Gravitational waves

Reference webpages:

http://en.wikipedia.org/wiki/Gravitational_wave
and Chapter 10 in Thorne.

Questions to keep in mind are:

1. How good is the current indirect evidence for gravitational waves?
2. What will gravitational waves allow us to learn?
3. How critical are gravitational wave observations to our acceptance of black holes?

Introduction

A great wave of the future for black hole research involves the direct detection of gravitational radiation, also called gravitational waves, from sources including binary black holes that spiral together and merge. Much of my own research involves conceptions of astrophysical sources of gravitational radiation, and what the detections of them would tell us about black holes and other exotic aspects of the universe. In this lecture we will discuss various aspects of gravitational waves, from simple analogies that I hope will clarify their basic aspects to the exciting near-future prospects for their detection.

The rubber sheet and other basics

We begin with an analogy that we have used before. We imagine that spacetime is like a rubber sheet that, with no massive objects around, is flat. With a massive object, the sheet is warped. Obviously this has misleading aspects; for example, it unfortunately encourages us to think about a "down" direction, whereas in reality spacetime is warped in all directions around a massive object. In any case, let us now think about *two* massive objects somewhat close to each other. These thus produce two warps in the sheet. If we moved them around each other, their movement would create ripples in the sheet, and the objects would move closer to each other until they finally touched.

This is a decent picture to keep in mind when we think of gravitational waves, at least waves from binaries. In the real situation it is spacetime that ripples, and the gravitational waves mean that the distances between objects (and the relative timing of clocks separated by some distance) is altered periodically as the waves go by. As always, if you are in free fall (say, in a small box just floating along) you will not notice any changes or acceleration because that is *always* true if you act only under the influence of gravity and make measurements over small distances and short times. However, if you measure the distance to distant things, that distance will change.

But why are waves emitted? As you recall, the thing that drove Einstein to come up with general relativity was his desire to have a dynamical theory that could incorporate accelerations (unlike special relativity). The relation to gravity is that Newton's theory is inconsistent with special relativity; specifically, since time doesn't appear in the force equation, it would mean that if the Sun moved, the Earth's orbit would react instantly to the movement instead of after a light travel time (a bit more than eight minutes in this case).

In Einstein's theory, and for that matter in any modern theory of forces and accelerations, the "knowledge" of movement has to be propagated at the appropriate speed, which is the speed of light for gravity and for electromagnetic waves. Thus if we were to jiggle the Sun the spacetime warp around it would move as well, and that movement would propagate outwards at the speed of light. That's a gravitational wave.

But this also gives us some insight into the types of events or sources that could emit gravitational waves. Consider a star that is perfectly spherically symmetric. In Newton's gravity, as well as Einstein's, the gravitational field outside this object is identical to what you would get if you put all the matter at a point at the center of the object. Now suppose you are far away from this object and you measure the gravitational field. Again, it is the same as if all the matter were at the center. Given this, what would happen if the object were to expand in a spherically symmetric way? It *still* has the same gravitational field, so you would not see any change and thus no gravitational radiation would be emitted. If it shrank instead, the same conclusion would emerge. Therefore, expansion or contraction of a spherically symmetric object does not emit any gravitational waves.

This may seem unsurprising until you take it to a limit. Suppose that a massive star were to explode in a spherically symmetric supernova. Most of its matter is flung at high speeds into space, but the spherical symmetry means that *no* gravitational waves are emitted! How about if the star collapsed into a black hole? Again, no gravitational waves if there is spherical symmetry! One consequence of this is that unless there are asymmetric aspects to supernovae, they will be weak emitters of gravitational radiation and will thus have to be close to us to be detectable.

It also turns out that something that is rotationally symmetric around an axis does not emit any gravitational waves if it rotates around that axis. Thus even a rapidly rotating neutron star need not emit any gravitational radiation.

Having eliminated two types of sources that *cannot* emit gravitational waves, what can? There are four categories that are usually considered:

1. Binaries. This is the only category that we know to be strong enough to detect with the next generation of instruments. As we will discuss later, double neutron star systems are known to exist, and other categories (e.g., a binary with two black holes) also almost

certainly exist, but we don't know how common they are. A binary consisting of two supermassive black holes probably forms after a merger between galaxies. All binaries spiral together upon emission of gravitational radiation, so you end up with a binary whose separation decreases and frequency increases with time.

