Gravity Wave Watching

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Abstract

It is suggested that gravity waves could, in several cases, be detected by means of already (or shortly to be) available technology, independently of current efforts of detection. The present is a follow-up on a recently suggested detection strategy based on gravity-wave-induced deviations of null geodesics. The new development is that a way was found to probe the waves close to the source, where they are several orders of magnitude larger than on the Earth. The effect translates into apparent shifts in stellar angular positions that could be as high as $10^{-7}$ arcsec, which is just about the present theoretical limit of detectability.
I. Introduction

It was argued recently that gravitational waves could, in principal, be detected through a new non-mechanical effect [1,2]. This effect can be easily understood by replacing the usual textbook case of gravity-wave-induced variations in proper distances between initially static massive particles, by the analogous case for massless particles. One is then monitoring deviations in null, rather than in timelike geodesics. When the massless particles are photons, the timelike geodesics can be light rays coming from distant (e.g. stellar) sources, or perhaps from man-made space-based laser sources. Thus, what is to be measured in this approach, are gravity-wave-induced shifts in apparent angular separations of appropriate light sources. This effect should not be confused with the much smaller shifts in real angular separations of light sources, due to gravity waves actually hitting the light source [3]. In [2], it is the photons from the source (not the source itself) that encounter the waves, as that could happen arbitrarily close to the Earth. Nor should the effect be confused with yet another smaller shift, that due to the overall focusing of geodesics by the energy of the gravity waves.

For an introduction to the physics of gravity waves and to the many proposed, and the few fully developed detection strategies, the reader is referred, in [4-22], to some reviews and key articles in the field.

Consider, now, the following illustration of the effect, as discussed in [2]: A gravitational pulse “with memory of position” [3,19,20,23-27] hits the Earth, coming from a supernova explosion, say, in the Northern sky. Alerted by the electromagnetic flash, the observer is now aware that a gravity wave has just whipped passed the Earth, and is traveling towards the Southern sky. For many years to come, light reaching the Earth from most sources in that hemisphere will have been through the gravity wave. Thus, if arbitrarily small angular shifts were detectable, the receding gravitational pulse could be “followed” for an extended duration. For most other schemes of gravity-wave detection, the same pulse would leave a single blip on the detector’s record, and then would be lost for ever. Here, the gravitational pulse, all along its receding journey, keeps interacting with photons that eventually reach the observer. Hence, in a sense, the photons act as detectors that interact with the pulse farther and farther away from the Earth.

At this point, the reader could be wondering what all the fuss is about, and she (or he) would be right, as far as this particular illustration is con-
cerned. For the waves get only dimmer (though at a negligible rate,) as they keep moving away from us, and the expected apparent angular shifts (of the order of the wave’s strength at the location of the photon-graviton interaction \([2]\),) are over ten orders of magnitude smaller than what present day angular resolution astrometry can handle.

However, as we shall now see, exploiting the same physics as above, but in a sense inverting the argument, one can arrive at a scheme for detecting gravity waves directly, using present-day resolution-power technology.

Consider the following configuration. A steady source of gravity waves (e.g. a neutron star or a binary star, call it for short SG,) is giving off radiation with each polarization component having the form

\[
h = \frac{H}{r} \exp\{i\Omega(r - t)\},
\]

where \(r\) is the distance to the center of the gravity-wave source SG, and \(\Omega\) is of the order of the time frequency of that source. (E.g. \(\Omega = 2\omega\) when the source is a system with rotation frequency \(\omega\).) \(H\) is a constant that can be roughly estimated in the quadrupole approximation by

\[
H \sim MR^2\Omega^2, \tag{2}
\]

where \(M\) and \(R\) are the mass and size of SG.

