High-Energy Astrophysics Lecture 9: Pulsars, Supernova remnants and Gamma-ray bursts

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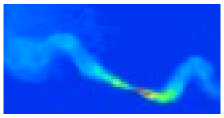


Overview

- **Pulsars** Discovery and identification with neutron stars. Spin-down, age and surface field. Radiation mechanism. Evolution and millisecond pulsars.
- **Supernova remnants** Shell and filled-centre remnants. Dynamical evolution and the Sedov solution.
- **Gamma-ray bursts** Discovery and extragalactic nature. Fireball models and possible progenitors.

Pulsars

Pulsars: historical context

- **1932** Discovery of the neutron (Chadwick)
- **1934** Baade & Zwicky suggest formation of neutron stars in supernova explosions
- **1939** Oppenheimer & Volkov derive radius ~ 20km and mass ~1.4 solar masses for neutron stars.
- **1967** Discovery of pulsating radio sources by Jocelyn Bell during a survey for interplanetary scintillation.
- **1968** Crab pulsar identified (period 33 ms). Pulsars identified with rotating neutron stars.

Discovery of pulsars

Crab pulsar

- At the centre of a supernova remnant of known date (1054).
- P = 33 ms, dP/dt = 36 ns/day
- Centrifugal force $F = RM\omega^2$. If M = 1.4 solar masses, then $R < 1.7 \times 10^5$ m. Compare white dwarf radius (10^7 m).
- Hence neutron star.

Crab nebula, showing pulsar location

Pulsar spin-down

- Rate of loss of rotational kinetic energy

  $-dE/dt = -d/dt(I\Omega^2/2) = -I\,\Omega\, d\Omega/dt$

- If the pulsar radiates primarily by magnetic dipole radiation, then for a dipole moment p_m

  $-dE/dt = \mu_0\Omega^4 p_m^2/6\pi c^3$

- Hence $d\Omega/dt \propto -\Omega^3$
- More generally, define a braking index n such that

  $d\Omega/dt \propto -\Omega^n$

- Typical observed values of $n \approx 2 - 3$, so magnetic braking cannot be the whole story.

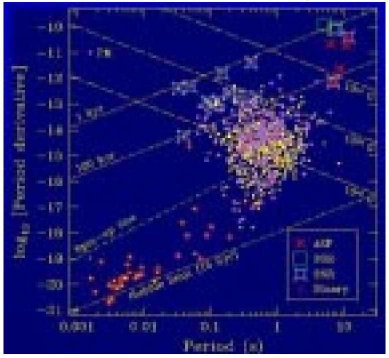
Pulsar ages

- For n = 3, the spin-down age is

  $\tau = P/(2dP/dt)$

- E.g. for the Crab pulsar, P = 33.4 ms, dP/dt = 4.21 x 10^{-13} s/s, so τ = 1257 years. The correct value is 949 years.
- In pulsar-driven supernova remnants like the Crab nebula (see later), the rate of loss of pulsar rotational KE (6.4 x 10^{31} W) is sufficient to power the non-thermal radiation from the nebula (~5 x 10^{31} W).

Observed P - $\dot{P}$ relation for pulsars



Pulsar magnetic fields

- For a dipole field at the surface of the neutron star, the surface field strength is

  $B \approx \mu_0 p_m/4\pi R^3$

  Hence:

  $-d\Omega/dt = (8\pi\Omega^3 R^6 B^2/3\mu_0 c^3 I)$

- For a uniform sphere rotating about its axis, $I = 2MR^2/5$, so

  $B = (3\mu_0 c^3 M/80\pi^3 R^4)^{1/2} (P\, dP/dt)^{1/2}$

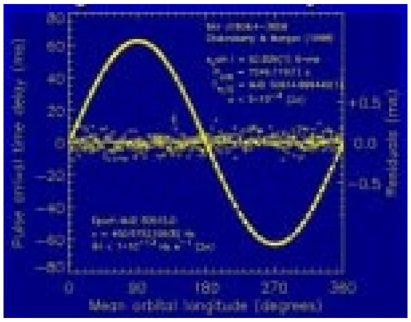
  $\approx 3 \times 10^{15} (P\, dP/dt)^{1/2}$ T

- Typical pulsar surface fields are in the range 2 x 10^6 - 2 x 10^9 T.

