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Fast radio bursts: the last sign of supramassive neutron stars

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ABSTRACT

Context. Several fast radio bursts have been discovered recently, showing a bright, highly dispersed millisecond radio pulse. The pulses do not repeat and are not associated with a known pulsar or gamma-ray burst. The high dispersion suggests sources at cosmological distances, hence implying an extremely high radio luminosity, far larger than the power of single pulses from a pulsar.
Aims. We suggest that a fast radio burst represents the final signal of a supramassive rotating neutron star that collapses to a black hole due to magnetic braking. The neutron star is initially above the critical mass for non-rotating models and is supported by rapid rotation. As magnetic braking constantly reduces the spin, the neutron star will suddenly collapse to a black hole several thousand to million years after its birth.
Methods. We discuss several formation scenarios for supramassive neutron stars and estimate the possible observational signatures making use of the results of recent numerical general-relativistic calculations.
Results. While the collapse will hide the stellar surface behind an event horizon, the magnetic-field lines will snap violently. This can turn an almost ordinary pulsar into a bright radio "blitzar": Accelerated electrons from the travelling magnetic shock dissipate a significant fraction of the magnetosphere and produce a massive radio burst that is observable out to $z > 0.7$. Only a few percent of the neutron stars needs to be supramassive in order to explain the observed rate.
Conclusions. We suggest the intriguing possibility that fast radio bursts might trace the solitary and almost silent formation of stellar mass black holes at high redshifts. These bursts could be an electromagnetic complement to gravitational-wave emission and reveal a new formation and evolutionary channel for black holes and neutron stars that are not seen as gamma-ray bursts. If supramassive neutron stars are formed at birth and not by accretion, radio observations of these bursts could trace the core-collapse supernova rate throughout the universe.

Key words. radiation mechanisms: non-thermal

1. Introduction

The formation of neutron stars (NSs) and stellar mass black holes (BHs) is typically associated with some rather energetic observational signatures, such as a supernova (SN) or a gamma-ray burst (GRBs). The latter are short-term flares of X-ray and gamma-ray emission, lasting only a fraction of seconds to a few seconds, which have attracted a considerably attention in the past. The total energy radiated in a GRB is $\sim 10^{48-50}$ erg sec^{-1} and the bright emission was explained initially in a fireball model (Cavallo & Rees 1978; Paczynski 1986; Eichler et al. 1989), where a significant fraction of the energy is thermalized in an optically thick outflow eventually radiated in the form of high-energy emission (see Nakar 2007; Lee & Ramirez-Ruiz 2007, for recent reviews).

Short GRBs, of duration less than 2 s, are thought to be associated with NS-NS mergers and not to trace well star formation (Gehrels et al. 2005). Their average timescale is around 50 ms (Nakar 2007) with some spread. Long GRBs, with a duration longer than 2 s, may be associated with the SN of a massive star, thereby well tracing cosmic star formation (Woosley & Bloom 2006). For the latter scenario, the GRB is suggested to be due to a plasma jet that propagates through the dense outer layers of the exploding star (Woosley 1993). Hence, baryon loading and particle acceleration in internal or external shocks play an important role in the observational appearance of GRBs. However, do all forms of collapse lead to such bright observational signatures?

We here discuss the possibility of the collapse of an isolated and magnetized supramassive rotating neutron star (SURON) to a BH in a rarefied environment. Such a collapse would be inevitable if a rapidly spinning NS was formed above the critical mass for a non-rotating NS. Over time, magnetic braking would clear out the immediate environment of the star and slow it down. This will eventually lead to a sudden collapse of the SURON to a BH, with a significant delay after its formation. The formation of an event horizon over the free-fall timescale, i.e., < 1 ms, would immediately hide most of the matter and radiation apart from the SURON's magnetosphere. Instead, the magnetosphere will experience a violent disruption leading to a strong magnetic shock wave travelling outwards near the speed of light and producing radio emission. Hence, the observational signatures of such a system would be quite different from those of short or long GRBs and more akin to that of pulsar emission.

