To the Editors of 'The Observatory'

Further Discussion of the Speeds of Light, Gravitational Waves, and Gravity

Taylor[1] asked the question whether the fact that $c = c_g$, where c is the speed of light and c_g the speed of gravitational waves (GWs), is an assumption of General Relativity (GR) or whether there is some deeper justification, and suggested a *gedanken* experiment which he claimed proves that $c = c_g$. Thornburg[2] showed that there is a logical error in Taylor's argument: assuming that that which he wishes to prove is true. (Although it is true that Taylor excluded "material particles", *e.g.*, neutrinos, from his argument, Thornburg's claim that cg could be replaced by the speed of neutrinos doesn't change the logical structure of the argument. While it is true that we now know that neutrinos have mass, for a long time it was assumed that they did not, and the argument could have been made then, its validity to be determined experimentally, as in the case of the question whether $c = c_g$.) As pointed out by Thornburg, $c = c_g$ holds strictly in GR but not necessarily in some other relativistic gravity theories, and there is now strong observational evidence[3] that $c = c_g$, a point not disputed by Taylor[4], who then emphasized that he is concerned with finding an *explanation* of why $c = c_g$ in GR.

Whether an obvious explanation for the equivalence of c and c_g exists within the context of GR is a valid question, though of course what is obvious depends on the observer, so to speak. It is certainly the case that not all accounts of relativity, especially Special Relativity, are easy to follow; a common mistake is not to distinguish between purely relative effects (A sees B's clock run slow and *vice versa*), real effects (B's clock is behind A's when the two are compared at rest after B travels away and returns, this depending only on the length and speed of the journey and not on the acceleration and is explicable within the context of Special Relativity), and effects, such as the appearance of moving objects, which depend on the finite velocity of light[5–7]. However, one must distinguish between clear predictions of a theory as understood by experts, about which there is no debate, and confusion in popular-science depictions.

Taylor[4] then suggested that $c = c_g$ might follow from quantum gravity. While it is true that in quantum field theory the photon is massless, and hence propagates at c, this does not follow from first principles, but is an assumption, shored up by much observational evidence[8,9]. (For that matter, neutrinos are massless in the Standard Model[10], essentially because all neutrinos are left-handed, their masses thus indicating that the Standard Model is not complete; although the evidence for massless photons is much stronger, in the end this question must also be decided experimentally, as long as no-one has shown from first principles that photons *must* be massless.) Thus, similar arguments from a quantum theory of gravity would no more prove the masslessness of the graviton than quantum field theory proves the masslessness of the photon; in fact, 'massive gravity', *i.e.*, theories in which the graviton has a finite mass, is an active area of research[11].

Taylor then asks whether the speed of propagation of *gravity itself* (say, cG) must necessarily be the same as the speed of propagation of *gravitational waves*. In this case as well, the question is more whether an obvious explanation exists than whether this is a genuine puzzle within the context of GR. One thing which is clear, however, is that a black hole cannot swallow its own gravitational field nor, in the case of a Kerr–Newman (or, with no angular momentum, a Reissner–Nordström) black hole, its electric field[12]. This can be understood intuitively as follows. First, since GR is not a quantum theory, gravitons are a red herring. The gravitational field outside of the horizon can be calculated from the mass before collapse to a black hole; indeed, a distant observer never sees anything cross the horizon, because it is infinitely redshifted. Nevertheless, there is a quantum theory of electromagnetism, and the standard result is that the electric field can 'escape' from the black hole. Classically, the answer to this puzzle is the same as in the case of the gravitational field. With regard to photons (and gravitons), since the field is mediated by *virtual* particles, these are not constrained to be interior to light cones (*i.e.*, can 'travel faster than light', though not, of course, carry information), so there is no problem.

There are also more observational tests which have bearing on this issue. Will pointed out that the precession of the perihelion of the planets can be used to provide upper limits on the mass of the graviton (a massive graviton would imply that $c_g < c$, though in general the converse is not true) and hence constraints on alternative theories of gravity, the effect increasing with the distance from the Sun, in contrast to the case in GR. Constraints also depend on the quality of observations, the best constraints being provided by the orbit of Mars[13,14]. Will also pointed out that a 'massive graviton' would lead to differences in arrival times between GWs of different frequencies; the fact that these are not observed implies that gravitons are massless (or, strictly speaking, puts strong upper limits on their mass)[14,15]. At present, the Solar System bounds are stricter than those from GWs, but this might change when the space-based gravitational-wave observatory *LISA* becomes operational[14,16]. (Note that these Solar System constraints do not directly test whether $c = c_g$, but rather, by constraining alternative theories, increase our confidence that GR is correct, in which case $c = c_g$.) Some modified-gravity theories predict different Shapiro delays for photons and GWs; this would lead to differences in arrival times on the order of several hundred days in the case of GW170817[17,18]. The extremely small difference in arrival times[3], compatible with 0, rules those out. That is independent of the constraint, based on the same difference in arrival times, which rules out theories in which the speeds of photons and GWs differ.

In summary, the speed of light is the same as the speed of gravitational waves: $c = c_g$ follows from GR and is also verified experimentally, since the arrival times of electromagnetic and gravitational waves are essentially the same (this conclusion is supported by the lack of observed dispersion in GWs). The same observation also rules out some modified-gravity theories which predict different Shapiro delays for photons and GWs. Like Solar System dynamics, while not testing directly whether $c = c_g$, this increases our confidence that GR is correct, in which case $c = c_g$. The speed of light is also the same as the 'speed of gravity': $c = c_G$ is also built in to GR; (there are, however, theories where this is not the case[19]). In both cases, the sole remaining, but subjective, question is whether there is an 'obvious' explanation[20].

Yours faithfully,
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References

(1) C. Taylor, *The Observatory*, **137**, 130, 2017.

(2) J. Thornburg, *The Observatory*, **138**, 124, 2018.
(3) B. P. Abbott *et al.*, *ApJ Lett.*, **848**, L13, 2017.
(4) C. Taylor, *The Observatory*, **138**, 245, 2017.
(5) A. Lampa, *Z f Phys*, **27**, 138, 1924.
(6) J. Terrel, *Phys. Rev.*, **116**, 1041, 1959.
(7) R. Penrose, *Proc. Camb. Phil. Soc.*, **55**, 137, 1959.
(8) A. S. Goldhaber & M. M. Nieto, *Rev. Mod. Phys.*, **82**, 939, 2010.
(9) J-F. Glicenstein, *ApJ*, **850**, 102, 2017.
(10) K. Zuber, *Neutrino Physics* (Institute of Physics), 2004.
(11) C. de Rham, *Living Reviews in Relativity*, **17**, 7, 2014.
(12) http://math.ucr.edu/home/baez/physics/Relativity/BlackHoles/black_gravity.html .
(13) C. Will, *Phys. Rev. Lett.*, **120**, 191101, 2018.
(14) C. Will, CQG+, https://cqgplus.com/2018/08/13/putting-a-limit-on-the-mass-of-the-graviton/ .
(15) C. Will, *PRD*, **57**, 2061, 1998.
(16) C. Will, *CQG*, **35**, 17, 2018.
(17) S. Boran *et al.*, *PRD*, **97**, 041501, 2018
(18) R. H. Sanders, arXiv 1805.06804 (honourable mention in the 2018 Gravity Research Foundation essay contest)
(19) S. Carlip, *Class. Quant. Grav.*, **21**, 3803, 2004
(20) J. Thornburg, *The Observatory*, **139**, ???, 2019.