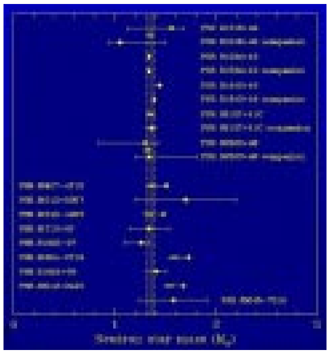
Origin and mass of pulsars

- Created in supernova explosions
- Angular momentum and magnetic flux conserved
- Mass predicted to be close to 1.4 solar masses (details dependent on the equation of state).
- Accretion will increase the mass.
- Measured masses of pulsars in binary systems close to 1.35 solar masses.

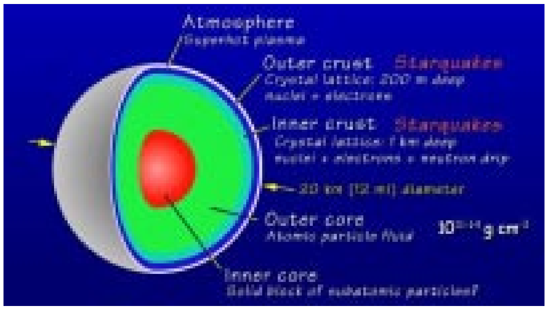
Pulse arrival times for a ms pulsar in a binary system



Masses of pulsars in binary systems



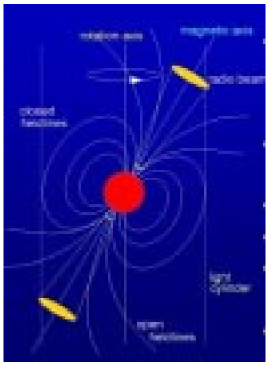
Internal structure of pulsars



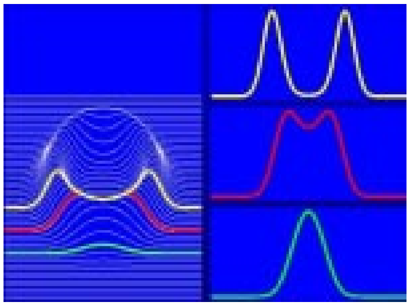
Radio emission from pulsars

- Close to pulsar surface, electromagnetic forces dominate ($F_{elec}/F_{grav} \sim 10^{12}$),
- Consequently, there is a fully-ionised plasma magnetosphere surrounding the pulsar.
- Division between open and closed field lines at the light cylinder, where the rotational velocity $R\Omega = c$.
- Radio emission mechanism from pulsars is not well understood, but must be beamed (to generate pulses) and coherent (to produce the extremely high observed brightness temperatures ~10^{31} K).

