Electromagnetic Emission from Blitzars and Its Impact on Non-repeating Fast Radio Bursts

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Abstract

It has been suggested that a non-repeating fast radio burst (FRB) represents the final signal of a magnetized neutron star collapsing to a black hole. In this model, a supramassive neutron star supported by rapid rotation, will collapse to a black hole several thousand to million years after its birth, as a result of spin-down. The collapse violently snaps the magnetic field lines anchored on the stellar surface, thus producing an electromagnetic pulse that will propagate outward and accelerate electrons, thus producing a massive radio burst, i.e., a “blitzar.” We present a systematic study of the gravitational collapse of rotating and magnetized neutron stars, with special attention to far-field evolution at late times after the collapse. By considering a series of neutron stars with rotation ranging from zero to millisecond periods and different magnetic-field strengths, we show that the blitzar emission is very robust and always characterized by a series sub-millisecond pulses decaying exponentially in amplitude. The luminosity and energy released when the magnetosphere is destroyed are well-reproduced by a simple expression in terms of the stellar magnetic field and radius. Finally, we assess the occurrence of pair production during a blitzar scenario. We conclude that, for typical magnetic-field strengths of $10^{12}$ G and spin frequencies of a few Hz, pair production is suppressed. Overall, the very good match between the results of the simulations and the luminosities normally observed for FRBs lends credibility to the blitzar model as a simple yet plausible explanation for the phenomenology of non-repeating FRBs.

Key words: black hole physics – magnetohydrodynamics (MHD) – methods: numerical – stars: neutron

1. Introduction

The gravitational collapse of a magnetized and rotating neutron star can lead to interesting and multimessenger emission, both in terms of gravitational waves (GW) and in terms of electromagnetic (EM) radiation in different bands. The detailed study of this combined emission can provide important insight into a number of astrophysical observations, particularly regarding a new type of astrophysical phenomena collectively referred to as fast radio bursts (FRBs); for a review, see Rane & Lorimer (2017).

FRBs are bright, millisecond radio single pulses that do not normally repeat and are not associated with a known pulsar or gamma-ray burst. The accounted dispersion measurements suggest that they are extragalactic, thus implying that their high radio luminosity is far larger than the single pulses from known pulsars. Furthermore, evidence of high magnetization levels has been observed through Faraday rotation measurements close to the source of a single FRB 110523 (Masui et al. 2015). Because these transient radio sources are yet to be linked with confidence to a theoretical model, dozens of them exist in the literature: some transient radio sources are yet to be linked with confirmed spins, others examine FRBs that have been detected only once and represent the large majority (Piro 2012; Kishiyama et al. 2013; Totani 2014; Mingarelli et al. 2015; Liebling & Palenzuela 2016; Wang et al. 2016; Zhang 2016).

The “blitzar” model of Falcke & Rezzolla (2014) is particularly relevant for our study, as it involves the gravitational collapse of rotating and magnetized neutron stars. More specifically, in this model, an isolated and magnetized neutron star that was born sufficiently massive can be supported against gravitational collapse by its rapid rotation. However, the star is also continuously spinning down because of loss of kinetic rotational energy in the form of EM dipolar emission; the spin-down continues up until the threshold to a dynamical instability to gravitational collapse—the neutral stability line—is reached and the star then collapses on a dynamical timescale (Takami et al. 2011; Weih et al. 2018). During the collapse, the magnetic field that was previously anchored on the surface of the star can either follow it as the surface is trapped behind the event horizon, or propagate outward in the form of EM waves as the magnetic field lines are snapped. If the magnetic field is initially dipolar, the structure of these EM waves will be quadrupolar, with large magnetic blobs carrying away most of the EM energy. Furthermore, the traveling large-scale magnetic shock that propagates outward can accelerate free electrons, which will produce radio signals dissipating the radiated energy (Falcke & Rezzolla 2014).

Along with EM radiation, the collapsing star will also produce GW radiation even if perfectly axisymmetric, simply because its quadrupole moment will have a nonzero time derivative. While we do not intend to focus here on the GW emission from these events, given that detailed studies already exist (see, e.g., Baiotti et al. (2007) for a comprehensive discussion), we will rather concentrate on how the EM emission is produced during the collapse and how it propagates outward as EM waves following the destruction of the large-scale and ordered magnetosphere. In particular, our aim is to follow the evolution of the neutron star’s magnetic field, both interior and exterior, during the collapse to a black hole. We also intend to quantify how the EM luminosity depends on the initial parameters of the neutron star, namely, its rotation rate and its magnetic field strength.

We should recall that the collapse of a magnetized rotating neutron star is an old problem that has been studied rather
extensively in the past, although only very recently in full general relativity. The first step was considered by Wilson (1975), who simulated the collapse in an ideal magnetohydrodynamical (MHD) framework, including the magnetic field only in the interior of the star. While that work represented a first attempt to simulate this process, the fact that the magnetic field was isolated to the stellar interior had the consequence that no EM radiation was produced in the process, because the magnetic field is dragged with the collapsing matter and eventually hides behind a horizon. More recently, Baumgarte & Shapiro (2003) investigated this scenario by considering the perturbative dynamics of the EM fields on a dynamical spacetime given by an Oppenheimer–Snyder collapse, that is, by the collapse of a nonrotating dust cloud. Starting with a dipolar magnetic field, Baumgarte & Shapiro (2003) especially analyzed how the magnetosphere exterior to the star changes during and mostly after the collapse of the star and the formation of the black hole. Furthermore, they showed that the magnetic flux decays exponentially in time after the collapse, following the quasinormal modes of the newly formed black hole, leaving an unstructured magnetic field in the vicinity of the black hole and outward-propagating EM waves in the far field.

Much of this behavior was later analyzed and confirmed by Dionysopoulou et al. (2013), who studied similar initial conditions of a nonrotating neutron star, but where the spacetime was self-consistently evolved via the solution of the Einstein equations and the EM fields within a fully general-relativistic resistive-MHD framework. The gravitational collapse of two magnetized and rotating neutron stars was instead investigated by Lehner et al. (2012), who considered and contrasted two different and extreme magnetospheric conditions: electrovacuum and force-free. In particular, they showed that, in the force-free case, the magnetic field is completely vanishes within a millisecond from black hole formation, mostly because of reconnection. On the other hand, in the case of the electrovacuum simulation, it was shown that the EM emission depends weakly on rotation. Following the work of Dionysopoulou et al. (2013) in resistive MHD and extending it to the case of rotating magnetized neutron stars in electrovacuum, Nathanaïl et al. (2017) have recently shown that the initial charge of the neutron star can be trapped behind the apparent horizon, thus forming a charged black hole of Kerr–Newman type.