Recently, a number of isolated fast radio bursts has been discovered that may make this scenario an intriguing possibility. In 2007 Lorimer et al. discovered a single bright and highly dispersed radio flash in archival pulsar survey data of the Parkes telescope that was not associated with any known pulsar or GRB. In the meantime, more of these events have been found (Keane et al. 2012; Thornton et al. 2013). While a terrestrial origin of these radio signals can not be fully excluded (Burke-Spolaor et al. 2011) and the bursts have not been confirmed by other telescopes yet (e.g., Bower et al. 2011), an origin of these one-off radio bursts at cosmological distances now seems a viable interpretation (Thornton et al. 2013).

Theoretical interpretations of the Lorimer burst have been rare until now and no canonical picture has emerged yet (Thornton et al. 2013). A connection with short hard GRBs and merging NSs has been proposed (Pshirkov & Postnov 2010; Lyutikov 2013), as well as supernova explosions in a binary system impacting a NS magnetosphere (Egorov & Postnov 2009), reconnection in the magnetosphere of neutron stars (Somov 2011), or even superconducting cosmic strings (Cai et al. 2012) and the evaporation of BHs in the presence of extra spatial dimensions (Kavic et al. 2008). In light of the new observations it may be worth revisiting these scenarios.

The basic properties of the six currently known radio bursts can be summarized as follows: they are short with timescales $\Delta T \lesssim 1$ ms; the radio fluxes are typically around 1 Jy at GHz frequencies, with the brightest and closest one reaching over 30 Jy; no associated GRBs have been seen at the time of the bursts; the rate is about 0.25 per square degree per day; the radio burst is dispersed, with shorter wavelengths preceding longer ones, following a $\Delta T \propto \lambda^2$ law. The dispersion is similar to what is seen in pulses from Galactic pulsars due to free electrons in the interstellar medium. However, the derived dispersion measures (DM), in the range of a few hundred to thousand pc cm^{-2}, far exceed the Galactic DM in those directions. Hence, dispersion due to the intergalactic medium has been suggested, which provides distance estimates of several Gpc and redshifts in the range $z = 0.3 - 1$. In two cases, there is also evidence for a frequency-dependent scattering tail as expected for bursts passing through a turbulent ionized medium (Lorimer et al. 2007; Thornton et al. 2013).

The distribution of the few bursts would be consistent with the cosmological star formation or core-collapse SN rate. The apparent isotropic luminosity of these bursts at a mean redshift of $z = 0.7$ and luminosity distance $D_\mathrm{l} \sim 4.3$ Gpc (using $H_0 = 79.4$ km sec^{-1} Mpc^{-1}, $\Omega_\mathrm{m} = 0.27$, $\Omega_\mathrm{vac} = 0.73$), for an observed spectrum $S_\nu \propto \nu^\alpha$, would be

$$L = 3 \times 10^{43} \left(\frac{\nu}{1.4\,\mathrm{GHz}}\right)^{1+\alpha} \left(\frac{S_\nu}{1\,\mathrm{Jy}}\right) \left(\frac{D_\mathrm{l}}{11\,\mathrm{Gpc}}\right)^2 \ \mathrm{erg\,sec^{-1}}\,. \tag{1}$$

This luminosity is more than nine orders of magnitude brighter than a giant kJy flare from the Crab pulsar. On the other hand, integrated over 1 ms this yields 3×10^{40} erg[1], which is only a tiny fraction of a SN energy and much less than a typical GRB. Of course, the total luminosity could be significantly higher if the spectrum were flat ($\alpha \simeq 0$) and would extend to higher frequencies.

Finally, we point out that the observed timescale of $\lesssim 1$ ms, together with the high luminosity and non-repetitive nature is very constraining. This is much shorter than that of SNe, long and short GRBs, or of merging NS binaries. This points towards the shortest timescale available for compact objects, namely, the free-fall timescale of NSs. Also, the lack of GRB signatures and the appearance of high-brightness temperature emission, implying coherent processes, is very reminiscent of emission mechanisms of pulsars. Hence, in the following we propose a scenario that is able to address all these issues.

