

Quark nova model for fast radio bursts

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Received 2015 September 22; accepted 2015 December 31

Abstract Fast radio bursts (FRBs) are puzzling, millisecond, energetic radio transients with no discernible source; observations show no counterparts in other frequency bands. The birth of a quark star from a parent neutron star experiencing a quark nova - previously thought undetectable when born in isolation - provides a natural explanation for the emission characteristics of FRBs. The generation of unstable r -process elements in the quark nova ejecta provides millisecond exponential injection of electrons into the surrounding strong magnetic field at the parent neutron star's light cylinder via β -decay. This radio synchrotron emission has a total duration of hundreds of milliseconds and matches the observed spectrum while reducing the inferred dispersion measure by approximately $200 \text{ cm}^{-3} \text{ pc}$. The model allows indirect measurement of neutron star magnetic fields and periods in addition to providing astronomical measurements of β -decay chains of unstable neutron rich nuclei. Using this model, we can calculate expected FRB average energies ($\sim 10^{41} \text{ erg}$) and spectral shapes, and provide a theoretical framework for determining distances.

Key words: stars: neutron — nuclear reactions, nucleosynthesis, abundances — radiation mechanisms: general — radio continuum: general

1 INTRODUCTION

The observation of fast radio bursts (FRBs) has created an interesting puzzle for astronomers. Explaining the origin of these millisecond bursts has proven difficult because no progenitor has been discovered and there is no detectable emission in other wavelengths. Many possible explanations for these bursts have been put forward: blitzars (Falcke & Rezzolla 2014), neutron star mergers (Totani 2013), magnetars (Popov & Postnov 2010, 2013; Lyubarsky 2014; Pen & Connor 2015), asteroid collisions with neutron stars (Geng & Huang 2015), and dark matter induced collapse of neutron stars (Fuller & Ott 2015), to name a few; however, none so far have been able to explain the many puzzling features of the emission: the signal dispersion, energetics, polarization, rate, emission frequency, and lack of a (visible) companion/source object.

Direct observational evidence for quark stars is difficult to accrue due to some of their similarities to neutron stars (e.g. compactness, high magnetic field, low luminosity). In our model, FRBs signal the birth of a quark star and as more FRB observations become available, they may be able to provide evidence for the existence of quark stars. Other theoretical observational signatures of quark stars include: gravitational waves from quark star oscillation modes (Gondek-Rosińska et al. 2003; Vásquez Flores & Lugones 2014); gravitational waves from a strange-quark planet and a quark star binary system (Geng et al. 2015); equation of state constraints of the mass-radius relationship

(Drago et al. 2015) and high-energy emission directly from the quark star in X-ray and gamma ray emission (Ouyed et al. 2011).

The Quark Nova (hereafter QN) model has many ingredients which prove useful when trying to explain FRBs. Firstly, the parent neutron star has a strong magnetic field which can generate radio synchrotron emission. Secondly, the neutron rich ejecta of the QN has a unique mechanism for producing these electrons via β -decay of nuclei following r -process nucleosynthesis in the QN ejecta (Jaikumar et al. 2007; Charignon et al. 2011; Kostka et al. 2014b). Our model makes use of the β -decay of nuclei in the ejecta of a QN to produce radio synchrotron emission. The exponential decay inherent to the nuclear decay explains the millisecond pulses observed in a way that no other model so far can.

As an isolated, old neutron star spins down, the central density increases. Neutron star spin-down, which increases the core density leading to quark deconfinement, in conjunction with accretion and s-quark seeding can trigger an explosive phase transition (Ouyed et al. 2002; Staff et al. 2006; Ouyed et al. 2013b). This explosion ejects a dense layer of neutrons which produce unstable heavy nuclei (Keränen et al. 2005; Ouyed & Leahy 2009). These unstable nuclei decay and become observable at the light cylinder (hereafter LC) where they emit synchrotron emission due to the strong magnetic field. (For a 10 s period and 10^{12} G parent neutron star this corresponds to $B \sim 300 \text{ G}$

at the LC.) This generates a unique geometry and field configuration where our emission occurs at the intersection of a cylinder and sphere in space traced out by the ejecta as it passes through the LC.

We expect FRBs to be associated with old, isolated neutron stars and not young, rapidly rotating neutron stars. Neutron stars born with short periods quickly spin down and increase their central densities and, when these neutron stars are born with sufficient mass, deconfinement densities are reached very quickly (within days to weeks). Instead of emitting as an FRB, these QN will interact with the supernova ejecta leading to either a super-luminous supernova (Kostka et al. 2014a), or a double-humped supernova (Ouyed et al. 2013a). This interaction with the surrounding material is expected to either disrupt the FRB emission, or bury the signal in the surrounding dense ejecta. The remaining neutron stars which are born massive and with high periods will take much longer (millions of years) to achieve the required critical core density. As such, we expect a continuum of FRB progenitors with a range of periods and magnetic fields to be emitting at various frequencies and luminosities.

Two important consequences of this scenario are: (1) an extended time spectrum as the sphere sweeps across higher and higher latitudes of the LC and (2) an exponential time profile with a millisecond duration from decay of β -decaying nuclei. As will be demonstrated later, these qualities match observations of FRBs and allow us to provide testable predictions for distances, energies, rates and bandwidth of future FRB measurements which we can link to old, isolated neutron star populations and nuclear rates.

2 MODEL OVERVIEW

As a neutron star ages, spin-down increases its central density. For massive enough neutron stars, this can cause a phase transition that gives birth to a quark star. The exploding neutron star ejects - at relativistic speeds - the outer layers of the neutron rich crust. The ejecta is converted to unstable r -process material in a fraction of a second and reaches a stationary r -process distribution which is maintained by the high-density of the ejecta and the latent emission of neutrons from fission (fission recycling). This distribution of unstable nuclei, which normally would decay within seconds, can continue to exist while the density is high and fissionable elements are able to release neutrons back into the system. This stationary distribution will be disrupted by decompression (or other disruption) of the QN ejecta as it passes through the LC of the surrounding parent neutron star magnetic field.

Once the ejecta is beyond the current sheets of the LC, the QN ejecta will no longer support a stationary r -process distribution and electromagnetic radiation from the ejecta will no longer be attenuated by the LC plasma, becoming visible¹. The nuclei will decay via a rapid series of β -

¹ The current sheets at the LC produce a Faraday cage effect which shields the emission of β -decay occurring before the r -process material crosses the LC.

decays. These generated electrons are emitted with MeV energies in a strong magnetic field producing radio synchrotron emission. The frequency and power of this emission depends, of course, on the magnetic field strength at the LC where the QN ejecta crosses it. As a result, the emission spectrum is controlled by the geometry of the spherical intersection of the ejecta with the LC and allows inference of the progenitor neutron star's period and magnetic field.

