Darmstadt Lecture 8 – Pulsars

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Darmstadt Lecture 8 – Pulsars `James.Lattimer@Stonybrook.edu`

Pulsars: What are they?

- Small source period can only be explained by compact objects – orbital motion, vibrations or spin. The Crab pulsar bursts 30 times a second.
- A binary star with total mass of $M = 1\ \mathrm{M}_\odot$ and a period of $P = 0.033$ s, according to Kepler's Law, would have a separation a equal to
$$a = \left(\frac{M}{\mathrm{M}_\odot}\right)^{1/3}\left(\frac{P}{1\ \mathrm{year}}\right)^{2/3} = 1.0 \cdot 10^{-6}\ \mathrm{AU} = 93\ \mathrm{miles}\,.$$
This separation is smaller than the radius of any solar mass object except a neutron star or black hole.
- The maximum radius R_{max} an object could have and still spin that fast without shedding mass from the equator is found from
$$\left(\frac{2\pi}{P}\right)^2 R_{max} = \frac{GM}{R_{max}^2} \quad \Rightarrow R_{max} = (GM)^{1/3}\left(\frac{P}{2\pi}\right)^{2/3}.$$
This gives $R_{max} = 15$ km. Again, only a neutron star or black hole works.
- There is no known mechanism for black holes to emit pulses of energy.
- The discovery that the Crab pulsar is slowing down is only consistent with a spinning object and rules out orbiting or vibrating stars.
- Binaries, losing energy, go into tighter orbits with higher frequencies.
- Vibrating objects, losing energy, develop higher oscillation frequencies.

Magnetic Dipole Model for Pulsars

A misaligned magnetic dipole ($\alpha > 0$) emits low-frequency electromagnetic radiation. Larmor formula for electric dipoles (charge q, acceleration $\dot{v}$) is

$$P_{rad} = \frac{2q^2\dot{v}^2}{3c^2} = \frac{2}{3c^3}(q\ddot{r}\sin\alpha)^2 = \frac{2\ddot{p}_\perp^2}{3c^2}$$

where $p_\perp$ is the perpendicular component of the electric dipole moment.

A uniformly magnetized sphere with radius R and surface field B has a magnetic dipole moment $|m| = BR^3$, and if rotating with period $P = 2\pi/\Omega$, has $m = |m|e^{-i\Omega t}$ and $|\ddot{m}| = \Omega^2|m|$. By analogy to an electric dipole,

$$P_{rad} = \frac{2}{3}\frac{\ddot{m}_\perp^2}{c^3} = \frac{2}{3c^2}\left(BR^3\sin\alpha\right)^2\left(\frac{2\pi}{P}\right)^4$$

This radiation appears at the low frequency $\nu = P^{-1} < 1$ kHz, too low to propagate throught the ionized ISM and be detected.

The total rotational energy and spin-down power, using $I = (2/5)MR^2$, are

$$E_{rot} = \frac{1}{2}I\Omega^2 \simeq 1.6\cdot 10^{50}\left(\frac{M}{M_\odot}\right)\left(\frac{R}{10\ \mathrm{km}}\right)^2\left(\frac{10\ \mathrm{ms}}{P}\right)^2\ \mathrm{erg},$$

$$P_{rot} = -I\Omega\dot{\Omega} \simeq 1.6\cdot 10^{40}\left(\frac{M}{M_\odot}\right)\left(\frac{R}{10\ \mathrm{km}}\right)^2\left(\frac{10\ \mathrm{ms}}{P}\right)^3\left(\frac{-\dot{P}}{10^{-12}}\right)\ \mathrm{erg\ s^{-1}}.$$

Magnetic Fields and Ages

Setting $P_{rad} = -P_{rot}$, one finds

$$B = \sqrt{\frac{3c^3 I P \dot{P}}{8\pi^2} \frac{1}{R^3} \frac{1}{\sin^2\alpha}} \simeq 2.9 \cdot 10^{12} \left(\frac{10\ \mathrm{km}}{R \sin\alpha}\right)^2 \sqrt{\frac{M}{M_\odot} \frac{P}{.01\ \mathrm{s}} \frac{\dot{P}}{10^{-12}}}\ \mathrm{G}$$

which is a minimum value since $\sin\alpha < 1$.

The **characteristic age** is estimated by assuming $P\dot{P} \simeq$ constant, or

$$\int_{P_0}^{P} P dP = P\dot{P} \int_0^\tau dt = P\dot{P}\tau = \frac{P^2 - P_0^2}{2},$$

giving, with $P_0 >> P$,

$$\tau = \frac{P}{2\dot{P}} \simeq 158 \frac{P}{.01\ \mathrm{s}} \frac{10^{-12}}{\dot{P}}\ \mathrm{yr}.$$

A death line exists when the voltage $V \propto B\Omega^2$ near the polar cap drops below that needed to generate e^+e^- pairs:

$$\Phi = \frac{BR^3\Omega^2}{2c^2} \simeq 6.6 \cdot 10^{16} \frac{B}{10^{12}\ \mathrm{G}} \left(\frac{0.01\ \mathrm{s}}{P}\right)^2 \left(\frac{R}{10\ \mathrm{km}}\right)^3\ \mathrm{V}.$$

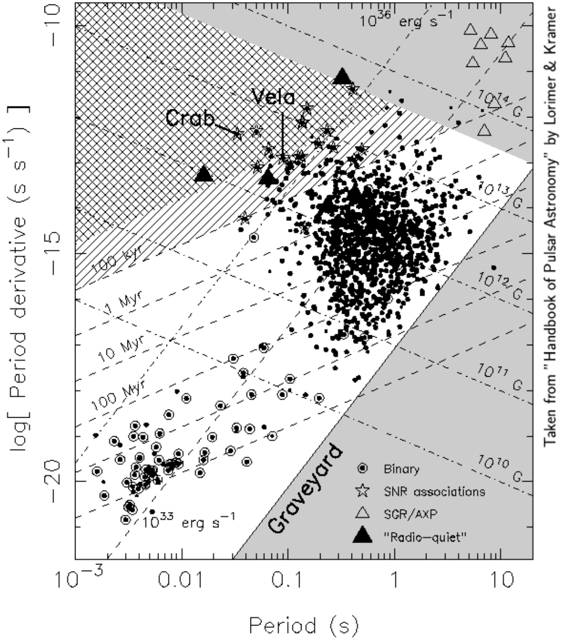
Note $BP^{-2} \propto \sqrt{\dot{P}P^{-3}} \propto P_{rot}$. Death line is where $BP^{-2} \sim 0.2 \cdot 10^{12}$ G s^{-2}.

A $\log \dot{P} - \log P$ diagram for pulsars is like an H-R diagram for stars.

The $P - \dot{P}$ Diagram

$B \propto \sqrt{P\dot{P}}$
$\tau \propto P/\dot{P}$
$P_{rot} \propto P^{-3}\dot{P}$

The "death line" is $P_{rot} \sim 10^{30}$ erg s^{-1}



Taken from "Handbook of Pulsar Astronomy" by Lorimer & Kramer

Distances to Pulsars

Pulsars can probe the ISM, which is a plasma with a refractive index

$$\mu = \sqrt{1 - \left(\frac{\omega_p}{2\pi\nu}\right)^2}, \qquad \omega_p = \sqrt{\frac{4\pi e^2 n_e}{m_e}} \simeq 8.97\sqrt{\frac{n_e}{\mathrm{cm}^{-3}}}\ \mathrm{kHz}$$

where ω_p is the plasma frequency.

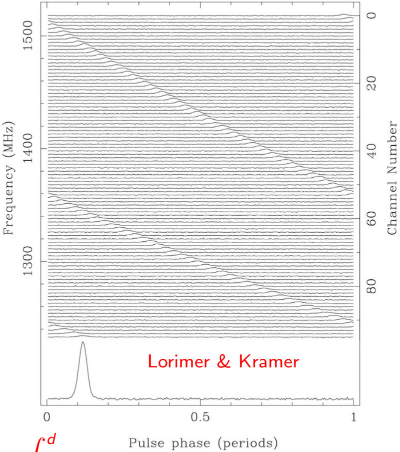
Typically, $n_e \sim 0.03\ \mathrm{cm}^{-3}$ and $\omega_p/(2\pi) \sim 1.5$ kHz.

When $2\pi\nu < \omega_p$, μ is imaginary and photons cannot propagate.