2. Braking-induced collapse of a supramassive NS

The basic scenario we consider here assumes an initial state of a magnetized NS with (gravitational) mass M and spin frequency $\Omega = 2\pi\tau^{-1}$, where $M_\mathrm{max}(\Omega) < M < M_\mathrm{max}(\Omega_\mathrm{K})$ and τ is the spin period. Here $M_\mathrm{max}(\Omega)$ is the maximum mass above which a NS is unstable to a collapse to a BH and Ω_K is the maximum spin a NS can have, sometimes called Keplerian or break-up spin. In the absence of rotation, $M_\mathrm{max}(0)$ would be the equivalent of the Chandrasekhar limit for NSs. Its exact value depends on the still unknown equation of state (EOS) of nuclear matter, but NSs with masses larger than $M_\mathrm{max}(0)$ can still be stable if they are supported by centrifugal forces. If we assume the NS is spinning at a fraction f of the break-up spin, then the resulting period is

$$\tau_\mathrm{rot} = 2\pi f^{-1} \sqrt{\frac{R^3}{GM}} = 0.4\, f^{-1}\, r_{10}^{3/2}\, m_2^{-1/2}\ \mathrm{ms}\,, \tag{2}$$

where $M = m_2\, 2.3 M\odot$ is the mass of the NS, $R = r_{10}\, 10\,\mathrm{km}$ its radius, and G the gravitational constant. Standard magnetic dipole radiation would then lead to a braking of the system on a timescale

$$\tau_\mathrm{braking} = \frac{6c^3 M_\mathrm{NS} \sin^{-2}(\alpha_\mathrm{B})}{5B^2R^4\Omega^2} = 1.2\, f^{-2}\, r_{10}^{-1} b_{12}^{-2}\ \mathrm{kyr}\,, \tag{3}$$

where $B = b_{12}\, 10^{12}\,\mathrm{G}$ is the magnetic field, c is the speed of light, and $\alpha_\mathrm{B} \simeq 45^\circ$ is the magnetic pitch angle. Hence, similar to highly magnetized pulsars (Duncan & Thompson 1992) the source would slow down significantly within a few hundred to a few thousand years. However, if the NS is supramassive, it will collapse to a BH and hence disappear from the general pulsar population.

Calculating the stability of rotating NSs is far from trivial. We here make use of fully general-relativistic numerical calculations where the star is modeled as a uniformly rotating polytrope with index $\Gamma = 2$ (Takami et al. 2011) and a polytropic constant chosen so that $M_\mathrm{max}(0) = 2.1 M_\odot$ to match recent observations of high-mass NSs (Antoniadis et al. 2013). Although simplified, our EOS provides here a simple and overall realistic reference.

Figure 1 illustrates the results of these calculations in a diagram showing the *gravitational* mass M, versus the central rest-mass density ρ_c. The black solid lines are sequences of models that are non-rotating, $\Omega = 0$, or rotating at break-up, $\Omega = \Omega_\mathrm{K}$, respectively. Hence, the green shaded area indicates the region where no equilibrium models are possible because they would be past the break-up limit. Shown as coloured lines are sequences of constant angular frequency normalized to the maximum possible spin frequency, i.e., Ω/Ω_K. We also show three sequences of constant *baryon* mass M_b, which can therefore be interpreted as evolutionary tracks of a NS as it spins down during its life. It is then easy to realize that, for instance, a SURON with $M_b = 2.4\, M_\odot$ (red solid line) could be produced near the break-up limit (but also at smaller rotation rates) and then spin down while maintaining its baryon mass. This corresponds to a motion to the right in Fig. 1, during which the NS reduces its gravitational mass (it contracts because of the decreased spin). This motion terminates around the stability line, the locus of the maxima of sequences of constant angular momentum, beyond which the star collapses to a Kerr BH (shown as a black dashed line). Similarly, a SURON with $M_b = 2.3\, M_\odot$ (green solid line) would also spin down, but now to a zero spin frequency, when it reaches $M_\mathrm{max}(0)$. At that point it will have become a spherical star and any perturbation will induce its collapse to a Schwarzschild BH. Finally, a normal NS with $M_b = 2.1\, M_\odot$ (blue solid line) would

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[1] Note that the power given in Table 1 in Thornton et al. (2013) is incorrect due to a conversion error.

