9.1: The Speed of Gravity

In Newtonian gravity, gravitational effects are assumed to propagate at infinite speed, so that for example the lunar tides correspond at any time to the position of the moon at the same instant. This clearly can't be true in relativity, since simultaneity isn't something that different observers even agree on. Not only should the "speed of gravity" be finite, but it seems implausible that it would be greater than c; in section 2.2, we argued based on empirically well established principles that there must be a maximum speed of cause and effect. Although the argument was only applicable to special relativity, i.e., to a flat spacetime, it seems likely to apply to general relativity as well, at least for low-amplitude waves on a flat background. As early as 1913, before Einstein had even developed the full theory of general relativity, he had carried out calculations in the weak-field limit showing that gravitational effects should propagate at c. We will work out an argument to this effect (using a different technique than Einstein's) in section 9.2. This seems eminently reasonable, since (a) it is likely to be consistent with causality, and (b) G and c are the only constants with units that appear in the field equations (obscured by our choice of units, in which G = 1 and c = 1), and the only velocity-scale that can be constructed from these two constants is c itself.[1]

> **Note**
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> High-amplitude waves need *not* propagate at c. For example, general relativity predicts that a gravitational-wave pulse propagating on a background of curved spacetime develops a trailing edge that propagates at less than c (Misner, Thorne, and Wheeler, p. 957). This effect is weak when the amplitude is small or the wavelength is short compared to the scale of the background curvature.

As shown by the following timeline, Einstein's prediction was surprisingly difficult to verify.

1913	Einstein predicts gravitational waves traveling at c.
1982	Hulse-Taylor pulsar (sections 6.2, 9.2) seen to lose energy at the rate predicted by general relativity's prediction of gravitational radiation.
2016-2017	Direct detection of gravitational waves and verification that they propagate at c.

Why did this process take over a century? Naive arguments suggest that it should have been much easier. Workers as early as Newton and Laplace had investigated the consequences of a gravitational force that propagated at some finite speed. It is easy to show that, if nonrelativistic ideas about spacetime are retained, the predicted results are dramatic and not consistent with observation. For example, the earth and moon orbit about their common center of mass, which is inside the earth but offset from the earth's center. Suppose that we retain Newton's ideas about spacetime, but modify Newton's law of gravity to incorporate a time delay, with changes in the gravitational field propagating at some speed u. The force acting on the moon would then point toward the earth's location at a slightly earlier time, and this force would therefore have a component parallel to the moon's direction of motion. The force would do positive work on the moon and also exert a positive torque, the result being that the moon would spiral away. This is not consistent with the fact that the earth-moon system has remained fairly stable for billions of years, unless we take u to be very large. From the stability of orbits in the solar system, Laplace estimated $u \gtrsim 10^{15}$ m/s, many orders of magnitude greater than c. This seemed to support the Newtonian picture, in which gravity acts instantaneously at a distance. A time delay in Newtonian spacetime would also have been easily detected by twentieth-century measurements using space probes and radio astronomy.[2]

The trouble with such arguments is that when we substitute relativistic spacetime for Newtonian spacetime, it is no longer expected that a time-delayed field will point toward the retarded position of the source. For example, if an electric charge moves inertially, and is observed in a frame in which it is moving, then Lorentz invariance requires that its electric field lines be straight, and converge on the charge's present position in that frame.[3] The speed of gravity therefore turns out to be much harder to measure than Laplace had believed.

References

[2] For an example of an erroneous 2003 claim to have performed such a test, see Fomalont and Kopeikin, http://arxiv.org/abs/astro-ph/0302294. Their claims were debunked by Samuel, http://arxiv.org/abs/astro-ph/0304006, and Will, http://arxiv.org/abs/astro-

ph/0301145.

3 Crowell, Special Relativity, section 10.4