Radiotransients: models for GCRT and mERB

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Recently, it became possible to detect 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 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.

Detected bursts

(Hyman et al. 2007)
Altogether 7 bursts detected.

- 5 bursts in 2002.
  VLA 330 MHz
  Duration of each ~ 10 minutes
  Flux ~ 1 Jy
  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 observations 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)

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 explored stages of isolated and accreting neutron stars:
Propellers, Superejectors,
mixed phases for isolated neutron stars,
pulsar wind caverns in binaries, ….
Observational appearances of NSs (if we are not speaking about cooling) are mainly determined by $P$, $P\dot{\text{}}$, $V$, $B$, (probably the inclination angle $\chi$), 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 $\chi$) 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.
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)
Transitions between different evolutionary stages can be treated in terms of **critical radii**

- Shvartsman radius. $R_{\text{sh}}$.
- 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 typically unimportant.

$$r_g = \frac{2GM}{c^2} \approx 2.95 \frac{M}{M_{\text{SUN}}} \text{ km}$$
Critical radii-II

1. Shvartsman radius
   It is determined by relativistic particles wind
   \[ R_{\text{Sh}} = \left( \frac{8 \kappa t \mu^2 G^2 M^2 \omega^4}{\dot{M} c v_\infty^5} \right)^{1/2}, \quad R_{\text{Sh}} > R_G \]

2. Corotation radius
   \[ \omega R_{\text{St}} < \sqrt{GM_x/R_{\text{St}}} \]
   \[ R_c = \left( \frac{GM_x}{\omega^2} \right)^{1/3} \sim 2.8 \times 10^8 m_x^{1/3} (P/1 \text{ s})^{2/3} \text{ cm} \]

3. Alfven radius
   \[ P_m(R_{\text{st}}) = P_a(R_{\text{st}}) \]
   \[ R_A = \left\{ \begin{array}{ll}
   \left( \frac{2 \mu^2 G^2 M^2}{M_c v_\infty^5} \right)^{1/6}, & R_A > R_G \\
   \left( \frac{\mu^2}{2M_c \sqrt{2GM}} \right)^{2/7}, & R_A \leq R_G 
   \end{array} \right. \]
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 critical radii.
# Classification

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

Georotator
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

\[ \Omega \]

\[ \vec{V} \]

Opened lines
Reconnection in a magnetotail of a magnetar

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

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

Energy in the tail

\[ \dot{E}_{\text{rec}} \sim 1.6 \times 10^{24} B_{12}^{2/3} n_{2/3}^{2/3} v_{200}^{4/3} \text{ ergs s}^{-1}. \]

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 contracts 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)

\[ \frac{\mu^2}{8\pi R^6} = GM_{\text{sh}} M / 4\pi R^4 \]

\[ B^2(R_{\text{co}})/8\pi = (M_{\text{sh}}/4\pi R_{\text{co}}^2)(GM/R_{\text{co}}^2) \]

\[ \Delta t_b = R_{\text{co}} / v_{\text{ff}} = P / 2\sqrt{2\pi} \]

\[ \Delta t = M_{\text{sh}} / \dot{M} = 10^8 s \mu_{30}^{-4/3} P^{-1/2} \rho_{-24}^{-1} v_{100}^3 \]
Superejector

Roche lobe overflow + Fast radio pulsar

\[ P_{SE} = 11 \text{ msec} \mu_{30}^{4/9}, \]
Pulsating cavern

Lipunov et al.
Floating cavern

$R_{SH} < R_G$

When a cavern reaches $R_G$ it sails away.

$\Delta t_b = \frac{R_G}{c} \approx 9\left(\frac{v}{50 \text{ km/s}}\right)^{-2} \text{ min.}$

Duration of a burst

Interval between bursts

$\Delta t = \left(\frac{a}{R_{Sh}}\right)^2 \frac{R_G}{c}$
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 $\sim<1$ 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 than 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.

Popov, Postnov arXiv:0710.2006

“Hyperflares of SGRs as an engine for millisecond extragalactic radio bursts”
Rate of hyperflares

Popov, Stern (2006) estimated the rate of hyperflares per galaxy as $\sim 1/1000$ 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 $\sim 20-200$ per year per cubic Gpc. This is in good correspondence with the estimate of mERBs rate.
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 detected 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 starformation 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.

   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.