Mach's Principle Could Save the Gravitons

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The requirement of the Mach-Einstein doctrine according to which reference systems are uniquely determined by gravity implies that gravity is not only described by the ten components of the metrical tensor g_{ik} of Riemannian space-time, but by all 16 components of the reference tetrads h_i^A (where $g_{ik} = h_i^A h_{Ak}$). Therefore, accepting this requirement one is automatically led to gravitational equations of Einstein-Mayer type (Einstein and Mayer 1931) specifying Riemannian apace-times with teleparallelism. Up to special-relativistic global Lorentz transformations, the teleparallelism realizes a uniquely determined physical reference system. Hence, the gravitational fields have localized energy-momentum components, and the gravitational waves correspond to numerable gravitons. Further, the Einstein-Mayer equations imply also the appearance of "wattless" fields acting as hidden-matter fields. It is just the existence of this hidden matter that breaks the local Lorentz symmetry of the GRT and determines the reference system. The hidden matter of the astrophysicists and the measurable gravitons of quantum gravity have the same origin, namely the teleparallelism of the space-time which is a consequence of the validity of Mach's principle.

1. Introduction: Two Unsolved Issues of General Relativity Problems

There are two crucial problems of general relativity to be solved: 1) the problem of dark matter and 2) the problem to give the quantization of gravitational fields a physical meaning.

As to the first problem, the situation is as follows: Today astrophysicists believe that galaxies, clusters *etc.* have dark halos of such a great volume that one has to guess that these halos contain over 90% of the mass of the universe, where the existence of halos is inferred solely from its gravitational effects. This means that there seems to exist a great amount of hidden matter possessing no other quality than (heavy) mass. But, for the only interaction showing this behavior is gravity, the "weakly interacting massive particles" one is searching for should somehow be related to gravitational interaction. Therefore, it was prophecy of actual cosmology when Mach (1912) wrote "that the masses which we see, and by which we by chance orientate ourselves, are perhaps not those which are really decisive."

The second problem has been well-known for many years. The principle of general relativity as realized in Einstein's gravitational theory of 1915 implies that the components of the gravitational energy-momentum are not localizable. Therefore, as was mentioned by Einstein (1954b), "electromagnetic waves can be put into a container, gravitational waves cannot." As a consequence, for the gravitational field, one cannot either follow the road of canonical quantization or define numerable gravitons as field quanta ascribed to Einstein's metrical field of gravity.

In the following we shall give arguments in favor of the thesis that both problems possibly can be solved at one blow. These arguments will bring us to a resolution of the two problems in terms of the Mach-Einstein doctrine, *i.e.*, in terms of the determination of the physical reference systems (the tetrads h_i^A) by the gravity of matter. This way, one falls back to the original question posed by Einstein as to the relation between the general principle of relativity and Mach's principle.

2. General Principle of Relativity vs. Quantum

To talk about the general principle of relativity means to talk about Einstein's theory of general relativity (GRT)—at any rate, as long as one confines oneself to field equations of second order satisfying the principle of equivalence. Indeed, then there is only one permissible Lagrange density, namely the Einstein-Hilbert Lagrangian L_{EH}. In the holonomic (*i.e.*, usual coordinate) representation, it is a scalar density with respect to coordinate transformations and an invariant under local Lorentz transformations, and, in the anholonomic (*i.e.*, tetrad) representation, it is invariant with respect to coordinate transformations and a scalar density under local Lorentz transformations.

In order to discuss issues like the energy-momentum content of fields one, however, needs a canonical representation of the Lagrangian which has to be bilinear in the first derivatives of the field variables. Now, the Einstein-Hilbert Lagrangian contains terms that are bilinear in the first derivatives *and* terms that are linear in the second derivatives of the field functions. But this Lagrangian is Euler-equivalent to two canonical expressions so that one can proceed with the construction of a canonical formalism. Problems, however, that one encounters arise from that these Lagrangians possess less symmetries than the Einstein-Hilbert Lagrangian.

