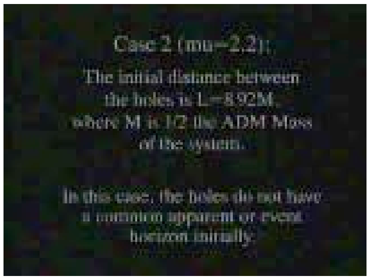
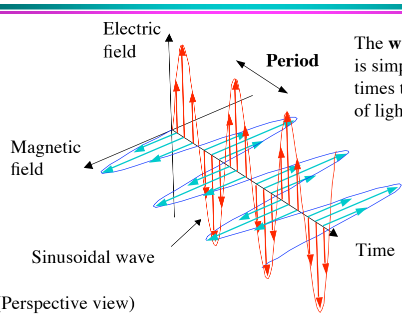
Astronomy 102.
November 10, 2005.



Light.

- Practically all of the information humanity has collected about celestial objects has arrived in the form of light.
  - Light, like every other elementary form of energy, exhibits both wave and particle properties, depending upon what sort of experiment is being performed on it.
  - In its **wave** guise, it consists of waves of electric and magnetic fields.
  - This was first inferred by Maxwell in the 1860s. By writing the Maxwell equations for space that contains no electric charges or currents, and combining the results, equations are generated for the electric and magnetic field that have **sinusoidal** waves of electric and magnetic field as their solution.

A "plane wave" of light: electric and magnetic fields at a point in space, as function of time.



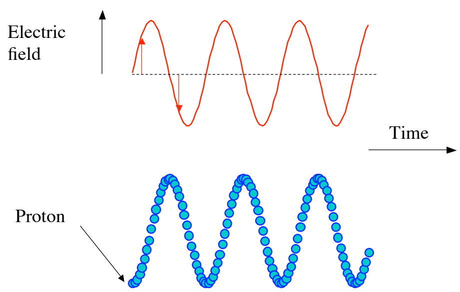
The **wavelength** is simply the period times the speed of light.

(Perspective view)

Some properties of light.

- The ripples of electric and magnetic field that comprise light travel through empty space at the speed of light (of course).
- An electric field exerts a force on electric charges, in the direction of the field. A magnetic fields exerts a weaker force on a moving charge, in the direction perpendicular to both the field and the velocity.
  - Individual electric charges -- like protons or electrons -- will accelerate in response to a passing light wave.
- In turn, if charges are accelerated -- perhaps by some other force -- they emit light.
- Light represents the transport of electromagnetic energy through empty space, without involving the transport of electric charges or currents.

Snapshots of a proton's position when light is passing by.



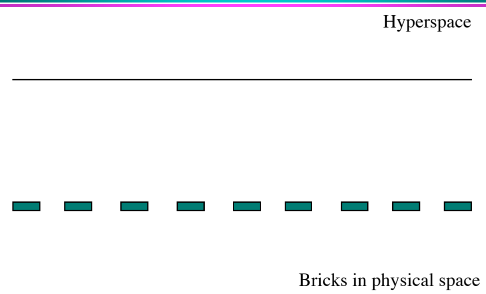
Gravitational radiation (a.k.a. gravity waves).

- One of the results Einstein obtained from his new general theory of relativity was that there should be a gravitational analogue of light.
  - By writing the Einstein field equations for space-time that contains no masses, and combining the results, equations are generated for the gravitational field (or equivalently the curvature of space-time) that have sinusoidal waves of gravitational field (or curvature) as their solution.
  - These waves should propagate through empty space-time at the same speed as light does.
  - Einstein noted that the effects of such a wave would be quite weak, though, and doubted that gravitational radiation would ever be observed.

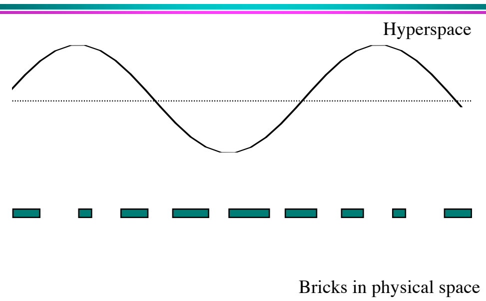
Some properties of gravitational radiation.

- A gravitational field exerts force on masses, in the direction of the field. Alternatively, one can think of this as changing curvature of space-time, leading to motion of masses.
  - Space-time will warp (mass will accelerate) in response to a passing gravity wave.
- In turn, if space-time is warped (or masses are accelerated) gravitational radiation is produced.
- Gravitational radiation represents the transport of gravitational energy through empty space, without involving the transport of (rest) masses.
- Note the direct analogy of gravity waves and light, and of masses and electric charges/currents.

Gravitational radiation as seen in physical space.



Gravitational radiation as seen in physical space.



Black holes and gravitational radiation.

