Lecture 3
Pulsars and pulsar wind nebulae

- Pulsars
  - Characteristic parameters
- Pulsar wind nebulae
  - Properties
  - Evolution
- Exotic central compact objects - Magnetars
The Crab Pulsar

http://www.jb.man.ac.uk/~pulsar/Education/Sounds/sounds.html
• Pulsars are rotating, magnetized neutron stars

• They steadily dissipate their rotational energy via relativistic winds

• Confinement of these outflows generates luminous pulsar wind nebulae (PWN)

• PWN can be seen across the em spectrum
The mass accreted from the disk is guided by the B field toward the magnetic poles. The material is then compressed and heated to $\sim 10^8 K$. As this hot column rotates it is observed as X-ray pulses.
Pulsar spin down luminosity: the rate at which rotational energy is dissipated

$$E_{\text{dot}} = 4\pi^2 I \frac{P_{\text{dot}}}{P^3}$$

$I = \text{NS moment of inertia} = \frac{2}{5} M R^2$

$$3 \times 10^{28} \text{ erg/s} \leq E_{\text{dot}} \leq 5 \times 10^{38} \text{ erg/s}$$

(J2144-3933) (Crab)

Typically only pulsars with $E_{\text{dot}} > 4 \times 10^{36} \text{ erg/s}$ produce prominent PWN (~15 known)

J2144-3933 is the slowest PSR ever detected
The characteristic age of a pulsar can be estimated from:

\[ \tau = \frac{P}{2 P_{\text{dot}}} \]

Though this equation overestimates the true age of the system

PWN are observed only for pulsars younger than \(~20000\) yrs
The equatorial surface magnetic field strength
(in the case of a dipole magnetic field)

\[ B = 3.2 \times 10^{19} (P P_{\text{dot}})^{1/2} \text{ Gauss} \]

Inferred B fields range from \(10^8\) G for millisec pulsars to \(10^{15}\) G for “magnetars”

Pulsars with prominent PWN have:

\[ B \sim 10^{12} \text{ to } 5 \times 10^{13} \text{ G} \]
Basic picture of PWNe

• A charge-filled magnetosphere surrounds the PSR

• Particles are accelerated near the polar caps of the PSR or in outer regions that extend to the light cylinder

• The wind of matter and antimatter leaving the PSR magnetosphere is dominated by Poynting flux, with much smaller contribution from particle energy flux.
Pulsar wind nebula

The deposition of energy by the pulsar generates a population of energetic e- and e+ , which in turn power a synchrotron emitting nebula

**RADIO:** \[ S_\nu \propto \nu^\alpha \] with \(-0.3 \leq \alpha \leq 0\)

**X-RAY:** \[ N_E \propto E^{-\Gamma} \] (number of photons with energy between E and E+dE)

with \[ \Gamma = (1-2\alpha) \sim 2 \]

This steepening in the spectrum implies one or more spectral breaks
The spectral break is produced for a power-law electron spectrum, if there is constant injection of particles plus a finite synchrotron-emitting lifetime.

The break frequency is:

\[ \nu_b = 10^{21} \left( \frac{B_{\text{PWN}}}{10^{-6} \text{ Gauss}} \right)^{-3} \left( \frac{t}{10^3 \text{ yrs}} \right)^{-2} \text{ Hz} \]

\( B_{\text{PWN}} \) is the nebular magnetic field

Particles radiating at \( \nu > \nu_b \) do not reach the outer portions of the PWNe
Spectral break in the PWN in G0.9+0.1
The characteristic lifetime of the particles responsible of the synchrotron emission increases as the energy decreases.

The size of the PWN decreases from radio to X-rays.

For an e- of energy E loosing energy to synchrotron radiation, the lifetime is

\[ \text{lifetime} = -\frac{E}{\frac{dE}{dt}} \propto \frac{E}{E^2 B^2} \propto \frac{1}{EB^2} \]

<table>
<thead>
<tr>
<th>Band</th>
<th>electron energy (ev)</th>
<th>electron lifetime (yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radio</td>
<td>$3 \times 10^8$</td>
<td>109000</td>
</tr>
<tr>
<td>Optical</td>
<td>$3 \times 10^{11}$</td>
<td>109</td>
</tr>
<tr>
<td>X-rays</td>
<td>$1.4 \times 10^{13}$</td>
<td>2.4</td>
</tr>
<tr>
<td>Gamma</td>
<td>$1.4 \times 10^{15}$</td>
<td>9 dias</td>
</tr>
</tbody>
</table>
In Crab Nebula, electrons emitting optical photons have a lifetime of only ~100 yrs; those in X-rays live only few years.

Such electrons clearly were not accelerated in the year 1054.
The efficiency of conversion of spin-down luminosity into synchrotron emission is defined by the efficiency factors

\[ \eta_R = \frac{L_R}{E_{\text{dot}}} \sim 10^{-4} \]

\[ \eta_X = \frac{L_X}{E_{\text{dot}}} \sim 10^{-3} \]

Though large variations from these values have been observed.
Gallery of X-ray bright pulsar wind nebulae

3C58

Crab

B1509-58 / G320.4-1.2

Vela

G54.1+0.3

NASA/CXC/SAO/P.Slane et al.