A distinguishing detail in our model is the duration of the emission, which has a duration of seconds instead of milliseconds. The signal is a continuous series of synchrotron emissions from bunches of electrons generated from β -decay, which produce coherent, millisecond duration pulses at each frequency over several seconds (or hundreds of milliseconds for a bandwidth limited observation), as can be seen in Figure 1. This is in apparent contrast with observations, which indicate a total emission duration of milliseconds. This discrepancy in the FRB duration stems from the de-dispersion process which stacks all frequency channels to a common initial time (as is done in pulsar de-dispersion and signal folding). As such, according to our model, the FRB emits a series of coherent, self-similar signals at different frequencies which have been erroneously stacked as a time synchronized pulse: the total duration of the FRB is actually several seconds long and the observed signal duration is still dominated by cold plasma dispersion, as is demonstrated by the red/orange signal in Figure 1.

The model comprises a combination of relatively standard physics phenomena: β -decay, magnetic field geometry and synchrotron emission. In composite, they generate a unique emission mechanism reminiscent of FRBs. The following sections (Sects. 2.1 to 2.4) will be spent outlining each component of the model in greater detail and setting out the relevant equations necessary to generate the equations which describe the synchrotron emission spectra of the r -process material generated in the QN ejecta (see Sect. 3).

2.1 R -process Elements

The formation of heavy elements by the r -process is one of the predictions of the QN model (Jaikumar et al. 2007; Charignon et al. 2011; Kostka et al. 2014b). Due to a large number of free neutrons delivered by the ejected neutron star crust, it is possible for heavy fissile nuclei to be created during the r -process. R -process calculations show that superheavy ($Z > 92$) fissile elements can be produced during the neutron captures. This leads to fission recycling during the r -process (Kostka et al. 2014b). Each fission event ejects (or releases) several ($\sim 5 - 10$) neutrons back into the r -processing system. (This is due to neutron evaporation during asymmetric fission and is the same mechanism present in nuclear reactors.) Because of this, once these fissionable elements are produced, we are guaranteed to have free neutrons continually resupplied to the system which

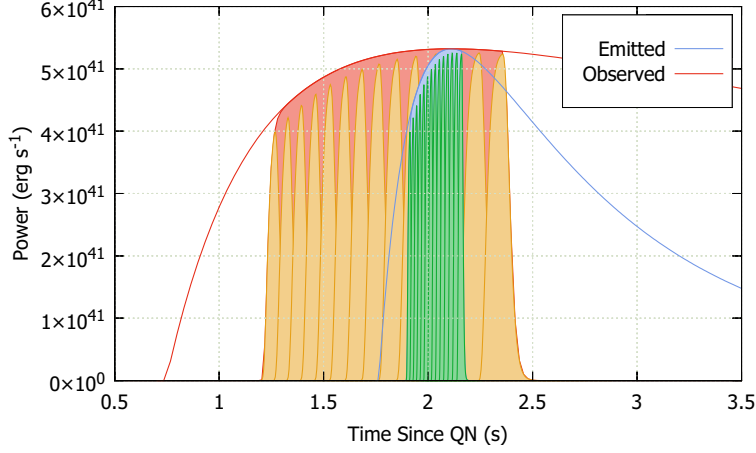


Fig. 1 Light curve of the FRB emission at the source (*blue*) and the observed emission with dispersion smearing (*red*). The filled portion of the curves indicates the viewable emission for bandwidth limited observation in the range of 1175–1525 MHz. The green and orange pulses are 25 MHz sub-bands of the signal which exhibit the characteristic millisecond pulse duration.

recombine into heavier elements which will undergo fission again and create a feedback loop in the r -process inside the QN ejecta. This allows for continued neutron captures and “ r -processing” much longer than traditionally expected (see Fig. 2). These unstable isotopes are then able to supply us with the electrons which will decay in coherent bunches over different magnetic fields to produce the final aggregate emission spectrum.

2.1.1 R -process Rates

The basic r -process mechanism operates as a competition between neutron capture reactions (n, γ) and its inverse photo-dissociation (γ, n) with the much slower β -decays slowly building up each successive isotope. This picture holds true early on while the ejecta is still hot and dense; however, as the gas expands and cools, the photo-dissociation rates fall off very quickly with temperature. The neutron-capture rates, on the other hand, do not have as strong a temperature dependence and are mainly a function of neutron density (see Fig. 3).

For an initially dense ejecta (which is of course the case for a neutron star crust ($\rho \sim 10^{14}$ g cm $^{-3}$) this means that neutron captures can continue at low temperatures even after significant initial decompression. Instead of competing with photo-dissociations, they will begin to compete with β -decays instead as shown in Figure 3. At this point, simulations show that the isotopic distribution enters an approximate steady state (possible because of the fission recycling) which is maintained by the re-emitted neutrons and high density of the ejecta. The rates shown here come from Möller et al. (2003) and the BRUSLIB database (Goriely et al. 2008, 2009). These rates are all theoretical due to the difficulty of measuring them in the lab (Krücken 2011) and represent a way of observationally constraining β -decay rates by measuring synchrotron radiation from these decay chains.

2.1.2 Decay Chain of Unstable Isotopes

For elements lighter than the actinides, β -decay (or electron capture) is the dominant decay mode available to them. These decay chains can be described by coupled differential equations which have a simple analytic solution known as the Bateman equations (Krane 1987)

$$A_n = N_0 \sum_{i=1}^n c_i e^{-\lambda_i t}, \quad (1)$$

$$c_m = \frac{\prod_{i=1}^n \lambda_i}{\prod_{i=1}^n (\lambda_i - \lambda_m)}, \quad (2)$$

where the prime indicates that the lower product excludes the term where $i = m$. This equation gives the activity (number of events per unit time) of a decay chain. For a purely β -decay chain this gives the rate at which free electrons are produced by nuclei. As can be seen in Figure 4, once β -decay dominates, the unstable nuclei will decay roughly exponentially and have a short burst of activity that will emit synchrotron radiation if subject to an external magnetic field. This naturally gives us an exponential fall-off time once neutron captures stop, which as discussed above, can be much later in the expansion than traditionally expected in the r -process due to the high density of the ejected material (which is abruptly triggered by decompression across the LC). Once emitted, the electrons will recombine with the surrounding weakly ionized plasma which should promptly emit in the keV range and could be visible if the plasma is diffuse enough; however, at much lower total emission power than the FRB burst itself (likely making it undetectable).

