The Stochastic Gravitational Wave Background: Some Astrophysical Sources

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ABSTRACT

This work is a review of some of the literature on expected astrophysical sources of stochastic gravitational waves. A brief introduction is provided on the nature and characteristics of a stochastic background. Results presented include the expected energy density parameter, Ω_{GW} ,for several sources. Particularly, we present backgrounds from eccentric, rotating neutron stars, supernovae, and double neutron star coalescence. Some of these predictions place Ω_{GW} at 100 Hz at 10^-9 or stronger. Such a signal could be detected by planned second generation interferometers such as Advanced LIGO.

I. Introduction

In recent years, the construction of long-baseline interferometric gravity wave detectors has made broadband, sensitive searches for gravitational waves a reality. Projects such as LIGO, TAMA, GEO, and VIRGO, as well as a network of resonant-mass detectors, are currently searching our local space-time for the illusive ghosts of Einstein's theory.

A gravitational wave (GW) signal may be classified into one of three categories: burst, periodic, or stochastic. Bursts are well localized in the time domain, periodic signals are well localized in the frequency domain, and stochastic signals are spread over many frequencies and long times (Allen 1996). Sources in the "burst group" may include coalescing binary systems of black holes and/or neutron stars, gravity waves from gamma ray bursts, and supernovae. The second group, periodic signals, most notably includes signals from rotating neutron stars. A detected signal falling under either of these classifications most likely originates from a single event or object in the sky.

The third type of signal can be more difficult to grasp conceptually. It is also, potentially, the most exciting. The stochastic GW background is the gravitational analog of the Cosmic Microwave Background (CMB) in the electromagnetic spectrum (Allen 1996). Like the CMB, the stochastic background would come from all (or, at least, many) points on the sky. Also like the CMB, a component of the stochastic background may carry information about the early universe (Maggiore 2000). However, unlike CMB photons, which had their last scattering about 10^5 *years* after the big bang, early universe gravitational signals in the LIGO frequency range may have decoupled 10^{-22} *seconds* after the dawn of time (Allen 1996). The information they contain could prove a valuable tool to cosmologists.

In addition, there is expected to be a second component to the GW stochastic background that has no obvious analog in the electromagnetic spectrum. This signal originates from the so-called "astrophysical" sources of stochastic GW's. Optical telescopes can be resolved to see only a small piece of the sky. GW detectors have no such resolving power – at any time a detector is sensitive to most of the sky! As a consequence, the GW stochastic background, in say, a given second, likely includes the sum of dozens or hundreds of signals coming from point sources all over the sky. The same types of objects that lead to resolvable signals when close enough - for example, coalescing binaries, rotating neutron stars, and supernovas – will contribute to the stochastic background in the form of many irresolvable signals coming from large distances.

An analogy to how we hear sound might make this more obvious. Imagine sitting down to dinner in a large ballroom, with the tables spread far apart. If a friend speaks in conversational volume while sitting on the other side of the room, you could never hear her, even were all the other dinner guests to hold their breath.

On the other hand, consider the sound of all the guests freely conversing. They are each far away – at least, most of them are not at your table. So, any one person is too quiet to hear. However, the collective noise of all those conversations would certainly be noticeable!

In this way, far away point sources of gravity waves may combine incoherently to produce a stochastic signal in GW detectors. This contribution to the stochastic signal is said to come from astrophysical sources, as opposed to a signal from the very early universe, which is known as cosmological (Abbott *et al.* 2006).

One of the basic differences between astrophysical signals and cosmological signals is the time that they are emitted. Cosmological sources come from a time well before last scattering. In terms of redshift, this means cosmological GW's originate at $z > 1000$. Astrophysical GW's typically come from some time after star formation has begun. In the papers considered below, the astrophysical sources all originate at $z < 5$.

