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# GRAVITATIONAL RADIATION AS A TEST OF RELATIVISTIC GRAVITY

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## ABSTRACT

Gravitational radiation can be used to test theories of gravitation. When the waves are ultimately detected directly, their speed and polarization properties can be measured and compared with predictions of alternative theories. The multipole nature of gravitational radiation has already been tested in the binary pulsar, where observations of the decay of the orbit verify the quadrupole formula for gravitational radiation damping of general relativity and put strong constraints on dipole gravitational radiation predicted by many alternative theories.

## I. INTRODUCTION

The first detection of gravitational radiation by Earth-bound detectors will usher in a new era of astronomy. The study of the waveform, spectrum, intensity, polarization, and directionality of the waves will give information about gravitational collapse, collisions between compact objects, and the gravitational-wave cosmic background (for a review of gravitational-wave astronomy, see Thorne 1987). In addition to its astrophysical and astronomical implications, gravitational radiation provides an important probe of the nature of the gravitational interaction itself, in the sense that gravitational-wave observations can be used to test the validity of general relativity versus alternative theories of gravity.

The *existence* of gravitational radiation does not provide a strong test, because any relativistic theory of gravity that incorporates Lorentz invariance, at even the most crude level, can be expected to predict gravitational waves. Instead, it is the detailed nature of the gravitational waves that can distinguish among alternative theories, in particular the speed and polarization of the waves, and the effect of the gravitational-radiation back-reaction on the source. The first two properties can be studied only via the direct detection of gravitational radiation. The third property has already been examined in detail using observations of the orbital motion of the binary pulsar.

## II. SPEED AND POLARIZATION OF GRAVITATIONAL WAVES

General relativity predicts that the speed of weak gravitational waves in the geometrical optics limit should equal that of light, but other theories do not necessarily predict this equality. Table 1 shows the predicted speeds in some alternative metric theories (units are such that the speed of light is unity) (for a review, see Section 10.1 of Will 1981, and Section 7.1 of Will 1984). Differences from the speed of light in these theories typically depend on the values of parameters that relate the local geometry that describes the gravitational-wave detector to the background cosmological spacetime.

TABLE 1

PROPERTIES OF GRAVITATIONAL RADIATION IN ALTERNATIVE METRIC THEORIES OF GRAVITY (WILL 1981, 1984)

| THEORY | GRAVITATIONAL WAVE SPEED | NUMBER OF POLARIZATION STATES |
|---|---|---|
| General relativity | 1 | 2 |
| Scalar-tensor theory | 1 | 3 |
| Vector-tensor theory | various | 6 |
| Rosen's bimetric theory | $(c_1/c_0)^{1/2}$ | 6 |
| Rastall's theory | $1 + 1/2\ K^2 + O(K^3)$ | 5 |
| BSLL theory | $1 + 1/2\ (\omega_0+\omega_1) + O(\omega^2)$ | 6 |
| Stratified theories | * | 6 |

*speed is complicated function of parameters.

The speed of gravitational waves can be measured by determining the time of arrival of a pulse of waves from a supernova collapse, and comparing that time with the time of arrival of the pulse of light or neutrinos (assuming that the pulses are emitted almost simultaneously at the source) (Eardley *et al.* 1973). Such a comparison has already constrained the difference of the speeds of neutrinos and photons from SN 1987A (Longo 1987, 1988; Krauss and Tremaine 1988). If $v_g$ is the gravitational-wave speed, and $T_i$ denotes the arrival time of the appropriate signal, then the upper limit on $|v_g - 1|$ that could be achieved by observations of a supernova at a distance d is given by

$$|v_g - 1| < \begin{cases} 10^{-9}\left(\dfrac{1\ \mathrm{kpc}}{d}\right)\left(\dfrac{T_g - T_{\gamma\nu}}{\mathrm{min}}\right) \\ 10^{-9}\left(\dfrac{1\ \mathrm{Mpc}}{d}\right)\left(\dfrac{T_g - T_{\gamma\nu}}{\mathrm{week}}\right) \end{cases}.$$

It seems likely that the first solid detection of a gravitational wave burst from a supernova will result in an interesting limit.