2.2 Geometry and Field Configuration

Assuming that the emission is triggered at the LC, we need to define a coordinate system with which to describe emission time and magnetic field strength (see Fig. 5). The LC

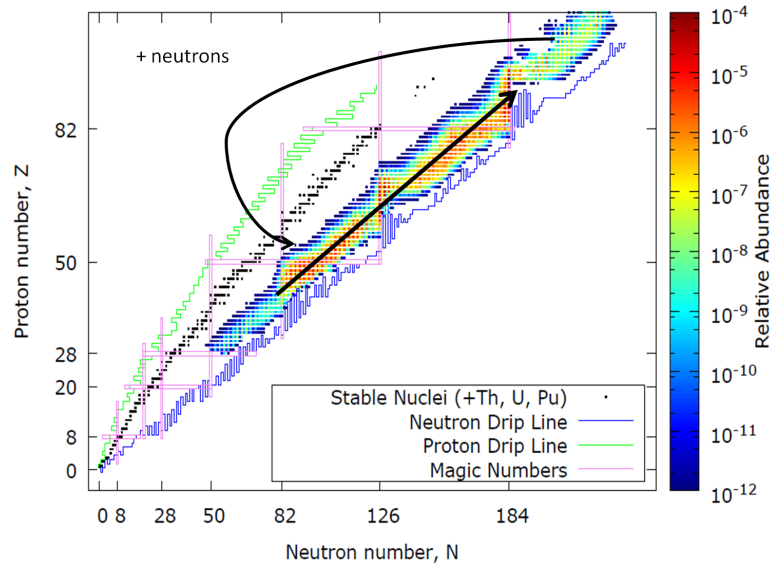


Fig. 2 Stationary distribution of the r -process near the end of the r -process. The neutron source becomes largely depleted and no major changes to the distribution occur; however, fissionable nuclei emit neutrons and create a cyclic recycling process which can maintain a distribution of unstable nuclei for several seconds (> 10 s) in contrast to the milliseconds required for generation of r -process material. The distribution is computed using r -Java 2.0 as in Kostka et al. (2014b).

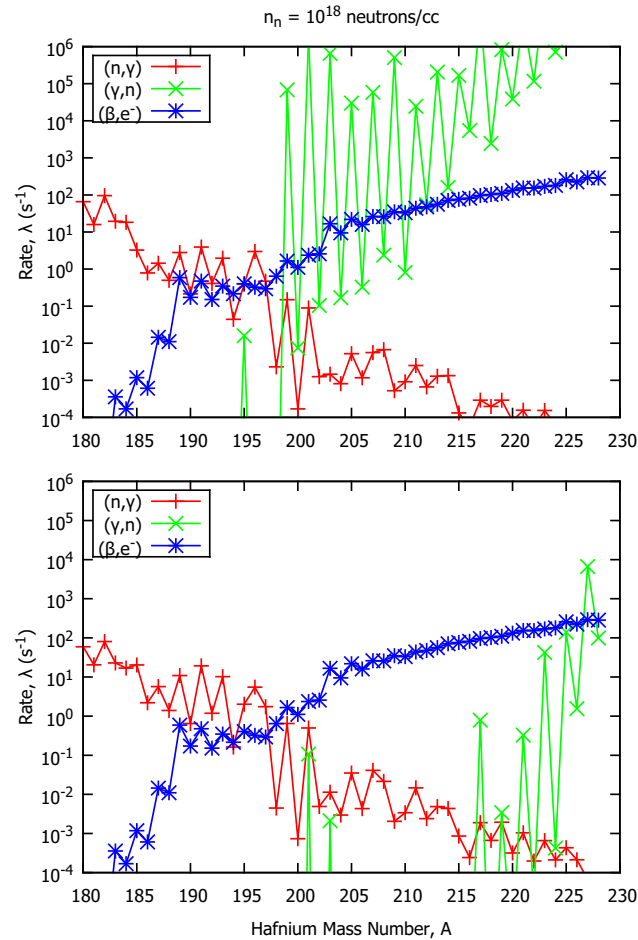


Fig. 3 Relevant temperature dependent rates for hafnium show different regimes in the r -process. The neutron density is 10^{18} cm^{-3} and the temperatures are $1.0 \times 10^9 \text{ K}$ (top) and $0.5 \times 10^9 \text{ K}$ (bottom).

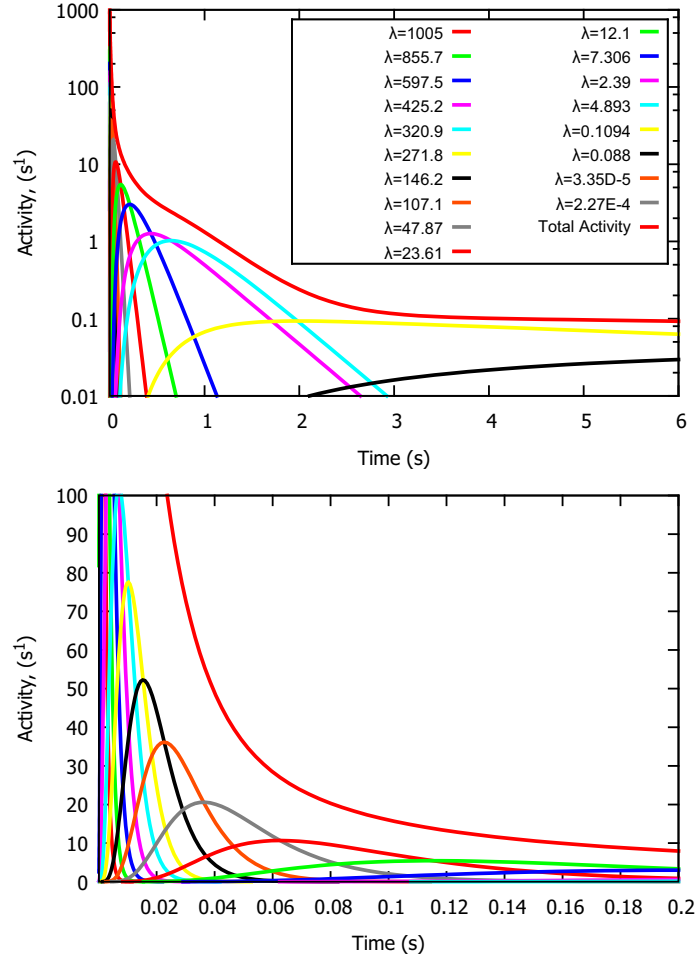


Fig. 4 Solution of the Bateman equations for the $A = 156$ β -decay chain beginning near the neutron drip line. Once the neutron decays stop competing with β -decays at the end of the r -process (when the density falls sufficiently), the activity of the material will β -decay with this characteristic exponential behavior. The top panel is logarithmic in the activity (y -axis) and the bottom panel is the very early portion of the above panel with the linear y -axis.

is simply defined as the point where a co-rotating magnetic field would be rotating at the speed of light. The magnetic field configuration has a breakpoint in it where the magnetic field lines no longer reconnect and fall off as a monopolar magnetic field. For an LC radius defined by: $r_{LC} = \frac{cP}{2\pi}$, where c is the speed of light and P is the period, the magnetic field strength at the LC at latitude ϕ is given by

$$B = B_0 \left(\frac{r_0 \cos \phi}{r_{LC}} \right)^a, \begin{cases} a = 3 & 0^\circ \leq \phi < 30^\circ \\ a = 2 & 30^\circ \leq \phi < 90^\circ. \end{cases} \quad (3)$$

This will cause radiation in the equatorial plane, where the dipolar field configuration exists, to be a factor of c weaker (c^2 for power).