Pulsar field and rotation



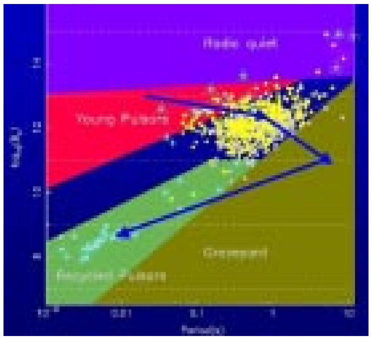
Hollow cone model for pulsar emission



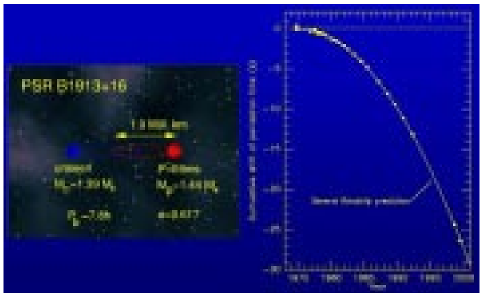
Pulsar evolution

- Isolated pulsars spin down and appear to stop radiating after 10^7 - 10^8 years.
- Millisecond pulsars result from spin-up by mass transfer in an accreting binary system (lecture 8).
- Periods as short as 1.5 ms have been measured.
- Pulsars in low-mass X-ray binaries tend to evolve to a stable configuration of white dwarf + neutron star.
- In high-mass X-ray binaries, there is likely to be a second supernova explosion, usually resulting in the destruction of the binary and the expulsion of the pulsar. Occasionally a NS-NS binary is formed.

Evolution of pulsars in the P - $\dot{P}$ plane



Precession of binary pulsar orbit - a test of General Relativity

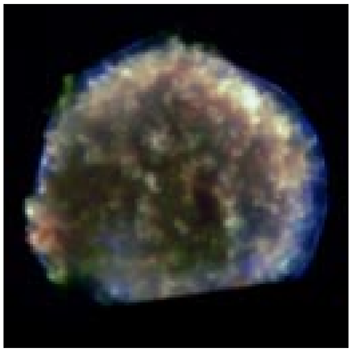


Supernova remnants

Supernova remnants

- **Shell supernova remnants** Radio, optical and X-ray emission comes from an expanding shell. The dynamics are essentially those of an expanding gas cloud.
- **Filled-centre**, **Crab-like** or **plerionic** remnants have brightness distributions which peak in the centre and are associated with pulsars.

Remnant of Tycho's supernova (1572)

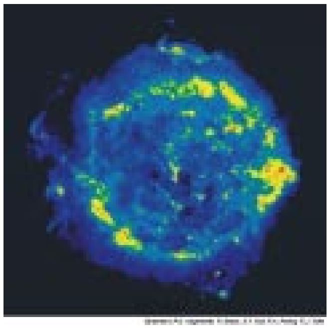


X-ray image: blue represents higher energies

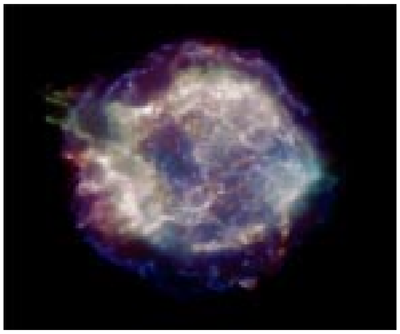
Outer edge is the shock front

Probably Type 1A (white dwarf progenitor); no obvious stellar remnant.

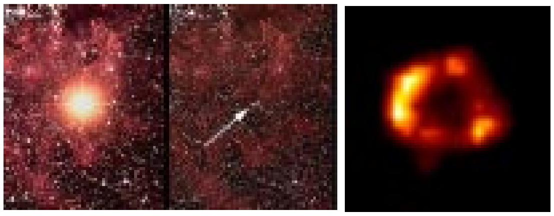
A shell supernova remnant - Cas A (radio)



Cas A (X-ray)

