Introduction to Physics of Neutron Stars

Pulsars — Magnetars

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Me

- 2010–2015 – Bachelor in physics + Master in astrophysics at MU
- 2015–2019 – PhD in astrophysics at MU
- 2014–2019 – Work in industry
- 2020–2022 – Research assistant at Technical University of Berlin: GAČR–DFG project on solar/pulsar coherent (at kinetic scales) radio emission processes
- 2023–2025 – Research assistant at University of Potsdam: PI of a DFG grant — pulsar coherent radio emission processes

Scientific interests:
Solar flares, magnetospheres of stars/compact objects, pulsars, fast radio bursts

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Recommended literature

Books

- Beskin et al., “*Physics of the pulsar magnetosphere*,” 1993
- Lorimer & Kramer, “*Handbook of pulsar astronomy*,” 2005
- Rezolla et al., “*The Physics and Astrophysics of Neutron Stars*,” 2018

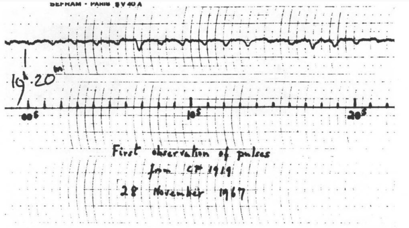
Papers

- Petri, “*Theory of pulsar magnetosphere and wind*”, JPP, 2016
- Kaspi & Beloborodov, “*Magnetars*”, ARAA, 2017
- Zhang, “*Physical Mechanism of fast radio bursts*”, Nature, 2020
- Philippov and Kramer, “Pulsar Magnetospheres and their radiation”, ARAA, 2022

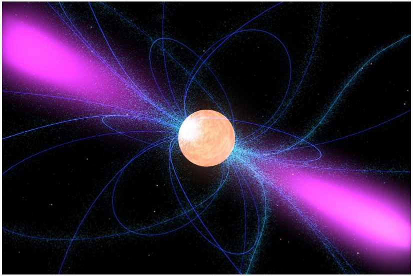
1. Introduction to neutron stars

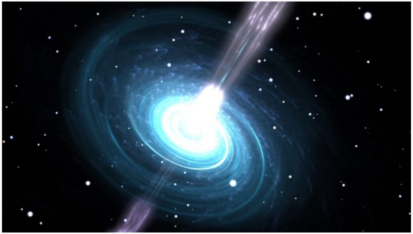
Discovery

- Jocelyn Bell in 1967
- 2000 wires as dipole antennas
- Analyzing roles of paper
- Advisor: Anthony Hewish & Martin Ryle
- Nobel price 1974



Neutron star



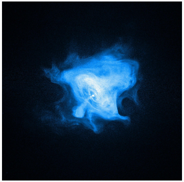


Neutron star properties

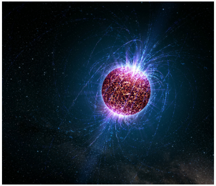
- Remnants of supernovae
- Composed of compressed matter, neutrons
- Very dense $\sim 5 \times 10^{17}$ kg m^{-3}, $> 10n_{\mathrm{atomcore}}$
- Short rotation periods $\lesssim 1$ s
- Radius ~10 km
- Hot surface ($\sim 10^5$ K)
- $M \sim$ 1.1–2.1 M_*
- Strong magnetic fields $\sim 10^8$ T (10^{12} G)
- Radio to γ-rays
- Plasma heating, particle acceleration
- Reliability of shown figures

Neutron stars provide insights into a broad range of various astrophysical phenomena

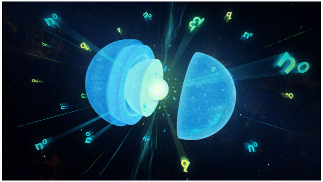
Pulsars



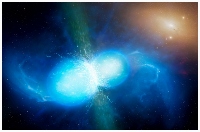
Magnetars



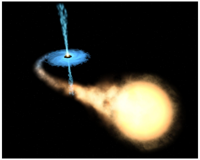
Extreme physical environments



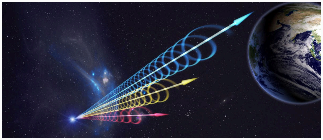
Gravitational waves



X-ray binaries
Microqusars



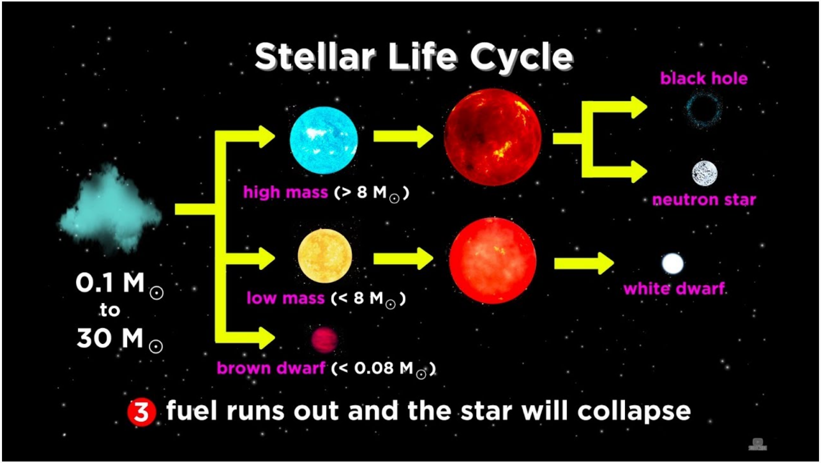
Fast radio bursts



1. Introduction to neutron stars

Neutron star

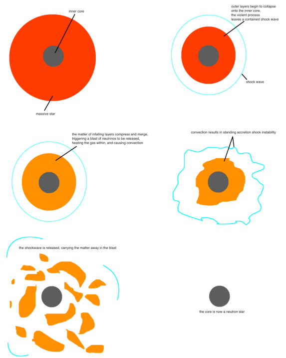
Formation


Stellar Life Cycle
0.1 $M_\odot$
to
30 $M_\odot$
high mass (> 8 $M_\odot$)
low mass (< 8 $M_\odot$)
brown dwarf (< 0.08 $M_\odot$)
black hole
neutron star
white dwarf
3 fuel runs out and the star will collapse

Formation

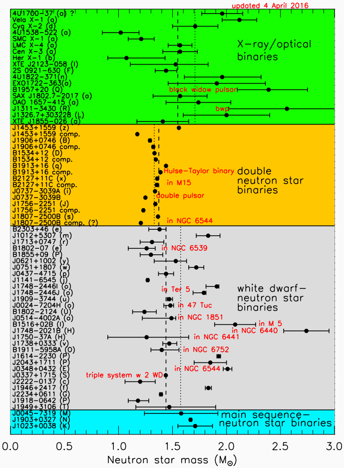
- Initial star mass $\gtrsim 8\,M_*$
- Inner core exceeds Chandrasekhar limit (1.4 M_*)
- Core-collapse supernovae (Type II, or Type Ib,c)
- Central core collapse into a compact object (NS or BH)
- Implosion $\rightarrow$ shock wave
- Outer layers outflow
- Electrons and protons combine $p^+ + e^- \rightarrow n + \nu_e$ (reversed β-decay)
- Initial temperature $10^{11} - 10^{12}$ K drops in few years to 10^6 K (BB in X-rays)
- Compact object kicked ($\sim$100 km s^{-1})

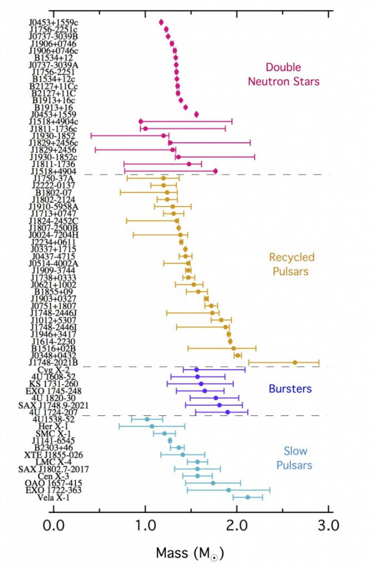
NS = neutron star; BH = black hole




© Malin/Pasachoff/Caltech

Mass of neutron star



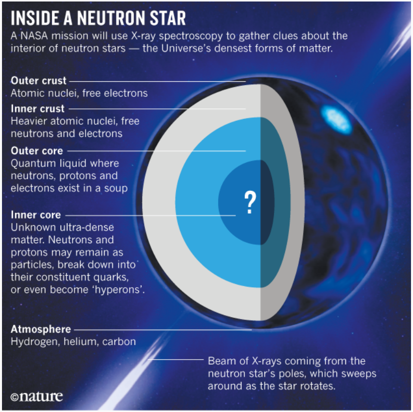


(Latimer & Prakash, 2005)

(Ozel & Freire 2016)

Neutron star inner structure

- Main problem: Equation of state
- Superconductivity and superfluidity of matter
- Strong frozen magnetic fields
- Two main models (AP4 and MS2), Many more existing
- Neutrons hold from decay by strong pressures (otherwise decay in $\sim$15 minutes)



INSIDE A NEUTRON STAR

A NASA mission will use X-ray spectroscopy to gather clues about the interior of neutron stars — the Universe's densest forms of matter.

