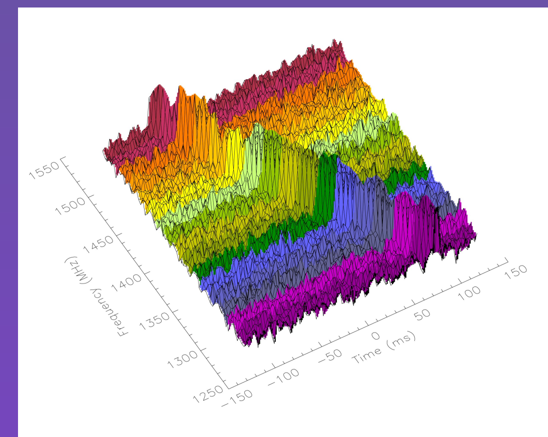
Radiotransients: models for GCRT and mERB

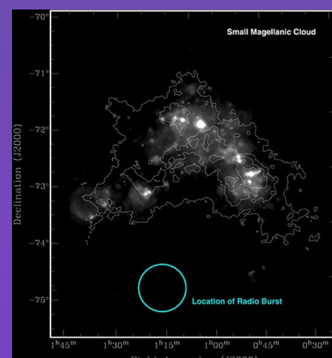
Sergei Popov
(SAI MSU)

Recently, it became possible to detected single radio bursts down to millisecond duration.

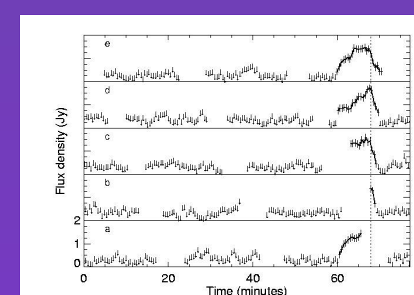
The first big discovery: RRATs (McLaughlin et al. 2006)



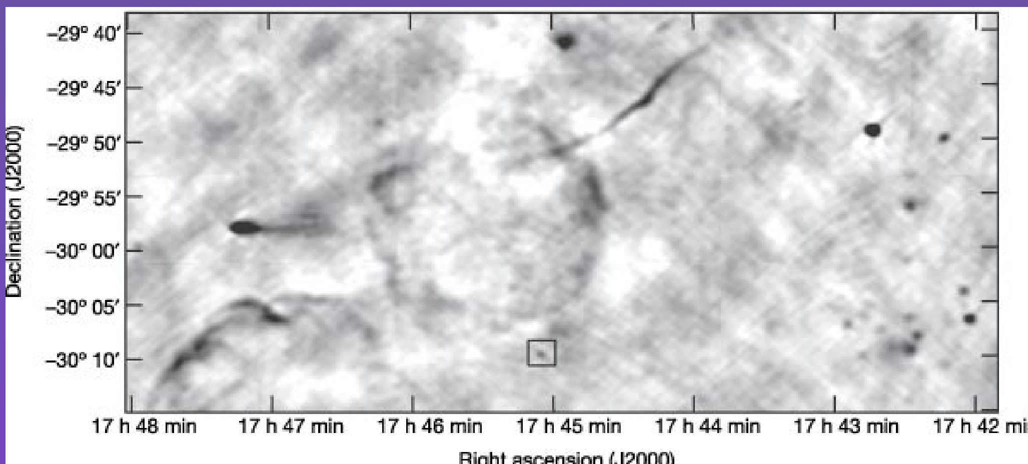
The second – mERB (Lorimer et al. 2007)



In addition, several radio transients with much longer bursts are known.
One of the most famous and mysterious is GCRT J1745-3009



GCRT J1745–3009

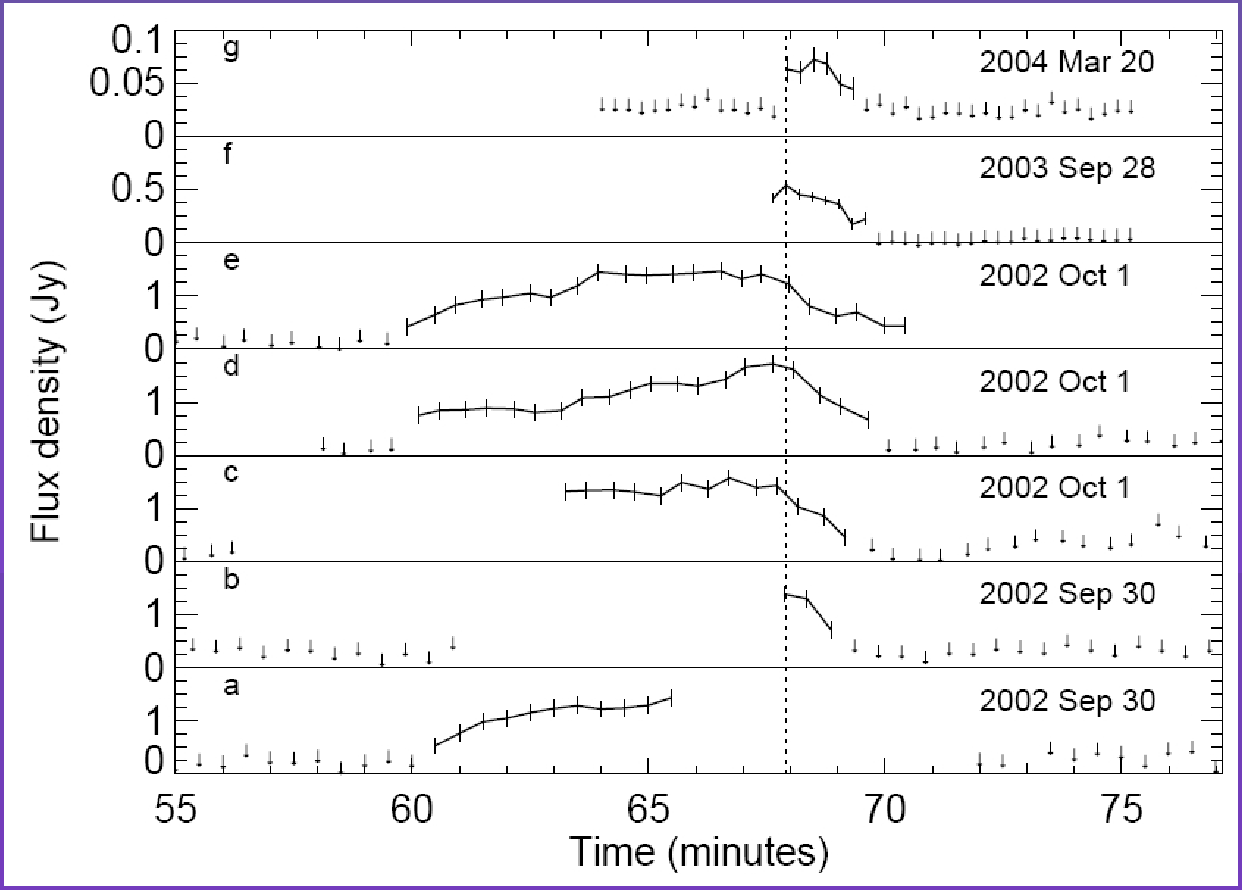


GCRT J1745–3009
is located at right ascension 17 h 45 min 50.8 s, declination -30° 09' 52" 10", indicated by the small box below the 20'-diameter shell of the supernova remnant, SNR 359.1–00.5.

