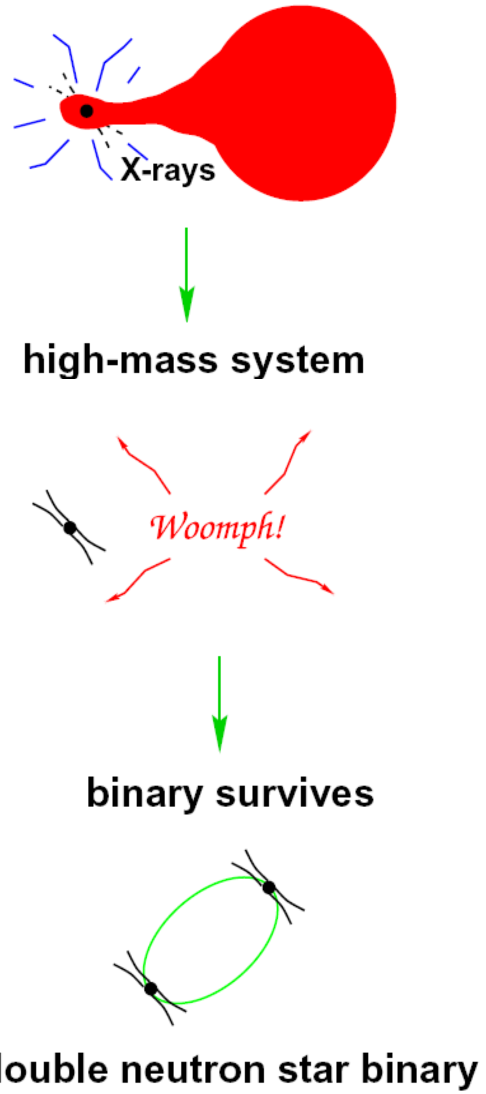
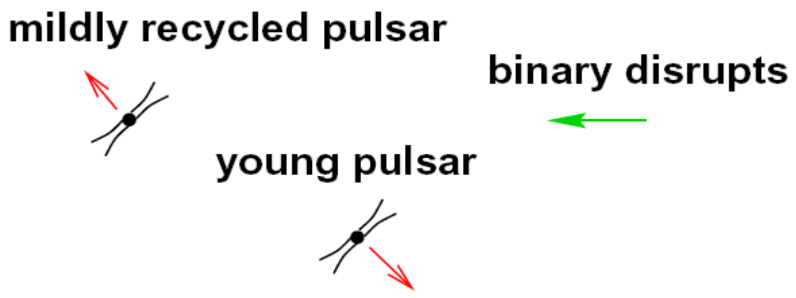
Pulsars and Supernovae II

10. CASE STUDY:
THE DOUBLE PULSAR SYSTEM
PSR J0737-3039A / B

Lecture 8 revision: Evolution of binary systems

- If the system is a high-mass X-ray binary (HMXB), the companion will quickly form a supernova.
- If the binary system survives, we have a double neutron star binary system. Eccentricity is generally large.

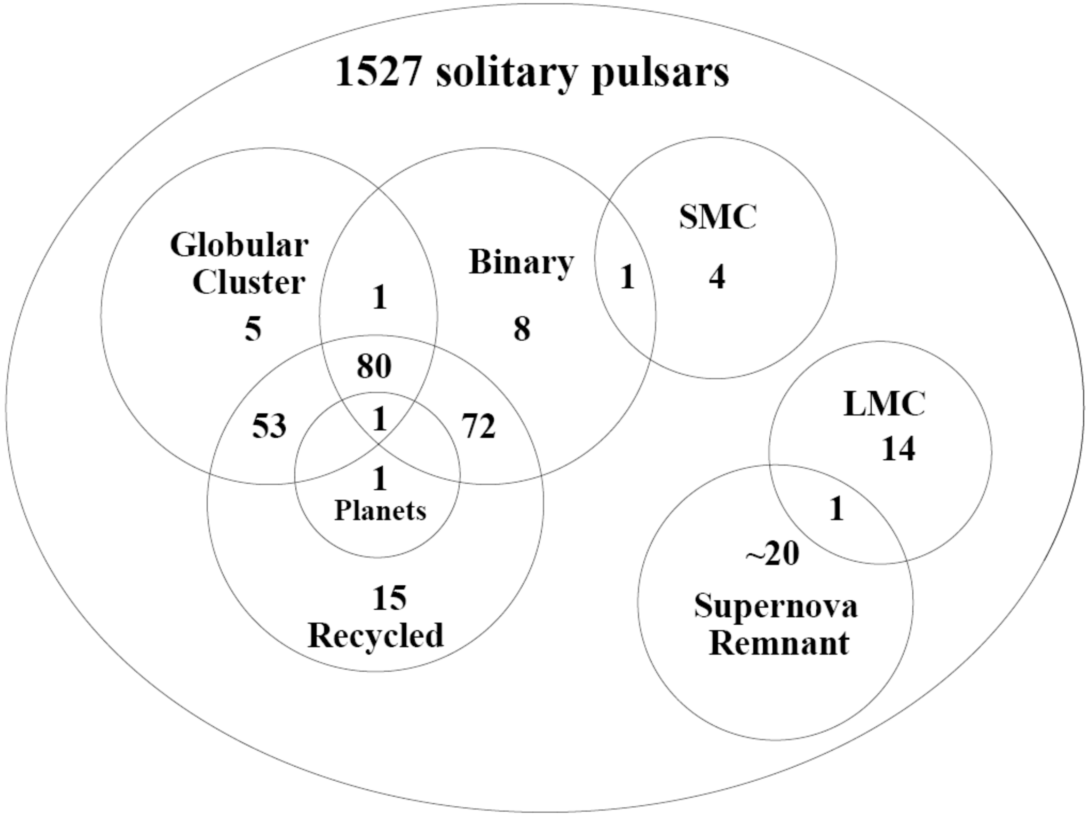




- If the binary system is disrupted (as seems to be common) we have two free pulsars -- one young and the other mildly recycled.

Background

- Only about 10% of known pulsars are millisecond pulsars (MSPs), but about 80% of these are in binary systems.



