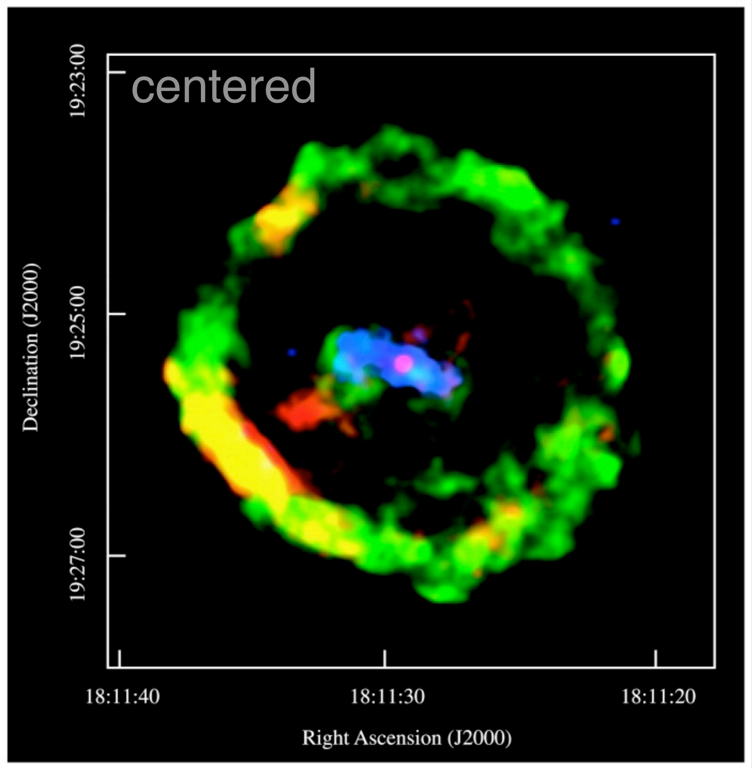
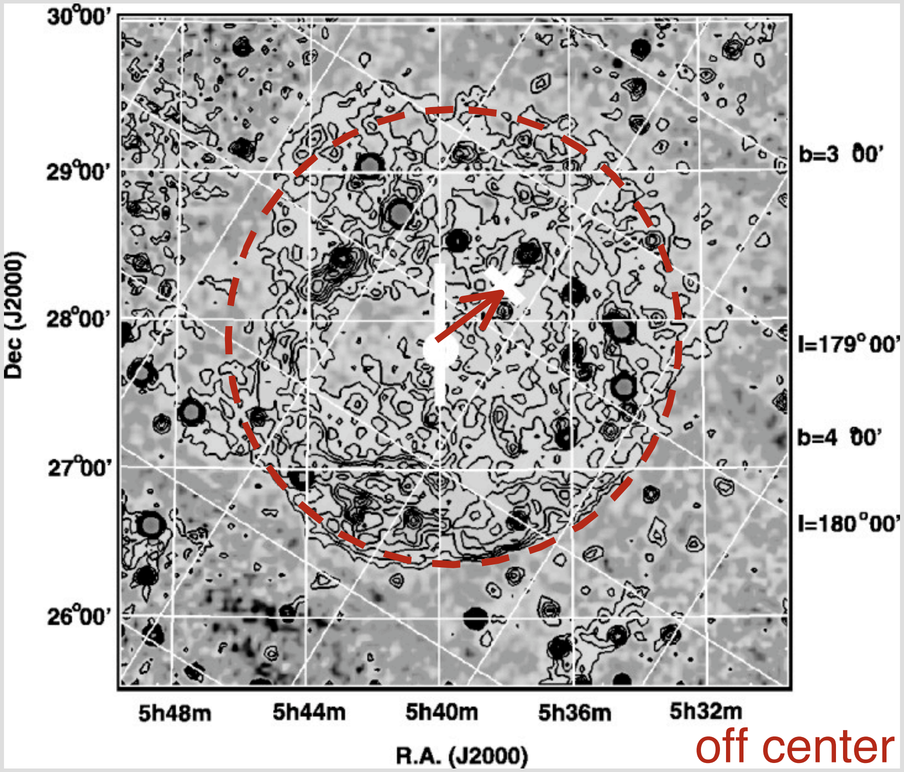
Distribution of radio pulsars

