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Experimental Repeal of the Speed Limit for Gravitational, Electrodynamic, and Quantum Field Interactions

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General relativity has a geometric and a field interpretation. If angular momentum conservation is invoked in the geometric interpretation to explain experiments, the causality principle is violated. The field interpretation avoids this problem by allowing faster-than-light propagation of gravity in forward time. All existing experiments are in agreement with that interpretation. This implies the existence of real superluminal propagation and communication of particles and fields, free of causality problems. The introduction of real physical faster-than-light propagation into gravitation, electrodynamics and quantum theory has important consequences for physics.

KEY WORDS: gravitation; speed; relativity; aberration; causality; experiments; faster-than-light; superluminal.

1. INTRODUCTION

One of the present problems in theoretical physics is the failure (until this day) of all known attempts to unify general relativity and electrodynamics and the consequent separate development of quantum theory.

This problem is exacerbated by recent experiments of Aspect[(1)] that confirm John Bell's discovery that quantum interactions are non-local between elementary particles, and by the recent controversy on the

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observed non-local character of gravitational interactions within the solar system.[2]

These experiments and observations appear at first difficult to reconcile with experimental evidence confirming the validity of restricted relativity since, if one accepts that all interactions have an exchange velocity $v \leqslant c$, any faster-than-light space-like successive interactions (associated with $v > c$) between two time-like paths of two massive particles can correspond to criss-crossing space-like paths which can break the causality principle.[3] [3]

The question of the existence of superluminal velocity of gravitational interactions, and their coexistence with possible gravitational waves, is not limited to gravitational theory. The same question has been raised in electrodynamic theory, where action-at-a-distance between current elements recently established[4] (called Ampère forces) seems to coexist with transversal Maxwellian waves; and in quantum mechanics, where they appear in the causal stochastic interpretation of quantum mechanics between entangled particles.[1]

As we shall show, the existence of such faster-than-light interactions is compatible with causality if special relativity (SR) is replaced with Lorentz's interpretation (LR) of relativity. In the latter interpretation, one describes real material objects causally moving within an absolute independent space-time, with a velocity $v > c$ (with proper internal energy-momentum and angular momenta) under the influence of Poincaré fields governed by the laws of relativity; i.e., which correspond to causal particle and field behavior.

In other terms, in this model, the gravitational field can carry gravitational waves propagating at lightspeed and Newtonian, attractive, superluminal fields (surrounding massive objects). Likewise, the electrodynamic fields that surround localized charged particles are described as a superposition of transverse Maxwellian waves and longitudinal superluminal Coulomb-type waves (like gravitation) between charged objects.

The aim of the present work is thus:

(1) to show that observed gravitational interactions in the solar system correspond to superluminal ($v \gg c$) interactions, and hence are taken as instantaneous in the inertial center-of-mass frame of massive objects;

[3] The causality principle states, in part, that a chain of successive events in time on any physical time-like path constitutes a unique invariant sequence of causes and effects that cannot be modified by any change of inertial frames.

(2) to show that much faster-than-light interactions satisfy the full causality principle between massive pairs of objects, in particular if:

   (a) they correspond to real faster-than-light phase-waves traveling on top of a real covariant physical Dirac-type aether;
   (b) they are carried by extended massive vacuum elements;
   (c) they satisfy the causal invariant condition $\{H_e, H_a\} = 0$ where H_e and H_a represent the invariant local emission and absorption Hamiltonians of two interacting particles: a model possibly imbedded in a real physical Lorentz aether.

(3) This also suggests that one should add a non-zero photon mass to Maxwell's theory, and substitute for the geometrical model of general relativity (with spin 2) a spin-1 model based on a real physical vacuum in a flat space-time such as that recently proposed by Puthoff.[5].

(4) This also implies the possibility to add to Newton's gravitational force acceleration dependent terms (reflecting vacuum interactions) and velocity dependent inertial induction terms, as recently proposed by Ghosh.[6]

In this work, we shall analyze gravitational phenomena in the solar system and summarize (as E1–E6 in Table 1) six experiments already published in Ref. 2 on the speed of gravity. To these we can now add E7 and E8. Of all these experiments, E2, the binary pulsars, places the strongest observational lower limit to the speed of gravity: $2 \times 10^{10}\ c$.

We shall then summarize recent experimental evidence on $v > c$ interactions in electromagnetism (the Graneau–Hathaway–Phipps experiments; and in quantum theory, the Aspect experiments[1]) and show (following Sudarshan, Droz-Vincent *et al.*[3]) that such $v > c$ interactions are causal if they satisfy reasonable physical constraints within the causal stochastic interpretation of quantum mechanics.[3]

2. SUPERLUMINAL ACTIONS IN ELECTROMAGNETISM AND QUANTUM THEORY

Evidently, the question of the existence of superluminal direct interactions between point-like sources is not limited to gravitational interactions. Recent experiments have indeed confirmed the existence of faster-than-light longitudinal Amperian forces between colinear current elements in electrodynamic theory.[1] Moreover, if one accepts the causal stochastic

Table 1. Experiments setting lower limits to gravitational and electrodynamic field propagation speeds

E1	A modern updating of the classical Laplace experiment[33] is based on the absence of any change in the angular momentum of the Earth's orbit (a necessary accompaniment of any propagation delay for gravity even in a static field).[34]
E2	An extension of this angular momentum argument to binary pulsars shows that the position, velocity, *and acceleration* of each mass is anticipated in much less than the light-time between the masses.[2]
E3	A non-null three-body experiment involving solar eclipses in the Sun-Earth-Moon system shows that optical and "gravitational" eclipses do not coincide.[34]
E4	Planetary radar ranging data shows that the direction of Earth's gravitational acceleration toward the Sun does not coincide with the direction of arriving solar photons.[34]
E5	Neutron interferometer experiments showed a dependence of acceleration on mass, and therefore a violation of the weak equivalence principle (the geometric interpretation of gravitation).[35]
E6	The Walker–Dual experiment showed in theory that changes in both gravitational and electrostatic fields propagate faster than the speed of light, c, a result given preliminary confirmation in a laboratory experiment.[8]
E7	An earlier laboratory experiment [Ref. 36, with summary description in Ref. 37] showed that charges respond to each other's instantaneous positions, and not to the "left-behind potential hill," when they are accelerated. This demonstrates that electrodynamic forces must likewise propagate at faster than lightspeed more convincingly than earlier experiments showing angular momentum conservation.
E8	In a new experiment involving a Bell Inequality, the measured Bell signal was 2.25 ± 0.03, whereas a value of 2 is the maximum allowed by local realistic theories of nature. This shows that local realism is in conflict with experiment.[38]

interpretation of quantum theory, massive correlated quantum particles follow time-like paths under the influence of superluminal interactions resulting from the quantum potential.

Since these results have already been published, we shall only summarize them here and give a brief list of references.

(1) In the case of electrodynamic interactions a recent experiment by Graneau, Roscoe, and Phipps can be considered as an experimental confirmation proof of the real, physical existence of Ampère's longitudinal, faster-than-c electrodynamic force.[7]

This shows that the common belief that all forces acting on a current-carrying metallic conductor are perpendicular to the current streamlines (the Lorentz Force Law) does not cover the whole situation and that one should utilize Ampère's force law between colinear current elements.

Experiment shows that the Lorentz law, which predicts forces between pairs of current elements and is required to absorb or emit momentum in order to retain the principal of momentum conservation, must be completed by the Ampère law, which implies superluminal forces between current elements (and thus satisfies Newton's third law) so that

$$\Delta F_{m,n} = -k \frac{i_m i_n d_m d_n}{r_{m,n}^2}$$

where i_m and i_n are currents flowing into current elements d_m and d_n, their length separated (in their rest frame) by $r_{m,n}$, and k being a dimensionless function which takes into account the relative orientation.

(2) Experiment also supports Aspect's discovery[1] that correlated photon pairs violate Bell's inequalities (which imply that they interact with velocities $> c$; i.e., interact instantaneously in their rest frame (FAPP) between their respective polarizations).

(3) Experiment evidence now indicates that electrodynamic fields propagate superluminally in the near field next to an oscillation dipole source.[8] A high frequency 437 MHz, 2-watt sinusoidal signal is transmitted from a dipole antenna to a parallel near-field dipole-detecting antenna. Analysis of the phase vs. distance curve indicates that superluminal field waves are generated approximately one quarter wavelength outside the source and propagate toward and away from the source; i.e., are consistent with a $J_3 = 0$ component of spin. If confirmed, this result also suggest a non-zero photon mass.[3]

3. PRINCIPLES AND DEFINITIONS

Mathematics and physics take fundamentally different approaches to describing nature. The former is more concerned with what might be possible, and the latter with what is definitely real. Mathematics is constrained by the need for internal consistency, but is generally oblivious to external constraints. Physics has its laws and axioms too, and these can change as knowledge improves, or even be falsified by real or thought experiments. But physics is rigorously constrained by its principles, which are the products of reasoning alone, not subject to falsification, and have no counterparts in mathematics.[(9)] Examples are the causality principle ("every effect must have a proximate, antecedent cause"); the prohibition against "creation *ex nihilo*" (something from nothing); and "the finite cannot become infinite." Violations of such principles are ruled out by logic as requiring magic, a miracle, or the supernatural. Although mathematically allowed, they are said to be "physically impossible."