In the holonomic representation of GRT, where all geometric objects are referred to the coordinates x^k of a Riemannian space-time, this is the Lagrangian introduced by Einstein (1916). It is invariant with respect to local Lorentz transformations, but it is not a covariant scalar density under coordinate transformations. Accordingly, the corresponding canonical energy-momentum complex formed according to the usual rules of the canonical field formalism is not a tensor but only an affine tensor. Therefore, one can give it each value one wants by an appropriate choice of the coordinate system (Bauer 1918, Einstein 1918, Freud 1939, Schrödinger 1918). In other words, starting from this Lagrangian one cannot define the energy-momentum of the gravitational field.

Otherwise, in the representation based on the anholonomic coordinates h_k^A representing a reference (or frame) field (where the metric is given by $g_{ik} = h_{Ai} h_k^A$), there exists a Lagrangian that, at first sight, is more promising. It was introduced by Møller (1961, 1966) in order to solve the energy-momentum problem of general relativity theory. This Lagrangian L_M is a scalar density under coordinate transformations, and as a consequence, one is led to an energy-momentum complex that is a genuine space-time tensor. The problem, however, is that both the Lagrangian and the energy-momentum tensor are objects that are not covariant with respect to local Lorentz transformations. Therefore, one meets the following problem: On the one hand, notwithstanding the missing Lorentz invariance of $L_{M,}$, its variation with respect to the tetrad field provides the Einstein field equations that are covariant under local Lorentz transformations and fix the 10 combinations $g_{ik} = h_{Al} h_k^A$ of the tetrad field. On the other hand, since the Møller energy-momentum complex is not Lorentz covariant, it can be given an arbitrary value by an appropriate choice of the reference system.

Hence, in GRT one cannot define a localized distribution of gravitational energy-momentum, and thus it is impossible to speak either of "containers" including a definite amount of energy or of the number of “gravitons,” *i.e.*, of the quanta of the gravitational field (Einstein 1954b). Therefore, the concept of gravitons is an approximate formalization only, which has its use in the harmonization of Einstein’s gravitational equations with atomic and quantized matter fields, but which does not predict any effect that may be used to distinguish quantum from classical GRT. Thus, according to GRT, one should not find measurable quantum effects of gravitational fields (Borzeszkowski and Treder 1988, 1993).

In other words, the principle of general relativity and quantum gravity are incompatible. Thus, if one wants to arrive at quantum gravity, then one should give up the principle of general relativity, after all. The remarks made above signal that this could be done by giving Einstein’s or Møller’s energy-momentum complex a physical meaning by fixing the reference systems, *i.e.* by specifying the coordinates or the tetrads. Before following this idea, let us turn to another but related confrontation, namely to that one between the principle of general relativity and Mach’s principle.

3. General Principle of Relativity vs. Mach’s Principle

In reading Einstein’s papers and notes made for himself in their context (*The Collected Papers of Albert Einstein*, Vol.4, 1995, and Vol.5, 1993) one sees that the *ansatzes* of 1913 and 1914 which, estimated from the viewpoint of the final formulation of GRT, appear as mathematically still incorrect had also a physical motivation which does not allow one to call them mathematically false. The material now generally accessible makes it obviously that Einstein’s doubts about the form of the relativistic gravitational equations were also due to the fact that the physical content of the principle of general relativity was not clear: Because, for Einstein, Mach’s principle was an essential aspect of general relativity at that time he was even ready to accept restrictions on general covariance and thus of general relativity when this would make the gravitational theory “Machian.”*