Other sources in the image include the sources to the west which are part of Sagittarius E, the linear feature, 'The Snake', to the north, and 'The Mouse' to the northeast of GCRT J1745–3009.

Discovered by Hyman et al. Nature 434, 50-52 (3 March 2005)

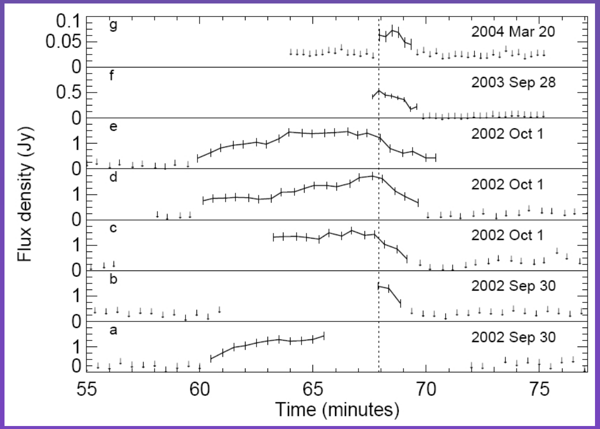
Detected bursts



(Hyman et al. 2007)

Bursts

Altogether 7 bursts detected.



- 5 bursts in 2002.
  VLA 330 MHz
  Duration of each ~ 10 minutes
  Flux ~ 1Jy
  Periodicity ~ 77 minutes
  Between bursts limit <75 mJy

- a burst in 2003.
  GMRT 330 MHz
  The maxima was not detected.
  Probably the burst is similar to 2002 bursts

- a burst in 2004
  GMRT 330 MHz
  Different from earlier.
  Weaker ~0.05 Jy
  Shorter ~2 minutes

Duty cycle <7% (~ 120 hours of obserbations altogether)

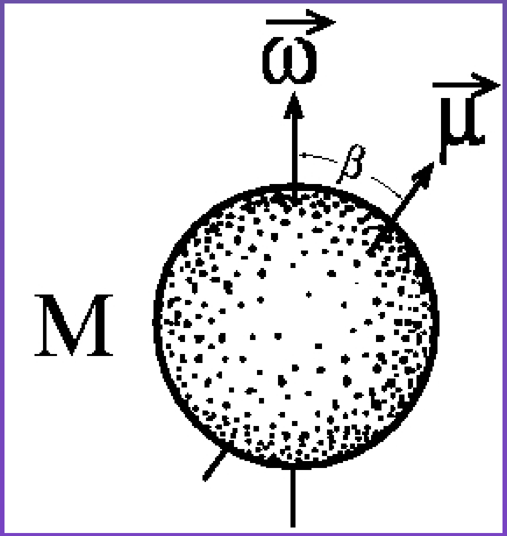
Proposed models to explain the source

- Near-by objects (brown dwarf, low-mass star, exoplanet,...). Hyman et al. (2005)
- Nulling pulsar. Kulkarni, Phinney (2005)
- Double pulsar. Turolla et al. (2005)
- Transient white dwarf pulsar. Zhang, Gil (2005)
- Precessing pulsar. Zhu, Xu (2005)

If the source is at the Galactic center, then the total energy release in a flare is about 10^{34} erg/s.

Here we discuss a set of possibilities
related to less eplored stages of
isolated and accreting neutron stars:
Propellers, Superejectors,
mixed phases for isolated neutron stars,
pulsar wind caverns in binaries, ...

Magnetic rotator



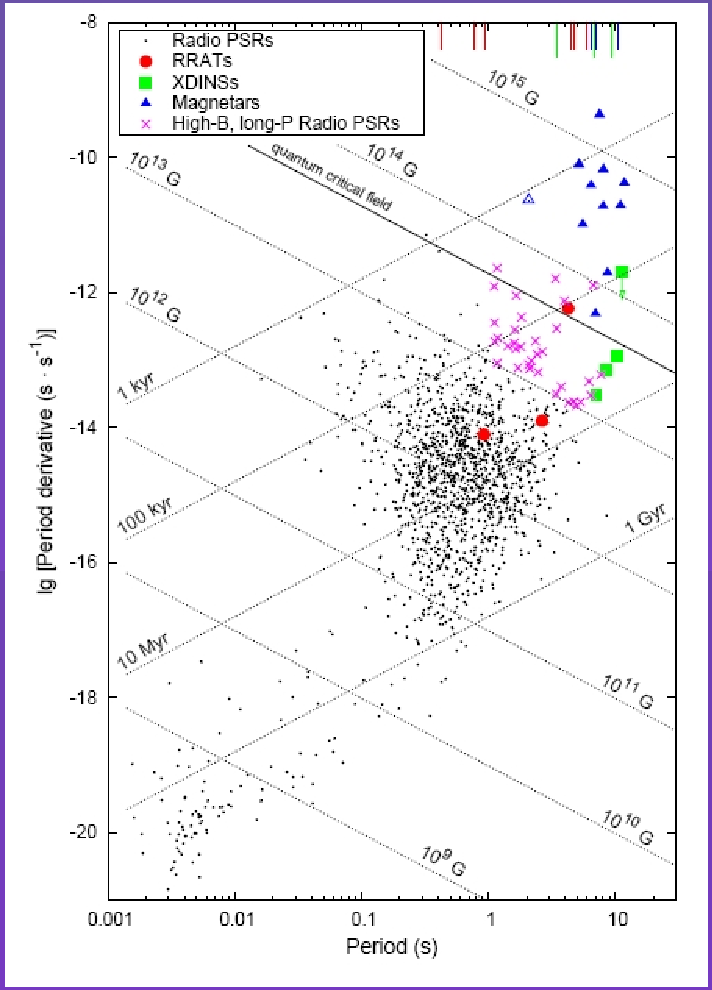
Observational appearences of NSs
(if we are not speaking about cooling)
are mainly determined by P, Pdot, V, B,
(probably the inclination angle χ),
and properties of the surrounding medium.
B is not evolving significantly in most cases,
so it is important to discuss spin evolution.

