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Philosophy of Space and Expanding Universe in G. J. Whitrow

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Abstract One of the few authors to have explicitly connected the physical issue of the expansion of the universe with the philosophical topic of the metaphysical status of space is Gerald James Whitrow. This paper examines his view and tries to highlight its strong and weak points, thereby clarifying its obscure aspects. In general, this really interesting philosophical approach to one of the most important phenomena concerning our universe, and therefore modern cosmology, has been very rarely tackled. This unicity increases the value, from a physical, philosophical and historical point of view, of Whitrow's attempt and calls for new research.

Keywords Whitrow · Cosmology · Philosophy · Universe · Space

1 Introduction

A man of extraordinary erudition, Gerald James Whitrow (1912–2000) was a British physical mathematician, cosmologist and historian of science. His main contributions were in the field of cosmology and astrophysics, but he also wrote noteworthy essays in history and philosophy of science, above all on the concept of time. His masterpiece is, without a shadow of a doubt, *The Natural Philosophy of Time*, a book published in two editions in 1961 and 1980. My attention will be focused on this monumental book, a comprehensive study of the role of time in human culture, particularly in sciences such as physics, cosmology, mathematics, psychology, physiology as well as epistemology. The general philosophical thesis of this book is that time is real, it is a necessary and inevitable concept in all of the sciences, it is an irreducible and ultimate feature of our world, and its passage is not a subjective illusion, as Whitrow affirms when summarizing his book:

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"The very essence of time is its transience [...]. Time does not exist independently of events, but is an aspect of the nature of the universe and all that comprises it" (1980, p. 372).

However, I do not intend to discuss the concept of time, instead I will dwell upon space, specifically upon the philosophical implications regarding space as they emerge, according to Whitrow, from the modern cosmological view of our expanding cosmos.

Philosophy of space is a branch of philosophy which deals with issues surrounding the ontology, epistemology and nature of space. This topic has provided a focus for sustained philosophical debate for centuries. In modern times, a milestone has been the dispute/correspondence between Samuel Clarke (actually, Isaac Newton's spokesman) and Gottfried Leibniz. Very roughly, the former sustained the so-called *absolutism*, arguing for the necessity of a space regarded as a sort of absolute container existing independently of its material contents. The latter supported *relationism*, according to which space is to be thought of as the structure of all possible spatial relations among bodies, so it is not an existing entity. With the Einsteinian revolution, the three-dimensional immutable Euclidean space of classical physics has been replaced with the four-dimensional, variably curved spacetime of General Relativity.[1] But the main question still persists: What sort of entity is spacetime? Thus, the absolutism/relationism controversy continues to this day, though in more sophisticated forms, but still inspiring fascinating interactions between metaphysics and physics. Most philosophers of physics consider this topic one of the most important, but, unfortunately, it is relatively little known among physicists. This is evident, in particular, in some aspects belonging to cosmology. For instance, the modern conception of the expanding universe is based on the concept of "expanding space" (or "expanding metric"), nonetheless such a concept remains obscure and completely overlooked in many cosmology textbooks, and usually cosmologists do not even consider it as an issue that deserves at least to be mentioned.[2]

Therefore, Whitrow's stance is important not only per se and because it is probably the first attempt to introduce such a philosophical approach in modern cosmology, but also because it could be a stimulus for new insights and a better comprehension of the physical foundations of cosmology itself. So, what I will attempt to carry out hereafter is an analysis of his position on this subject as treated in his aforementioned book, in order to critically examine and hopefully unfold those aspects that are, in my opinion, not immediately clear. This paper is divided into three main sections. Section 2 introduces Whitrow's view, and my criticisms, about the possible philosophical interpretations of the expanding universe. Section 3 analyses how those philosophical views can be associated, according to him, with the mathematical techniques usually adopted to describe the expansion. The reasons for my disagreement are also explained here. Finally, Sect. 4, after having briefly introduced some important approaches to the foundations of General Relativity and of standard cosmological models, tries to clarify, at least partially, Whitrow's general stance.

[1] Also the philosophical terminology has partially changed: the more recent term "substantivalism" is adopted instead of "absolutism". Both designate realist views on space, but the former has an Einsteinian "flavour" (space is a sort of substance influenced by matter), whereas the latter has a Newtonian, but physically outdated, "overtone" (space is an immutable entity).

[2] The exceptions are few. For example: Baryshev and Teerikorpi (2002, sect. 12.4.1), Misner et al. (1973, pp. 739–740), Schutz (2003, p. 365).

2 Intrinsic Versus Extrinsic View of the Universe's Expansion

Whitrow philosophically examines the topic of the expanding universe in Sect. 6.4 of the second edition of his *The Natural Philosophy of Time*.[3] He begins this section concerning the relation between cosmic time and the expanding universe, saying: "Basically, two different types of relation may be envisaged between matter as a whole and space, depending on whether we adopt the 'relational' or the 'absolute' theory of space" (1980, p. 288). According to the former theory, usually associated with Leibniz but in reality much older, "space is the nexus of spatial relationships of material objects", whereas for the latter, usually associated with Newton, space is "intrinsically distinct from matter" and exists in its own right and is therefore absolute (*ibid*.).