Now, consider a light source (dubbed SL hereafter,) situated even further away from us, along the line Earth-SG. (A situation where such a good alignment might happen naturally will be discussed below.) The photons we receive on the Earth from SL have, at some point in the past, crossed an area of relatively strong gravity waves. The maximum amplitude experienced by a photon is \(h_{\text{max}} \sim H/b\), where \(b\) is the impact parameter with respect to the center of SG. From the conclusions of \([2]\), there is then some reason to suspect that the position of SL, as observed from the Earth, is continuously experiencing apparent angular shifts with an amplitude proportional to \(h(r = b)\). A priori, this effect could be larger than the one in \([2]\) by as many orders of magnitude as there is in the ratio \(r_E/b\), where \(r_E\) is the distance from SG to the Earth.

Upon inspection, it turns out that rather different considerations apply here than for the plane wave with memory of \([2]\), leading to a modified
formula for the expected angular shifts. However, the calculations below show 1) that the effect here also is physical, 2) that its magnitude, in not too unlikely optimal situations, falls close to present limits of detectability.

Before proceeding to the next illustration, note that the angular shifts studied here are variations not about the actual position of SL, but about that position as displaced by non-radiative light deflections. However, those non-radiative deflections are either virtually constant in time (as in the example above,) and are therefore irrelevant here (besides being actually unmeasurable,) or, as in the illustration below, they have a well-known time dependence and can be easily subtracted. In any case, Schwarzschild angular shifts, for most interesting candidate sites, have a much larger time-scale than (and therefore should not interfere with potential measurements of) the expected shifts from gravity waves.

Now, let our gravity-wave source SG be a rotating neutron star. A good candidate should be rotating rapidly enough to yield waves with a sufficient strength (see (2)), but not so rapid that the light crossing its gravity waves would shift too quickly for the sensitivity limit of the observer’s hardware. (In the case of insufficient integration time, the overall effect of the waves would be a blurring of SL’s image, with a characteristic signature.)

As for the role of the light source SL, let be played here by a companion star, locked with our neutron star SG into a binary system. Different SL candidates (ordinary main-sequence stars, pulsars, etc.,) will have different observational merits. Among the factors that come into play are the apparent magnitude of SL (shorter minimal integration times for larger magnitudes,) and its wavelength (better angular resolution for longer waves, best resolution for radio waves.) Because quite different considerations apply for each type of companion SL, we limit ourselves here to deriving the main equations describing the effect, and obtaining orders of magnitude for reasonable optimal situations. A more detailed study of some promising actual astronomical sites, will be published elsewhere [28].

Taking a rapid pulsar as the companion SL (to the slower neutron star SG,) offers a particularly good opportunity for following the time evolution of the various parameters involved: Since it can be known to an excellent precision where each component of the binary pulsar is situated at any given moment (time resolution much finer than the period of either the neutron star SG or the pulsar SL,) one has an excellent time axis over which to draw eventual light deflection observations (see below.)
Just such a system has been considered recently to try and detect gravity waves through an effect that has little to do with the angular shifts studied here \cite{29}. In that paper, it is the Shapiro time-delay effect of the neutron star's gravity waves on the pulsar's frequency that is considered. It is found to fall not too far from present limits of time-resolution power. In fact, the main problem there is less likely to be the time resolution than the photometric sensitivity, most pulsars being very dim radio sources (some notable exceptions are considered in \cite{28}.)

Finally, we should perhaps call the attention on one more possible source of confusion. In the case (referred to as case-two hereafter,) where the gravity-wave source SG is a neutron star and the light source SL an ordinary star or perhaps a pulsar, there are two quite different types of gravity waves involved. One is the neutron star SG's radiation, which has a frequency of typically several or many Hertz. The other is the gravitational radiation generated by the binary system as a whole. These much longer waves (minimal period of a few hours,) are the ones probed in the case (case-one,) where the binary system as a whole was playing the role of SG, the light source SL being some much farther, unrelated body. In the following, when SG and SL are the two components of a binary (case-two,) the lower-frequency radiation of the whole binary system will not be considered. When we speak of the near-zone (distances less than one gravitational wavelength,) we mean the near-zone of SG, which is the neutron star in case-two, and the whole binary in case-one.

