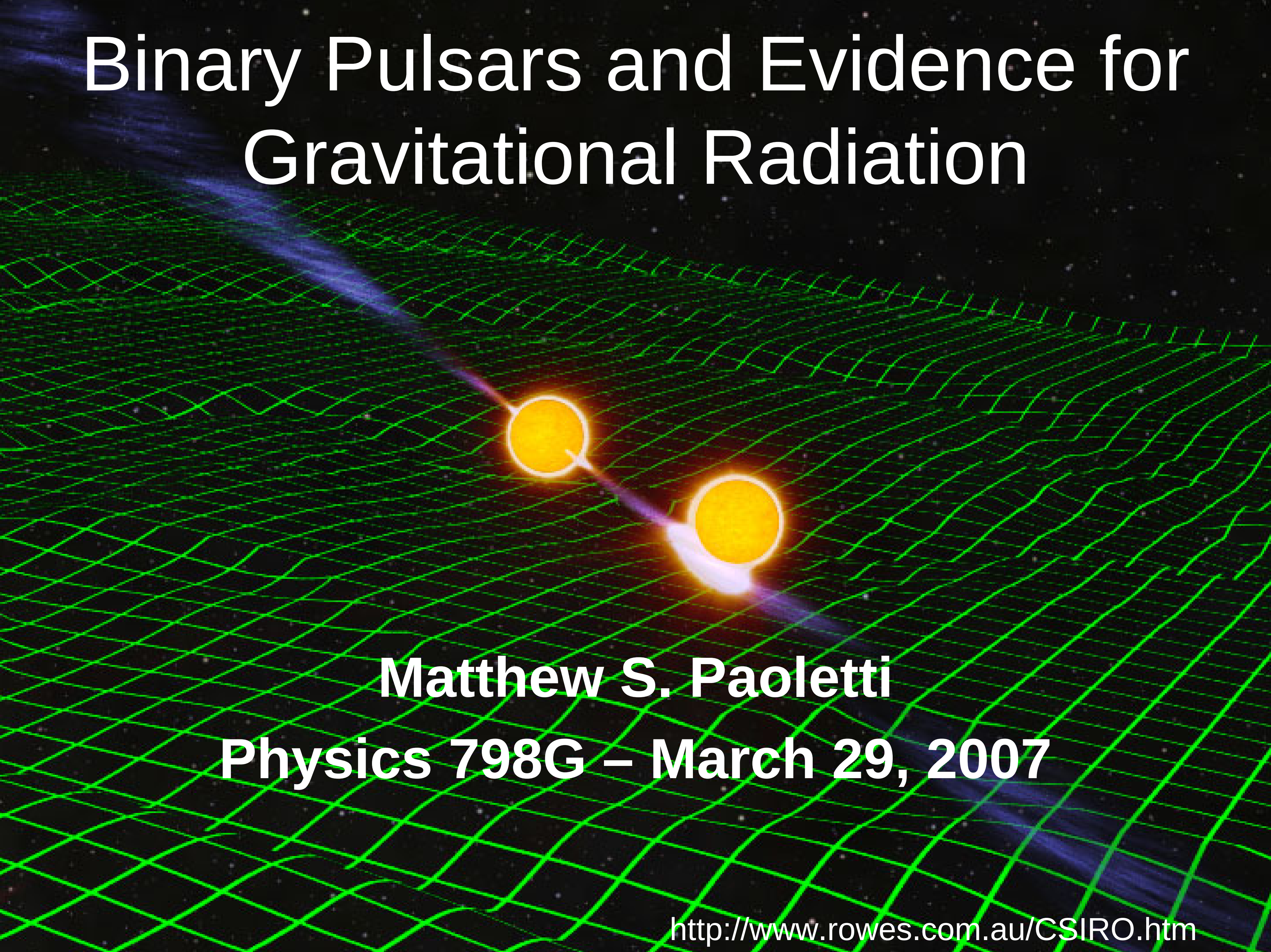

Binary Pulsars and Evidence for Gravitational Radiation

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http://www.rowes.com.au/CSIRO.htm

Motivation

- Three classical tests of GR
  – Bending of light as it passes the sun
  – Gravitational redshift
  – Precession of perihelion of Mercury

- However, these interactions restricted to the weak-field, slow-motion interactions present within solar system