We here further explore the scenario investigated by Nathanaïl et al. (2017), focusing mostly on the late-time evolution of the far field, where we can identify and analyze the millisecond-long EM pulses produced during the gravitational collapse and the violent disruption of the magnetosphere. Once produced in the vicinity of the surface of the star and the apparent horizon that soon forms, these EM pulses propagate outward, carrying enormous amounts of energy, with magnitudes that are in good agreement with those associated with FRBs. Furthermore, we here explore how the energetics of the emission depends on the basic properties of the stars, i.e., spin rate and magnetic field strength, and provide a simplified algebraic expressions that reproduces our results well.

The plan of the paper is as follows. In Section 2, we briefly review the numerical setup and how the initial data are computed. In Section 3, we discuss the significance of our results due to pair creation during collapse. Our analysis of the numerical results follows in Section 4. Finally, our discussion of the astrophysical impact of the results and our conclusions are presented in Section 5.

2. Numerical Setup and Initial Data

The simulations reported below have been performed using the general-relativistic resistive-MHD code WhiskyRMHD (Dionysopoulou et al. 2013, 2015). The code uses high-resolution shock-capturing methods, such as the Harten–Lax–van Leer–Einfeldt approximate Riemann solver. Following Nathanaïl et al. (2017), we reconstruct our primitive variables at the cell interfaces using the enhanced piecewise parabolic reconstruction, which does not reduce to first order at local maxima (Colella & Sekora 2008; Reisswig et al. 2013). For the evolution of the spacetime, the WhiskyRMHD code makes use of the Einstein Toolkit framework (Löffler et al. 2012), which exploits the McLachlan code for the spacetime evolution and the Carpet driver for fixed-box mesh refinement (Schnetter et al. 2004). An important point in our resistive-MHD treatment is the calculation of the electric charge \( q \), which we compute at every timestep via the divergence of the electric field, i.e., \( q = \nabla \cdot E^t \); as adopted in several other works (Bucciantini & Del Zanna 2013; Dionysopoulou et al. 2013; Nathanaïl et al. 2017; Qian et al. 2017).

Because our study is mainly focused upon the evolution of the magnetic field in the exterior of the star and the luminosity produced during and after the collapse, the use of a resistive-MHD framework is particularly convenient. In particular, we can assume a negligibly small electrical conductivity in the exterior of the star, such that it can effectively (although not exactly) reproduce an electrovacuum regime. At the same time, we can use a very large value of the electrical conductivity in the stellar interior so that we can reproduce the highly conducting matter. However, connecting the two regimes of low and high conductivity across the star and its exterior has the consequence that the set of resistive-MHD equations becomes stiff and hence requires special time-stepping strategies. Following Palenzuela et al. (2009), we employ an implicit-explicit Runge–Kutta time-stepping (RKIMEX) algorithm (Pareschi & Russo 2005), the details of our implementation can be found in Dionysopoulou et al. (2013, 2015). We use the same setup here as Nathanaïl et al. (2017), and choose a finest resolution of 147 m with a total domain size of 1075 km, which in combination with the implicit time evolution scheme makes these runs rather expensive.

The initial neutron-star models are computed using the Magstar code (Bocquet et al. 1995) of the LORENE library (http://www.lorenty.obspm.fr). In particular, Magstar computes self-consistent uniformly rotating neutron stars by solving the coupled system of the Einstein–Maxwell equations. In this way, and using a polytropic equation of state (Rezzolla & Zanotti 2013) \( \rho = K \rho^a \) with \( a = 2 \) and \( K = 164.708 \), we have computed a total of 17 initial stellar models, whose properties are collected in Table 1. The evolutions have been performed using a simple gamma law \( p = \rho c (\Gamma - 1) \) to allow for shock heating. Note that each model is characterized by a rotational frequency \(^3\) and by a magnetic field strength \(^4\), for instance, model F300.B13 refers to a magnetized neutron star with spin frequency of \( f = 300 \) Hz and a dipolar magnetic field with a value at the pole \( B_{pol} = 10^{13} \) G. Collectively, the models

\(^3\) Note that we choose an upper limit for the spinning frequency of 800 Hz because this is already higher than the fastest pulsar presently observed, i.e., PSR J1748-2446ad, whose rotation period is 1.3 ms (Hessels et al. 2006).

\(^4\) While a magnetic field of \( 10^{13} \) G is about two orders of magnitude larger than what is normally expected in a blazar. As we will show in Section 4.2, the results follow a simple scaling relation with the magnetic field strength, but using a large value reduces the computational costs.
presented in Table 1 can be considered as representative of the magnetic field strengths and of the rotational frequencies to be expected by supramassive magnetized neutron stars just before collapse.

Although the solution provided by Magstar includes self-consistent electric and magnetic fields, a certain freedom remains in the choice of an initial electric field that is consistent with our electrovacuum prescription. In fact, while the electric field in the neutron star’s interior is always unambiguously given by the ideal MHD condition, i.e., \( E^i = -e^{ik} (\Omega) B_k \), where \( (\Omega) \) is the corotation velocity and \( e^{ik} \) the totally antisymmetric permutation symbol, the electric field outside the star should be such that there are no charges outside, i.e., the electric field should be divergence-free in the stellar exterior. A similar ambiguity was discussed by Nathanail et al. (2017). After considering several different options, they found that the optimal initial electric field minimizing the exterior charge density is the one derived from the analytical solution of a rotating magnetized sphere in general relativity (Rezzolla et al. 2001, 2003).

Alternative approaches using a force-free description of the magnetosphere have instead prescribed the electric field in terms of the corotation velocity and of the magnetic field (Lehner et al. 2012; Palenzuela 2013); this approach is appropriate inside the light cylinder \( r_L = c / \Omega \) of such a magnetosphere.