This is not to say that it would not be interesting to consider the radiation of the whole binary even, in case-two. But, because we would then be not only in the near-zone of the source, but within the source itself, we would have to address the issue of disentangling dynamic Newtonian from relativistic contributions in that case \cite{28}.
II. Equations for the effect

Our first simplification will be to consider the effect of only one polarization component of the gravity waves, namely the one that distorts geodesics in directions that are parallel to the plane of rotation of the gravity-wave source SG (that is the equatorial plane when SG is a neutron star, and the orbital plane when it is a binary.) This simplification does not affect substantially our conclusions, since the other component of the waves (the one with effects that are parallel to the rotation axis,) is usually of the same order of magnitude and frequency. (Although, attention to this other component can be extremely useful in disentangling radiative from dipole Newtonian effects in the near zone of SG.) Thus, we will be studying movements completely contained in the source’s rotation plane.

With these simplifications, the line element, in the spherical transverse-traceless gauge, has the simple form:

\[ dt^2 - dr^2 - g d\phi^2 = 0 , \]

(3)

where

\[ g \equiv (1 + h)r^2 . \]

(4)

Here the coordinates are centered on SG and light rays stretch from \( \phi \sim 0 \) to \( \phi \sim \pi \). \( h \) is the gravitational-wave strength given by (1). As mentioned above, the Schwarzschild component of the metric is not included, its contribution being either irrelevant (e.g. when SG and SL are very distant unrelated objects,) or easy to subtract from the observations (e.g when SG and SL are locked into a binary system.) For the flat \( (h = 0) \) spacetime, of course, our equations should describe straight trajectories stretching from \( \phi = 0 \) to \( \phi = \pi \), with closest encounter with SG at \( r = b \), where \( b \) is the “impact parameter”.

One can either stick to these polar coordinates or, alternatively, introduce a null coordinate \( v \equiv r - t \). It turns out that the gain from such a change for this particular problem is not considerable. So we shall stick here with \( t \), \( r \) and \( \phi \).
Null geodesics are described by the equations

$$\frac{dp^t}{d\lambda} + \frac{1}{2} g_{tt} p^t p^2 = 0 ,$$

(5)

$$\frac{dp^r}{d\lambda} - \frac{1}{2} g_{tr} p^r p^2 = 0 ,$$

(6)

$$\frac{dp^\phi}{d\lambda} + \frac{g_{t\phi}}{g} p^t p^\phi + \frac{g_{r\phi}}{g} p^r p^\phi - \frac{1}{2} \frac{g_{\phi\phi}}{g} p^\phi p^2 = 0 .$$

(7)

Here $p^\alpha \equiv dx^\alpha / d\lambda$ are the photon’s momenta. Commas indicate ordinary partial derivatives.

Our aim is to determine $\phi$ as a function of $r$. We start by calculating $p^\phi$. We see immediately from (7) that, even for a finite $h$, there are straight line solutions, namely $p^\phi = 0$. These are actually trajectories made of two (one incoming and one outcoming) components, with a discontinuous kink at $r = 0$. This is telling us that here, as in the plane wave case [2], photons that hit the wave fronts at right angles suffer no radiative deflection.

For $p^\phi \neq 0$, that is, for non-vanishing impact parameters, one gets from (7) the simple expression

$$p^\phi = \frac{L}{g} ,$$

(8)

where $L$ is an integration constant.

Let us write (6) in the form

$$p^r = \frac{1}{2} \int_C g_{r\phi} p^\phi d\phi ,$$

(9)

where $C$ is a constant to be determined shortly. Dividing this equation by (8) and using (1,4), one obtains

$$\frac{dr}{d\phi} = \frac{p^r}{p^\phi} = (1 + h) r^2 \int_C \frac{2 + (1 + i\Omega r)h}{2(1 + h) r} d\phi .$$

(10)
In the absence of gravity waves, one should be able to recover the straight-line solution

\[ r_{\text{flat}} = \frac{b}{\sin \phi}. \]  

(11)

This fixes the value of \( C \) at \( \pi/2 \), as one can see immediately from (10,11).