2. Continuous sources. As an example from this category, consider a lumpy rotating neutron star. It is not symmetric around its axis of rotation, so it can emit gravitational waves. It lasts longer than a binary, which might make up for its much smaller expected amplitude.
3. Bursts. Suppose we have a supernova that is not spherically symmetric. This might happen due to turbulence during the collapse, or some off-center recoil (as is inferred from observations of the speed of neutron stars).
4. Stochastic sources. This is actually a description for a situation where we have so many sources with overlapping frequencies that individual ones cannot be distinguished. A mundane example would be the tens of millions of white dwarf binaries in our galaxies with orbital periods of hours. A more exciting, but probably less detectable, example would be gravitational waves from the very early universe.

Binary pulsars

By the mid 1970s enough tests had been made of general relativity that most physicists believed in it. However, most of the tests were not especially high-precision, and some aspects (such as the prediction of gravitational waves) appeared to be out of reach. As we will mention later, starting in the 1960s there had been claims of their direct detection, but with the benefit of hindsight (and even at the time) these claims would have required sources of absurdly great strength.

However, the discovery of pulsars in 1967 had set off a flurry of activity, and by 1974 it was clear that these sources were the best known clocks in the universe. Given that they are such good clocks, it means that they can be used to detect very subtle effects. In particular, if there were to be a pulsar in a binary with another neutron star, there are many effects that could be measured beyond the usual ones. That is, in addition to the radial velocity and orbital period that we mentioned last lecture, we could measure:

- The precession of the pericenter. This is the same effect that was first measured for Mercury. However, neutron star binaries could be much closer to each other than Mercury is to the Sun, so the effect could be much more dramatic.
- The "Einstein delay". For an eccentric binary, when the pulsar is closest to the other neutron star the gravitational redshift from their mutual gravitational well is greatest. In addition, that is the point at which the orbital speed is greatest, hence so is the

magnitude of special relativistic time dilation. This delay varies over orbital phase for an eccentric binary.

- The "Shapiro delay". Suppose that the binary is edge-on to us. When the pulsar is directly between us and its neutron star companion, the radio waves from the pulsar come directly to us. If instead the companion is directly between us and the pulsar, the radio waves from the pulsar have to bend around the companion to get to us, and this takes longer. There is thus a delay that depends on the phase of the orbit. If the orbit is not edge-on but at some arbitrary angle, then the shape of the delay with phase, as well as its magnitude, take on predictable forms.
- Orbital decay. This is what happens due to gravitational radiation. Note that the nature of gravity is that when the system *loses* energy, it becomes more compact and thus the period gets shorter and the orbit becomes faster.

This gives so many extra parameters that can be measured (five more, because the Shapiro delay gives two) that not just the masses of the neutron stars, but the underlying theory of general relativity itself can be tested with high precision. To make it even better, neutron stars are so small compared to their separation that there are no complications with the way that tidal forces act on bigger things.

With this reasoning, in 1974 Professor Joe Taylor of the University of Massachussets started a program to look for binary pulsars using the giant Arecibo Radio Observatory in Puerto Rico. After a few attempts, his student Russell Hulse discovered the first one. Only a few have been seen since, but the result has been that in several important respects general relativity hs been confirmed to better than a part in 1000. For this discovery, Hulse and Taylor won the 1993 Nobel Prize in Physics.

For our purposes, the important point is that the orbital decay of the Hulse-Taylor binary pulsar and others happens at exactly the rate predicted for gravitational radiation in general relativity. This resolves beyond a reasonable doubt that gravitational radiation exists at the level predicted (there are always the unreasonable doubters, of course!). But this evidence is indirect. How could gravitational waves be detected directly, and what is their expected strength?