The group velocity $v_g = \mu c < c$. When $2\pi\omega_p << \nu$,

$$v_g \simeq c\left(1 - \frac{2\pi^2\omega_p^2}{\nu^2}\right),$$

an increasing function of frequency.

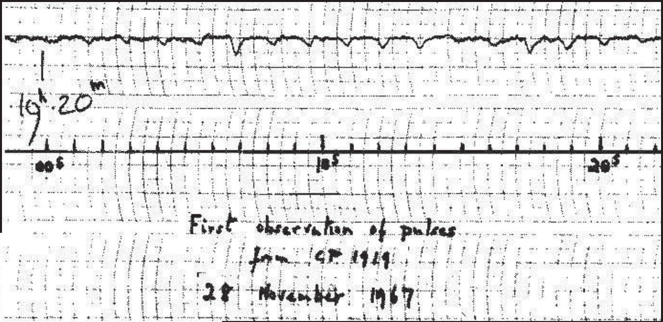


Lorimer & Kramer

This produces a **dispersion** delay

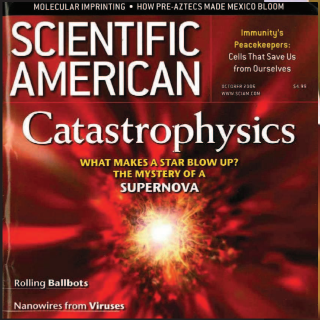
$$t_d = \int_0^d \frac{dx}{v_g} - \frac{d}{c} \simeq \frac{e^2\mathrm{DM}}{2\pi m_e c\nu^2}, \qquad \mathrm{DM} \equiv \int_0^d n_e dx \text{ is the disperson measure.}$$

The Discovery of Pulsars



PhD student **Jocelyn Bell** and
Prof. **Antony Hewish**
Initially “**Little Green Men**”
Hewish won Nobel Prize in 1974

Supernova!



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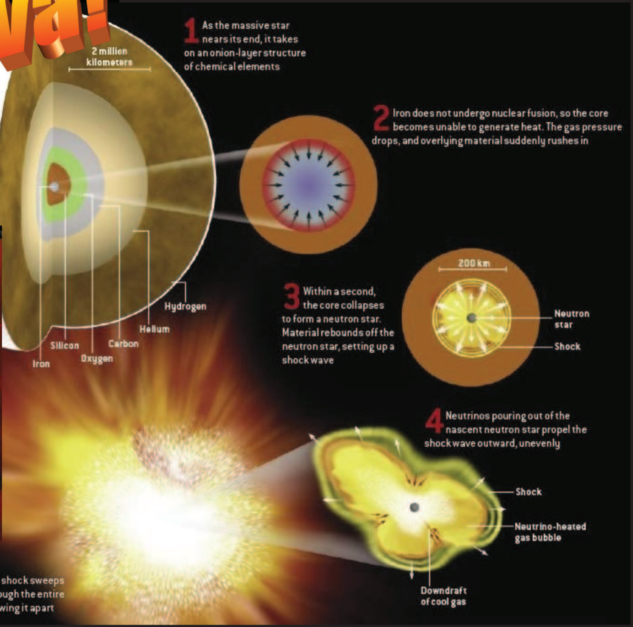
Catastrophysics

WHAT MAKES A STAR BLOW UP?
THE MYSTERY OF A
SUPERNOVA

Rolling **Ballbots**

Nanowires from **Viruses**



1 As the massive star nears its end, it takes on an onion-layer structure of chemical elements

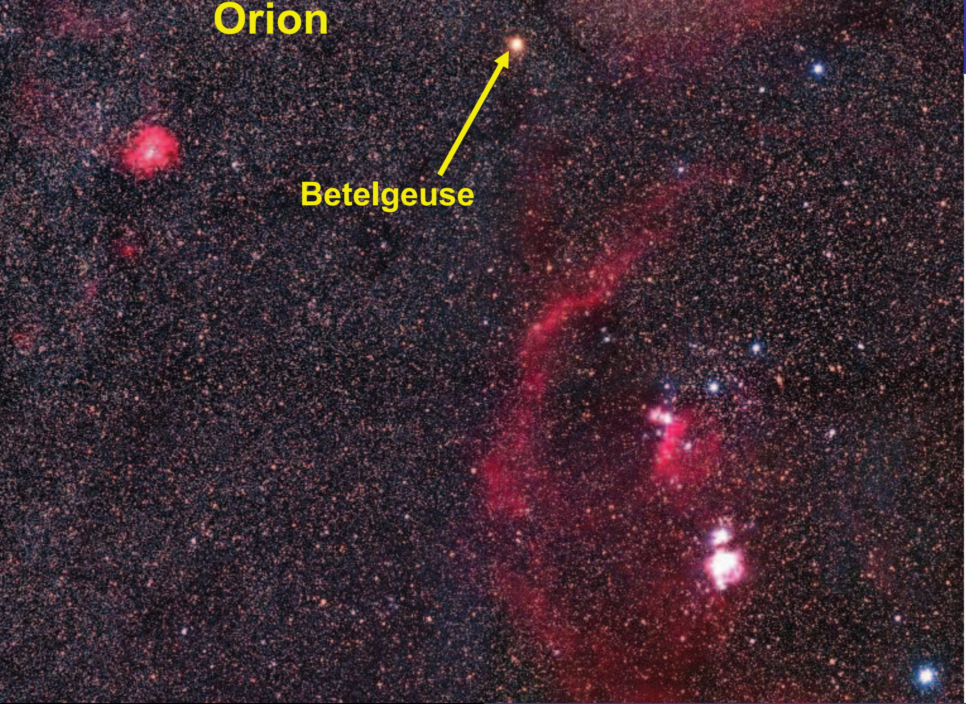
2 Iron does not undergo nuclear fusion, so the core becomes unable to generate heat. The gas pressure drops, and overlying material suddenly rushes in

3 Within a second, the core collapses to form a neutron star. Material rebounds off the neutron star, setting up a shock wave

4 Neutrinos pouring out of the nascent neutron star propel the shock wave outward, unevenly

5 The shock sweeps through the entire star, blowing it apart

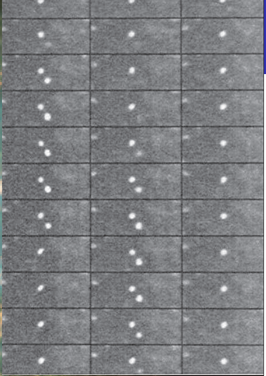
Orion



Baade & Zwicky (1934)

"With all reserve we advance the view that a super-nova represents the transition of an ordinary star into a neutron star. Such a star may possess a very small radius and an extremely high density..."

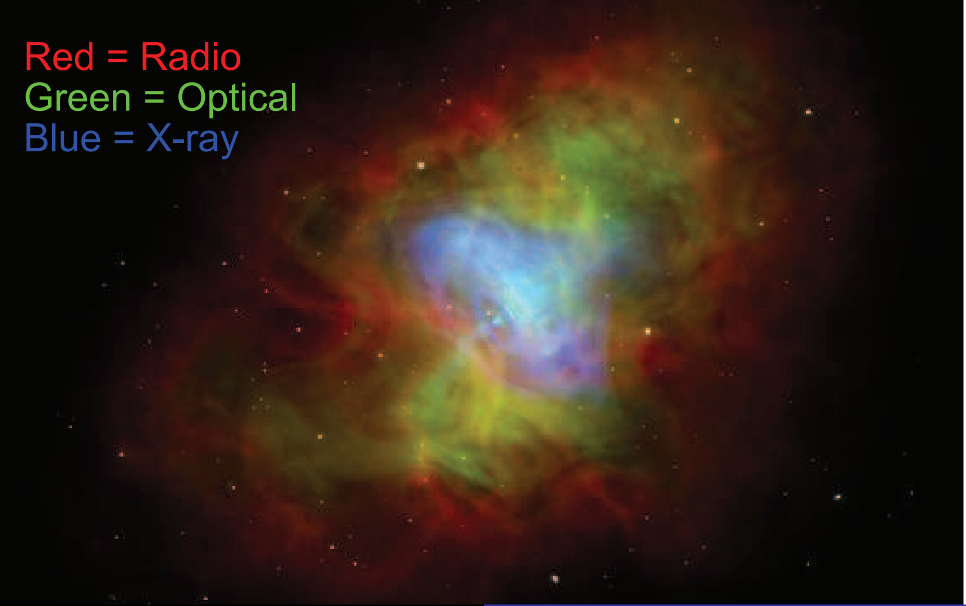
Crab Nebula
SN1054AD



Pulsar rotates 30 times per second!