For a relativistic, spherical shell this also provides a straightforward description for the arrival time of the material at the LC

$$t_{\text{arr}} = t - \frac{P}{2\pi\beta} \sec \phi, \quad (4)$$

which provides a time delay between emission at different latitude angles.

2.3 LC Details and Magnetic Field

The magnetic field configuration outside due to the LC will transition to a monopolar magnetic field for an aligned rotator (Michel 1973; Contopoulos et al. 1999) or will have a more complicated shape for an unaligned rotator (Spitkovsky 2006). As the QN ejecta passes through this region, the magnetic field will be disrupted and the details of the dynamics would be complicated to simulate; however, the disruption of the currents and the change of the magnetic field are assumed to cause a disruption of the QN ejecta. The details of the expansion across the LC are beyond the scope of this paper; however, as the ejecta passes through the boundary, there will be decompression of the material as the magnetic field distribution changes and the currents at the LC will interact with the matter and be disrupted. Since the LC inhibits emission of electromagnetic radiation across the LC (Jessner et al. 2000), this physical

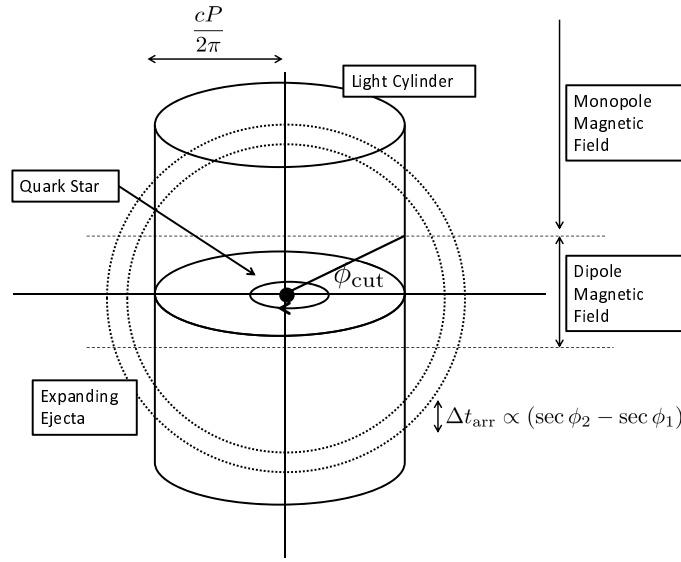


Fig. 5 Diagram outlining the geometry of the model. The latitude angle is specified relative to the quark star location and depicts the angle at which the spherical QN ejecta intersects the LC. The figure depicts two intersections of the ejecta with the cylinder at two different latitude angles separated by the arrival time of the two latitude angles.

disruption can help to explain the sudden rise in the emission of the FRBs.

Both the neutron star and quark star will have an LC and so there is some possible ambiguity in what magnetic field will be present at the LC when the ejecta crosses it. Since QN ejecta is highly relativistic ($v \sim 0.99c$) we expect it to reach the LC of the parent neutron star before there is time for the quark star to fully rearrange the magnetic field around it which occurs much more slowly (Ouyed et al. 2006). This can allow inference of properties of the neutron star population which undergo a QN and emit these FRBs.

2.4 Synchrotron Emission

The emitted electrons are assumed to have a constant γ across all decaying elements. This is done both to simplify the model and also due to a lack of nuclear data of β -decay electron energy distributions. If we look at the flux density, this factor is suppressed and so the assumption ends up not factoring into comparisons for flux density (see Eqs. (14) and (15) for the expanded form of the equations).

The synchrotron frequency and power per electron are given by

$$\nu_{\text{sync}} = \kappa_{\nu} \gamma^2 B, \quad (5)$$

$$P_e = \kappa_p \gamma_{\perp}^2 B^2, \quad (6)$$

where $\kappa_p = 1.6 \times 10^{-15} \text{ erg s}^{-1} \text{ G}^{-2}$ and $\kappa_{\nu} = 1.2 \times 10^6 \text{ Hz G}^{-1}$ are constants (Lang 1999). For simplicity, we have used the synchrotron peak frequency in place of the sharply peaked complete distribution.

If we assume the electrons only emit for a short time (either due to recombination or dissipative processes) then

the number of synchrotron electrons is the same as the activity, A . The activity is, of course, related to the decay constants of the unstable neutron-rich r -process nuclei

$$N_{\text{total}}(t) = \sum_i^{\text{chain}} \frac{A_i}{\lambda_i}. \quad (7)$$

We write this explicitly to emphasize that there are many nuclear species present at the end of the r -process and there are many decay rates simultaneously contributing. This makes it difficult to constrain individual β -decay rates, but can help to constrain nuclear theory models (not unlike the r -process).

2.5 Summary of Model Components

Our model involves many individual components as outlined above in Sections 2.1-2.4 and so we will shortly summarize how each qualitatively affects the emitted spectra. The r -process and fission recycling generate the electrons required for synchrotron emission and the LC provides a valve-like disruption and a monopolar magnetic field. The spectrum is affected by the characteristics of the geometry and nuclear decay that exist in a QN. The exponential decay generates an exponential pulse at each particular emission frequency; whereas, the period of the neutron star affects magnetic field strength that the nuclei see as they cross the LC. In this simple model, the QN ejecta emits at decreasing energies and frequencies as the latitude of intersection increases and the exact bandwidth of the emission is determined by the parent neutron star's period and LC field.

In Equations (14) and (15) we show a total expression for the emitted spectrum.

3 TOTAL POWER AND SPECTRUM

The total number of nuclei and, by extension, electron emitters at a particular latitude is expressed as

$$\begin{aligned} N_e &= \sum_i \left(\frac{A_i}{\lambda_i} \right) \int_{\phi_1}^{\phi} \cos \phi' d\phi' \\ &= \sum_i \left(\frac{A_i}{\lambda_i} \right) (\sin \phi - \sin \phi_1). \end{aligned} \quad (8)$$

The number of emitting electrons is then conveniently defined as a fraction of the total activity of the ejecta which is related to the total number of initial radioactive isotopes as defined in Equation (1). This is simply the total number of isotopes in the QN ejecta and is given by

$$N_0 = \frac{m_{\text{QN,ejecta}}}{A_{\text{avg}} m_H}. \quad (9)$$

The power then decays exponentially in time according to the activity of the nuclear species in the ejecta as it passes through the LC.