Fortunately, the results of the simulations do not depend sensitively on the choice made for the electric field. Furthermore, as we show in the Appendix, the variation of the EM luminosity with the different prescriptions is minimal and the light curves overlap over the whole duration of the intense EM emission. Hence, we have opted for the simplest and most robust method of prescribing the electric field using the corotation velocity, as this does not require corrections for deviations from spherical symmetry in the case of the fast rotating models. Nonetheless, we have also performed some simulations with the rotating magnetized sphere prescription for several models, to give an error range to our calculations as detailed in the Appendix.

### 3. Pair Production

Because we will be modeling the blazar model in a purely electrovacuum scenario, it is important to check whether this is a reasonable approximation or if instead electron-positron pair production needs to be properly taken into account in this scenario. In view of this, in what follows, we explore the significance of pair production during the collapse of a rotating neutron star. In essence, we review the basic mechanisms of pair production, as known from studies of pulsar magnetospheres (Harding & Lai 2006), concentrating in particular on the photon-photon and photon-magnetic field mechanisms.

We recall that the occurrence of photon–photon pair creation in a pulsar depends sensitively on two fundamental parameters: the surface temperature of the neutron star and the magnetic field strength. Because the blazar model involves supramassive neutron stars that are thousands to millions of years old, their surface temperature \( T_s \) is expected to be well below \( T_s < 10^{16} \) K (Chabrier et al. 2006). For such temperatures in the pair formation region, the field strength should be \( B > 0.1 B_c \) (Harding & Muslimov 2001), where \( B_c = 4.4 \times 10^{13} \) G is the so-called critical magnetic-field strength. Thus, for an initial magnetic field of \( < 4.4 \times 10^{12} \) G, which is normally expected in a blazar and the one considered in our simulations here, photon-photon pair creation is strongly suppressed.

Another source of pair production is the photon–magnetic field mechanism, which involves the interaction of high-energy photons with strong magnetic fields, which proceeds as follows. When in the exterior of the pulsar, a region is emptied of charges, thus creating a so-called “gap,” an electric field parallel to the magnetic field develops as a result of unipolar induction. This huge voltage drop across magnetic field lines is capable of pulling charges from...
Using now Equations (3) and (1), we find the criterion for triggering pair creation

\[
\Delta V < \Delta V_{pp} \simeq 3 \times 10^{15} \left( \frac{r_c}{20 \text{ km}} \right)^{2/3} \left( \frac{B_{\text{loc}}}{10^{10} \text{ G}} \right)^{-1/3} \left( \frac{h}{0.2 \text{ km}} \right)^{-1/3} \text{statV},
\]

or equivalently

\[
E < E_{pp} \simeq 1.5 \times 10^{14} \left( \frac{r_c}{20 \text{ km}} \right)^{2/3} \left( \frac{B_{\text{loc}}}{10^{10} \text{ G}} \right)^{-1/3} \left( \frac{h}{0.2 \text{ km}} \right)^{-4/3} \text{statV cm}^{-1}.
\]

In other words, no pair creation is expected from the interaction of photons with the magnetic field as long as the voltage drop is below the critical one \( \Delta V_{pp} \simeq 3 \times 10^{15} \text{ statV} \). For a typical pulsar, the voltage drop can be estimated as

\[
\Delta V_{\text{typ}} \sim 1.2 \times 10^{12} \left( \frac{B_{\text{loc}}}{10^{11} \text{ G}} \right) \left( \frac{\Omega}{1880 \text{ rad s}^{-1}} \right) \left( \frac{h}{0.2 \text{ km}} \right)^2 \text{statV},
\]

where \( \Omega \) is the angular velocity of the star.

While estimate (6) is simple to carry out for a stationary pulsar, determining whether the voltage drop is always below the critical one in a collapsing scenario, where all quantities in Equation (4) change dynamically, is obviously more complicated. In particular, during the collapse, the magnetic field lines are changing rapidly and the path of the accelerated charge is not prescribed, but would need to be found self-consistently.\(^5\)

\(^5\) Note that the light traveltime over a scale height of \( \sim 10 \text{ km} \) is \( \sim 30 \mu \text{s} \), which is longer than the typical timescale of variation of the magnetic field lines.

Notwithstanding these caveats, in Section 4.3 we will follow the evolution of the parallel electric field in order to check whether or not a sufficient voltage drop is created during the collapse and hence whether pair production is at work. We can already anticipate here that, while pair production can take place during the collapse for sufficiently large magnetic fields, this process is not efficient for the typical values of the initial magnetic field in blazars.

4. Numerical Results

In what follows, we will present the results of the simulations involving the 17 neutron-star models that we have simulated. We recall that the bulk properties of the matter dynamics have already been studied in detail by several authors, starting with Font et al. (2002), and more recently by Baiotti et al. (2007) and Liebling et al. (2010). As those works show in detail, the hydrodynamical collapse to a black hole proceeds rapidly—essentially on a dynamical timescale—and does not leave any remnant matter outside the apparent horizon, thus fully justifying the assumption of an electrovacuum as the background over which the EM waves emitted during collapse will propagate in electrovacuum. Furthermore, because the overall phenomenological evolution is very similar for all of the models described in Table 1, we will discuss in more detail only the results for the models F000.B13, F300.B13, and F600.B13, as they are representative of three qualitatively different behaviors. More specifically, we will next first discuss the dynamics of the magnetic field during the collapse (Section 4.1), and subsequently the properties of the EM emission and the magnitudes of the energy losses (Section 4.2).

4.1. Magnetic Field Dynamics

Although the nonrotating model F000.B13 was already considered by Dionyssopoulou et al. (2013), we will briefly discuss it here because it provides a useful reference solution. We recall that the neutron star is initially endowed with a dipolar magnetic field, as can be seen in the first panel of Figure 1. When the collapse begins, a strong discontinuity is produced in the magnetosphere as the whole surface of the star suddenly starts to move inward. This “magnetic shock” propagates outward at the speed of light, reaching \( \sim 300 \text{ km} \) in almost \( \sim 1 \text{ ms} \) and essentially destroying the dipolar field structure (see middle panels of Figures 1 and 2). Behind this shock, and when the apparent horizon is formed, the magnetic field lines are violently snapped. At this point, quadrupolar EM radiation is produced and the EM fields propagate outward, essentially as EM waves in electrovacuum. At the same time, the electric and magnetic fields near the stellar surface and the apparent horizon constantly decay, losing any ordered large-scale structure because they cannot be sourced by the emerging Schwarzschild black hole (see right panel of Figure 1). Figure 2 provides essentially the same information reported by Figure 1, but shows it on a larger scale of \( \sim 450 \text{ km} \) so as to highlight the coherent large-scale structure of...
the magnetic field and the quadrupolar nature of the emitted EM radiation.

