing", a "container" which, though different and existing independently of its physical "contents" (material things and energy-forms), is in some sense just as substantial and real.[49] In particular, for substantivalists, «unobservable spatial and temporal properties of matter

[48] Among other things, it seems that some experiments could directly reveal which situation is real. In F. Melchiorri and B. Melchiorri's opinion, there could be, in principle, an experiment concerning the motion of the Earth around the Sun and measurements on the dipole anisotropy of the cosmic microwave background radiation, that could discriminate between peculiar motions of clusters and the expansion of space (see Melchiorri and Melchiorri 1994). Morgan (1988) is of the same opinion. However, a philosophical analysis of the universal expansion has, strangely, never been a tasty subject. The only author, at least to my knowledge, to have dealt with it is Whitrow (1980, p. 288-294). His conclusions are different from mine, but unfortunately I do not have here enough space to unfold and criticize them.

[49] Two main kinds of substantivalism are recognized: *manifold substantivalism*, which considers spacetime represented by the manifold of events (the bare set of points with a topological and a differential structure); *metric field substantivalism*, which identifies spacetime with the gravitational-metric field. One of the matter in dispute regards just the nature of this field: is it a physical field containing a form of energy (for instance, gravitational waves) and hence must be considered as *part* of the contents, or is it *the* container insofar as its spatiotemporal properties (it determines the spacelike-timelike distinction, the affine connection of spacetime, the distances between points) cannot be expunged from a meaningful notion of spacetime? See Earman and Norton's 1987 classic paper.

(e.g., “is at position *x*”) are not reducible to observable relational properties of matter (e.g., coincidence, betweenness)» (Earman and Norton 1987, p. 515). The latter is regarded as a denial of the main substantivalist thesis: the world is constituted by its actual material objects and physical events, and spacetime is viewed as a mere abstraction instantiated by their spatial and temporal relations (only the “contents” exist, not the “container”). No ontological commitment to spacetime points (or spatial points and temporal instants) is claimed.[50]

Now, before looking at the cosmos through the dictates of substantivalism and relationism, in order to better understand what cosmological expansion, interpreted by the expanding space paradigm, *is*, it will be useful to briefly analyse the expansion in the light of two philosophical approaches – Nerlich's *detachment thesis* and the *nocturnal doubling* thought experiment – showing essentially what cosmological expansion *is not*.

7.2 Nerlich's detachment thesis

According to Nerlich, the distinction between flat and curved spaces may have a significance for the reality of space, so this distinction has a great bearing on the debate between substantivalists and relationists. His pro-substantivalist argument is essentially based on the tangible manifestations of spatial curvature.

Substantivalists sustain that objects inherit their spatial properties from the regions of space that they occupy; thus space is a sort of intermediary between objects, in the sense that their spatial relations are instantiated by a space conceived of as a material entity in its own right. Relationists, on the contrary, claim that objects possess distinctive relational properties, i.e., objects are directly related to one another by spatial relations regarded as *distances* separating them, and space is a mere invisible redundant entity. In brief, substantivalism appeals to *space-thing relations* (position in space; the quantity of space filled or occupied by a material object), whereas relationism appeals to *thing-thing relations* (spatial distance between things). Since relationism needs a sort of “innocuousness” of space, it must seek to cut the substantivalist tie between the spatial relations among things and the mediation of space. In other words, relationism has to appeal to the so-called *detachment thesis*: «*Thing-*

[50] In the rest of the paper I take into account only this traditional view of relationism. It is not possible here to extend my analysis to other modern forms.

thing spatial relations are logically independent of thing-space relations» (Nerlich 1991, p. 172).

In conditional form it then states: if one changes thing-space relations, there are no consequential changes for thing-thing relations. Leibniz's famous argument, for example, relies on this thesis: if the physical universe as a whole were shifted some arbitrary distance in a certain direction with respect to space, all thing-space relations would change whereas all thing-thing relations (i.e., spatial relations empirically detectable) would remain the same. Since all thing-space spatial relations are idle, space, i.e., the *relatum* of these relations, does not manifest consequences, and thus it is idle too and its existence is not necessary. Thus «relationism has no point without the detachment thesis» (Nerlich 1991, p. 189) insofar as such a thesis permits, or even requires, in a way, the reduction of space to thing-thing spatial relations. It is important to note that at the core of this argument lies the fact that thing-thing spatial relations are considered «*privileged properties*» because they are observable, whereas thing-space relations are considered as «*inconsequential properties*» because they «can change without any accompanying change in specifiably privileged properties» (Nerlich 1991, p. 171); in this way inconsequential properties *cannot* be considered real properties.