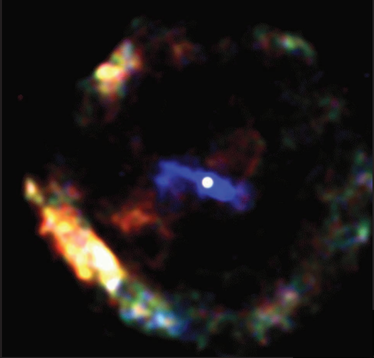
Anasazi Indian cave pictogram, Chaco Canyon, NM

The Crab is visible at all energies!



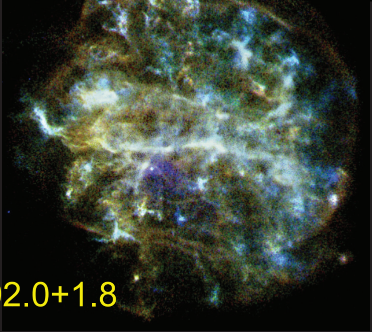
Red = Radio
Green = Optical
Blue = X-ray

Pulsars!



G11.2-0.3

G21.5-0.9

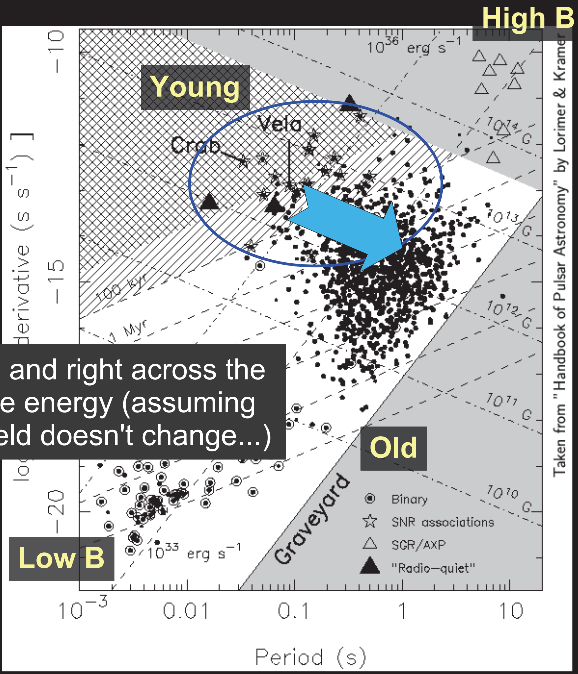


G292.0+1.8

Pulsar Flavors

Young PSRs

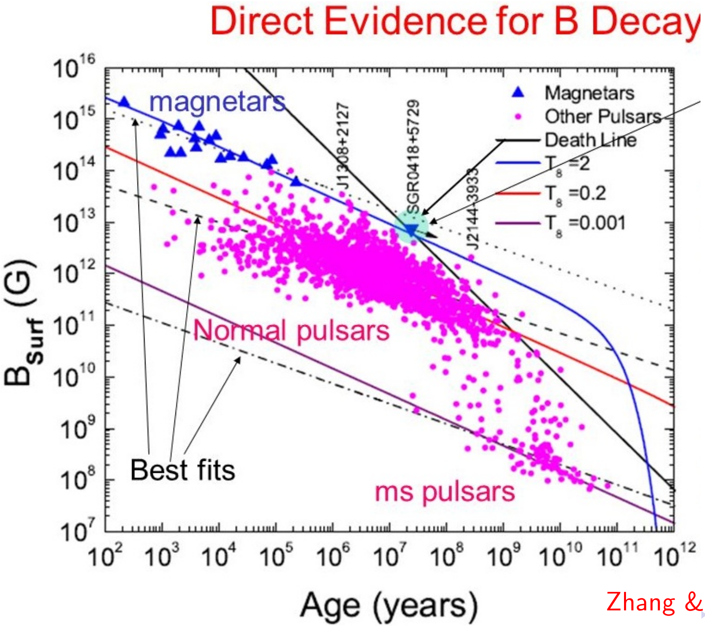
(high B, fast spin, very energetic)



Taken from "Handbook of Pulsar Astronomy" by Lorimer & Kramer

Pulsars move down and right across the diagram as they lose energy (assuming that the magnetic field doesn't change...)

Magnetic Field Evolution??



Zhang & Xie

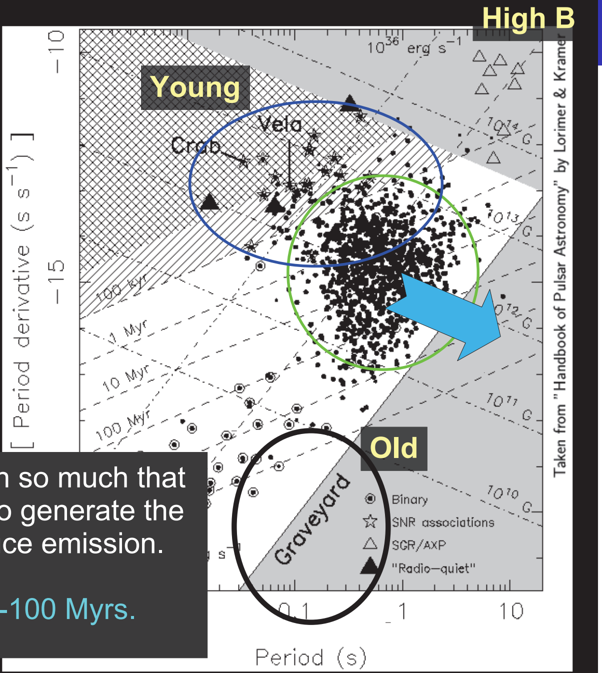
Pulsar Flavors

Young PSRs

(high B, fast spin, very energetic)

Normal PSRs

(average B, slow spin)

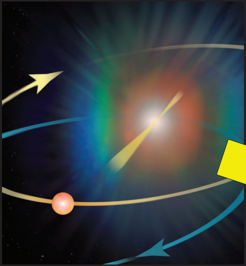


Taken from "Handbook of Pulsar Astronomy" by Lorimer & Kramer

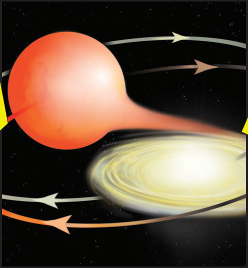
Eventually they slow down so much that there is not enough spin to generate the electric fields which produce emission.

Their lifetimes are 10-100 Myrs.

Millisecond Pulsars: via “Recycling”

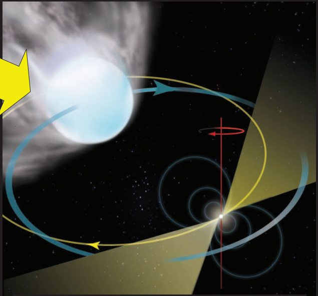


Supernova produces a neutron star



Red Giant transfers matter to neutron star

Alpar et al 1982
Radhakrishnan & Srinivasan 1984



Millisecond Pulsar emerges with a white dwarf companion

Picture credits: Bill Saxton, NRAO/AUI/NSF

Pulsar Flavors

Young PSRs

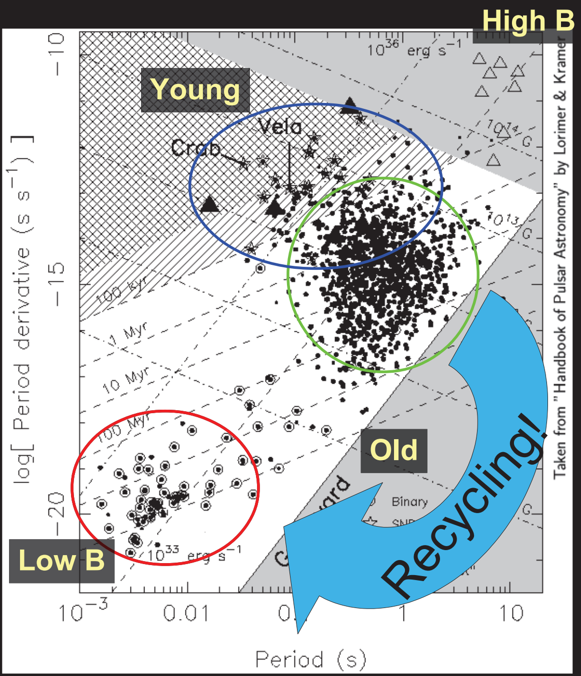
(high B, fast spin, very energetic)

