Dark Matter-induced Collapse of Neutron Stars: A Possible Link Between Fast Radio Bursts and the Missing Pulsar Problem

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ABSTRACT

Fast radio bursts (FRBs) are an emerging class of short and bright radio transients whose sources remain enigmatic. Within the galactic center, the non-detection of pulsars within the inner $\sim 10$ pc has created a missing pulsar problem that has intensified with time. With all reserve, we advance the notion that the two problems could be linked by a common solution: the collapse of neutron stars (NS) due to capture and sedimentation of dark matter (DM) within their cores. Bramante & Linden (2014), Phys. Rev. Lett. 19, 191301 showed that certain DM properties allow for rapid NS collapse within the high DM density environments near galactic centers while permitting NS survival elsewhere. Each DM-induced collapse could generate an FRB as the NS magnetosphere is suddenly expelled. This scenario could explain several features of FRBs: their short time scales, large energies, locally produced scattering tails, and high event rates. We predict that FRBs are localized to galactic centers, and that our own galactic center harbors a large population of NS-mass ($M\sim 1.4M_\odot$) black holes.

The DM-induced collapse scenario is intrinsically unlikely because it can only occur in a small region of allowable DM parameter space. However, if observed to occur, it would place tight constraints on DM properties.

Key words: dark matter, relativistic processes, stars: neutron, stars: black holes, Galaxy: centre, radio continuum: general

1 INTRODUCTION

1.1 Fast Radio Bursts

Fast radio bursts (FRBs) are a recently discovered class of radio transients (Lorimer et al. 2007; Keane et al. 2012; Thornton et al. 2013; Burke-Spolaor & Bannister 2014; Spitler et al. 2014b) shrouded in both mystery and controversy. They are characterized by short ($t\sim\text{ms}$) isolated radio bursts detected at $\sim$ GHz frequencies with large dispersion measures ($D_M\sim\text{several}\times 100\text{ cm}^{-3}\text{pc}$). The estimated event rate of detectable FRBs is large, up to $10^4$ per sky per day (Thornton et al. 2013).

Unless FRBs are a form of local radio interference, they likely originate at cosmological distances (Luan & Goldreich 2014; Dunnison 2014; Katz 2014b; Tuntsov 2014). If their observed $D_M$ originates from the intergalactic medium, typical FRB distances are large, $D\sim 2\text{ Gpc}$ and emitted radio energies are high ($10^{38}$ to $4\times 10^{40}$ erg) (Thornton et al. 2013; Kulkarni et al. 2014; Dolag et al. 2014). Conversely, the scattering tails observed in some FRBs cannot be explained by scattering by the IGM, and likely originates within the host galaxy of the source (Luan & Goldreich 2014; Katz 2014b). This may indicate that at least some FRBs originate near galactic centers. Typical comoving distances of $D\sim 2\text{ Gpc}$ and an event rate of $10^4\text{ yr}^{-1}$ imply a volumetric rate of $R\sim 10^{-4}\text{ yr}^{-1}\text{ Mpc}^{-3}$, comparable to the volumetric core-collapse supernova rate (Li et al. 2011). Many progenitors have been suggested to be the sources of FRBs, although most seem unlikely (see the discussion in Kulkarni et al. 2014). Here we simply re-iterate that the short durations, large luminosities, and high brightness temperatures naturally suggest a neutron star (NS) origin.

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1.2 Missing Galactic Center Pulsar Problem

Within our own galaxy, the missing pulsar problem at the galactic center (GC) has recently become more puzzling. Despite several deep searches (Johnston et al. 2006; Denes et al. 2009; Macquart et al. 2010; Bates et al. 2011), no ordinary pulsars have been discovered within a projected distance of 10 pc of the GC despite predictions that there should be more than $10^3$ active radio pulsars in this region (Pfahl & Loeb 2004). The problem recently intensified with the radio detection of a magnetar within the central parsec (Eatough et al. 2013). Subsequent studies (Bower et al. 2014; Spitler et al. 2014a) indicated that the magnetar indeed lies very close to Sgr A* and that the temporal scattering was not severe enough to have prevented the detection of ordinary pulsars in previous surveys.