A specific example where math and physics take different paths, relevant to this article, is the matter of gradients. Consider the gradient of gravitational potential, where potential is a scalar quantity. In mathematics, the gradient of a scalar field is a unique, unambiguous thing; for example, it is the result of applying the differential operator $\nabla = \frac{\partial}{\partial x}\,\hat{\mathbf{i}} + \frac{\partial}{\partial y}\,\hat{\mathbf{j}} + \frac{\partial}{\partial z}\,\hat{\mathbf{k}}$ to a scalar. Note that the gradient of a scalar is a vector, not another scalar. If the differential operator is applied to every point of a scalar field, the result is a vector field. We must now make some important distinctions. First, the scalar and vector fields are in general not one and the same, and no connection between the properties of these two fields can be automatically inferred.[4] Second, the direction of causality is not necessarily indicated by statements such as "force is the gradient of potential." It is equally possible that potential is derived from force. Third, if the source mass generating a vector field begins to move, does the scalar field gradient point toward the instantaneous or retarded position of the source? That depends on whether the vector field updates and regenerates instantly or with delay. So when we say that the gravitational acceleration of a target body follows the potential field gradient, we must ask which gradient it will follow—instantaneous or retarded. Physics has issues that math does not. Moreover, retarded potentials allow for delays only in the mass distribution and in changes of distance between masses in a scalar field. But retarded gradients must allow also for delays in the direction of the vector (force) field, which is normally the dominant effect of retardation and is necessarily different for the target body frame of reference than for the source mass frame. Again, physics has issues that math does not unless we reinterpret the math using sensible physics.

A corollary of the causality principle is the prohibition of true "action-at-a-distance," because every effect must have a *proximate* cause. That means that something (call it an "agent"), whether particle or wave or wavicle or other, must pass (or fail to pass) between a source of gravity and an accelerated target to produce the acceleration. Moreover, this agent is the carrier of the momentum transferred between source and target. In

[4] For example, potential is a scalar field with units of velocity squared. Force is a vector field with units of mass times acceleration. Obviously, constraints on velocities are not constraints on accelerations.

math, momentum transfers to the target could take place in any effective direction. We need merely write an equation to describe which one. But in physics, the only available source for the momentum transfers is the actual mass and velocity of the agents that communicate between source mass and target body. And the speed and direction of travel of those agents (necessarily radial from a monopole source mass) comprise the velocity vector portion of the momentum transferred to the target. In physics, no freedom to choose another direction exists unless a secondary cause with a force of its own is introduced.

The matter of definitions of terms is also important. In mathematics, one can associate a mathematical symbol with a physical concept, then manipulate symbols and derive new information about the concept. But in physics, definitions must connect concepts to observations or experiments. For gravitation, this difference of approach has led to two different interpretations of GR: the "field" interpretation with forces and motions through 3-space measured by coordinate time; and the 4-dimensional "geometric" interpretation in which "gravity is just geometry" without need of forces as such. The field interpretation usually associates field with "force field;" whereas the geometric interpretation usually associates it with "potential field." Einstein and early relativists dealt with both interpretations as if they were fully interchangeable; but in the context of this paper, we will see that they are not.

In modern times, professional relativists have come predominantly from the ranks of mathematicians, resulting in the almost exclusive ascendancy of the geometric interpretation. This viewpoint has been carried to its extreme form in modern GR textbooks such as that of Wald, who denies the viability of the field interpretation altogether with these words: "The basic framework of the theory of general relativity arises from considering … that we cannot in principle—even by complicated procedures—construct inertial observers in the sense of special relativity and measure the gravitational force. This is accomplished by the following bold hypothesis: The space-time metric is not flat, as was assumed in special relativity. The world lines of freely falling bodies in a gravitational field are simply the geodesics of the (curved) space-time metric. In this way, the 'background observers' (geodesics of the space-time metric) automatically coincide with what was previously viewed as motion in a gravitational force field. As a result we have no meaningful way of describing gravity as a force field; rather, we are forced to view gravity as an aspect of space-time structure. Although absolute gravitational force has no meaning, the relative gravitational force (i.e., tidal force) between two nearby points still has meaning and can be measured by observing the relative acceleration of two freely falling bodies. …"[10]

At the other extreme, Feynman preserves the force and motion concepts with their classical meanings, and comments: "It is one of the peculiar aspects of the theory of gravitation, that it has both a field interpretation and a geometrical interpretation. ... the fact is that a spin-two field has this geometrical interpretation: this is not something readily explainable—it is just marvelous. The geometrical interpretation is not really necessary or essential to physics."[11]

In this paper, we will argue that the geometric interpretation violates the causality principle, and is therefore falsified in physics. (Of course, it remains mathematically valid.) To that, we can add the results of the neutron interferometer experiments[35] that purport to falsify the geometric interpretation directly because a dependence of gravitational acceleration on the body's own mass is demonstrated; so more than geometry is required to account for the motion. We will therefore follow the field interpretation herein, defining our terms in the traditional physics way, and associating fields with force fields, not potential fields, except where otherwise noted.

By contrast with solutions to the field equations of GR, which involve the potential field, the standard GR equations of motion[12] are expressions for gravitational 3-space acceleration—the second derivative of the position vector with respect to time. "Time" here means "coordinate time" in a relativistic context. Multiplying acceleration by target body mass (a constant) yields an expression for what we may call "gravitational force" by definition. If we integrate this force expression with respect to radius vector r (instantaneous distance from source mass to target body), we arrive at an expression for what celestial mechanicians call "gravitational potential." For the gravitational field, this makes gravitational force the instantaneous gradient of gravitational potential. These are all standard concepts in relativistic celestial mechanics.

GR involves gravitational source masses and their fields. If a source mass and its force field move in lockstep, so that when the source mass is changed in certain ways, the whole field is instantly (in coordinate time) changed in the same way, this is called a "rigid field," and is logically equivalent to a field with "instantaneous" propagation of changes. But if a change in the motion of a source mass results in a delayed corresponding change in its force field, then the propagation of that field is said to be "retarded." If ambiguity arises, the appropriate coordinate time is that of a clock at rest with respect to the center of mass of the system under consideration, but infinitely far removed from the gravitational influence of those masses.

Truly rigid force fields are physically impossible (in the sense defined above) because they violate one or more principles of physics. They amount to the transmission of a local cause (e.g., an acceleration of a source mass) to the distant field without intermediaries carrying momentum and without propagation delay. It is perfectly understandable why GR has adopted rigid force fields as an approximation of reality. No experiment has yet detected the propagation delay, so an infinite propagation speed for fields is still the best approximation we can make. But it is important to understand that it is an approximation, because truly rigid fields would not have antecedent causes (violating the causality principle); would have infinite propagation speeds (violating "the finite cannot become infinite"); and would impart momentum to target bodies that arose from nothingness (violating "creation *ex nihilo*"). Moreover, truly rigid fields are conceptually inconsistent with the hypothesized non-rigid behavior of the field when the acceleration of the source mass changes magnitude or direction.

Although physically impossible, we agree the current conception of rigid force fields is a fair and adequate approximation that is pragmatically the best solution to adopt in the absence of an experimental measurement of the actual force propagation speed. There is, after all, plenty of precedent for making pragmatic approximations that are physically impossible. For example, one might approximate the speed of particles in a particle accelerator as the speed of light even though it is physically impossible for an accelerator to force particles all the way to that speed. The Newtonian "universal law of gravitation" is likewise physically impossible in the same sense, a point strongly made by Newton, who disassociated himself from any belief in the possibility of infinite propagation speeds, despite their use in his theory.(12)

Finally, we will need to take note of the distinction between Einstein's special relativity (SR) and the mathematically identical, physically quite different Lorentzian relativity (LR), a modern updating of the Lorentz Ether Theory.(13) In the former, motion affects time and space. In the latter, motion affects clocks and rulers, but nothing can affect time or space. In the former, all inertial frames are equivalent; while in the latter, a preferred frame, now identified with the local gravity field, always exists. Too often, physicists fail to appreciate that none of the eleven independent experiments confirming various aspects of SR distinguish it from LR, at least not in favor of SR.(14, 23) Yet the conclusion that faster-than-light propagation in forward time is impossible rests on SR being a better model of nature than LR—a proposition presently in doubt.(15)

4. GRAVITATIONAL WAVES AND FORCE VARIATIONS CONFUSED

Because no experimental data suggests that gravitational force fields might propagate as slowly as lightspeed c, most of the debate revolves around confusion over the meaning of the expression "the speed of gravity." It is undisputed that gravitational waves, assuming these entities exist, propagate at light speed c. However, gravitational waves are still hypothetical, yet are often confused with changes in gravitational fields ("force variations"). The existence of the latter is firmly established as they are detected daily with gravimeters. If a massive body of stellar dimensions can generate a significant gravitational wave (e.g., by explosion), that wave would still be ultra-weak, and unable to contribute to the acceleration of any other astrophysical body at a presently detectable level. Indeed, our most sensitive detectors have not yet succeeded in identifying gravitational waves from any astrophysical source, despite indirect evidence for their existence from binary pulsars. Would-be gravitational wave detectors attempt to observe detector motions that are only a fraction of an atomic diameter.

By contrast, gravitational fields and field variations produce large accelerations of major astrophysical bodies. If our Sun were a double star, the easily detected force variations emanating from the pair would not win anyone a Nobel Prize for the first detection of gravitational waves. Changes in gravitational fields, whether themselves of wave-like character or not, are a distinctly different phenomenon from the "gravitational waves" of GR. For example, a neutron star binary pair might have an orbital period as short as a millisecond, producing force variation cycles every half millisecond. Photons and gravitational waves travel 150 km in a half millisecond, so different delays in their arrival time at various detection stations will be seen. But several of the experiments E1–E6 in Table I, especially E2, show that force variations have no measurable propagation delay comparable to that of light. The gravitational maxima of the neutron binary would be quite out of phase with the optical eclipses and gravitational wave cycles because of differing propagation speeds for gravity and light, just as was shown in experiment E3.