NASA/CXC/ASU/J. Hester et al.

NASA/CXC/MIT/B.Gaensler et al.

NASA/CXC/PSU/G.Pavlov et al.

NASA/CXC/U.Mass/F.Lu et al.
PWN Evolution

I. PWN inside a free expansion SNR
The NS and its PWN are initially surrounded by an expanding SNR (located near its center)

The PSR is embedded in slowly moving unshocked ejecta from the explosion

The PSR wind is highly over-pressured and the PWN expands rapidly (supersonically) driving a shock into the ejecta
In the vacuum dipole approximation:

\[ E_{\text{dot}0} = 1.6 \times 10^{39} \left( \frac{B_p}{3 \times 10^{12} \text{ G}} \right) \left( \frac{R_{ns}}{12 \text{ km}} \right)^6 \left( \frac{P_0}{20 \text{ ms}} \right)^{-4} \text{ erg/s} \]

\[ R_{\text{PWN}} \sim 1.5 \left( E_{\text{dot}0} \right)^{1/5} \left( E_{\text{SN}} \right)^{3/10} \left( M_{ej} \right)^{-1/2} t^{6/5} \]

For \( E_{\text{dot}0}=10^{38} \text{ erg/s} \), \( E_{\text{SN}}=10^{51} \text{ erg} \), \( M_{ej}=10 \text{ M}_\odot \),
\( t=1000 \text{ yr} \), \( R_{\text{PWN}} \sim 1.1 \text{ pc} \)

\( B_p \) is the dipole magnetic field at the pole of the star
\( R_{ns} \) radius of the neutron star
\( P_0 \) initial period
The PWN expansion steadily increases and the PWN remains centered

Matheson & Safi-Harb 2005
SNR G11.2-0.3

Chandra X-rays

VLA radio + X-rays
SNR Kes 75
The young SNR G292.0+1.8 and its PWN

Optically this is an “Oxigen-rich” SNR, with metal rich ejecta. Progenitor mass about 25 to 40 Mo
Interaction with the SNR reverse shock

When the SNR enters in the adiabatic phase:

The reverse shock \textit{collides} with the outward moving PWN forward shock after a time $t_{\text{coll}} < t_{\text{Sedov}}$
(few thousand years)
The reverse shock compress the PWN by a large factor, and the PWN responds with increase in pressure and a sudden expansion.

The system reverberates several times on a timescale of several thousand years with a sudden increase in the nebular magnetic field.

The crushing of the PWN produces RT instabilities, which can produce a chaotic, filamentary structure and mixing of thermal and non-thermal material within the PWN.

COMPLICATIONS:
- PSR proper motion that takes it away from SNR (~ 300 – 400 km/s)
- Asymmetric expansion of SNR
PWN in the SNR G0.9+0.1
II. PWN inside a Sedov SNR

• Once the reverberations have faded, the PSR can again power a steadily expanding bubble.

• This bubble expands into hot, shocked ejecta at subsonic speeds, and no longer accelerates

• If $t < \tau_0$ the initial spin-down timescale of the PSR,

\[ E_{\text{dot}} \text{ is } \sim \text{ constant and } R_{\text{PWN}} \propto t^{11/15} \]

• If $t > \tau_0$, then $E_{\text{dot}}$ is decaying and

\[ R_{\text{PWN}} \propto t^{3/10} \]
At this point, the distance traveled by the PSR from the explosion site become comparable or even larger than the radius of an equivalent spherical PWN around a stationary PSR.

The PSR escapes from its original wind bubble, leaving behind a relic PWN.

Then it generates a new, smaller PWN around its current position.
Figure 3: (a) A 2.4-GHz Parkes map of the Vela SNR (G263.9–3.3), (Duncan et al. 1996). A limb-brightened shell and a central radio PWN can both be seen. The cross indicates the location of the associated pulsar B0833–45, while the white arrow indicates its direction of motion (Dodson et al. 2003). The fact that the pulsar is neither at nor moving away from the PWN’s center indicates that a reverse shock interaction has taken place. (b) The composite SNR G327.1–1.1. An 843 MHz Molonglo image is shown in red (Whiteoak & Green 1996), while a 0.2–12 keV *XMM-Newton* image is in blue. The radio morphology consists of a faint shell enclosing a central PWN. The peak of X-ray emission indicates the likely position of an (as yet undetected) pulsar. The offset between the X-ray and radio nebulae indicates that the radio nebula is a “relic PWN” as discussed in §3.3. The pulsar is likely to be still moving subsonically through the SNR interior, generating a new PWN as it moves away from its birthsite.
When the PSR has moved ~ 70% of $R_{\text{SNR}}$, the sound speed of the shocked ejecta drops and eventually the space motion of the PSR becomes supersonic.

A bow shock is formed
The mouse

Gaensler et al. 2004
IC443: radio, optical and X-rays
G341.2+0.9

Giacani y col. 2001

PSR B 1643-43

W44-PSR B

Giacani y col 1997
For standard parameters, it is expected that a PSR cross its SNR shell after \( \sim 40,000 \) yr.