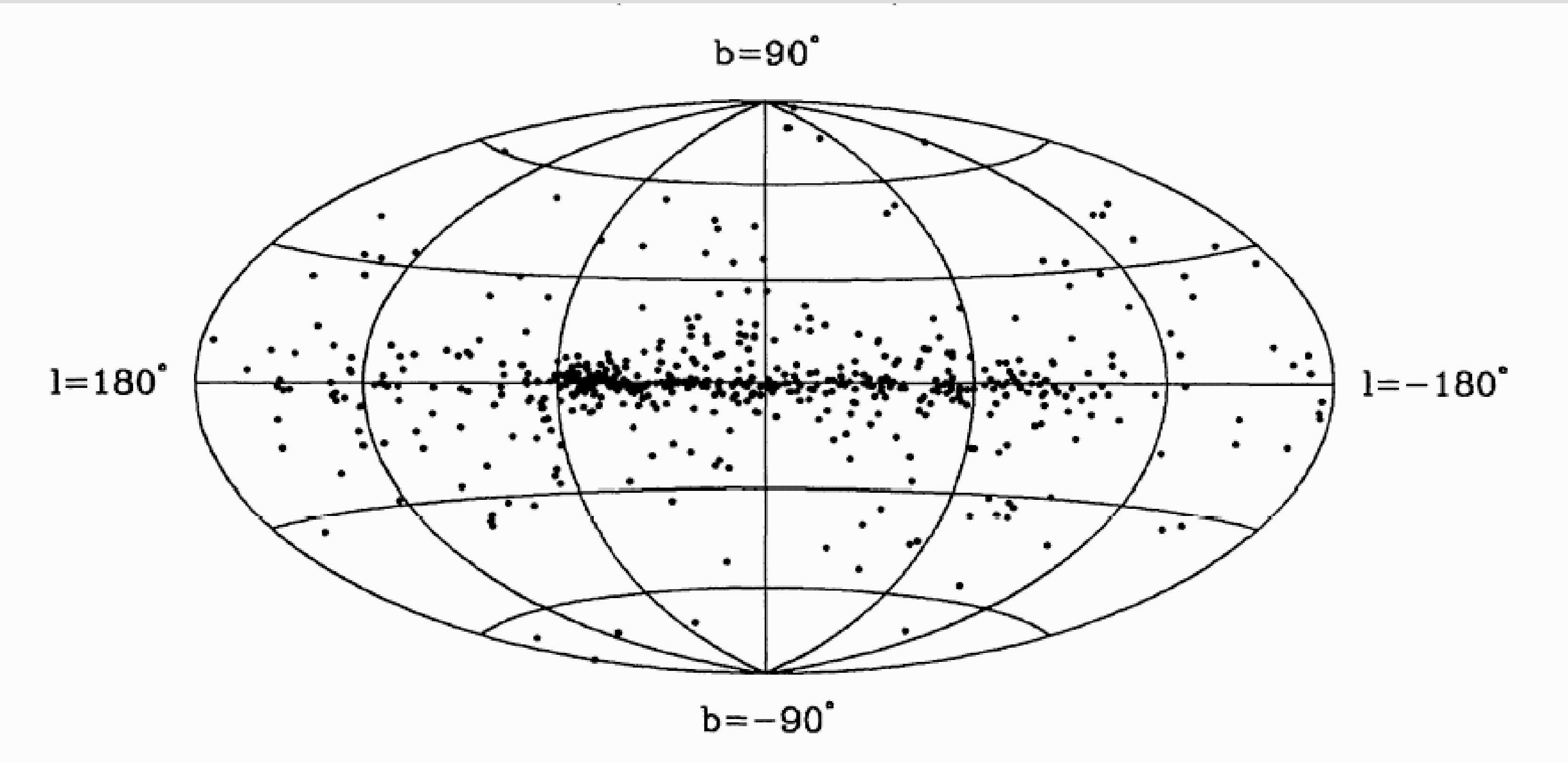
Can detect pulsars that are much older than the oldest distinct supernova remnants. So most pulsars are not in supernova remnants.