Together with changes in B (and χ)
one can speak about

magneto-rotational evolution

We are going to discuss the main stages of this evolution, namely:
Ejector, Propeller, Accretor, and *Georotator*
following the classification by Lipunov

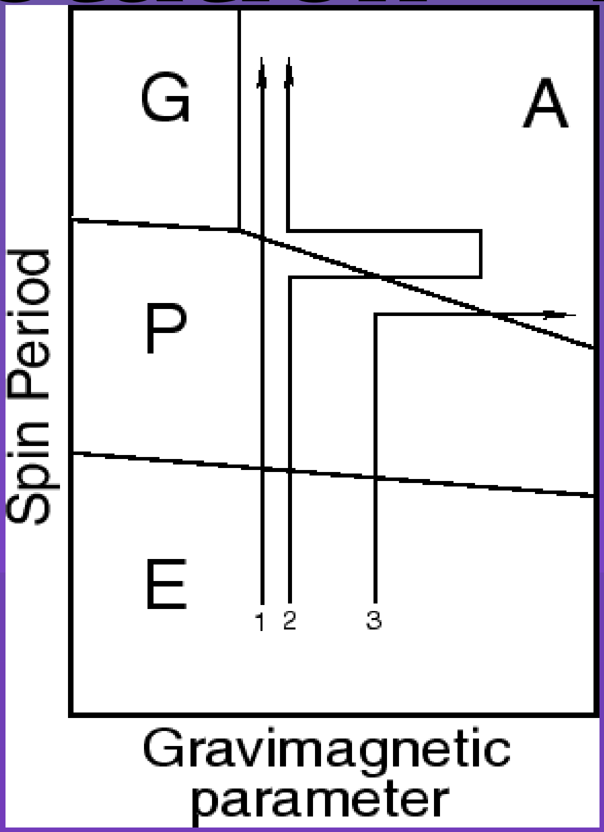
P-Pdot diagram



For radio pulsar magneto-rotational evolution is usually illustrated in the P-Pdot diagram.

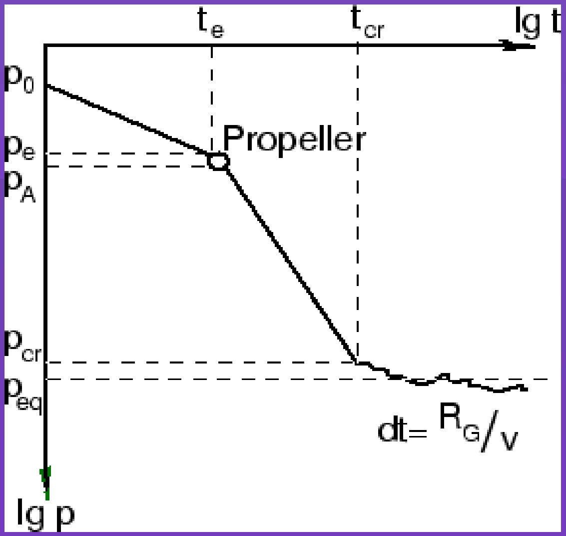
However, we are interested also in the evolution after this stage.

Evolution of neutron stars. rotation + magnetic field



Ejector → Propeller → Accretor → Georotator

1 – spin down
2 – passage through a molecular cloud
3 – magnetic field decay



See the book by Lipunov (1987, 1992)

astro-ph/0101031

Critical radii -I

Transitions between different evolutionary stages can be treated in terms of

critical radii

- Ejector stage. Radius of the light cylinder. $R_l=c/\omega$.
  Shvartsman radius. R_{sh}.
- Propeller stage. Corotation radius. R_c
- Accretor stage. Magnetospheric (Alfven) radius. R_A
- Georotator stage. Magnetospheric (Alfven) radius. R_A

As observational appearence is related to interaction with the surrounding medium the radius of *gravitational capture* is always important. $R_G=2GM/V^2$.

Schwarzshild radii is typicall unimportant.

$$r_g = \frac{2GM}{c^2} \approx 2.95 \; \frac{M}{M_{SUN}} \; \text{km}$$

Critical radii-II

1. Shvartsman radius
   It is determined by
   relativistic particles wind

$$R_{\mathrm{Sh}} = \left(\frac{8\kappa_t \mu^2 G^2 M^2 \omega^4}{\dot{M}_c v_\infty^5 c^4} \right)^{1/2}, \qquad R_{\mathrm{Sh}} > R_G$$

2. Corotation radius

$$\omega R_{\mathrm{St}} < \sqrt{G M_x / R_{\mathrm{St}}}$$

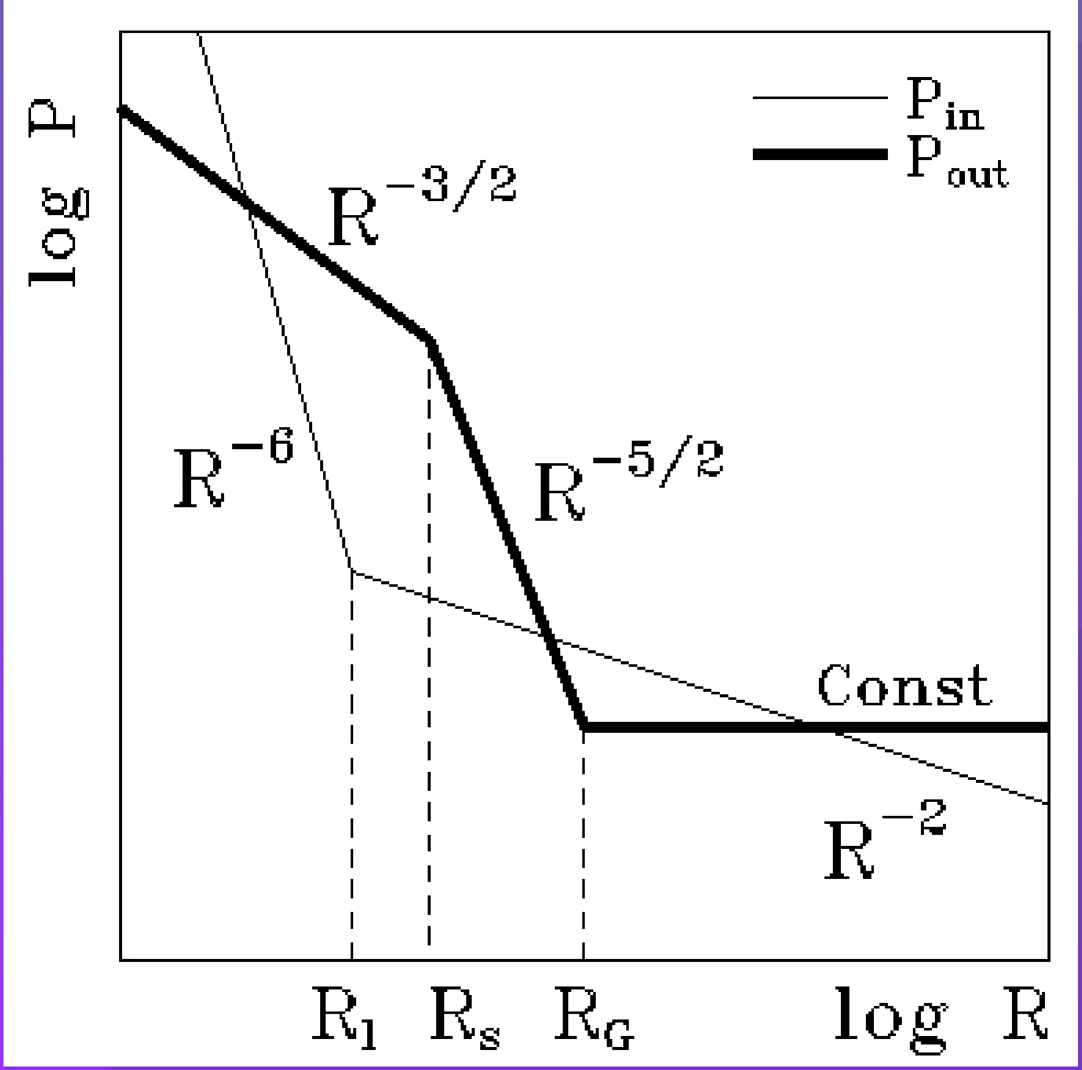
$$R_c = (G M_x / \omega^2)^{1/3} \sim 2.8 \times 10^8 m_x^{1/3} (P/1\ \mathrm{s})^{2/3}\ \mathrm{cm}$$