Later on, after a brief historical survey of these views of space, he introduces the different ways in which the expansion of the universe could be considered by supporters of relational and absolute theories:

> According to the 'absolute' theory, such expansion would be an expansion of the material universe into outer empty space, like the diffusion of a gas into a surrounding vacuum. According to the 'relational' theory, there is nothing—not even empty space—outside the universe and its expansion is simply a change in the scale relationship of the universe as a whole to the linear dimensions of typical constituents: for example, the diameter of a typical atom, the radius of an electron or proton, or the wavelength of a photon emitted in a specific atomic transition. (*ibid*., p. 290)

Thus, according to Whitrow, expansion should be regarded *extrinsically*, i.e. with reference to the space in which it is embedded in order to fulfil the absolutist dictates, that is, expansion should be "hosted" in a supposedly empty spatial container bigger than the universe itself. In such a way, Whitrow defines the absolute view of space looking at, as it were, what happens *outside* the expanding universe itself. The relational view is also approached in this extrinsic way with the simple observation that this philosophical position cannot consider the expansion as occurring in an external empty space whose existence is obviously forbidden. A relational theory should regard the expansion only on the basis of a changing scale relationship between the "size" of the whole universe and the unchanging dimensions of some of its constituents at small scales.

An early criticism of Whitrow's initial considerations regards precisely his extrinsic approach. The point is that, mathematically speaking, an external pre-existing space is not mandatory at all. Curvature is a property that may or may not be conceived as belonging to a space embedded in a larger space. In general, curvature is *extrinsic* if it is owned by an object in relation to a higher-dimensional space that contains it, and such a curvature is determinable only by confronting the object's elements in relation to the space-container's elements. Instead, curvature is *intrinsic* if it is determinable using only operations performed on the elements of the object itself. The surface of a cylinder in three-dimensional space is an example of extrinsic curvature: intrinsically the geometry of the cylinder is flat, but the lines on its surface are curved if confronted with the straight lines of the external space. Instead, a sphere has an intrinsic curvature determinable by operations performed within its surface itself. Therefore, a space of any dimension can be intrinsically curved in the sense that cur-

[3] I will quote and comment on only the second edition, but the parts I am interested in here are practically identical in the first edition (§ V.4). In order to better elucidate Whitrow's view on this topic, I also examined all his books (Bondi et al. 1960; Jones et al. 1956; Whitrow 1949,1959; 1967; 1972; 1980; 1988) and most of his papers, unfortunately without finding any comments related to the philosophy of space.

vature is a property defined at every point of that space rather than defined with respect to a higher-dimensional ambient space.

Naturally, the mathematics of the intrinsic and extrinsic curvature is one thing, the ontological status, and therefore the possibility of a physical existence, of the dimensions involved in that distinction is another. In other words, from a physical—i.e. concerning reality—point of view, it could be that the intrinsic curvature, though being conceptually (mathematically) independent of the extrinsic one, exists in the real world in conjunction with it, so we could live, for instance, in a spherical space and measure its curvature "intrinsically", but without knowing that such a sphere is actually embedded in a space of higher dimensions. But it could also be possible that real curved spaces simply exist without any embedding in higher dimension spaces. We simply do not know, and probably we will never know considering that it is hard to imagine that our most advanced measurements and experiments, even in a remote future, could give us some information about hypothetical higher dimensions spaces. We just know that General Relativity "works" intrinsically: it proposes that gravity actually results from an intrinsic curvature of spacetime, without the need to postulate further spatial dimensions.

The universe's expansion can similarly be considered with these two approaches. In fact, we do not know if our universe is expanding in a higher dimension space or in *literally* nothing. However, I think that, if one prefers to adopt an ontology deriving, as far as possible, from our best physical theories, and in the meantime opting for a kind of ontological parsimony, the better choice is simply to regard the expansion as a sort of spatially auto-contained phenomenon intrinsic to the universe itself. This means, for instance, that doubling the radius of curvature (i.e. halving the curvature) or expanding a certain volume of space are possible phenomena that have nothing to do with spaces of superior dimensions. In other words, the expansion of the universe as a whole does not take place in the spacetime but it is a process which creates spacetime.[4]

Hence, contrary to Whitrow's remarks, the existence of some bigger containing space is not a necessary prerequisite to preserve an absolutist point of view. In all probability, Whitrow's stance is influenced by an "old-fashioned" Newtonian view about space, according to which space is an infinite immutable all-embracing container that does not participate in "material affairs", namely space is completely detached from the expansion of its matter contents. However, also in this case, keeping in mind that the term "universe" defines that unique all-comprehending entity which necessarily must include space itself (the whole universe is literally *everything*, literally *everywhere*), it is still possible to maintain an intrinsic approach to the expansion without any detriment to absolutism or to relationism by simply focusing on the ontological status of the "inner" space in relation to the universe itself.