More interestingly: not all *supernova remnants* have pulsars at their center.





Together with observations of the distribution and proper motion of radio pulsars across the sky, this suggests that pulsars have velocities that can be as large as 10^3 km s^{-1}.



Much larger than the space velocities of massive stars - suggests neutron stars receive a **kick** at time of formation.

Producing neutron star kicks

Binding energy of a neutron star is: $\sim \frac{GM^2}{R} \sim 5 \times 10^{53}$ erg

Kinetic energy of a neutron star moving at 1000 km s^{-1} is:

$$\frac{1}{2} M v^2 = 1.5 \times 10^{49} \text{ erg}$$

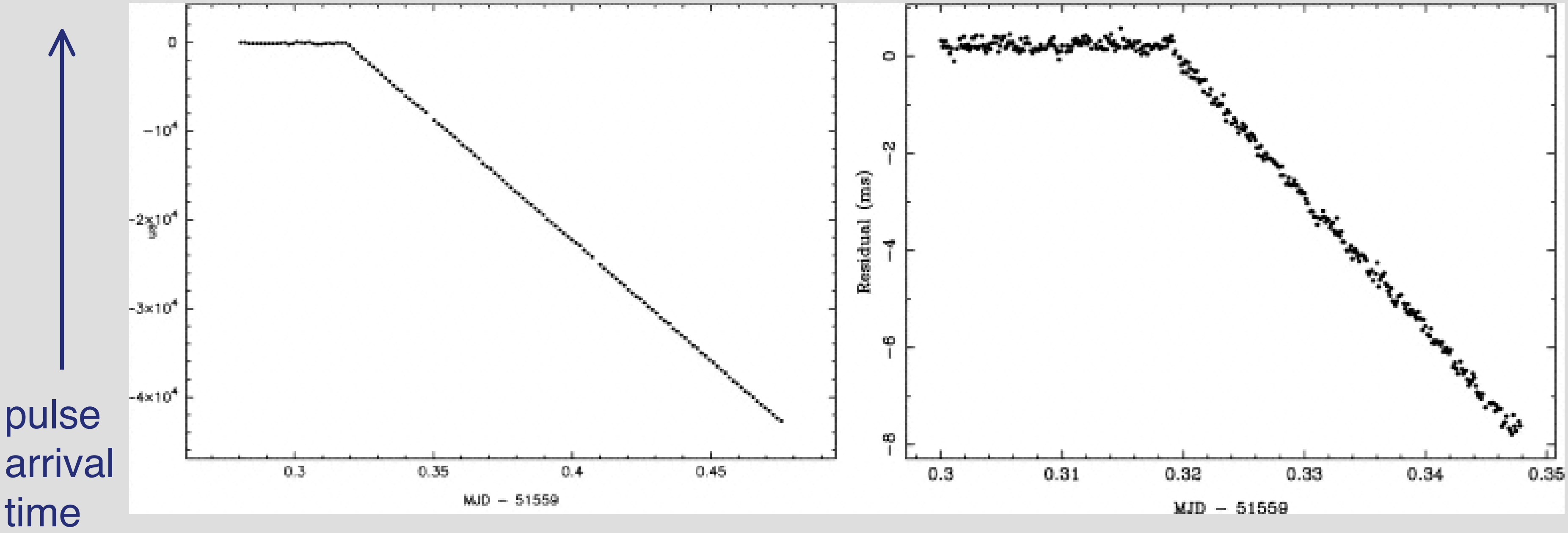
⇒ No energetic problem: small asymmetry in the emission of neutrinos or mass from the supernova would be enough to give the neutron star enough kick energy.