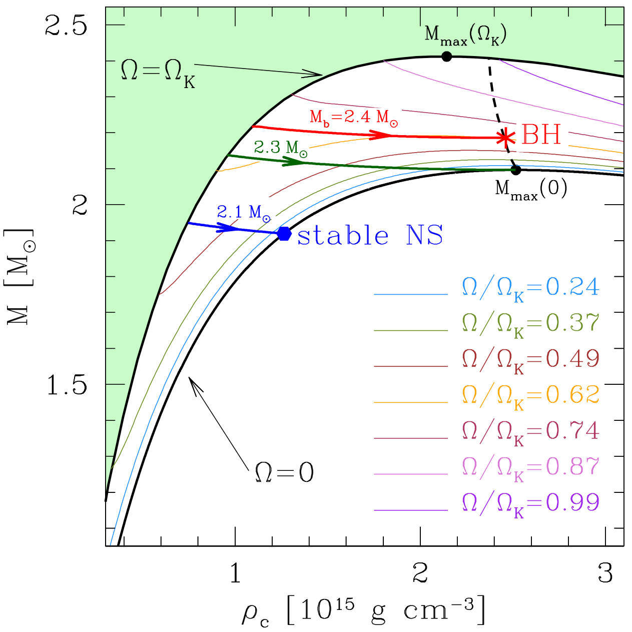

Fig. 1. Gravitational mass versus central rest-mass density for NS models with different spins. The green shaded area is the region where no equilibrium models are possible because of excessive spin. The black solid lines are sequences of models that are non-rotating, $\Omega = 0$, or rotating at break-up, $\Omega = \Omega_K$, respectively (see text for more details). The arrows indicate example tracks of NSs with baryonic masses of 2.1, 2.3, and 2.4 $M_\odot$ as they slow down due to magnetic braking.

also spin down to a zero frequency, but end up on the stable branch of equilibrium models, remaining there ever after.

In essence, for our representative EOS *any* spinning NS with a $M > 2.1\,M_\odot$ ($M_b > 2.3\,M_\odot$), will eventually collapse to a BH. The lifetime of the SURON will be of the order $\sim \tau_{\rm braking}$ and since this depends on f^{-2}, it follows from Fig. 1 that NSs which are just a few percent above $M_{\rm max}(0)$ have the longest lifetimes and can collapse millions of years after their formation. On the other hand, a NS with $M_b \simeq 2.4\,M_\odot$ has a decay timescale of 3000 years. Hence, SURONs are not necessarily highly spinning.

All these timescales are long enough for the initial SN to have faded away by the time of collapse. Moreover, these timescales are also long enough that the baryonic pollution of the NS surroundings will have been cleared out, e.g., through ejection, fall-back, or magnetic winds, such that a magnetosphere is established. Clear evidence for this is given by the Crab pulsar, which is pulsating already 10^3 years after its formation.

We also note that neutrino cooling and the associated mass loss is important only during the first 10-20 sec after the formation of the proto-neutron star (12 sec were measured for SN1987A), which can be as large as 10% of the mass. Only a few days later, however, the temperature has already decreased to $\sim 0.1\,$MeV $\sim 10^{10}\,$K, so that even if the star cooled down to a zero temperature it would lose at most an equivalent mass $\sim 0.1\,$MeV $\times\, 10^{57}$ nucleons $\simeq 10^{50}$ erg $\simeq 10^{-4}\,M$. In other words, while neutrino cooling can lead to observational signatures also thousands of years after the NS formation, see, e.g. Page et al. (2011), it soon becomes irrelevant in determining the equilibrium properties of the SURON.