The injection of energy from the pulsar may brighten and re-energize the SNR shell during its passage.
Spectral steepening in all directions away from the central zone. To the E the old shell is rejuvenated by PSR relativistic electrons.
PWN in the SNR CTB80
III. PSR in the interstellar gas

Once outside its SNR, the motion of the PSR is often highly supersonic resulting in a bow-shock PWN.

When the PSR propagates through HI, the forward shock is visible in H$\alpha$, as well as in radio and X-rays (synchrotron from shocked wind)

The “black widow”, PWN around PSR B1957+20

Green: optical, Red: X-rays
(blue background stars)
Stappers et al. 2003
Formation of torus and jet structures

- Rotation of the PSR forms an expanding, toroidal magnetic field.
- The magnetization parameter varies with latitude being much larger at the poles than at the equator, resulting in a toroidal structure of the wind.
- The magnetic collimation also produces jet-like flows along the PSR rotation axis.
In this case, kink instabilities in the toroidal field may transform $E_{\text{kin}}$ into $E_{\text{particle}}$, thus accelerating particles and brightening the shell.

This may explain the curved nature of the jets and their change in brightness on timescales of months.
PWN in the SNR MSH15-52 with torus and jets

Figure 7: Multi-wavelength images of the PWN powered by the young pulsar B1509–58. *ROSAT* PSPC data (in blue contours, at levels of 5%, 10%, 20%, 40% and 60% of the peak) show the extent of the X-ray PWN (Trussoni et al. 1996), while 843 MHz Molonglo data (in red) correspond to the surrounding SNR G320.4–1.2 (Whiteoak & Green 1996). TeV emission from HESS is shown in green (Aharonian et al. 2005b). The cross marks the position of PSR B1509–58.
The end of PWNe

Eventually most PSRs will end up in low density regions, far from the Galactic plane while $E_{\text{dot}}$ drops.

There motion will not longer be supersonic and their energy output insufficient to power a synchrotron PWN.

PSRs must end their lives surrounded by “ghost nebulae”, a slowly expanding cavity of relativistic material.

Alternatively, old PSRs in binary systems can be spun up via accretion from the companion.
AXP, GRB, CCO, magnetars etc
Statistics

- In our Galaxy there are: **265** catalogued SNRs
- It is expected that ~85% of SN explosions produce neutron stars: SN Ib/c + SN II ~**225** SNRs with NS
- Number of catalogued PSR: **1794**
  
- Certain or possible SNR/NS association < **100**
Exotic central compact objects

- radio-quiet/ radio-silent NS (RQNS)
- anomalous X-ray pulsars (AXRP)
- soft gamma-ray repeaters (SGRS)
Star with $M > 10M_\odot$ → core collapse → SN → neutron star

If the fall-back is large → black hole

modest → disk accretor

little or none →

- $B \sim 10^9$ → radio quiet pulsar
  - cooling → rapid
  - nothing

- $B \sim 10^{12}$ → rotation
  - slow
  - thermal X-ray pt. src.
  - synch. nebula

- rapid
  - + companion
    - X-ray pulsar
    (following Helfand)

- $B \sim 10^{15}$ → SGR/AXP Magnetar
Radio-quiet (/ radio silent) neutron stars

- Point sources with extreme spectrum:
  - very bright in X-rays / $\gamma$-rays
  - very faint at optical wavelengths
  - absent in radio

- Several of them located in the centers of SNRs, but also found in isolation (like Geminga)
**Radio quiet**: normal rotation-powered neutron stars non-detected in radio because they are:
* faint
* far
  * the beam is unfavorably oriented

**Radio silent**: NS born with large periods and/or high B

Apparently very high B ($> 4 \times 10^{13}$ Gauss) would inhibit the production of $\text{e}^-/\text{e}^+$ pairs in the magnetosphere, essential for radio emission (Baring & Harding 1998).
Anomalous X-ray pulsars (AXRPs)

- Pulsed in X-rays - Period 5-12 sec
- Luminosity (X) \( \sim 10^{35-36} \) erg/sec >> \( L_{\text{rot}} \)
- Characteristic ages of \( 10^3 \) to \( 10^5 \) yrs
- Soft spectra
- No obvious optical counterpart
- Large magnetic fields \( 10^{13} - 10^{15} \) G
  
  (Sun 1 G, Earth 0.5 G)
**Magnetars** have short (< 1 sec) X-ray and gamma-ray bursts and sudden flux enhancement that decay on timescales of weeks to months.

Too bright to be powered by rotational energy loss.

What is the origin of the high magnetic fields in magnetars? Fossil field from progenitor? Rapid spinning of proto neutron star?

Emission may be connected with magnetic reconnection due to breaking of the NS outer crust.
Radio-quiet neutron stars
Pulsar J1846-0258 (Kes 75)

Age ~ 730 yr
P = 324 ms
B = 5 \times 10^{13} \text{ Gauss}
Edot \sim 1 \times 10^{37} \text{ erg/s}
Lx \sim 2 \times 10^{36} \text{ erg/s}

The youngest known pulsar
Synchrotron age ~885 yr
Radio quiet NSs in Cas A and Puppis A