II. Characterization

In the literature, bounds on the stochastic background are usually stated in terms of a dimensionless quantity, Ω (Abbott et al. 2006).

$$\Omega(f) = (f/\rho_c)(d\rho_{GW}/df)$$

Here, f is the GW frequency being considered, ρ_c is the critical energy density necessary for a flat universe, and ρ_{GW} is the energy density of the stochastic gravitational wave signal. So, $\Omega(f)$ is a measure of the differential energy density of the stochastic signal in a unit logarithmic frequency interval (Allen 1996). If the stochastic signal meets the criteria of being isotropic, stationary, and Gaussian, this function $\Omega(f)$ is enough to completely characterize the background (Allen 1996). This is analogous to saying that the CMB is completely characterized as blackbody radiation at 2.7 K.

As a practical point, setting bounds on $\Omega(f)$ in a given frequency range with a GW detector demands some kind of model for the frequency dependence of Ω. This leads to a quantity Ω_0 often quoted in the literature. This quantity is the value (or bound) of $\Omega(f)$, assuming that $\Omega(f)$ has no frequency dependence. For detectors probing Ω in a narrow bandwidth, $\Omega_0 \approx \Omega(f)$.

GW detectors measure the dimensionless strain, h. In terms of detectability, we might wish to think of Ω in terms of the strain associated with it. If we ask for the strain that would be produced in a bandwidth equal to the observational frequency (Allen 1996), we find:

$$h(f) \approx (100\text{Hz}/f)\,(2\text{x}10^{-20})\,\sqrt{\Omega(f)}$$

III. Measurement

Known bounds, excluding GW detectors, on the GW spectrum from indirect measurements are shown in Figure 1 (Maggiore 2000). The binary pulsar bound can be explained as follows. Pulsars are very good clocks. As a signal from a pulsar travels to us through a stochastic GW signal, there would be fluctuations in the pulsar signal due to the GW's. However, we see that pulsar signals do NOT fluctuate to very high precision. This allows one to place an upper bound on the strength of stochastic waves. In a similar sense, GW's would cause fluctuations in the CMB. The COBE mission reports the extent to which the CMB does not fluctuate, and so we get another bound on the strength of the GW's.

Finally, quantum physics accurately predicts the ratios of the most abundant elements in the universe, forged in the furnace of the early universe. This calculation, which is a cornerstone of modern cosmology, is sensitive to the number of types of particles in the early universe. If gravitons were a significant fraction of these particles, the calculation changes, and we get the wrong ratios of elements. This gives us what is known as the nucleosynthesis upper bound on Ω_{GW}.

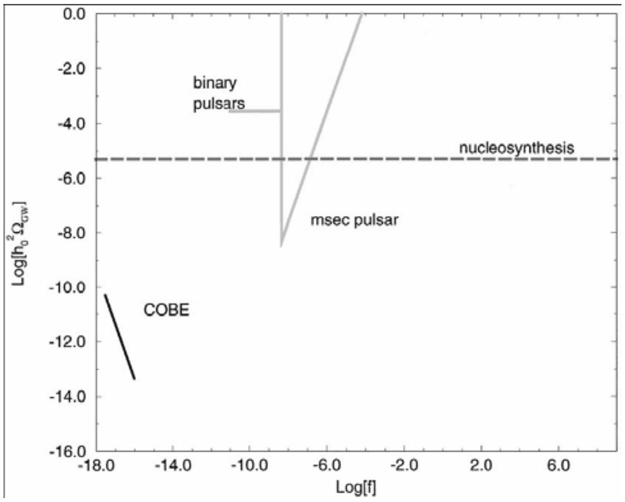

Figure 1 Some indirect upper bounds on the gravitational stochastic background (Maggiore 2000)

Notable about this graphic is the dearth of information concerning Ω_{GW}. In particular, astrophysical sources are not subject to the nucleosynthesis bound, because nucleosynthesis occurs many years before astrophysical signals are produced. So, without bounds coming from GW detectors, there are essentially *no bounds* on astrophysical stochastic GW's at frequencies above 1 mHz!