The meaning of the "speed of gravity" is perhaps clearest in the case of a binary star with orbital period P, observed from a distance greater than cP, where c is the speed of light. Such a pair of stars will have made one or more revolutions during the time it takes light to reach the observer. Without dispute, the observer sees the positions of the stars as they were when the light left them—their retarded positions. However, the observer's gravimeter would detect gravitational pulses as the pair line up with the line of sight (maximum) or the plane of the sky (minimum). Both experiment E2 in Table I and the GR equations of motion (see Section 6) agree that the gravimeter will see pulses nearly in phase with the true, instantaneous positions of the stars rather than their retarded positions. That is an effect that has traveled the distance to the observer in much less time than light can travel that distance, which means that this gravitational effect traveled much faster than light more or less by definition of "speed."

(Some relativists maintain that the gravimeter will see only the extrapolated retarded position. Among the logical difficulties this creates, consider a mass with no net motion, but oscillating back-and-forth in line with the observer at just below lightspeed. Whenever that mass is moving forward, if its gravitational field propagated at lightspeed, then its extrapolated position when the field arrived at a distant observer would be very close to the observer, producing a large acceleration. And whenever the mass was moving away, then its extrapolated position would be extremely remote, producing negligible acceleration. Yet the real mass is always at a moderate distance where it should produce a steady, moderate acceleration. It never really gets close enough to the observer to produce a large acceleration. So the hypothetical large acceleration predicted for the observer in this scenario would be lacking a physical cause.)

It is common to "explain" this apparently superluminal phenomenon using the concepts of "nearfield" and "farfield."[12] The propagation speed of gravitational waves is said to be nearly instantaneous in the nearfield, but to gradually reduce to near lightspeed before reaching the farfield. In the case just cited, the distance cP divides the two fields. However, it is clear from context that the authors in Ref. 12 were speaking of gravitational waves, not gravitational force. The dilemma would be clearer by considering a single fixed star as the source. That example takes away any possible meaning to a nearfield/farfield boundary because there is no wave and therefore no characteristic length. In principle, a very small planet can orbit a high-density, compact star in less than a millisecond. Surely the existence of such a small body does nothing to establish a nearfield/farfield boundary for the star's gravitational field. If it did, all ordinary planets would be in the star's farfield, contrary to observations.

Now if the existence of a companion doesn't establish the characteristic boundary, then the only remaining difference between the fixed single star and the double star cases is the acceleration each induces in the other. So a star emits a gravitational force field that changes only when the star accelerates. But with what characteristic length does it change? A star can have a given acceleration because of moving in a small circle about a large companion or because of moving in a large circle about a small companion. These orbital periods are very different. Yet the star has only its acceleration to determine what it emits, and that must be emitted isotropically. So there is still no logical way for the force field of a single star or either component of a double star to acquire a characteristic length for its force field. The speed of regeneration is whatever it is, and a companion cannot help to determine that.[5]

Moreover, gravitational fields and changes in those fields (due to acceleration of a source mass) all emanate from the source of gravity. By contrast, gravitational waves emanate from a target of gravity as it is forced to accelerate for any reason, as in the case of a supernova. (The gravitational field of a supernova changes only relatively slowly for a spherically symmetric explosion.) Gravitational radiation ($\equiv$ waves) arises from a body's inertial mass, not its gravitational mass. This is because it is determined by the permeability and permittivity of the "space-time medium," rather than by the curvature of that medium. Gravitational waves are therefore an effect of acceleration, not a cause; and could presumably be generated even by two hypothetical non-gravitating orbiting masses held in place by a connecting tether. (Because Einstein's equivalence principle equates these two types of mass for all bodies, such a hypothetical example might be impossible in the physical world.) Gravitational waves can also be thought of as changes in the potential fields around masses, or as changes in a hypothetical "light-carrying medium" in which masses are embedded. As such, gravitational waves may be seen as simply very-long-wavelength portions of the electromagnetic spectrum.

Correspondingly, propagation delays for gravitational force (or whatever produces gravitational acceleration in 3-space) would cause orbits to gain angular momentum and expand at a rate independent of the mass of the orbiting body; whereas radiation of gravitational waves causes orbits to lose angular momentum and shrink at a rate that does dependent on the mass of the orbiting body.

In summary, we can use the analogy of a buoy (Fig. 1). If the anchor holding the buoy in place is moved, the chain connecting them causes the buoy to move. This is analogous to gravitational force variations between a source mass (anchor/Sun) and a target body (buoy/Earth). As the buoy moves, it sets off water waves. These are analogous to gravitational waves, which disturb "space-time" (or "the light-carrying medium," whatever its nature). The anchor or source mass is a cause of changes in target motion;

[5] All smooth accelerations can be reduced to a series of impulses (like Lorentz boosts). But an impulse has no wavelength. Moreover, because motion can usually be approximated as linear during the light transit time, relativity requires there be no experimental difference between the effects of a source motion vs. an equivalent target motion. Both of these points show that a meaningful nearfield/farfield distinction should be impossible.

Fig. 1. Analogy to illustrate gravitational force (anchor and chain pulling on buoy), and gravitational waves (water ripples emanating from buoy).

the water waves are an effect of those changes.[6] There is no physical connection between the speed of force field (chain) motion and the speed of potential field (water) waves.

Understanding the very meaning of the "speed of gravity" requires resolving any confusion that may remain between these two unrelated concepts. The "speed of gravity" refers to whatever causally links the source of gravity to the 3-space acceleration of a target body. Dividing the distance between a source of gravity and a target body by the "speed of gravity" answers the question: "If a source of gravity accelerates, how much time will elapse before the target body responds?" As we argued above and in Fig. 3 and Table I of a previous paper,[2] we showed this is much less than the light-time between the two bodies in the case of binary pulsars. Further points relevant to electrodynamic analogies and retarded potentials raised by Marsch & Nissim-Sabat[16] and Ibison *et al.*[17] were already answered earlier.[18] In brief, equations for retarded potentials omit transverse aberration when their gradients are taken. But this omitted effect is the largest physical manifestation of propagation delay. So the

[6] Supernova explosions also generate gravitational waves. To complete our anchor/buoy analogy, this would be like the anchor exploding, which would clearly send out water waves—the analog of gravitational waves.

standard treatment of retarded potentials cannot address questions of interest here. We will elaborate in the next section.

S. Carlip[19] has now also commented on a previous paper.[2] Carlip argues for the consistency of some of these experiments with the geometric interpretation of general relativity, assuming that gravity propagates at lightspeed. However, neither experiment E5 or E6 in Table I (if independently verified) is consistent with the geometric or lightspeed interpretations of GR, although they are consistent with the field interpretation of the same equations in flat space-time.[20, 21] In brief, Carlip (following common practice) hypothesizes a "velocity-dependent force" to cancel the effect of propagation delay that would result from lightspeed propagation of forces. In essence, this creates the math needed to fix the problem, but has no basis in physics. We will examine this closely in Section 8.

5. COMPARING GRAVITATIONAL AND ELECTROMAGNETIC (LIGHT) FIELDS

As explained with diagrams and equations in a previous paper,[2] aberration is the change in the effective direction of approach to a moving target necessitated by the propagation delay of any projectile (whether particle, wave, wavicle, or other). We apply that here to two different types of field-generating forces: gravitation and the radiation pressure from sunlight.

If gravity and light originate simultaneously at the same source (e.g., the Sun) and propagate to the same target (e.g., the Earth) at the same speed (e.g., c), then aberration will be the same for both. [That is because $\tan(aberration) = v_{orbit}/V_{propagation}$, where v_{orbit} is the transverse orbital speed of the target body and $V_{propagation}$ is the propagation speed of field regeneration. Approximately (in radians), $aberration \approx v_{orbit}/V_{propagation}$.] Therefore, gravity and light should produce 3-space accelerations in the same direction (or exact opposite direction, if push and pull are reversed[7]), differing only in magnitude by a constant scale factor. Specifically, the momentum transferred to or removed from the target to produce the acceleration is some constant (usually a mass, with or without a relativistic "gamma" factor) times $\mathbf{V}_{propagation}$, a vector, for both gravity and light.

[7] Real particles always have positive momentum in the direction of their motion. However, in the flux of a dense field of particles acting in all directions at once, blocking some particles with positive momentum produces the same effect as transmitting isolated particles with negative momentum.

The only physical way to break this equality would require postulating some source of the momentum transfer other than, or in addition to, the propagation speed of the field. Such a postulate would seem to constitute new physics, and would appear to be in trouble with the causality principle because, to accomplish its purpose, it could not consist of a radial force from the source mass. In the absence of any serious such proposal for a new force, and given that gravity and radiation pressure do not produce anti-parallel forces in experiment E4, one of our premises must be violated. The only premise open to question is the equality of propagation speeds of the two types of force. If gravity propagates very much faster than light, all experimental evidence is immediately satisfied.

We see that all relevant characteristics except possibly field propagation speed are common for the two types of force. Therefore their physical propagation behavior ought to be the same if field propagation speed is the same, or different if field propagation speed is different, because there is nothing else relevant that might distinguish the two types of force. Experiments show without ambiguity that the resulting accelerations are applied in different directions, which implies different field propagation speeds.