Outer crust
Atomic nuclei, free electrons

Inner crust
Heavier atomic nuclei, free neutrons and electrons

Outer core
Quantum liquid where neutrons, protons and electrons exist in a soup

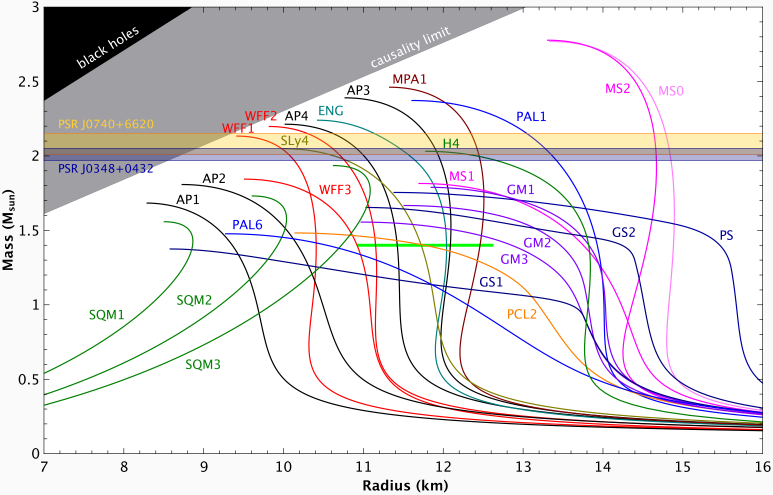
Inner core
Unknown ultra-dense matter. Neutrons and protons may remain as particles, break down into their constituent quarks, or even become 'hyperons'.

Atmosphere
Hydrogen, helium, carbon

Beam of X-rays coming from the neutron star's poles, which sweeps around as the star rotates.

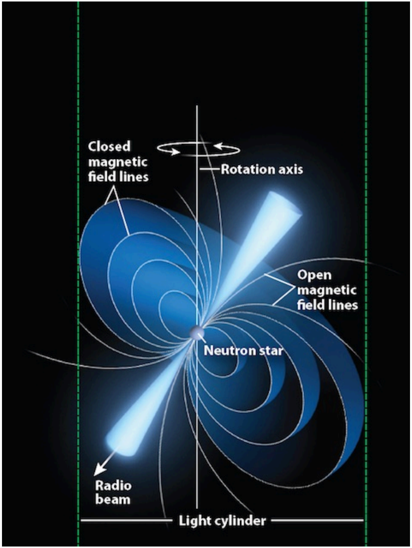
©nature

Neutron star models



Magnetosphere

Toy/book model:



Properties:

- Magnetic dipole
- Higher pole moments under debate
- Inclination between rotation and magnetic axes
- Light cylinder – $R_{\mathrm{LC}} = Pc/2\pi$, $R_{\mathrm{LC}} \sim 500\,R_\star$
- Open and closed magnetic fields
- Atmosphere only a fraction of millimeter thickness

Gravitation effect – Light deflection

- Bending of radiation from surface
- Effect of spaghettification
- Red shift of light from star surface

Spin down

- Rotational kinetic energy of star decreases
- Rotation periods increase
- Measuring slow down → amount of energy release
- Spin-down luminosity

$$\dot{E} = \frac{d(I\Omega^2/2)}{dt} = I\Omega\dot{\Omega} = 4\pi^2 \dot{P} P^{-3} \tag{1}$$

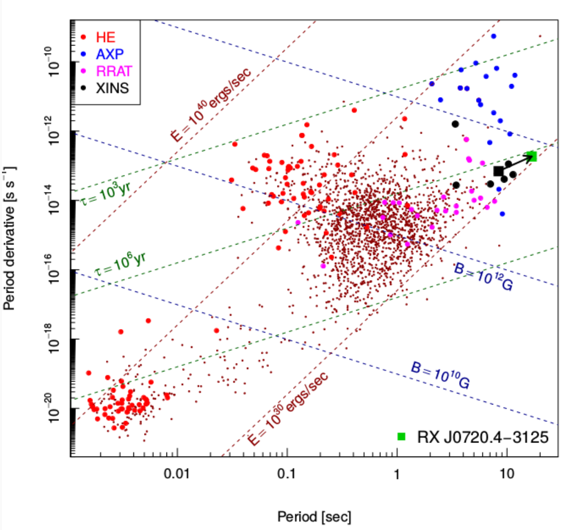
$I = 10^{45}$ g cm^{-2}
$\dot{E} \sim 10^{25}$ W (10^{32} erg s^{-1})
(Other energy releases neglected)

- Dependence of spin down on period
- Dependence of energy release on period
- Spin down caused by dipole radiation power

$$\dot{E}_{\mathrm{rad}} = \frac{2}{3c^3}(B_{\mathrm{surface}} R_\star^3 \sin\alpha) \left(\frac{2\pi}{P}\right)^4 \tag{2}$$

- α is the dipole inclination angle

$P\dot{P}$ diagram



Small dots: Radio pulsars

HE: High energy pulsars

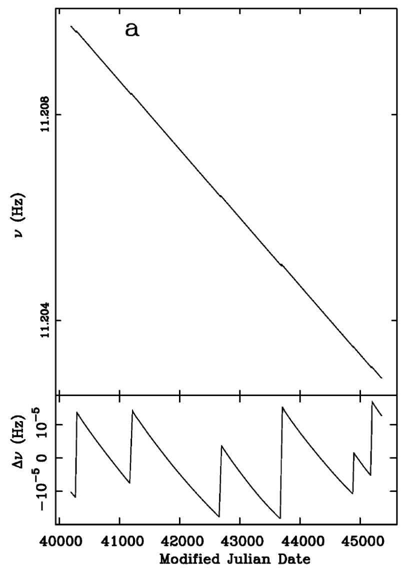
AXP: Anomalous X-ray pulsars

RRAT: Radio transients

XINS: Thermally emitting isolated neutron stars

Glitches

- Sudden changes of rotational period
- 1. Changes in structure of star core
- 2. Changes in structure of mg. fields
  The mg. field disturbance propagate along field lines
- More often for young NS



(Lyne et al. 1999)

Braking index

- Quantifies the spin down
- Dipole emission

$$\dot{E}_{\text{dipole}} = \frac{2}{3c^3}|m|^2\Omega^4\sin^2\alpha \tag{3}$$

- Change of NS rotational frequency

$$\dot{\nu} = -K\nu^n \tag{4}$$

- n is braking index
- Measured as $n = \nu\ddot{\nu}/\dot{\nu}^2$
- Values: 1.4 – 2.9

Estimation of pulsar age

$$T = \frac{P}{(n-1)\dot{P}}\left[1 - \left(\frac{P_0}{P}\right)^{n-1}\right] \tag{5}$$

Characteristic age

$$\tau = \frac{P}{2\dot{P}} \tag{6}$$

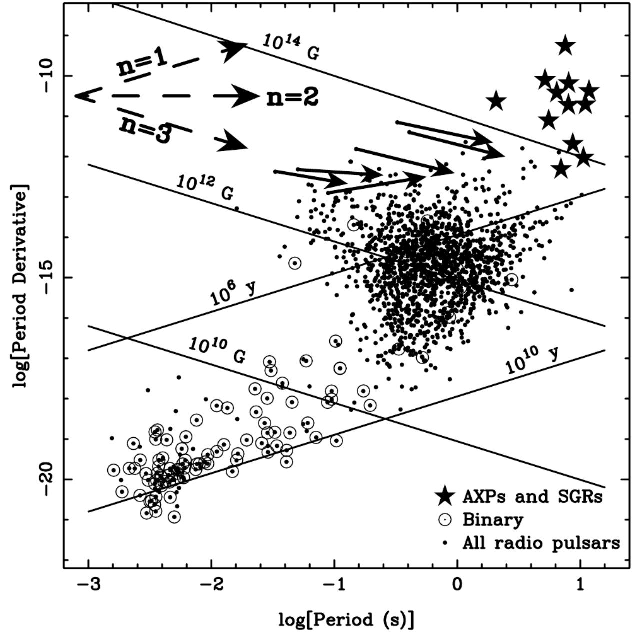
- Crab: $\tau = 1240$ yr, known: 970
- Born periods $P_0 = 14 - 140$ ms

Magnetic fields at surface

$$B_0 = \sqrt{\frac{3c^3}{8\pi^2}\frac{I}{R_\star^6\sin^2\alpha}P\dot{P}} \tag{7}$$