7.3 NOCTURNAL DOUBLING

Another thought experiment (a variant of Leibniz's shift argument) based, at least in a relationist perspective, on the detachment thesis, is the so-called *nocturnal doubling* (also proposed by Henri Poincaré). It proposes that if everything (objects, distances, etc.) were to double in size overnight, there would be no real difference because *everything* would still be related just as it was to everything else. (You would wake up in your bed doubled in size, but also you yourself would be twice your previous size, and so would be your room, your house, and your town; the distances between all these things, and even the laws of nature, would have been altered to conceal the doubling). But this is true thanks to a tacit assumption: as Nerlich (1991) shows, only a doubling – and, in the same manner, a Leibniz shift – happening in a Euclidean space has no discernible consequences. In a non-Euclidean space, on the other hand, the doubling would be different: displacements of things could yield significant differences in their shapes if the curvature of space varies from point to point. Imagine, for example, a 2-dimensional undulate surface containing valleys, mountains and plains (i.e., places of negative, positive and zero curvature, respectively). Now, the doubling experiment depends on the place we start it: we obtain different results in the size and shape of objects if they get pushed from a valley on to a plain, or from a mountain top into a saddle-back.

This fact would cause many problems to a relationist, because in such a context the variations in thing-space relations produce manifest variations in observable thing-thing relations. Therefore, thing-space relations are directly *consequential* and thing-thing relations are *not* logically independent of thing-space relations as detachment thesis claims. If thing-thing spatial relations changes are real, so are real the properties (the thing-space spatial relations) that induce those changes (the thesis stating that consequential properties are real properties is called by Nerlich *Discernibility Principle*, DP), accordingly must be real the entity possessing the consequential properties: the space.

From a relationist point of view, the only way to *apparently* weaken Nerlich's criticism is to consider a *complete* nocturnal doubling, that is, a thought experiment that doubles strictly everything, *space included*, thereby a doubling that does not happen *in* space, but *with* space. In this case, as in a Euclidean space, there is no change at all in thing-thing spatial relations because they vary in correspondence with variations of thing-space relations (objects do not get pushed, for example, from a valley on to a plain, but it is the valley itself that is doubled in size correspondently with the objects contained in it). Obviously, such a weakening is only apparent because the pro-substantivalism move is actually still stronger because the entire argument relies on an ontological commitment to space itself.

I have made this long detour in order to point out how cosmological expansion, at least in the expanding space paradigm, is different from both nocturnal and complete doubling. In fact, in the expanding universe the doubling (which can be considered as a sort of temporary stage of a continuous expansion) refers not to the size of every ordinary object (as happens in the nocturnal doubling both in Euclidean and non-Euclidean spaces), but only to the size of *configurations* of large scale cosmological objects (their respective distances like, for example, a cluster triangle) *when* is compared to the size of *local* reference standards. This is the crucial difference that makes the expansion of the universe an *observable* phenomenon and gives it a physical meaning. We verify empirically that these detectable reference standards – namely, the local gravitationally-bound systems, such as galaxies, double stars, planetary systems, or even atomic standards – do not expand, and thereby deduce that the expansion is not universal as the complete nocturnal doubling requires. In brief, "universal metric doubling" happens neither *in* space (as nocturnal doubling) nor *with* space (as complete doubling), but, as often repeated, is a phenomenon *of* space.

More generally, the detachment thesis argument itself is not strictly applicable to the cosmological expansion case because there is no change in thing-space relations: clusters remain embedded in the same (approximately) point of space, and so thing-space relations are neither inconsequential nor consequential but simply "silent". On the other hand, the variation itself of thing-thing spatial relations[51] depending on the expansion of space cannot be detached from dependence on the space itself. This is evident, if one accepts the cosmological interpretation of distant redshifts, by the changes in thing-thing relations (distances among clusters) appearing to be mediated by paths (intervals or stretches) of *physical* space insofar as wavelengths stretchings instantiate a sort of thing-space relations. Indeed, if the stretching can be considered as a kind of *consequential* property owned by a path because of its *action* on electromagnetic waves, then it is a *real* property as Nerlich's DP claims, so that space itself – in a way "the totality of all paths" – becomes a real entity necessary both to explain and predict the detectable behaviour of cosmic objects and light. Accordingly, compared with the following Nerlich's thought, it seems to us that something more, i.e., a kind of "action of space", is at stake in our cosmological context:

> The DP together with the nature of non-Euclidean geometry suggests that the hypothesis of space can do genuine explanatory work (even though it makes no appeal to the action of space). (Nerlich 1991, p. 188)

8. HOW EXPANSION IMPLIES A METRIC FIELD SUBSTANTIVALISM

In the last paragraph I argued for the necessary existence of stretching paths in order to explain the cosmological redshift, and this has plain consequences[52] for our aforementioned ontologies. Substantivalists, indeed, naturally require, in order to have spatial relatedness among things, the existence of paths connecting these things, whereas relationists, speaking of spatial relations,

[51] Note that here the situation is almost the opposite of Leibniz's shift argument: all thing-space relations remain the same while thing-thing relations *at large scales* change.