To clarify, note than an accelerating target is necessarily changing its momentum vector. Momentum is the product of mass times velocity (or energy over c^2 times velocity, if the projectile is "massless" as in a wave) for whatever "projectile" carries the force from source to target. The "velocity" factor in the momentum is the velocity vector of the carrier, whose direction of travel is along the radial from source to target. Because the momentum is necessarily directed along the radial direction, no part of the exchanged momentum could be applied in some other direction. Specifically, if the projectiles are photons and the force is radiation pressure, the target is pushed in the direction of the arriving photons. Whatever is the mechanism of gravity, how could the direction of its pull be other than along the radial to the source mass? The physics and the meanings of words such as "momentum = mass times velocity" dictate only a single possibility for the vector direction of momentum transfers: the radial direction between source mass and target body. And if that is true, the only physical way left to explain the different effective direction of the force is a different propagation speed for a retarded field.

The same remarks apply to electrodynamic forces between charges. If the field propagation speed were lightspeed, we would be forced to interpret the momentum transfers as applied in a different direction from the direction of travel of the momentum carriers because of aberration. That is why, when the details are examined closely, we hear statements such as "virtual 'photons' (the hypothetical carriers of electrodynamic forces, not to be confused with real photons) travel at infinite speeds." So this "lightspeed propagation" assumption is unphysical and unnecessary. One can have the same equations (to the accuracy of observations) and interpret them in a physically consistent way if the momentum carriers travel much faster than light.

Lorentzian relativity allows faster-than-light (ftl) propagation in forward time.[22] Although the Lorentz transformations are the same in Lorentzian and special relativity,[8] in LR they describe what happens to moving clocks, and in SR they describe what happens to time and space. In SR, the speed of light is the same for all frames *by postulate*, and time ceases to pass for motion at the speed of light. Time would reverse, potentially violating causality, if that speed were exceeded. In LR, time and space are unchanged by motion, a local preferred frame exists, the speed of light is affected by observer motion relative to the local preferred frame, and the effect of motion on clocks is not reciprocal between two frames. Therefore, motion at all speeds takes place in forward time, eliminating any possibility of causality violations. So the only real issue about LR is whether it is experimentally viable, and that has now been answered in the affirmative by examining its consistency with the list of all eleven independent experiments testing the relativity of motion.[23] Therefore, ftl propagation is no longer forbidden in physics, and ftl force carriers are the most reasonable interpretation of the equations of gravity and electrodynamics. We expect that no one would ever have thought otherwise if he/she had not mistakenly believed that ftl propagation was forbidden in physics.

A frequent remark by those trained in SR and unfamiliar with LR is: "Why not just measure the speed of light and see if it is affected by observer motion?" Measuring a speed requires dividing a distance traveled by a time interval elapsed. Measuring a time interval requires differencing two clocks, which must therefore be synchronized. If we synchronize them Einstein's way, the speed of light is constant by construction. If we synchronize them Lorentz's way (as is done in the Global Positioning System, for example, where clocks are adjusted in epoch and rate to achieve continuous synchronization for clocks in all inertial frames), the speed of light is constant only in the local preferred frame (e.g., the Earth-centered-inertial frame), but not in other frames such as the observer's instantaneous co-moving inertial frame. So the measured speed of light depends on the adopted postulate.

[8] Because of the lack of frame reciprocity in LR, the clock offset terms of the usual transformations are unnecessary. So the normal form of the equations relating reference frame (X, T) to frame (x, t) with relative motion v are: $t = T/\gamma$ and $x = \gamma(X - vT)$, where $1/\sqrt{1-v^2/c^2}$. For example, this is the form of the equations used in the Global Positioning System (GPS) to relate times and lengths from any moving frame back to the common reference frame, the Earth-centered inertial coordinate system.

If the force field around a charge propagated with lightspeed delays, then Maxwell's equations would be wrong because they neglect transverse aberration, the main manifestation of field propagation delay. The fact that the equations are correct to first order in v/c tells us that the field propagation speed must be very fast compared to lightspeed, because the neglect of transverse aberration is the logical equivalent of adopting infinite field propagation speed. If Maxwell's equations did work for force fields propagating at lightspeed, then they would also work for radiation pressure from light fields too, which they do not (because propagation delays exist, but a "velocity-dependent canceling force" does not). If the field has a measurable delay in reshaping itself to register the motion or acceleration of its source, then one would need to add propagation delay into Maxwell's equations (for example, by taking partials with respect to retarded coordinates instead of instantaneous coordinates). The absence of such propagation delay in the equations means that instantaneous propagation of fields is already built in.

It has come to be assumed by many in modern physics that changes in electric fields caused by acceleration of a charge *are* electromagnetic waves. However, this assumption is subject to the same confusion as failing to distinguish changes in gravitational fields from gravitational waves, as we discussed in Section 4. It is essential to distinguish hard facts from flexible interpretations. The equivalence of changes in electric fields with (e.g.) light waves is an interpretation that gets into logical difficulties when the minimum propagation speed of such changes indicated by experiments is considered. An interpretation with no such difficulties is based on a separation of these concepts: The acceleration of a charge sets off a wave in an underlying "light-carrying medium," which is a light wave propagating at speed c; whereas the electric field of the charge accelerates nearly in lockstep with its source by regenerating at a speed much faster than lightspeed.

6. HOW THE "SPEED OF GRAVITY" APPEARS IN THE GR EQUATIONS OF MOTION

The speed of light, c, appears in the Schwarzschild solution to the Einstein field equations, and in the GR equations of motion. It plays the dual role of permeability or permittivity of space-time (a measure of its resistance to curvature) and as the wave speed in the equation for gravitational waves. It appears in all GR terms in n-body equations of motion beyond the basic Newtonian acceleration terms. See, for example, Misner *et al.*,[12] where c has been normalized to unity; or the source of those equations, Einstein *et al.*[24] or Robertson and Noonan,[25] where c is retained explicitly.

These equations are lengthy because they are for n bodies and include higher-order terms of an infinite Taylor series expansion. For our purposes here, only terms that are first-order in potential or first- or second-order in velocity are relevant. The sum of all higher-order terms to infinity is negligible for all astrophysical cases under consideration. This allows us to ignore most of the terms in the equations of motion as insignificant for this discussion, allowing a great economy of form and ease of understanding.

Newton's general formula for the gravitational acceleration of a planet of negligible mass in the field of the Sun is

$$\ddot{\mathbf{r}} = -\frac{GM}{r^3}\,\mathbf{r}, \tag{1}$$

where $\mathbf{r}$ is the vector from Sun to planet and r is its magnitude; G is the universal gravitational constant; M is the mass of the Sun; $\ddot{\mathbf{r}} = d^2\mathbf{r}/dt^2$ is the 3-space acceleration vector of the planet relative to the Sun; and t is ("coordinate") time.[26] Without directional information ($\mathbf{r} \to r$), this would reduce to the more familiar inverse square form. But we need to retain directionality (the vector form) in this discussion.

The GR equations of motion are taken from Misner *et al.*,[12] with notation adjusted to agree with the above conventions. We now need additional definitions. $\mathbf{v} = \dot{\mathbf{r}} = d\mathbf{r}/dt$ is the 3-space velocity vector of the planet relative to the Sun; c (as before) is the speed of light, and $\varphi = GM/r$ is the scalar gravitational potential of the planet in the Sun's field. Then the GR equations of motion for a planet in the Sun's field are

$$\ddot{\mathbf{r}} = -\frac{GM}{r^3}\left[\mathbf{r}\left(1 - \frac{4\varphi}{c^2} + \frac{\mathbf{v}^2}{c^2}\right) - \mathbf{v}\left(\frac{4(\mathbf{r}\cdot\mathbf{v})}{c^2}\right)\right]. \tag{2}$$

A careful examination of Einstein *et al.*[24] or Robertson and Noonan[25] would yield the same expression. These terms are sufficient to produce solar light-bending, redshift, radar time-delay, and perihelion advance, the classical effects that differentiate GR from Newtonian gravity. All other terms involve higher powers of the velocity or potential, and are therefore much smaller. Note that this equation reduces to the Newtonian law in the low velocity ($\mathbf{v} \to 0$), weak field ($\varphi \to 0$) limit. In the geometric interpretation of GR, the new terms that appear here represent "space-time curvature." In the field interpretation, they can be thought of as path-bending in a refracting medium (the potential field).[20, 21] These terms have nothing to do with the speed of gravity.

In both the Newtonian and the GR equation of motion, all quantities take on their instantaneous values for any given time t. No one disputes that Newtonian gravity has infinite propagation speed built in.[12] In GR, one of several ways to get equations of motion is to form a Hamiltonian (an expression for the total energy, potential plus kinetic, for a system of bodies), and take partial derivatives with respect to some chosen coordinates and momenta. In this crucial step for GR, the partials are always taken with respect to instantaneous, rather than retarded, coordinates and momenta, thereby neglecting aberration and implicitly adopting instantaneous gravity. Retarded values are not used because then the equations of motion would no longer conserve angular momentum; i.e., they would be wrong. But the logical consequences of this choice have seldom been elaborated.

To explicitly see the effect that a finite speed of gravity would have, we can parameterize it. Let the speed of gravity be V. Then the propagation time for gravity would be r/V, a small quantity. Because this propagation delay time is short, we can save unneeded work in our derivation by taking the motion of the planet during the gravity propagation time to be linear, and by ignoring small changes in already small quantities such as φ/c^2 or $\mathbf{v}^2/c^2$. Therefore, the only quantity that changes significantly during the gravity propagation time is $\mathbf{r}' = \mathbf{r} - \mathbf{v}(r/V)$, where prime ($'$) denotes a gravity-propagation-time retarded value.