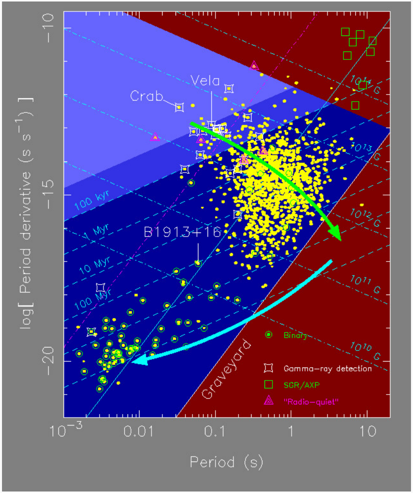
- $B_0 \sim 10^{12}$ G (10^8 T)

Braking index



Pulsar death

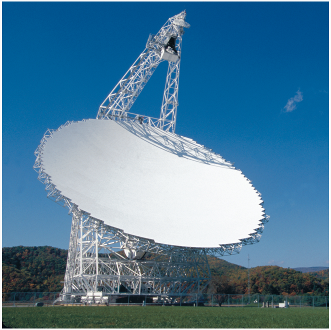
- As NS period increases, efficiency of energy conversion decreases
- For large periods, their emission vanishes
- Can be recycled if in binary



2. Pulsar Observations

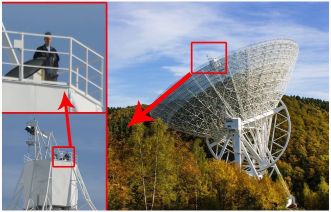
Radio telescopes

GBT



FAST

Effelsberg



Arecibo

Radio telescopes

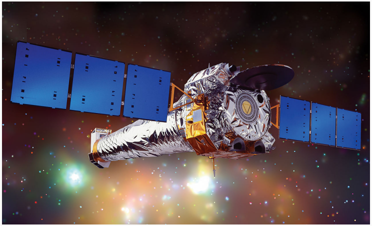
MeerCAT

ALMA

VLA

Telescopes

Chandra

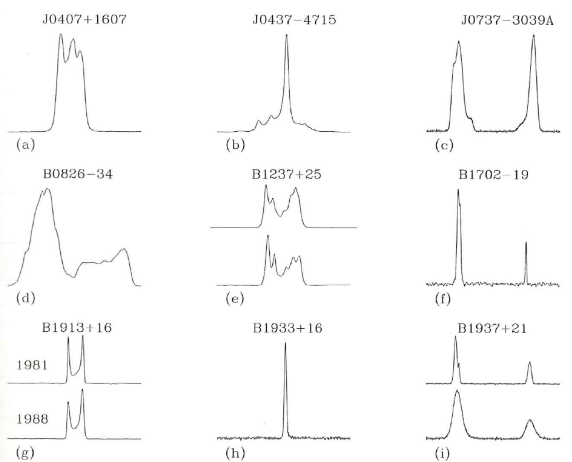


Integral

Fermi

NICER

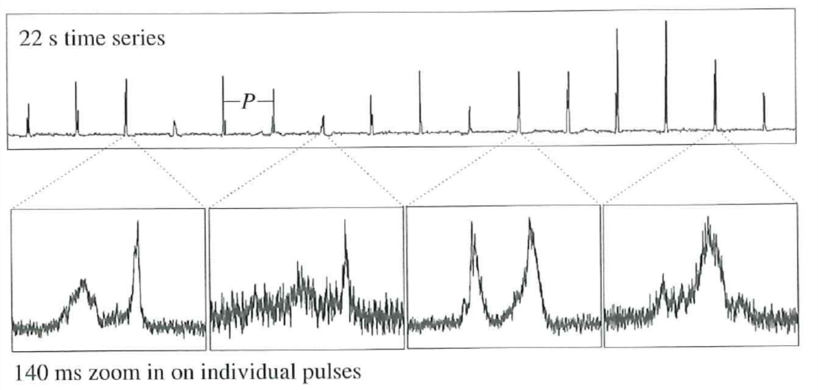
Average pulses



(Lorimer & Kramer 2005) – Effelsberg

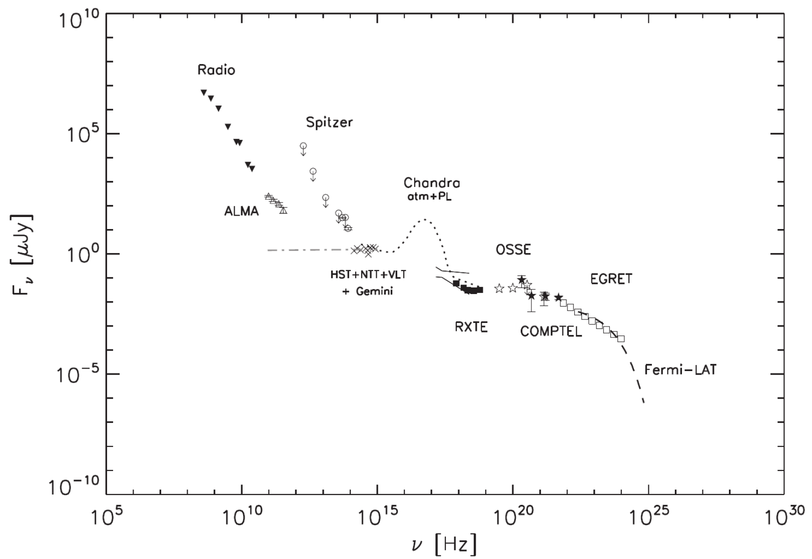
- PSR B1913+16
  separate epochs
- PSR B1237+25
  only part of rotation phase
- PSR B1934+21
  1.4 GHz
- Others 430 MHz
- Interpulses,
  2 explanations
- Duty cycle

Individual pulses



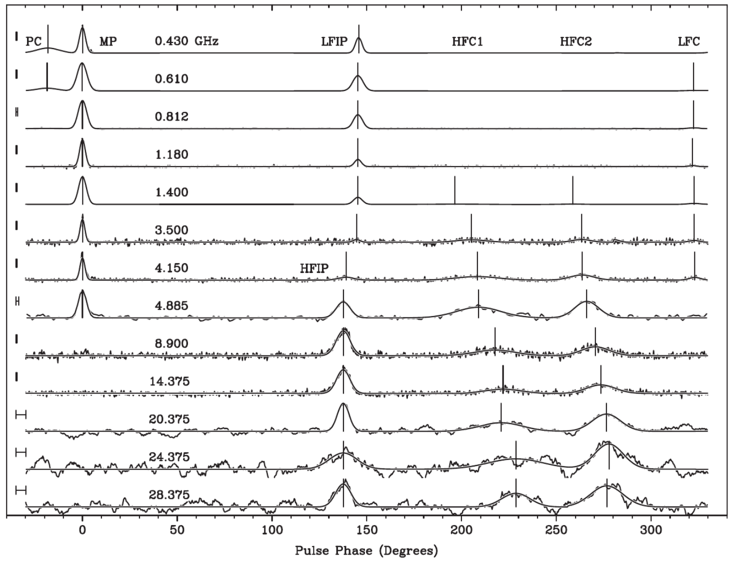
PSR B0301+19, Arecibo, Lorimer & Kramer 2005

Vela pulsar spectrum



(Mignani et al. 2017)

Crab pulsar



(Hankins & Eilek 2015)

Dispersion measure

- Signal delay

$$\Delta t = \frac{1}{c}\left(\int_0^d \frac{dl}{v_\mathrm{g}}\right) - \frac{d}{c} \qquad (8)$$

- Group velocity

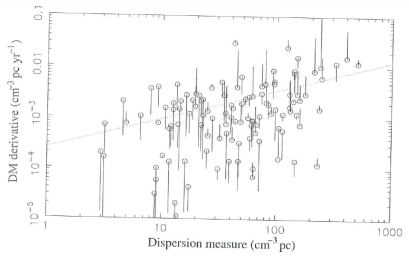
$$v_g = cN = c\sqrt{1-\left(\frac{f_p}{f}\right)^2} \qquad (9)$$

  (N – refractive index, f_p – plasma frequency)

- Signal delay (after expansion of N)

$$\Delta t = \frac{e^2}{2m_e c}\frac{\int_0^d n_e dl}{f^2} = C\frac{DM}{f^2} \qquad (10)$$

$$DM = \int_0^d n_e dl \qquad (11)$$



Faraday rotation

- Difference in phase between left and right polarization

$$\Delta\Psi_{\mathrm{Far}}(f) = \int_0^d (k_R(f) - k_L(f))dl, \tag{12}$$

where

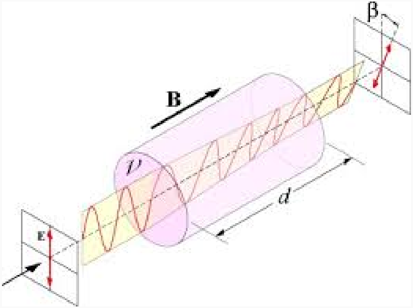
$$k(f) = \frac{2\pi}{c} f \sqrt{1 - \frac{f_p^2}{f^2} \mp \frac{f_p^2 f_B}{f^3}} \tag{13}$$