Can repeat exercise for momentum as well as energy.

Seems plausible, but no definite mechanism is known:

- asymmetry in the supernova explosion
- irregularities in the progenitor star
- …

Glitches



In some pulsars, the steady spin down is sometimes interrupted by a sudden, almost instantaneous, spin **up** - a **glitch**.

Thought to arise because the neutron star has a fluid interior which is only weakly coupled to the crust. As the crust is braked, a mismatch in angular velocity develops which is suddenly corrected.

Binary pulsar

In 1974, Russell Hulse and Joe Taylor discovered a pulsar in a close binary system. From analysis of the arrival time of the pulses, they determined that the orbit was eccentric (e = 0.62), with a period of 7.8 hours.

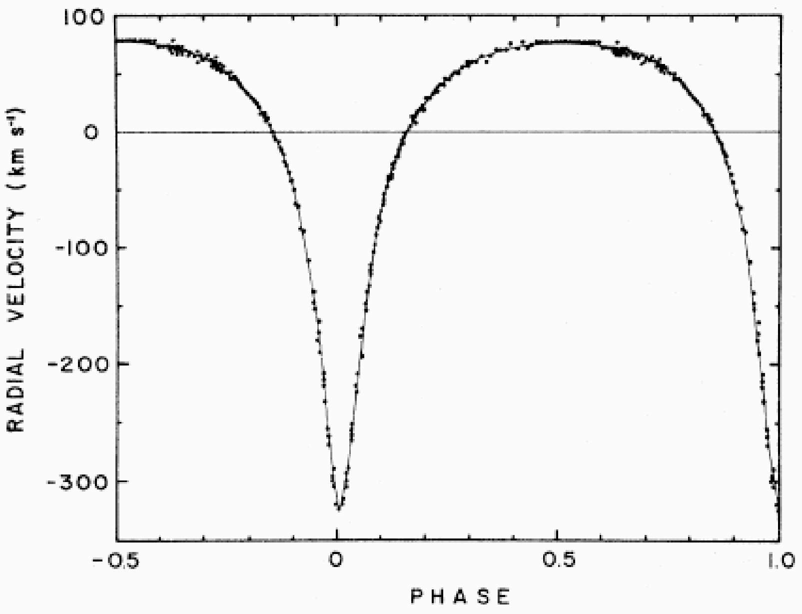
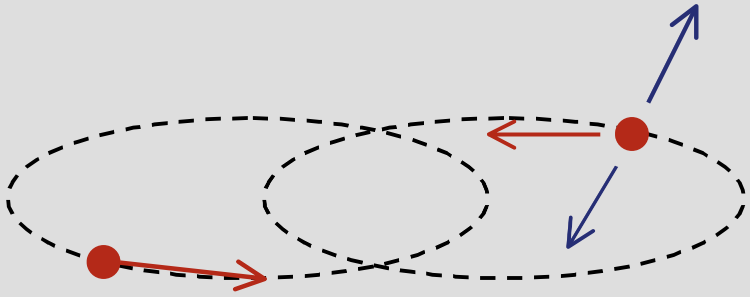


FIG. 12. The complete velocity curve for PSR 1913+16 from the discovery paper, fitted with a Keplerian orbital solution. The orbital phase is the fraction of a binary orbital period of 7^h45^m (from R. A. Hulse and J. H. Taylor, 1975a).



Observations of this system provide very accurate masses for the stars:

$$\left.\begin{aligned} M_1 &= 1.442 \pm 0.003 M_{sun} \\ M_2 &= 1.386 \pm 0.003 M_{sun} \end{aligned}\right\} \text{double neutron star binary!}$$

To a very good approximation this is a system of two point masses in orbit around each other.

Expect that energy is being lost from the binary in the form of gravitational radiation. As energy is lost, stars should be spiralling together toward collision.