We can spare ourselves additional small, unneeded terms by considering only the transverse motion of the planet, ignoring radial effects (which are smaller than the terms we keep by a factor of the eccentricity of the orbit). This allows us to use the approximation $r = r'$; i.e., the Sun-planet distance has little or no change, although its direction still changes rapidly. That will restrict our focus to transverse velocity, which is the quantity that gives rise to transverse aberration. With this simplification that changes nothing material to this discussion, Newton's retarded gravitation law

$$\ddot{\mathbf{r}} = -\frac{GM}{r^3}\mathbf{r}'$$

becomes

$$\ddot{\mathbf{r}} = -\frac{GM}{r^3}\mathbf{r} + \frac{GM}{Vr^2}\mathbf{v} \tag{3}$$

This is Newton's law with the speed of gravity explicitly shown. Obviously, this new term vanishes as the speed of gravity $V \to \infty$, which shows that we recover the normal Newtonian law under that condition, as expected. Note, however, that we can already see a coming problem with the geometric, lightspeed interpretation of GR. In the weak-field, low-velocity limit of this Newtonian law, if we claim that gravity propagates at the speed of light, the new term in equation will not vanish.

To introduce the speed of gravity into the GR equations, we make the same substitution of retarded for instantaneous values. Not surprisingly, only the Newtonian part of the GR equations of motion is large enough and changes fast enough that retardation is significant. We therefore end up with the same new term.

$$\ddot{\mathbf{r}} = -\frac{GM}{r^3}\left[\mathbf{r}\left(1-\frac{4\varphi}{c^2}+\frac{\mathbf{v}^2}{c^2}\right)-\mathbf{v}\left(\frac{4(\mathbf{r}\cdot\mathbf{v})}{c^2}\right)\right]+\frac{GM}{Vr^2}\mathbf{v} \tag{4}$$

These are the GR equations of motion with the speed of gravity retained explicitly. This new term still goes to zero as the speed of gravity $V \to \infty$, in which case we recover normal GR. To recover Newtonian gravity from this equation, we would also have to set the "space-time curvature" or "permeability of space" that characterizes GR to zero by letting $c \to \infty$. The consequences of setting c to infinity or V to infinity should not be confused.

It should also be noted that the speed of gravity term is proportional to v/V (first order in velocity), whereas the most similar "curvature" term is proportional to v^2/c^2 (second order in velocity). In the most favorable comparison case, $V = c$, the latter term is still much smaller than the former. For typical solar system cases, the difference is four orders of magnitude. In short, second and higher-order terms in v, even summed to infinity, are too small to affect this discussion of the speed of gravity.

The assumption that gravity propagates at lightspeed would change the GR equation of motion to Eq. (4) with $V = c$, which is observationally unacceptable. It is therefore without doubt that gravity has no detectable propagation delay or aberration. Only the implications of that fact are in dispute. The statement that "the speed of gravity equals the speed of light" is manifestly false, and is heard often only because of the confusion with the propagation speed of gravitational waves, or because of those who would invent unphysical "velocity-dependent forces" with no purpose to exist except to cancel propagation delay effects in these equations.

7. RETARDED POTENTIALS AND GRADIENTS

Consider the rubber sheet analogy for the geometric interpretation of GR, found in many textbooks, wherein the gravitational field is likened to

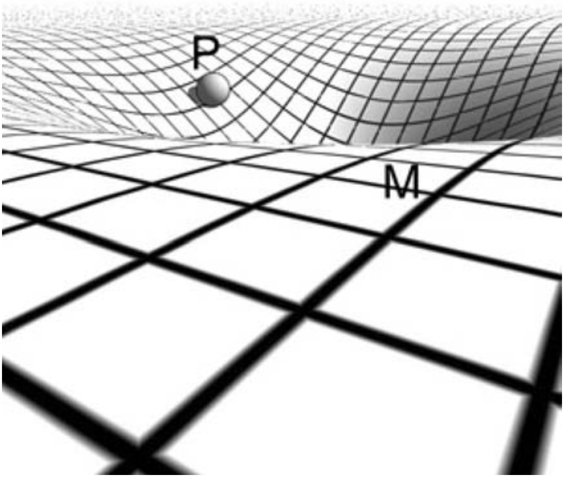

Fig. 2. Rubber sheet analogy for gravity. Source mass M makes dent in sheet, causing target body at P to roll "downhill" toward M. [Copyright 1997 by Boris Starosta, ⟨http://starosta.com⟩].

a rubber sheet with a huge dent located at a source mass M. A target body sits on the sloping side wall of this dent at some point P. In the static situation, there is no ambiguity. The rubber sheet is like the gravitational potential field of M, and the slope of the side wall is like the gradient of the potential. In the static case, the gradient at P (the analog of gravitational force) is unique and unambiguous, and points at M. See Fig. 2.

Now let M have some transverse motion relative to the rubber sheet and relative to point P, which will remain fixed on the rubber sheet. As M moves, the dent moves. Let's assume the rubber sheet takes some finite time to adjust its shape to the new location of M. If the adjustment wave propagates out at speed c, and if point P is a distance r away from M, then the propagation delay is a time interval r/c. If M moves at speed v, P will always feel a gradient (slope of side wall) that lags behind the true, instantaneous position of M by the approximate angle v/c in radians. Call this scenario "example 1."

In example 1, the gradient cannot point toward the new position of M until the adjustment wave has time to propagate from M to P. The conventional way around this difficulty is to hypothesize a "velocity field" in the rubber sheet paralleling the motion of M and maintaining the needed gradients. Now one trouble with that picture is that the "velocity field" has independent existence. So what would make it ever pass out of existence?

Even if M sets off a new "velocity field" based on some new motion, that shouldn't affect the old "velocity field." If one suggested some characteristic decay time for an old "velocity field," it would go away too soon at large distances from the source and too late at small distances, so the logical dilemma would persist.

Going back to fundamentals, static fields are either continually regenerated by a source mass, or are rigid in the sense of having no moving parts.[9] But the fact that, for gravitation, a "velocity field" is insufficient, and an "acceleration field" is also needed to keep rigid fields in conformity with observations, weighs heavily against the rigid field interpretation. Even the Sun accelerates as it moves around the solar system barycenter, and planets respond almost instantly to such accelerations. Binary pulsars are an even more dramatic demonstration of the effect (experiment E2). And finally, if fields were rigid rather than regenerated, they would be unable to continually update as needed in the case of two black holes in mutual, elongated elliptical orbits.[(2)]

However, let's now consider the case where M remains fixed on the rubber sheet, and P has the transverse motion. Then the direction of the gradient would once again point toward the instantaneous position of M. Call this "example 2." In this case, the gradient direction is independent of the transverse motion of P; i.e., it has no aberration. This is what the geometric interpretation of GR proposes.

In this example 2, nothing propagates from M to P. So aberration is not applicable, and apparent agreement with experiment is secured. Note that this agreement does not result from a propagation speed of c, but from no propagation at all. This is a case of a mathematically elegant solution that is physically impossible as an explanation for gravity. A gradient, a slope, or a curvature cannot induce a body at rest in a field (e.g., at point P) to begin moving unless a force acts on that body. This is because, without a force to initiate motion, the body has no reason to choose any one direction over any other direction. Moreover, momentum would not be conserved if the field had no moving parts, yet a body at rest in it began moving in some direction without a force acting. (Recall that, by "force," we mean "the rate of transfer of momentum.")

[9] From a distance, a waterfall appears static. Up close, it might turn out to be a frozen waterfall with no moving parts, in which case it cannot transport momentum; i.e., it cannot act as a source of energy. Or it might be a flowing waterfall in which, despite the overall sameness, each water drop is continually replaced by another from behind. This kind of waterfall can drive a turbine. Likewise, "static" fields must be continuously regenerated to be able to carry momentum and produce acceleration of target bodies. Fields with no moving parts cannot physically do that.

In the rubber sheet analogy, if the small target body is at rest on the side of a dent caused by a source mass, it will remain at rest forever until some force acts. The rubber sheet analogy works in our imaginations only because we instinctively imagine gravity under the rubber sheet, with its pull providing a meaning to the concept of "downhill." But without pre-existing gravity, the small body has no cause to accelerate, either on the rubber sheet or in the geometrical interpretation of GR. The lack of a cause for acceleration means it would violate the causality principle.

So how do real forces propagate? The field interpretation of GR still provides the best answer. The change from field equation solutions to equations of motion is analogous to going from a potential to a force by taking a gradient. The process of "taking a gradient" (or taking partial derivatives in general) is unique and unambiguous only after one has decided the issue under discussion here—whether the distant fields are in accord with the instantaneous or retarded *directions* of their sources. This choice has an immediate, first-order effect on the direction of the resulting force—by the amount of the angle of aberration.

Over 100 years of history support the choice of instantaneous force fields as the observationally correct one. However, it is still wrongly claimed that instantaneous fields are consistent with force propagation at lightspeed. Lightspeed propagation requires choosing retarded fields and field directions. Note the emphasis on directions. Using retarded distances or matter distributions, as is done with retarded potentials, is unimportant for force field purposes because their effects are negligible in comparison to the retarded-source-mass-direction effect.