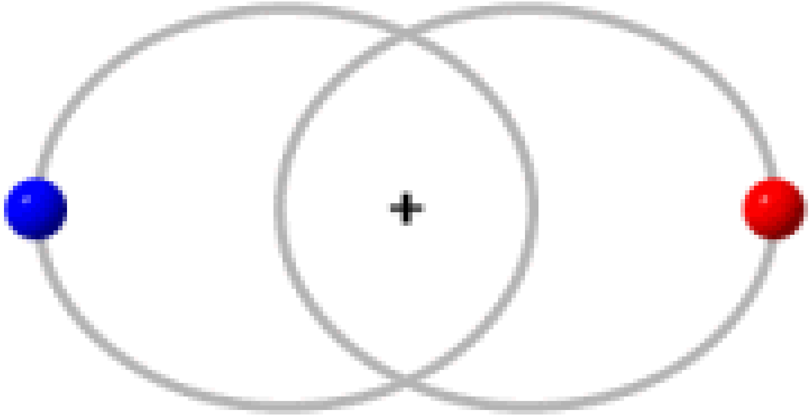
Motivation

- In weak-field, slow-motion limit nonlinear and gravitational radiation effects are negligible
- Post-Newtonian effects insignificant and barely detectable
- Classical tests do not provide sufficient test bed for competing theories of gravity

- Gravitational radiation predictions do differ among theories of gravity, but need a significant source of gravitational radiation

Binary Pulsars

- Composed of at least one pulsar and a companion massive object
- Pulsar regularly emits detectable pulses of radiation – provide extremely stable clocks



http://commons.wikimedia.org/wiki/Image:Doublesystar.gif

Binary Pulsars

- Masses of two bodies on order of solar mass
- Rapidly orbit each other

Binary pulsars go beyond the weak-field, slow-motion interactions experimentalists were restricted to prior to their discovery

Objective

Use the stable “clocks” of binary pulsars to indirectly measure gravitational radiation emission to test theories of gravity in their relativistic limits

Discovery of First Pulsar

- Discovered in 1967 by Burnell and Hewish
- Team found a regular signal of pulsed radiation with a period of roughly a few seconds
- The team determined the radiation source was extraterrestrial

What could possibly be the source of such a perfect signal?

Discovery of First Pulsar

- Team dubbed the source of radio waves “LGM-1” for “Little Green Men”

http://www.igougo.com/travelcontent/

Discovery of First Pulsar

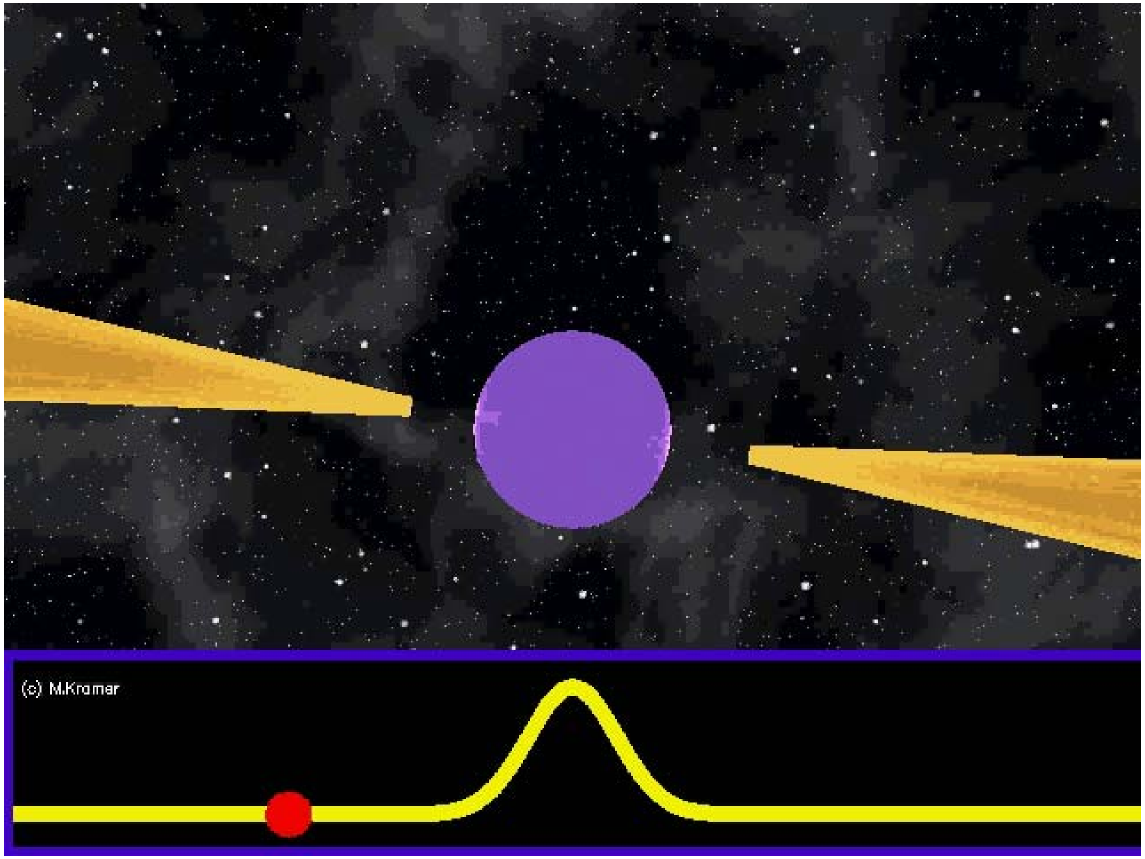
- Later determined source of radiation was a rapidly rotating, highly magnetized neutron star
- Radiation mechanism still not understood:

"Pulsars are a physicist's dream come true. They are made of the most extreme matter that we know of in the Universe, and their highly stable rotation makes them super-precise cosmic clocks - but, embarrassingly, we do not know how these clocks work."

http://www.pparc.ac.uk/Nw/rel241.asp?Tx=1

Pulsar Emission

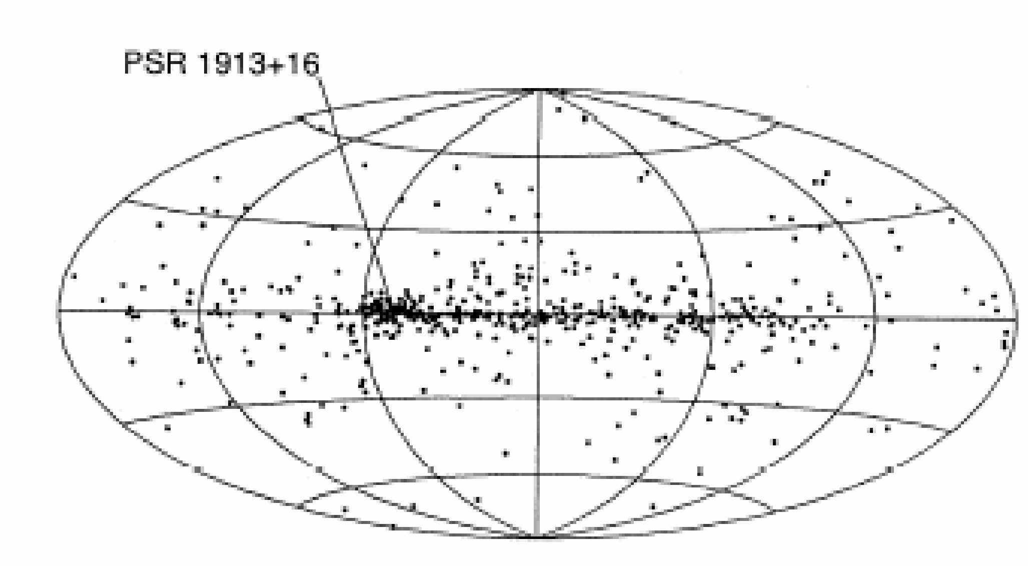
- Pulsar behaves like a lighthouse, emitting a finite cone of light that rotates
- Light comes in strong, short pulses allowing them to serve as clocks



http://www.jb.man.ac.uk/~pulsar/doublepulsarcd/

Galactic Map

- As of July 1994, 558 pulsars had been located within the galaxy
- Image shows celestial map in Galactic coordinates



J.H. Taylor, *Rev. Mod. Phys.* **66**, 711 (1994)

Discovery of First Binary Pulsar

- After discovery of first pulsar, search for more ensued by Hulse and Taylor using 305 m radio telescope at Arecibo Observatory in Puerto Rico