Hence, we argue that, if SURONs are formed, they will have to collapse eventually and the collapse will take place in a clean environment that is rather different from that typically invoked for GRBs.

The rates estimated by Thornton et al. (2013) for fast radio bursts are ~ 0.25 deg^{-2} day^{-1}. This we can compare to the observed rate of core collapse SN, e.g., Dahlen et al. (2004), which is within a factor of two from the core-collapse SN rate expected from the star formation rate (Horiuchi et al. 2011).

Extrapolating this to $z = 1$, using the fitting function provided in Horiuchi et al. (2011), one arrives at a rate of 8 SNe deg^{-2} day^{-1}. Hence, one needs only about 3% of the massive stars to undergo a collapse as we envisage here to produce the fast radio bursts. Given that the fraction of rapidly-rotating massive stars could be up to 20%, mainly due to binary interaction (de Mink et al. 2013), this suggestion does not seem unreasonable.

The main uncertainty is how a SN with a rapidly rotating progenitor proceeds to the NS stage. In principle, rapidly spinning NSs with high magnetic fields can be formed (Fryer & Warren 2004), but the same magnetic field could also cause the NS to slow down already during the formation process. Given that binary interactions play such an important role, one could also consider an alternative formation scenario, where a slowly rotating NS gains mass and spin through accretion from its companion in ultra-compact x-ray binaries (van Haaften et al. 2013) as in the standard scenario (Bhattacharya & van den Heuvel 1991) for ms-pulsars (MSPs).

In fact, the so-called "black widow" systems can show rather massive NSs, with masses up to 2 $M_\odot$ (Demorest et al. 2010), which might have already been born massive before accretion and spin-up (Tauris et al. 2011). The problem here is that spin-up seems to suppress the magnetic field and it is not clear whether accretion-induced spin-up can preserve the strong magnetic fields needed for the emission.

If SURONs were produced in this way, the number of detectable ones could be small because of the fast spin-down and short lifetime for the most massive stars. Lastly, one could consider a formation scenario that was originally proposed to explain MSPs, where a NS and a white dwarf merge (van den Heuvel & Bonsema 1984). This too might lead to a rapidly spinning, highly magnetized, and "overweight" NS. Any scenario involving pulsar recycling rather than a direct formation, however, would not follow the high-mass star formation rate and hence can be observationally discriminated with more bursts to come.

3. Emission from the collapse

Next we estimate the observational signatures of the collapse of a SURON. Given that pulsar-emission mechanisms are notoriously difficult to calculate, we concentrate on an order-of-magnitude description and a discussion of the basic mechanisms. The relevant timescale for the collapse is the free-fall timescale, $\tau_{\rm ff} = 0.04\, r_{10}^{3/2}\, m_2^{-1/2}$ ms (Baiotti et al. 2005; Baumgarte & Shapiro 2003; Giacomazzo et al. 2011; Lehner et al. 2012).

Within a few $\tau_{\rm ff}$, the crust of the NS, that is crucial for thermal X-ray emission, will be covered by the emerging event horizon. For example, the time from the first appearance of the event horizon near the center of the NS until the NS surface is entirely covered by the event horizon can be as short as 0.15 ms for a slowly rotating star with dimensionless spin $J/M^2 \sim 0.2$ (Baiotti et al. 2005, Fig. 16, left panel). This is a situation one could envisage for our SURONs. For a star near break-up and with $J/M^2 \sim 0.54$, this duration increases to 0.35 ms (Baiotti et al. 2005, Fig. 16, right panel)[2]. This is also the timescale over which the largest changes in stellar structure take place. Hence, there is a marked difference with respect to binary NS mergers and short GRBs, whose characteristic timescales are at least one order of magnitude longer. Consequently, any thermal emission associated with the cracking of the surface will be quickly suppressed.