[52] Remind: «As ontologists, we should be no less worried by the nature of the parts of space (volumes, paths, points) than by the nature of the whole» (Nerlich 1991, p. 179).

refer to distances separating objects, namely to relations operating, as it were, «*across* space but not *through* it» (Dainton 2001, p. 145): relations are held to connect spatially separated objects directly, without passing, or extending, through the medium of intervening empty space.[53] In the case of cosmological redshift, how wavelength is stretched claims a relation between emitter and observer operating just *through* space, not across it: light is redshifted just because it "clears a path" through an expanding metric that, point by point, influences its wavelength. And this way to operate is unacceptable for relationists.[54]

In this way, the cosmological interpretation of redshift is like an epistemic access to the ontology of spacetime, which *must* exist as a substantial entity since it is provided with a property «causally efficacious with respect to some events involving matter» (Hinckfuss 1975, p. 141). However, this *causal efficacy*, despite being the necessary condition by which we may discover, as Nerlich (1994a, p. 178) affirms, that space has a certain property, is truly a slippery concept, above all in questions pertaining spacetime. Due to this fact, it is better to specify that this concept means only that the explanation of the changing shape of photons' wavelengths can be regarded as causal, not that space acts as an expanding force. Indeed, in the FLRW metric, clusters are free fall particles, i.e., they are following geodesics in curved spacetime and have zero acceleration: clusters' worldlines merely extend, diverge and endure. From this point of view no causal efficacy of space is at stake. In other words, cosmological spacetime satisfies, in the behaviour of freely falling particles, that twofold explanatory role recognized by Nerlich:

> It explains (familiarly enough) how the apparent gravitational dynamics of free-fall particles in general frames of reference vanishes into the mere kinematics of

[53] Nerlich again is exhaustive: «One reason for taking space as a real thing is the strongly intuitive belief that there can be no basic, simple, binary spatial relations. Just such relations are the foundation of relationism, so long as its basic spatial facts lie in spatial relations among objects or occupied points of space or spacetime. Consider the familiar (though not quite basic) relation *x is at a distance from y*. There is a strong and familiar intuition that this can be satisfied by a pair of objects only if they are connected by a path. Equivalently, if one thing is at a distance from another then there is somewhere half way between them. Distances are infinitely divisible, whether the intervening distance is physically occupied or whether the space is empty. [...] We don't understand how spatial relations can hold unmediated» (Nerlich 1994b, p. 19).

[54] As previously underlined, I am referring only to the most traditional relationist view according to which space is a sort of abstract web of relations between *actual* objects. However, as Chris Smeenk has pointed out (private conversation), other more slippery forms of relationism, accepting also relations between *possible* objects, should be analysed.

> geodesics in flat or curved spacetimes. It explains also by citing *identities* in various ways. E.g., the deviation of geodesics is not *caused* by spacetime curvature: it *is* spacetime curvature. (Nerlich 2008, p. 2)[55]

Therefore, we have clusters whose gravitational dynamics is subsumed into the FLRW geodesics, and we have the identity between their diverging worldlines and spacetime curvature. However, in our cosmological case we also have the stronger necessity to explain *where* the energy lost by redshifted photons is.

In fact, the worldline of a photon is null geodesic, but its energy, in the cosmological redshift case, is not constant along its worldline[56], and this *physical* fact is motivated by – is *necessarily ascribed to* – an entity that causes the increase of its associated wavelength. And such an entity is not only a theoretical term. It is an unobservable "thing" that acts directly producing an "observable" effect.[57] And even if we want to be more cautious and remain silent about causation, we can make sense of certain counterfactuals like this: if this path had not been stretching, there would not have been that loss of energy.[58] As in the case of gravitational waves, in the cosmological redshift case it is of relevance that *something physical* exists between the times of physical

[55] On the subtle meaning of the concept of geodesic see also DiSalle 1995, p. 327 and Nerlich 1991, p. 177.