Then

$$\Delta\Psi_{\mathrm{Far}}(f) = \frac{2e^3}{m_e^2 c f^2} \int_0^d n_e B_{\|} dl \tag{14}$$

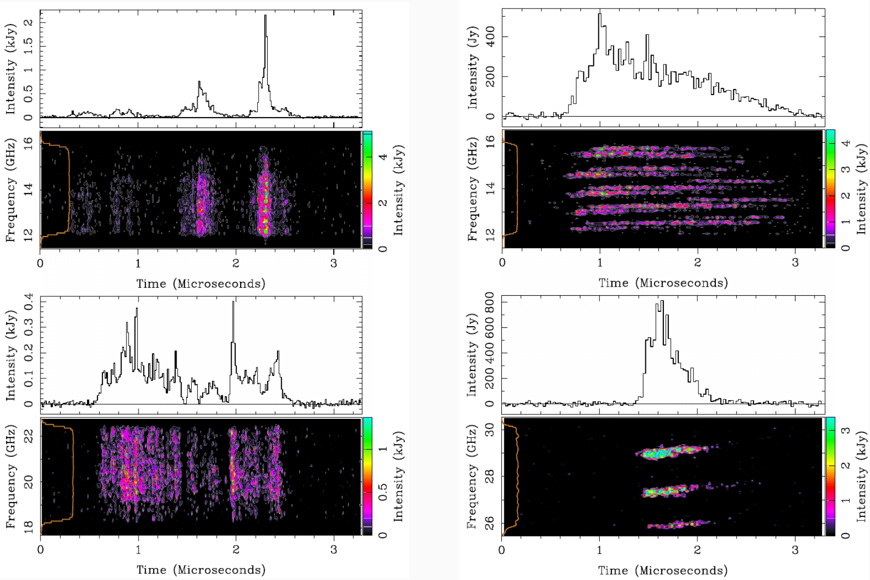
$$\Delta\Psi_{\mathrm{PPA}} = \Delta\Psi_{\mathrm{Far}}(f)/2 \equiv RM/f^2 \tag{15}$$

$$RM = \frac{e^3}{m_e^2 c f^2} \int_0^d n_e B_{\|} dl \tag{16}$$



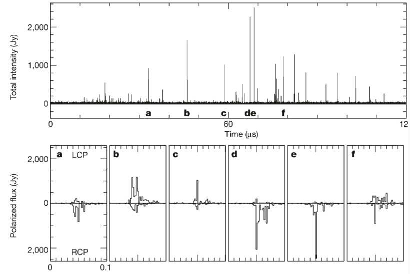
$$\langle B_{\|} \rangle = \frac{\int_0^d n_e B_{\|} dl}{\int_0^d n_e dl} = 1.2\mu\mathrm{G} \left(\frac{RM}{\mathrm{rad\,m^{-2}}}\right) \left(\frac{DM}{\mathrm{cm^{-3}\,pc}}\right)^{-1}$$

Submicrosecond pulses

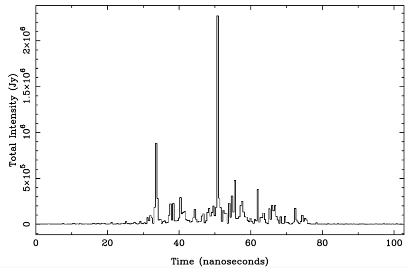


(Hankins & Eilek 2016) – Crab

Nanoshots



(Hankins et al. 2003)



(Hankins & Eilek 2007)

Brightness temperature T_b

- Black body radiation

$$\frac{dI(\nu)}{d\nu} = \frac{2h\nu^3}{c^2}\frac{1}{e^{\frac{h\nu}{kT}} - 1} \tag{17}$$

- Temperature

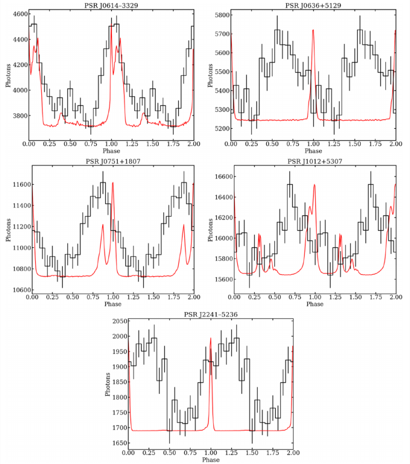
$$T_b = \frac{h\nu}{k_B}\ln^{-1}\left(1 + \frac{2h\nu^3}{I(\nu)c^2}\right) \tag{18}$$

- For $h\nu < kT$
- Brighness temperature

$$T_b = \frac{I(\nu)c^2}{2k_B\nu^2} \tag{19}$$

X-ray observations

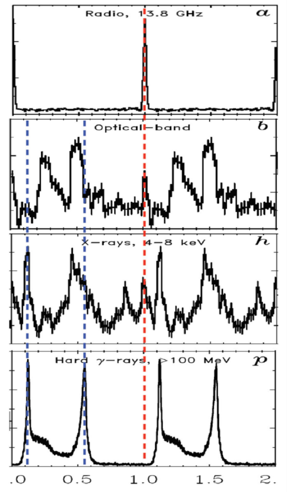
NICER (X-ray) + Nançay (1.4 GHz)



(Guillot et al. 2019)

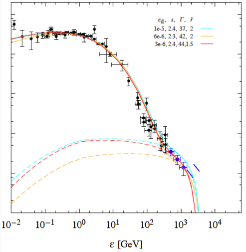
Gamma rays

Vela

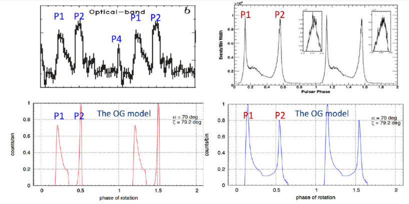


(Kuiper & Hermsen 2015) – Vela

Crab



Vela

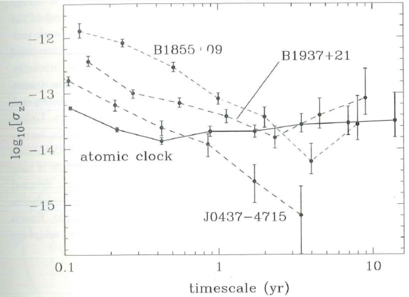


(Rudak 2018) – Crab

3. Physical applications

High precision timing

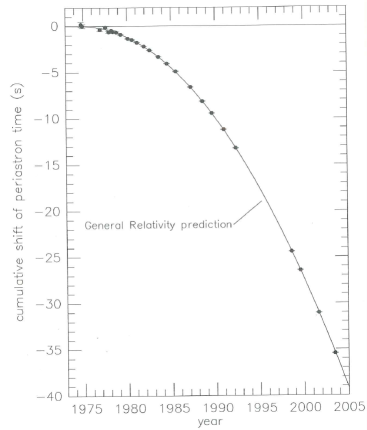
- Precide measurements of times of pulse arrivals
- Depends on time resolution and S/N ratio
- Low variance between individual pulses
- Millisecond pulsars are ideal
- Precision ~ 100 ns for over > 1 year
- Stability of pulsar internal clock limited (due to "unknown" slow down mechanism)
- Cross-check with terrestrial clocks



(Hotan 2005)

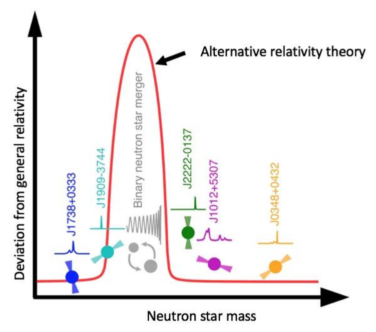
Testing general theory of relativity

Shift of periastron



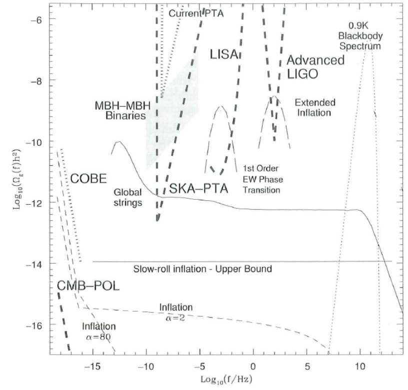
(Weisberg & Taylor 2005)

Window of opportunity



Gravitational waves

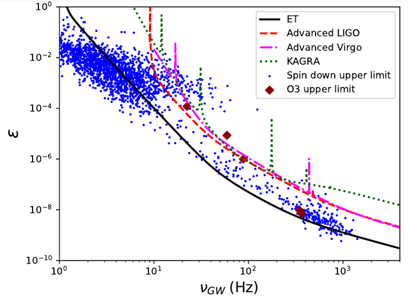
- Continuous gravitational waves
- Compact binary gravitational waves
- (Stochastic gravitational wave)
- (Burst gravitational waves)



(Lorimer & Kramer 2005)