It is evident that the hypothesis of an outer empty space, in which expansion takes place, differentiates the absolute and relational theories in a more immediate and clear-cut manner: speaking of an outer space is already an ontological commitment to an absolute space. On the contrary, if the outer space is dropped, the differentiation between these two positions no longer appears so obvious. In a sense, they could seem to overlap insofar as both are now to

[4] According to Misner et al. (1973, p. 740) "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". It is true that the term "creation", and similars, does not smack of "good science", but I agree with Baryshev and Teerikorpi (2002, p. 197): "To say that space expands is close to saying that space is created. To the space within the Hubble radius a volume like that of our Local Group of galaxies is added every second. […] There is the physical phenomenon of increasing volume, no matter which word, 'expansion' or 'creation', is used. If the distance between two galaxies increases, but the galaxies do not move *inside* space, then a natural way to understand this is that space emerges in the region between them".

be analysed by looking at the expanding universe intrinsically. However, as we shall see in a moment, the nature of the "intrinsic" expansion still remains different when judged from the relationist and absolutist perspectives.

In any case, I restate my opinion, the intrinsic approach is preferable because it does not rely on a gratuitous ontological commitment to an outer space. The fact that Whitrow does not contemplate this approach (at least in his philosophical distinction of the expansion), which in itself is not an abstruse and unusual point of view, is a little bit strange for a physical mathematician of his level. Surely, when considering his main contributions to science, he belongs to the first half of the last century rather than to the second, so his approach to some scientific issues could sometimes feel the effects, in terms of "updated" knowledge and especially of mentality, of this more distant provenance. However, the intrinsic view about the expansion of the universe is by no means recent. For instance, already in 1949 the great cosmologist H. P. Robertson affirmed:

> We propose ultimately to deal exclusively with properties intrinsic to the space under consideration—properties which in the later physical applications can be measured within the space itself—and are not dependent upon some extrinsic construction, such as its relation to an hypothesized higher dimensional embedding space. (Robertson 1949, p. 317)

3 Mathematical Techniques and Philosophies of Space

Whitrow's analysis proceeds with the following considerations stating an association between the two mathematical techniques, as he calls them, usually adopted to describe the expansion of the universe, and the two previously mentioned philosophies of space:

> Since the idea of world expansion was first suggested, two different mathematical techniques have been invented for the construction of world models: the technique of an *expanding space* and the *kinematic technique*. It has been customary to regard these merely as two different mathematical methods, and indeed it has been shown that there exists a close relationship between them. Nevertheless, there is a vital philosophical difference, for the expanding-space technique is the natural concomitant of the relational concept of space, whereas the kinematic technique is most naturally associated with the idea of absolute space. Thus, in the one case there is motion *of* space and in the other motion *in* space, i.e. in the former space is the framework of all matter and this framework expands, whereas in the latter attention is concentrated on the type of motion of the fundamental particles [footnote: "Idealizations of the principal aggregates of matter (clusters of galaxies)"] rather than the space structure (Infeld and Schild 1945).[5] (*ibid*., p. 290)

Thus Whitrow proposes the following two relationships: the technique of expanding space is to be coupled with the relationist view of space (in this case, he specifies, there is motion *of* space), whereas the kinematic technique is to be related to the absolutist view of space (in this case there is motion *in* space).

In my opinion, Whitrow's position is not shareable for at least two reasons. The first, but secondary in importance, is that these mathematical techniques differ not only because they may be assigned to two different philosophical views, as Whitrow affirms, but because they

5 Note that by "space structure", Infeld and Schild mean "the curvature $kR^{-2}(\tau)$ of the 3-space τ = constant" (Infeld and Schild 1945, p. 251).

are deduced from two different *physical* phenomena. Their common ground is the increasing wavelength measured in the radiation coming from distant galaxies. This increase can have the nature of a Doppler redshift or a cosmological redshift. Although both are proof of an increasing distance between the galaxies and us observers, they are the results of two different physical phenomena that, according to modern cosmology, occur at different spatial scales in our universe.

When we talk about the expanding universe, we refer to those large-scales pertaining to dimensions at least as big as a cluster of galaxies. In this context, the Cosmological Principle holds, so it is only the cosmological redshift, as derived from the so-called *Friedmann–Lemaître–Robertson–Walker* (FLRW) metric (in turn obtained from the Cosmological Principle), which must be taken into account.[6] The cosmological redshift is interpreted as the effect of an expanding metric. In other words, the mutual recession of the galaxy clusters, expressed by the locution "expanding universe", is a physical phenomenon explained in terms of another physical phenomenon usually labelled as *expansion of space*. This is very roughly the standard view of modern cosmology.

The Doppler redshift, on the contrary, is an interpretation of the measured spectral shifts consistent only with a small-scale phenomenon, namely the receding motion of celestial bodies in bound systems detached from the large-scale expansion. So the Doppler shift is explained as being due to a kinematic phenomenon, i.e. the relative movements *in* space between the emitting source of the redshifted wavelength and the receiver. This is the kinematic approach to expansion, typical of Milne's cosmology, a model in which there are *effective* motions of the fundamental particles in a non-expanding flat spacetime.[7]

The nature of the Doppler and of the cosmological redshifts is of necessity different also because astronomers measure redshifts so high that if they had a Doppler nature, the involved velocities of the emitting sources would be greater than the speed of light, namely there would be a violation of Special Relativity. Thus superluminal recession is explained only by the expanding space phenomenon. On the other hand, cosmology deals with curved spacetimes, and in such spacetimes relative velocities are undefined for widely separated objects, therefore also a relativistic kinematical Doppler view, based on a Minkowski frame, cannot be applied: "The velocity is due to the rate of expansion of space, not movement through space, and therefore cannot be calculated with the SR [special relativistic] Doppler shift formula" (Davis and Lineweaver 2004, p. 99). Put briefly, "the cosmological redshift is really an *expansion* effect rather than a velocity effect" (Rindler 2006, p. 375).