[56] The question regarding the loss of energy of photons in an expanding space, and a possible non-conservation of energy on cosmic scale, is debated. Harrison (1995; 2000) maintains that energy in expanding, spatially unbounded, homogeneous and isotropic universe (conforming to the FLRW metric) is not conserved. He notes that, whereas in the Doppler and gravitational redshifts in spatially bounded systems the "lost" energy is manifest in identifiable alternative forms (thus it is conserved), in the case of cosmological redshifts this does not occur, neither if we take into account the possibility that the lost energy of photons transforms into metric disturbances, namely in deformations of the FLRW metric. Also in this case, indeed, the propagating deformations would lose energy because of the cosmological redshift and the question would result the same: what happens to the lost energy of the gravitational waves? The violation of conservation laws in expanding space is sustained also by Baryshev (2005). Carlip and Scranton (1999, p. 8) remark that the electromagnetic energy of the cosmic background radiation is not conserved during expansion, but «there is nothing particularly 'cosmological' about this loss – a photon rising in a static gravitational potential experiences a similar energy loss». In the energy accounting, they conclude, one has to include gravitational potential energy, but in GR is difficult to define a *local* gravitational energy density. The point is indeed that energy conservation is only a good local concept: there is no general global energy conservation law in GR (Peebles 1993, p. 139).

[57] Electromagnetic waves are unobservable but the physical effect of their stretching is revealed on our spectrometers.

[58] Also in this weaker formulation, space assumes an important role in explaining why wavelengths are stretched. Mellor (1980, p. 287) maintains that the cause-effect relationship, mediated by spacetime, should be expressed by counterfactuals.

phenomena of emission and reception: in the former case, energy released from a certain star needs an entity that possesses it to transfer to a detector on Earth (this entity is a region of metric curvature that propagates at *c*), in the latter, the same *medium*, this time revealed by its "stretching" properties, is needed to explain "where" this "lost" energy goes: it is transferred to the gravitational field (Pitts 2004).[59] Such a change in the energy-momentum of individual photons dictated by the evolving FLRW metric is an example of how spacetime geometry redefines matter (Sumner and Sumner 2007, p. 2).

Therefore, both in the cosmological redshift and in the gravitational wave cases, a substantival metric field, i.e., a structure that can carry and store energy, is needed for the explanation of these cosmological phenomena. In such a way a substantivalist ontology for the spacetime emerges.[60]

Furthermore, thinking about the expansion of the universe, the fact of the matter naturally highlighted by the expanding space paradigm is that, whereas the peculiar velocity must make reference to a material object (including photons), the recession velocity

> should not be regarded as the property of a source; rather, it should be considered as the property of the point of space in question, whether that point happens to be occupied by a source, a passing photon, or nothing at all. (Kiang 2003, p. 12)[61]

This is a further typical substantivalist commitment to the ontology of spacetime (and of its points), completely different from the relationist claim committed to reduce all spatiotemporal properties to properties of objects, that is to say, in our case, to motions, through space, in which velocities are to be regarded as belonging to cosmic objects.[62]

[59] The status of gravitational waves is debated among philosophers. For instance, Hoefer 2000 maintains that we do not have sufficient reasons to accept that the metric field can possess "genuine energy" because gravitational energy is not clearly localizable; thus, it behaves differently from material energy. See also Baker 2005 for a reply to Hoefer and a clear explanation of the difficulties that relationists have to face in order to explain gravitational waves emitted from a binary star system.

[60] Note that I am not considering the metric field as a field *in* spacetime but as *the* spacetime: if such a field and its properties (see footnote 49) were removed, spacetime could not be imagined to exist. The properties possessed by the mere manifold of points, indeed, are only dimension and topological structure, and it does not even distinguish between time and spatial dimensions. See Hoefer 1996 for an elucidation of these points.

[61] For a similar analysis see also Prokhovnik 1985, p. 73. He assigns at every point of space a vectorial velocity so that the expanding universe can be represented as a velocity space.

[62] Speaking of temporal becoming, also Dorato recognizes a «form of spacetime substantivalism» in contemporary cosmologies: «"The expansion of the universe" *is* in some sense the expansion of

9. IS A RELATIONAL READING OF EXPANDING UNIVERSE POSSIBLE?

For relationists, even though objects can change their distance relations with one another, at any given time only objects and spatial relations exist, and we can imagine drawing up representations, or maps, that reflect all these different possible dispositions of objects. Therefore, all propositions about the distances between objects, or about their sizes, are not false, or meaningless (relationists, indeed, only claim that spatial facts do not require or involve a spatial substance). By seeing things from this perspective, could a relationist say that the increase in cosmological distances is only *described* by the framework of expanding space, that is, this latter is only a useful representation, and one that does not fit a real thing?