3. Alfven radius

$$P_m(R_{\mathrm{st}}) = P_a(R_{\mathrm{st}})$$

$$R_A = \begin{cases} \left(\dfrac{2\mu^2 G^2 M^2}{\dot{M}_c v_\infty^5} \right)^{1/6}, & R_A > R_G \\ \left(\dfrac{\mu^2}{2\dot{M}_c \sqrt{2GM}} \right)^{2/7}, & R_A \le R_G \end{cases}$$

Pressure



$$P_m = \begin{cases} \dfrac{\mu^2}{8\pi R^6}, & R \le R_l \\ \dfrac{L_m}{4\pi R^2 c}, & R > R_l \end{cases}$$

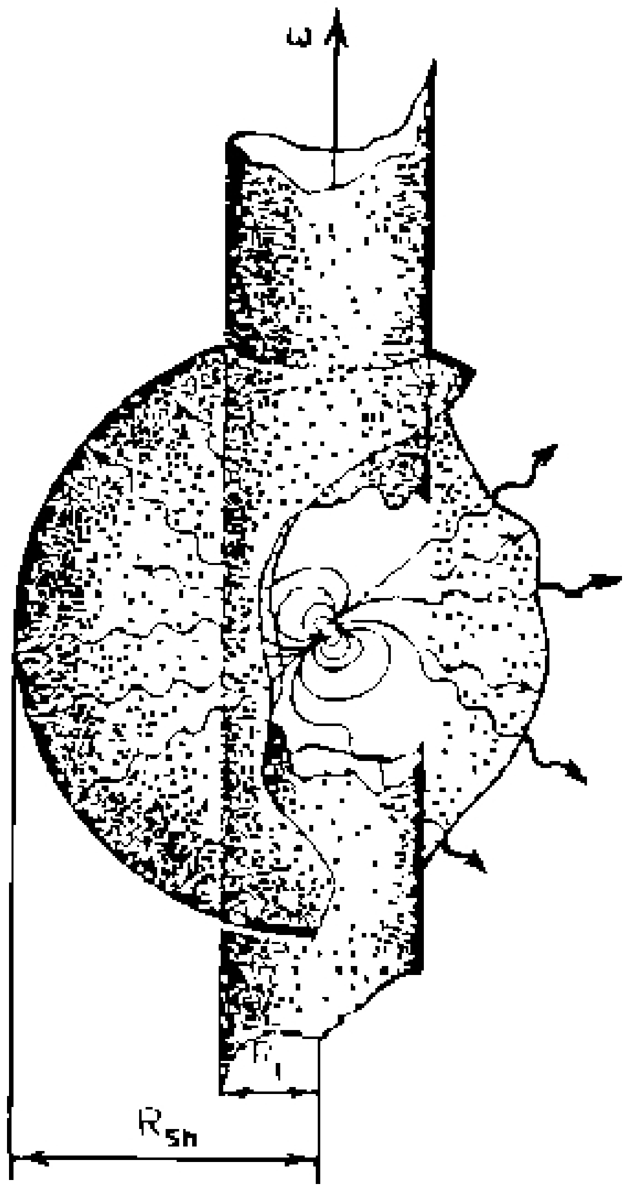
$$L_m = \kappa_t \frac{\mu^2}{R_l^3}\omega$$

We can define a stopping radius R_{st}, at which external and internal pressures are equal.

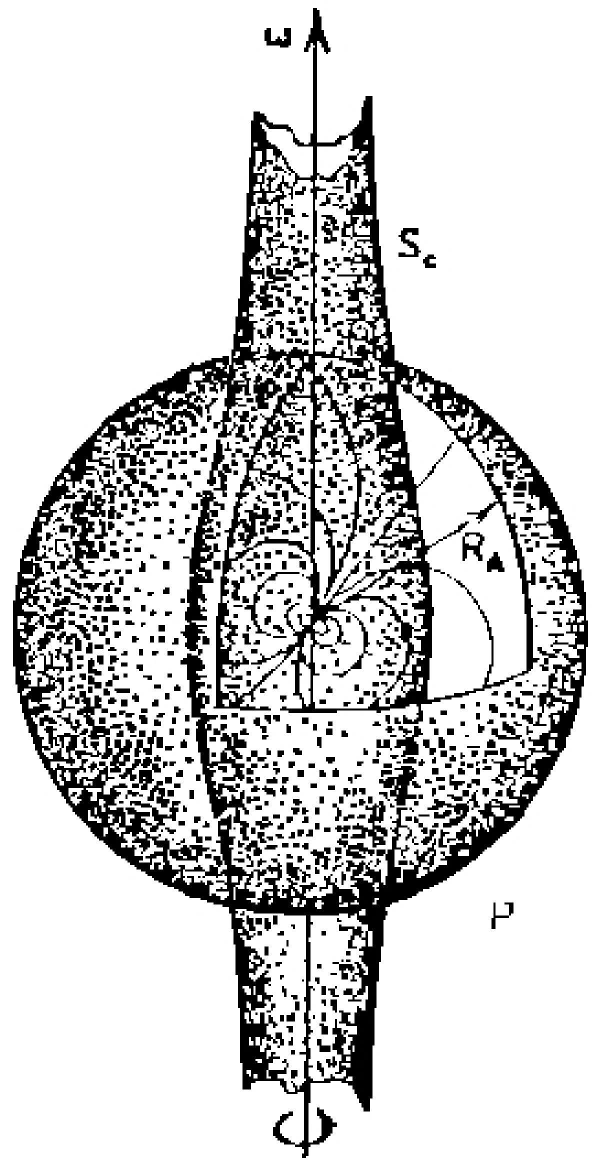
The stage is determined by relation of this radius to other critial radii.