In order to determine the total power over the entire area we integrate the polar angle and latitude while keeping in mind that there is a time delay associated with the arrival of each latitude angle, ϕ , due to the intersection of the spherical shock wave with the LC (giving us the Heaviside theta function, Θ).

We can then construct expressions for both the instantaneous power and spectral flux density as follows

$$P = \Theta(t) P_e N_e, \quad (10)$$

$$S = \frac{\Theta(t) P_e N_e}{\nu}, \quad (11)$$

which are all evaluated at the arrival time (Eq. (4)), which has an angular dependence. These expressions can then be integrated to get the total power or spectral flux density

$$P(t) = \iint_{S(\theta,\phi)} dP = \iint_{S(\theta,\phi)} \left[\frac{\partial P}{\partial \phi} \right] d\Omega, \quad (12)$$

$$S(t) = \iint_{S(\theta,\phi)} dS = \iint_{S(\theta,\phi)} \left[\frac{\partial S}{\partial \phi} \right] d\Omega, \quad (13)$$

which are both very unfriendly looking integrands; however, they both only have functional dependence on latitude angle, ϕ .

It is worth noting here that these integrals are evaluated at the source (in a frame near the LC). This means that cosmological redshift and dispersion are not accounted for in these expressions. While redshift is not included in this paper, new smaller dispersion measures (DMs) are computed using the intrinsic time delay between emitted frequencies given by our model which traces out the magnetic field strength of the LC. These power and flux equations can of course both be integrated with respect to time to compute the total energy and the fluence respectively.

Table 1 Summary of Parameter Values used in Figs. 6 and 8

Parameter	Value used
B_0	10^{12} G
ϕ_{cut}	30°
P	10 s
$\{\lambda_i\}$	$\{1004, 855, 597, 425, 320\}$ s $^{-1}$
β	0.99
γ	2
r_0	10 km
$m_{\text{QN,ejecta}}$	$10^{-3} M_\odot$
A_{avg}	180

The full integral equations for the power and flux density are then Equations (14) and (15). The expressions are left unevaluated as derivatives because they become lengthy and do not add any insight.

$$\begin{aligned} P(t = t_{\text{arr}}, \theta, \phi) &= \iint_{S(\theta,\phi)} \frac{\partial}{\partial \phi} \left[\Theta(t) \kappa_p \gamma_\perp^2 B_0^2 \right. \\ &\quad \times \left(\frac{2\pi r_{NS} \cos(\phi)}{cP} \right)^{2a} \sum_i^{\text{chain}} \left(\frac{A_n(t)}{\lambda_n} \right) \\ &\quad \left. \times (\sin \phi - \sin \phi_1) \right] d\Omega, \end{aligned} \quad (14)$$

$$\begin{aligned} S(t = t_{\text{arr}}, \theta, \phi) &= \iint_{S(\theta,\phi)} \frac{\partial}{\partial \phi} \left[\Theta(t) \frac{\kappa_p}{\kappa_\nu} B_0 \right. \\ &\quad \times \left(\frac{2\pi r_0 \cos(\phi)}{cP} \right)^a \sum_i^{\text{chain}} \left(\frac{A_n(t)}{\lambda_n} \right) \\ &\quad \left. \times (\sin \phi - \sin \phi_1) \right] d\Omega. \end{aligned} \quad (15)$$

3.1 Model Assumptions and Limitations

The model has two major assumptions: 1) the high density ejecta from the QN maintains a distribution of unstable nuclei for far longer than is normally thought possible and 2) the interaction at the LC causes a disruption of the r -process distribution. The r -process stationary distribution and its lifetime have been simulated using the nucleosynthesis code r -Java 2.0². While it is a surprising result, we have theoretical background and simulation results to show that it is theoretically possible. The second assumption is much more difficult to quantify. To our knowledge, there has been no theoretical work done on the behavior of dense nuclear material as it passes at relativistic velocities across an LC. This would require complex magnetohydrodynamic modeling of material near what is already a difficult numerical problem. In order for the model to work, we require a disruption of the r -process distribution at the LC. The most straightforward way to accomplish this

² r -Java 2.0 is an open use nucleosynthesis code developed at the University of Calgary at quarknova.ca (Kostka et al. 2014b).

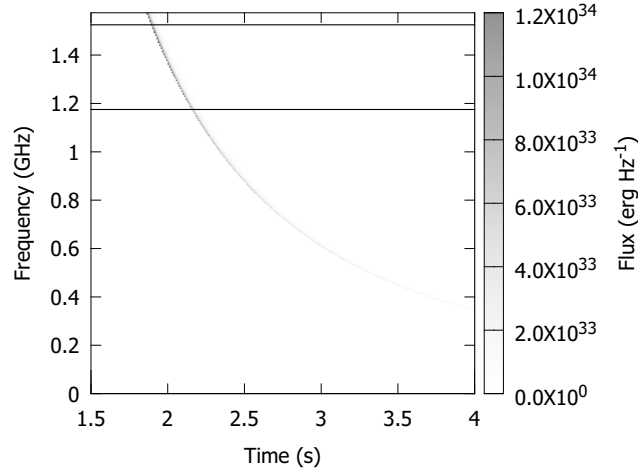


Fig. 6 A spectrum of the flux density at the emission location. The upper edge of the spectrum is a cut-off frequency determined by the transition angle of the magnetic field where the magnetic field becomes monopolar ($\phi = 30^\circ$). The two horizontal lines indicate the bandwidth which has been measured by Thornton et al. (2013). This plot is a fit to data using the parameters outlined in Table 1 (no statistical fitting was performed to find best fits to the data).