We now switch to the radial variable \( u \equiv 1/r \). Then, deriving (10) with respect to \( \phi \), and retaining only terms that are linear in \( h \), we find

\[ u'' + u = -h' \int_{\pi/2}^{\phi} u d\phi - \frac{h}{2}(u + i\Omega), \]

(12)

where primes indicate derivatives with respect to \( \phi \).

In accordance with our linear treatment, the fluctuation \( h \) can be expressed in terms of \( \phi \) only by substituting, in (1), the expressions for \( r \) and \( t \) corresponding to the vacuum straight-line solution. These expressions are (11) and

\[ t_{\text{flat}} = -b \frac{\cos \phi}{\sin \phi}. \]  

(13)

(The origins of coordinates in (11,13) are chosen in such a way that \( t_{\text{flat}} = 0 \) and \( r_{\text{flat}} = b \) at \( \phi = \pi/2 \).) Thus, we have

\[ h = \frac{H}{b} \sin \phi \exp \left\{ i\Omega b \frac{1 + \cos \phi}{\sin \phi} \right\}, \]

(14)

and

\[ h' \equiv \frac{dh}{d\phi} = \frac{h}{\sin \phi} \left( \cos \phi - i\Omega b \frac{1 + \cos \phi}{\sin \phi} \right). \]

(15)

On the other hand, the integral in (12) is only needed to zeroth order. Hence, using (11), it is just \(- \cos \phi/b\).
We are now in a position to write the equation governing light deflection from spherical gravity waves:

\[ u'' + u = \frac{h}{b \sin \phi} \left( 1 - \frac{3}{2} \sin^2 \phi - i \Omega b \left[ \frac{1 + \cos \phi}{\sin \phi} - \frac{\sin \phi}{2} \right] \right) . \] (16)

This equation can be solved perturbatively by looking for a function \( u_1 \) satisfying

\[ u = u_0 + u_1 , \] (17)

where \( u_0 \) is the background solution, i.e.,

\[ u''_0 + u_0 = 0 , \] (18)

which is the equation of a straight line (see (11)). Then, the equation for \( u_1 \) is just (16), with \( u \) replaced by \( u_1 \) on the left-hand side.
III. Interpretation

The implications of (16) can be seen most clearly in the optimal case of very close encounter, when the impact parameter is less than one gravitational wavelength: \( b < \Lambda \equiv \frac{2\pi}{\Omega} \). (Equation (16) can also be integrated analytically outside this region [32], but that will not be considered here.) As we shall see, such favorable configurations are not all that implausible (see also [28,32].)

For what we called earlier case-one scenarios (SG and SL unrelated, far-apart objects,) if we consider a binary star like \( \mu \)-Sco (see below) as our gravity-wave source SG, then we have to find a candidate light source SL within an angle equal to SG’s wavelength (about 18 light-hours) divided by SG’s distance to the Earth (about 109 parsecs.) This gives an angular size of about 1 arcsec. This constraint is less stringent still if we consider a case-two situation (SG and SL tightly bound together.) Although the wavelength here is much shorter (say 0.1 light-second for a 10 Hz neutron star,) the distances are short enough (many such systems are only about 1 light-second across,) that the constraint on the orbit’s inclination with respect to the Earth for obtaining a near-zone deflection is not too extreme (details below.) Among the over 500 known pulsars, several are known to be (and statistically many more should be) eclipsing or near to eclipsing binaries. In the logic of this paper, these obviously hold excellent prospects for gravity-wave detection.