This is why it seems to me that there is something more than an (albeit important) philosophical difference—as Whitrow believes—between these two mathematical approaches to the universal expansion: there is also something physical, which implies different mathematical techniques and, in the meantime, allows us, as we will now see, to discriminate two philosophical pictures.[8]

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[6] For an introduction to these notions see Sect. 4.2.

[7] Infeld and Schild, in the paper quoted by Whitrow himself, more generally affirm: "By kinematical cosmology is usually understood that part of relativistic cosmology which deals with the metric form of our universe, characterized by a four-dimensional space-time manifold, and with the motion of free particles and light rays in this universe" (Infeld and Schild 1945, p. 250). So kinematical cosmology ignores the dynamical aspects of cosmology, namely "the connection between the Riemannian curvature tensor on the one hand and the energy-momentum tensor on the other" (*ibid.*).

[8] Significantly, Whitrow, in the book under scrutiny here, speaks exclusively of the Doppler shift. Actually, in just one case (p. 296) he uses the formula of the cosmological redshift, i.e. the so-called *Lemaître's equation*, in which redshift is determined by the ratio of the scale factors (giving the variations in size of the metric) at emission and reception of the electromagnetic wavelength. But he does not attach any importance to such an

The second and most important reason for my (partial) disagreement with Whitrow concerns the association between the two mathematical techniques and the philosophies of space he puts forward. In my opinion, his association should be inverted: the notion of an expanding-space should rather be taken to reveal an absolutist (or better, a substantivalist) metaphysics, whereas the kinematic approach would most naturally be associated with a relationist position.[9] With regard to the latter association, however, I will show a partial agreement with Whitrow.

As to the expanding-space technique, I do not immediately see how it could be used to support a relational conception of space, given that Whitrow indubitably considers space, in this association, as an *existing* entity. On the other hand, if, as he writes, “there is motion *of* space”, and “space is the framework of all matter and this framework expands”, then it seems absolutely necessary that such attributions of motion or of expansion should result in an ontological commitment to space itself. And, it goes without saying that a similar commitment to the existence of space would be contrary to any Leibnizian relationist standpoint, i.e. any *eliminative* view of relationism according to which space can be completely reduced to spatial relations among objects. Moreover, if Whitrow regards this framework only as a mathematical tool, how could he then explain the differences between absolute and relational views? It seems that this can only be done by adopting the aforementioned extrinsic approach, namely the one countenancing the possible existence of an absolute external space. But, as already said, this approach is unsatisfactory. It therefore appears clear that Whitrow is committed to a weaker form of relationism, one which accepts the existence of a *dependent* spatial background; this is especially evident when he writes that according to the relational concept of the universe “there is no independent spatial background against which systematic changes in the geometrical structure of the universe occur” (*ibid*., p. 294).

I am, however, inclined to think that it is precisely *that* spatial background which, according to the expanding-space technique, changes *independently* of the matter contents. Such independence, in particular, is highlighted in de Sitter’s solutions to Einstein’s field equations, contemplating *empty* (although with a non-null cosmological constant) yet still expanding universes.[10] It is true that such independence might be proved controversial, for instance by proposing that the expanding space be an *emergent* phenomenon closely tied up with clusters recession, or else by pointing out that the energy expressed by the cosmological constant, considered as part of the spacetime contents, would render the space structure supervenient on that energy. These possibilities, or others similar, could be maintained both by non-eliminative relationists who accept the existence of a space(time) ontologically dependent on matter-energy, and by relationists who believe that space(time) is mathematically represented by the manifold of points alone while the metric field is a *physical* dynamical field which, by

Footnote 8 continued
equation, neither in terms of the physical phenomenon underlying it, nor in terms of its possible philosophical consequences.

[9] I am thinking here of the “traditional” Leibnizian view of relationism, i.e. the one Whitrow initially refers to. I will also briefly consider those somewhat more “slippery” positions which, by accepting the existence of a space(time) ontologically dependent on matter, tend to blur the traditional metaphysical distinction between relationism and absolutism/substantivalism, in particular with regard to the separation between container and contained.

[10] As a reviewer interestingly underlines, according to Rugh and Zinkernagel (2009), the vacuum solutions cannot provide a material basis for the physical time (or length) scale, so that, without such a scale, the very idea of the expansion could be undermined. This is a deep issue and would deserve closer and longer inspection. However, I am not completely convinced that the time duration is the only way to capture the expansion and I suspect that other factors, such as the time order and the curvature given by the cosmological constant, could do it.

containing gravitational energy, has a nature closer to matter rather than to a spatiotemporal entity.