Lorimer 2008

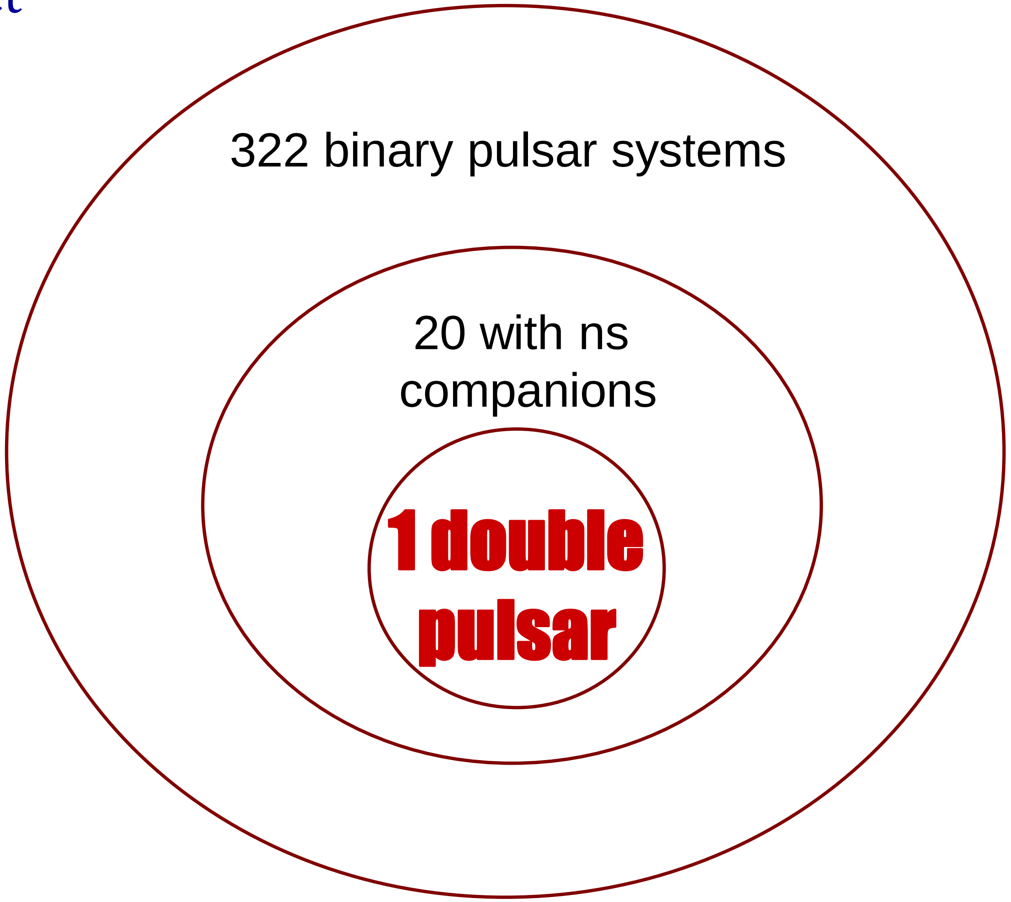
Background

- Just one binary system is known that comprises TWO pulsars, the double pulsar system J0737-3039.

- ns-ns systems can be very compact resulting is short orbital periods, and large rates of change of Doppler shift, making them hard to find.

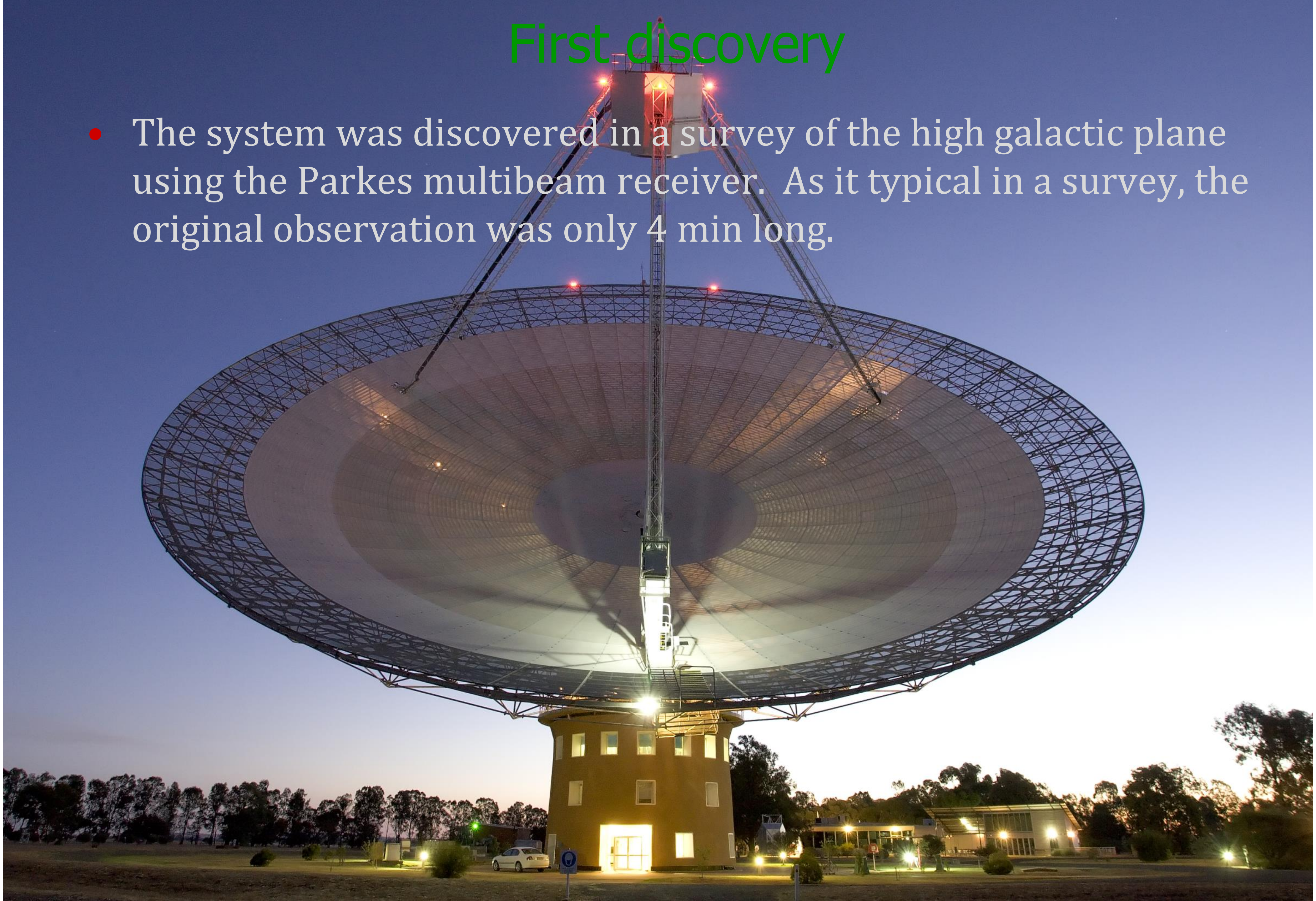
- All these ns-ns systems are relativistic (in the sense that GR corrections are important), including both the Hulse-Taylor pulsar PSR B1913+16 and the double pulsar system J0737-3039.