Gravitational waves

- Continuous gravitational waves
- Compact binary gravitational waves
- (Stochastic gravitational wave)
- (Burst gravitational waves)

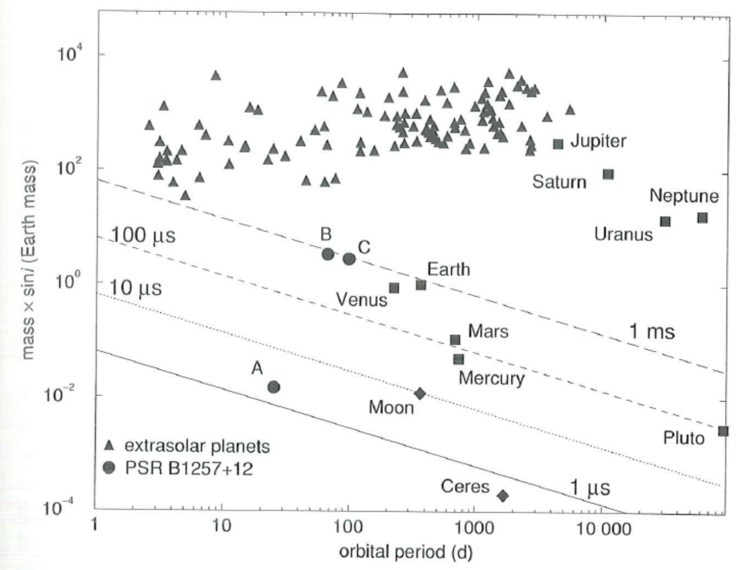


(Haskell & Schwenzer 2021)

Merging neutron stars

- Source of gravitational waves
- Might produce short gamma ray bursts or kilonovae
- Produce a neutron star or a black hole (Tolman–Oppenheimer–Volkoff limit)
- First detection on 17th August 2017 by gravitational waves, later short gamma ray burst
- Total mass 2.82 M_*
- It collapsed into a black hole or a magnetar in milliseconds
- Direct evidence of production of heavier elements and that neutron star is composed of neutrons

Extrasolar planets



(Marcy & Buttler 2000)

Plasma physics in extreme conditions

- Relativistic temperatures

$$\rho = \frac{mc^2}{k_B T} \lesssim 1$$

- Relativistic particle velocity distributions – e.g. Maxwell–Jüttner
- Magnetic fields 10^{14} G ($\omega_{ce} \sim 10^{20}$ Hz)
- Particle Lorentz factors γ up to 10^7, typical 10^3 ($v/c = 0.9999995$)
- Large kinetic energy densities
- Huge field energy densities
- Plasma beta parameter $\beta \ll 1$

4. Magnetospheres of Pulsars

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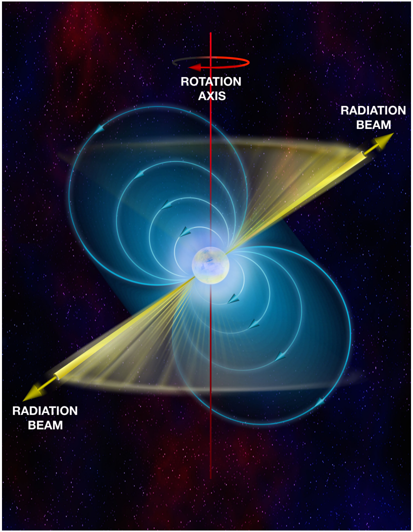
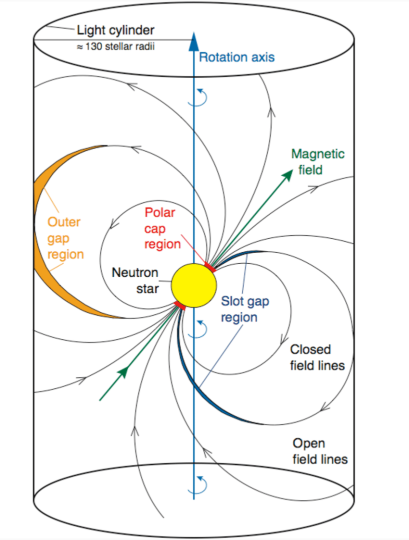
Physics of the magnetosphere

Pulsar model

-





Force free magnetosphere

- Force ratio

$$\frac{f_{EM}}{f_G} = \frac{eE_{\parallel} R_*^2}{GM_* m_p} \approx 10^9 \qquad (20)$$

- Goldreich–Julian density

$$\rho_e = \epsilon_0 \boldsymbol{\nabla} \cdot \boldsymbol{E} = -2\epsilon_0 \boldsymbol{\Omega} \cdot \boldsymbol{B} \qquad (21)$$

- Particle (EB) drift

$$\boldsymbol{v}_{E,d} = \frac{\boldsymbol{E} \times \boldsymbol{B}}{B^2} \qquad (22)$$

  → No currents between e^- and p^+.
  And drift along mg. fields (+ stationarity)
  For deviation from charge-neutrality
  → currents

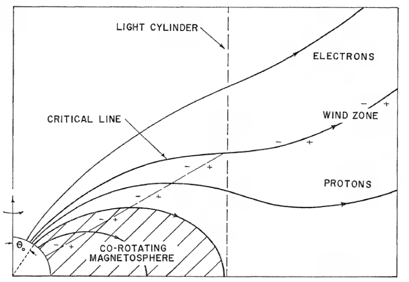
- Ideal MHD

$$\boldsymbol{v}_{E,d} = \boldsymbol{\Omega} \times \boldsymbol{r} - \frac{\boldsymbol{B} \cdot (\boldsymbol{\Omega} \times \boldsymbol{r})}{B^2} \boldsymbol{B}. \qquad (23)$$

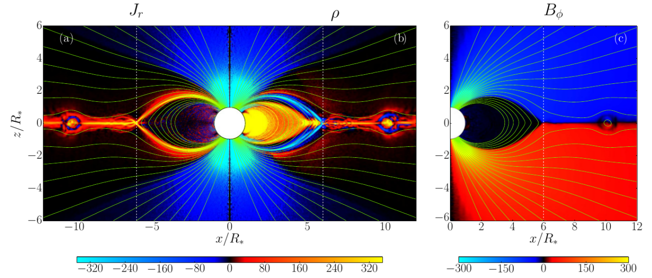
From ideal Ohm's law

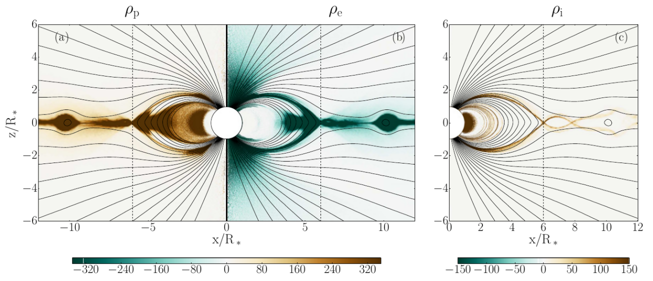
$$\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B} = 0 \qquad (24)$$

Problem between open and closed fields.



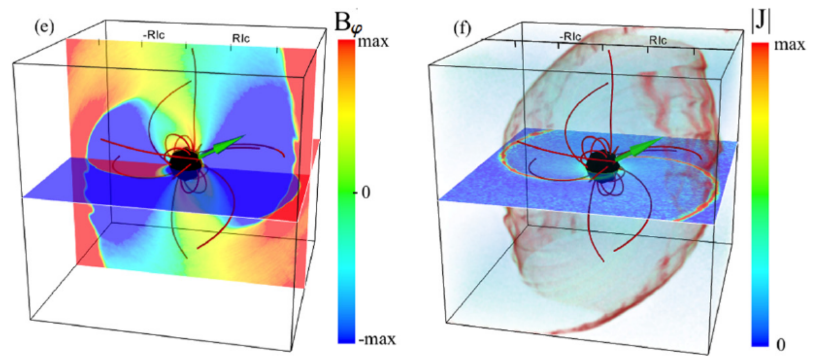
2D magnetospheric simulations





(Chen & Beloborodov 2014)

3D magnetospheric simulations



(Philippov et al. 2015)

Electron-positron production

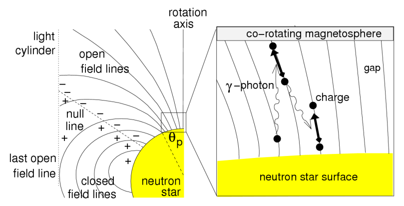
- Breaking of force–free magnetospheric models in regions called gaps
- Electric currents do not compensate plasma co-rotation

$$\nabla \times \boldsymbol{B} = \boldsymbol{j} + \epsilon_0 \mu_0 \frac{\partial \boldsymbol{E}}{\partial t} \qquad (25)$$

- Electric fields can reach $\sim 10^{13}$ V/m
- "Primary particles accelerated" (10^7 MeV)
- Curvature emission of γ-photons
- Inverse Compton scattering may occur

$$\gamma + \boldsymbol{B} \rightarrow e^+ + e^- + \boldsymbol{B} \qquad (26)$$

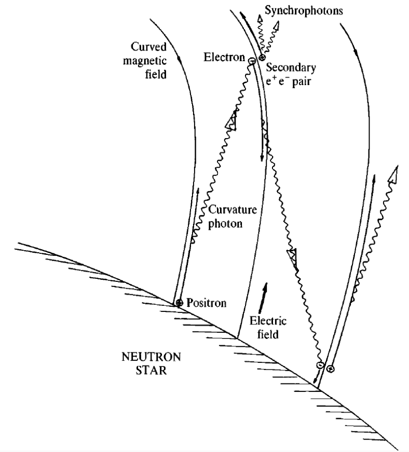
- Production of "secondary particles" ($10^2 - 10^4$ MeV)
- Multiplicity factor $\kappa \sim 10^2 - 10^5$.