It nonetheless seems to me that the heart of the substantivalist–relationist debate is the existence of spacetime, whereas its alleged ontological dependence on matter is a secondary, although important, issue. And such dependence, in these weaker forms of relationism, appears to be an interpretative question, namely an essentially philosophical matter. On the contrary, the question of the existence, and to a certain degree also of the independence, can be answered, in my opinion, by a couple of arguments from physics which lead to metaphysical conclusions quite distant from the relationists ones, namely those based on the cosmological redshift, and on the cosmological constant respectively. Both arguments are fundamental tesserae of the (astro)physics mosaic which seem to underpin a real substantival spacetime, in that they imply nontrivial causal powers that ought to be ascribed to spacetime in order to make sense of what physics tells us. In the case of the cosmological redshift, indeed, a physical medium must exist between the times of emission and reception of the electromagnetic wave, and such a medium has a sort of active role in the stretching of wavelengths. The peculiarity of this kind of redshift is that the frequency shift does not depend on the states of motion of the emitter nor of the receiver (and neither on their other properties): the emitter and receiver could even be at rest, at the instants of the emission and reception respectively, whereas cosmological redshift would still be positive, provided (obviously) that some expansion of the universe had occurred during the intervening time. In other words, the wavelength changes continuously along its path because space(time) itself stretches it.[11] This further implies that "the recession velocity [the one referred to the expansion] 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 2004, p. 284).

In the case of the cosmological constant, such a constant describes a property of the same physical medium, namely an amount of curvature not entirely created by the presence of matter. Thus spacetime does not merely mediate causation between objects but, because of this supplement of curvature, it can also cause objects to accelerate. Spacetime must therefore be a substance because of its active role in gravitational causation [this stance is well sustained by Baker (2005)].

To conclude, both the properties/effects of the cosmological redshift and the cosmological constant do not depend on matter-energy as their sources, contrary to the relationists' claim that all supposed spatiotemporal properties should be reducible to properties of objects. As a consequence, these phenomena commit us to understanding spacetime as an entity separate from the objects contained within it.

This is, very roughly, why I maintain a realist/substantivalist position about the expansion of the universe, and hence why I am criticizing the first of Whitrow's associations. In any case, I think that Whitrow's reasoning is not at all clear, because his implicit adoption of a weaker form of relationism appears to be at odds with Leibnizian relationism and the related considerations about space he previously introduced. But let me postpone this issue on Whitrow's relationism to Sect. 4.

In the meantime, let us look at the second of Whitrow's associations. I think that the kinematic technique may be associated, as he claims, with an absolutist conception of space. It is true that if our attention is concentrated—to use Whitrow's words—on the type of motion of the fundamental particles, then we may regard their motions as occurring in an absolute

[11] This is not the place to go into the details or the possible criticisms of this view. I will cover these aspects in another paper.

space *à la* Newton. Nonetheless, are we sure that in the kinematic technique an ontological commitment to an absolute space should be regarded as necessary? I do not think so. If our attention is concentrated *on the fundamental particles alone*, namely, on the trivial fact of their existence, what results is simply the necessity to associate the kinematic technique to a relationist position according to which the expansion would be given by the increasing distances among the moving particles. In other words, I agree with Whitrow that the focal point of this situation is the motion of particles. But, in doing so, the space structure is reduced to the underpinning *mathematical* framework whose absoluteness, namely the claim that it possesses a *physical* existence, is not a necessary consequence as advocated by Whitrow. In fact, even if an absolutist may legitimately approve this absoluteness by seeing space as an actual entity "hosting" particles, a relationist may legitimately claim that this framework is nothing but an unreifiable "nexus of spatial relationships" (to use Whitrow's words) of the moving particles.

Moreover, such reasoning appears even more plausible if we consider Milne's cosmology as the typical kinematic technique, just as Whitrow seems to implicitly do.[12] Milne himself considers space, in his model, as a mere "conceptual thing", a non-existing entity.[13] Therefore, in my opinion, if we concentrate our attention only on the fundamental particles, the immediate and possibly trivial result is an obvious ontological commitment to the particles themselves and not to a supposed underlying absolute space. For this reason, I think that the kinematic technique should be more naturally associated with a relationist position rather than an absolutist one.

Furthermore, speaking about the three-dimensional spacelike hypersurfaces which change with the lapse of cosmic time, Whitrow subsequently says: "According to the relational concept of space, we need not consider the motions of the individual particles but the sequence of changes of the space structure as a whole" (p. 291). Also this statement appears to be mysterious insofar as I think that a relationist should be precisely involved in the motions of the individual particles and should relegate space structure to the limbo of abstract constructions or, at most, of the entities supervenient on the displacements of particles. Consequently, from a relational viewpoint it does not make much sense to speak of changes to space structure as a whole if these changes are not intended as abstract variations *derived* from the different dispositions of the actual particles.

This concludes the "*pars destruens*" of Whitrow's standpoint. In the next section, dedicated to the "*pars construens*", I hypothesize a partial explanation of his view.