As of 2021…



First discovery

- The system was discovered in a survey of the high galactic plane using the Parkes multibeam receiver. As it typical in a survey, the original observation was only 4 min long.



First discovery

- At first, only one pulsar was seen in the binary system – a 22.7 ms pulsar (now) designated J0737-3039A. The system is the most relativistic known.

- It is in a short-period orbit (2.4 h) and is therefore relatively close to merger with its companion (85 Myr). Its first claim to fame was that this increased the statistical estimate of the ns merger rate in the Galaxy.

- This was important because in turn it increased the probability of detecting gravitational waves from coalescing neutron stars (now *p*=1!)

An increased estimate of the merger rate of double neutron stars from observations of a highly relativistic system

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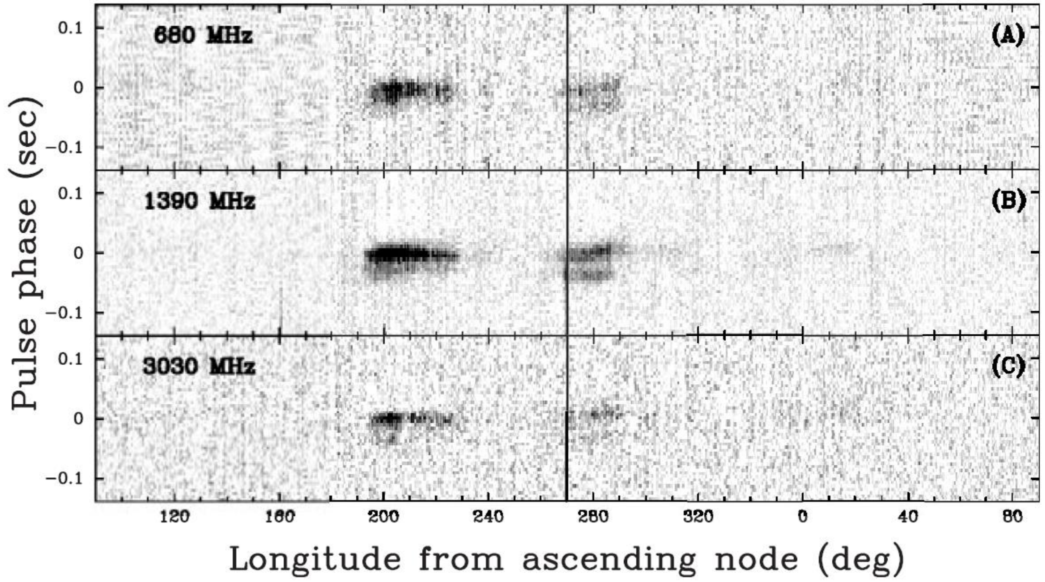
The merger[1] of close binary systems containing two neutron stars should produce a burst of gravitational waves, as predicted by the theory of general relativity[2]. A reliable estimate of the double-neutron-star merger rate in the Galaxy is crucial in order to predict whether current gravity wave detectors will be successful in detecting such bursts. Present estimates of this rate are rather low[3–7], because we know of only a few double-neutron-star binaries with merger times less than the age of the Universe. Here we report the discovery of a 22-ms pulsar, PSR J0737–3039, which is a member of a highly relativistic double-neutron-star binary with an orbital period of 2.4 hours. This system will merge in about 85 Myr, a time much shorter than for any other known neutron-star binary. Together with the relatively low radio luminosity of PSR J0737–3039, this timescale implies an order-of-magnitude increase in the predicted merger rate for double-neutron-star systems in our Galaxy (and in the rest of the Universe).

Nature, **426**, 531-533 (2003)

Second discovery!

- Pulsars seem to attract serendipity:
  - Shortly after the discovery, Duncan Lorimer was observing at Parkes and testing some search software on readily available test data – data taken on PSR J0737-3039. To his surprise he found a second signal with the same dispersion but a period of 2.77 s, and with the opposite orbital Doppler shift to the known pulsar.
  - This second pulsar appears to switch on only for two ~10 min intervals at the same point in every 2.4 h orbit -- unfortunately these intervals were not used in the initial discovery!

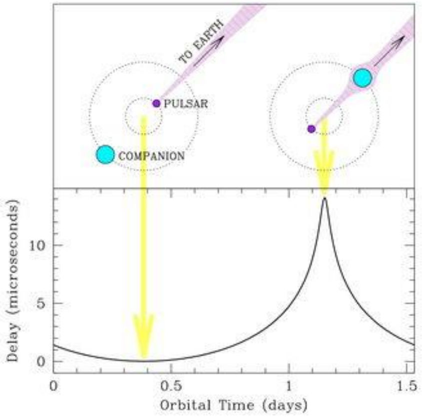


Lyne et al. 2004

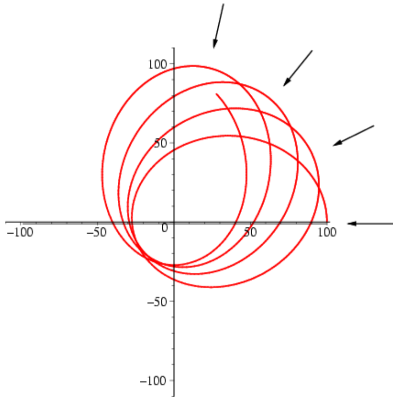
Post-newtonian effects

- The pulsars are orbiting at $\sim 0.001c$, so relativistic effects are important. In addition to $P_{\mathrm{orb}}, a, i, e, \omega$ and T_0 we need additional 'post keplerian' orbital parameters:
  - Shapiro delay parameters (gravitational delay of radiation) r, s
  - Periastron advance $\dot{\omega}$
  - Gravitational redshift variations over the orbit (Einstein delay) γ
  - Orbital decay rate due to gravitational wave damping $\dot{P}_{\mathrm{b}}$