Gravity wave detectors are currently probing for a stochastic signal. The last released LIGO data reports a bound on Ω_{GW} in the frequency range 50-150 Hz of $\Omega_0 < 6.5\text{x}10^{-5}$. This bound will quickly become obsolete, as the current LIGO run is more sensitive. A probe of order 10^{-6} is expected from the data being currently collected (Allen 1996). The advanced configuration of LIGO, with observations scheduled to begin in 2013 (ligo.caltech.edu 2005), will likely probe Ω_{GW} in the same frequency band to 10^{-8} or 10^{-9} (Maggiore 2000).

IV. Some Expected Astrophysical Sources

A. Eccentric, Rotating Neutron Stars

Regimbau and de Freitas Pacheco (2001) provide a prediction of the GW background due to eccentric, rotating neutron stars. Neutron stars have gravitational fields strong enough to produce GW's, and through pulsar data, are known to rotate with (millisecond?) periods. If these rapidly spinning neutron stars have even small asymmetries with respect to their axis of rotation, they could be significant sources of GW's. The quantity ε quantifies the equatorial ellipticity of the neutron star; $\varepsilon = 0$ is axi-symmetric and so emits no GW waves. The authors estimate an average $\varepsilon = 10^{-6}$ with little justification. The calculation of Ω_{GW} from such sources scales as ε^2, so a lack of data on this number introduces considerable uncertainty into this calculation.

The authors use known data on neutron stars with Monte Carlo style simulations to estimate the properties of the true population of pulsars in the galaxy. They then assume the properties of our galactic population to apply to other galaxies as well.

However, an overall scaling in the number of neutron stars occurs in other galaxies due to the star formation rate (SFR). The rate at which stars are born is dependent on redshift, z. That is, galaxies further back in time (younger galaxies), are thought to produce stars at a different rate than local galaxies. The SFR may be probed using Hubble data; however, the curve is difficult to measure with certainty due to a lack of knowledge on dust in the universe.

The authors find that Ω_{GW} could be as high as $3\text{x}10^{-9}$ around 1–1.5 kHz. However, for a different model of the SFR, corresponding to different assumptions about dust, they find Ω_{GW} to peak at $2\text{x}10^{-11}$. This discrepancy shows how a direct probe of stochastic GW's could help model the SFR in ways that optical data can not. The high frequency band of these sources makes detection with current interferometer networks unlikely. However, the authors illustrate that a near future detector, such as Advanced LIGO, in conjunction with a resonant-mass detector tuned to about a kHz, could access this region.

It is worth noting that rapidly rotating neutron stars may provide gravitational waves via another mechanism as well. A certain type of fluctuation in the neutron star itself, known as r-modes, may produce GW. Maggiore (2000) reports that the stochastic signal neutron star r-modes is likely to be measurable by Advanced LIGO.

B. Supernovas

Coward and Burman (2002) consider supernovas that form neutron stars. They use three models of supernova collapse. Here, again, there is a serious uncertainty introduced at the beginning of the calculation, as models of supernova collapse are still evolving. This paper also depends on the SFR; the high mass stars that become neutron stars are short lived, so there is little time lag between the SFR and the supernova rate.

The authors calculate that the rate of neutron star forming supernovas observed from earth is about 35 per second. Based on the relevant time scale in supernova calculations, the expected dominant frequency is around 200-300 Hz.

The authors' simulation predicts a typical strain of 10^{-26}. Using the above relation between strain and Ω_{GW}, this suggests a value of $\Omega_{GW} \approx 10^{-12}$. This is too small to be seen by even Advanced LIGO detectors.

However, the large uncertainty in GW signal coming from a supernova should be emphasized. In particular, Maggiore (2000) considers supernovas that collapse to black holes. An estimate of $\Omega_{GW} \approx 10^{-10}$ coming from these events appears in this paper. It is not unrealistic that such a signal could be seen by advanced ground based detectors, especially given the current uncertainty in what to expect.