Normal PSRs

(average B, slow spin)

Millisecond PSRs

(low B, very fast, very old, very stable spin, best for basic physics tests)



Taken from "Handbook of Pulsar Astronomy" by Lorimer & Kramer

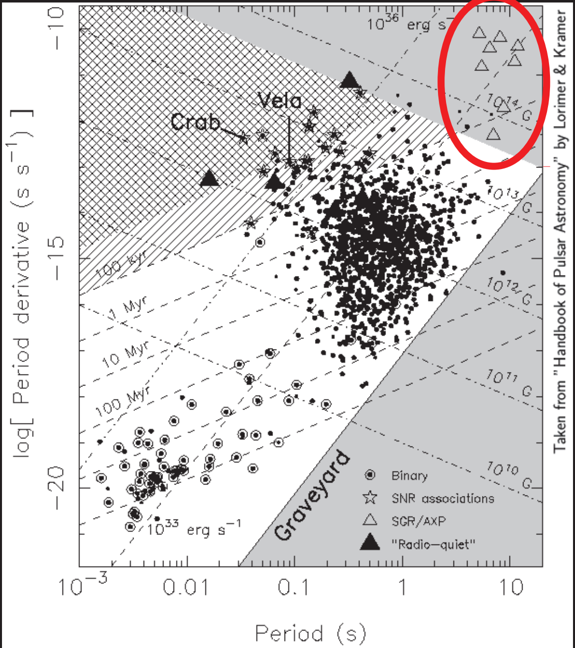
What's a Magnetar?

Neutron stars with extremely strong magnetic fields:

$10^{14\text{-}15}$ Gauss

(~1000x stronger than normal PSRs)

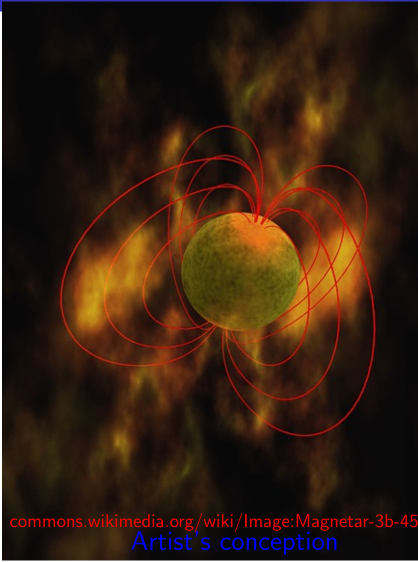
Powered by decay of magnetic field, not rotation!



Taken from "Handbook of Pulsar Astronomy" by Lorimer & Kramer

Magnetars – Extreme Neutron Stars

- Anticipated 1992 by Duncan & Thompson
- Characterized by superstrong magnetic fields, $B \sim 10^{15}$ G
- Likely physical explanation for soft gamma repeaters (SGRs) and anomalous X-ray pulsars (AXPs)
- Superstrong fields lead to strong braking of the rotation rate, which is observed.
- Estimates are that 1 in 10 supernovae produces a magnetar, not a normal star.
- Strong fields generated by a convection-driven, globally-extending, dynamo in the proto-neutron star if the rotation rate is faster ($>$ 100 Hz) than usual.
- Strong fields decay within 10,000 yrs, then activity (X-ray and γ-ray emission) stop.
- Given the observed number of magnetars, there could be 30 million or more dead magnetars in the Galaxy.



commons.wikimedia.org/wiki/Image:Magnetar-3b-45

Artist's conception

- SGR 1900+14, despite its large distance of 20,000 light years, on the night of August 27, 1998, ionized ionospheric atoms to daytime levels.

Why Highly Magnetized Neutron Stars?

Spin down of star to about 8 s period in the 10,000 yr age of SNR (magnetic dissipation)

Provide enough energy for flares

Account for short, 0.2 s, duration of the hard spike (timescale of large-scale magnetic field readjustment)

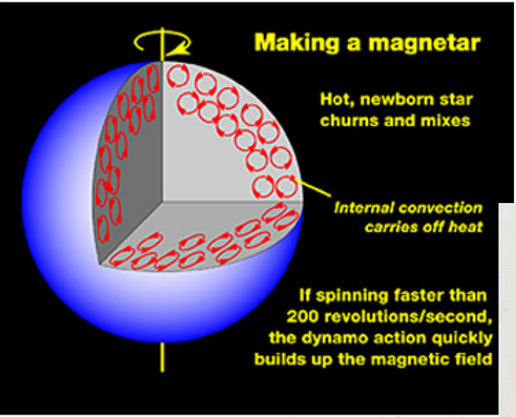
Provide enough energy for steady X-ray glow of SGRs

Make a hot particle gas (fireball) to explain soft tail and intensity of bursts

After fireball disperses, makes a residue held down by magnetic forces

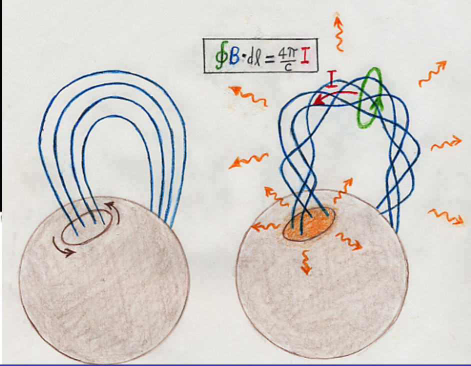
Explains periodicity in light curve

Model for SGRs

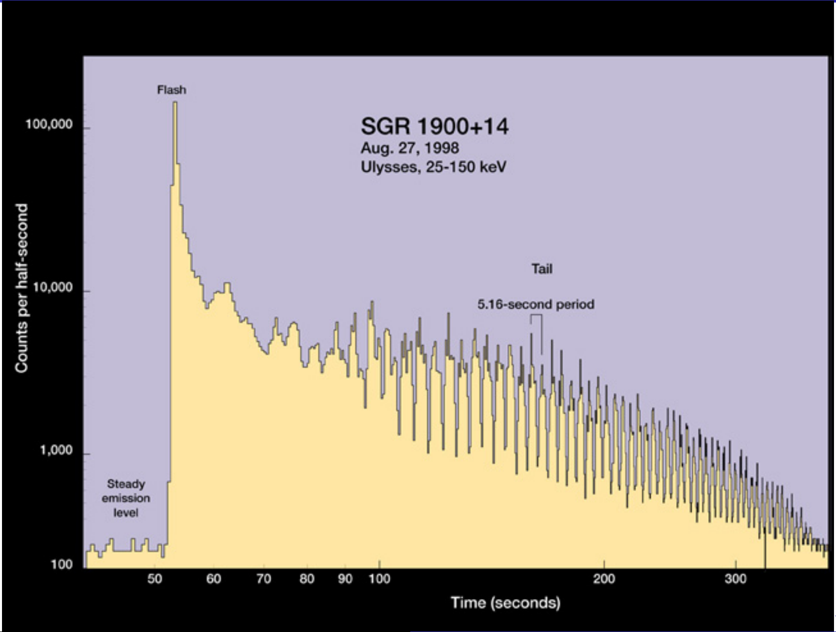


Dave Dooling, NASA Marshall Space Flight Cent

Duncan & Thompson



SGR Light Curve



Some of the 21 Known Magnetars

SGR 1806-20, $d = 50,000$ lt-yr (Sagittarius), $b = 10^{15}$ G. 2004 burst was brightest event outside solar system sighted on Earth. Energy released was 10^{46} erg; from a distance of 10 lt-yr would have destroyed the ozone layer. Ionosphere expanded

SGR 1900+14, $d = 20,000$ lt-yr (Aquila). In 1998, forced NEAR Shoemaker to shut down and saturated detectors BeppoSAX, WIND and RXTE. A ring seen was probably formed in 1998 burst.