4 An Attempt to Clarify Whitrow's View

A clue towards a possible partial explanation of Whitrow's first association between a relationist view and the expanding space technique might be revealed on the following pages of his book: on page 290, when he introduces the so-called *Weyl's Principle* (I will explain this in Sect. 4.2) saying: "Whichever technique is used, it is customary to follow Weyl…". And on page 292, when he affirms: "Three-dimensional spatial cross-section is determined solely by the fundamental particles, i.e. it is a relational space and not an absolute space with an independent existence of its own". He then adds: the hypothesis that "the material universe

[12] Remember that Whitrow was, with A. G. Walker, Milne's main collaborator from 1932 to 1950, particularly in the development of this cosmological model.

[13] See, for instance, Milne (1934). For a brief overview of Milne's view on space see Macchia (2014, sect. 7).

in its large-scale feature can be identified with world space" is a *relational* hypothesis, in the sense that it is "not an *a priori* condition which must be satisfied, but purely a condition characterizing the class of world models to be discussed" (i.e., FLRW models). The opposite case, he further underlines, would be given by the relative motions (of the fundamental particles) "regarded as occurring in a space which is not given solely by the fundamental particles themselves".

Now, it seems to me that, when Whitrow points out that "the three-dimensional spatial cross-section is determined solely by the fundamental particles", he is tacitly and loosely adopting a way of thinking closer to what Castagnino (1971, p. 2203) has defined as the *inverse problem of General Relativity*. Castagnino proved that the assumption of a Riemannian spacetime geometry can be dispensed with.

In order to introduce such an approach, we have to take a very short detour through the axiomatizations in General Relativity and the foundations of modern cosmological models.

4.1 Deductive and Constructive Axiomatizations in General Relativity

The spacetime of General Relativity is usually introduced by a *top-down* approach with formulae like: "Spacetime *is* a 4-dimensional differentiable manifold… endowed with a semi-Riemannian metric…".[14] The higher level spatiotemporal structure is therefore introduced *from the outset* and assumed to be primitive, with a unifying explanatory role with respect to the lower level structures (affine, projective, conformal) governing the physical behaviour of light and particles. This is called a *deductive* axiomatic approach. We can sum it up with Majer and Schmidt's words by saying that it approximately "begins with a set of postulates concerning the existence of high level structures and/or principles and then proceeds by logical deduction to lower level phenomena which may be directly confronted by experiment" (Majer and Schmidt 1994, p. 17).

On the contrary, according to the *constructive* (or *inductive*) axiomatic approach: "The constructive axioms deal with directly observable phenomena at as low a level as possible. The aim is to formulate axioms which may be directly confronted by experiment, and then deduce from these low level axioms the existence of higher level structures" (Coleman and Korté 1994, p. 68). In brief, such an approach is the "reverse" of the deductive one. In the case of General Relativity, the problem of *deriving* the semi-Riemannian "arena" by physically motivated axioms—thus following the constructive methodology—rather than *postulating* it at the outset, is exactly the aforementioned *inverse problem* as named by Castagnino.

This inverse approach deals with the following topic: do the geodesics, defined by a given metric, have anything to do with the inertial motion of particles? Does an identity subsist between timelike geodesics and inertial motions? Penrose (1968) points out that, when General Relativity was first proposed, this identity was postulated by Einstein, whereas only afterwards was it demonstrated that it was actually a consequence of Einstein's field equations (see references in Penrose 1968, p. 131). Penrose underlines that if we run the argument the other way, we have "to regard inertial motion as primary and to try and construct the metric as a secondary concept" (Penrose, *ibid.*). So that "if both the timelike geodesics (inertial particle worldlines) and null geodesics (unscattered light rays) are known, then the metric of spacetime can be constructed uniquely up to an overall factor" (*ibid.*).

How this inverse procedure can be realised has been a debated issue, particularly in regards to which primitive objects should be necessary from the outset to (re)build the spacetime metric. Among these attempts, the most influential, often judged a kind of paradigm for

[14] For an example see Friedman (1983, p. 32).

constructive spacetime axiomatics and which has driven many further studies, is the so-called *EPS approach* (or *EPS spacetime*). It derives its name from a work by Ehlers et al. (1972). Starting from an initial structureless set of point-events, using only two of the simplest physical phenomena such as freely falling particles and the propagation of light rays, and with a small set of constructive axioms experimentally verified, these authors were able to conceptually build up, step by step, all of the General Relativity spatiotemporal structures until they reduced them to the desired pseudo-Riemannian metric.

Other authors, who have tackled such a methodology with a more philosophical inclination, have mainly focused their attention on the possibilities of the EPS procedure to undermine the conventionality of geometry.[15] According to Ehlers, however, EPS construction complies with a Leibnizian relationism; EPS ontology, on the other hand, consists only of particles and light rays, whereas spacetime has been ontologically demoted to their "by-product". He explicitly states:

> It has been shown that on the basis of simple facts the spacetime geometry of General Relativity can be constructed without resorting to concepts or theorems of theories which presuppose such a geometry [...] Only concepts by which relations between events, particles and light rays are describable have been introduced. This fully agrees with Leibniz's position of viewing space and time not as objects but rather as sets of spatial or temporal relations among things. (quoted in Jammer 1993, p. 229)

Obviously, this is not the place to establish whether the EPS construction is flawless and which ontology it implies. As far as I know, the debate on these issues has so far not reached any univocal responses. Here, I am just interested in Ehlers' hypothesis about relationism and its possible implications in Whitrow's analysis. Therefore, let us take a brief look at how deductive and constructive approaches could roughly work in cosmology.

