13. Gravity Waves

Reading: Thorne, ch. 10. The section on "Bars" (pp. 365-378) is less important than the material before and after, and you don't need to follow the details described in Boxes 10.1, 10.2, and 10.3. Note also that pp. 393-396 are speculations on what gravity wave observatories *might* observe in the future, not a description of what they *have* observed. (Thorne's 1993 speculation that we might have reached this stage by 2007 proved overoptimistic, but maybe by 2017 ...)

Gravity Waves

General Relativity predicts the existence of gravity waves, ripples of spacetime curvature that propagate at c.

Analogous to waves on a rubber sheet.

If a gravity wave passes between two observers, the spatial separation between them oscillates.

The wave is characterized by a direction, a period of oscillation, and an amplitude called the *strain* and denoted h:

$$h = \frac{\Delta d}{d} = \text{fractional change of distance},$$

where Δd is the amount of oscillation produced for observers separated by d.

The energy of the wave is $\propto h^2$.

Sources of Gravity Waves

Gravity waves are produced by accelerating masses.

Most likely strong sources:

- Binary black holes
- Binary neutron stars (or NS-BH binaries)
- Supernova explosions

Widely separated binaries (many $R_{\rm Sch}$ separation) are steady sources, period of wave is orbital period.

As gravity waves carry off energy, orbital separation of binary components shrinks, eventually leading to a merger.

Waves are strongest when sources are close to merging: strong curvature rapidly changing.

A merger produces a short burst of strong gravity waves at the end of a long steady stream of weaker gravity waves.

For *merging* black holes at distance D, the strain is roughly

$$h \approx \frac{1}{5}\frac{R_{\rm Sch}}{D},$$

where $R_{\rm Sch}$ is the Schwarzschild radius of the black holes.

Falls with distance as the wave spreads out.

The characteristic period of the waves from a merger is

$$P \approx \frac{2\pi R_{\rm Sch}}{c} \approx 10^{-3}\left(\frac{M}{10\,M_\odot}\right)\ \text{s}.$$

Detecting Gravity Waves

Strong empirical evidence for gravity waves comes from observations of the Hulse-Taylor binary pulsar, discovered in 1975.

These are two neutron stars (one of which we observe as a pulsar), orbiting each other with an eight-hour period.

The orbit can be measured very precisely by timing the arrival of the radio pulses.

This binary system should be emitting gravity waves and losing energy.

The binary orbit loses energy and shrinks at exactly the rate predicted by GR, to within 1%.

We'd like to detect gravity waves directly and use them as a new tool for observing the universe.

Consider a merging $10M_\odot$ BH binary in our Galaxy.

Strain at a distance of 30,000 light-years is

$$h \approx \frac{1}{5} \times \frac{30 \text{ km}}{(3 \times 10^5 \,\text{km}\,\text{s}^{-1})(3 \times 10^7 \text{s/yr})(3 \times 10^4 \text{yr})} \approx 10^{-17}.$$

Length of a 2-meter bar oscillates by 10^{-17} m, about 1/1000 the diameter of an atomic nucleus.

Amazingly, this level of sensitivity can just about be achieved with a bar detector.

BUT: Black hole mergers are rare, and steady black hole binaries emit weaker waves.

In one year, the closest merging black hole is likely to be at a distance of 300 million light years, 10^4 times further, implying $h \sim 10^{-21}$.

LIGO

The Laser Interferometer Gravitational-Wave Observatory (LIGO) uses two L-shaped laser interferometers (in Louisiana and Washington), with each arm 4 km long.

A laser reflects back and forth between mirrors in each arm roughly 75 times, making the effective length $75 \times 8 = 600$km.

A passing gravity wave would change the length of one arm relative to another, and this change is detected by the interference pattern of the laser light with itself.

For $h \sim 10^{-21}$, the change in path length is 600 km $\times 10^{-21} \sim 10^{-15}$ m, roughly the diameter of an atomic nucleus.

This is approximately the sensitivity of LIGO!

Challenges: Need seismic isolation, powerful lasers, perfect optics, excellent vacuum system.

Because gravity waves travel at the speed of light, the shortest period to which LIGO is sensitive is roughly

$$P_{\text{min}} \sim \frac{600\,\text{km}}{3 \times 10^5 \,\text{km}\,\text{s}^{-1}} \sim 10^{-3}\text{s}.$$

The maximum period to which it is sensitive is $\sim 0.01 - 0.1$s, limited mainly by seismic noise.

LIGO is thus suited to detecting gravity waves from stellar mass black holes or neutron stars that are close to merging, or from the formation of neutron stars in supernovae, which have characteristic periods $\sim 10^{-3}$s.

LIGO began design and construction in 1992 and has recently completed its first "science runs."

These have not yet yielded any clear detections, but the limits from not detecting anything are already mildly interesting.

LIGO's sensitivity will be substantially advanced over the next few years.

At that point, we expect it to start detecting sources: merging neutron stars and black holes in relatively nearby galaxies ($D < 300$ million light years), and possibly "surprises" such as gravity waves from asymmetric stellar explosions.

LISA

To get to longer periods, we need to go to space.

The Laser Interferometer Space Antenna is a planned mission (presently joint U.S./European, though it may become European only) that would use 3 satellites in solar orbit, separated by 5 million km.

Laser interferometers would measure the separations of the satellites with a precision of 10 trillionths of a meter (0.01 nano-meters), providing sensitivity to a strain

$$h \sim \frac{10^{-11}\,\mathrm{m}}{5 \times 10^{9}\,\mathrm{m}} \sim 10^{-21}.$$

Because of larger separation, LISA is sensitive to longer period waves,

$$P_{\min} \sim \frac{5 \times 10^{6}\,\mathrm{km}}{3 \times 10^{5}\,\mathrm{km\,s^{-1}}} \sim 10\mathrm{s}.$$

The full period range for LISA is roughly 10 sec - 10^4 sec.

For merging black holes, the minimum period corresponds to $M \sim 10^6 M_\odot$.

The sensitivity of LISA is enough to measure black hole mergers in this mass range with high precision out to the farthest reaches of the observable universe, 10 billion light years away.

LISA could also measure *steady* gravity waves from stellar mass binaries (black holes, neutron stars, white dwarfs) with periods of ~ 1000 seconds.

Very optimistically, LISA could be launched some time in the 2020s.

This schedule is driven partly by technology, but mostly by money; it would cost several billion dollars, and NASA, at least, is backing off of expensive missions these days.

Information from gravity waves

Gravity wave detection should open a new window on the universe, like radio and X-ray astronomy did decades ago.

Gravity waves are most likely to tell us about violent events involving strong gravity.

With a very high-precision measurement of gravity waves from a black hole merger, one should in principle be able to determine:

- Location on the sky.
- Distance.
- Mass of the two black holes.
- Direction and elongation of their orbit.
- Spins of the two black holes.

These measurements would allow remarkable new tests of General Relativity and new insights into black holes and their effects.

Gravity wave astronomy could become one of the most exciting frontiers of astronomy over the next 10-20 years.