In my opinion this is not possible. Let us look at the differing relationist and substantivalist conceptions of movement. The substantivalist view roughly sustains that an object moves *if and only if* it occupies different spatial locations at different times, whereas for the relationist view a body moves *if and only if* its distance relations with other material objects change (obviously, also a substantivalist recognizes that objects move relative to one another, but the change of their distance relations is not a necessary condition for the movement). Now, in the global comoving coordinate system, clusters occupy the same locations at different times, but their distance relations increase so that relationists *must* say that clusters are moving, whereas their spatial coordinates do not change; the only way to overcome this contradiction is by regarding the comoving coordinate system as a mere mathematical representative tool. *However*, in doing so, relationists have to adopt a global Minkowskian frame that is not able to account for the high redshifts and related problems seen so far. On the contrary, substantivalists naturally can both say that clusters are *really* at rest because they do not occupy different spatial

spacetime itself, since galaxies clearly do *not* expand in a pre-existing spacetime» (Dorato 2006, p. 565; *his italics*). A substantivalist conclusion about the universal expansion is reached by Baker 2005 too, who charges the substantiality of spacetime to the cosmological constant Λ insofar as it provides an amount of curvature not entirely created by matter. I agree with his reasoning, however I think that Λ – usually related, though its physical status still remains unclear, to an accelerating expansion – is not necessary for a substantivalist commitment. Indeed, such a commitment is already satisfied, as hopefully shown so far, at the more fundamental level of the expansion itself as deduced from the symmetries of the FLRW metric, without involving the dynamics of the Friedmann models (remind: the cosmological redshift is independent of the way the universe expands – quickly, slowly, with jerks – i.e., of the evolution of $R(t)$: its rate of expansion $\dot{R}$ and acceleration $\ddot{R}$).

locations (in fact the change of distance relations is not a binding assumption for the movement) and explain why distance relations are changing.

Furthermore, it is worth noting that even if a picture of clusters moving in a static space were possible, it would not necessarily contradict a substantivalist ontology. Consequently, whereas cosmological shift implies solely substantivalism, a Doppler shift interpretation would not *uniquely* sustain relationism. In any case, trying to obtain a "relationist reduction" of the cosmological redshift phenomenon induces us to look for *physical* explanations chiefly based on clusters' displacement in space, that is, to look inevitably for special-relativistic (for instance Milnian) analogues to the general-relativistic expansion and to its related phenomena. Nonetheless, special-relativistic views undeniably break down outside of a local domain.

A last possible route for relationists might be to accept the standard interpretation of the cosmological redshift and in the meantime deny that metric field constitutes the spacetime itself: the metric tensor, incorporating the gravitational field and carrying energy and momentum, should be considered as a matter field, namely as part of the contents of spacetime.[63] Thus the stretching action would not be a property of spacetime. However, I do not think that this is a promising route because it is undeniable also by the relationists that the metric field has peculiarities of ontological priority respect to the other matter fields (it can exist without any material content, but the opposite is not true). Moreover, as briefly mentioned above, it is really hard to show how a spacetime deprived of the typical *spatiotemporal* characteristics of the metric field, might have any sense.

10. Conclusions

I have discussed the meaning of the expansion of the universe and shown how the large-scale expansion, when regarded as expanding space, is a natural feature of FLRW models that allows us to unambiguously explain observational phenomena and data, in particular the high redshifts of distant cosmic objects. The direct interpretation of these redshifts is indeed cosmological: photons' wavelengths are stretched by the underlying dynamical geometry of the universe. Thus, without the concept of "stretching space" we are not able to

[63] Some authors, for instance Earman and Norton (1987) and Rovelli (1997), defend this view, but the former attain manifold substantivalism, whereas the latter relationism.

understand the expansion from a global viewpoint insofar as special-relativistic descriptions – constrained to consider the expansion as given by clusters' peculiar motions in a static space and the wavelength shifts as Doppler effects – necessarily result as approximations valid only in local domains of general-relativistic curved spacetimes. Therefore, *if* the cosmological interpretation is correct, the expansion of space is a large-scale phenomenon occurring among clusters, and even if no force is involved, its effects explaining both wavelength stretching and "where" the energy lost by photons is conserved, are evidence of the substantial nature of the metric field. These general-relativistic facts support a substantivalist position on spacetime since a traditional relationist one is to be necessarily committed to fallacious special-relativistic descriptions. Hence the expansion of the universe reveals the inadequacies of such a metaphysics.

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