4.2 Two Approaches to the Foundations of the Standard Cosmological Model

Standard cosmological models, the best description of the large-scale structure of our universe, are formally given by $\langle M, g_{ab}, T_{ab}\rangle$, with M being the spacetime manifold, g_{ab} the FLRW metric, and T_{ab} the stress-energy tensor representing the idealized material contents of the universe taking a perfect fluid form with zero pressure called dust. The FLRW metric is usually derived from the Cosmological Principle, stating that the universe is spatially homogeneous and isotropic on large scales. Spacetime is split up into space and time by imposing homogeneity and isotropy: isotropy guarantees that the worldlines are orthogonal to each spatial hypersurface (see Misner et al. 1973, p. 714); the existence of what is called *cosmic time* is a corollary of homogeneity (see Rindler 2006, p. 359). In this way, one obtains an evolution of spatial hypersurfaces in cosmic time.

In this idealization, clusters of galaxies (or even clusters of clusters) are taken as those grains of dust, i.e. as the elementary constituents of the expanding universe since these giant agglomerates of matter follow the Hubble expansion pattern quite closely. Although clusters form a discrete set, one can extend it to a *continuum* by a smooth-fluid approximation. The idea is that the speed of matter in a given large-scale region of the universe is averaged and this speed and the mass of this region are assigned to a fictitious entity called a *fundamental particle* (one can imagine it placed at the center of mass of that region). Fundamental particles are *freely falling* insofar as their motions are affected by no forces except gravity and inertia.

[15] Coleman and Korté (1980) and Nerlich (1994, pp. 216–218), for instance, think that conventionalism is defeated, whereas Sklar (1985, pp. 129–149) sees no reason for this conclusion.

These material particles, when regarded as mere geometric points, constitute the kinematic *substratum* of the expanding universe model. Each point is crossed by only one worldline representing the cluster's trajectory. A reference frame is attached to each particle so that all matter of that region is at rest relative to that frame. In this way, a sort of global *comoving* (i.e. moving with the expanding motion of matter) reference frame system is defined.

The substratum is usually thought of as a kind of perfectly continuous background, a reference frame in uniform expansion. As each one of its points is an entity ideally "containing" all the matter present in a given cosmic region, the substratum can be considered, at a "large-scale level of abstraction", as an entity *in its own right*, whose particles are its real "atomic" (indivisible) material constituents.

Therefore, summing it all up, the substratum is usually intended, in Rindler's (2006, p. 358) words, as a "space-filling set of moving [fundamental] particles". However, the substratum can actually be seen not only as a space-*filling* set but also as a space-*constituting* set of particles. This is possible if one adopts another approach to the foundations of the FLRW metric,[16] in which another principle, *Weyl's Principle*, assumes a status remarkably more elevated than the Cosmological Principle.

In the 1920s, Weyl suggested that the distribution of stars (today, clusters) could be described as a bundle of non-intersecting timelike worldlines, diverging (the universe is expanding) from a common point in the past. The highly streamlined *large scale* motions of clusters (no randomness, no vorticity, no collision, *except* at a singular point, i.e. the common "origin" in the past) provide *natural synchrony calibration* for all events (the intersection theoretically defines the zero of time).[17] This guarantees that spacetime is globally resolved into space *and* time, i.e. that it can be foliated in a sequence of "space slices", orthogonal to the bundle, whose succession instantiates the flow of cosmic time.

In this approach, Weyl's Principle, the first to be introduced, allows the definition of cosmic time and then spacetime foliation. The Cosmological Principle simply intervenes "later", imposing homogeneity and isotropy on spatial hypersurfaces. In such an approach, the accent is placed on the fundamental particles and on their geodesics. Mathematically speaking, the starting point is the trajectories of matter and not some basic metric assumed *a priori*, as Pauri affirms: "Matters are turned around with respect to the standard approach: a geodesic is a geodesic of some metric; here a particular geodesic structure [a particular family of effective motions] is assumed in order to *construct* a metric having certain desired properties" (Pauri 1991, pp. 319–320).

Note that actually Weyl's Principle is implicitly assumed—mathematically disguised in the notion of isotropy (for instance, see Wald 1984, p. 92)—in the first approach as well (see Rugh and Zinkernagel 2011; also Pauri 1991, p. 334). The reason for this assumption is that Weyl's Principle is *necessary* for a physically well-defined notion of cosmic time. This importantly means that: "Weyl's Principle [...] is a precondition for the cosmological principle; the former can be satisfied without the latter being satisfied but not vice versa" (Rugh and Zinkernagel 2011, p. 417). This last fact could be judged as a good reason to privilege the second approach, even though, from a physical point of view, they are equivalent. The difference is philosophical and will be seen in a moment.