Going back to the inspection of (16) in the near-zone, a particular photon crosses the region of strongest \( h \) in less time than it takes the gravitational wave profile that he encounters to change appreciably. (Note that the \( 1/r \) fall-off of \( h \) makes it drop by a few orders of magnitude within a single wavelength). This means that the photon sees essentially a standing bulge of curvature (centered on the source), hence (16) can be integrated with \( h \approx H/r \equiv H \sin \phi/b \) (see(1,11)). Subtracting this maximal trajectory from the one for when \( h \) is at its lowest gives the desired shift.

Let us then compute the contribution of each term in (16) to \( u_1 \), and subtract the two values of \( \phi \) at \( u = 0 \) \((r = \infty) \) to find the total shift for near-field deflection. We obtain

\[
\Delta \phi = \frac{H}{b} - \frac{H}{b} - i\Omega H(\frac{\pi}{2} + 1) + i\Omega \frac{\pi}{8}
\]
\[ + \frac{H}{b} - \frac{H}{b} - i\Omega H (\frac{\pi}{2} - 1) + i\Omega \frac{\pi}{8} , \quad \text{(19)} \]

where we have kept the order of the terms in (16).

First, we see that the effects of the \( \Omega \)-independent terms in (16) can cancel out exactly. This means that there is no Schwarzschild-like light deflection. (In the Schwarzschild case, the RHS in (16) reduces to a \( u^2 \) term analogous to our \( hu \propto \sin^2 \phi \).)

Summing up all contributions, we obtain a formula for maximal shifts from near-field deflections:

\[ |\Delta \phi|_{\text{max}} \approx \frac{3}{4} \pi \Omega H , \quad \text{(20)} \]

or

\[ |\Delta \phi|_{\text{max}} \approx \frac{3}{2} \pi^2 h_{\text{max}}(r = \Lambda) . \quad \text{(21)} \]

Note that the amplitude does not increase as one penetrates deeper into the near-zone. This is because, a smaller value of \( b \) corresponding to a smaller angle of incidence (angle between a light ray and a given spherical wavefront), the effect (on \( \Delta \phi \)) of the corresponding increase in \( h \) gets cancelled by the decrease in the sine of the angle (see [2].)

As mentioned earlier, choosing a candidate site involves weighing the sometimes contradictory effects of a number of parameters, and finding a compromise that best accommodates the observational constraints. One obvious problem is that longer gravitational wavelengths, which correspond to wider near-zones, and hence to less stringent constraints on the alignment, often correspond to weaker gravity-wave amplitudes (see (2)). While we leave for [28] a more detailed evaluation of various candidates’ merits, we try here to estimate typical orders of magnitude for this effect in optimal, but realistic situations.

Consider first, as our SG, the binary of giant stars \( \mu \)-Sco in the Scorpius constellation. It is situated at a distance from the Earth \( r_E = 109 \) parsecs, and has an expected gravity wave frequency \( f \approx 1.6 \times 10^{-6} \text{Hz} \). The expected dimensionless amplitude of gravity waves at \( r = r_E \) is \( h(r_E) \approx 2 \times 10^{-20} \), implying that \( H \approx 6 \text{cm} \). Such a source, which is among the strongest in
the Earth’s vicinity, has unfortunately no chance of being detected by Earth-bound experiments, due chiefly to seismic noise.

Let us see, in this instance, how far our effect falls from present limits of resolution power astrometry. The best resolution achieved today comes from Very Long Baseline Interferometry. There, the limit comes essentially from the shortest wavelengths that survive water and oxygen absorption (say 0.1mm,) and the size of the Earth. The ratio gives about $10^{-5}$ arcsec. There are however definite projects for reaching $10^{-7}$ arcsec in a few years with space-based interferometry.