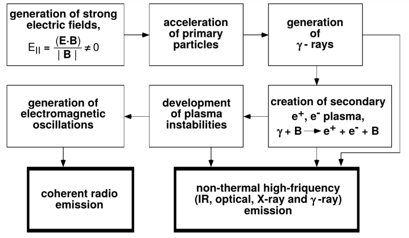
Other electron-positron sources

- γ photons from hot star surface
- photon-photon interactions

Formation of relativistic beams



(Gurevich et al. 1993)



generation of strong electric fields,

$E_{||} = \frac{(\mathbf{E}\cdot\mathbf{B})}{|\mathbf{B}|} \neq 0$

acceleration of primary particles

generation of γ - rays

creation of secondary e^+, e^- plasma, $\gamma + B \rightarrow e^+ + e^- + B$

development of plasma instabilities

generation of electromagnetic oscillations

coherent radio emission

non-thermal high-friquency (IR, optical, X-ray and γ-ray) emission

(Usov 2002, ArXiv)

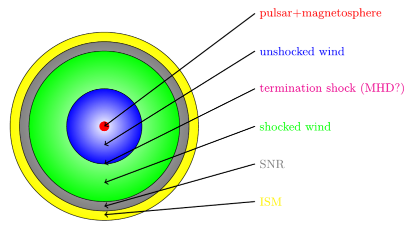
Model of pulsar wind

Types of wind:

- Quasi-neutral (MHD) wind of relativistic particles, currents between species, large particle density required
- Relativistic charged wind, species separated, questions about effectiveness, current only one species
- Large-amplitude low-frequency elmg. wave in a low density plasma

Focus mainly on propagation effects.

(Petri, 2016)



pulsar+magnetosphere

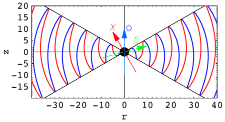
unshocked wind

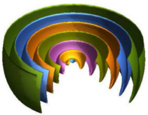
termination shock (MHD?)

shocked wind

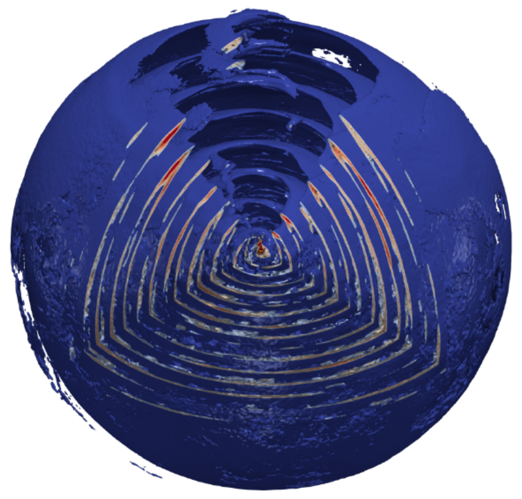
SNR

ISM





Outer magnetosphere



(Cerutti et al. 2020)

5. Magnetars

Discovery

Soft gamma repeaters (SGRs)

- (Vegnera 11 and 12) detection of hard X-ray / soft gamma-ray repeater (SGR 1900+14)
- Softer spectra than gamma ray bursts (GRBs)
- New class of high energy sources
- 8 s period (SGR 0526-66) suggests a neutron star, but much larger than other newly born pulsars (<100 ms)
- Ultrastrong magnetic fields needed for such decay in 10^4 years
- Fields provide energy source for large activity
- Magnetic fields confirmed from spin-down measurements in 1998

(Mazets 1979a,b; Thompson & Duncan 1992,1996)

Anomalous X-ray pulsars (AXPs)

- Indipendent theory evolution
- 1980 ”an extraordinary new celestial X-ray source”
- Pulsations with period $\sim$3.5 s (Later 7 s)
- Later suggested as a new type of accretion powered X-ray (neutron star) binary

Main parameters

- Periods 2–12 s
- Born with periods ∼100 ms → rapid magnetic breaking
- Large spin-down rates $\sim 10^{-3}$ yr^{-1}
- Mg. fields from spind down rates $> 10^{14}$ G
- Spin down energy $<$ X-ray luminosity
- X-ray luminosity $10^{30} - 10^{35}$ erg s^{-1} (2–10 keV)
- Soft X-ray – black body radiation
- Hard X-ray – hardening

- Sometimes observed at other wavelength (radio to UV)
- Located in galactic plane → young sources
- Spatial velocities ~ 200 km s^{-1}
- Some associated with supernova remnants

(Olausen & Kaspi 2014)

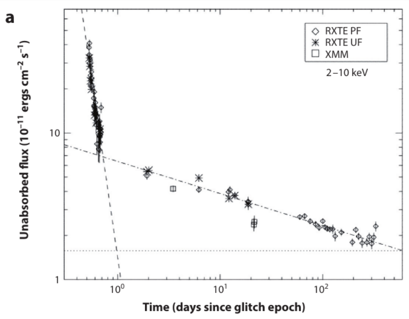
Activity

Generally vary strongly between magnetars.
Bursts:

- Durations ms – s, typically 100 ms
- Energies $10^{36} - 10^{44}$ $\mathrm{erg\,s^{-1}}$
- More common during outbursts

Outbursts:

- $10 - 10^{3}$ time increase of X-ray flux
- Energy flux $< 10^{36}$ $\mathrm{erg\,s^{-1}}$
- Accompanied by glitches
- Rapid initial decay in minutes – hours
- Slow decay of days – years



(Woods et al. 2004)

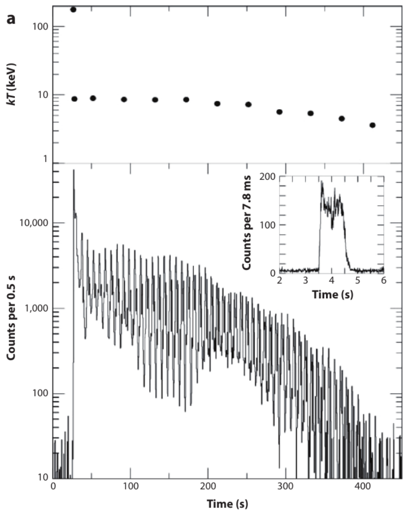
Giant flares

Giant flares

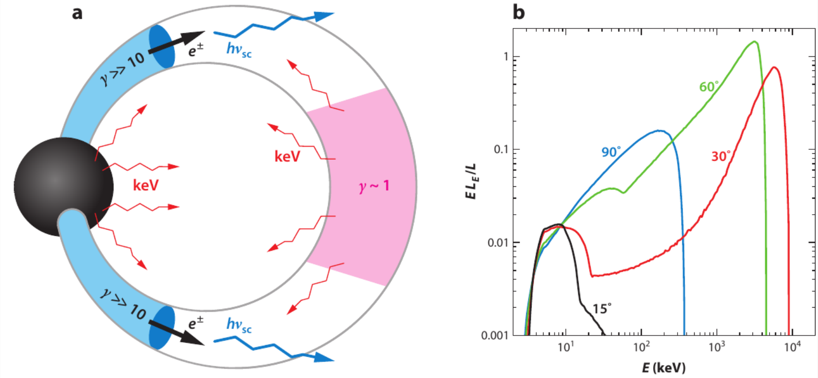
- Three sources detected
- Power $10^{44} - 10^{47}$ erg s^{-1}

Pulsations

- Star pulsations (magnetosphere)



Mechanism of a burst

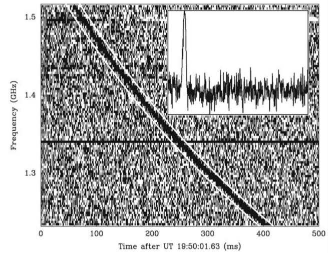


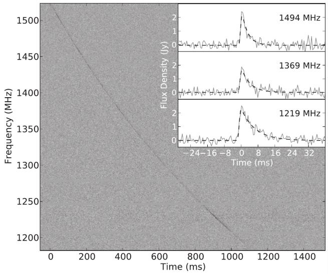
(Beloborodov 2013)