What cannot be shown in detail in Figures 1 and 2 are the magnetic field properties near the apparent horizon. A careful analysis of the dynamics of the magnetic field lines reveals that, when the apparent horizon is formed, magnetic field lines still pass through it. However, as the black hole starts to ringdown, magnetic loops are generated right outside the horizon and then propagate outward. At this point in time, no magnetic field line passes through the horizon and the magnetic field lines’ strength has decreased considerably.

Although what is described above refers to a nonrotating model, the overall magnetic field evolution is quite similar, at least on large scales, for the rotating ones as well. This is shown in Figure 3, which is the same as in Figure 1, but refers in the top row to the initial model F300.B13, i.e., a neutron star rotating at 300 Hz and with a pole magnetic field of $10^{13}$ G, while in the bottom row it refers to the initial model F600.B13. It is also true in these cases that, as the collapse begins

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**Figure 1.** Magnetic field strength $|B|$ in the $(x, z)$ plane, shown with a color bar and at three different times for the nonrotating model F000.B13. Also reported are the stellar surface (solid black line in the left panel), the apparent horizon (solid red line in the middle and right panels), and the magnetic field lines (white lines). The initial magnetic field strength at the pole is $10^{13}$ G; note the lack of a final ordered magnetic field at late times (right panel) because the black hole produced is of Schwarzschild type.

**Figure 2.** Evolution of the magnetic field lines in the $(x, z)$ plane for the same initial model F000.B13 shown in Figure 1, but presented here on a larger scale to highlight the global structure of the propagating EM wave. The initial neutron star is indicated in green in the left panel as a reference scale. The apparent horizon is not included in the middle or left panels, as it is too small for the scales considered.

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6 We are considering very high spin rates in order to explore the variation of the released EM energy as a function of the stellar rotation. However, typical values for the spin frequency in the blazar scenario are of a few Hz only.
and the neutron-star’s surface starts to shrink, the magnetosphere is disrupted and a magnetic shock is produced by the snapped magnetic field lines. Again, a quadrupolar EM radiation is produced near the black hole, which propagates outward as a travelling EM wave. Note that, in the case of rotating collapsing stars, all magnetic loops that are formed near the apparent horizon actually pass through it and are sourced by some current below the apparent horizon.

Another important difference between the rotating and nonrotating models is the different late-time magnetic field dynamics close to the black hole. This can be appreciated by comparing the right panel of Figure 1 with the corresponding right panels of Figure 3. While in the first case, the magnetic field is in fact unstructured at all scales, in the second case the magnetic field exhibits a clear dipolar structure whose strength depends on the initial rotation of the collapsing star: a higher rotation rate yields a higher asymptotic magnetic field at the horizon. This is shown in the left panel of Figure 4, which reports the maximum magnetic field strengths for the selected nonrotating and rotating neutron stars models: F000.B13, F300.B13, and F600.B13.

The reason behind this different behavior is simple; it lies in the fact that the rotating models have an initial charge induced by the nonzero electric field. Indeed, although our prescription for the electric field—i.e., a corotating interior electric field matched to a divergence-free electric field produced by a rotating magnetized sphere—is the one that minimizes the induced charge, our rotating neutron star models are electrically charged initially. As a result, their gravitational collapse will not lead to Kerr black holes, but rather to Kerr–Newman black holes (Nathanail et al. 2017).

Because we do not model any additional process that would change the net charge of the system, e.g., via pair creation, the initial charge of the neutron star is essentially all conserved and is acquired by the black hole. Such a charge \( Q \) is only a very small fraction of the mass of the black hole \( M_{\text{BH}} \), i.e., \( Q \sim 10^{-4} M_{\text{BH}} \), even for the highest-rotation model (Nathanail et al. 2017), but it leaves the black hole with EM fields that could be astrophysically significant.

The evolution of the electric field for the three representative cases is shown in the right panel of Figure 4; it has a behavior that is very similar to that of the magnetic field (left panel). However, it should be borne in mind that the net charge measured is effectively very small and at the limit of the numerical accuracy of our simulations (we recall that our highest spatial resolution is \( h = 0.1 M_{\odot} \) at most). In reality, however, if such a collapse would take place in an astrophysical scenario, then the abundant free charges that accompany astrophysical plasmas would neutralize it very rapidly, therefore yielding a standard Kerr solution.

Dionyssopoulou et al. (2013), as well as Baumgarte & Shapiro (2003) and Lehner et al. (2012), computed the late-time evolution of these EM fields in terms of the magnetic flux across a given surface, and showed that they decay exponentially, following the ringdown of the newly formed nonrotating black hole. This behavior has been reproduced by our simulations and can be seen in Figure 4, for both the magnetic (left panel) and the electric fields (right panel). Hence, as remarked by Falcke & Rezzolla (2014), should the EM emission from an FRB be accompanied by an exponentially decaying EM signal, it would provide unambiguous evidence that a black hole has indeed been produced together with the FRB (see also Figure 5 and related discussion).

### 4.2. EM-energy Emission

Having established that the collapse of a magnetized neutron star, be it nonrotating or rotating, leads to a magnetospheric destruction and to the production of an intense emission of EM waves, we will next discuss the energetics and the typical duration of these signals so as to compare the results of our simulations with the phenomenology associated with FRBs.

In particular, we compute the EM luminosity generated during the collapse through the expression

\[
L_{\text{EM}} := \oint_{\Sigma} S_{\text{EM}} \cdot d\Sigma,
\]

on a spherical coordinate surface \( \Sigma \) at a radial distance \( r \approx 205 \text{ km} \) from the collapsing neutron star, where \( S_{\text{EM}} \) is the Poynting vector.

Figure 5 reports the computed luminosity (7) as a function of time for three representative models in a linear (left panel) and in a logarithmic scale (right panel), respectively. The signals from the different stellar models are expressed in retarded time and are aligned so that they coincide when the largest peak reaches the detector. Clearly, all of the luminosity curves show a well-defined and dominant sub-millisecond pulse, in close analogy with the observations of FRBs (Rane & Lorimer 2017). Furthermore, the main pulse is always accompanied by both a precursor that is about 10% smaller and then by a successive pulse that is of similar amplitude (see left panel of Figure 5).