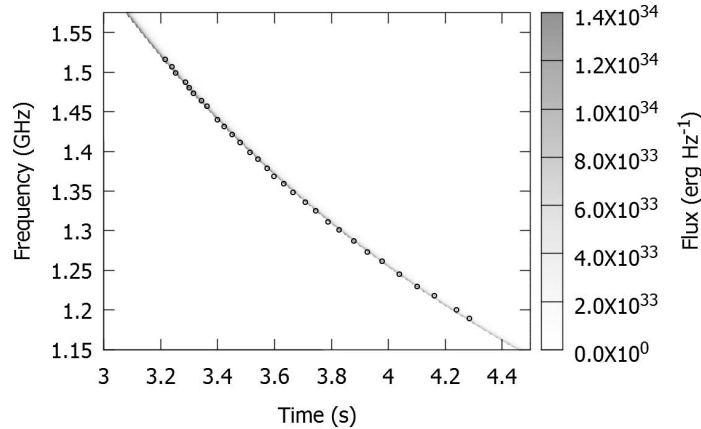


Fig. 7 A spectrum of the measured data (*points*) with our theoretical model predictions. A DM of $725 \text{ cm}^{-3} \text{ pc}$ has been applied to account for the time delay discrepancy between the emission at source and measurement. The circles on the plot show where the observational data peak in the spectrum.

is with rapid decompression of the material as shown quantitatively by the following equation

$$r_{(n,\gamma)} = n_n \langle \sigma \rangle Y_i, \quad (16)$$

where $r_{(n,\gamma)}$ is the neutron capture rate of isotope i , n_n is the neutron number density, $\langle \sigma \rangle$ is the average cross section and Y_i is the number of isotopes in the system. If the ejecta is rapidly decompressed at the LC, this would lead to a rapid decay of all isotopes to stable isotopes.

Other approximations include: a symmetric spherical thin shell expansion of the ejecta, simplified electron energy distributions and use of theoretical decay rates, simplification of the synchrotron radiation spectrum of an electron, and a simplified selection for β -decay rates. These are each worth exploring in detail to provide a more accurate model; however, the agreement with observations leads us to conclude that these assumptions are all appropriate and physically valid.

4 RESULTS

Application of the model to the radio burst FRB 110220—the most spectroscopically complete FRB in Thornton et al. (2013)—is presented in Figures 6, 7 and 8 using model parameters summarized in Table 1. The total spectrum emitted using these parameters is presented in Figure 6. The emission has a maximum frequency and decays for the lower frequencies over time. A comparison to the measured data of FRB 110220 (after a newly inferred DM is applied) is shown in Figures 7 and 8.

4.1 DM, Burst Profile and Distance

The geometry and fields provide inherent cut-off ranges and characteristic emission timescales for our emitted spectra. The sudden turn-on (as represented by our Heaviside function) at the LC provides us with a frequency

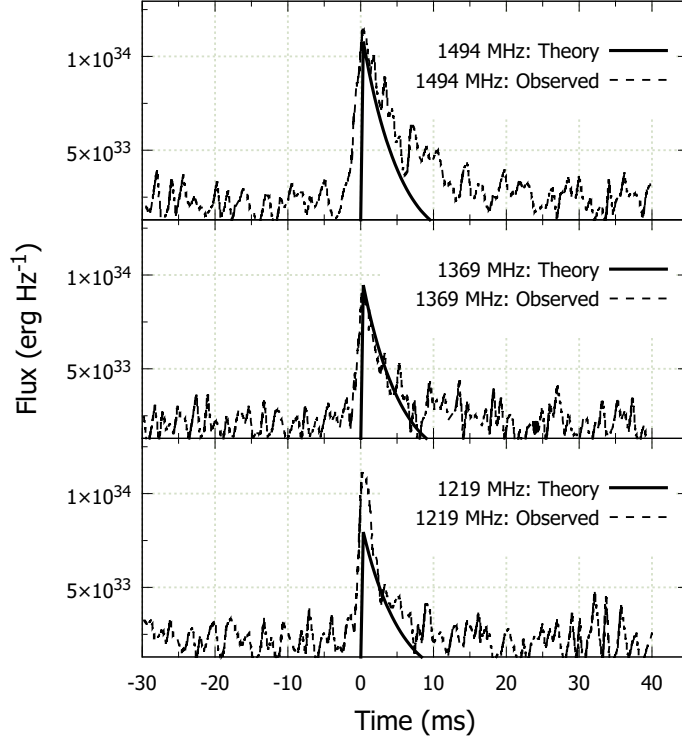


Fig. 8 Slices into the spectrum of Fig. 6 at 1.494, 1.369 and 1.219 GHz (*from top to bottom*). The relative height (or flatness) of the flux at these frequencies across the observing band provides a constraint on the period of the neutron star progenitor. This plot is a fit to data using the parameters outlined in Table 1 (no statistical fitting was performed to find best fits to the data).

leading edge which depends on magnetic field strength, period and – to a lesser extent – magnetic field configuration. The leading edge of the pulse for each frequency (as seen in a spectrum) is a direct consequence of the geometry. The curve traced out in frequency over time is given by

$$\nu_{\text{edge}} = \kappa_{\nu} \gamma^2 B_0 \left(\frac{r_0}{\beta c} \right)^a \frac{1}{t^a}, \quad (17)$$

where parameter a is the magnetic field configuration power. Using this, we get a time delay *at the source* between two frequencies. This can be combined with observations to calculate a DM of the pulse which will be smaller than that calculated assuming synchronous emission. For FRB 110220, this leads to a DM of $725 \text{ cm}^{-3} \text{ pc}$ as fit in Figure 7 which is a reduction from $944 \text{ cm}^{-3} \text{ pc}$ as measured in Thornton et al. (2013).

There is an ambiguity in fitting a DM from the pulse time which is resolved by the magnetic field strength and the breakpoint between dipolar and monopolar field lines. Since the radiation emitted at the equatorial region is so much fainter, the maximum frequency of the measured spectra is given by

$$\nu_{\text{max}} = \kappa_{\nu} \gamma^2 B_0 \left(\frac{2\pi r_0 \cos \phi_{\text{cut}}}{cP} \right)^2. \quad (18)$$

This can be used to help infer the correct DM of the measured radio burst. This, in combination with the spectral flux at each frequency, can be used to calculate a

more accurate DM and distance. The P^{-2} dependence in Equation (18) leads to a wide range of possible frequencies. For example, given a millisecond period neutron star ($P = 1 \text{ ms}$, $B = 10^{14} \text{ G}$) the peak frequency would be $16 \times 10^{18} \text{ Hz}$, putting it in the X-ray regime. This extreme case is unlikely to be realized, as discussed in Section 1. More realistic parameters suggest that FRB-like spectra are present in the optical and infrared bands, which depend on the period and magnetic field strength of FRB progenitors. Determination of the likelihood of emission at different frequencies from this mechanism would require detailed neutron star population studies aimed specifically at determining FRB-QN rates.

In tandem with the new DM, we can estimate the distance to these QNe-FRBs by integrating the flux density or power spectra and comparing this to the measured energy or fluence. This is possible even for bandwidth limited measurements provided there is an estimate from the above quantities of the period and magnetic field by only integrating over the same range of frequencies present in the measurement. If these bursts are in fact cosmological, the cosmological redshift will have to be incorporated into the above equations.