It remains possible that (for some unknown reason) ordinary pulsars near the GC have a steep spectral index and are not bright enough at high frequencies to be detected with current instrumentation (Bates et al. 2011). Alternatively, Dexter & O’Leary (2014) have suggested that the missing pulsar problem is created by a very high magnetar formation efficiency near the GC, such that GC pulsars spin down so rapidly that they are unlikely to be observed before crossing the death line. Given our current (incomplete) understanding of magnetar formation (e.g., Thompson & Duncan 1993; Keane & Kramer 2008), there is no known physical process or condition that could favor magnetar formation near the GC.

1.3 Dark Matter-Induced Neutron Star Collapse

We propose that the seemingly separate problems posed by FRBs and missing pulsars may have the same solution: the DM-induced collapse of neutron stars (NS). In this scenario (recently described by Bramante & Linden 2014, see also Kouvaris & Tinyakov 2011; Kouvaris 2012; McDermott et al. 2012; Bramante et al. 2013 and references therein), ambient DM particles scatter off of nucleons within an NS and become gravitationally bound. The DM particles continue to scatter until they thermalize at the NS temperature and sink to the center of the NS where they accumulate within a small volume. When the DM agglomeration exceeds a critical mass, the DM forms a black hole (BH) at the NS center that may consume the NS. The NS collapses into the BH on a dynamical time scale ($t_{\text{dyn}} \sim 1\,\text{ms}$), and a $\sim 1.4 M_\odot$ BH remnant is left behind.

During the collapse, the magnetosphere must suddenly detach from the BH horizon, and the rapid reconfiguration of the field lines generates a burst of electromagnetic energy. If a small fraction of this energy is radiated in radio wavelengths, an FRB is generated. The process occurs most rapidly near the GC where DM densities are highest, causing NSs near the GC to quickly collapse (but permitting long-term NS survival in the solar neighborhood and in globular clusters), thereby accounting for the lack of pulsar detections near the GC.

There is only a limited range in DM properties that allow for the process described above to occur. These have been explored in the works listed above, here we simply restate their basic results. First, there is only a narrow (2-3 orders of magnitude) range of DM scattering cross sections $\sigma$ that allows for rapid DM accumulation within GC NSs while allowing more local NSs to survive for several Gyr. Second, the DM must be weakly annihilating, otherwise it will annihilate upon accumulation at the center of the NS and will not be able to form a BH. Third, the DM mass, particle type (boson vs. fermion), self interaction, and NS temperature must allow for DM sedimentation and BH formation at the center of the NS.

The DM-collapse scenario also hinges on the DM density profiles of NS host galaxies. The DM capture rate is proportional to the ambient DM density, $\rho_{\text{DM}}$, and so the NS life time scales as $t_\nu \propto \rho_{\text{DM}}^{-1}$. To collapse a GC pulsar located at a galacto-centric radius $r = 1\,\text{pc}$ within $10^6\,\text{yr}$, while allowing for the $10^{10}\,\text{yr}$ survival of a solar neighborhood NS ($r \sim 10^4\,\text{pc}$), requires the DM density within the inner parsec to be enhanced by at least a factor of $10^5$.

2 GENERATION OF A FAST RADIO BURST

The detailed electromagnetic signature of a collapsing NS is well beyond the scope of this paper, but here we make some rough estimates. The FRB emission energy cannot greatly exceed the energy contained in the magnetosphere,

$$E_M \sim 10^{42} \text{erg} B_{12}^4,$$

where $B_{12}$ is the dipole field strength in units of $10^{12}\,\text{G}$. The radio emission from our collapsing NS scenario is similar to that described in Falcke & Rezzolla (2014) (FR14), who examined rapidly-rotating supramassive NS collapse.

During the collapse, electrons/positrons bound to field lines generate coherent radiation as the field reconfigures. If $\nu \sim 10^{-3}$ of the field energy is emitted as radiation near GHz frequencies, an FRB can be generated. However, the coherent curvature radiation will initially have frequency near $\nu \sim 1/t_{\text{dyn}} \sim \text{kHz}$. To emerge at GHz frequencies, the radiation must be up-converted to higher frequencies. FR14 argue that this will occur until the coherent radiation is near the plasma frequency

$$\nu_p \sim 2 \times 10^{12} \frac{B_{12}^2}{P_1^{1/2}} \, \text{kHz},$$

where $B_{12}$ is the field strength in units of $10^{12}\,\text{G}$, and $P_1$ is the spin period in seconds. Following their analysis, we calculate that electrons are boosted to Lorentz factors of $\gamma \sim 60 B_{12}^{1/6} P_1^{-1/2}$, and radiate a power near GHz frequencies of

$$P_R \sim 2 \times 10^{41} \text{erg} \, \text{s}^{-1} B_{12}^{13/6} P_1^{-13/6}.$$