Classification

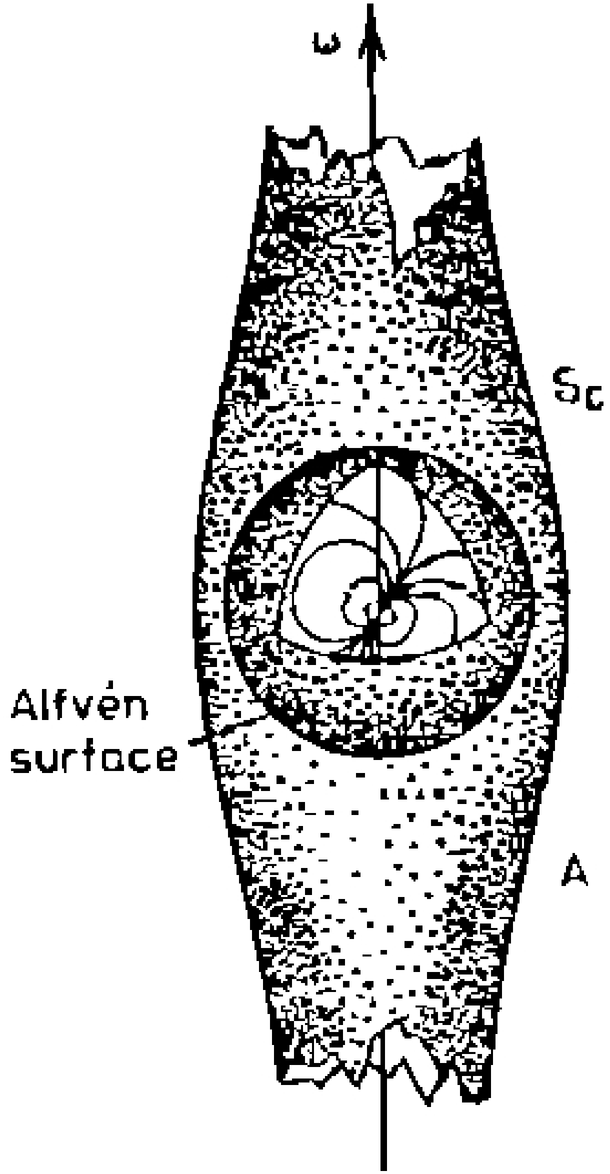
Abbreviation	Type	Characteristic radii relation	Accretion rate	Observational appearances
E	Ejector	$R_{st} > R_G$ $R_{st} > R_l$	$\dot{M}_c \leq \dot{M}_{cr}$	Radiopulsars, Soft γ-ray repeaters, Cyg X-3? LSI+61 303?
P	Propeller	$R_c < R_{st}$ $R_{st} \leq R_G$ $R_{st} \leq R_l$	$\dot{M}_c \leq \dot{M}_{cr}$	X-ray transients? Rapid burster? γ-bursters??? Magnetic Ap-stars
A	Accretor	$R_{st} \leq R_G$ $R_{st} \leq R_l$	$\dot{M}_c \leq \dot{M}_{cr}$	X-ray pulsars, bursters, cataclysmic variables, intermediate polars
G	Georotator	$R_G < R_{st}$ $R_{st} \leq R_c$	$\dot{M}_c \leq \dot{M}_{cr}$	Earth, Jupiter
M	Magnetor	$R_{st} > a$ $R_c > a$???	$\dot{M}_c \leq \dot{M}_{cr}$	AM Her, polars

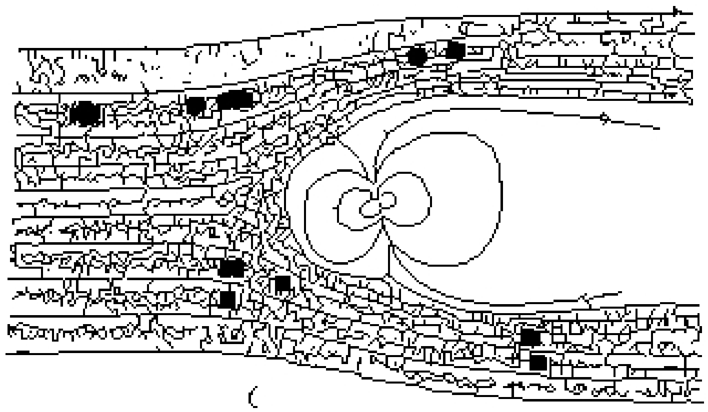


Ejector



Propeller





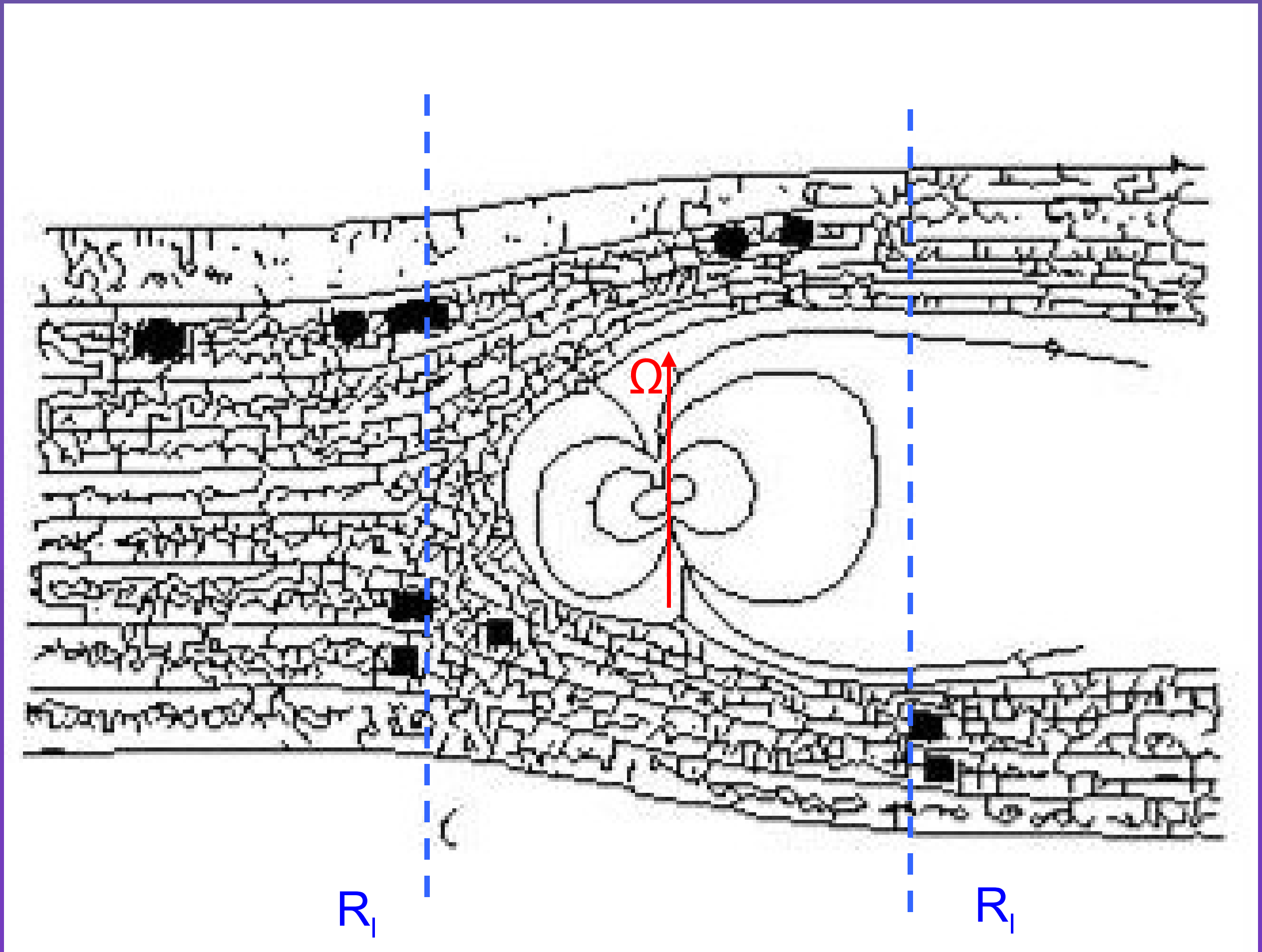
Accretor **Georotator**

Isolated magnetar

In this set of models ~77-min period is the spin period of a magnetar. Such long periods are possible due to spin-down in a presence of a disc (see the arguments in de Luca et al. 2006 in relation to RCW103).