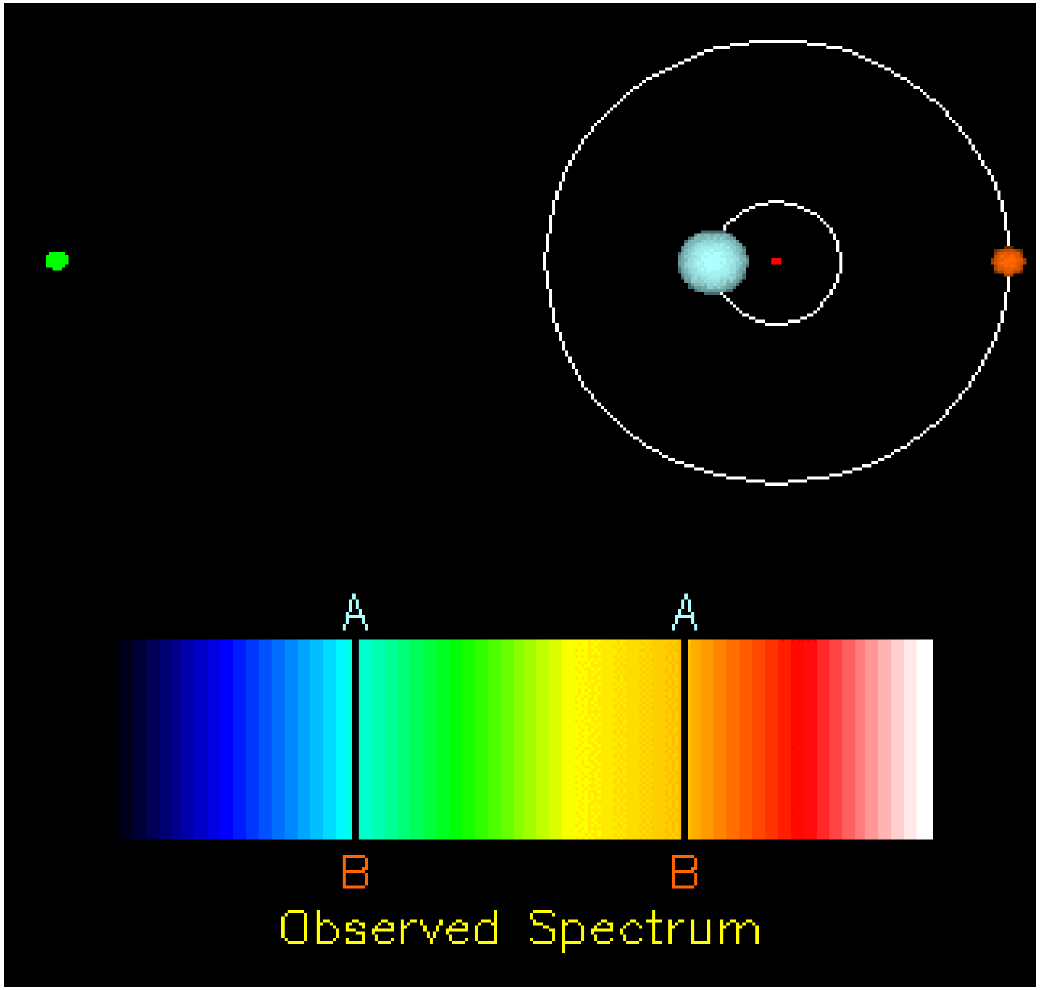
http://burro.astr.cwru.edu/Academics/Astr201/Telescopes/arecibo.jpg

Discovery of First Binary Pulsar

- Team found 40 pulsars prior to PSR 1913+16
- Sought to measure period to within ± 1 μs
- Impeded by apparent changes in period of up to 80 μs from day to day
- At times period changed 8 μs over 5-minute observation
- Largest changes in other pulsars on order of 10 μs per year, typical changes many orders of magnitude lower