4.2 FRB Rates

Assuming that FRB progenitors are old neutron stars, we can estimate their rate based on a simplified population

Table 2 Summary of FRB Rates Calculated using a Simplistic Population Synthesis of Neutron Star Population

Critical Period (s)	Rate ($\text{yr}^{-1} \text{ galaxy}^{-1}$)
1	0.0028
10	0.0027
Death Line	0.0028

model. We give a rough estimate of the FRB rate by making use of the following assumptions: a constant core-collapse supernova rate ($0.02 \text{ yr}^{-1} \text{ galaxy}^{-1}$), a lognormal magnetic field distribution ($\chi(\log B) = 13.43 \pm 0.76$) and a normal distribution for the initial period ($\pi(P_0) = 290 \pm 100 \text{ ms}$), where the values for the initial period and magnetic field are taken from Regimbau & de Freitas Pacheco (2001) (the magnetic field distribution is from the “unseen” population of Model A). In order to decide the lifetime of the neutron stars when they go FRB we have made two choices: 1) they go QN-FRB after a common timescale (or age), or 2) they go QN-FRB once they reach a certain location in the $P\dot{P}$ diagram. For the second case, we consider neutron stars reaching critical density near the observed death line and employ the death line of Zhang et al. (2000)

$$\log\left(\frac{\dot{P}}{\text{s s}^{-1}}\right) = 2 \log\left(\frac{P}{\text{s}}\right) - 16.52. \quad (19)$$

After modeling the neutron star population of a Milky-Way-like galaxy, the last step is to estimate the fraction of neutron stars which are QN candidates. Since only slowly rotating, massive neutron stars are FRB candidates, we only count the neutron stars with periods greater than 100 ms and whose stellar progenitors had masses between 20–40 M_{\odot} . Integration of the initial mass function (Kroupa 2001) and the initial period distribution (assuming the period and magnetic field are independent) identifies approximately 14% of neutron stars as QN candidates. This approach does not take into account any possible viewing selection effects (e.g. threshold observing brightness, viewing angle, beaming, etc.), which may affect the detectability of these events. Both the period and death line estimates of the rate give consistent results of approximately 3 per thousand year per galaxy, as summarized in Table 2, which is consistent with the observed FRB rate assuming that the observed FRBs are extragalactic.

5 MODEL CONSEQUENCES AND PREDICTIONS

While we can generate excellent fits to currently available FRB data, there are other important observables and consequences that come along with the scenario we have put forth to explain these radio transients. As mentioned earlier, we can use this model to constrain certain physical and astronomical phenomena. The relation to nuclear properties is somewhat complex due to the number of nuclear species present and is best left for more detailed analysis and higher resolution measurements. There are, however,

two astronomical puzzles that we believe can be explained assuming this model is in fact correct.

5.1 Neutron Star Population

Assuming the model is correct, FRBs provide measurements of the period and magnetic field strength of isolated neutron stars before they undergo a QN. Based on the agreement of the model with FRB 110220 and the spectral consistency of the FRB measurements, it appears that these are neutron stars that undergo QN. These neutron stars have periods of around 10 seconds and magnetic fields of 10^{12} Gauss (as determined by our parameter selection and its fit to observational data). This is perhaps puzzling if we look at the so-called $P\dot{P}$ diagram: there are no observed neutron stars in this region (Lorimer & Kramer 2012). This empty region of the $P\dot{P}$ diagram is beyond what is referred to as the “death line” and we propose an explanation for this: once an isolated neutron star spins down to the 1 to 10 second period and enters the neutron star graveyard, it reaches deconfinement densities at its core and dies via a QN explosion. This instantaneously moves the neutron star into the 10^{15} Gauss regime of the diagram as quark stars generate these high magnetic fields after birth (Iwazaki 2005). Instead of magnetars, we then populate this anomalous region of the $P\dot{P}$ diagram with quark stars whose magnetic fields decay not through spin down, but through magnetic field expulsion from the color superconducting core (Niebergal et al. 2010, 2006). This drives the quark star from its new position straight downwards as the star ages and provides an explanation for the observed high magnetic field population in the $P\dot{P}$ diagram.

5.2 511 keV Line and Super-heavy Fissionable Elements

The production of super-heavy ($A > 240, Z > 92$) elements is responsible for the fission recycling in the QN ejecta. While these calculations are based on theoretical predictions of mass models, fission recycling from these elements is theoretically expected. Some of these super-heavy nuclei are also thought to be quasi-stable and long-lived. While they are (currently) impossible to make in the lab, these neutron-rich super-heavy nuclei may outlive the β -decaying nuclei and undergo fission much later. If this is correct, these super-heavy nuclei would undergo fission and emit photons over a long period of time and produce extended emission of MeV photons. These emitted photons then have the appropriate energy for efficient production of electron-positron pairs (via γ - γ annihilation). The annihilation events would produce 511 keV photons when the produced positrons find an electron and provide a potential explanation for the positron emission which is an observed phenomenon that still has no definitive explanation for its Galactic origin (Weidenspointner et al. 2008).

This radiation would of course not be as energetic as the original FRB and is likely not measurable from an ex-

tragalactic source; however, this does provide a possible explanation for the 511 keV photons observed in our own Galaxy. The current observed annihilation rate of positrons inferred from the 511 keV positronium line is $\sim 10^{43} \text{ s}^{-1}$ (Knödseder et al. 2005). Based on our model, we can then constrain the lifetime of super-heavy neutron rich nuclei to be on the order of 1000 years using the following logic.

Given a Galactic QN rate of 1 per thousand years, if we assume the following parameters: $M_{\text{QN,ejected}} = 10^{-2} M_{\odot}$, average nuclei mass $A \sim 100$ and 10% of nuclei (by number) are super-heavy fissionable elements, we can expect about $10^{-5} M_{\odot}$ nuclei to be produced in the QN ejecta which gives about 10^{51} fissionable nuclei per QN event. Given the expected QN rate of 0.001 year^{-1} this produces an average of 10^{48} super-heavy nuclei per year. If we compare this to the current event rate, this implies a characteristic lifetime of about 1000 years for the fission events (see Petroff et al. (2015) for further discussion of observational qualities and proposed astrophysical theories).

While these calculations are an order of magnitude approximation, they have several promising features. QNe come from massive ($20\text{--}40 M_{\odot}$) stars and are expected to operate (like the r -process) continually over the entire history of the Galaxy. This naturally leads to a concentration of 511 keV lines near the active portions of the Galaxy (the bulge and the disk) where most of this emission is observed. This matches the observed clustering of the 511 positron emission that has been measured (Weidenspointner et al. 2008). Additionally, because a quark star is an aligned rotator, we expect no radio pulsations to be observed alongside this emission which, again, seems to agree with observations and is one of the difficult aspects in explaining these positronium annihilation events. Finally, the Galactic center and plane have many high energy photons which would allow for efficient conversion of the MeV photons from fission to electron-positron pairs (because the pair production requires a $\gamma\text{-}\gamma$ interaction). This emission should then carry a P Cygni profile as well as a net exponential decay which could be detected from observations.