General relativity predicts two polarization states (corresponding to two helicity states of a spin-2 graviton) for the most general weak gravitational wave, but virtually every other metric theory of gravity predicts more states, up to six. The action of these six independent states on a ring of test particles placed in the path of a gravitational wave is shown in Figure 1. In general relativity, only the $\mathrm{Re}\Psi_4$ and $\mathrm{Im}\Psi_4$ modes are present: in the Brans-Dicke and other scaler-tensor theories, these two plus the $\Phi_{22}$ mode are present. Table 1 also notes the number of modes predicted by the theories listed (for review, see Section 10.2 of Will 1981, and Section 7.2 of Will 1984). Using an appropriate array of gravitational-wave detectors, it is possible to determine or to restrict the number of polarizations and thereby to test gravitational theories (for discussion of detection strategies see Will 1981, Section 10.2; and Eardley, Lee and Lightman 1973).

## III. GRAVITATIONAL RADIATION REACTION

The discovery of the binary pulsar in 1974 provided a tool to study gravitational radiation prior to its actual detection by laboratory instruments. The unexpected stability of the pulsar "clock" and the cleanliness of the orbit allowed radio astronomers to determine the orbital and other parameters of the system to extraordinary accuracy. Furthermore, the observation of the relativistic periastron advance, and of the effects on pulse arrival times of the gravitational redshift and second-order Doppler shift, and of the Shapiro time-delay, have further constrained the nature of the system. Finally, the measurement of the rate of change of orbital period gave the first evidence for the effects of gravitational radiation damping. In general relativity, these four effects depend in a known way on measured orbital parameters and on the unknown masses $m_p$ and $m_c$ of the pulsar and companion (assuming that the companion is sufficiently compact that tidal and rotational distortion effects can be ignored). In the gravitational radiation case, the relevant formula is the "quadrupole formula," whose foundation is the basic fact that, in general relativity, the lowest multipole moment involved in the emission of gravitational waves (in situations where a multipole decomposition is relevant) is quadrupole. The constraints provided on the masses by these four observations are shown in Figure 2. The system is highly overdetermined (four constraints on two parameters), yet all four constraints share a common overlap region, yielding $m_p = 1.42 \pm 0.03$ and $m_c = 1.40 \pm 0.03$ solar masses: a completely consistent solution in general relativity. With these values for the masses, the predicted rate of change of orbital period agrees with the observed change to better than 5 percent (for reviews see Will 1984, Taylor 1987).

Some have argued that this provides a "strong-field" test of general relativity, in constrast to the solar-system "weak-field" tests, in the following sense. It seems likely that the companion, like the pulsar, is a neutron star, therefore both bodies contain strongly relativistic internal gravitational fields. Nevertheless, their motion and generation of gravitational waves are characteristic of their weak interbody gravitational fields and low orbital velocities, and are independent of their internal relativistic structure. This irrelevance of the internal structure is part of the so-called Strong Equivalence Principle (Sections 3.3 and 11.3 of Will 1981), a principle that appears to be unique to general relativity. It is also sometimes called the Effacing Principle (Damour 1987). The Brans-Dicke theory, for example violates SEP.

On the other hand, in most alternative theories of gravity, the motion of compact objects *is* affected by their internal structure (violation of SEP); in addition, most theories predict "dipole" gravitational radiation, whose source is the internal gravitational binding energy of the two stars. In the binary pulsar, dipole radiation can lead to significantly larger damping than quadrupole radiation, because it depends on fewer powers of the small parameter $v_{orbit}/c$. Because of these two phenomena, violations of SEP, and dipole gravitational radiation, the likelihood of a consistent solution for $m_p$ and $m_c$ in a given alternative theory of gravity, is extremely small. For example, the Rosen bimetric theory, which otherwise agreed with solar system observations, was a casualty of this test (Section 10.3 of Will 1981).