Now, the numbers for $\mu$-Sco imply a near-zone which spreads over an angular distance of $c/\pi f \sim 1$ arcsec, where $c$ is the speed of light. This does not seem too tiny to allow for a non-negligible chance of discovering a potential candidate for the role of SL. (Note that the Hipparcos satellite routinely maps the sky at a resolution of $10^{-4}$ arcsec.) For obvious reasons, only the binaries that are closest to the Earth have so far received attention in the literature. But the closeness of SG to the Earth is not a sine qua non in the present context. Hence, a great many more binaries than the ones catalogued so far could be observationally interesting here.

The shift’s amplitude expected from (20) is

$$|\Delta \phi|_{\text{max}} \approx \frac{3}{2} \frac{\pi^2 H}{\Lambda} \approx 2 \times 10^{-8} \text{arcsec},$$

which falls short of the limit of detectability by only one order of magnitude.

The situation for a case-two scenario (SG and SE in a binary) turns out to be even more promising. The period and strength of neutron-stars as gravity-wave sources are poorly known. The limits on neutron-star parameters are mostly drawn from pulsar data, but it is still uncertain how a typical ordinary neutron star compares to a typical pulsar. For instance, neutron-star rotation frequencies are thought to range all the way up to about $10^3$ Hz, the observed higher limit for pulsars, but the lower limit is very uncertain.) Also, neutron-star gravity-wave strengths could vary widely depending on which of the possible mechanisms of gravity-wave production is actually at work. Eventually, only observation (why not of gravity waves,) will put stringent constraints on neutron-star parameters.

To fix ideas, take SG to be a neutron star with $f \approx 1$ Hz, and SL to be a pulsar with a much higher frequency. SG and SL form a tight binary system.
Their average separation is only about one light-second. (The famous binary pulsar PSR 1913+16, e.g., is less than 3 light-seconds across, and several tighter binaries have been observed.)

The alignment constraint here is really a constraint on the orbit’s inclination with respect to the Earth. For the light from SL to cross the near-zone of SG on its way to us, the sine of that angle should be smaller than \( \Lambda/R \), where \( R \) is the orbit’s half-size. But this ratio, given the numbers above, is typically close to one. Hence, we have here a set of candidates that naturally satisfy the alignment requirement.

Now, if we assume that the neutron star is generating gravity waves through the CFS (Chandrasekhar- Friedman-Schutz) instability [30,31], then a possible value for \( H \) would be \( H \approx 10^{-6} m \) (see [4] and references therein.) For \( f = 1 \) Hz, this yields

\[
|\Delta \phi|_{max} \approx 10^{-7} \text{arcsec} .
\]  

(23)

And thus, even neutron-star gravity waves, some of the faintest to reach the Earth, could be detected after all, and relatively soon.

Finally, interesting candidates for the case-two scenario (SG and SL gravitationally bound) are not limited to tight binaries of neutron stars. Take the X-ray source Her X-1. This is thought to consist of a neutron star \( (f \approx 1 \text{Hz}) \) and a 2.2 solar-mass star, forming a binary system with an orbital period of 1.7 day. Because the orbit is larger here than in the case above (smaller \( \Lambda/R \)), strong shifts such as (23) are more likely if the system is not too far from the eclipsing position. As it turns out, this is actually an eclipsing binary, so excellent alignment occurs naturally every 1.7 day. We could also cite, in this class of candidates, several of the many multiple stars observed in the galaxy. These usually contain one or more binaries. The \( \alpha \)-Gem system, for instance, is made of three binary stars, with periods of 0.8, 2.9 and 9.2 days. Such configurations as this are, obviously, potential sites for rich
gravity-wave physics in the sense of this paper.

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References

[1] R. Fakir (1991), *Gravity Waves and Hipparcos*, proposal presented in Table Ronde on Moroccan-European Collaboration in Astronomy, Moroccan Center for Scientific Research Archives, June 1991, Rabat, Morocco.

[2] R. Fakir (1992), *Gravitational Wave Detection, a Non-Mechanical Effect*, The Astrophysical Journal, vol.418, 20.