Ways to detect gravitational radiation

In 1948, an innovative experimenter named Joe Weber joined the physics faculty at the University of Maryland. Weber had been a lieutenant commander in the Navy during World War II, and his engineering expertise was such that he was given his faculty appointment without having yet earned his Ph.D. (he acquired his doctorate in 1951). He was a remarkably original thinker; for example, he was the first person to have the idea of a laser, although other people independently came up with the idea and produced the first working examples and thus got the Nobel Prize.

In the late 1950s he became interested in general relativity, and spent his first sabbatical at Princeton with John Archibald Wheeler learning the subject. Weber realized that the detection of gravitational waves would constitute a strong new test of general relativity, and he started to think about how this might happen. He realized that from a single point it was not possible to see the waves; as indicated above, if you were in a small box in space you would not even realize a wave had passed, because even when a gravitational wave goes by you are under the influence of pure gravity and thus in free fall. However, points separated by some distance react differently to a passing wave, and this can lead to observable effects. After considerable pondering, Weber came up with the two methods that people are pursuing today. The second, laser interferometry, was not feasible when Weber began his experiments in the 1960s, but it is the main current method and we will address it below. The first, the use of resonant bars, was his focus.

To understand resonant bars, we need first to think about resonances. Objects have natural frequencies, and if they are pushed at those frequencies then they will move at a much greater amplitude than at other frequencies. A familiar example involves pushing someone on a swing. The person will naturally swing at some frequency, and if you push in phase with that (i.e., if you push once per swing, thus at the swing's frequency) you can get the person to a good height. If for some reason you pushed randomly, or at a different frequency, the swing would just jiggle back and forth without getting very high.

The point of the bar detectors was that if a bar's natural frequency matched the frequency of a passing gravitational wave, then when the wave passed through the bar it would squeeze and stretch the bar and push the oscillations of the bar to a relatively high amplitude (but see below for how small those amplitudes really are!). Based on instrumental limitations and a very rough estimate of the relevant frequencies, Weber and subsequent experimenters used pure bars (e.g., of aluminum) that have resonant frequencies of about 1000 Hz, i.e., they oscillate about 1000 times per second. This is comparable to the frequency in the last stages of an inspiral between two neutron stars, or to some of the frequencies that might be produced during an asymmetric supernova.

Sure enough, starting in the late 1960s Weber began to announce his discovery of gravitational radiation. Gravitational waves pass through matter as if it isn't there (even much more than neutrinos do!), so you can't focus them or get good directional information. It is therefore more like hearing than seeing, but with some directional knowledge Weber suggested that the waves were coming from the center of our galaxy. This produced a great deal of interest, and other groups constructed their own bars to look but no one could confirm Weber's result.

With the benefit of hindsight we can realize that Weber's detections must have been spurious. For reasonable sources at reasonable distances, a typical amplitude of a wave will mean that the distances between parts of a detector change only by 1 part in 10^{22} or so. For perspective, the Earth is about 10^7 meters in diameter, so such a wave, if it spanned the Earth, would change the Earth's diameter by just 10^{-15} meters, or about the diameter of a proton! Weber's devices could never have detected such weak signals. Could it be that, just once, an extraordinarily improbable but theoretically possible merger event happened really close, so that the amplitude we saw at Earth was much larger than expected? Not really. Weber made many such claims, and certainly not all of them were real! A particularly damaging blow to the credibility of the reports occurred in the mid-1970s, when another scientist sent his bar data to Weber to look for coincidences (where Weber's bar and the other bar would both report the same event). Weber sent back the data with several coincidences marked, suggesting that this strongly confirmed his suggestions. But it turned out that Weber was using Eastern Standard Time, whereas the other scientist was using Universal Time. All the coincidences were thus not real events, and it seems that despite Weber's brilliance as an experimenter, his statistical inexperience was problematic.

I met Weber in 1999, shortly after arriving as a professor at Maryland. Like most in the field, I consider him to be a pioneer, with a remarkable vision, whose drive started the field of gravitational wave detection. I therefore respectfully introduced myself, but he had had too many years of being thought misguided, and he immediately went into a defensive mode in which he announced his newest conception, which would improve sensitivities by a factor of 10^{25}. I felt sad; this was a great man whose fixation had isolated him from the field.