Interestingly, this pattern of peaks is rather similar to the one observed for FRB 121002 (Champion et al. 2016), thus highlighting that a blitzer model can rather naturally accommodate the multi-peaked phenomenology of FRBs. Furthermore, as discussed earlier, even when the black hole is formed, the EM emission does not cease and the black hole rings down, shedding its EM perturbations in terms of a wave-train of EM pulses (see right panel of Figure 5). It is exactly the detection of this ringdown signature that would corroborate the blitzer model as the most plausible one to describe non-repeating FRBs.

Figure 5 also allows us to deduce two important results that will also be further discussed in the following. First, the overall EM energy radiated in the whole collapse depends only very weakly on the stellar rotation rate (indeed, the radiated energy differs only by 30% when going from the nonrotating model to the most rapidly rotating model considered, having scaled out the small differences in the initial magnetic field while assuming a \( B^2 \) scaling). Second, the timescale for the EM emission is comparable in all cases and 99.99% of the energy is emitted within one millisecond; this result will be used later on when estimating an expression for the radiated energy.

It is possible to appreciate the multi-peaked structure of the EM emission from the collapsing star through the two-dimensional section on the \((x, z)\) plane of the radial component of the Poynting vector \( S \), and it appears in the integral (7) for the EM luminosity. This is shown in Figure 6, where all the pulses are visible and distinct as they travel outward. Considering that the color code reports the Poynting vector in a logarithmic scale and that the pulses move at the speed of light, we can reconstruct from Figure 6 both the precursor and the exponentially decaying structure of the EM luminosity shown in Figure 5. Figure 6 also highlights the quadrupolar
nature of the EM emission, with most of the intensity concentrated near the equatorial plane of the rotating star. This lack of anisotropy has direct consequences on the event rate of blitzars and detection rate of FRBs, indicating that if blitzars are responsible for FRBs, then the event rate should be close to a factor of two larger than the detection rate. As a final remark, we should point out that the correct event rate of blitzars would be determined by simulating realistic pulsars, meaning that the rotational axis is misaligned with the magnetic dipole moment. We intend to extend our present work to the misaligned case.

Having described the overall energetic of the EM emission, it is interesting to correlate the measured radiated energy with

\[ \text{Figure 3. Top row is the same as in Figure 1, but for the case of the initial model F300.B13, i.e., a neutron star rotating at 300 Hz and with a magnetic field of } 10^{13} \text{ G. Note the presence at late times (right panel) of an ordered magnetic field because the black hole produced is of Kerr–Newman type. Bottom row is the same as in Figure 1, but for the case of the initial model F600.B13.} \]
the basic properties of the stellar models, namely, the magnetic-field strength and the rotation rate. The ultimate goal is to derive a phenomenological expression that would provide a simple estimate of such quantities on the basis of the measured energetics of the observed FRB. Hence, we compute the radiated energy simply as the time integral of the EM luminosity, i.e.,

$$E_{\text{EM}} := \int L_{\text{EM}}(t) dt,$$

and report in Table 1 the values computed for all of the different models. A quick look at the table shows that this radiated energy is effectively almost constant across all models and that the radiated EM energy is only weakly dependent on the rate of rotation of the star. This behavior is rather different from the corresponding energy radiated in GWs $E_{\text{GW}}$. While the two energies are indeed comparable—i.e., $E_{\text{GW}} \approx E_{\text{EM}} \approx 10^{43}$ erg, for a collapsing neutron star with initial magnetic field $B_{\text{pol}} \approx 10^{13}$ G and rotation frequency $f_{\text{spin}} \approx 100$ Hz—the radiated GW energy has been shown to depend steeply on the dimensionless angular momentum of the star $\tilde{J} := J/M^2$; in particular, it follows a relation of the type $E_{\text{GW}} \propto \tilde{J}^4$ for rotation rates almost up to the mass-shedding limit (Baiotti et al. 2007). This difference, however, is not surprising and can be explained by the fact that, while the EM energy radiated reflects the actual energy stored in the magnetosphere, which does not vary significantly with rotation, the GW energy depends on a high time derivative of the quadrupole moment and is therefore much more sensitive to the variations of the latter with the spin rate.

Next, we take the phenomenological expression proposed by Falcke & Rezzolla (2014) for the available power in the magnetosphere of a typical pulsar (see Equation (4) of Falcke & Rezzolla 2014):

$$P_{\text{MS}} \approx 8.4 \times 10^{44} \eta_{B} t_{\text{ms}} b_{12} r_{10}^3 \text{ erg s}^{-1},$$

where $\eta_{B}$ is the magnetic-energy efficiency, i.e., the fraction of magnetic energy in the magnetosphere that is effectively dissipated, $\Delta t = t_{\text{ms}}$ ms is the duration of the burst, and $b_{12}$ and $r_{10}$ are the magnetic field of the star and its radius in units of $10^{12}$ G and 10 km, respectively, i.e., $B_{\text{pol}} = b_{12} 10^{12}$ G and $R = r_{10} 10$ km. Note that, although $\eta_{B}$ is unknown (but see below), a value of order unity for the luminosity is in very good agreement with the one observed in FRBs. Hereafter, we will refer to the magnetic energy efficiency as $\eta_{\text{EM}}$, because all our results were obtained assuming an electrovacuum.

Note that expression (9) assumes a quadratic scaling on the initial magnetic field; while this is reasonable from an energetic point of view, it remains an assumption. However, it can be easily verified by computing the energy emission when considering initial stellar models with the same spin frequency but a different degree of magnetization, i.e., in terms of the initial models $F500.B10$-$F500.B15$. The results of this calculation are shown in Figure 7, which reports the emitted energy $E_{\text{EM}}$ extracted at 205 km as a function of the initial value of the magnetic field at the pole $B_{\text{pol}}$. The log–log plot clearly shows that there is a power scaling between $E_{\text{EM}}$ and $B_{\text{pol}}$, and a fitting procedure shows that the scaling exponent is indeed 2.04 ± 0.02, as predicted by Falcke & Rezzolla (2014). The data in Figure 7 also allow us to fix the magnetic-energy efficiency $\eta_{\text{EM}}$. As mentioned above, in fact, the timescale for the EM emission is essentially independent of the initial stellar rotation rates, at least for the rates considered here (cf. Figure 5), and is of the order of one millisecond, i.e., $\Delta t_{\text{EM}}/ms = 1 = t_{\text{ms}}$.