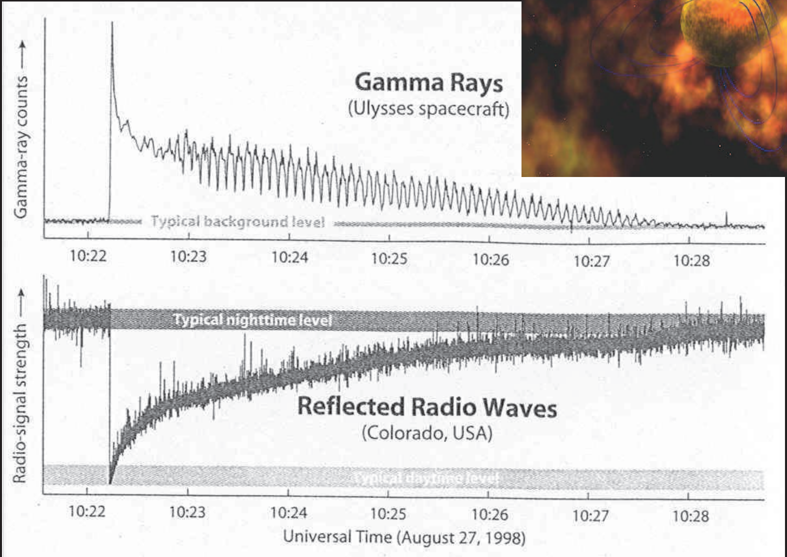
SGR 0501+4516, $d = 15,000$ lt-yr

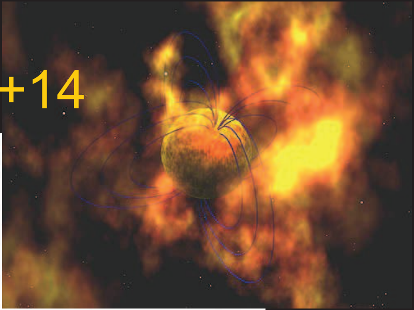
1E 1048.1-5937, $d = 9000$ lt-yr (Carina) is the nearest known magnetar (AXP)

SWIFT J195509+261046, formerly GRB 070610

CXO J164710.2-455216 (AXP) in Westerlund 1 (galactic cluster)

Giant X-ray Flares: Magnetar SGR 1900+14





The Primary Pulsar Telescopes

Arecibo

GBT

Parkes

Jodrell Bank

Pulsars are Precise Clocks

PSR J0437-4715

At 00:00 UT Jan 18 2011:

P = 5.7574519420243 ms
+/- 0.0000000000001ms

The last digit changes by 1 every half hour!

This digit changes by 1 every 500 years!

This extreme precision is what allows us to ***use pulsars as tools*** to do unique physics!

Pulsar Timing: *Pulse Phase Tracking*

Unambiguously account for every rotation of a pulsar over years

Measurement
(TOAs: Times of Arrival)

Model
(prediction)

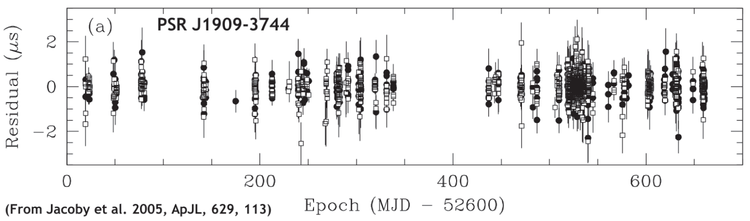
Observation 1

Obs 2

Obs 3

Pulses

Measurement - Model = Timing Residuals

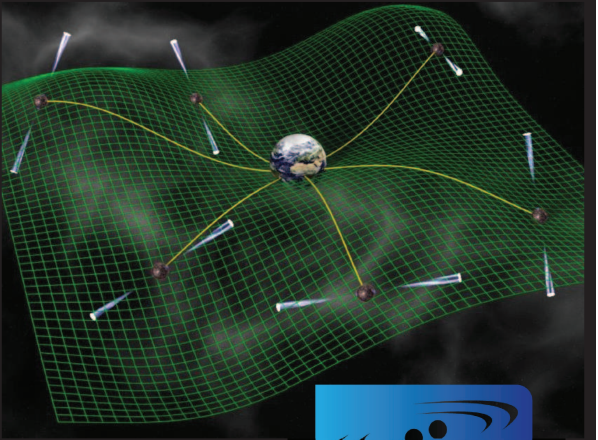


(From Jacoby et al. 2005, ApJL, 629, 113)

200ns RMS
over 2 yrs

Gravitational Wave Detection with a Pulsar Timing Array

- Looking for nHz freq gravitational waves from super massive black hole binaries
- Need good MSPs
- Significance scales directly with the number of MSPs being timed.
- Must time the pulsars for 5-10 years at a precision of ~100 nanosec!
- North American (**NANOGrav**), European (EPTA), and Australian (PPTA) efforts



NANOGrav

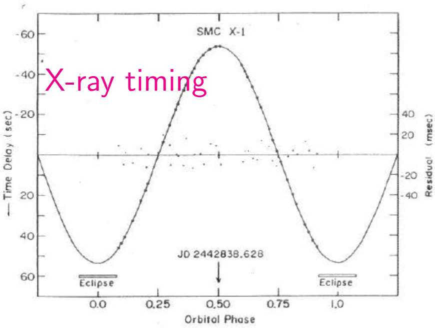
Binary Mass Measurements

Mass function

$$f(M_1) = \frac{P(v_2 \sin i)^3}{2\pi G} = \frac{(M_1 \sin i)^3}{(M_1+M_2)^2} > M_1$$

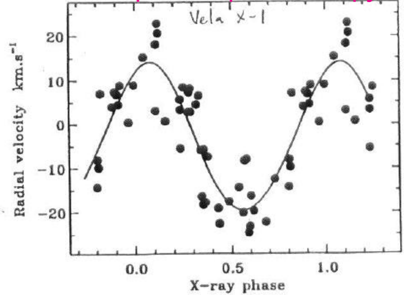
$$f(M_2) = \frac{P(v_1 \sin i)^3}{2\pi G} = \frac{(M_2 \sin i)^3}{(M_1+M_2)^2} > M_2$$

In an X-ray binary, $v_{optical}$ has the largest uncertainties. In some cases $\sin i \sim 1$ if eclipses are observed. If no eclipses observed, limits to i can be made based on the estimated radius of the optical star.



X-ray timing

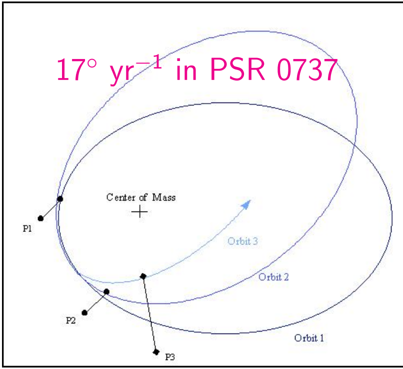
Optical spectroscopy



Pulsar Mass Measurements

Mass function for pulsar precisely obtained.

It is also possible in some cases to obtain the rate of periastron advance and the combined effects of variations in the transverse Doppler effect and the gravitational redshift around an elliptical orbit:



17° yr^{-1} in PSR 0737

$$\dot{\omega} = \frac{3}{1-e^2}\left(\frac{2\pi}{P}\right)^{5/3}\left(\frac{GM}{c^2}\right)^{2/3}$$

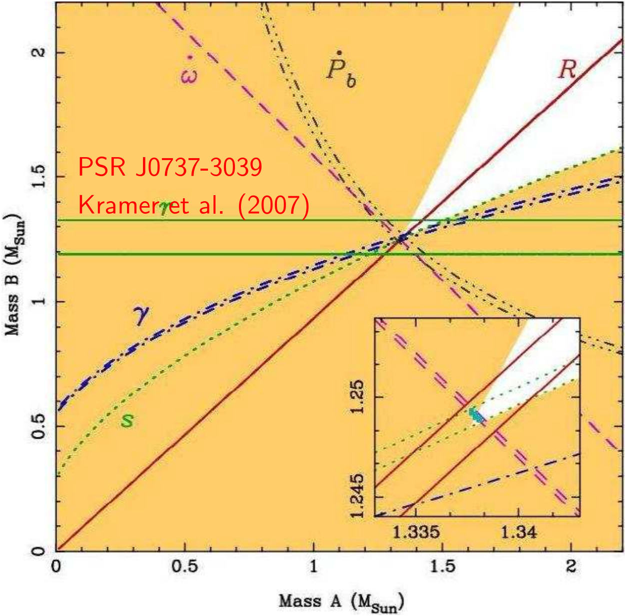
$$\gamma = \left(\frac{P}{2\pi}\right)^{1/3} e M_2 (M + M_2)\left(\frac{G}{M^2c^2}\right)^{2/3}$$

Gravitational radiation leads to orbit decay:

$$\dot{P} = -\frac{192\pi}{5c^5}\left(\frac{2\pi G}{P}\right)^{5/3}(1-e^2)^{-7/2}\left(1+\frac{73}{24}e^2+\frac{37}{96}e^4\right)\frac{M_1M_2}{M^{1/2}}$$

In edge-on systems, it's possible to detect Shapiro time delay, with parameters r (imagnitude) and $s = \sin i$ (shape).