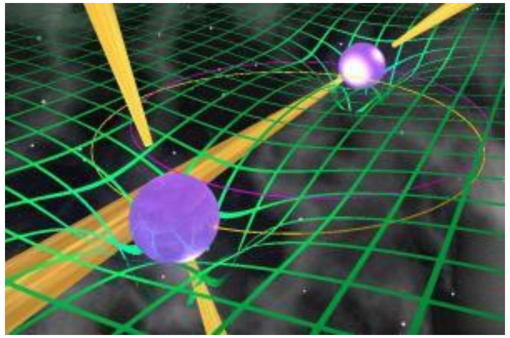
r, s



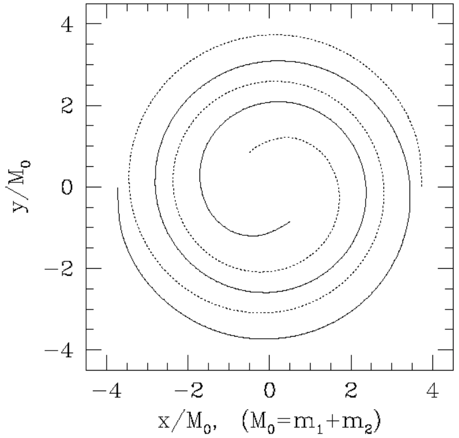
$\dot{\omega}$



γ

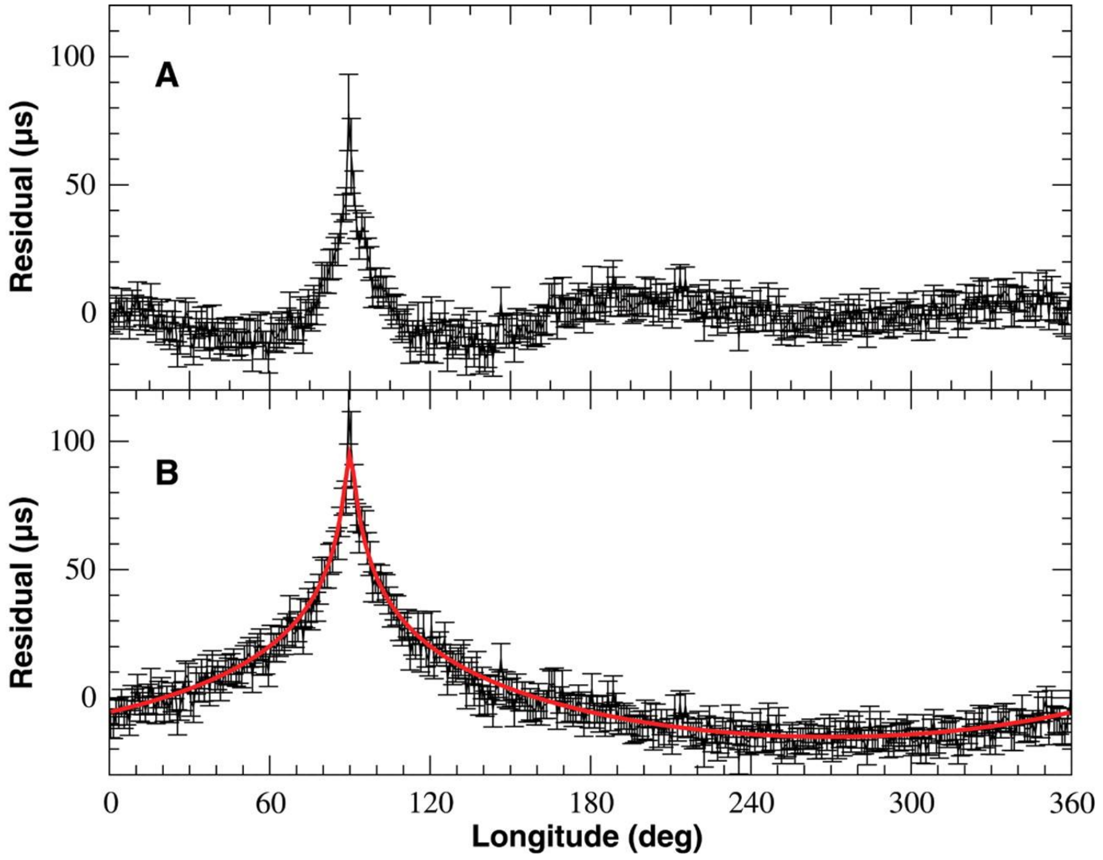


$\dot{P}_{\mathrm{b}}$

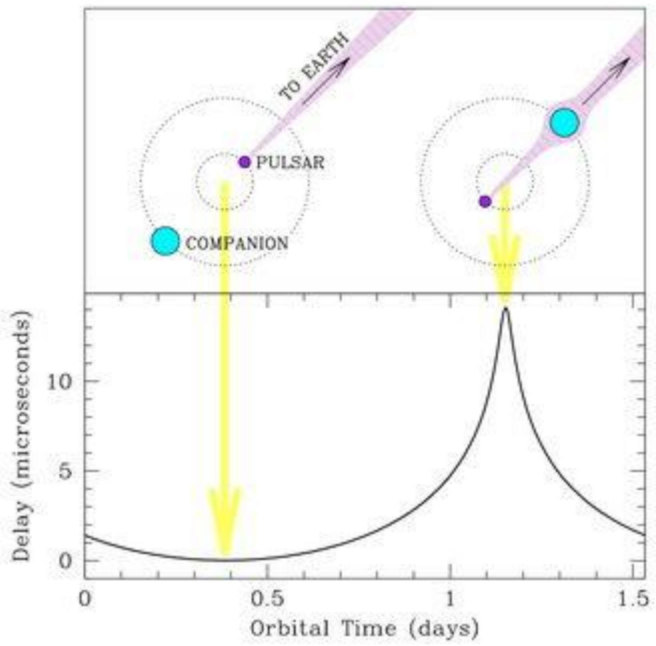


Shapiro delays

- The strong Shapiro delay implies we are seeing the orbits nearly ‘edge-on’ ($i = 87° \pm 1°$).