The stochastic signal from these supernovas is not "truly stochastic", but rather comes in the form of so-called "popcorn noise" (Coward & Burman 2002). Truly stochastic signal would have an energy profile that is fairly uniform in time. On the other hand, energy from supernovas would come in the form of closely spaced "pops." When such signals are detected, this signature will help distinguish this contribution of the stochastic background from many other contributions (Coward & Burman 2002).

C. NS – NS Coalescences

One of the most important sources of gravity waves is the coalescence of compact binaries. At large distance, unresolved coalescences make up a GW stochastic background. Strength of this signal again depends on the SFR. In addition, there are additional assumptions required about the evolution of compact binary systems. Neutron stars come from massive stars that, through supernova transformations, blow off a large percentage of their mass and form neutron stars. What fraction of massive stars exist as binary pairs? Of those massive stars that exist in binary pairs, what fraction remain binaries after experiencing the "kick" of two supernova explosions? The answers to these questions are not known precisely. Varying estimates in the literature lead to estimates of neutron star binaries that differ by an order of magnitude or more (Regimbau & de Freitas Pacheco 2006).

Regimbau and de Freitas Pacheco (2006) make estimates based on data from observed NS-NS binaries. Particularly, observations of the eccentricity of NS-NS orbits lead to predictions about how hard they were kicked in the supernovas.

The simulation leads to GW contributions in both the popcorn and continuous bands. Considering only the continuous bands, the authors find a peak Ω_{GW} of 10^{-9} at 670 Hz. However, considering the popcorn contribution as well, this signal gets stronger, about 10^{-9} at 100 Hz, and stronger at higher frequencies. Such a signal could be detectable at the sensitivity levels of Advanced LIGO.

V. Science Goals

The science of measuring these astrophysical sources through their stochastic GW's is an information rich picture of the universe at redshifts $z \approx$ 2-5 (Maggiore 2000). As previously mentioned, the measurement of these waves (or strong upper bounds) would provide information towards the star formation rate. Additionally, the signal would combine information related to rates of supernovas, mass and angular momentum distributions of compact objects, and ratios between formation of black holes and neutron stars.

Information in the EM spectrum addressing similar issues is fundamentally limited for at least two reasons. First, a lack of understanding of cosmic dust limits our ability to interpret EM signals from this region. GW's do not suffer from this limitation, as they couple extremely weakly to dust. By measuring the SFR through GW signals and comparing to models, information about this dust could be extracted, improving the ability to interpret EM signals. Second, EM emission from compact objects depends on particular processes, such as pulsar signals and accretion disks, that may or may not accompany a given neutron star or black hole. So, EM emission only allows viewing of a fraction of these very interesting objects. GW's come from different sorts of processes associated with these objects, so are a nice complement to EM measurements.

VI. Conclusions

Stochastic GW's from astrophysical sources promises to carry a wealth of astronomical information for redshifts of about 2 – 5. GW detectors are currently placing new bounds on this signal at a rapid pace. While there are no known astrophysical processes likely to produce a stochastic signal strong enough for this generation of detectors, several processes are good candidates for next generation detectors. For example, Advanced LIGO, scheduled to come online in 2013, has a good chance of seeing some form of astrophysical stochastic signal. The distance between the two LIGO sites fundamentally limits LIGO's ability to measure high frequency stochastic signals (Allen 1996). However, the use of resonant mass detectors in conjunction with one or both locations could allow probing into frequencies up to about 1 kHz, widening the scope of astrophysical processes that may be explored.

Additionally, understanding and modeling the astrophysical background may be an important step if this signal is convoluted with an older signal of cosmological origin. That is, to see the cosmological background, the astrophysical component may have to be removed (Maggiore 2000). In this sense, learning about our local universe, while a reward in itself, may have the added benefit of clearing our vision back to the beginning of time.

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