PSR J0737-3039

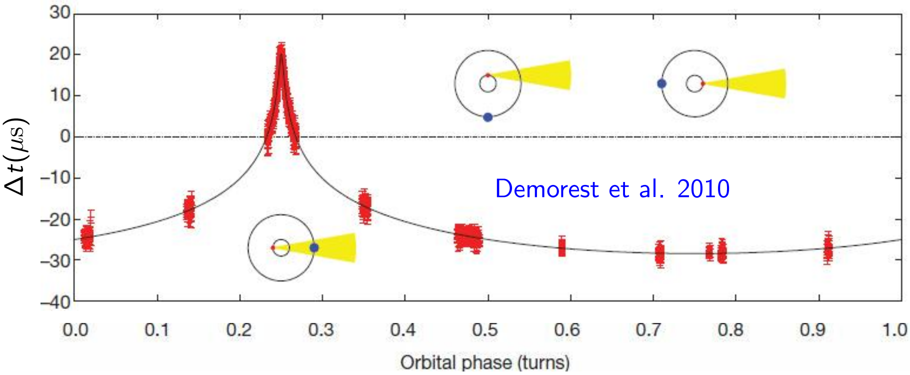


PSR J0737-3039

Kramer et al. (2007)

PSR J1614-2230

3.15 ms pulsar in 8.69d orbit with 0.5 $M_\odot$ white dwarf companion.
Shapiro delay tightly confines the edge-on inclination: $\sin i = 0.99984$
Pulsar mass is 1.928 ± 0.017 $M_\odot$
Distance > 1 kpc, $B \simeq 1.8 \times 10^8$ G



Demorest et al. 2010

Shapiro Time Delay

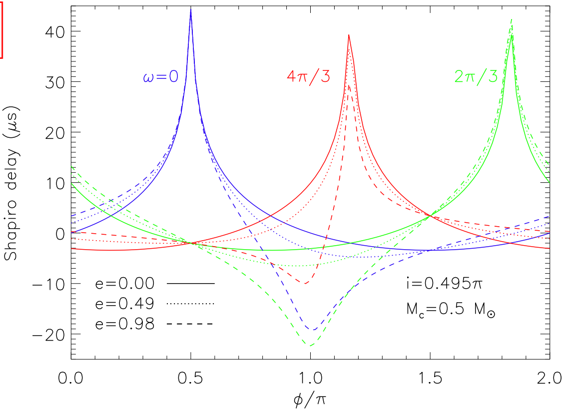
Shapiro delay produces a delay in pulse arrival times

$$\frac{\delta_S(\phi)}{2M_2 T_\odot} = \ln\left[\frac{1+e\cos\phi}{1-\sin(\omega+\phi)\sin i}\right]$$

with ϕ the **true anomaly**, the orbital angular parameter defining the position of the pulsar relative to the periastron position ω.

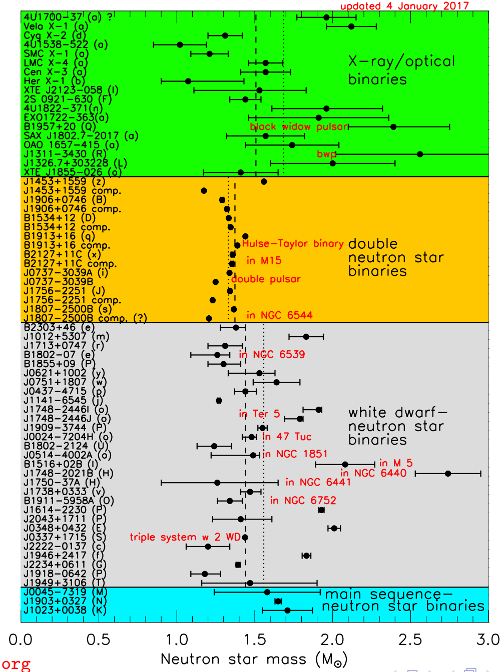
$$T_\odot = \frac{GM_\odot}{c^3} = 4.9255\ \mu\mathrm{s}$$

δ_S is a periodic function with approximate amplitude



$$\Delta_S \simeq 2M_2 T_\odot \left|\ln\left[\left(\frac{1+e\sin\omega}{1-e\sin\omega}\right)\left(\frac{1+\sin i}{1-\sin i}\right)\right]\right|.$$

This is large only if $\sin i \sim 1$ or if both e and $\sin\omega$ are nearly unity.



vanKerkwijk 2010

Romani et al. 2012

Although simple average mass of w.d. companions is 0.23 $M_\odot$ larger, weighted average is 0.04 $M_\odot$ smaller

Demorest et al. 2010
Fonseca et al. 2016

Antoniadis et al. 2013

Barr et al. 2016

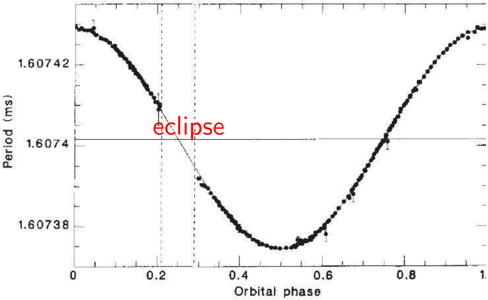
Champion et al. 2008

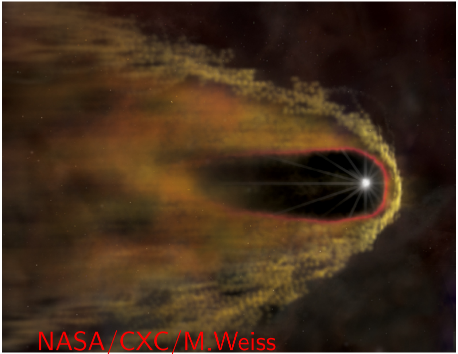
Lattimer (2012)
stellarcollapse.org

Black Widow Pulsar PSR B1957+20

A 1.6ms pulsar in circular 9.17h orbit with $\sim 0.03\ M_\odot$ companion.
The pulsar is eclipsed for 50-60 minutes each orbit; the eclipsing object has a volume much larger than the secondary or its Roche lobe.
The pulsar is ablating the companion leading to mass loss and the eclipsing plasma cloud. The secondary may nearly fill its Roche lobe.
Ablation by the pulsar leads to secondary's eventual disappearance.
The optical light curve tracks the motion of the secondary's irradiated hot spot rather than its center of mass motion.

pulsar radial velocity




NASA/CXC/M.Weiss

Black Widow Pulsar PSR B1957+20

The peak radial velocity of the center of mass of component *i* is:

$$K_i = 2\pi \frac{a_i \sin i}{P}$$

$$q = \frac{M_P}{M_*} = \frac{a_*}{a_P} = \frac{K_*}{K_P}$$

$$K_* = K_{obs}\left(1 + \frac{R_*}{a_*}\right)$$

Companion's hot spot has a smaller orbit than its center of mass.