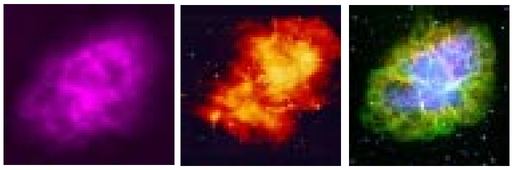


A recent supernova - 1987A



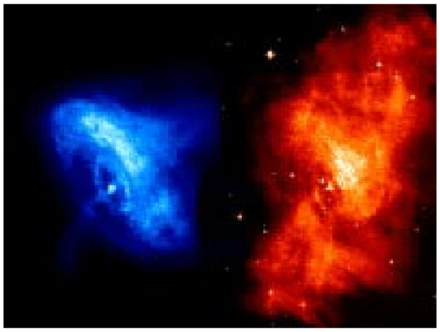
After **Before** **Remnant (X-rays)**

A pulsar-driven supernova remnant - the Crab Nebula

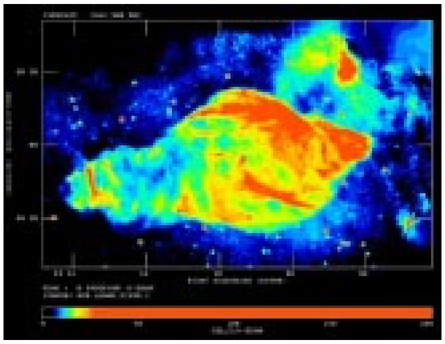


Radio **Near infra-red** **Optical**

Motions in the Crab Nebula



W50 - supernova remnant around SS433



Dynamics of shell supernova remnants

- Four phases:

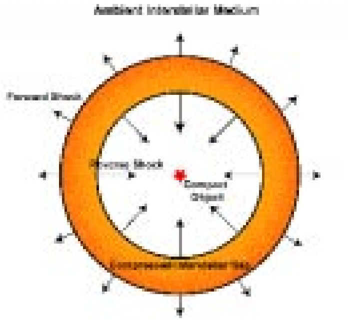
  (1) Energy liberated in collapse is deposited in the outer layers of the star, which are heated to a high temperature and ejected at (1 - 2) x 10^4 km s^{-1}. Uniform expansion with $v \propto r$ until the mass of swept-up material becomes significant. Highly supersonic expansion requires shock in ISM outside a contact discontinuity. The shocked ISM is heated and radiates by thermal bremsstrahlung.

  (2) When swept-up mass > ejected mass, the expansion is described by the adiabatic blast-wave (Sedov-Taylor) solution. Dynamics from dimensional analysis.

The Sedov solution

- Dynamical variables are radius and time.
- Dimensions of E/ρ_0 are L^5T^{-2}, so the dimensionless quantity $(E/\rho_0)\, t^2/r^5$ must control the expansion.
- Hence $r \propto (E/\rho_0)^{1/5}\, t^{2/5}$ (verified for A-bomb explosions!)
- Changes to expansion: outer shells are decelerated, so internal material catches up. Density increases at the rim of the shell and a reverse shock is formed.
- Cas A has mass ratio ~ 1; Tycho is expanding according to Sedov relation.

Sedov expansion phase for a shell supernova remnant



Dynamics of shell supernova remnants - 2

- Two further phases:

  (3) **Snowplough phase**. As the remnant continues to expand, the region behind the shock front cools below 10^9 K and cooling by optical emission lines becomes important (e.g. Cygnus loop; age ~ 50000 years).

  (4) **Subsonic expansion** and dispersal into the ISM.

Relativistic particle acceleration in shell supernova remnants

- Cas A: synchrotron minimum energy ~2 x 10^{41} J (higher if relativistic protons are produced). Compare total KE of explosion ~ ~2 x 10^{44} J. Hence energetically feasible to accelerate particles.
- **First-order Fermi acceleration** in supernova remnant shocks can accelerate particles to ultrarelativistic energies.
- Maximum duration of supernova expansion (~10^5 years) sets a maximum energy ~10^{14} - 10^{15} eV for the accelerated particles, so supernova remnants cannot produce the highest-energy cosmic rays.

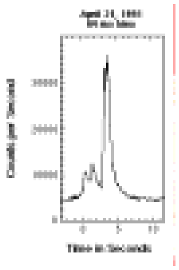
Gamma-ray bursts

Gamma-ray bursts: history

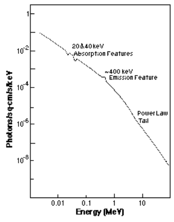
- First reported in 1973 (found during attempts to monitor terrestrial nuclear explosions).
- Brief, intense pulses of gamma-rays.
- Sources isotropically distributed on the sky.
- First localised in 1997. High-energy X-rays from the afterglow of the burst were found with the Beppo-SAX satellite, in turn allowing detection of the optical afterglow and hence a precise position.
- Detection of the host galaxy at $z = 0.695$ established that gamma-ray bursts are distant and therefore extremely luminous.