Discovery of First Binary Pulsar

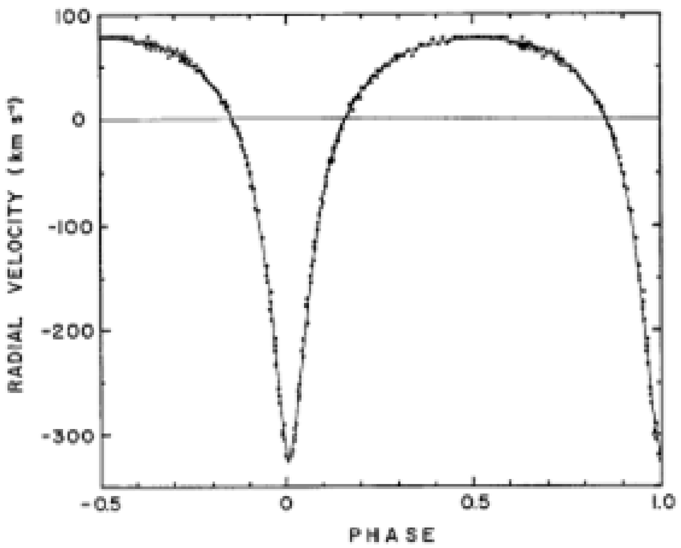
- Doppler shifts produced by orbital motion explained observed period changes (analogous to spectral line shifts)



http://ircamera.as.arizona.edu/NatSci102/NatSci102/movies/spcbin_an.gif

Discovery of First Binary Pulsar

- From Doppler shifts radial velocity determined
- Period and eccentricity of orbit:
  - $P_b = 27908 \pm 7$ s
  - $e = 0.615 \pm 0.010$
- Taking orbit into account, period of pulsar determined to be an extremely stable 59 ms



R.A. Hulse and J.H. Taylor, *Astrophys. J. Lett.* **195**, L51 (1975)

Gravitational Radiation

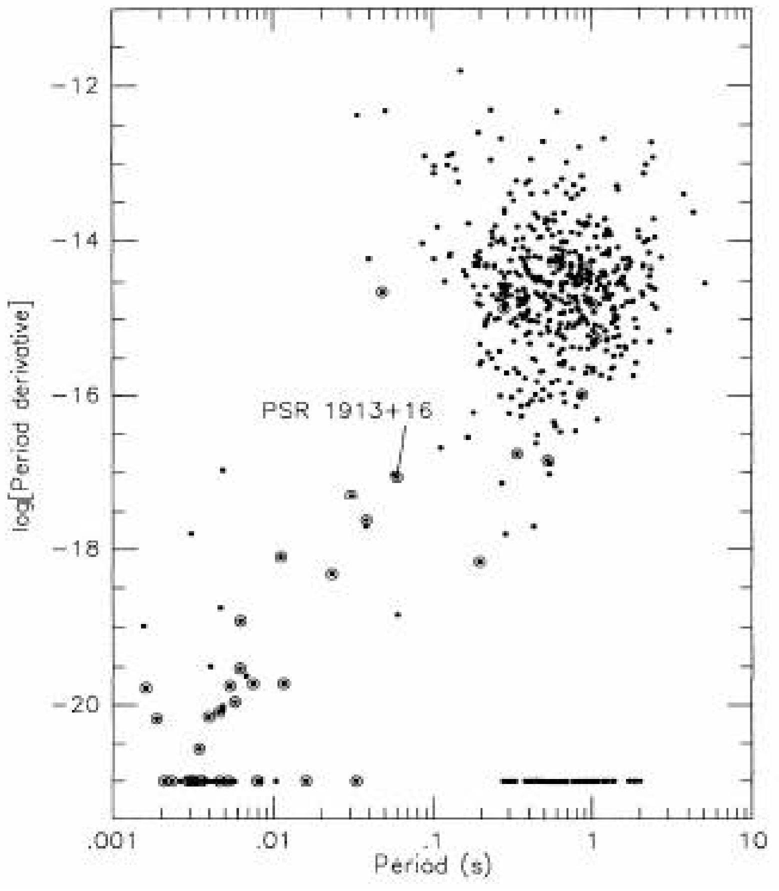
- General relativity and competing theories predict that orbiting massive bodies should emit quadrupolar gravitational radiation

- Gravitational radiation carries energy and angular momentum away from the system