6. Fast radio bursts

Discovery

- First burst detected 24th July 2001 – Parkes 64-m telescope
- Published by Lorimer et al. 2007
- Debate about “Lorimer burst” or “peryton”
- Originating from “microwave-ovens”
- Other reported by Petroff in 2013
- Telescope: Parkes, Arecibo, GBT, ASKAP, CHIME, FAST, STARE2
- Every 6 months “quamtum leap”





Observed properties 1/2

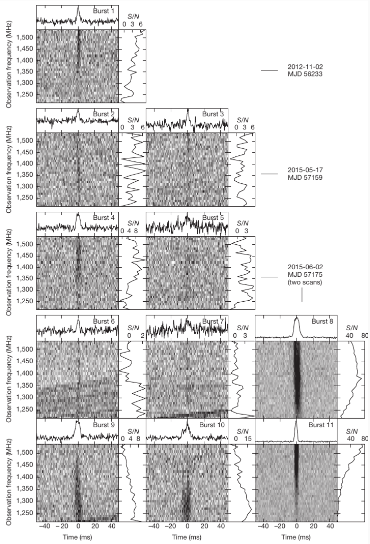
- Duration of 1 ms $\rightarrow L = ct \sim 10^5 - 10^6\ m \rightarrow$ compact sources
- Repetition, > 20 repeating sources $\rightarrow$ can be majority repeating?
- Repetition ms – s $\rightarrow$ pulsars? – no such source
- Typical repetition after days $\rightarrow$ binary/precession models?
- Pulse structure complex
- Subpulse down frequency drifts
- DM $\sim 100 - 2600$, typical $300 - 400$
- Luminosities $10^{38} - 10^{46}$ erg s^{-1}
- Reduction by a beaming factor
- Luminosity large for pulsars, but low for GRB

Observed properties 2/2

- Not clear association to SGR
- Brighness temperatures $\sim 10^{36}$ K → coherent source
- Detection range 300 MHz – 8 GHz, No LOFAR detection → hard spectral pulses
- Linear polarization > 50 %
- No polarization swing across pulse
- Some FRBs constant polarization angle in all pulses
- Large rotation measures $1 - 10^5$ rad m^{-2}
- Isotropic over sky
- Rate $\sim 10^3$ events per day (> 1 mJy)
- Massive galaxies

Repeating FRB 121102 (z = 0.19)

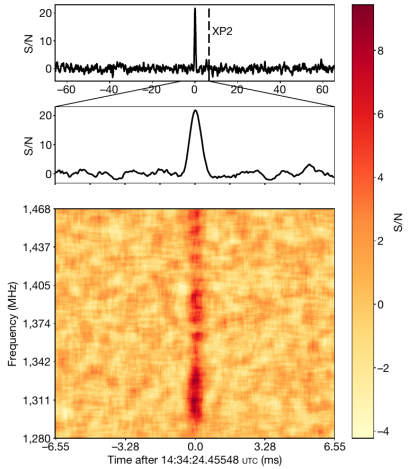
- DM ~ 560 pc cm^{-3}
- Establishing extragalactic/cosmological origin



(Spitler et al. 2016)

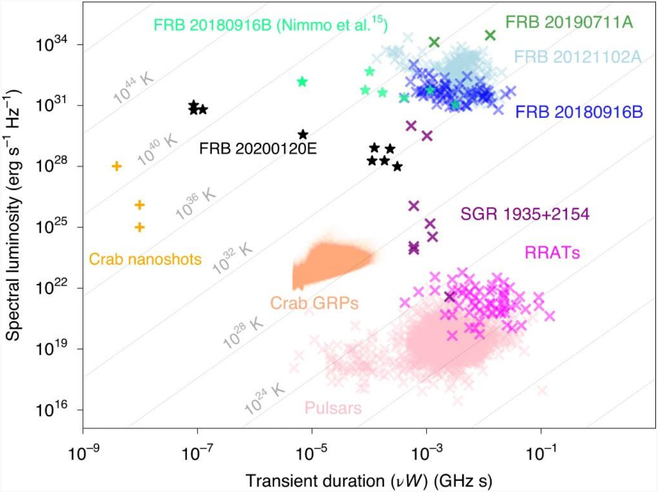
Combines radio and X-ray detection – Galactic magnetar

- CHIME & STARE2
- Soft-gamma-repeater SGR 1935+2154
- During its active phase
- Magnetars are origin of, at least some, FRBs



(Tavani et al. 2020)

FRB Effective Isotropic Luminosity



(Nimmo et al. 2022)

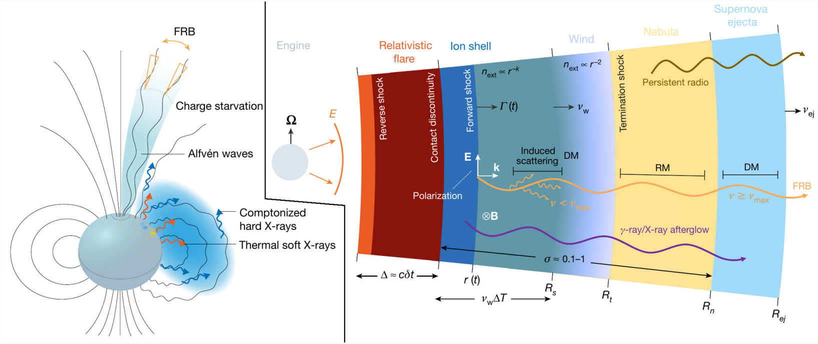
Open Questions

- Are there multiple species?
- Where are they from?
- What creates/produces them?

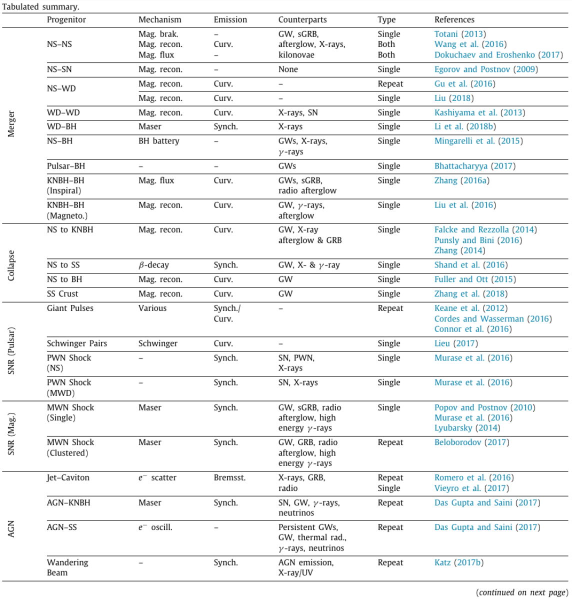
(Zhang et al. 2018)

FRB models

- Pulsar-like models
- GRB-like models
- Main energy source is magnetic energy (not spin-down energy)



List of FRB models (not all)

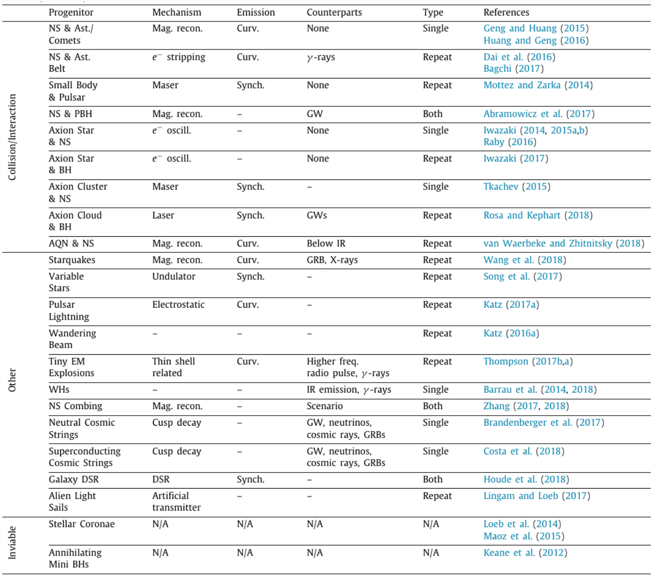


Tabulated summary.