The Cosmological Principle-based and Weyl's Principle-based approaches may be roughly seen, respectively, as examples of deductive and constructive methodologies. In the former,

[16] For example, see Bondi (1960), Narlikar (2010), Pauri (1995), Raychaudhuri (1979).

[17] Note that *small*-scale objects (galaxies, planets, etc.) have chaotic *peculiar* motions. Nonetheless, their very low velocities (less than one-thousandth of the light velocity in the vacuum c) make them negligible when compared to the large-scale *recessional* velocities of clusters (comparable to c).

homogeneity and isotropy select the FLRW metric from a general semi-Riemannian metric given from the outset. In the latter, instead, an "inverse movement" *à la* Castagnino is at work.[18]

Now, let us go back to philosophy. From an ontological point of view, the important result of this last reasoning is that the fundamental particles assume a sort of "ontological pre-eminence" over the spatiotemporal structures. This involves an important element of *relationality* in the conceptual foundations of FLRW spacetime. In Pauri's words: "The universal 'substratum' is defined by a specific structure of *virtual* (not in the quantum-mechanical sense!) trajectories of *fundamental* particles which *relationally constitute* spacetime" (Pauri 1991, p. 319).

Hence, the nature of spacetime is supervenient on the substratum. Each spacetime point is identified with, but is not ontologically independent of, a fundamental particle. In this sense, as I previously said, the substratum can be thought of as a space-*constituting* rather than as a space-*filling* set of particles (as instead happens in the Cosmological Principle-based approach).

4.3 Whitrow's True View, Hopefully

Having said all this, it seems to me that Whitrow's association between the expanding space technique and the relationist philosophy could be comprehended exactly by following Weyl's Principle-based approach. Indeed, in such a case, speaking of the expanding space would mean speaking of an entity that does not have an existence of its own, i.e. whose nature is ontologically dependent on fundamental particles and their divergent motions. Therefore relationism could be the natural result.

On the other hand, such a view seems to be also in line with Milne's approach. In his *Kinematical Relativity*, in fact, he refers to the substratum not as something in which material objects are situated, but—as North (1965, p. 364) comments—"as 'a system of frames of reference in motion'.[19] As such, his particle-observers must be regarded as prior to it, rather than conversely". Given the closeness of Milne and Whitrow, such a view, I suppose, adds credit to my hypothesis.

The fact that this is a promising route towards the clarification of Whitrow's credo appears to be further confirmed by North himself in his famous historical book *The Measure of the Universe* just quoted. In it, on pages 368–369, he briefly tackles Whitrow's aforementioned reflections. North is undecided about Whitrow's relational conception of space: Whitrow would seem to be close both to what North calls a "weak material view" (i.e., space is determined solely by the fundamental particles), and to the more extreme "strong material view" (i.e., space is to be identified with the material of the universe). The latter view, North says, is an

> almost Cartesian attitude, which makes space a set of relata rather than relations, and which is often associated with the notion of 'embedding'. It is more extreme than the first relational view of space [the weak one] only if we are considering the material correlates of the fundamental particles of a model rather than the latter. (North 1965, p. 366)[20]

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[18] Although the particles of EPS and of Weyl's Principle are conceptually similar, I am not claiming that this inverse approach should necessarily be that of EPS, nor that an inverse approach is immune to problems (see, for instance, Macchia 2011). Mine is just a qualitative not a quantitative analysis in order to meet Whitrow's standpoint.

[19] Milne (1948, p. 8).

[20] I think that North deduces his consideration from the following reflection. With regards to the "weak view", when one looks at "the material correlates of the fundamental particles" rather than at the particles

Whitrow, in fact, adopts both relational conceptions of space: the weak one has already been clearly mentioned, the strong one when, for instance, he affirms: "The material universe in its large-scale feature can be identified with world space" (*ibid*., p. 292).

Finally North tends to think that Whitrow is perhaps closer to the weak view "since his attention is not directed to the physical properties of the material particles of the model, but to the possibility of making certain kinds of observations from a restricted class of them (such as observations of the distances of other particles of the class)" (North 1965, p. 368).

In any case, the prominent point for me is that North highlights that, in Whitrow's analysis, the status of the fundamental particles, especially in their relation to real matter, is essential for the evaluation of space ontology. This seems to confirm my hypothesis on Whitrow's association.

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Footnote 20 continued
themselves, as he says, one finds that the real universe does not possess at least one important characteristic of the substratum: *continuity*. It is the continuity that would make such a space (deduced from the fundamental particles) a set of relata devoid of spatial relations (as in the "strong view") due to the continuous distribution of fundamental particles considered like a fluid. But this distribution does not fit the real universe, where clusters form a *discrete* set, namely there is "space" (or void, or, in a sense, only spatial relations) among clusters. Thus, this weak view is, as it were, purely relational. Instead, with regards to the "strong view", this discreteness problem does not subsist insofar as only the material correlates (not the voids among them) of the universe are taken into account to identify space, so that space is a kind of "almost Cartesian" plenum coming from the continuity of matter itself. However, let me remark that in the Cartesian view the identification between matter and space seems completely arbitrary.

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