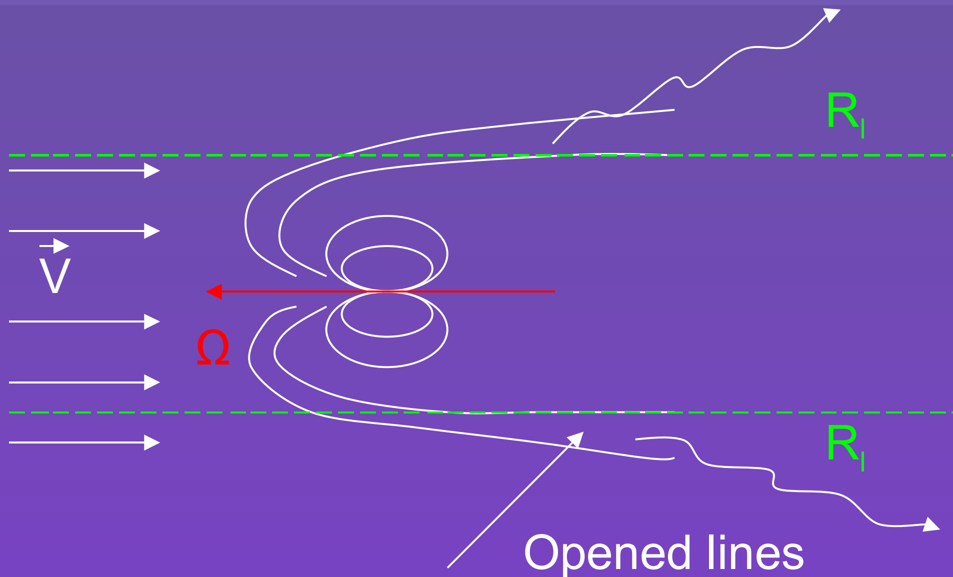
Here we propose several configurations in which a region of opened field lines is formed, however a NS already evolved off the Ejector stage.

Magnetotail of a magnetar



If the tail goes beyond the light cylinder, then we have a region of opened field lines.

Magnetowings of a magnetar

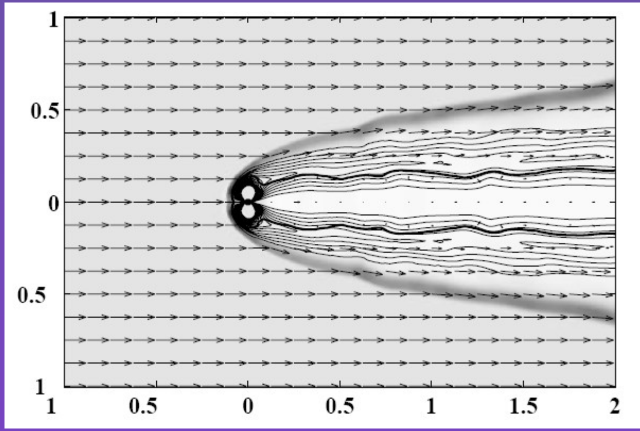


Reconnection in a magnetotail of a magnetar

This situation was studied in some detailes by Toropina et al. (2001).

$$E_{\rm tot} \approx \frac{1}{8\pi}\int_0^S dz\, \pi[R(z)]^2[B(z)]^2 ,$$

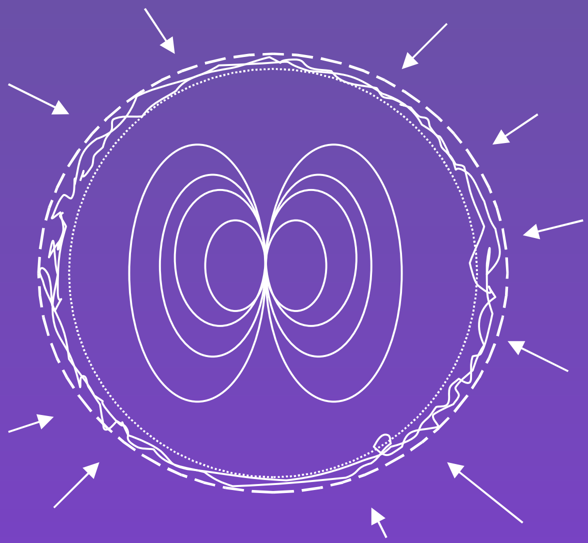
Energy in the tail



$$\dot{E}_{\rm rec} \sim 1.6 \times 10^{24} B_{12}^{2/3} n^{2/3} v_{200}^{4/3}\ {\rm ergs\ s^{-1}} .$$

Energy release rate in a single flare in the case of a low density tail

Transient propeller



If cooling is efficient enough, then it is possible to form an envelope around a NS at the stage of Propeller.
The envelope grows in mass and contract till it reaches the corotation radius, then it collapses to a NS, there is a flash and ejection is possible.
(see, for example, Lipunov 1992)

$$\mu^2/8\pi R^6 = GM_{\rm sh}M/4\pi R^4$$

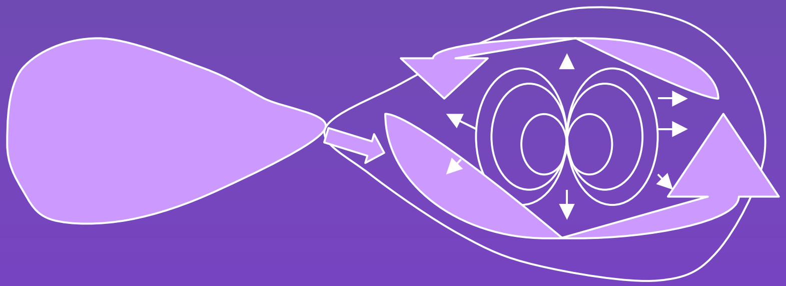
$$\Delta t_{\rm b} = R_{\rm co}/v_{\rm ff} = P/2\sqrt{2}\pi$$

$$B^2(R_{\rm co})/8\pi = (M_{\rm sh}/4\pi R_{\rm co}^2)(GM/R_{\rm co}^2)$$

$$\Delta t = M_{\rm sh}/\dot{M} = 10^8\,{\rm s}\,\mu_{30}^2 P^{-4/3}\rho_{-24}^{-1}v_{100}^3$$