For some theories of gravity that are in some sense "close" to general relativity, such as the Brans-Dicke theory, the binary pulsar may not be a strong testing ground for dipole gravitational radiation because of the likelihood that the two objects are neutron stars of almost the same mass. In this event, dipole radiation, even if permitted, would vanish or be negligible by virtue of the symmetry. Another possibility for testing dipole gravitational radiation is a class of close binary systems containing a neutron star and a low-mass secondary, such as the "11 minute binary," 4U 1820-30, detected in 1986. Although systems such as this are often complicated by such astrophysically "messy" phenomena as mass transfer, it may still be possible to obtain interesting and even crucial limits on alternative theories. A limit was recently set on the nonsymmetric gravitational theory of Moffat, using the reported limits on the rate of change of orbital period of 4U 1820-30, together with a reasonable model for the mass transfer (Krisher 1987). Apart from its astrophysical importance, the continued search for short-period binaries containing compact objects may provide important new arenas for testing relativistic gravity.

## ACKNOWLEDGEMENTS

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## REFERENCES

Damour, T. 1987, in *300 Years of Gravitation*, eds. S. W. Hawking and W. Israel, P. 128, Cambridge University Press, Cambridge.

Eardley, D. M., Lee, D. L., and Lightman, A. P. (1973). *Phys. Rev.* , *D* **10**, 3308.

Eardley, D. M., Lee, D. L., Lightman, A. P., Wagoner, R. V., and Will, C. M. 1973, *Phys. Rev. Lett.* , **30**, 884.

Krisher, T. P. 1987, *Astrophys., J. Lett.*, **320**, L47.

Krauss, L. M. and Tremaine, S. 1988, *Phys. Rev. Lett.*, **60**, 176.

Longo, M. J. 1987, *Phys. Rev., D* **36**, 3276.

Longo, M. J. 1988, *Phys. Rev. Lett.*, **60**, 173.

Taylor, J. H. 1987, in *General Relativity and Gravitation*, ed. M. A. H. MacCallum, p. 209, Cambridge University Press, Cambridge.

Thorne, K. S. 1987, in *300 Years of Gravitation*, eds. S. W. Hawking and W. Israel, p. 330, Cambridge University Press, Cambridge.

Will, C. M. 1981, *Theory and Experiment in Gravitational Physics*, Cambridge University Press, Cambridge.

Will, C. M. 1984, *Phys. Reports*, **113**, 345.

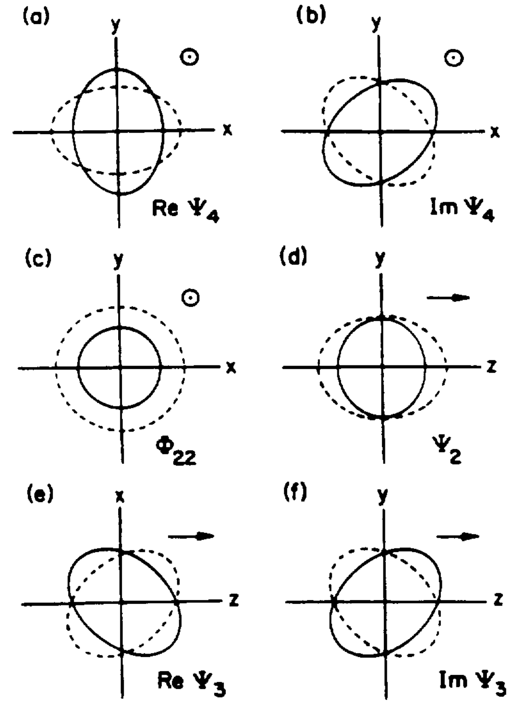


FIG. 1. — The six polarization modes of a weak plane gravitational wave permitted in any metric theory of gravity. Shown is the displacement that each mode induces on a sphere of test particles. The wave propagates in the +z direction and has time dependence cos $\omega t$. The solid line is a snapshot at $\omega t = 0$; the broken line one at $\omega t = \pi$. There is no displacement perpendicular to the plane of the figure. In (a), (b), and (c), the wave propagates out of the plane; in (d), (e), and (f), the wave propagates in the plane.