We expect the emission to be generated over roughly one magnetosphere light crossing time, $t \sim 1\,\text{ms}$. The corresponding radio energy emission is then $E_R \sim 2 \times 10^{39}\,\text{erg}$, but can be substantially larger for higher field strengths or smaller rotation periods. While the frequency of equation 2 and the power estimate of equation 3 are encouraging, the details of the emission process may be quite complex, and these estimates may not be robust.

The radiative power of equation 3 can be compared to simulations of the non-rotating collapse of a NS by Lehner et al. (2012) (see also Palenzuela 2013; Dionysopoulos et al. 2013), who find $P_{\text{rad}} \sim 10^{33} - 10^{34} B_{12}^4 \, \text{erg} \, \text{s}^{-1}$ over a duration of roughly a millisecond, implying $E_{\text{rad}} \sim 10^{39} - 10^{40} B_{12}^4$ erg. Unfortunately, these authors do not compute a radiation spectrum, so it is unclear how much energy is emitted in

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the radio band. If a significant fraction of it is emitted near GHz frequencies, as argued by FR14, then an FRB could be generated. It is possible that some of the radiation is emitted at optical/UV/X-ray/γ-ray wavelengths, however, any transient produced is unlikely to be detected. Its maximum luminosity is $L \lesssim 10^{45} \text{erg s}^{-1}$, and its duration is expected to last $t \lesssim 1 \text{ms}$, preventing even very rapid follow-up observations.

The energy estimates above are similar to the isotropic radio energies estimated by [Thornton et al. 2013] and Spitler et al. (2014b), but smaller than those estimated by Kulkarni et al. (2014) and Dolag et al. (2014). The total energy emitted depends on the slope of the spectral emission, and we do not attempt to quantify those details here. We simply note that our rudimentary estimates yield a radio luminosity similar to that inferred for FRBs. Slightly beamed emission (as seen in Lehner et al. 2012) would entail smaller total radiative luminosities, but larger collapse rates.

The observed scattering tails in some FRBs are also consistent with the DM-induced collapse scenario, as Luan & Goldreich (2014) and Katz (2014a) have shown that the scattering is most likely generated near the source deep within a host galaxy. Similarly, our scenario entails that FRBs occur near GCs where the scattering could be produced, e.g., by the ionized surfaces of nearby molecular clouds (Lazio & Cordes 1998). Moreover, at least some of the observed $D_M$ may be contributed by the host galaxy. The NE2001 model for the electron density distribution (Cordes & Lazio 2002) implies an average number density of $n_e \sim 0.2 \text{cm}^{-3}$ within the inner 500 pc (Ferri`ere et al. 2007). A typical FRB occurring within the inner 500 pc (see Section 3) would then incur a dispersion measure of $D_M \sim 100 \text{cm}^{-3} \text{pc}$, depending on the viewing angle. An additional $5 \text{cm}^{-3} \text{pc}$ will likely be contributed by its host’s galactic halo (Dolag et al. 2014), entailing a net contribution of $D_M \approx 150 \text{cm}^{-3} \text{pc}$ from the host galaxy. If the FRB occurs within the inner $\sim 100 \text{pc}$, the local $D_M$ could be much larger, on the order of $D_M \sim 10^3 \text{cm}^{-3} \text{pc}$ (Cordes & Lazio 2002). This implies FRBs could be somewhat closer (by $\sim 25\%$ or more) than estimated by assuming the observed $D_M$ is generated in the IGM.

### 3 Rates and Galactic Center Neutron Star Depletion

The NS collapse time is determined by the DM accumulation rate and the amount of DM required to form a BH at the NS center. We calculate both using the method outlined in Bramante & Linden (2014). In general, only a very small amount of DM ($M_{DM} \lesssim 10^{-11} M_\odot$) is accreted before collapse. The most salient detail of the process is that the collapse times scale as $t_c \propto t_{DM}^{-\frac{1}{3}}$, allowing for short collapse times in high DM density environments.