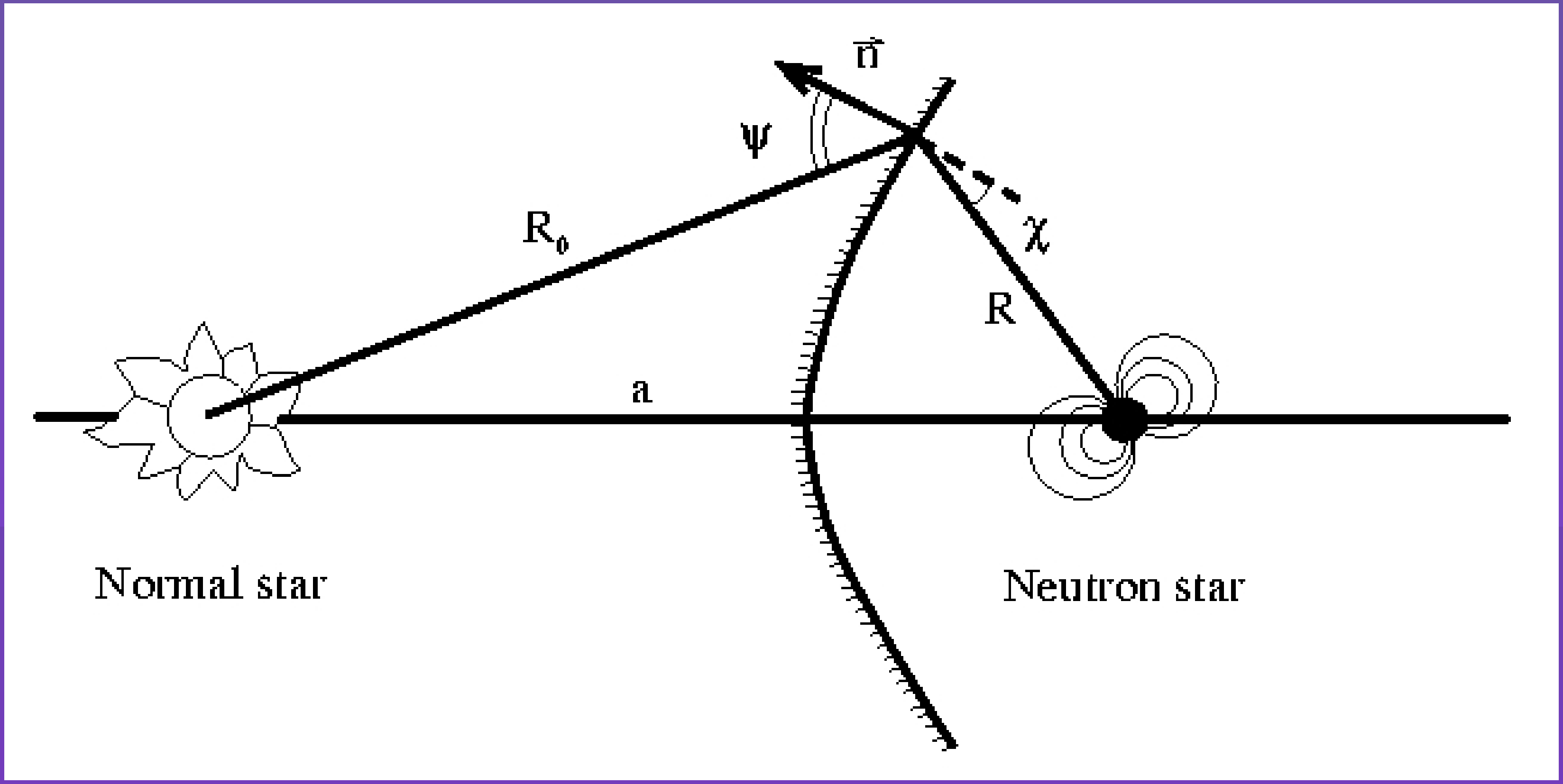
Superejector

Roche lobe overflow +
Fast radio pulsar



$$P_{\rm SE} = 11\ {\rm msec}\ \mu_{30}^{4/9},$$

Pulsating cavern

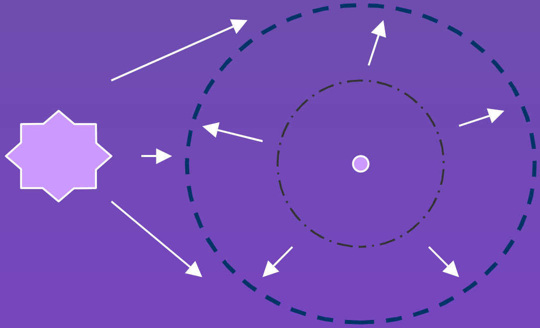


Lipunov et al.

Floating cavern

$R_{SH}<R_G$

When a cavern reaches R_G it sails away.



$$\Delta t_{\rm b} = R_{\rm G}/c \approx 9(v/50\,{\rm km/s})^{-2}\,{\rm min}.$$

Duration of a burst

Interval between bursts

$$\Delta t = (a/R_{\rm Sh})^2 R_{\rm G}/c.$$

Populational aspects

It seems that GCRT J1745-3009 is the only source in the direction towards the galactic center (in a region about few sq. degree).

If the source is close-by then we can expect to see more at low fluxes.

So we conclude, that the source is at a distance ~8 kpc.

Then we can estimate the number of such sources in the Galaxy.

The number appears to be ~100-1000.

An intermediate stage for magnetars?

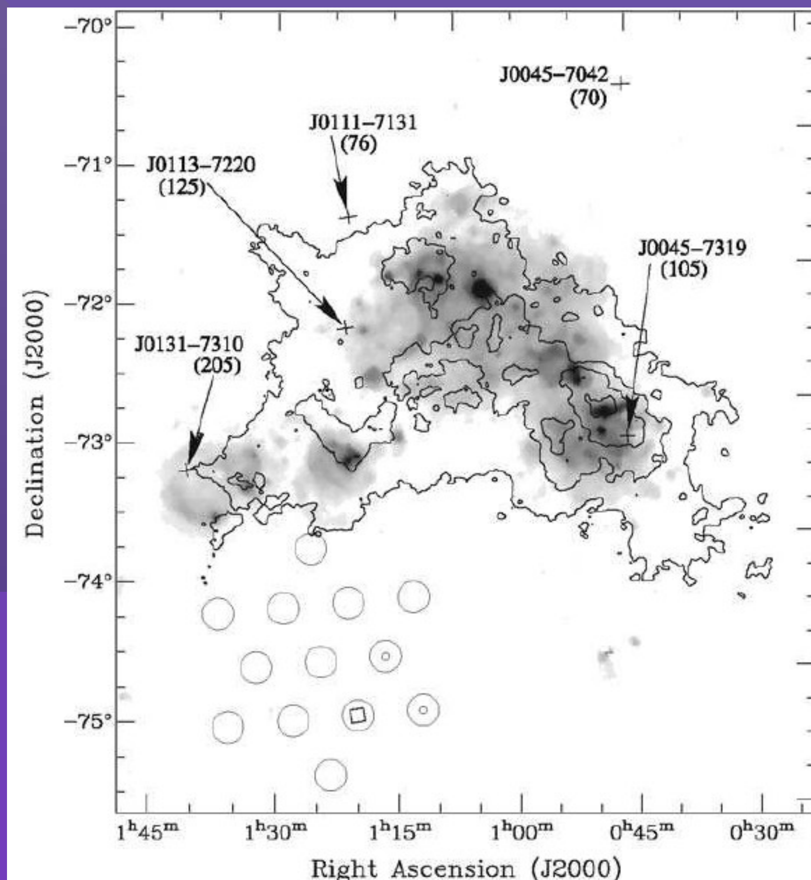
If there are 100-1000 sources in the Galaxy,
and every NS passes through such a stage,
then duration is ~10^3-10^4 yrs. This is too small.