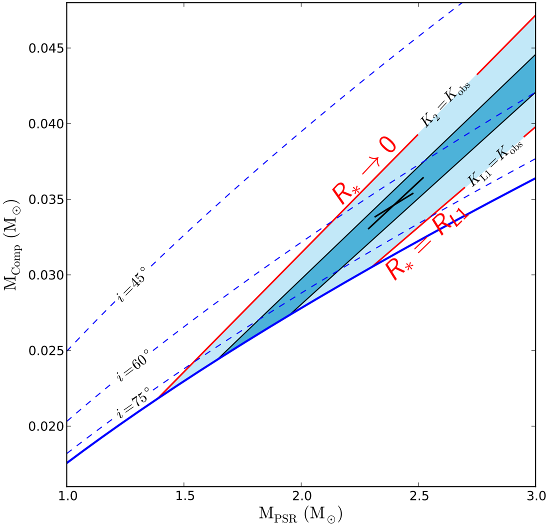
$$M_P = q(1+q)^2 \frac{P}{2\pi G}\left(\frac{K_P}{\sin i}\right)^3$$

Modeling of light curve shape suggests that

$M_P > 1.8 M_\odot, \quad \sin i < 66^\circ$

Most probable values:

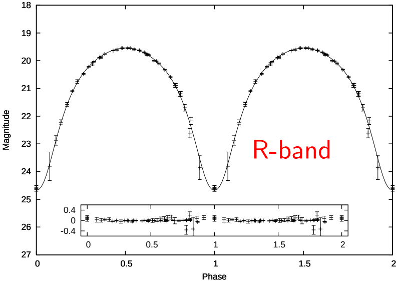
$2.20 M_\odot < M_P < 2.55 M_\odot$

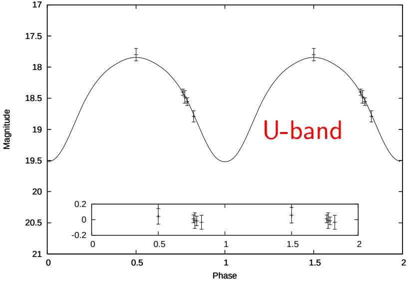


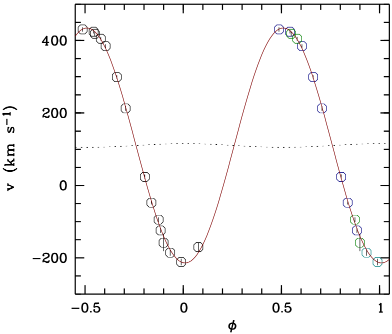
van Kerkwijk 2010

Companion Light Curves and Radial Velocity

Reynolds et al. 2007







System Masses

Radial velocity amplitudes:

$$K_i = 2\pi a_i \sin i/P$$

Light curve shape ⇒ $i \simeq 65 \pm 2^\circ$

$K_1 = 5.093\ \mathrm{km/s}$, $K_{obs} = 324 \pm 3\ \mathrm{km/s}$

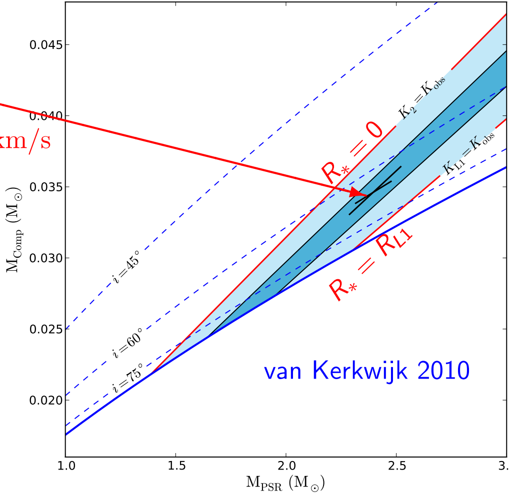
$$q = M_p/M_* = K_*/K_p = a_*/a_P$$

$$K_* \simeq K_{obs}(1 + R_*/a_*)$$

$$G(M_P + M_*)P^2 = (4\pi)^2(a_P + a_*)^3$$

$$R_{L1} = 0.46 a_p (1+q)^{2/3}$$

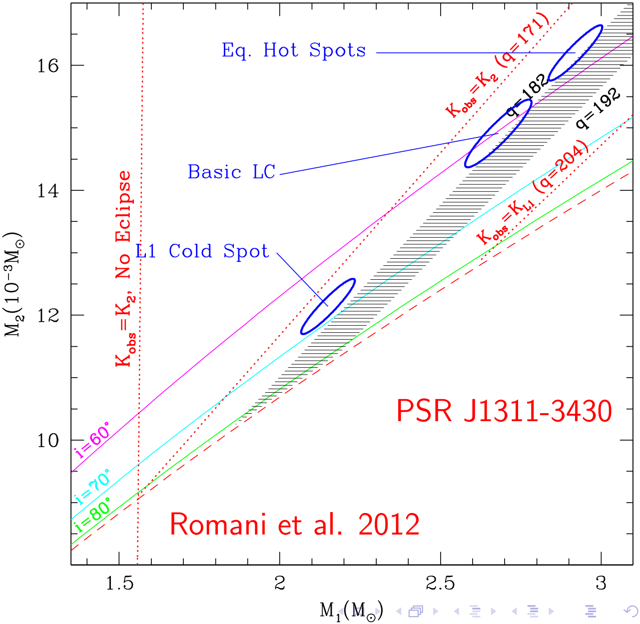
$$M_P = q(1+q)^2 \frac{P}{2\pi G}\left(\frac{K_P}{\sin i}\right)^3$$



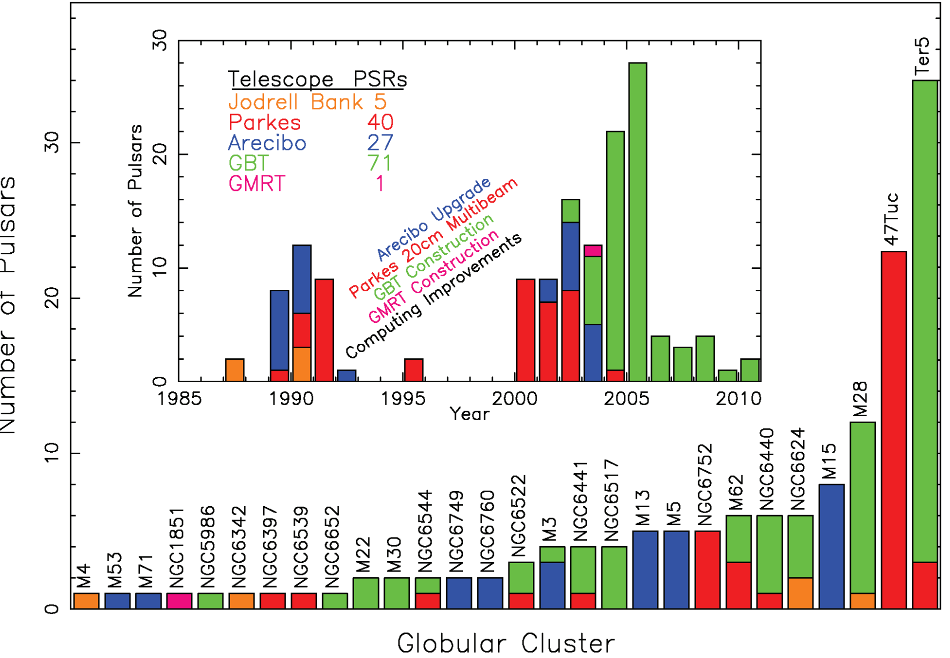
van Kerkwijk 2010

$$\left(\frac{2\pi}{P}\right)^2 \frac{(a_P \sin i)^3}{G} = \frac{(M_* \sin i)^3}{(M_P + M_*)^2} = 5.2\times10^{-6} M_\odot$$