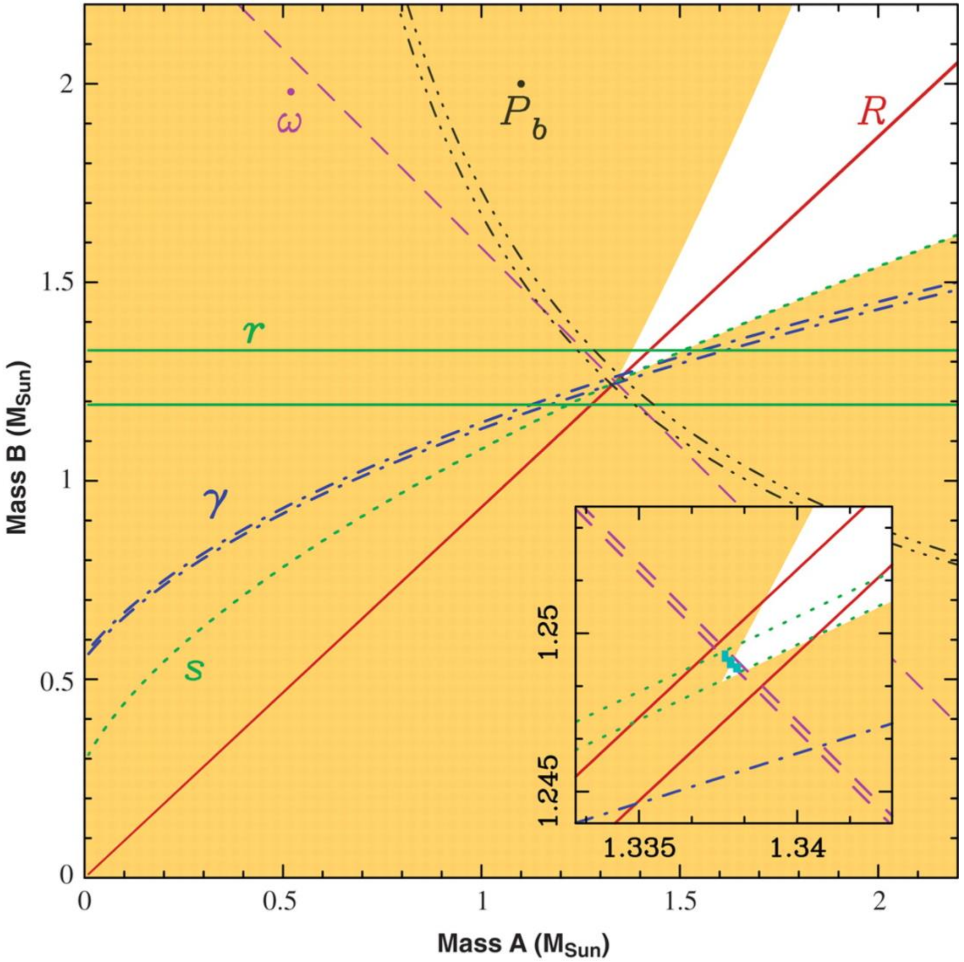
Kramer et al. 2006



Mass-mass diagram

- Because both are pulsars, we can measure $a_A \sin i$ and $a_B \sin i$ and therefore measure the mass ratio $R = \frac{m_A}{m_B} = 1.069$.

Shaded regions excluded by $|M \sin i < M|$



Kramer et al. 2006

Testing GR

- The measured PK parameters are in good agreement with the predictions of GR:

PK parameter	Observed value	Expected value from GR	Ratio of observed to expected value
$\dot{P}_b$	1.252(17)	1.24787(13)	1.003(14)
γ (ms)	0.3856(26)	0.38418(22)	1.0036(68)
s	0.99974(−39,+16)	0.99987(−48,+13)	0.99987(50)
r (μs)	6.21(33)	6.153(26)	1.009(55)

Kramer et al. 2006

- Orbital decay of ~7mm per day.

- In addition, GR spin precession ('geodetic precession') has been seen too, slowly changing the beam geometry. Pulsar B (2.8 s period) precessed out of view in March 2008. Should come back into view ~2035.

Overall system parameters

Timing parameter	PSR J0737-3039A	PSR J0737-3039B
Right ascension α	$07^h37^m51^s.24927(3)$	—
Declination δ	$-30°39'40''.7195(5)$	—
Proper motion in the RA direction (mas year^{-1})	−3.3(4)	—
Proper motion in declination (mas year^{-1})	2.6(5)	—
Parallax π (mas)	3(2)	—
Spin frequency ν (Hz)	44.054069392744(2)	0.36056035506(1)
Spin frequency derivative $\dot{\nu}$ (s^{-2})	$-3.4156(1) \times 10^{-15}$	$-0.116(1) \times 10^{-15}$
Timing epoch (MJD)	53,156.0	53,156.0
Dispersion measure DM (cm^{-3} pc)	48.920(5)	—
Orbital period P_b (day)	0.10225156248(5)	—
Eccentricity e	0.0877775(9)	—
Projected semimajor axis $x = (a/c)\sin i$ (s)	1.415032(1)	1.5161(16)
Longitude of periastron ω (°)	87.0331(8)	87.0331 + 180.0
Epoch of periastron T_0 (MJD)	53,155.9074280(2)	—
Advance of periastron $\dot{\omega}$ (°/year)	16.89947(68)	[16.96(5)]
Gravitational redshift parameter γ (ms)	0.3856(26)	—
Shapiro delay parameter s	0.99974(−39,+16)	—
Shapiro delay parameter r (μs)	6.21(33)	—
Orbital period derivative $\dot{P}_b$	$-1.252(17) \times 10^{-12}$	—
Timing data span (MJD)	52,760 to 53,736	52,760 to 53,736
Number of time offsets fitted	10	12
RMS timing residual σ (μs)	54	2169
Total proper motion (mas year^{-1})	4.2(4)	
Distance d(DM) (pc)	~500	
Distance $d(\pi)$ (pc)	200 to 1,000	
Transverse velocity (d = 500 pc) (km s^{-1})	10(1)	
Orbital inclination angle (°)	88.69(−76,+50)	
Mass function ($M_\odot$)	0.29096571(87)	0.3579(11)
Mass ratio R	1.0714(11)	
Total system mass ($M_\odot$)	2.58708(16)	
Neutron star mass ($m_\odot$)	1.3381(7)	1.2489(7)

Kramer et al. 2006

Pulsar interactions

- We see the system edge-on, so that (the more energetic) pulsar A probes the magnetophere of pulsar B as it shines through it.
- Scintillation data indicate that the orbit is less than 0.3 degrees from edge-on!