The magnetosphere, on the other hand, is the only part of the NS which will not disappear in the collapse as it is well outside the NS. According to the no-hair theorem, which prevents magnetic fields from puncturing the event horizon, the entire magnetic field should in principle detach and reconnect outside the horizon. This results in large currents and intense electromagnetic emission. Though the validity of the no-hair theorem in this context has been questioned (Lyutikov & McKinney 2011), a strong magnetic shock wave moving at near the speed of light is indeed seen in 3D resistive magnetohydrodynamic simulations of the collapse of non-rotating NSs (Dionysopoulou et al. 2012, Fig. 14).

The total power that can be radiated by the magnetosphere in the collapse is given by $P_{\rm MS} = \eta_{\rm B}(B^2/4\pi)\,V/\Delta T$. Given that the magnetic field in the magnetosphere is decaying quickly with radius we here consider only a small shell comparable to the NS radius around the star, i.e., the volume is $V \simeq 4\pi(2R)^3/3$. Moreover, $\eta_{\rm B}$ is the fraction of magnetic energy that is available for dissipation and $\Delta T = t_{\rm ms}$ ms is the observed burst length. This is an upper limit, as the observed pulse widths could have been broadened by scattering.

Dionysopoulou et al. (2012) have also computed the temporal evolution of the ejected magnetic luminosity for the non-rotating case. Their Fig. 15 shows a dominant peak of order ~ 0.1 ms width ($\sim 2\times\tau_{\rm ff}$) after the event horizon has formed, and a fainter precursor produced during the actual collapse. The dominant pulse is followed by additional pulses, which decay exponentially and signal the ringdown of the newly formed black hole. Precursor and the two leading pulses carry most of the transmitted power and contain about 5% of the available magnetic energy. Accordingly, we will use $\eta_{\rm B,5\%} = 5\%\eta_{\rm B}$ in the following. The bulk of the energy is released within 0.5 ms.

The available power in the magnetosphere of a typical pulsar,

$$P_{\rm MS} = 4\times10^{43}\ \eta_{\rm B,5\%}\,t_{\rm ms}^{-1}\,b_{12}^{2}\,r_{10}^{3/2}\,m_2^{1/2}\ {\rm erg\,sec^{-1}}, \qquad (4)$$

is thus of the right order of magnitude compared to the observations [cf., eq. (1)].

For simplicity we describe the magnetosphere with a simple aligned dipolar magnetic field B, rotating at $f\Omega_{\rm K}$ and filled with a pair plasma with particle number density $n_{\rm e}$, which we take to be a factor $\kappa_{\rm GJ}$ times the Goldreich-Julian density (Goldreich & Julian 1969)

$$n_{\rm e} = \kappa_{\rm GJ}\frac{B\Omega}{2ce\pi} = 3\times10^{13}\ f\,\kappa_{\rm GJ}\,b_{12}\,m_2^{1/2}r_{10}^{-3/2}\ {\rm cm^{-3}}\,. \qquad (5)$$

In a standard pulsar magnetosphere electron and positrons ($\rm e^+/e^-$) are spatially separated from each other in current sheets and glued to the magnetic field lines by the strong Lorentz forces. The strong magnetic shock waves generated in the collapse will accelerate the $\rm e^+/e^-$ pairs over spatial scales $\sim R$. Because the gyro radius of any of these particles is only $R_{\rm gyr} \simeq 1\times10^{-9}\,b_{12}$ cm, the particles will flow essentially along the magnetic field lines.

To describe the emission we can use a basic relativistic curvature radiation model (Gunn & Ostriker 1971; Ruderman & Sutherland 1975) over radius R. This is, in fact, the typical scale of the distortions of the magnetic field lines induced by the collapse. Curvature radiation simply describes how relativistic electrons radiate when following a bent trajectory. Hence, this is an almost unavoidable emission process under these conditions.