As a result, we can express the emitted energy as

$$E_{\text{EM}} = P_{\text{MS}} \Delta t_{\text{EM}} \approx 8.4 \times 10^{44} \eta_{\text{EM}} b_{12} r_{10}^3 \text{ erg}.$$

Using expression (10) and the data in Figure 7, we therefore deduce via the quadratic fit that the magnetic-energy efficiency is $\eta_{\text{EM}} = 1.8\%$, as it is for the computed models $F500.B10$-$F500.B15$. We note that, although the efficiency $\eta_{\text{EM}}$ is only weakly dependent on the initial stellar rotation rate, it is not totally independent. Repeating similar calculations for all stellar models in Table 1 reveals that the highest efficiency of $\eta_{\text{EM}} = 3.6\%$ is for the model with a spinning frequency of $f_{\text{spin}} = 100$ Hz and the lowest one $\eta_{\text{EM}} = 1.4\%$ is for the model with a spinning frequency of $f_{\text{spin}} = 400$ Hz. This variance is not unexpected, as the dependence of $\eta_{\text{EM}}$ on $f_{\text{spin}}$ is weak and it is well-known that the dynamics of the collapse “slows down” as the spin rate of the neutron stars increases (Baiotti et al. 2007). Given this variance, we compute an average...
The value of $\eta_{\text{inv}} = (2.1 \pm 0.5)\%$ and hence obtain a phenomenological expression for the EM power released by a blitzar as given by

$$P_{\text{MS}} \simeq 1.7 \times 10^{43} \tau_{\text{ms}}^{-1} b_{12}^2 r_{10}^3 \text{erg s}^{-1}, \quad (11)$$

while the corresponding energy is

$$E_{\text{EM}} \simeq 1.7 \times 10^{40} b_{12}^2 r_{10}^3 \text{erg}. \quad (12)$$

Within the blitzar model, therefore, once an FRB of a given energy is measured, using Equations (11) and (12) it is possible, at least in principle, to set constraints on either the radius of the collapsing star or on its magnetic field.

We should remark that the considerations made so far are “bolometric” in the sense that we are simply computing the EM energy emitted from the collapsing process in terms of the Poynting flux measured at large distances from the source. In this respect, we have not at all discussed how this bulk energy is then channeled, most likely in a coherent manner, to produce the observed radio emission in FRBs. A simplified curvature-radiation model that uses blitzar emission to reproduce the observed FRB phenomenology is discussed by Falcke & Rezzolla (2014), and we still consider it a reasonable first radiation model for blitzars. Our future intention is to couple our present simulations with a curvature-radiation model, in order to produce realistic radiation imprints of a blitzar. At the same time, we refer the interested reader to the recent works of Katz (2014), Kumar et al. (2017), and Ghisellini & Locatelli (2018).

### 4.3. On the Pair Production in a Blitzar Scenario

As anticipated in Section 3, it is important to assess the occurrence of pair production under the physical conditions that are produced during a blitzar scenario. To this purpose, we numerically follow the evolution of the maximum value of the parallel electric field, $E_{||} := |\mathbf{E} \cdot \mathbf{B} / |\mathbf{B}|$, responsible for any particle acceleration and hence pair production. Our reference model is that of a typical supramassive neutron star involved in a blitzar scenario, namely, a star with the magnetic field $B_{\text{pol}} = 10^{12}$ G and period of 1 s ($f_{\text{spin}} = 1$ Hz). With such an initial magnetic field and rotation rate, the star is supposed to have passed its death line, where no pair creation and pulsar emission is expected to take place (Chen & Ruderman 1993).

In Figure 8, we show the evolution of the rest-mass density (left portions of the panels) and of the maximum of the parallel electric field (right portions of the panels) at three representative times in a typical evolution: one just before all matter is lost inside the black hole and two shortly thereafter; these are also the times when $E_{||}$ reaches its highest value. Also shown in Figure 8 are the stellar surface (solid black line in the left panel), the apparent horizon (dashed red line), and the magnetic field lines (orange lines).

Note that, as the collapse proceeds, the parallel electric field grows, but also that the largest values are confined within the star and below its surface. Indeed, the parallel electric field remains below the critical value for pair creation $E_{\text{pp}}$ (see Equation (5)). The maximum of this growth takes place shortly before all matter is lost behind an apparent horizon, so there is only a very short window in time, i.e., on the order of a fraction of a microsecond, during which charges could be pulled from the stellar surface.

In summary, the results presented in Figure 8 show that the typical strength of the magnetic field in a blitzar scenario, i.e., $B_{\text{pol}} = 10^{12}$ G, is at the limit of the physical conditions below which pair creation is strongly suppressed. This finding provides us with confidence in the robustness of the results presented here in a pure electrovacuum scenario. On the other hand, the results in Figure 8 also indicate that, for larger initial magnetic fields, pair creation is very likely to take place.

Interestingly, if pair creation does take place during the collapse, the EM emission is likely to be different, thus providing an important signature for the occurrence of the pair creation. More specifically, it is reasonable to assume that, along with the emission discussed so far and due to the global snapping of the magnetic field lines, those photons produced from the pair cascade that do not have sufficient energy to further pair create could then diffuse through the stellar exterior, leading to an additional emission. This scenario, which could be considered a “dirty blitzar,” would then have a multi-frequency radiation spectrum. A more detailed study is necessary to further explore this speculation, both in the theoretical modeling and in the analysis of the observational data.
5. Conclusions

Understanding the physics of astronomical systems dominated by extreme gravity and ultra-strong magnetic fields is at the heart of high-energy astrophysics. In this context, the collapse of a rotating and magnetized neutron star represents a perfect example, one that has been explored via numerical simulations in full general relativity by several authors in the recent past (Baumgarte & Shapiro 2003; Lehner et al. 2012; Dionysopoulou et al. 2013). In addition to the physical insight that these investigations have brought, they have also been useful in defining a theoretical framework that provides a simple explanation of some of the most exciting yet mysterious astronomical objects that have been recently observed: FRBs. The blitzar model, in fact, involves the gravitational collapse of a rotating and magnetized neutron star and was proposed early on as a possible and plausible explanation for non-repeating FRBs (Falcke & Rezzolla 2014). More specifically, this model suggests that an isolated and magnetized supramassive neutron star, i.e., a neutron star whose mass is the maximum mass for nonrotating configurations, collapses when it has lost sufficient angular momentum via the emission of EM energy through dipolar radiation. When this happens, the rotating star disrupts its magnetosphere and launches a coherent EM emission in the radio band (Falcke & Rezzolla 2014).