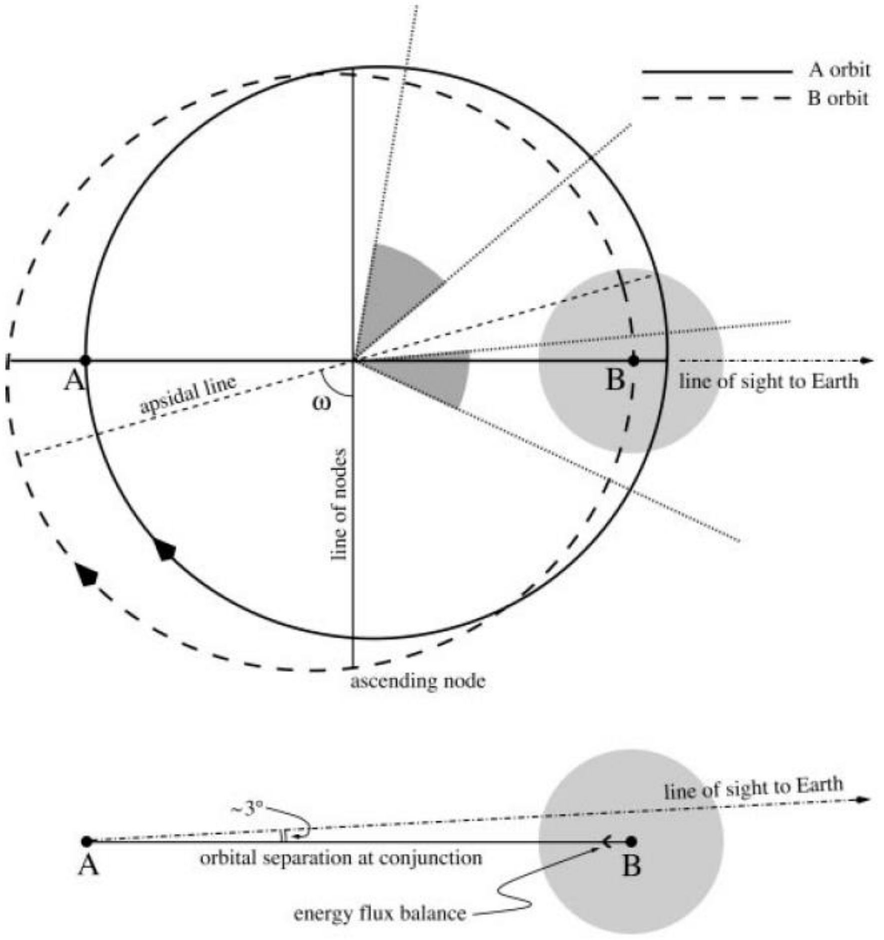
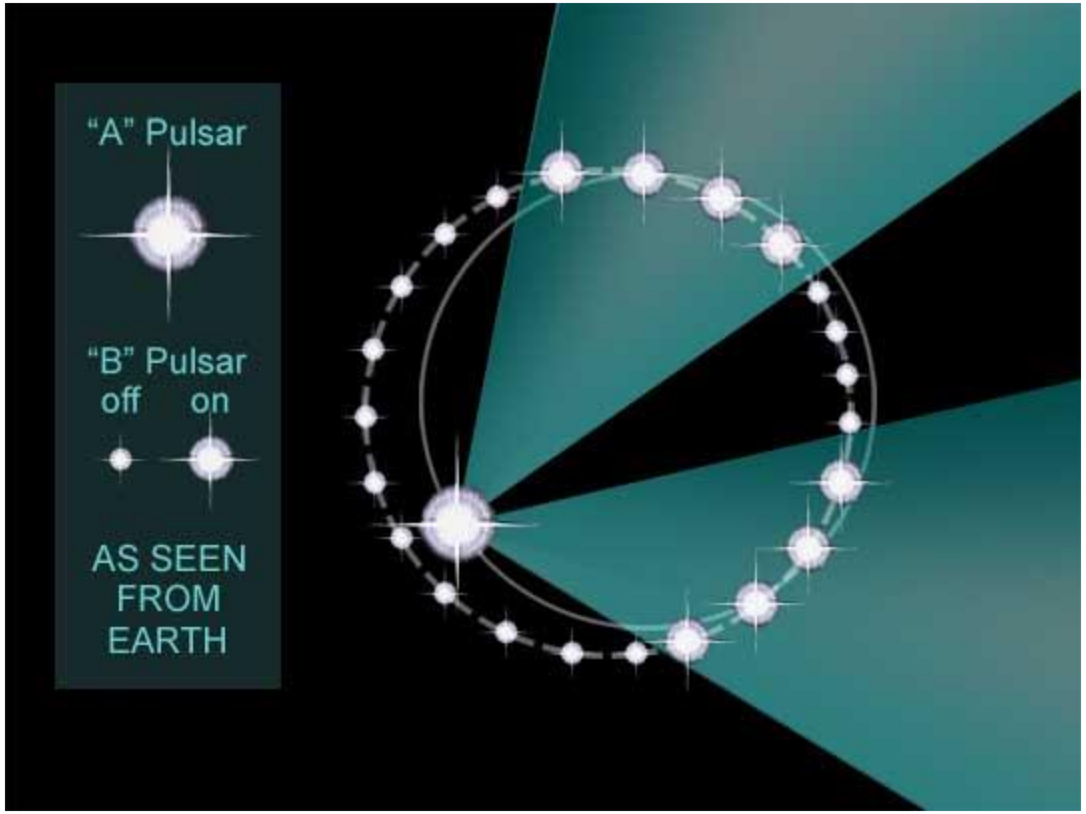


Fig. 4. The physical configuration of the binary system, at conjunction, as on 19 August 2003 [modified Julian date (MJD) 52870], showing the relative sizes of the two orbits and B's magnetosphere. At conjunction, the two neutron stars are separated by ~2.8 light-s or about 800,000 km. (**Top**) View from above the orbital plane with the Earth to the right. The shaded segments indicate orbital phases where B is detected strongly (see Fig. 1). The apsidal line is the major axis of the orbits, and the line of nodes is the intersection of the orbital plane and the plane through the center of mass of the system, which is normal to the line of sight. (**Bottom**) View from the side, showing the passage of the line of sight from A to the Earth through the magnetosphere of B. The approximate position of the pressure balance between the relativistic wind from A and the magnetic field of B is indicated.

Lyne et al. 2004

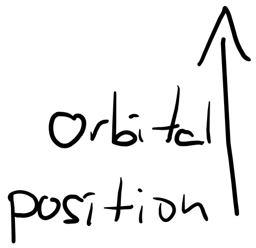
Pulsar interaction

- In addition there is some sort of coupling that energises pulsar B at certain orbital phases – probably the points where the magnetosphere is most strongly excited



Pulsar interaction

- The bright times and profiles for pulsar B are changing with time.