Another Black Widow Pulsar



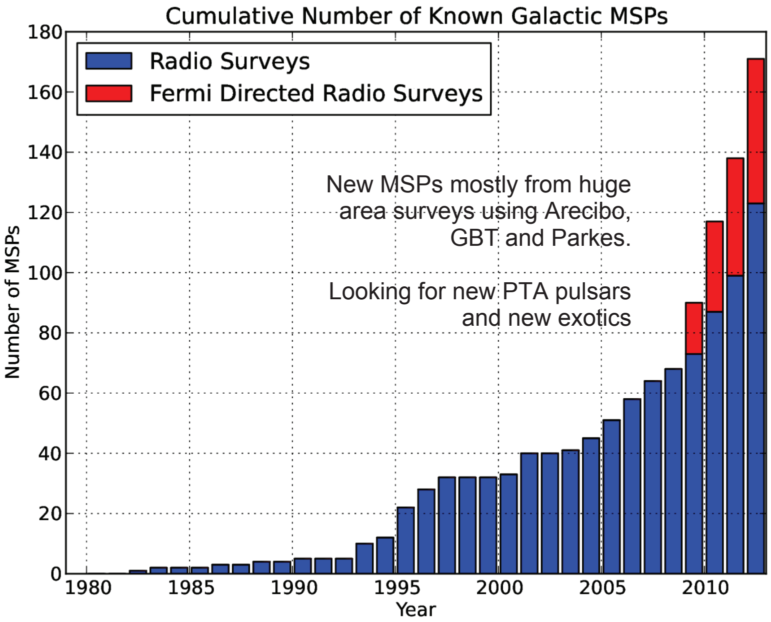
144 pulsars in 28 clusters



Precession in 15+ PSRs in Clusters

Name	P(ms)	Pb(d)	E	Mcmin	Mtot	Mpmed
Ter5ai	21.228	0.85	0.440	0.49	**1.887(1)**	**1.32**
Ter5J	80.338	1.10	0.350	0.34	**2.205(3)**	**1.74**
Ter5I	9.570	1.33	0.428	0.21	**2.1660(5)**	**1.87**
Ter5Z	2.463	3.49	0.761	0.22	**1.743(3)**	**1.48**
Ter5U	3.289	3.57	0.605	0.39	**2.246(2)**	**1.73**
Ter5W	4.205	4.88	0.016	0.25	**2.09(7)**	**1.69**
Ter5X	2.999	5.00	0.302	0.25	**1.92(1)**	**1.60**
M5B	7.947	6.85	0.138	0.13	**2.3(1)**	**2.12**
M28C	4.158	8.08	0.847	0.26	**1.631(1)**	**1.33**
NGC6544B	4.186	9.96	0.747	1.22	**2.567(2)**	**1.17**
NGC6441A	111.601	17.33	0.712	0.59	**2.0(2)**	**1.35**
NGC1851A	4.991	18.79	0.888	0.92	**2.44(5)**	**1.34**
NGC6440B	16.760	20.55	0.570	0.08	**2.8(3)**	**2.68**
Ter5Q	2.812	30.30	0.722	0.46	**2.422(9)**	**1.79**
M28D	79.835	30.41	0.776	0.38	**1.2(7)**	

SMR, PCCF, Freire et al 2007, 2008a+b, Lynch et al 2011



New MSPs mostly from huge area surveys using Arecibo, GBT and Parkes.

Looking for new PTA pulsars and new exotics

Black Widows and Redbacks in Galactic Field

	Pulsar	P_s (ms)	$E/10^{34}$ (erg/s)	d_{NE2001} (kpc)	P_B (hrs)	M_C (min. solar)
Old BWs	B1957+20 F	1.61	[illegible]	2.5	9.2	0.021
	J0610-2100 F	3.86	0.23	3.5	6.9	0.025
	J2051-0827	4.51	0.53	1.0	2.4	0.027
New BWs	J2241-5236^{P} F	2.19	2.5	0.5	3.4	0.012
	J2214+3000^{G8} F	3.12	1.9	3.6	10.0	0.014
	J1745+1017^{N} F	2.65	1.3	1.3	17.5	0.014
	J2234+09^{P} F	3.63	[illegible]	[illegible]	10	0.015
	J0023+09^{G3} F	3.05	3.4	0.7	3.3	0.016
	J1301+08^{G8} F	1.84	??	0.7	6.5	0.024
	J1124-36^{G3} F	2.41	??	1.7	5.4	0.027
	J2256-1024^{3} F	2.29	5.2	0.6	5.1	0.034
	J2047+10^{G8} F	4.29	??	2.0	3.0	0.035
	J1731-1847^{1}	2.3	7.6	2.5	7.5	0.04
	J1810+17^{G3} F	1.66	4.0	2.0	3.6	0.044
New RBs	J1628-32^{G8} F	3.21	??	1.2	5.0	0.16
	J1816+45^{4} F	3.19	??	2.4	8.7	0.16
	J1023+0038^{3} F	1.69	[illegible]	0.6 (1.3)	4.8	0.2
	J2215+51^{G3} F	2.61	[illegible]	3.0	4.2	0.22
	J1723-28^{2}	1.86	??	0.75	14.8	0.24
	J2129-04^{G3} F	7.61	??	0.9	15.2	0.37

F=Fermi detected; 1. HTRUPS Keith et al. 2010 2. PMB pulsar, Crawford et al. 2010 3. GBT Drift Scan 4. GBNCC
Fermi targeted discoveries: G8=GBT 820 MHz, G3=GBT 350 MHz, N=Nancay, P=Parkes

3 Black Widows over past 25 years

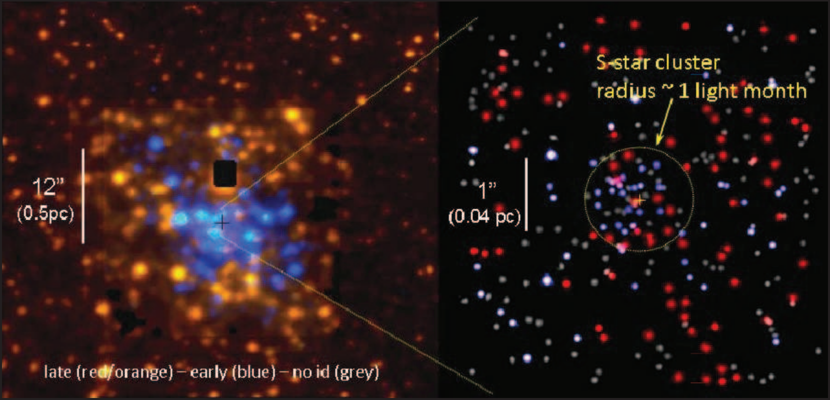
9/11 new Black Widows in past 3 yrs from Fermi!

4/6 "Redbacks" in past 3 yrs from Fermi!

Table from Mallory Roberts

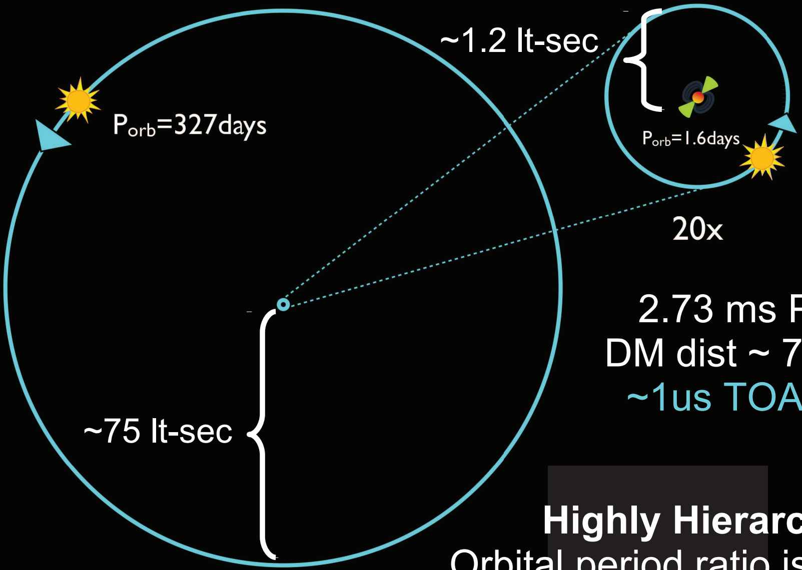
Pulsars around SgrA*?

- 100s of massive young stars within ~0.1pc
- 10s-100s of PSRs with orbits <100yrs? (e.g. Pfahl & Loeb 2004)
- PSR timing much more precise than IR imaging and astrometry



Genzel, Eisenhauer, Gillesen 2010

J0337+1715: Stellar Triple System



2.73 ms Pulsar
DM dist ~ 750 pc
~1us TOA / min

Highly Hierarchical:
Orbital period ratio is ~200

A fully solved system:

(thanks to Anne Archibald)

- Full three-body, high-precision model
- All masses and inclinations fully determined to high precision (10^{-4} for masses):
        - Mpsr = 1.442 Msun
        - Mc_inner = 0.198 Msun
        - Mc_outer = 0.411 Msun (another WD!)
    - Orbits inclinations are co-planar at 39.18(4) deg
    - Inner mass ratio perfectly matches optical value
    - Apsides are aligned (despite inner orbits e ~ $7\text{x}10^{-4}$!)
- Osculating orbital elements are obvious