To support mathematical and physical arguments given in his 1913 paper with Grossmann (Einstein and Grossmann 1913), Einstein introduced the following argument in his “Comments” (Einstein 1914c). Consider a manifold with a region L containing none of the sources of the gravitational field (a “hole”), where accordingly the T_{ik} vanish. Then, by the matter outside of L, the metric g_{ik} is everywhere completely determined, also in L. Now, instead of the original coordinates x^i, we introduce new coordinates $x^{i,}$ of the following kind. Outside of L they be identical to x^i, but in L be $x^i \neq x^{i,}$. Of course, by such a substitution one can, at least for a part of L, reach that $g'_{ik} \neq g_{ik}$. Otherwise, it holds everywhere $T'_{ik} \neq T_{ik}$, namely outside of L for we have $x^i = x^{i,}$ in this region and in L because $T_{ik} = 0 = T'_{ik}$ holds. Hence, when arbitrary coordinate transformations are admitted, then in the case here under consideration more than one solution g_{ik} belongs to a given T_{ik}. That is Einstein’s argument so far; it shows that Einstein had considered the solution g'_{ik} to be physically distinct from the solution g_{ik} and that he therefore believed generally covariant field

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* At that time, even the great mathematician David Hilbert (1916) accepted such restrictions. In the original version of his First Notes on general relativity he asserts that the theory cannot be generally covariant. In addition to 10 generally covariant equations there must be four non-covariant equations. This was recently communicated by L. Corry, J. Renn, and J. Stachel (1997) who had the chance to look into the hitherto unnoticed first set of proofs of Hilbert’s paper.
A restriction of general relativity by non-covariant gravitational equations might also imply a change of the special-relativistic case. Possibly, this leads to that modification of the theory of special relativity which, for other reasons, was proposed by Selleri (1996).

equations not to provide unique solutions of a physical problem. Only after over two years he realized that the two solutions are mathematically distinct representations of the same physical situation.

However, Einstein's "hole" argument does not only show the mathematical difficulties Einstein had to contend with at this time, but it makes also clear that he was unsatisfied by the fact that, in a theory with covariant gravitational equations, Mach's principle is not satisfied. In Einstein's reading of Mach, the totality of masses induces a g_{ik} field (the gravitational field) which itself governs all physical processes, including the propagation of light rays and the behavior of length and time *étalons*, *i.e.*, measurement rods and watches (Einstein 1913c). That means that matter should also determine the reference systems definable by light, rods, and watches. However, in a theory of general relativity one can chose everywhere arbitrary reference coordinates and reference tetrads, respectively, both in *L* and outside of *L:* The matter described by T_{ik} does not fix either the reference systems or the gravitational field uniquely.

Therefore, in 1913 and 1914 Einstein, partly in joint papers with Grossmann, (Einstein and Grossmann 1913, Einstein 1913 a, b, Einstein 1914 a, b, c, d) argued as follows. The special- relativistic matter equations imply four equations saying that the divergence of the symmetric energy-momentum tensor T_{ik} of matter is equal to zero. These four equations are the special-relativistic laws of energy-momentum conservation which in the case where a gravitational field is present and under the condition that the principle of equivalence is satisfied, necessarily, must be written in a covariant form. Now, if one, again in accordance with an aspect of the equivalence principle, assumes that the tensor T_{ik} is the source term of gravity, then one obtains the dynamical equations saying that the covariant divergence of T_{ik} vanishes. These equations should imply that the gravitational equations determine the metrical tensor g_{ik} of a Riemannian space-time up to affine (*i.e.*, linear) transformations.

As mentioned above and also found in Einstein's correspondence (1913c), Einstein considered this specification of the physically preferred reference systems as an expression of Mach's principle because it is an implication of the motion of (cosmic) matter. This principle determines those reference systems which should replace the Newtonian inertial systems. (This version of Mach's principle is sometimes called Mach-Einstein doctrine.) According to this standpoint, the replacement of the inertial systems by "Machian reference systems" is the content of the relativistic gravitational theory (Einstein 1954a).

However, according to the Einstein-Grossmann approach, such preferred reference systems can only exist when the gravitational equations themselves are not generally covariant, *i.e.*, when Einstein's final gravitational equations of late 1915 are replaced by non-coordinate-covariant equations. This way one arrives in fact at a generalization of special relativity since arbitrary affine transformations replace the rigid Lorentz transformations, but the price one has to pay is to abandon the concept of general covariance and thus of general relativity.