As an example, let's compare two different fields. The Sun emits light, just as it emits gravity. Light forms an inverse square field around the Sun, just as gravity does. For the gravitational field, gravitational force is the gradient of gravitational potential.[10] Analogously for the light field, light intensity is the gradient of light amplitude. For a non-moving observer, we could do a one-to-one mapping of potential and amplitude, or of force and intensity. In either case, the difference everywhere is a constant scale factor.

[10] Force is the gradient of potential only in the geometric interpretation of GR. In the modern field interpretation recommended here, the force and potential fields are independent media, with the latter influencing the former so that potential is the integral of force. Consider potential as the analog of density in a calm, motionless atmosphere, far from the surface of a source mass. Atmospheric density would then vary inversely with distance from the mass center. So the gradient of density is proportional to the force. But the gradient of density doesn't cause the force; rather, the causality is the other way around. And the propagation speed of the force is unrelated to the wave speed of the atmosphere, analogous to the speed of gravitational force being unrelated to the speed of waves in the gravitational potential field.

If light or gravity propagated instantaneously, then an observer on Earth orbiting the Sun would detect that instantaneous field. However, the combination of a finite field propagation speed and an orbiting observer would make the field appear retarded as seen by the observer.

Specifically, for the case of solar light observed from Earth, which unquestionably has a finite propagation speed, intensity drops off with the inverse square of distance along a radial from the *retarded* position of the Sun. Note that this is a different direction in space than the field direction seen by a non-moving observer. Nonetheless, it is a real directional difference, not an optical illusion. The Sun not only looks to be in a different place among the stars, but the momentum transferred to Earth by the pressure of sunlight, the radiation pressure force, acts along the radial from the retarded Sun, not the radial from the true Sun. This is the well-known "Poynting–Robertson effect"—too weak to move planets, but very effective on dust particles and balloon satellites. Correspondingly, the gradient of the amplitude for this field as observed from orbiting Earth points toward the retarded Sun, not the instantaneous Sun.

By analogy, if gravity propagated at the same speed as light, the gradient of the potential of the gravitational field, as seen by an orbiting observer, would point toward the retarded position of the source, not its instantaneous position. Whether or not something later cancels this retardation effect, it cannot be omitted as the opening step in describing the gravitational field. When taking the field gradient to get the direction of gravitational force, or when taking partial derivatives to derive equations of motion, if the field has a finite propagation speed, such gradients and partials must respect the retarded directionality of the field for a moving observer. The fact that the gradients and partials actually used in GR ignore transverse aberration, the chief effect of propagation delay, is the logical equivalent of adopting instantaneous gravitational field propagation in GR.

We should not be deceived by consideration of retardation in the distance or mass or charge distribution, a common practice in textbooks on electrodynamics and gravitation. For example, let a scalar potential be given by GM/r, which has a magnitude but no direction. Retardations in the value of r are of almost no consequence because they are often small and slowly changing (e.g., for near-circular orbits); and they give rise to only periodic effects in orbits, not cumulative ones. Similar remarks apply to retardation of changes in mass or charge distribution. Many physicists and mathematicians have been deceived by demonstrations of retardation effects in potentials, unaware that these are neither observationally detectable nor experimentally testable at the present time, and that the primary effects of retardation (in the gradient of the potential, the force) are being neglected by such demonstrations.

By contrast, the gradient of the potential has magnitude and direction. For example, $-(GM/r^3)\,\mathbf{r}$ is the gradient of the potential just given. Again, retardation in r is relatively unimportant. But retardation in $\mathbf{r}$ is all-important in this context because it is of order v (the velocity) to the first power, not diminished by eccentricity or any other parameter; and it gives rise to secular (i.e., progressively increasing) effects that can eventually exceed any threshold for observational detection.

In practice, this suppression of aberration is done through so-called "retarded potentials." In electromagnetism, these are called "Lienard–Wiechert potentials." For examples of the use of retarded potentials, see Ref. 12 or 27. Let $\phi(\mathbf{x}, t)$ be the gravitational potential at a field point $\mathbf{x}$ and time t, dV be an element of volume in the source of the potential, $\mathbf{X}=(X, Y, Z)$ be the coordinates of that volume element in the source, $\rho(\mathbf{X}, t)$ be the matter density at point $\mathbf{X}$ and time T, $\mathbf{r}=\mathbf{x}-\mathbf{X}$, $r=|\mathbf{r}|$ be the distance from the source volume element at time T to the field point at time t, and $\mathbf{v}$ be the relative velocity between the field point and the source. Then two different forms of retarded potentials in common use for gravitation are these:

$$\phi(\mathbf{x}, t) - G \iiint \frac{\rho(\mathbf{X}, t-r/c)}{r}\, dX\, dY\, dZ \tag{[1]}$$

$$\phi(\mathbf{x}, t) = \frac{GM}{r-(\mathbf{v}\bullet\mathbf{r}/c)} \tag{[2]}$$

In [1], we have used $T=t-r/c$ as the retarded time. Then the triple integral might be thought of as evaluating the density one light time ago in place of the present density. In [2], the mutual distance is taken to depend on the scalar distance of the source one light time ago. The simple substitution $c\to\infty$ reduces either of these forms to its Newtonian counterpart.

However, by concentrating on fields instead of vector forces and on retarded potentials instead of their gradients, no consideration is given to the effect of the transverse motion between source and target during the light time; i.e., the aberration. Ignoring aberration (roughly v_T/V_g, where v_T is the transverse component of the velocity $\mathbf{v}$) is logically equivalent to adopting an infinite propagation speed for gravitational force ($V_g=\infty$). That point is often not noticed because of the emphasis placed on the density distribution or the mutual distance in the potential formulas being taken at its retarded position, as if a finite propagation speed for gravity were being adopted by keeping c finite in these selected places, which of course is not the case. Nevertheless, the only practical consequence of a finite force propagation speed that matters in most applications, the aberration, makes no appearance in these potentials. And that clever trick then allows a theory with the speed of light appearing explicitly in its equations to be equivalent to a theory with infinite force propagation speed (Newtonian gravity) in the weak-field, low velocity limit (i.e., in most practical applications).

Unlike retardation in r (scalar), which usually can't be detected, retardation in $\mathbf{r}$ (vector) gives rise to the Poynting-Robertson force when we are dealing with radiation pressure. Retardation in $\mathbf{r}$ would also be the largest consequence of gravity or electric force propagating at a speed as slow as c. But no such retardation terms appear in either Maxwell's or Einstein's equations. The absence of such terms is the logical equivalent of setting the field propagation speed to infinity, which drives the first-order-in-v term to zero.

At this point, we have shown that:

- Transverse aberration must always be considered when transverse motion of the target body occurs.
- Specifically, transverse aberration is present for light, a field propagating at the speed of light.
- Aberration must also apply to transverse motions through electrodynamic or gravitational fields.
- The absence of aberration in the equations of motion is the logical equivalent of taking the field propagation speed to be infinity, because that drives aberration to zero.

We note again that strongly faster-than-light (ftl) propagation speeds violate no laws of physics because Lorentzian relativity (LR) is experimentally viable and allows ftl propagation speeds; and the field interpretation of GR is as compatible with LR as it is with SR.

These findings allow us to conclude that ftl propagation in forward time is definitely possible; and gravitational and electrodynamic forces are examples of such ftl propagation.

8. CARLIP'S PAPER

In the geometric interpretation of GR, gravity is not a "force" and cannot propagate because target body motion simply follows a curved geodesic path through "space-time" without any force acting. Experiment E5 disputes the possibility that this forceless interpretation of gravity could be correct. So does the dependence of the full GR equations of motion for a target body on that body's own mass. Both are failures of the weak equivalence principle—the notion that "gravity is just geometry."

In his paper, Carlip recognizes the concept of gravitational force, as in the field interpretation of GR. But he claims that the experiments E1–E4 are not direct propagation speed measurements for gravity. They are, however, measurements of aberration or v/V, where the only unknown is the speed of gravity, V. This makes Carlip's point semantic because the "indirectness" of these measures is not significant to their interpretation.

Carlip claims that we have made an implicit assumption that gravitational acceleration is central and has no velocity-dependent terms. If aberration were non-zero, the acceleration would be non-central. However, observations all confirm that it is in fact central to order v/c; i.e., directed along instantaneous radials from the source mass. GR implies that gravitational acceleration is target-body-velocity dependent at order v^2/c^2, as shown in Eqs. (2) and (4); but velocity-independent to order v/c. It is also source-mass-velocity dependent in some of the small terms we omitted. However, all these velocity-dependent terms are typically orders of magnitude too small to cancel the aberration term if $V = c$. So Carlip's point is again irrelevant to this discussion because no velocity-dependent terms exist at first order in v except any he might postulate just for the purpose of canceling unwanted propagation delay terms.

We also note that both the phase and group speeds of both electrical and gravitational fields from a rapidly oscillating source go to infinity as the source oscillation frequency goes to zero, resulting in zero transverse aberration.[28] Walker's field propagation analysis of a stationary source using Lienard–Wiechert potentials indicates that the longitudinal field generated by a stationary source propagates with infinite speed when the source frequency is zero. From a moving target frame perspective the field would not appear aberrated because the aberrational component of the field would be zero because of this infinite speed. For an oscillating source, the source velocity is clearly zero when the source frequency is zero $\{$i.e., $v = d/dt[\sin(\omega t)] = \omega\cos(\omega t) = 0$ if $\omega = 0\}$, and therefore the source velocity cannot be the cause of aberration cancellation.