The emitted power for a single relativistic electron or positron with Lorentz factor γ is then $P_e = 2\gamma^4 e^2 c/3R^2$, with a characteristic frequency

$$\nu_{\rm curv} = \frac{3c\gamma^3}{4\pi R} = 7\ \gamma^3\,r_{10}^{-1}\ {\rm kHz}\,. \qquad (6)$$

When $\gamma \sim 1$, the corresponding wavelength is comparable to the size of the shock wave and the entire emission is *coherent*[3], giving a total power of $P_{\rm t} = N_e^2 P_e$, where $N_e = n_{\rm e}\,V$ is the total number of particles. At higher frequencies and higher γ, the coherence length remains one wavelength but becomes smaller than the emitting region (e.g., Falcke & Gorham 2003; Aloisio & Blasi 2002). Hence, we have a number $N_{\rm slices} \simeq V\,R^{-2}(c/\nu_{\rm curv})^{-1} = \gamma^3$ of coherently emitting slices perpendicular to the line of sight (defined such that $N_{\rm slices} = 1$ for $\gamma = 1$).

The emitted power then becomes $P_{\rm t} = \eta_{\rm e}\,N_{\rm slices}^{-1}\,N_e^2\,P_e$, where $\eta_{\rm e}$ accounts for the fraction of $\rm e^+/e^-$ pairs that are accelerated to Lorentz factor γ. Hence,

$$P_{\rm t} = 2\times10^{44}\ \eta_{\rm e}\,f^2\,\kappa_{\rm GJ}^2\,\gamma\,b_{12}^2\,m_2\,r_{10}\ {\rm erg\,sec^{-1}}\,. \qquad (7)$$

Simple energy conservation imposes that $P_{\rm MS} \geq P_{\rm t}$ and it follows from eqs. (4) and (7) that

$$\gamma_{\rm max} \leq \frac{9c\eta_{\rm b}}{8\,R\,\Delta T\,\kappa_{\rm GJ}^2\,\eta_{\rm e}\,\Omega^2} = 0.2\ \eta_{\rm e}^{-1}t_{\rm ms}^{-1}\,f^{-2}\,\kappa_{\rm GJ}^{-2}\,\eta_{\rm B,5\%}\,r_{10}^{2}\,m_2^{-1}\,. \qquad (8)$$

However, for the radio emission to propagate through the plasma, the radiation also has to be above the plasma frequency for a $\rm e^+/e^-$ pair plasma, $\omega_{\rm p} = \sqrt{4\pi ne^2/m_e}$, which, for $n = n_{\rm GJ}$, is

$$\nu_{\rm p} = \frac{\omega_{\rm p}}{2\pi} = \sqrt{\frac{eB\Omega}{2\pi^2 cm_e}} = 50\ f^{1/2}\,\kappa_{\rm GJ}^{1/2}\,b_{12}^{1/2}\,m_2^{1/4}\,r_{10}^{-3/4}\ {\rm GHz}\,. \qquad (9)$$

For $\gamma \sim 1$ the ensuing kHz radio emission would be absorbed in the plasma and converted to plasma waves, which would again heat the $\rm e^+/e^-$. Hence, in order for the radiation to escape effectively we need $\nu_{\rm curv} \gtrsim \nu_{\rm p}$. Combining eqs. (9) and (6), we find

$$\gamma_{\rm min} \gtrsim 190\,f^{1/6}\,\kappa_{\rm GJ}^{1/6}\,b_{12}^{1/6}\,m_2^{1/12}\,r_{10}^{1/12}\,. \qquad (10)$$

To reconcile eqs. (8) and (10) and to avoid that more power is radiated than is available in the magnetosphere, one finds that the fraction of relativistic electrons with $\gamma = \gamma_{\rm min}$ has to be of the order

$$\eta_{\rm e,max} \lesssim 0.1\,\%\ f_{\rm rot}^{-13/6}\,\kappa_{\rm GJ}^{-13/6}\,t_{\rm rad}^{-1}\,r_{10}^{23/12}\,\eta_{\rm b,5\%}\,b_{12}^{-1/6}m_2^{-7/12}\,. \qquad (11)$$

Typical power-law distributions of the accelerated electrons of the form $dN_{\rm e}(\gamma)/d\gamma \propto \gamma^{-p}$ could easily provide such an electron fraction for $p \simeq 2.5$. The very effective curvature radiation will ensure that the bulk of the $\rm e^+/e^-$ pairs cannot have

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[2] Indeed, it has been shown that the timescale for the collapse increases quadratically with the dimensionless spin(Baiotti et al. 2007).