- As we have seen, space (and time) are warped strongly near strong sources of gravity. In particular, space is stuck, and time is stopped, at any event horizon.
  - Thus: rotation of a black hole horizon causes nearby space to rotate as well, as we've seen.
  - Thus: rapid changes in the size or shape of a black hole can generate gravitational radiation. The effect is often likened to ripples propagating through space-time, and in turn to the ripples produced by throwing a rock in a pond.
- First example: stellar collapse and formation of a black hole, showing an embedding diagram of the equatorial plane.

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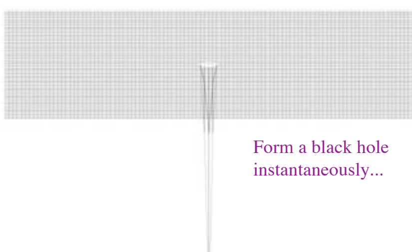
Generation of gravitational radiation by stellar collapse (view from hyperspace).



Form a black hole instantaneously...

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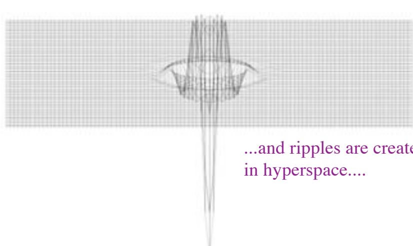
Generation of gravitational radiation by stellar collapse (view from hyperspace).



...and ripples are created in hyperspace....

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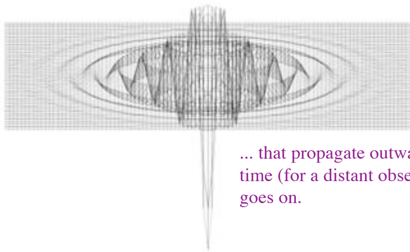
Generation of gravitational radiation by stellar collapse (view from hyperspace).



... that propagate outwards as time (for a distant observer) goes on.

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Mid-Lecture Break.

Hanford Observatory

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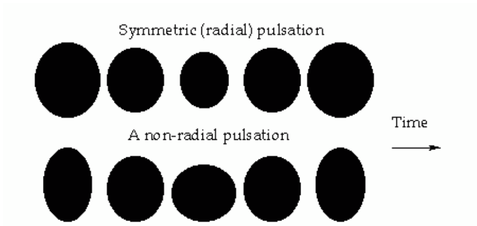
Black hole pulsation and gravitational radiation.

Black hole horizons can pulsate, like some stars do, and like bells do when you ring them.



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Black hole pulsation and gravitational radiation.

- Event horizons are easily "rung" when they are formed, or when the black hole accretes a substantial lump of mass.
- **Simulations**: the embedding diagram of the equatorial plane of a distorted black hole, showing emission of gravity waves. (By Ed Seidel *et al*., NCSA/U. Ill. Urbana-Champaign.)

http://www.ncsa.uiuc.edu/Cyberia/NumRel/MoviesEdge.html

Black hole pulsation and gravitational radiation.

- Some of the incident gravitational waves are quickly swallowed by the black hole, which then begins regular oscillations, generating waves as it vibrates. With each vibration of the black hole, a new lobe of gravitational waves is formed. By measuring the waves emitted by a black hole, physicists will be able to determine not only the existence, but also the mass of a black hole.

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Black hole - black hole collision and gravitational radiation.

- The most energetic source of gravitational radiation hitherto conceived is the coalescence of two black holes.
- **Simulation:** embedding diagrams (in 2-D and 3-D) for the head-on collision and coalescence of two equal-mass black holes. (By Ed Seidel *et al*., NCSA/ U. Ill. Urbana-Champaign.)

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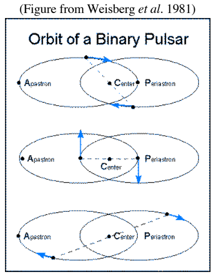
Discovery of gravity waves: The Hulse-Taylor binary pulsar.

- In the 1970s, Princeton professor Joe Taylor and his graduate student Russell Hulse discovered and observed extensively a binary pulsar, now known as PSR 1913+16.
  - The binary pulsar, as its name implies, consists of two neutron stars revolving around each other.
  - Pulses can be timed with exquisite accuracy. The pulse arrival times have a delay or advance resulting from the orbital motion.
  - With high-precision pulse timing, Hulse and Taylor were able to derive the size of the orbit, the masses of the stars, and their velocities very accurately. By watching for a long time, they observed that the orbit is **shrinking**.

Discovery of gravity waves: The Hulse-Taylor binary pulsar.

- The pulsar and its companion both follow elliptical orbits around their common center of mass. Each star moves in its orbit according to Kepler's Laws; at all times the two stars are found on opposite sides of a line passing through the center of mass. The period of the orbital motion is 7.75 hours, and the stars are believed to be nearly equal in mass, about 1.4 solar masses. As shown in the figure here, the orbits are quite eccentric. The minimum separation at *periastron* is about 1.1 solar radii; the maximum separation at *apastron* is 4.8 solar radii.