Then we can consider that just part of NS
can appear as sources of this kind.

If we consider magnetars as potential sources,
then the duration is up to 10^5 yrs.

Such a time scale is consistent with an
intermediate stage of a magnetar:
a propeller or a similar stage.

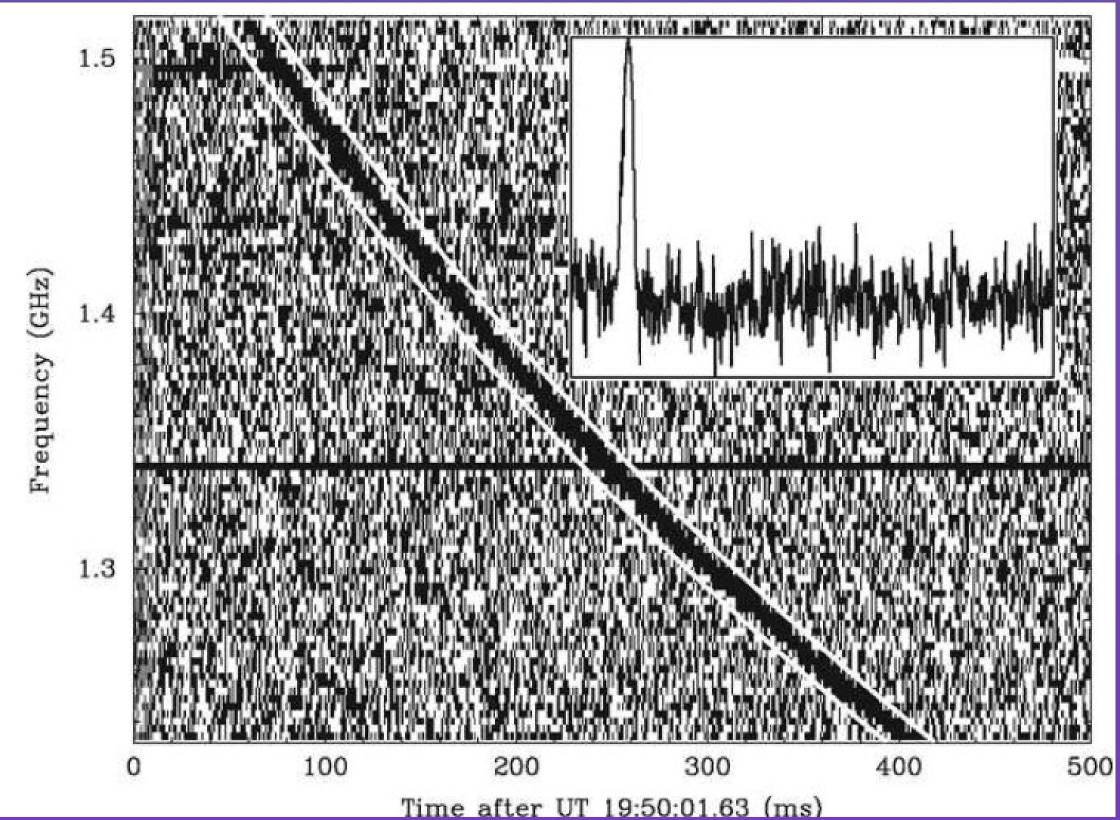
mERB: millisecond extragalactic radio burst



Discovered by Lorimer et al.
[Science 318, 777 (2007)]
1.4 GHz, Parkes

~30-40 Jy, < 5 msec
3 degrees from SMC

mERB: millisecond extragalactic radio burst



Large DM 375 cm^{-3} pc
Extragalactic
Distance ~< 1 Gpc
(>600 Mpc from optical limits on the host galaxy)

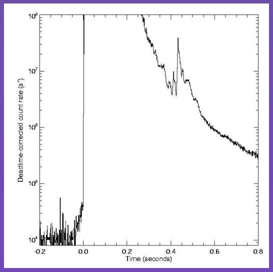
Rate is about 90/day/Gpc^3

This rate is much lower than the SN rate, and much larger that the rate of GRBs.

[Science 318, 777 (2007)]

A hypothesis: hyperflare of an extragalactic magnetar

We note that the rate about 50-100 per day per cubic Gpc is about the expected rate of extragalactic hyperflares of magnetars.



The possible mechanism of radio emission
can be related to the tearing mode instability
in the magnetar magnetosphere as discussed by Lyutikov (2002)
and can produce the radio flux corresponding
to the observed 30 Jy from the mERB
using a simple scaling of the burst energy.

Rate of hyperflares

Popov, Stern (2006) estimated the rate of hyperflares per galaxy
as ~1/1000 yrs.
Lazzati et al. (2005) provide an estimate somehow larger <1/130 yrs, but this is an upper limit.

These values are 5-50 times lower than the galactic rate of SN.

So, the rate of hyperflares is expected to be ~20-200 per year per cubic Gpc.
This is in good correspondence with the estimate of mERBs rate.

Radio emission

Lyutikov (2002) proposed that a standard (weak) burst of a SGR produce a radioburst with a flux at ~1 GHz ~1 Jy from 10 kpc for a burst with $L_x \sim 10^{36}$ erg/s.

For $L_x = 10^{47}$ erg/s and distance 600 Mpc we obtain ~30 Jy in excellent correspondence with data on mERB.

Timing properties

The raising part of the burst 27 Dec 2004 was about 5 msec.
This is about what was observed for the mERB.

However, the duration of a radio burst in the model by Lyutikov can be even smaller, down to tens of microseconds ($t_A \sim R_{NS}/c$).
This does not contradict data on the mERB.

Discussion on mERB

1. No GRB was detetcted at the time of mERB
   This is natural as a hyperflare is undetectable from ~600 Mpc.

2. Host galaxy.
   SGRs are expected to be related to starormation sites.
   So, the host galaxy can be a starforming galaxy with dust.
   Then it can be closer than 600 Mpc.
   Observations by Spitzer are welcomed.

3. Birth of a magnetar.
   We note, that the rate is also coincident with an expected birthrate of SGRs.
   However, no corresponding SN was detected. So, this is unlikely.

4. Testing of the model by Lyutikov.
   We want to encourage observers to look for millisecond radio bursts
   coincident with weak bursts of galactic magnetars.