These losses produce decrease in orbital period and eccentricity

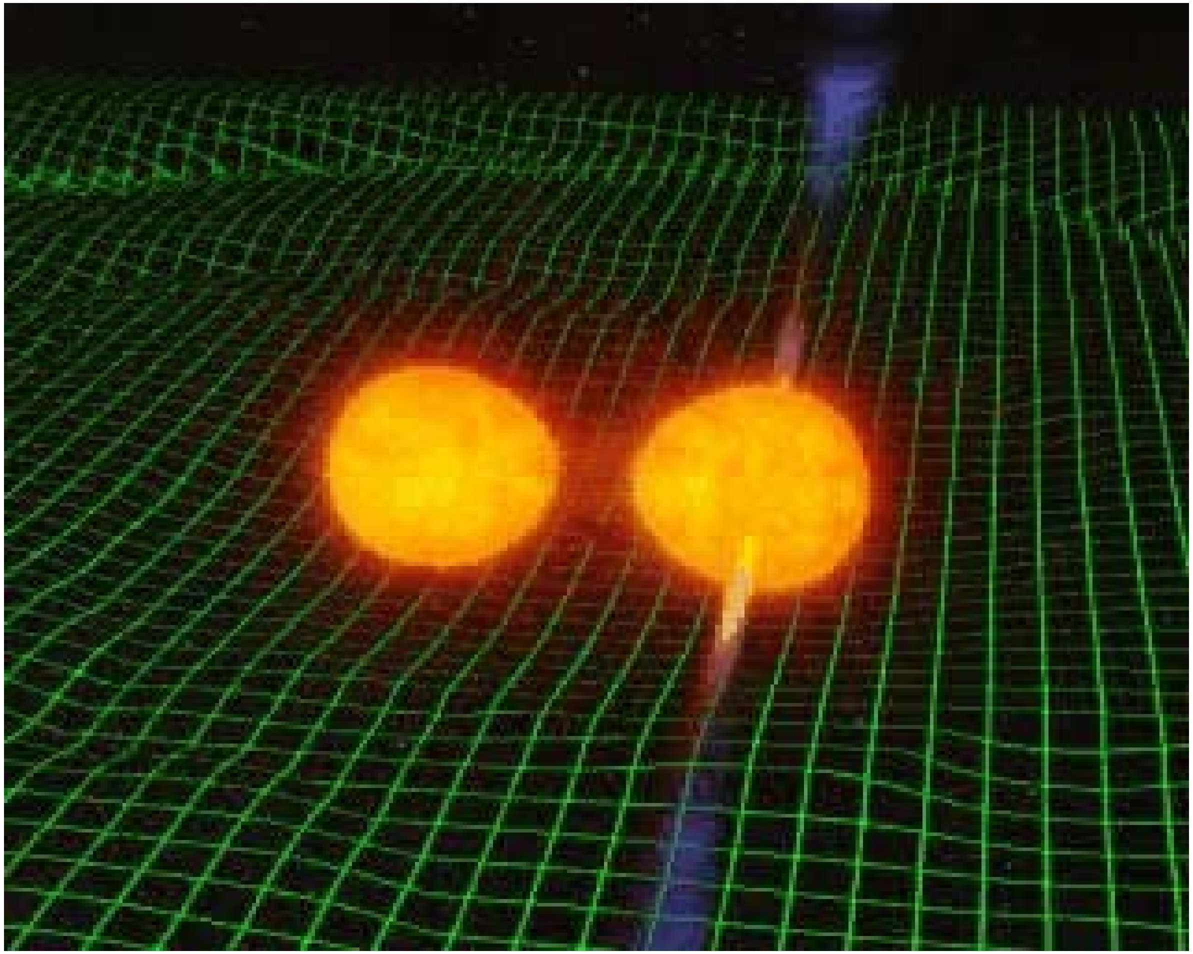
Gravitational Radiation

- Decay of orbital period is indirect test of predictions for gravitational radiation emission
- Spin-down rates span nine orders of magnitude, thereby spanning several regimes



J.H. Taylor, *Rev. Mod. Phys.* **66**, 711 (1994)

Merger of Binary and Companion



http://www.jb.man.ac.uk/~pulsar/doublepulsarcd/

Decay of Binary Orbit

- General relativity predicts that decay of orbital period is given by:

$$\dot{P}_{b,GR} = -\frac{192\pi G^{5/3}}{5c^5}\left(\frac{P_b}{2\pi}\right)^{-5/3}(1-e^2)\times$$

$$\left(1+\frac{73}{24}e^2+\frac{37}{96}e^4\right)m_p m_c\left(m_p+m_c\right)^{-1/3}$$

- Notice, it is always negative (as expected)
- Becomes more negative with time implying flux of radiation increases with time

Masses are free parameters and need to be determined by other measurements

Determination of Masses

- Non-relativistic analysis yields five orbital parameters
- Relativistic analysis produces another three