Gamma-ray bursts

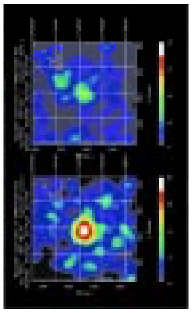
Brief pulses of gamma rays



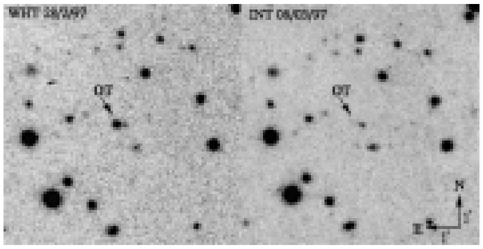
Energy spectrum



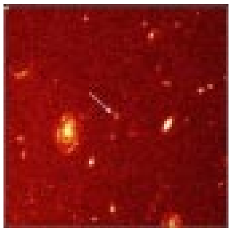
Discovery images of X-ray afterglows



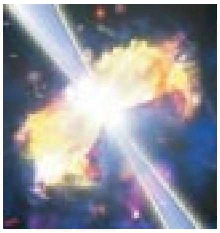
Discovery images of optical afterglows



Gamma-ray burst location and physics



GRB's occur in distant galaxies



A possible formation mechanism - hypernovae

Gamma-ray bursts:

- Small size implied by variability timescale (~ seconds) and high flux require a high photon density at the source. Photon-photon interactions prevent emission of observed MeV photons unless there is **relativistic expansion**.
- **Fireball model**; maybe highly collimated.
- Energy release (if radiation is isotropic) up to 10^{47} J, but with a large dispersion.
- Host galaxies at redshifts up to ~2; all appear to be forming stars. Hence association of gamma-ray bursts with massive stars.
- Possible association of a weak (8×10^{40} J) GRB with a supernova.

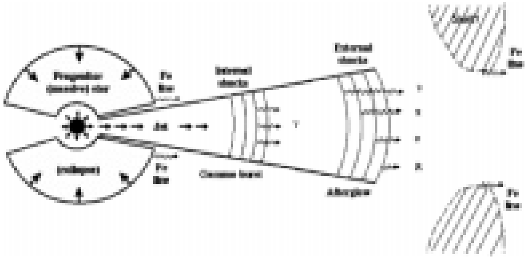
Fireball models

- Analogous to supernovae, except that the expansion is highly relativistic, with small fraction of entrained baryons. Define $\eta = E/M_0c^2$
- Initial adiabatic expansion with internal + kinetic energy = constant; $\gamma \propto r$ until it saturates at $\gamma = \eta$. Then constant-speed ballistic expansion.
- As with SNR, ballistic phase ends when sufficient external material is swept up. Rapid deceleration with $\gamma \propto r^{-3/2}$. Formation of internal and external shocks.
- Transition to the Sedov solution when the expansion becomes non-relativistic.

Radiation from fireballs

- Afterglow emission appears to be synchrotron radiation from external shock.
- Mechanism for the prompt emission is less clear (maybe a combination of synchrotron and inverse Compton emission). Thought to originate from internal shock.
- Line emission detected in X-rays from associated material (not moving at the fireball velocity).

Gamma-ray burst model



GRB progenitors

- Two main mechanisms suggested so far: **collapse of very massive stars** and **neutron star mergers**.
- Collapsar models favoured for the long-duration bursts identified so far, because of association with star-forming regions and high energy output.
- Collimation may be required because the largest energy outputs (10^{47} J) exceed that available from stellar collapse if the radiation is isotropic.
- What drives the expansion? Neutrino annihilation? Electromagnetic energy extraction from a black hole (cf. AGN jets).

Simulation of jet formation in a collapsing star