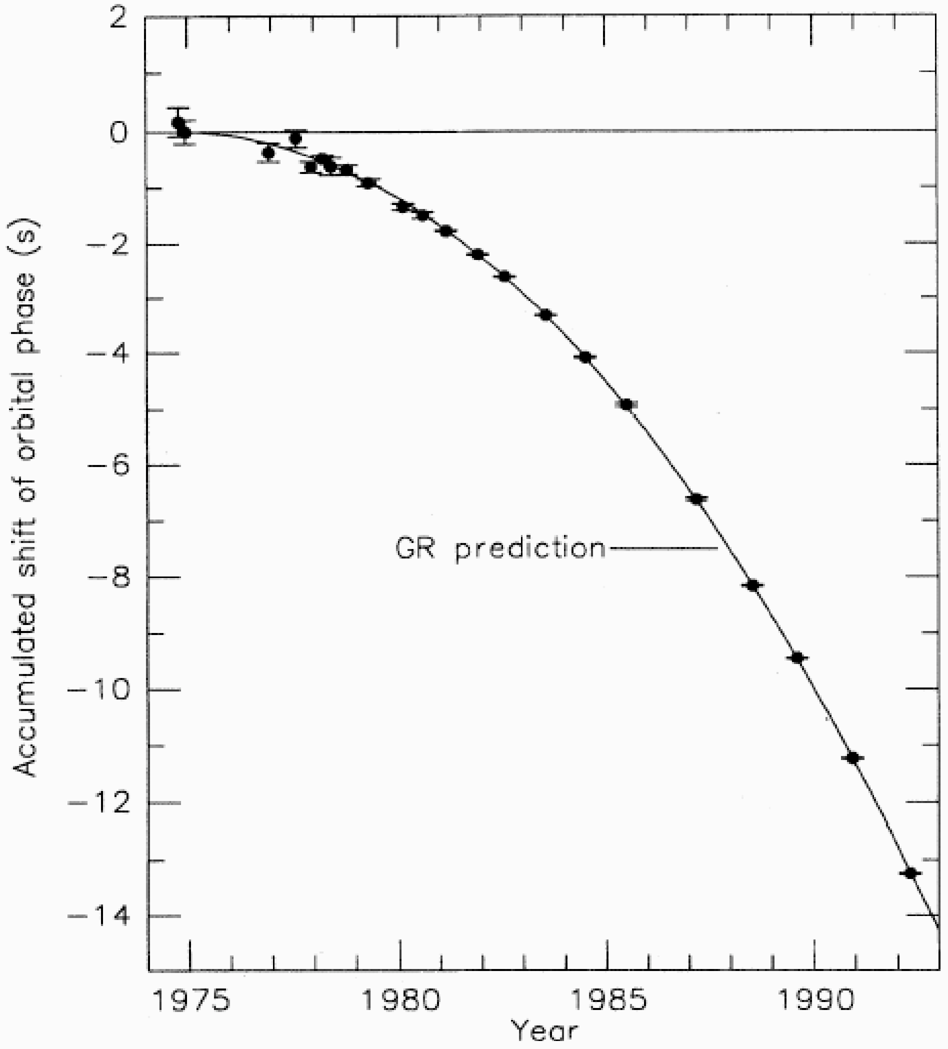


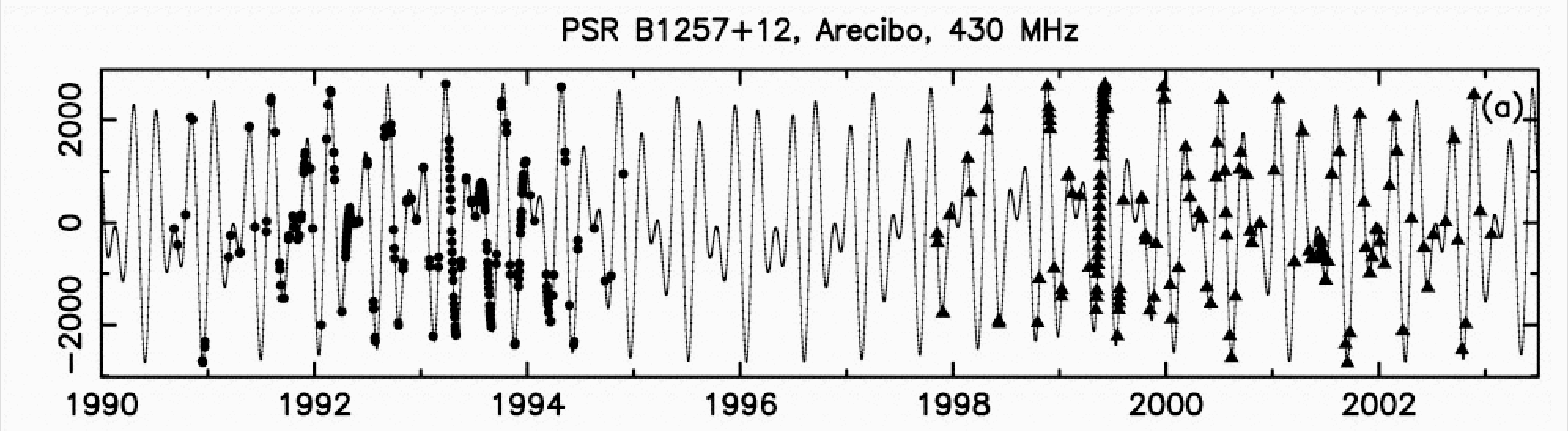
FIG. 10. Accumulated shift of the times of periastron in the PSR 1913+16 system, relative to an assumed orbit with constant period. The parabolic curve represents the general relativistic prediction for energy losses from gravitational radiation.

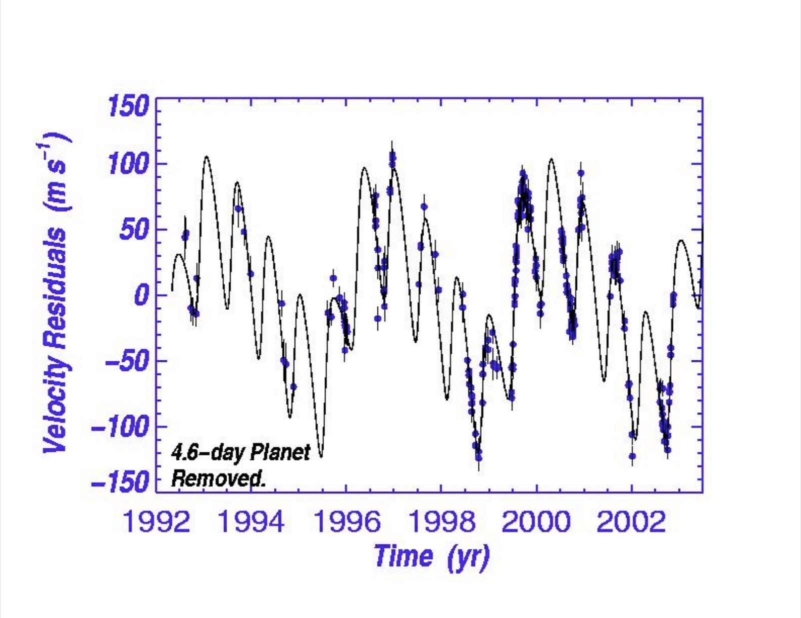
Observed change in time of closest approach matches the General Relativity prediction.

Orbit shrinks by ~3 mm per orbit of the binary system.

Pulsar planets

Timing of the pulsar B1257+12 showed periodic changes in the arrival times of pulses:





c.f. the radial velocity curve of the multiple planet system Ups Andromeda

Data suggests at least three (possibly four) planetary mass companions:

	Orbital radius (au)	Planet mass (Earth masses)	Eccentricity
A	0.19	0.02	0.0
B	0.36	4.3	0.0186
C	0.46	3.9	0.0252

Phenomenon appears to be rare - 48 similar pulsars show no sign of planets at similar levels of sensitivity.

Formation mechanism uncertain - planets almost certainly formed **after** the supernova explosion that created the neutron star.