We have here explored the validity of this model, going beyond the numerical modeling presented by Dionysopoulou et al. (2013), who considered the gravitational collapse of a magnetized but nonrotating neutron star within a resistive-MHD framework in general relativity. In particular, we have performed accurate numerical simulations of collapsing neutron stars, adopting a framework similar to that of Dionysopoulou et al. (2013) but considering here a large number of rotating neutron-star models that differ either in rotation rate or in the initial magnetization. Overall, and as observed also in the case of nonrotating stars, we have found that, even when rotation is involved, the disruption of the magnetosphere still takes place on a dynamical timescale. The EM emission is characterized by a precursor signal, followed by a main emission pulse and then by an exponentially decaying signal, as is typical of the ringdown of black holes from EM perturbations. All the different peaks in the EM wave train have a sub-millisecond separation, and thus highlight that the blitzar model can easily accommodate multi-peaked FRB signals such as the one for FRB (Champion et al. 2016). Furthermore, should the EM emission from an FRB be accompanied by an exponentially decaying EM signal, it would provide unambiguous evidence that a black hole has indeed been produced along with the FRB.

When considering the EM energy properties of the blitzar emission, we have found that this is only very weakly dependent on the initial stellar rotation rate, at least for the rotation rates considered here, which go up to spin frequency of the fastest known pulsar, i.e., PSR J1748-2446ad. Similarly, the timescale for the EM emission to have decreased by four orders of magnitude is on the order of one millisecond, in reasonable agreement with the observations of FRBs.

Figure 6. Radial component of the Poynting vector $S$ in the $(x, z)$ plane for models $F000.B13, F300.B13$, and $F600.B13$. It is this complex structure that leads to the multi-peaked EM emission reported in Figure 5. Note that the small time difference between the models is a result of the slightly delayed collapse for fast rotating models. Note that the small differences in the initial magnetic field strengths at the poles (see Table 1) have been scaled out, assuming a $B^2$ scaling.

Figure 7. Scaling of the emitted EM energy extracted at 205 km with the initial value of the magnetic field on the pole $B_{pol}$. The models shown are FRB500.B10–FRB500.B15.
Exploiting this property and the results of a number of simulations of stellar models that differ only in the strength of the initial magnetic field, we have been able to show that the radiated EM energy scales quadratically with the magnetic field and that the collapse is able to release, in Poynting flux, about 2% of the EM energy initially stored in the magnetosphere. This magnetic energy efficiency is essentially independent of the initial magnetic field and only very weakly dependent on the rotation rates. This result has thus allowed us to derive a phenomenological expression for the emitted EM energy. Hence, once an FRB of a given energy is measured, it would in principle be possible to set constraints on either the radius of the collapsing star or on its magnetic field, if the emission is indeed produced by a blitzar.

Before concluding, we should stress that, while the simulations reported here represent a significant progress in the modeling of non-repeating FRBs as blitzars, they also have a number of limitations that call for additional studies and improvements. First, the results presented here are only “bolometric” in the sense that we are simply computing the EM energy emitted from the collapsing process in terms of the Poynting flux measured at large distances from the source. No attempt has been made to go beyond the curvature-radiation model of Falcke & Rezzolla (2014) to discuss how the radiated bulk energy is transformed into the observed radio emission in FRBs. While this is beyond the scope of this paper, it is part of our program of modeling blitzar emission. Second, we have here considered a simplified equation of state to describe the nuclear matter and a single value for the mass of the collapsing star. It would be of great interest to explore how the results presented here change when stellar models of different masses and different radii are considered.

Finally, while a resistive-MHD approach is a versatile approach to describe the transition between a highly conductive neutron star interior and the electrovacuum that should characterize pulsars, it still represents an approximation that can be further improved by varying the choice for the initial electric field, the prescription for the conductivity profile, and possibly the match to a force-free exterior. All of these options will be explored in our future work.

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Appendix

Initial Electric Field

In Section 2, we discuss the different possible choices for the initial electric field; in this Appendix, we explore the impact they have on the energetic output from a collapsing reference model. To maximize such impact, we consider a rather extreme example, namely, a star rotating at 800 Hz with an initial magnetic field of $10^{13}$ G, i.e., model F800.B13.

We recall that, in view of its infinite conductivity, the electric field for the neutron-star interior is given by the ideal MHD condition, i.e., $E^i = -\epsilon^i_a (\psi_c) B_a$. This interior solution needs to be matched at the stellar surface and then extended to the outer edge of the computational domain in such a way that the closed magnetosphere is corotating but still compatible with our electrovacuum representation of the stellar exterior. In practice, since any choice of an electric field would numerically introduce electric charges, the main goal of the prescription is to reduce the total net charge and any spurious effect that may arise at the stellar surface.

The first option is to employ the analytic description of the electric field outside a rotating, magnetized, and charged sphere in special relativity proposed by Ruffini & Treves (1973) (we refer to this solution as to the “SR rotating sphere”). The second option is the general-relativistic equivalent of this solution, namely the electric field coming from the analytical description of a rotating magnetized sphere in general relativity (Rezzolla et al. 2001, 2003); this solution is further modified by the addition of monopolar and quadrupolar terms in order to account also for the net electric charge of the star (Ruffini & Treves 1973). In this way, the modified solution of Rezzolla et al. (2001) is the one that minimizes the exterior charge density, and hence is the one that was used throughout the paper (we refer to this solution as to the “SR rotating sphere”). The third and fourth options that we have considered are given respectively by another corotation solution for the stellar exterior (we refer to this solution as “Corotation”) and by the...
default solution provided by the Magstar code (we refer to this solution as “MagStar”).