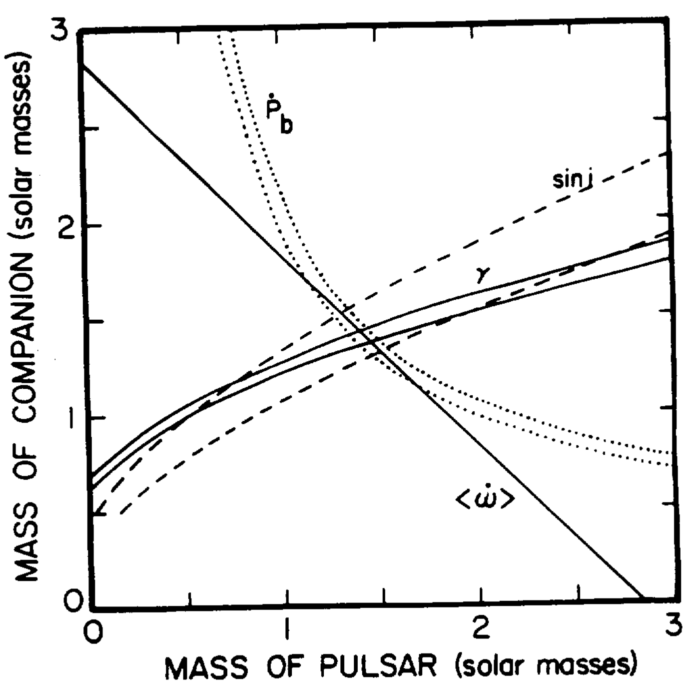


FIG. 2. — Curves showing constraints on the mass of the pulsar and its companion provided by measured values and estimated errors of the periastron shift ( $\dot{\omega}$ ), gravitational redshift second order Doppler shift ($\gamma$), orbital period change ($\dot{P}_b$), and Shapiro time delay (sin i). All four constraints overlap in the region near 1.4 solar masses for each body.

## DISCUSSION

NORDTVEDT: It seems that if strange gravitons traveled at a speed different than light, then these gravitons would Cerenkov radiate into photons or vice-versa. Can this be used to rule out strange gravitons?

WILL: That is possible, although the details depend on the particular theory in question. For example, Caves (Ann. Phys. N.Y. **125**, 35 (1977)) used such arguments to place a limit on Rosen's bimetric theory.

TREUHAFT: To what extent does a simple measurement of the difference in arrival time of gravitons and photons separate propagation characteristics from source physics (i.e. at what level can the emission times be assumed to be identical)?

WILL: The limits given above hold provided that the emission time difference is small compared to minutes (galactic source) or compared to a week (extragalactic source). Since one expects the time-scale for the processes leading to photon, neutrino and gravity-wave bursts to be on the order of milliseconds, the assumption should be valid, unless there are unforeseen delays between processes.

HELLINGS: Do you have any comment on possible scalar radiation? In particular, what theoretical limits can be set on it from experimental observations?

WILL: Measurements or limits on the possible polarizations of a detected gravitational wave could limit the existence of scalar gravitational waves, and Paik (Phys. Rev. D. 15, 409 (1977)) studied a disk gravitational-wave antenna design that would be particularly sensitive to scalar waves, represented by the mode $F_{22}$ shown in Figure 1. The binary pulsar could in principle limit the effects of scalar gravitational radiation damping, through its contribution to dipole and quadrupole radiation. The details, however, depend on the theory in question, so for the case of Brans-Dicke type theories, the limits are disappointing compared to standard solar-system tests of those theories, because of the apparent symmetry of the system. As to scalar low-mass fields that may play a role in short-range gravity, the answer may depend on the details of the field theory that predicts the scalar field.

HELLINGS: A measurement using Peter Bender's interferometer of the phase of gravity waves from a known binary star could be used to measure the speed of gravity waves as a phase offset from the expected phase from knowledge of the optical data.