Hyperflares of SGRs as an engine for millisecond extragalactic radio bursts

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ABSTRACT

We propose that the strong millisecond extragalactic radio burst (mERB) discovered by Lorimer et al. (2007) may be related to a hyperflare from an extragalactic soft gamma-ray repeater. The expected rate of such hyperflares, \( \sim 20 \text{--} 100 \text{ d}^{-1} \text{ Gpc}^{-3} \), is in good correspondence with the value estimated by Lorimer et al. 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 \( \sim 30 \text{ Jy} \) from the mERB using a simple scaling of the burst energy.

Key words: stars: neutron — gamma-rays: bursts — pulsars: general

1 INTRODUCTION

Progress in observational technique in radio astronomy made it possible to detect single millisecond scale bursts (Cordes & McLaughlin 2003). Recently Lorimer et al. (2007) reported a serendipitous discovery of a strong non-thermal millisecond radio burst with peculiar properties. The radio flux at 1.4 GHz is 30 ± 10 Jy, the duration of the event is shorter than 5 msec and its dispersion measure (DM) is 375 cm\(^{-3}\)pc suggesting the extragalactic nature of the source at a distance of \( \sim 1 \text{ Gpc} \). No host galaxy up to 18 B-magnitude has been found implying a distance limit of \( \sim 600 \text{ Mpc} \) for a Milky Way-like host. Such a distance implies a radio energy release in the burst of \( \sim 10^{40} \text{ ergs} \) with a brightness temperature of \( \sim 10^{34} \text{ K} \). The total rate of such bursts is estimated to be around \( 9 \text{ d}^{-1} \text{ Gpc}^{-3} \), which is much lower than the core-collapse supernova (SN) rate \( \sim 1000 \text{ d}^{-1} \text{ Gpc}^{-3} \), but well in excess of the gamma-ray burst (GRB) rate \( \sim 4 \text{ d}^{-1} \text{ Gpc}^{-3} \), and the expected rate of binary neutron star coalescences \( \sim 2 \text{ d}^{-1} \text{ Gpc}^{-3} \).

The short time scale means the origin in a compact region \( \sim 1500 \text{ km} \) (in the non-relativistic case), suggesting neutron stars as the most probable sources of mERBs. Lorimer et al. (2007) discuss several possible known sources of the strong millisecond radio bursts, including rotating radio transients (RRATs) and giant pulses from radio pulsars, but none of them appear to be energetic enough.

However, if the transient is related to the energy release by a compact magnetized object characterized by the rotational period \( P \) and the dipole magnetic moment \( \mu \), the following scaling considerations may be appropriate to provide the observed \( 10^{40} \text{ ergs} \) in the radio burst. For example, the giant radio pulses in the Crab pulsar with a peak luminosity of 4 kJy kpc\(^{-2}\) can be observed in a search like the one performed by Lorimer et al. (2007) from distances up to 100 kpc. Although the precise mechanism of the giant pulses is still unknown, we can assume that at least this amount of energy can be provided by some mechanism in the radio band. Then simple scaling of the Crab rotational power to \( 500 \text{ Mpc} \) yields \( 2.5 \times 10^{45} \text{ erg s}^{-1} \) as much a rotational energy release, i.e. \( 2.5 \times 10^{45} \text{ erg s}^{-1} \). As \( \dot{E}_{\text{rot}} \propto \mu^2 P^{-4} \), this power is attainable for a msec spin period and the magnetic field an order of magnitude higher than that of the Crab pulsar. These physical conditions can in principle be realized during the birth of a ms magnetar (Usoskin (1992) or at the late phases of coalescence of binary neutron stars with magnetic fields, as was considered by Lipunov & Panchenko (1996) (see also Vietri (1996) and Hansen & Lyutikov (2001)).

Unfortunately, binary neutron star coalescences, even considering the high uncertainty in the current estimates of their galactic rate (Postnov & Yungelson 2006), are expected to happen almost a hundred times less frequently than the reported rate of mERBs. In addition, they are thought to be accompanied by short gamma-ray bursts (Blinnikov et al. 1984, see the review in Nakar (2007)). The fact that none was detected at the time of this radio burst can be due to gamma-ray beaming off-set or intrinsic weakness, but non-detection of msec periodicity may be a stronger constraint. Observations of the simultaneous gravitational wave bursts and gamma-ray burst will be decisive for the binary NS nature of the mERB.