It is also possible that the heavy nuclei do not spontaneously experience fission, but instead undergo photo-fission triggered by the high energy photons present in large numbers especially near the Galactic center. This would lead to a slightly different observable: instead of half-lives we could infer photo-fission cross sections which would give indirect measurements of the level density and fission barrier heights of these nuclei. Instead of a plain exponential, we would instead observe rates proportional to the photon density.

6 CONCLUSIONS

QNe are capable of generating fast radio pulses using electrons generated by r -process nuclei. Assuming decompression or any other disruption of the r -process at the neutron star's LC, we have shown how the emission spectrum has

an intrinsic time delay across its frequency band and has a predictable bandwidth (cut-off frequency) which can be used to measure magnetic field strength and period of otherwise undetectable neutron stars. If correct, FRBs can be used to probe and measure properties of unstable nuclear matter and measure properties of old neutron star populations. Our model predicts that these explosions are indeed one of the most energetic explosions in radio astronomy (with energies on the order of 10^{41} erg); however, they need not necessarily be cosmological as was inferred from previous analysis of the data. The model naturally provides explanations for the timescales and energies of the FRB emissions using synchrotron emission in the strong magnetic field of a newly-formed QN.

References

- Charignon, C., Kostka, M., Koning, N., Jaikumar, P., & Ouyed, R. 2011, *A&A*, 531, A79
- Contopoulos, I., Kazanas, D., & Fendt, C. 1999, *ApJ*, 511, 351
- Drago, A., Lavagno, A., Pagliara, G., & Pigato, D. 2015, arXiv:1509.02131
- Falcke, H., & Rezzolla, L. 2014, *A&A*, 562, A137
- Fuller, J., & Ott, C. D. 2015, *MNRAS*, 450, L71
- Geng, J. J., & Huang, Y. F. 2015, *ApJ*, 809, 24
- Geng, J. J., Huang, Y. F., & Lu, T. 2015, *ApJ*, 804, 21
- Gondek-Rosińska, D.,ourgoulhon, E., & Haensel, P. 2003, *A&A*, 412, 777
- Goriely, S., Hilaire, S., & Koning, A. J. 2008, *A&A*, 487, 767
- Goriely, S., Hilaire, S., & Koning, A. J. 2009, in *American Institute of Physics Conference Series*, 1090, eds. J. Jolie, A. Zilges, N. Warr, & A. Blazhev, 629
- Iwazaki, A. 2005, *Phys. Rev. D*, 72, 114003
- Jaikumar, P., Meyer, B. S., Otsuki, K., & Ouyed, R. 2007, *A&A*, 471, 227
- Jessner, A., Lesch, H., & Kunzl, T. 2000, in *Astronomical Society of the Pacific Conference Series*, 202, IAU Colloq. 177: Pulsar Astronomy - 2000 and Beyond, eds. M. Kramer, N. Wex, & R. Wielebinski, 463
- Keränen, P., Ouyed, R., & Jaikumar, P. 2005, *ApJ*, 618, 485
- Knödseder, J., Jean, P., Lonjou, V., et al. 2005, *A&A*, 441, 513
- Kostka, M., Koning, N., Leahy, D., Ouyed, R., & Steffen, W. 2014a, *Revista Mexicana de Astronomía y Astrofísica*, 50, 167
- Kostka, M., Koning, N., Shand, Z., Ouyed, R., & Jaikumar, P. 2014b, *A&A*, 568, A97
- Krane, K. S. 1987, *Introductory Nuclear Physics*, ed. Kenneth S. Krane, 864 (Wiley-VCH)
- Kroupa, P. 2001, *MNRAS*, 322, 231
- Krücken, R. 2011, *Contemporary Physics*, 52, 101
- Lang, K. R. 1999, *Astrophysical formulae* (New York: Springer)
- Lorimer, D. R., & Kramer, M. 2012, *Handbook of Pulsar Astronomy* (UK: Cambridge Univ. Press)
- Lyubarsky, Y. 2014, *MNRAS*, 442, L9
- Michel, F. C. 1973, *ApJ*, 180, 207

- Möller, P., Pfeiffer, B., & Kratz, K.-L. 2003, *Phys. Rev. C*, 67, 055802
- Niebergal, B., Ouyed, R., & Leahy, D. 2006, *ApJ*, 646, L17
- Niebergal, B., Ouyed, R., Negreiros, R., & Weber, F. 2010, *Phys. Rev. D*, 81, 043005
- Ouyed, R., Dey, J., & Dey, M. 2002, *A&A*, 390, L39
- Ouyed, R., Koning, N., & Leahy, D. 2013a, *RAA (Research in Astronomy and Astrophysics)*, 13, 1463
- Ouyed, R., & Leahy, D. 2009, *ApJ*, 696, 562
- Ouyed, R., Niebergal, B., Dobler, W., & Leahy, D. 2006, *ApJ*, 653, 558
- Ouyed, R., Niebergal, B., & Jaikumar, P. 2013b, arXiv:1304.8048
- Ouyed, R., Staff, J., & Jaikumar, P. 2011, *ApJ*, 729, 60
- Pen, U.-L., & Connor, L. 2015, *ApJ*, 807, 179
- Petroff, E., Bailes, M., Barr, E. D., et al. 2015, *MNRAS*, 447, 246
- Popov, S. B., & Postnov, K. A. 2010, in *Evolution of Cosmic Objects through their Physical Activity*, eds. H. A. Harutyunian, A. M. Mickaelian, & Y. Terzian, 129
- Popov, S. B., & Postnov, K. A. 2013, arXiv:1307.4924
- Regimbau, T., & de Freitas Pacheco, J. A. 2001, *A&A*, 374, 182
- Spitkovsky, A. 2006, *ApJ*, 648, L51
- Staff, J. E., Ouyed, R., & Jaikumar, P. 2006, *ApJ*, 645, L145
- Thornton, D., Stappers, B., Bailes, M., et al. 2013, *Science*, 341, 53
- Totani, T. 2013, *PASJ*, 65, L12
- Vásquez Flores, C., & Lugones, G. 2014, *Classical and Quantum Gravity*, 31, 155002
- Weidenspointner, G., Skinner, G. K., Jean, P., et al. 2008, *New Astron. Rev.*, 52, 454
- Zhang, B., Harding, A. K., & Muslimov, A. G. 2000, *ApJ*, 531, L135