[3] V.B. Braginski and L.P. Grishchuk, *Soviet Physics-JETP* 62, 427 (1985).

[4] K.S. Thorne, in *300 Years of Gravitation*, S.W. Hawking and W. Israel, Eds.(Cambridge University Press, Cambridge, 1987.)

[5] K.S. Thorne, *Science* 256, 325 (1992).

[6] K.S. Thorne, in *Recent Advances in General Relativity*, A. Janis and J. Porter, Eds.(Birkhauser, Boston, 1992.)

[7] L.P. Grishchuk, Annals of the New York Academy of Sciences, vol.302, 439 (1977).

[8] A. Einstein, *Preuss. Akad. Wiss. Berlin, Sitzungsberichte der physicalisch-mathematischen Klasse*, p.688 (1916).

[9] A. Einstein, *Preuss. Akad. Wiss. Berlin, Sitzungsberichte der physicalisch-mathematischen Klasse*, p.154 (1918).

[10] H. Weyl, *Space-Time-Matter*. Methuen:London (1922).

[11] A.S. Eddington, *The Mathematical Theory of Relativity*, 2nd edn, Cambridge University Press, Cambridge (1924).

[12] C.W. Misner, K.S. Thorne, J.A. Wheeler, *Gravitation* (Freeman, San Francisco,1973.)

[13] M. Zimmerman and K.S. Thorne, in *Essays in General Relativity*, F.G. Tipler, ed. (Academic Press: New York,1980.)
[14] J.R. Bond and B.J. Carr, *Monthly Notices of the Royal Astronomical Society* 207, 585 (1984).

[15] L. Smarr, *Sources of Gravitational Waves* (Cambridge University Press, Cambridge, 1979.)

[16] see reviews in N. Deruelle and T. Piran, *Gravitational Radiation* (North Holland: Amsterdam, 1983.)

[17] J. Weber, *Physical Review* 117, 306 (1960).

[18] see for example J.A. Tyson and R.P. Giffard, *Annual Reviews of Astronomy and Astrophysics* 16, 521 (1978), E. Amaldi and G. Pizella, in *Relativity, Quanta and Cosmology in the Development of the Scientific Thought of Einstein*, vol.1, 96 (1979), and references in D.G. Blair, *The Detection of Gravitational Waves* (Cambridge University Press, Cambridge, 1991) and P.F. Michelson, J.C. Price and R.C. Taber, *Science* 237, 150 (1987).

[19] D. Christodoulou, *Physical Review Letters* 67, 1486 (1991).

[20] K.S. Thorne, *Physical Review D* 45, 520 (1992).

[21] R.E. Vogt, *The U.S. LIGO Project* in *Proc. of the Sixth Marcel Grossmann Meeting on GRG, MGC, Kyoto, Japan, 1991*.

[22] C. Bradaschia et. al., *Nucl. Instrum. & Methods*, A289, 518 (1990).

[23] S.J. Kovacs and K.S. Thorne, *The Astrophysical Journal* 224, 62 (1978).

[24] L.P. Grishchuk and A.G. Polnarev, *Sov.Phys. JETP* 69, October 1989.

[25] R.J. Bontz and R.H. Price, *The Astrophysical Journal* 228, 560 (1979).

[26] L. Smarr, *Physical Review D* 15, 2069 (1977).

[27] V.B. Braginsky and K.S. Thorne, *Nature* 327, 123 (1987).

[28] R. Fakir (1993), *Gravity Waves and Light*, in preparation.

[29] R. Fakir (1993), *Almost Readily Detectable Time Delays from Gravity Waves?*, UBC preprint UBCTP-93-006.
[30] S. Chandrasekhar, *Physical Review Letters*, 24, 611 (1970).

[31] J.L. Friedman and B.F. Schutz, *The Astrophysical Journal*, 222, 281 (1978).

[32] R. Fakir (1993), *Early Direct Detection of Gravity Waves*, UBC preprint UBCTP-93-016.