Magnetars appear more preferential. Their esti-
mated rate of birth (roughly, $10^{-3}$ yr$^{-1}$ per galaxy; Woods & Thompson 2000, and may be even higher; see P. Wood, 2007, talk at the conference "40-years of pulsars") can be consistent with that of mERBs. The non-thermal coherent radio emission can also be produced at their birth by instabilities in relativistic plasma which can be created by the Poynting flux outflow (Usov 1994).

However, both binary neutron star mergings nor magnetar birth have not been firmly observed so far. Here we propose to discuss another possibility that the strong mERB could be associated with hyperflares of extragalactic soft gamma-ray repeaters.

## 2 MERBS FROM SGRS

Soft gamma-ray repeaters (SGRs) show a very complicated outburst activity in hard rays (Hurley et al. 1999, for a review see Woods & Thompson 2000), but the most pronounced are hyperflares (HFs) like the event on Dec. 27, 2004 from SGR 1806-20 (Borkowski et al. 2005) with an outburst activity in hard rays (Hurley et al. 1999, for a review see Woods & Thompson 2000). Recently, several candidates for extragalactic HFs have been proposed (Frederiks et al. 2007; Ofek et al. 2006, see also Golentskii et al. 2007; Crider 2006).

Is it possible that the mERB is related to an extragalactic HF? To address this question, we first note that the inferred rate of mERBs is similar to the rate of HFs of SGRs obtained from searches for SGR flares in close-by galaxies and the Virgo cluster. Popov & Stern (2006) argue that the rate of HFs is $\sim 10^{-3}$ yr$^{-1}$ per a Milky Way-like galaxy. Lazzati, Ghirlanda & Ghisellini (2003) give slightly less stringent limit for the rate of HFs: $< 1/130$ yr$^{-1}$. Considering low statistics, however, here we use a more conservative estimate 0.001-0.003 per year per a Milky Way-like galaxy. This is $\sim 10 - 50$ times smaller than the galactic rate of SN, so from the SN rate $\sim 1000$ d$^{-1}$ Gpc$^{-3}$ we estimate the expected rate of SGR HFs to be $\sim 20 - 100$ d$^{-1}$ Gpc$^{-3}$ in good correspondence with the rate of mERBs obtained by Lorimer et al. (2007).

The possible mechanism of a prompt intense radio burst from SGR flares was discussed by Lyutikov (2002) (see also Lyutikov 2006). He proposed that a $\sim 10$ msse radio burst can be generated in the magnetar magnetosphere due to the tearing mode instability, following the similarity between solar flares and SGR bursts (in solar flares radio bursts accompany X-ray flares). For galactic SGRs with X-ray luminosity $10^{36} - 10^{39}$ erg s$^{-1}$ and 10 kpc distance he estimated a possible radio flux at $\sim 1$ GHz of about $1 - 1000$ Jy. Guided by these values, for a HF with peak gamma-ray luminosity of $L = 10^{47}$ erg s$^{-1}$ (as observed in the Dec. 27 2004 HF from SGR 1806-20) and 600 Mpc we obtain a radio flux of $\sim 30$ Jy, in correspondence with observations by Lorimer et al. (2002).

The millisecond time scale of the mERB is consistent with an event in a magnetar magnetosphere. For example, the light curve of the Dec. 27, 2004 event (see Fig. 1b in Palmer et al. 2003) shows a few features with the duration of a few milliseconds at the initial stage. The raising part of the main spike of the Dec 27, 2004 HF is also about 5 msec. The time scale of the radio burst produced by the discussed mechanism can be much smaller than 5 msec, since the crossing time of Alfvén waves in internal parts of the NS magnetosphere is just $t_A \sim R_{NS}/c \sim 30$ mcsec (see discussion in Lyutikov 2006). We note here that Lorimer et al. (2007) actually stress that the observed burst could indeed be much shorter than 5 msec.