The left panel of Figure 9 offers a comparison of these four prescriptions for the electric field in terms of the EM luminosity. Clearly, the main features of the luminosity produced during the collapse are all very similar, with some differences becoming visible only in the late stages of the evolution, when the luminosity has decreased by about five orders of magnitude and is close to the constant noise level of our code. Similarly, the right panel of Figure 9 shows a comparison among the total emitted EM energies for the different prescriptions. Also in this case, the different luminosities are very similar and all in the range \( \sim (4.5-5) \times 10^{45} \text{ erg} \). Note that the differences reported are actually smaller than the errors introduced when extracting the radiation at different coordinate radii.

In view of the results in Figure 9, we can safely conclude that the results of our analysis are robust and not influenced by our particular choice for the initial electric field.

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**References**

Baiotti, L., Hawke, I., & Rezzolla, L. 2007, *CQGra*, 24, S187
Baumgarte, T. W., & Shapiro, S. L. 2003, *ApJ*, 585, 930
Bocquet, M., Bonazzola, S., Gourgoulhon, E., & Novak, J. 1995, *A&A*, 301, 757
Bucciantini, N., & Del Zanna, L. 2013, *MNRAS*, 428, 71
Chabrier, G., Saumon, D., & Potekhin, A. Y. 2006, *JPhA*, 39, 4411
Champion, D. J., et al. 2016, *MNRAS*, 460, L30
Chen, K., & Ruderman, M. 1993, *ApJ*, 402, 264
Colloca, P., & Sekora, M. D. 2008, *ICoPh*, 227, 7069
Cordes, J. M., & Wasserman, I. 2016, *MNRAS*, 457, 232
Dionysopoulou, K., Alie, D., Palenzuela, C., Rezzolla, L., & Giacomazzo, B. 2013, *PhRvD*, 88, 044020
Dionysopoulou, K., Alie, D., & Rezzolla, L. 2015, *PhRvD*, 92, 084064
Falcke, H., & Rezzolla, L. 2014, *A&A*, 562, A137

\(^{7}\) Note that because of its higher rotation rate and magnetic field, model \( F800.B13 \) has a larger luminosity than what shown for the other models in Figure 5.

Font, J. A., et al. 2002, *PhRvD*, 65, 084024
Ghisellini, G., & Locatelli, N. 2018, *A&A*, 613, A61
Harding, A. K., & Lai, D. 2006, *RPPh*, 69, 2631
Harding, A. K., & Muslimov, A. G. 2001, *ApJ*, 556, 987
Hessels, J. W., Ransom, S. M., Stairs, I. H., et al. 2006, *Sci*, 311, 1901
Kashiyama, K., Ioka, K., & Mészáros, P. 2013, *ApJL*, 776, L39
Katz, J. I. 2014, *PhRvD*, 89, 103009
Katz, J. I. 2016, *ApJ*, 826, 226
Kumar, P., Lu, W., & Bhattacharya, M. 2017, *MNRAS*, 468, 2726
Lehner, L., Palenzuela, C., Liebling, S. L., Thompson, C., & Hanna, C. 2012, *PhRvD*, 86, 104035
Liebling, S. L., Lehner, L., Neilsen, D., & Palenzuela, C. 2010, *PhRvD*, 81, 124023
Lieblung, S. L., & Palenzuela, C. 2016, *PhRvD*, 94, 064046
Löffler, F., et al. 2012, *CQGra*, 29, 115001
Lyu, Y.-S., & Postnov, K. A. 2010, in Proc. of the Conf. Dedicated to Viktor Ambartsumian’s 100th Anniversary, Evolution of Cosmic Objects through Their Physical Activity, ed. H. A. Harutyunyan, A. M. Mickaelian, & Y. Terzian (Yerevan: NAS RA), 129
Mingarelli, C. M. F., Levin, J., & Lazio, T. J. W. 2015, *ApJL*, 814, L20
Nathanail, A., Most, E. R., & Rezzolla, L. 2017, *PhRvD*, 96, L39
Palenzuela, C. 2013, *MNRAS*, 431, 1853
Palenzuela, C., Lehner, L., Reula, O., & Rezzolla, L. 2009, *MNRAS*, 394, 1727
Pareschi, L., & Russo, G. 2005, *JCom*, 25, 129
Pen, U.-L., & Connor, L. 2015, *ApJ*, 807, 179
Piro, A. L. 2012, *ApJ*, 755, 80
Popov, S. B., & Postnov, K. A. 2010, in Proc. of the Conf. Dedicated to Viktor Ambartsumian’s 100th Anniversary, Evolution of Cosmic Objects through Their Physical Activity, ed. H. A. Harutyunyan, A. M. Mickaelian, & Y. Terzian (Yerevan: NAS RA), 129
Qian, Q., Fendt, C., Noble, S., & Bugli, M. 2017, *ApJ*, 834, 29
Rane, A., & Lorimer, D. 2017, *JApA*, 38, 55
Reisswig, C., Haas, R., Ott, C. D., et al. 2013, *PhRvD*, 87, 064023
Rezzolla, L., Ahmedov, B. J., & Miller, J. C. 2001, *MNRAS*, 322, 723
Rezzolla, L., Ahmedov, B. J., & Miller, J. C. 2003, *MNRAS*, 338, 816
Rezzolla, L., & Zanotti, O. 2013, *Relativistic Hydrodynamics* (Oxford: Oxford Univ. Press)
Ruderman, M. A., & Sutherland, P. G. 1975, *ApJ*, 196, 51
Ruffini, R., & Treves, A. 1973, *ApJL*, 13, 109
Schnetter, E., Hawley, S. H., & Hawke, I. 2004, *CQGra*, 21, 1465
Sturrock, P. A. 1971, *ApJ*, 164, 529
Takami, K., Rezzolla, L., & Yoshida, S. 2011, *MNRAS*, 416, L1
Tóth, L. 2013, *PASJ*, 65, L12
Wang, J.-S., Yang, Y.-P., Wu, X.-F., Dai, Z.-G., & Wang, F.-Y. 2016, *ApJL*, 822, L7
Weih, L. R., Most, E. R., & Rezzolla, L. 2018, *MNRAS*, 473, L126
Wilson, J. R. 1975, in *Annals of the New York Academy of Sciences* Vol. 262, Seventh Texas Symposium on Relativistic Astrophysics, ed. P. G. Bergman, E. J. Fenyes, & L. Motz (New York: Wiley), 123
Zhang, B. 2016, *ApJL*, 827, L31