	Progenitor	Mechanism	Emission	Counterparts	Type	References
Merger	NS–NS	Mag. brak. Mag. recon. Mag. flux	– Curv. –	GW, sGRB, afterglow, X-rays, kilonovae	Single Both Both	Totani (2013) Wang et al. (2016) Dokuchaev and Eroshenko (2017)
	NS–SN	Mag. recon.	–	None	Single	Egorov and Postnov (2009)
	NS–WD	Mag. recon.	Curv.	–	Repeat	Gu et al. (2016)
		Mag. recon.	Curv.	–	Single	Liu (2018)
	WD–WD	Mag. recon.	Curv.	X-rays, SN	Single	Kashiyama et al. (2013)
	WD–BH	Maser	Synch.	X-rays	Single	Li et al. (2018b)
	NS–BH	BH battery	–	GWs, X-rays, γ-rays	Single	Mingarelli et al. (2015)
	Pulsar–BH	–	–	GWs	Single	Bhattacharyya (2017)
	KNBH–BH (Inspiral)	Mag. flux	Curv.	GWs, sGRB, radio afterglow	Single	Zhang (2016a)
	KNBH–BH (Magneto.)	Mag. recon.	Curv.	GW, γ-rays, afterglow	Single	Liu et al. (2016)
Collapse	NS to KNBH	Mag. recon.	Curv.	GW, X-ray afterglow & GRB	Single	Falcke and Rezzolla (2014) Punsly and Bini (2016) Zhang (2014)
	NS to SS	β-decay	Synch.	GW, X- & γ-ray	Single	Shand et al. (2016)
	NS to BH	Mag. recon.	Curv.	GW	Single	Fuller and Ott (2015)
	SS Crust	Mag. recon.	Curv.	GW	Single	Zhang et al. (2018)
SNR (Pulsar)	Giant Pulses	Various	Synch./ Curv.	–	Repeat	Keane et al. (2012) Cordes and Wasserman (2016) Connor et al. (2016)
	Schwinger Pairs	Schwinger	Curv.	–	Single	Lieu (2017)
	PWN Shock (NS)	–	Synch.	SN, PWN, X-rays	Single	Murase et al. (2016)
	PWN Shock (MWD)	–	Synch.	SN, X-rays	Single	Murase et al. (2016)
SNR (Mag.)	MWN Shock (Single)	Maser	Synch.	GW, sGRB, radio afterglow, high energy γ-rays	Single	Popov and Postnov (2010) Murase et al. (2016) Lyubarsky (2014)
	MWN Shock (Clustered)	Maser	Synch.	GW, GRB, radio afterglow, high energy γ-rays	Repeat	Beloborodov (2017)
AGN	Jet–Caviton	e^- scatter	Bremsst.	X-rays, GRB, radio	Repeat Single	Romero et al. (2016) Vieyro et al. (2017)
	AGN–KNBH	Maser	Synch.	SN, GW, γ-rays, neutrinos	Repeat	Das Gupta and Saini (2017)
	AGN–SS	e^- oscill.	–	Persistent GWs, GW, thermal rad., γ-rays, neutrinos	Repeat	Das Gupta and Saini (2017)
	Wandering Beam	–	Synch.	AGN emission, X-ray/UV	Repeat	Katz (2017b)

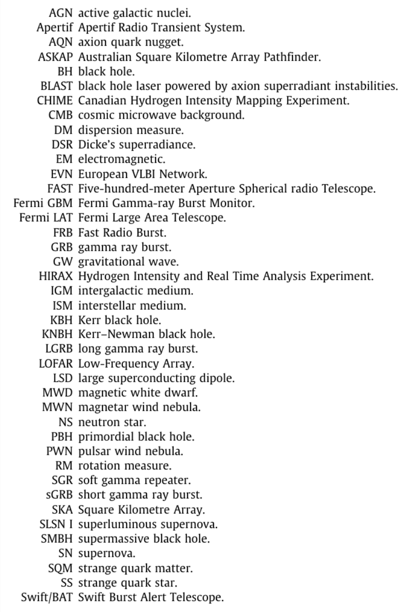
(*continued on next page*)

List of FRB models (not all)



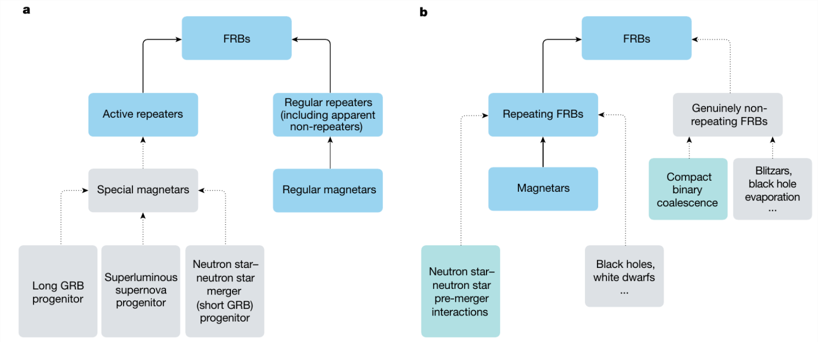
	Progenitor	Mechanism	Emission	Counterparts	Type	References
Collision/Interaction	NS & Ast./ Comets	Mag. recon.	Curv.	None	Single	Geng and Huang (2015) Huang and Geng (2016)
	NS & Ast. Belt	e^- stripping	Curv.	γ-rays	Repeat	Dai et al. (2016) Bagchi (2017)
	Small Body & Pulsar	Maser	Synch.	None	Repeat	Mottez and Zarka (2014)
	NS & PBH	Mag. recon.	–	GW	Both	Abramowicz et al. (2017)
	Axion Star & NS	e^- oscill.	–	None	Single	Iwazaki (2014, 2015a,b) Raby (2016)
	Axion Star & BH	e^- oscill.	–	None	Repeat	Iwazaki (2017)
	Axion Cluster & NS	Maser	Synch.	–	Single	Tkachev (2015)
	Axion Cloud & BH	Laser	Synch.	GWs	Repeat	Rosa and Kephart (2018)
	AQN & NS	Mag. recon.	Curv.	Below IR	Repeat	van Waerbeke and Zhitnitsky (2018)
Other	Starquakes	Mag. recon.	Curv.	GRB, X-rays	Repeat	Wang et al. (2018)
	Variable Stars	Undulator	Synch.	–	Repeat	Song et al. (2017)
	Pulsar Lightning	Electrostatic	Curv.	–	Repeat	Katz (2017a)
	Wandering Beam	–	–	–	Repeat	Katz (2016a)
	Tiny EM Explosions	Thin shell related	Curv.	Higher freq. radio pulse, γ-rays	Repeat	Thompson (2017b,a)
	WHs	–	–	IR emission, γ-rays	Single	Barrau et al. (2014, 2018)
	NS Combing	Mag. recon.	–	Scenario	Both	Zhang (2017, 2018)
	Neutral Cosmic Strings	Cusp decay	–	GW, neutrinos, cosmic rays, GRBs	Single	Brandenberger et al. (2017)
	Superconducting Cosmic Strings	Cusp decay	–	GW, neutrinos, cosmic rays, GRBs	Single	Costa et al. (2018)
	Galaxy DSR	DSR	Synch.	–	Both	Houde et al. (2018)
	Alien Light Sails	Artificial transmitter	–	–	Repeat	Lingam and Loeb (2017)
Inviable	Stellar Coronae	N/A	N/A	N/A	N/A	Loeb et al. (2014) Maoz et al. (2015)
	Annihilating Mini BHs	N/A	N/A	N/A	N/A	Keane et al. (2012)

List of FRB models (not all)



AGN	active galactic nuclei.
Apertif	Apertif Radio Transient System.
AQN	axion quark nugget.
ASKAP	Australian Square Kilometre Array Pathfinder.
BH	black hole.
BLAST	black hole laser powered by axion superradiant instabilities.
CHIME	Canadian Hydrogen Intensity Mapping Experiment.
CMB	cosmic microwave background.
DM	dispersion measure.
DSR	Dicke's superradiance.
EM	electromagnetic.
EVN	European VLBI Network.
FAST	Five-hundred-meter Aperture Spherical radio Telescope.
Fermi GBM	Fermi Gamma-ray Burst Monitor.
Fermi LAT	Fermi Large Area Telescope.
FRB	Fast Radio Burst.
GRB	gamma ray burst.
GW	gravitational wave.
HIRAX	Hydrogen Intensity and Real Time Analysis Experiment.
IGM	intergalactic medium.
ISM	interstellar medium.
KBH	Kerr black hole.
KNBH	Kerr–Newman black hole.
LGRB	long gamma ray burst.
LOFAR	Low-Frequency Array.
LSD	large superconducting dipole.
MWD	magnetic white dwarf.
MWN	magnetar wind nebula.
NS	neutron star.
PBH	primordial black hole.
PWN	pulsar wind nebula.
RM	rotation measure.
SGR	soft gamma repeater.
sGRB	short gamma ray burst.
SKA	Square Kilometre Array.
SLSN I	superluminous supernova.
SMBH	supermassive black hole.
SN	supernova.
SQM	strange quark matter.
SS	strange quark star.
Swift/BAT	Swift Burst Alert Telescope.

Probability of source of FRBs



Observational facts – blue Speculations – grey Speculated multi-messenger – green (Zhang et al. 2020)

Conclusions to neutron stars

- Neutron stars, pulsars, millisecond pulsars, magnetars, soft gamma repeaters, active X-ray pulsars, γ-ray sources, fast radio bursts
- Observational and theoretical approaches
- Large variety and uncertainty in emission processes of electromagnetic waves
- Dynamics of the magnetosphere
- Supergiant pulses and FRBs have same mechanism
- Now is the time of first global magnetopsheric simulations