In addition to strong HF, SGRs show less intensive and more frequent giant flares (GFs), like those on March 5, 1979 from SGR 0526-66 and Aug. 27, 1998 from SGR 1900+14. Their galactic rate is estimated to be about 0.05 - 0.02 yr$^{-1}$, similar to the SN rate (Woods & Thompson 2006). Because of low statistics it is unknown if GFs and HFs from SGRs form continuous luminosity distribution. If they do, then mERB energy distribution should follow the same power law $dN/dE \sim E^{-\gamma}$ with the index $\gamma \approx 1.6 - 1.7$ (Guzus et al. 1999). But then, as noted by Lorimer et al. (2007) one would expect to see more weaker mERBs, which is apparently not the case. If one assumes that these events belong to different classes without bursts of intermediate energies, it is possible to explain why the first detected mERB was about two orders of magnitude above the threshold. If GFs can also produce mRBs with energies scaling similar to X-ray - soft-$\gamma$ bursts, as proposed by Lyutikov (2002), then they are too dim (or rare, if they come from much smaller volume corresponding to smaller distances) to be detected in a search like the one performed by Lorimer et al. (2007). If the HF which produced the mERB was followed by usual (weak) bursts with energies $< 10^{48}$ erg s$^{-1}$, as it is assumed to be typical for GFs and the HFs, then these events would produce too dim radio bursts ($0.03$ mJy according to the scaling suggested by Lyutikov 2002) to be detected.

## 3 DISCUSSION

SGRs are assumed to be young ($< 10^4$ yrs) neutron stars, so extragalactic flares are expected to be related to galaxies with high star formation rate (Popov & Stern 2006). Potentially, this can give a hint about possible properties of the host galaxy of the mERB discovered by Lorimer et al. (2007). For example, the possible host galaxy can be rather dim in the optical due to dust; not necessarily it should be a Milky Way-like galaxy: it can be a smaller irregular galaxy with active star formation. In this case it can lie closer than the 600 Mpc distance as inferred from the optical limit. Intrinsic DM can also be higher in star forming galaxies. So it would be interesting to use the Spitzer space telescope to search for the host galaxy of this event in the infrared.

Unfortunately, there is no much hope to find many mERBs in dedicated searches for activity of extragalactic SGRs, as HFs are very rare events. Radio monitoring of galaxies even with extremely high rate of star formation appears to be not very promising in the sense of looking for more mERBs. For example, even in the "SN factories" discussed in Popov, Stern (2006) with the star formation rate about two orders of magnitude as high as in the Milky Way, we can expect to have only few extragalactic giant flares per year (from their distances of tens Mpc the scaling discussed by Lyutikov 2002 would yield detectable GFs-related radio bursts).

Nevertheless, when performing archive searches for more mERB candidates it can be useful to check first di-
reactions with large integrated star formation rate along the
line of sight. To find more mERBs related to SGR HFs this
could be more promising than the direct search in programs
like STARE (Katz et al. 1998) and FLIRT (Balsano et al.
1998), because mERBs can have no counterparts in other
wavelengths.

To our knowledge, nobody was able to test directly the
prediction by Lyutikov (2002) by observing galactic SGRs
and/or AXPs exactly during bursts in radio with msec time
resolution. Recently, some observations of AXPs have been
reported (Burgay et al. 2006; Crawford, Hessels & Kaspi
2007). These authors put strong limits on the integrated
pulsed emission and RRAT-like bursts of several AXPs, how-
ever, nothing can be said about mRB during X-/γ bursts.

Here we note that the absence of high energy bursts
during RRAT flares suggests a different mechanism from the
one discussed by Lyutikov (2002) for radio flares from SGRs. Observed radio fluxes of RRATs are about 0.1 -
4 Jy (McLaughlin et al. 2006), which in the model from
Lyutikov (2002) corresponds to X-/γ-ray luminosities about
10^{35} - 10^{36} erg s^{-1} for the estimated RRATs distances ∼2 -
7 kpc. For X-ray bursts several hundred milliseconds long
this is bright enough to be detected by RXTE taking into
account that bursts are frequent and regular. Also, stringent
limits have been put on X-ray bursts from one of the RRAT
J1819-1458 observed by Chandra (McLaughlin et al. 2006).
However, if X-ray bursts are very short, then fluence can be
low, below the detection threshold.

Lorimer et al. (2007) note that no gamma-ray burst was
detected at the moment of the mERB (August 24, 2001). In
the case of a HF from the distance ∼600 Mpc it is not sur-
prising. For example, BATSE could detect events like the
Dec. 27, 2004 flare only from a distance of ∼30 - 40 Mpc
(Hurley et al. 2005; Popov & Stern 2006). SWIFT can de-
tect HFs (similar to Dec. 27, 2004) from larger distances
(∼70 Mpc, Hurley et al. 2002), which is still much lower
than 600 Mpc.