Laser interferometers

Weber's passion drove others to think about ways to detect gravitational radiation. A problem with the bar approach is that it is resonant over just a small range in frequencies. Therefore, a source that missed this frequency (e.g., if the frequency was 950 Hz but the resonance was at 1000 Hz), or one that swept rapidly through frequencies and thus spent little time near the resonance (such as a NS-NS coalescence) would be difficult to spot.

Most of the community has therefore gone instead towards Weber's second concept, which uses another one of his idea: lasers. Lasers have very precisely defined frequencies and their beams spread little with distance, meaning that they can be very intense with little power (consider: would you rather look into a 100 Watt light bulb, or a 5 milliwatt laser?). Light can "interfere" with itself, meaning that the intensity you get when you add light beams does not need to be the sum of the intensities of the individual beams; it could be less (destructive interference) or more (constructive interference). Which happens depends on how the phases of the light line up. If the sources are in phase, the intensity is greater than their sum. If they are exactly out of phase, the intensity is less. This means that the intensity tells you how close the sources are to the same phase.

The key for detection of gravitational waves is that this effect allows you to measure relative distances very precisely. Suppose (as in reality) you set up a system with two pipes for lasers, at right angles relative to each other. Under normal circumstances, suppose that the distances along the pipes are exactly equal to each other, so that a laser sent from the joint in the "L" down either direction, and reflected back by a mirror, comes back with the same phase independent of which pipe it was. The lasers thus constructively interfere with each other. If the distance down one pipe is changed differently from the other by a gravitational wave, then the interference will change. This, plus an enormous amount of technical detail, is the basis behind the Laser Interferometric Gravitational-wave Observatory (LIGO) and similar observatories around the world. These are not quite sensitive enough yet to detect the predicted sources, and they have not made such detections, but within 5 years it is predicted that they will. I am the current chair of the Program Advisory Committee to LIGO, which is exciting because I get to hear updates about their remarkable progress in technology and data analysis.

Templates, numerical relativity, and prospects

One issue for gravitational wave detection that is different from normal electromagnetic detection is that *all* sources of gravitational waves are really weak. In order to detect them, it is therefore important that you have some idea of what they will be like. It's a bit like being at a noisy party, where if you are talking to someone it can help your understanding to see their lips move even if you're not a lip-reader, because it gives you a sense for what you are saying and you can therefore extract meaning more easily from the background of noise.

What really happens is that for a source such as an inspiraling binary, we know from theory and computer simulations how the frequency and amplitude of the signal should change with time. When two black holes get close together and merge, this requires full computer solution of Einstein's nonlinear equations; this has only been possible since 2005, but the progress has been so rapid that more than ten groups can do fully general simulations (with any mass ratio as long as it isn't too extreme, and any spins or orientations). Life is made somewhat easier because general relativity has no absolute mass scale; the inspiral of two 10 solar mass nonspinning black holes is identical except for scale to the inspiral of two 10 billion solar mass nonspinning black holes. Thus templates have been produced that can be matched to the signals obtained with the next generation of detectors.

Our observation of double neutron star binaries that will merge within a few billion years or less has allowed computation of the rate expected per galaxy, and thus the rate expected for the next generation of detectors given the distance to which they will be able to see. There are still many uncertainties, but the best estimates put this in the range of a few to a few hundred detections per year. We don't currently know of any BH-NS or BH-BH binaries, so their rates are much more uncertain, but many scenarios have been put forward (including some by me) that suggest that tens of detections per year would be reasonable.

What would we learn from this, given that binary pulsar timing already tells us that gravitational waves exist? Their direct detection itself will be a significant triumph of our understanding and of technology, and will probably result in a Nobel Prize for the project leaders. From the fundamental physics standpoint, comparison of gravitational radiation waveforms with those predicted from general relativity (and computed using numerical relativity) will provide, for the first time, a test of the predictions of general relativity in the strong gravity regime (recall that our current tests all apply to weak gravity). It would, for example, establish that event horizons exist in a very direct way. It will also give us unique insights into the properties of neutron stars, specifically how big they are for a given mass, which will tell us about a realm of nuclear physics that we can't explore in laboratories. I'm very excited!