Measured Orbital Parameters for B1913+16 System

Fitted Parameter	Value
$a_p \sin i$ (s)	2.3417725 (8)
e	0.6171338 (4)
T_0 (MJD)	52144.90097844 (5)
P_b (d)	0.322997448930 (4)
ω_0 (deg)	292.54487 (8)
$\langle\dot{\omega}\rangle$ (deg/yr)	4.226595 (5)
γ (s)	0.0042919 (8)
$\dot{P}_b$ (10^{-12} s/s)...	−2.4184 (9)

J.M. Weisberg and J.H. Taylor, *Binary Radio Pulsars ASP Conference Series,* 1 (2004)

Determination of Masses

- Orbit and masses may be fully specified by first seven orbital parameters, eighth over determines system and serves as test bed of theories

General Relativity must be assumed correct to place restrictions on masses

- Assuming GR, restrictions on masses appear as curves or bands in companion mass versus pulsar mass parameter space

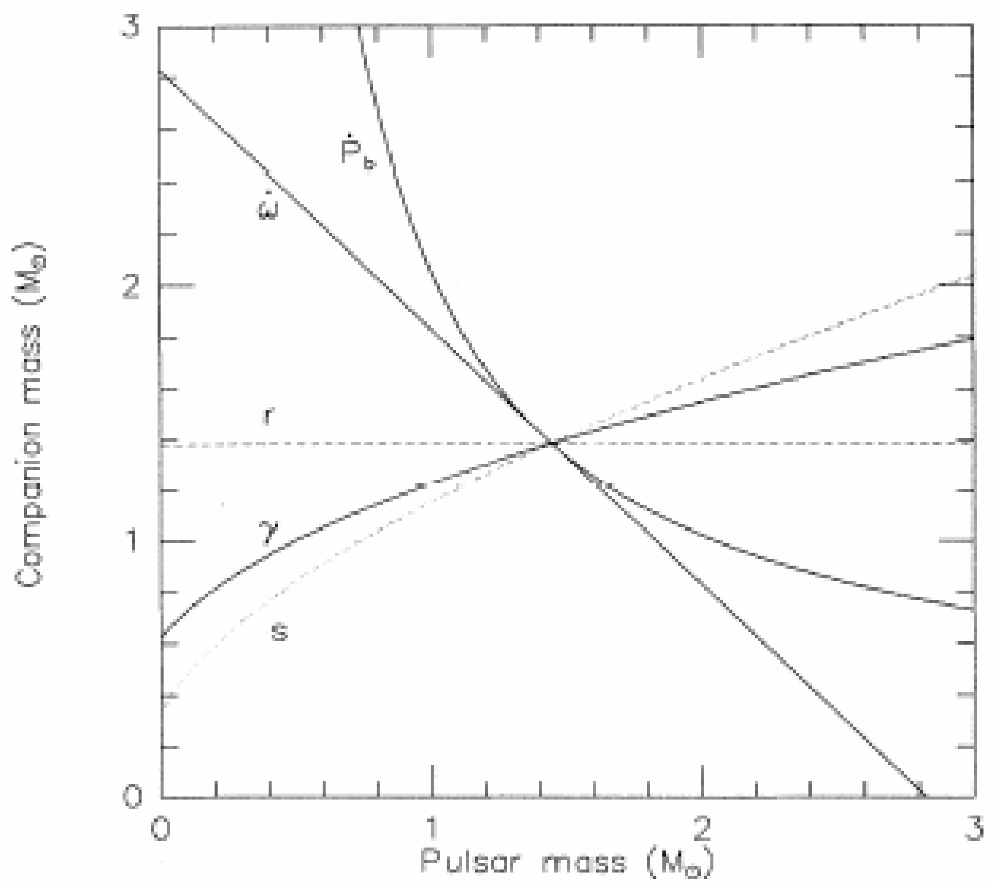
Determination of Masses

- Intersection of curves at single point precisely determines masses:

$m_1 = 1.4414 \pm 0.0002$

$m_2 = 1.3867 \pm 0.0002$

times the mass of the sun



J.H. Taylor, *Rev. Mod. Phys.* **66**, 711 (1994)