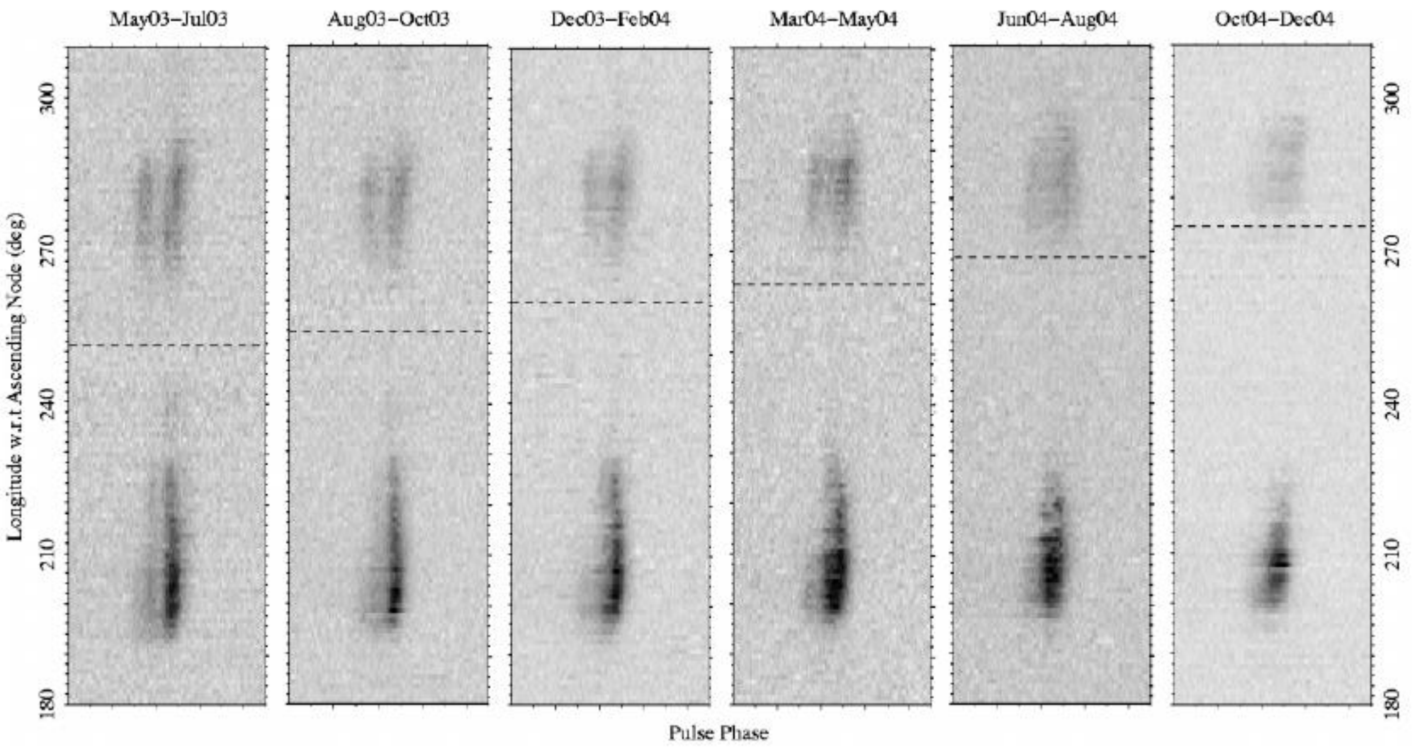
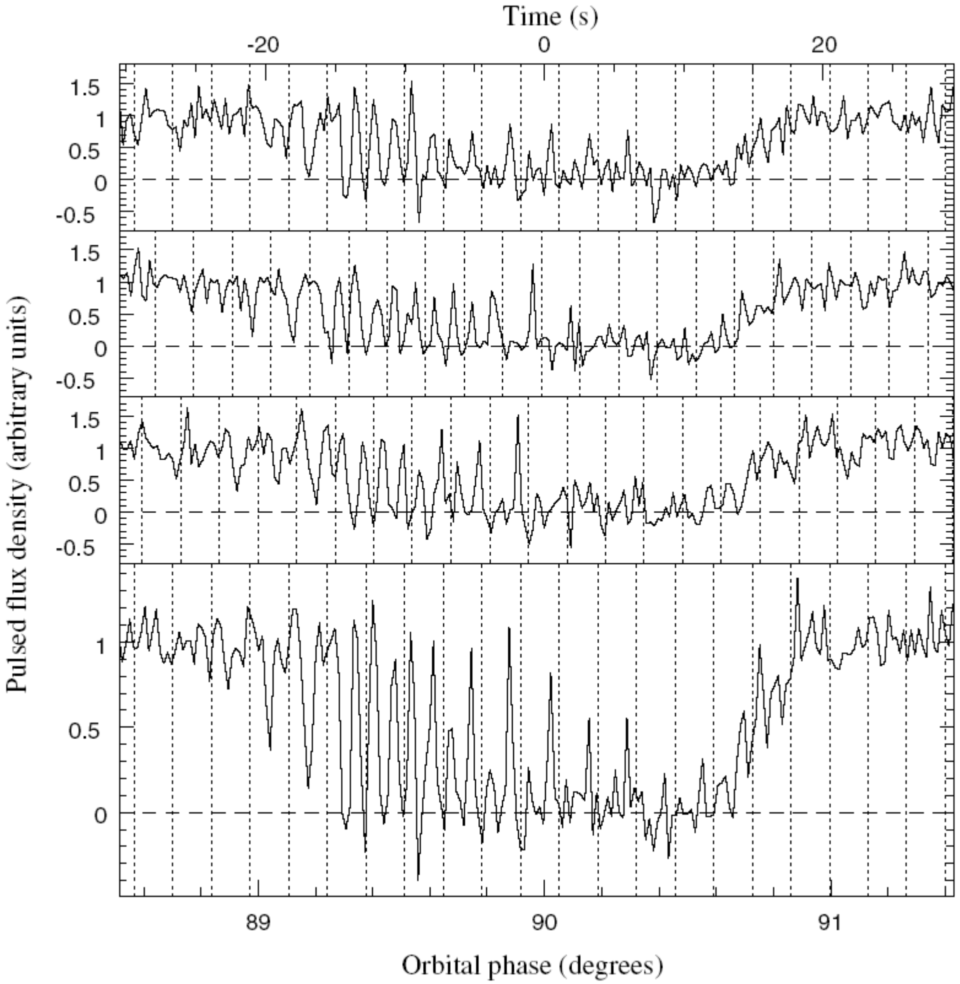


FIG. 1.—Intensity of the PSR J0737−3039B pulse emission at 1390 MHz as a function of orbital longitude and pulse phase at six epochs. Only the longitude range 180°–310° covering the two bright phases bp1 (*lower*) and bp2 (*upper*) and a pulse-phase window of 0.1 pulse periods centered on the pulse are shown. The dashed lines represent the longitude of periastron at each epoch.