After the HF of Dec. 27, 2004 (as also after the Aug.
27, 1998 one), a weak radio source have been detected (see,
for example, Gaensler et al. 2003; Granot et al. 2006 and
references therein). However, it is impossible to register such
a dim object from the distance ∼600 Mpc.

Some other exotic possibilities, like deconfinement in-
side a compact object leading to a quark star formation and
complete reconfiguration of the magnetic field, can be dis-
cussed. Most of them are also expected to be accompanied
by a SN-like or/and a GRB-like event.

We conclude that the rate of HFs of SGRs of several tens
per day within 1 Gpc volume is similar to the inferred rate
of mERBs. The time scale, the absence of counterparts at
other wavelengths, as well as the non-observation of the host
galaxy up to the 18th B-magnitude, are consistent with the
HF hypothesis. The physical mechanism of the radio burst
can be related to the tearing mode instability, as proposed
by Lyutikov (2002). New observations are decisive to check
if extragalactic binary neutron star mergings or hyperflares
from SGRs underly mERBs.

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REFERENCES
Blinnikov S.I., Novikov I.D., Perevodkaikova T.V.,
Polnarev A.G., 1984, Sov. Astron. Lett., 10, 177
Balsano R.J. et al., 1998, AIP Conference Proceedings, Vol.
428, p. 585
Borkowski J., et al., 2005, GCN, 2920
Burgay M. et al., 2006, MNRAS, 372, 410
Cordes K.M., McLaughlin M.A.: 2003, ApJ, 596, 1142
Crawford F., Hessels J.W.T., Kaspi V.M., ApJ, 662, 1183
Crider A., 2006, in: “Gamma-Ray Bursts in the Swift Era”,
Eds. S.S. Holt, N. Gehrels, and J.A. Nousek. AIP Confer-
ence Proceedings, Vol. 836. Melville, NY: American Insti-
tute of Physics, p.64 [ArXiv: astro-ph/0601019]
Frederiks D.D. et al., 2007, Astron. Letters, 33, 19
Gaensler B.M. et al., 2005, Nature, 434, 1104
Göğüş E. et al., 1999, ApJ 526, 93
Golenetskii, S. et al., 2007, GCN, 6088
Granot J. et al., 2006, ApJ, 638, 391
Hansen B.M.S., Lyutikov M., 2001, MNRAS, 322, 695
Hurley K. et al., 1999, Nature, 397, 41
Hurley K. et al., 2005, Nature, 434, 1098
Katz C.A., Hewitt J.N., Moore C.B., Corey B.E., 1998,
AIP Conference Proceedings, Vol. 428, p. 591 [arXiv:
astro-ph/9712330]
Lazzati D., Ghirlanda G., Ghisellini G., 2005, MNRAS,
362, L8
Lipunov V.M., Panchenko I.E., 1996, A&A, 312, 937
Lorimer D.R., Bailes M., McLaughlin M.A., Narkevic D.J.,
Crawford F., 2007, Science, 318, 777
Lyutikov M., 2002, ApJ, 580, L65
Lyutikov M., 2006, MNRAS, 367, 1594
McLaughlin M.A. et al., 2006, Nature, 439, 817
McLaughlin M.A. et al., 2007, ApJ, (in press) [arXiv:
0708.1149]
Nakar E., 2007, Phys. Rep., 442, 166
Nakar E., Gal-Yam A., Piran T., Fox D.B., 2006, ApJ, 640,
849
Ofek E.O. et al., 2006, ApJ, 652, 507
Ofek E.O., 2007, ApJ, 659, 339
Palmer D.M. et al., 2005, Nature, 434, 1107
Popov S.B., Stern B. E., 2006, MNRAS, 365, 885
Postnov K.A., Yungelson L.R., 2006, LRR, 6
Usov V., 1992, Nature, 357, 472
Usov V., 1994, MNRAS, 267, 1033
Vietri M., 1996, ApJ, 471, L95
Woods P.M., Thompson C., 2006, In: “Compact stellar X-
ray sources, Eds. W. Lewin and M. van der Klis, Cam-
bridge Astrophysics Series, No. 39, Cambridge University
Press, p. 547 [astro-ph/0406133]