Evidence for Gravitational Radiation

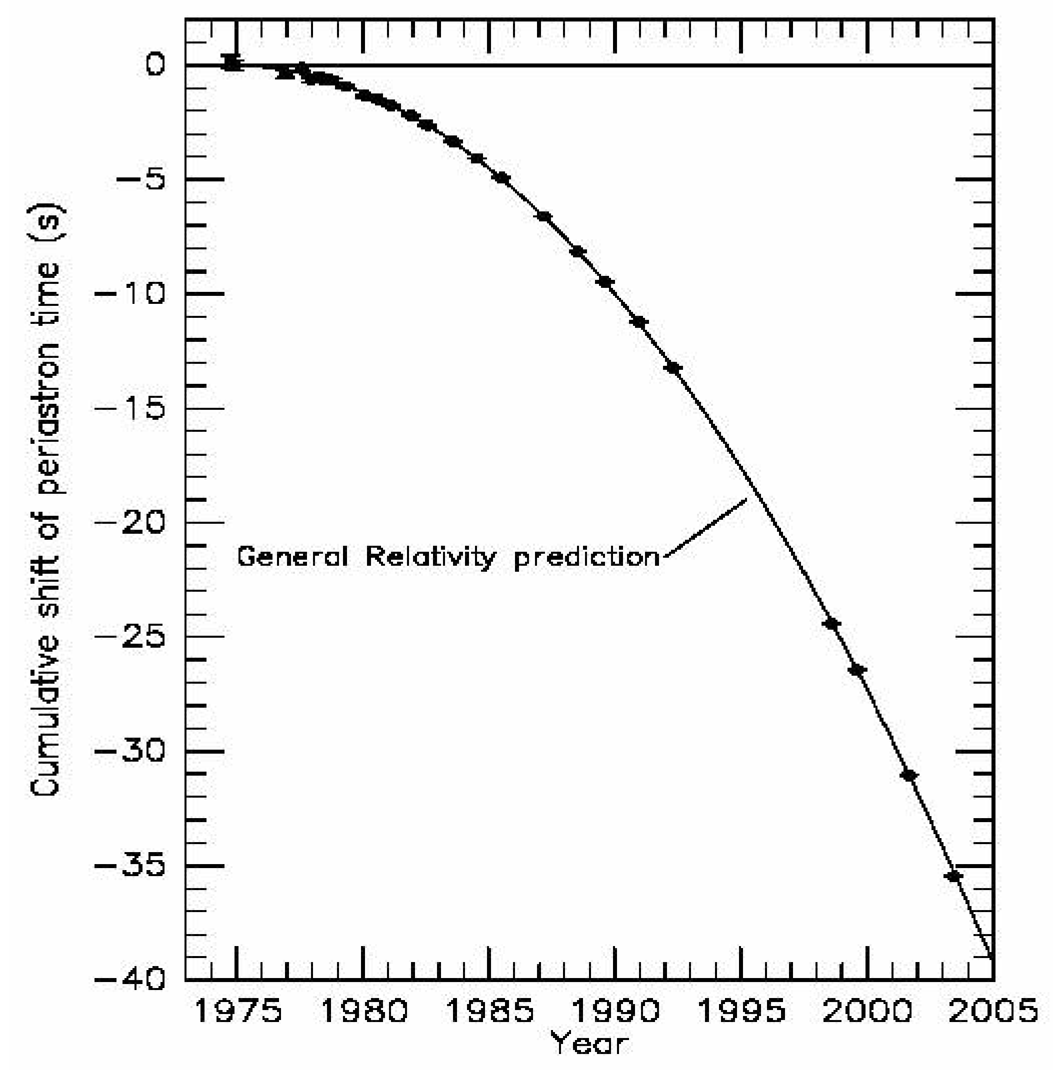
- Knowing the masses, GR can predict the decay of the orbit and may be compared to observed value

$$\frac{\dot{P}_{b,corrected}}{\dot{P}_{b,GR}} = 1.0013 \pm 0.0021$$

- Agree at the $(0.13 \pm 0.21)\%$ level

Evidence for Gravitational Radiation

- Orbital decay has been observed and compared to GR prediction for over 30 years



Conclusions

- Binary pulsar PSR 1913+16 enables tests of GR in strong-field, rapid-motion limit
- Observations of orbital decay confirm the GR prediction of gravitational radiation emission

Observed orbital decay is in good agreement *only* with GR

- Predictions of alternate, competing theories conflict strongly with observations presented here

Conclusions

- Despite repeated experimental verifications of GR, theory is not quantum mechanical
- Universe appears to be quantum mechanical, so GR cannot be final theory

But, any new theory of gravity will have to asymptote to GR in a wide range of limits to agree with experiment

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