[3] The N^2 scaling of impulsive coherent emission mechanisms of charged particles in magnetic fields is in fact experimentally demonstrated by low-frequency radio emission observed from cosmic ray air shower fronts (Falcke & Gorham 2003; Falcke et al. 2005), which has inspired our treatment.

much higher Lorentz factors than in eq. 10. Hence, the magnetosphere is already effectively dissipated by the GHz radio emission, which is also bright enough to explain the observed fast radio bursts.

This also naturally limits the maximum particle energy and suppresses additional X-ray or gamma-ray emission. Of course, higher Lorentz factors can still be reached by a smaller fraction of e^+/e^- pairs for which $\eta_e(\gamma) \ll 1$ as long as they are not energetically dominant.

We point out that the spectrum of curvature radiation is flat. However, given the rather complex nature of the shocked exploding magnetosphere and the mixing between particles, plasma waves, and radio emission the resulting spectrum could be markedly different. This requires a more targeted effort, than what we can do here.

Finally, we remark that we have assumed spherical symmetry, so that beaming does not play a role in the energy budget. However, for a dipolar magnetic field the shock wave will have a bi-polar anisotropy and the emission could be beamed and increase the observed flux. Even for isotropic emission, the relativistic beaming will have the effect that the observer sees only a small patch of the emitting region. This, together with the ordered structure of the magnetosphere, could lead to a high degree of polarization.

4. Summary and Discussion

We have argued that the short time scale of the observed fast radio bursts, if indeed cosmological, may be indicative of NS collapse. Moreover, the strong pulsar-like radio emission argues for emission associated with a magnetosphere and low baryon content. Supramassive rotating NSs can in principle provide such a setting.

If SURONs are formed, and there is no reason to believe they should not form, then they would collapse within several thousand to million years due to magnetic braking. The collapse of a SURON would proceed mostly quietly, producing a strong electromagnetic pulse due to the strong snapping of the magnetic field in the magnetosphere. Such a radio-emitting collapsar, which we dub *"blitzar"*[4] due to its bright radio flash, could be a viable explanation for the recently discovered fast radio bursts. The parameters needed for the NS are not significantly different from those of normal young pulsars, except for the higher mass. None of the processes we invoke in our scenario are in any way exotic. The SURON even need not be spinning very rapidly, as long as the mass excess is small.

Nonetheless, the energy demands to produce a fast radio burst from a blitzar could quickly increase, if the observed radio spectrum is seen to extend with a flat spectrum to high frequencies or if the radiative efficiency of the magnetosphere is even lower than we assume. In this case, magnetic fields in excess of 10^{12} G could be needed, which are in fact observed in the pulsar population.

Formation scenarios for SURONs could involve a direct collapse in a SN explosion or spin-up due to accretion or merger with a white dwarf. It remains to be seen if any of those scenarios can produce high spin *and* high magnetic fields. Spin effects during the NS formation in a GRB may also have observational consequences (Lipunova et al. 2009). SURONs should exist in our own Galaxy, but only as a small fraction of the pulsar population due to their short lifetime and the small fractional birthrate.

Future searches for fast radio bursts can determine whether blitzars indeed trace the star formation rate in the universe. This would lend support for an association with NS formation. Simultaneous optical and X-ray data could constrain the emission process, baryon load, and the delay of the collapse.

Finally, we point out that the picture sketched here could provide an interesting window onto the formation of isolated stellar-mass BHs, which would be otherwise invisible because the corresponding gravitational-wave emission is small. The ringdown of the event horizon could be visible in the radio emission of a blitzar as a succession of exponentially decaying sub-ms pulses. Detecting these decaying pulses will require observations with high signal-to-noise and low intergalactic and interstellar scattering, but would provide a unique signature for the birth of a BH.

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[4] Blitz (German) = lightning flash

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