(Figure from Weisberg *et al.* 1981)



http://astrosun.tn.cornell.edu/courses/astro201/psr1913.htm

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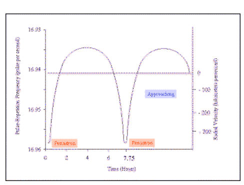
Discovery of gravity waves: The Hulse-Taylor binary pulsar.

- The pulse repetition frequency, that is, the number of pulses received each second, can be used to infer the radial velocity of the pulsar as it moves through its orbit. When the pulsar is moving towards us and is close to its periastron, the pulses should come closer together; therefore, more will be received per second and the pulse repetition rate will be highest. When it is moving away from us near its apastron, the pulses should be more spread out and fewer should be detected per second.



(Figure from Weisberg *et al.* 1981)

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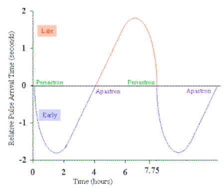
Discovery of gravity waves: The Hulse-Taylor binary pulsar.

- The pulsar arrival times also vary as the pulsar moves through its orbit. When the pulsar is on the side of its orbit closest to the Earth, the pulses arrive more than 3 seconds earlier that they do when it is on the side furthest from the Earth. The difference is caused by the shorter distance from Earth to the pulsar when it is on the the close side of its orbit. The difference of 3 light seconds implies that the orbit is about 1 million kilometers across.



(Figure from Weisberg *et al.* 1981)

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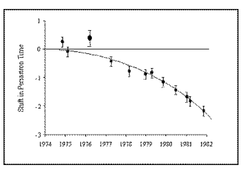
Discovery of gravity waves: The Hulse-Taylor binary pulsar.

- In 1983, Taylor and collaborators reported that there was a systematic shift in the observed time of periastron relative to that expected if the orbital separation remained constant. In the diagram shown here, data taken in the first decade after the discovery showed a decrease in the orbital period as reported by Taylor and his colleagues of about 76 millionths of a second per year. By 1982, the pulsar was arriving at its periastron more than a second earlier than would have been expected if the orbit had remained constant since 1974.



(Figure from Weisberg *et al.* 1981)

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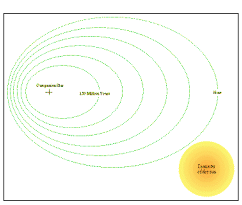
Discovery of gravity waves: The Hulse-Taylor binary pulsar.

- Relativity predicts that the binary system will lose energy with time as orbital energy is converted to gravitational radiation.
- The pulsar's orbit is shrinking with time as shown in this diagram; currently, the orbit shrinks by about 3.1 mm per orbit. The two stars should merge in about 300 million years from now.
- Such a merger might produce strong enough gravitational radiation to be detected by instruments like the Laser Interferometer Gravitational-Wave Observatory.


(Figure from Weisberg *et al.* 1981)

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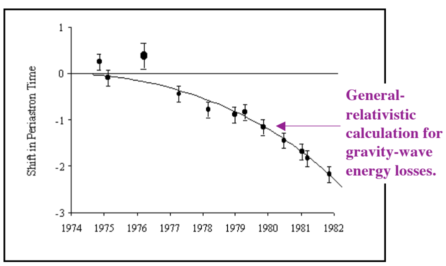
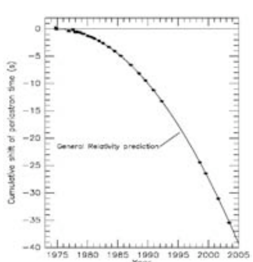
Discovery of gravity waves: The Hulse-Taylor binary pulsar.

- Hulse and Taylor calculated the gravitational-radiation loss expected from general relativity, for the stellar masses, orbital size and speed.
- The GR result is in precise agreement with their measurements.
- This observation therefore constitutes the discovery of gravitational radiation, and an important experimental verification of general relativity.
- The 1993 Nobel Prize in Physics went to Hulse and Taylor for this work.

Discovery of gravity waves: The Hulse-Taylor binary pulsar.



The Hulse-Taylor binary pulsar: adding more data.

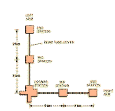


Direct detection of gravitational radiation.

- How can we detect gravity waves directly?
  - **Bar detectors:** make very precise length measurements of a solid bar, which will stretch back and forth when a gravity wave passes by, as the bricks in one of our previous pictures do.
    (Obsolete, replaced by ...)
  - **Laser interferometers**: ultra-precise "bar-length" measurements, in principle capable of bypassing some of the limitations of the ordinary bar detectors.
    - LIGO (the Laser Interferometer Gravity-wave Observatory), based upon this technology, is taking data.

Direct detection of gravitational radiation.

- Unfortunately, gravity waves from distant or ordinary processes *are* as weak as Einstein thought, and we are probably still many years (decades?) away from the direct detection of gravity waves by instruments like LIGO.



All done for today!
See you on Tuesday!

- Do not forget:
  - No homework due this week!
  - Exam # 2 will be held on Thursday November 17, and covers the material discussed in Lecture 11 - Lecture 18.

NGC 7635: The Bubble Nebula
Credit & Copyright: Russell Croman.