In Carlip's paper, we are not challenging his mathematics, but rather his physics. In his argumentation before his equation (1.1), Carlip says "it is well known that if a charged source moves at a constant velocity, the electric field experienced by a test particle points toward the source's 'instantaneous' position rather than its retarded position. ... This effect does not mean that the electric field propagates instantaneously; rather, the field of a moving charge has a velocity-dependent component that cancels the effect of propagation delay to first order." Here, we must disagree. The field emanates from the retarded position of the charge; so it must act from

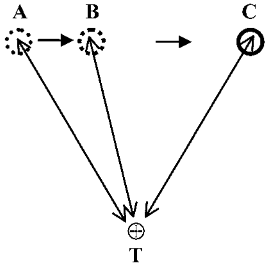

Fig. 3. Consider a radiation field emanating toward a fixed target T from a source moving along the path A → B → C. When the source is at C, we note three cases: 1) If the radiation propagates instantaneously, it arrives at the target along the vector CT. 2) If the radiation has propagation delay, it arrives along the vector BT. 3) If the radiation also has field momentum from source motion, it arrives along the vector AT.

that direction when it arrives at a target unless the field has momentum of its own. Any such momentum would have to be acquired from the field's source and therefore directed in the direction of motion of that source. (The alternative would be to create momentum from nothing, which is forbidden by the principles of physics.) But for both attractive and repulsive forces, momentum in that direction would always operate to increase the apparent propagation delay rather than to cancel it. See Fig. 3. (Because all motion is relative, no experiment can distinguish what happens here from the fixed-source, moving-target situation.) Given the nature of physical momentum as we know it, a force that appears to emanate from the instantaneous position of its source must propagate with negligible delay (i.e., some approximation of infinite speed). The observed behavior of electric fields therefore means that electric forces (and the hypothetical "virtual photons" that carry them) must propagate much faster than real photons, notwithstanding the unfortunate word "photon" in the carrier's name.

One problem with Carlip's interpretations is that he adopts a force vector that points closely toward the true, instantaneous position of the source (to first-order in v), when he should be beginning with one that points to the retarded source position. This effectively assumes what Carlip proposes to demonstrate. Obviously, a vector toward the instantaneous source position can be decomposed into a retarded position vector plus an update vector for motion during the propagation delay. But one should begin with a retarded position vector and discuss the physics behind canceling that retardation.

Carlip says propagation speed is not directly measured by most experiments, but only aberration; and that assumptions are required to convert aberration to speed. However, aberration (to good approximation) may be equated to the ratio of relative transverse target body speed to force propagation speed. Because the former speed is always known in the experiments, it is easy to compute the propagation speed, given the aberration.

Carlip says we must also assume that the force is central. However, in the cases of gravitation and electrodynamics, the forces *are* central, and there is no confusion from dipole or multipole sources, as in magnetism. In both GR and QED, forces propagate from a source mass (which can be considered as a point mass for our purposes here) linearly to a target body, at which point momentum (positive or negative) is transferred to the target and the target body accelerates. Electromagnetic forces such as radiation pressure do the same thing. However, these do exhibit propagation delay and aberration, whereas gravitation and electrodynamic (Coulomb) forces do not (at a detectible level). Given that the force source, path, and target are the same, the only available difference to account for the different direction of action of the force is differing propagation speeds.

Carlip says that the expected aberration is almost exactly canceled by a velocity-dependent term, which is also what makes the force "non-central." However, there is no physical mechanism for such a hypothetical velocity-dependent term to cancel a first-order effect in velocity such as aberration. One must invoke either conservation of angular momentum or Lorentz invariance in the equations to justify such an ad hoc canceller of a known physical effect, aberration, that must exist. But both of these are using the end to justify the means, and have no basis in physics.

Carlip concedes that the equations can be written in terms of instantaneous or retarded source positions, but argues that the retarded equations with velocity-dependent cancellation of propagation delay effects are to be preferred. He also points out one consequence of that choice: If a source suddenly stops or changes direction, the target will accelerate toward extrapolated positions from the original motion that the source never actually occupies. This will continue until the changed field propagates to the target, when the target will abruptly begin accelerating toward the extrapolated position of the source's new motion. This, of course, means a discontinuity in the acceleration of the target despite no discontinuity in the source. Another problem with this scenario is that it creates a mini-paradox. The extrapolated positions of a source moving on a circle would all lie on a bigger circle, the radius of which would be different for targets at different distances from the source. And the source would always appear to act from positions it never really occupied, and never appear to act from positions it did occupy. This, of course, wreaks havoc with the physical notion of causality. And none of this strangeness is needed if we simply adopt the faster-than-light field-propagation interpretation of the equations of motion.

Carlip says that the sudden change in the field is what we mean by the electromagnetic radiation of an accelerated charge (e.g., emission of a light wave), and that an interpretation in which the field changes propagated nearly instantly could only exist "at the expense of 'de-unifying' Maxwell's equations and breaking the connection between electric fields and electromagnetic radiation." However, reality is rather the opposite. It is true that the relative velocity between charges or masses determines the energy, and hence the frequency, imparted to the emitted electromagnetic wave. But the connection between energy and frequency still involves a parameter, the Planck constant, whose value must be determined empirically. So any unification of these two effects is a bit illusory in that we do not know the origin of that constant of proportionality, nor can we determine its value on theoretical grounds.

To be specific, the energy of an emitted light wave is $h\nu$, where h is Planck's constant and ν is frequency. Planck's constant is an empirically determined fundamental constant. We have no way to determine experimentally why an accelerating charge emits a light wave, but the frequency of the generated wave must give it an energy equal to the energy emitted by the charge. For example, if a force is applied to an electron, the work done is the product of the force and distance traveled. Distance is velocity multiplied by time interval. And force multiplied by time interval is the momentum of an impulse. So the energy change in the electron is the product of impulse momentum and electron velocity. Note that this same proportionality to velocity applies whatever the mechanism for the emission of the light wave.

By contrast with the usual quantum electrodynamics interpretation, for the nearly-instantaneous-propagation version of the equations, the same phenomena are predicted (electromagnetic waves in QED, gravitational waves in GR) through the mechanism of mechanical friction as the target body travels through the potential field of the source. This friction is likewise proportional to relative velocity, and therefore has the same functional form in all respects as the interpretation Carlip prefers. In that respect, one sacrifices no simplicity or understanding by switching interpretations. However, the near-instantaneous-propagation model differs in two important ways: It clearly shows without any ambiguity that gravitational waves are very-long-wavelength electromagnetic waves because both are disturbances of the same medium—the potential field of a source mass or charge. And it offers the prospect of a true unification of models by prospectively showing how to derive the Planck constant from theory in terms of the properties of this potential field, or those of the light-carrying medium in general.

We should here mention one other difference between electrodynamics and gravitation. In QED, the momentum of an electron relative to a nucleus is conserved exactly; whereas in GR, the momentum of an orbiting target body is gradually radiated away. In the standard QED interpretation, the gains in momentum from propagation delay are exactly equal to the momentum losses radiated away as electromagnetic waves. We are offered nothing more profound than nature's "wish" to conserve angular momentum as a physical explanation for this coincidence. But in our field interpretation, the wave properties of the electron constrain its speed to be the appropriate wave speed in the light-carrying medium or potential field. Because that speed is fixed, an impulse attempting to alter that speed instead causes the emission of a radiation wave.

Carlip says that Low has rigorously proven that no gravitational influence in GR can travel faster than the speed of light. But this is a tautological argument. He means only that, when one adopts the geometric interpretation of GR with light-speed propagation, nothing can propagate faster than light. But if one adopts the ftl-propagation interpretation, than all gravitational forces propagate faster than light; and only gravitational waves, which do not influence gravitational forces, propagate at lightspeed.

Carlip says that the velocity-dependent cancellation term is not "miraculous," but that an electrodynamic system that conserves momentum must have such a term. Indeed, that statement is true for electrodynamic systems with force propagation as slow as the speed of light. However, it begs the question on the table here. Nature does not guaranty that any system will conserve orbital angular momentum, as tidal forces and mechanical friction forces amply demonstrate; so a physical mechanism to conserve angular momentum is required to go along with this mathematical trick. But that is thus far lacking. Moreover, simply allowing ftl propagation of forces conserves angular momentum to observable accuracy without need of math tricks having no physics behind them.

Carlip says that GR has only one wave speed, and that is demonstrated by binary pulsars to be the speed of light. Again, this is true in the geometric interpretation of GR, but not true in the replacement interpretation we recommend. The potential field "medium" and the force field "medium" are not required by any physical law to be related, let alone identical. Moreover, reasonable interpretations of effects unique to GR (e.g., light-bending, gravitational redshift and pericenter advance) in flat space-time involve refraction in an optical medium,[21] and therefore require two physically distinct media, each with its own propagation speed.[29]

9. ANGULAR MOMENTUM AND TIDAL FRICTION

If gravitational aberration were non-zero, the angular momentum of an orbit would progressively increase with time, an effect that is not observed. Real orbits conserve orbital angular momentum to the accuracy

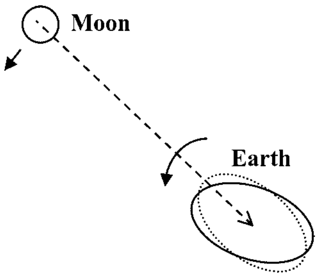

Fig. 4. The Moon makes the Earth bulge toward it. Friction causes the bulge to rotate slightly ahead with Earth's spin. The leading bulge acts just like an extra mass accelerating the Moon's orbit outward. Aberration also looks to the Moon like an offset of Earth's mass in the direction of lunar motion, producing an outward acceleration.

of all observations, except when tidal or non-gravitational forces or gravitational waves operate. Carlip claims that the conservation of angular momentum needed by GR justifies the cancellation of transverse aberration. He claims this cancellation is not magical, but arises naturally in the mathematics when one imposes angular momentum conservation.