The Einstein-Grossmann paper suggests that, under the assumption that the strong principle of equivalence holds, the theoretical realization of the Mach principle and of the principle of general relativity are alternative programs. In other words, one wins the impression that only the former or the latter program can be realized.

This conjecture can really be confirmed—at least, as long as only field equations of second order are considered. To this end, two sufficiently wide classes of theories (Einstein-Grossmann and Einstein-Mayer theories, respectively) have been discussed by us (Borzeszkowski and Treder 1996), where both embrace Einstein's GRT. It was shown that GRT is just that "degenerate case" of the two classes which satisfies the principle of general relativity but not the Mach-Einstein doctrine; in all the other cases one finds an opposite situation.

The first class contains theories of the Einstein-Grossmann type and embraces GRT in its holonomic representation. Apart from GRT, all members of this class are non-covariant and break this way the principle of general relativity. The second class, for historical reasons let us call them Einstein-Mayer theories (Einstein and Mayer 1931), works with reference tetrads as basic field variables and embrace Einstein's GRT in its anholonomic version. The gravitational equations of the latter class are even generally covariant and thus mathematically acceptable. Except for Einstein's equations of GRT, they are however not covariant under local Lorentz transformations and break the general principle of relativity by fixing the reference tetrads.

These considerations lead to an interesting "complementarity" between general relativity and Mach-Einstein doctrine. In GRT, via Einstein's equations, the covariant and Lorentz-invariant Riemann-Einstein structure of the space-time defines the dynamics of matter: The symmetric matter tensor T_{ik} is given by variation of the Lorentz-invariant scalar density L_{mat} and the dynamical equations satisfied by T_{ik} result as a consequence of the Bianchi identities valid for the left-hand side of Einstein's equations. Otherwise, in all other cases, *i.e.*, for the "Mach-Einstein theories" here under consideration the matter determines the coordinate or reference systems via gravity. In Einstein-Grossmann theories using a holonomic representation of the space-time structure, the coordinates are determined up to affine (*i.e.*, linear) transformations, and in Einstein-Mayer theories based on an anholonomic representation the reference systems (the tetrads) are specified up to global Lorentz transformations. The corresponding conditions on the coordinate and reference systems result from the postulate that the gravitational field is compatible with the strong equivalence of inertial and gravitational masses.

3. Mach's Principle and Quantum Gravity

One moral of the story is that general relativity conflicts with quantum gravity and Mach's principle. To see that this conflict, in both cases, arises for the same reason let us return to Einstein's "hole" consideration. It reveals the proper meaning of general covariance as it is realized in GRT. The point is that one should not forget that the terms "coordinate transformation" and, more generally, "transformations of the reference systems" here have quite a different meaning from that one in a space-time like the Minkowski world with specified space-time events which can be ascribed different coordinate values by certain transformations. One is working in a Riemannian space-time where, in the words of Stachel (Stachel 1991), one finds the following situation: "The physical properties of the points of the manifold inside the hole of any solution to the field equation depend *entirely* on the nature of the solution; hence, when one creates the second solution by dragging the physical significance is dragged along with the field. ... Until one introduces a metric, a manifold does not consist of physical events but just of mathematical points with *no* physical properties; it is the metric that imparts the physical character of events to the points of a manifold." - The inverse of the "Einstein's hole" is a finite mass distribution in a spatially infinite world containing no other matter sources. The discussion of this situation leads to conclusions that, in view of Einstein's statements in one of his 1914 papers (Einstein 1914d), motivated Weyl to speak of the "predominance of the ether" in GRT (Weyl 1924).