Burgay et al. 2005

Pulsar interaction

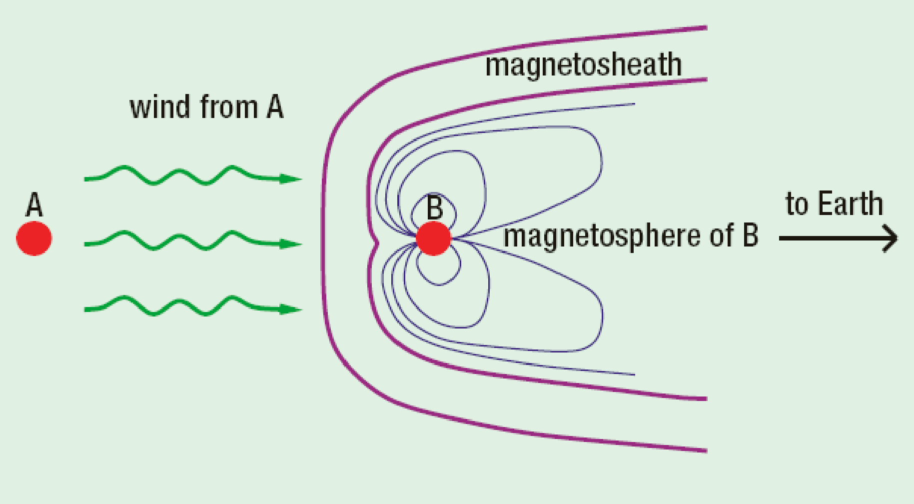
- As the wind from (MSP) pulsar A blows strongly onto the magnetosphere of pulsar B we get long-term and short-term variations in the output of pulsar B.
- About half of B's magnetosphere is blown away.
- The graph shows the eclipsed flux of A, with dotted lines showing times then B's active magnetic pole faces Earth. The eclipse lasts for ~30 s.



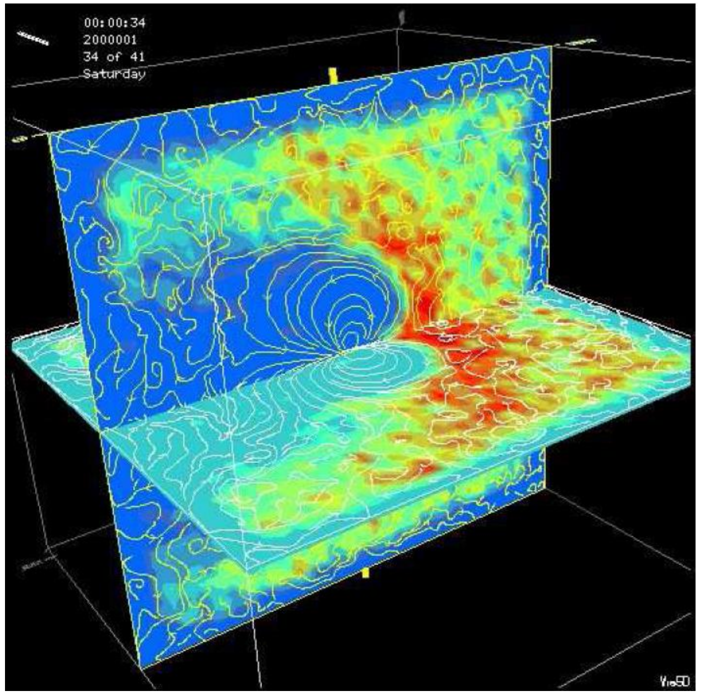
McLaughlin et al, 2004

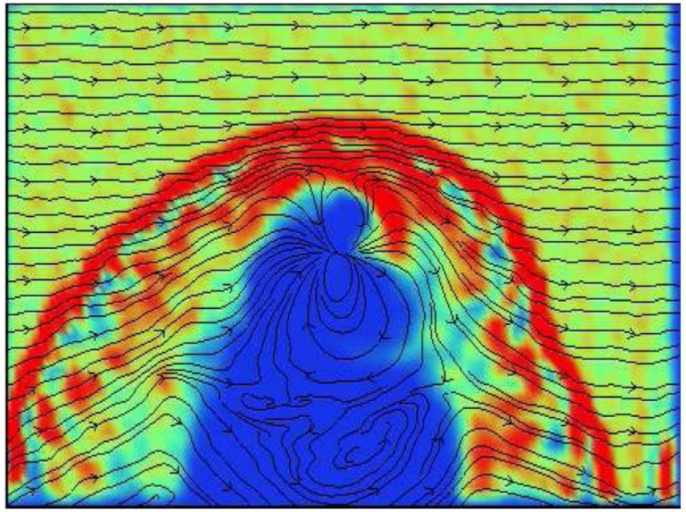
Pulsar B's magnetosheath

- The geometry is similar to the Earth's bowshock in the solar wind.
- Field of ~10 Gauss at the magnetopause.

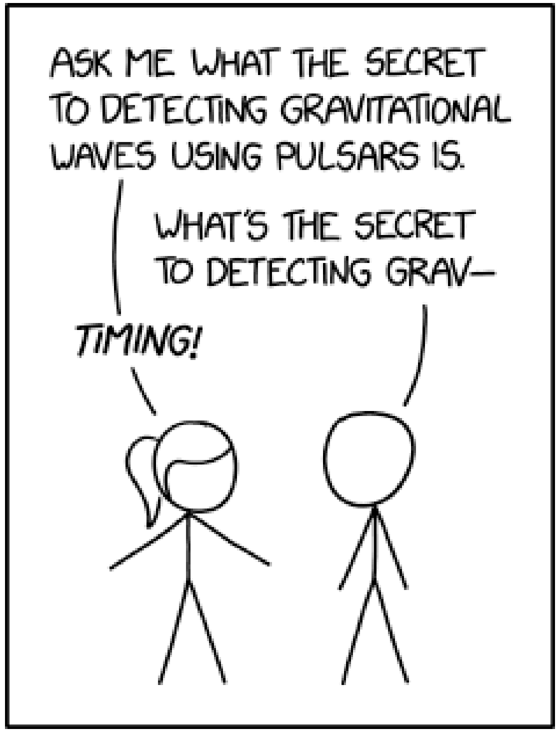


2: Diagram (not to scale) showing the interaction between the relativistic wind from pulsar A and the magnetosphere of pulsar B. The collision of A's wind and B's magnetosphere creates a magnetosheath of hot, magnetized plasma surrounding the magnetosphere of B. The rotation of B inside this sheath modulates A's eclipse, as shown in figure 2.





Good luck!



https://imgs.xkcd.com/comics/gravitational_wave_pulsars.png