It is true that imposing angular momentum conservation cancels aberration, but that begs the question. What physical justification exists for simply imposing orbital angular momentum conservation into equations when orbital angular momentum is not conserved by nature for other types of force? McCarthy[30] has pointed out that, to the Moon, the offset of the direction of Earth's gravitational force due to tidal friction is indistinguishable from the offset of the direction of Earth's gravitational force due to aberration. See Fig. 4. The Moon's gravity causes the Earth's shape to develop a bulge toward the Moon. Earth's rotation, having a higher angular rate than the Moon's orbital motion, tries to rotate that bulge ahead of the line joining the centers of Earth and Moon. If the Earth were free to reshape itself without resistance, it would do so and keep its bulge directly toward the Moon. However, friction within the solid Earth resists this reshaping, and allows the bulge to rotate ahead of the line of centers.

The bulge then acts as an excess mass in the Earth located slightly ahead of the line of centers that has a small component of force trying to accelerate the Moon to go faster in its orbit around Earth. As such, it is indistinguishable from the force that would arise from aberration if the speed of gravity were as slow as lightspeed. The point is that the Moon cannot tell if the forward acceleration it feels arises from a tidal bulge on Earth or from aberration, because either way the force of gravity is toward a point slightly off the line of centers in the "retarded" direction. So if gravitational aberration exists after all because gravity propagates at lightspeed, but is canceled by a velocity-dependent "anti-aberration" force provided by nature to conserve angular momentum (as Carlip claims), then nature must also cancel tidal friction because it has no means of distinguishing one type of non-central force from the other. However, that is contrary to observations. But how could the Moon possibly know when to cancel a non-central force component, and when to respond to it?

The only logical answer to this dilemma is that no such mysterious, *deus ex machina* force exists because gravity has no aberration in need of canceling. In that case, we may be certain that gravity propagates much faster than lightspeed.

10. RELATIVISTIC INTERPRETATION OF SUPERLUMINAL INTERACTIONS

Assuming that the existence of real superluminal interactions in gravity and electromagnetism will be confirmed in future experiments, two questions can be raised immediately; i.e.,

(a) What is the physical basis of superluminal interactions?

(b) Are they compatible with causality?

A possible answer to question (a) has been proposed by Dirac.[3] Assuming

(1) that all continuous fields are effectively built with extended “rigid44 sub-elements in space-time, and

(2) that each pair of internal points within such extended sub-elements are separated by a constant space-time interval,

one sees that a continuous chain of such rigid contiguous extended sub-elements can transmit, by contact (from the first to the last element) a superluminal shock (phase) interaction (wave).

In other terms, a possible answer to question (a) is to substitute for the space-time point structures of particles and fields, within the usual interpretation of quantum mechanics, extended rigid structures in space-time which allow subluminal ($v < c$) element motions and superluminal ($v > c$) motion traveling on sets of these extended structures.

A possible answer to question (b) has already been discussed in the literature within the frame of the causal stochastic interpretation of quantum mechanics proposed by de Broglie and Bohm. The “piloting” of point-like particles by real wave-fields $\psi_x = Re^{S/\hbar}$ implies the introduction of superluminal quantum potentials (of the form $Q = \frac{\hbar}{e\mu} \Box / R$ for spin 0). For example, consider a system of two interacting, massive particles 1 and 2 with centers of mass located at X_M^1 and X_M^2 and their center of mass $X_M = (m_1 X_M^1 + m_2 X_M^2)/(m_1 + m_2)$. One can describe their interaction as instantaneous in X_M's rest frame (which includes spin-spin and spin-orbit particle interactions), where the particles follows time-like paths L_1 and L_2

with proper-times τ_1 and τ_2 canonically conjugated with Hamiltonians H_1 and H_2. This is discussed in Ref. 3.

We can write (in the rest-frame of X_M) $\psi = \exp(R+iW)$ depending on the coordinates of particles 1 and 2. These follow correlated paths with moments $P^1_M = \partial^1_M W$ and $P^2_M = \partial^2_M W$, and one has shown (in the rest frame of Y_μ) that this correlated motion is causal provided the commutators (or classical Poisson bracket) of their Hamiltonians H_1 and H_2 commute so that $\{H_1, H_2\} = 0$ vanishes ... which is the case for all presently known physical Hamiltonians.[3]

In other terms, the known motions of classical and quantum theory are causal

(1) if one introduces relativistic extension and time-like paths of their sub-elements;

(2) if the Hamiltonians of a set $i = 1, \ldots$ of correlated elements (following time-like paths) satisfy the relations $\{H_i, H_j\} = 0$.

11. CONCLUSION

The evidence from all six experiments that bear on the question of the speed of gravity is unambiguous in excluding answers as slow as lightspeed. A similar remark applies to the propagation speed of electrodynamic forces. The strongest of these experiments sets a lower limit to the speed of gravity of $2 \times 10^{10}\,c$. All objections and questions about this conclusion raised during the last four years have now been addressed and answered. In particular, claims (championed by Steve Carlip) that such a result is inconsistent with general relativity are now shown to be false. Moreover, no serious claim of experimental support for gravity propagating at lightspeed has been advanced in modern times. Attempts to do so have seriously confused changes in gravitational force fields with gravitational radiation (an effect of changes in potential fields), the latter of which unquestionably would propagate at speed c, assuming it exists.

When a source mass accelerates, that induces changes in its gravitational force field. The lack of detectable aberration (propagation delay) for those changes means that the distant gravitational field accelerates when the source mass accelerates, in lockstep. To avoid direct violation of the causality principle, the propagation delay must be finite, even though much smaller than the corresponding propagation delay for photons. Because special relativity (SR) forbids propagation speeds faster than lightspeed in forward time, the customary interpretation of that theory is in conflict with, and is potentially falsified by, this result.[11] GR has always implicitly recognized these facts through its equations of motion, which use instantaneous coordinates and momenta rather than retarded ones. That and its reliance on a single frame to define "coordinate time" mean that GR is based as much on Lorentz's interpretation of relativity (LR) as on SR. These two theories, LR and SR, both employ the relativity principle and the same math (Lorentz transformations), but LR adopts a preferred frame and lacks the reciprocity between frames postulated by SR. Interestingly, no experiment testing SR or LR confirms frame reciprocity. Therefore, because LR is consistent with all experiments, it remains just as viable as SR as a model for the relativity of motion.[(23)] It follows that the falsification of the SR interpretation in favor of the LR interpretation has no immediate mathematical consequences for GR. The main physical consequence is negation of the proof that faster-than-light propagation is impossible.[12]

Because of the belief that GR is based on the SR interpretation of the relativity of motion, which disallows the possibility of faster-than-light propagation in forward time, the most common interpretation of GR is that the speed of gravity is the speed of light. This interpretation is also based on a misunderstanding of the implications of aberration and confusion between the meanings of gravitational force variations and gravitational waves. However, the consequences of a propagation speed of gravitational force variations as slow as lightspeed would be catastrophic for many astrophysical bodies, as can be tested in even elementary computer experiments with orbits; and such slow variations are strongly disallowed by physical principles and by all existing experimental evidence.

The following is the single, most important conclusion to be noted here, and would be true even if the geometric interpretation of GR could be shown to be consistent with all experimental evidence and with a gravity propagation speed of c. The mere existence of a viable alternative interpretation of the GR equations based on Lorentzian relativity, taken together with the continued experimental viability of LR, mean that the proof of the

[11] Hypothetical ftl particles called "tachyons" cannot save the theory because they propagate backward in time, thereby creating the possibility of causality violations; and because they do not have real mass. Momentum carriers that accelerate real target bodies must be tangible and have real mass.

[12] Other consequences are mainly interpretational. For example, the lack of frame reciprocity means that the equations of motion of GR with aberration canceled are not Lorentz invariant. If they were, they couldn't reduce to Newtonian gravitation—a non-Lorentz-invariant theory—in the weak-field, low-velocity limit. But other forces, such as tidal friction, are the same way. Nature never guaranteed us Lorentz invariance.

impossibility of propagation and communication in forward time at arbitrarily high speeds no longer has supportable experimental underpinnings.

If future experiments confirm that the speed of gravitational, electrodynamic, and quantum field interactions take place at speeds $\gg c$ even in laboratory experiments, some of the questions discussed in the present paper will become important. We will mention here only the question of the relation of space to physical fields (matter), as this relates to experiments supporting special relativity. Are they, or are they not, different concepts? If they are different ($v \gg c$), one should

(a) Develop Lorentz's interpretation of special relativity, considered as resulting from real physical properties of real physical measurements within a real chaotic "aether."

(b) Analyze phenomena in terms of real, moving, extended objects (particles) as perturbations within real space (possibly flat), also built with extended field elements; i.e., develop Einstein's, de Broglie's, and Bohm's suggestion that "vacuum" is a real, chaotic, extended, moving field carrying average collective wave-like motions of extended particle-like elements ... a model which goes beyond the classical model of point-like particles moving in flat space-time since it can carry $v > c$ (group) and $v > c$ real (phase) velocities.

(c) Re-discuss causality in physics as resulting from local contact interactions of extended elements so that causal interactions can move with both ($v \ll c$) and ($v \gg c$) in external flat space.[1, 31, 32]

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