It is just this close connection between metrical (gravitational) field and reference coordinates that enables us to realize the principle of equivalence requiring that the gravitational field can be transformed away locally by a transition to an Einstein lift. So it becomes plausible that the gravitational field cannot be ascribed a local energy-momentum tensor. However, if one confines oneself to the preferred class of reference systems related by affine coordinate transformations, both the Christoffel connection Γ^i_{kl} and the canonical energy-momentum complex t_i^k of the gravitational field gain the field-theoretical meaning of local field quantities of gravity. Indeed, when one has $\Gamma^i_{kl} \neq 0$ and $t_k^i \neq 0$ in a permitted reference system then the quantities obtained by affine transformations. are also unequal to zero, $\Gamma'^i_{kl} \neq 0$ and $t'^i_k \neq 0$.

In the anholonomic representation, the tight connection of reference systems and metric is even more evident for there the metric is given by a linear combination of the reference tetrads. Then, for the same reason, one has problems with Møller's energy-momentum complex. They can be solved by giving this complex a well defined physical meaning by fixing the reference systems up to global Lorentz transformations.

Our point is that, if one is willing to accept Mach's principle accompanied by a loss of invariance, then such a Machian gravitational theory provides new perspectives in quantization for this provides a framework which is much nearer to usual field theory than to GRT. Let us demonstrate this in the case of Einstein-Mayer theories for they are more serious candidates than the Einstein-Grossmann equations, due to the fact that they are working with general coordinate-covariant gravitational equations.

These Einstein-Mayer equations read (Borzeszkowski and Treder 1996, 1997, 1998):

$$\sqrt{-g}E_{ik} + \hat{\Theta}_{(ik)} = -\kappa\sqrt{-g}T_{ik} \quad \text{and} \quad \hat{\Theta}_{[ik]} = 0\,, \tag{1}$$

where E_{ik} is the Einstein tensor and $\hat{\Theta}_{ik}$ denotes an additional tensor formed from the tetrads and their derivatives and satisfying the conditions

$$\hat{\Theta}^k_{l\,;k} = 0 \tag{2}$$

These equations are not Lorentz-covariant because $\hat{\Theta}_{ik}$ is not a Lorentz-covariant tensor. Noether's theorem together with the Bianchi identities and the second equation of (1) provide the conservation law

$$\left(\kappa\sqrt{-g}T_l^k + \sqrt{-g}\,{}_M t_i^k\right)_{,k} = 0 \tag{3}$$

where ${}_M t_i^k$ is Møller's energy-momentum tensor. The quantity $\hat{\Theta}_{ik}$ represents "dark" or "hidden" matter which contributes only to the Einstein curvature E_{ik} of the Riemannian space-time. In regions where the usual and the dark matter vanish, $T_{ik} = \hat{\Theta} = 0$, the remaining tensor ${}_M t_i^k$ is the energy-momentum density of the gravitational field. In contrast to the situation in GRT, here ${}_M t_i^k$ is well defined because, up to affine transformations, the reference tetrads are fixed by the gravitational equations. Now, it becomes true what Møller (1961, 1966) stated, namely that ${}_M t_i^k$ is the localized energy-momentum density of gravity. According to the Einstein-Mayer theory of gravity, the energy-momentum density of gravitational fields is a measurable quantity, and, thus, the quantization of this theory leads to a physically meaningful theory of quantum gravity. All this is due to the Machian properties of this theory such that measurable quantum effects here result as "Machian effects" with reference to the universe.

So, "measurable gravitons" are in a similar sense a consequence of the Mach-Einstein "induction of the inertia by cosmic gravity" as, according to Heisenberg's theory of a unified field (Heisenberg

1967), the elementary particles with restmass. In both cases it is related to a cosmic breaking of certain symmetries. In our case, it is the breaking of local Lorentz covariance by teleparallelism that leads to a localization of gravitational energy-momentum and thus also to numerable gravitons (Møller 1961, Treder 1970). Gravitons appear as the "compensation" of this breaking (Treder 1967), and the teleparallelization means the unique determination of the reference systems by cosmic matter.

To summarize, the Mach-Einstein doctrine is the solution of the hole problem and implies the breaking of the local Lorentz covariance. This leads to hidden matter and to measurable gravitons. Such this doctrine is shown to posses not only the status of a cosmological but also of a quantum-field principle.

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