To estimate the FRB rate in a Milky Way-like galaxy, we construct a simple galactic model similar to the exponential spheroid model of Sofue (2004). The model contains components from the central star cluster at $r < 1 \text{pc}$, inner bulge at $r < 20 \text{pc}$, bulge at $r < 1 \text{kpc}$, and exponential disk at $r < 20 \text{kpc}$. We also include a DM component with a generalized NFW profile (Navarro et al. 1997),

$$\rho(r) = \frac{\rho_0}{(r/R_s)^\alpha(1 + r/R_s)^{3-\alpha}}$$

with scale radius $R_s = 12 \text{ kpc}$ and density normalization $\rho_0 = 1.1 \times 10^{-2} M_\odot \text{ pc}^{-3}$. These models have $\rho \propto r^{-\alpha}$ near GCs, with $\alpha = 1$ for a standard NFW profile. For simplicity, we assume a constant DM velocity dispersion of $v_{DM} = 200 \text{ km s}^{-1}$ at all radii. Figure 1 shows the density profile and enclosed mass of our model.

We caution that the DM profiles near the centers of galaxies are somewhat poorly constrained, especially within the inner $\sim 100 \text{pc}$, which is typically not probed by observations nor simulations. The current understanding is that in galaxies less massive than the Milky Way, the DM profiles are cored due to star formation feedback, i.e., their central density profiles are shallower than the cuspy $\rho_{DM} \propto r^{-1}$ profiles of an NFW profile (Del Popolo & Kroupa 2009; Maccì et al. 2012). However, simulations of more massive galaxies indicate DM profiles with $\rho_{DM} \propto r^{-1}$ (Di Cintio et al. 2014), or in many cases even steeper density profiles due to adiabatic contraction (Blumenthal et al. 1986; Gnedin et al. 2004; Gustafsson et al. 2006). Lensing studies have also revealed steep central DM density profiles in massive early type galaxies (Tortora et al. 2010; Sonnenfeld et al. 2012; Grillo 2012) and high DM densities within central cluster galaxies (Newman et al. 2013). Hence, we expect long (greater than a Hubble time) NS collapse times in low-mass galaxies, although short collapse times are achievable in massive spirals, early type galaxies, and central cluster galaxies, where central DM densities may greatly exceed $1 M_\odot \text{ pc}^{-3}$. Below, we shall consider a range of DM profiles, with slopes $0.5 < \alpha < 1.5$.

As a matter of demonstration, we choose a non-self-interacting and non-annihilating bosonic DM particle with mass of $m = 10 \text{MeV}/c^2$ and nucleon scattering cross section $\sigma = 3 \times 10^{-49} \text{ cm}^2$. For these choices, BH formation will occur upon formation of a super-Chandrasekhar mass Bose-Einstein condensate at the center of the NS, and the BS will be massive enough to consume the NS on a short timescale. For more massive DM particles, the number of DM particles required for BH formation will depend on the NS core temperature. Additional issues (e.g., self-interacting bosonic DM, fermionic DM, the DM thermalization time-scale, and BH evaporation) can affect the DM accumulation, sedimentation, and BH formation process. A full exploration of these issues is beyond the scope of this work, and we refer the reader to previous studies (e.g., Kouvaris & Tinyakov 2011; Kouvaris 2012; McDermott et al. 2012; Bramante et al. 2013).
radius, shown in Figure 1. In the solar neighborhood, the collapse time is \( t_c \approx 10^8 \) yr, while in the central parsec, \( t_c \lesssim \) few \( \times 10^6 \) yr. DM-induced collapse could thus substantially reduce the number of detectable radio pulsars within the central \( \approx 10 \) pc assuming typical radio pulsar lifetimes are \( 10^7 \) to \( 10^8 \) yr (Faucher-Giguère & Kaspi 2006). Steeper DM density profiles (green shaded area in Figure 1) will allow for shorter collapse times and more efficient pulsar destruction. Very steep profiles are problematic for the DM-induced collapse scenario because they predict very short collapse times that would preclude the observation of the GC magnetar, which is estimated to lie near \( r \approx 0.1 \) pc with an age of \( \sim 10^4 \) yr (Eatough et al. 2013; Bower et al. 2014; Spitler et al. 2014a; Dexter & O’Leary 2014). Shallower DM profiles (purple shaded area) would not allow for prompt NS collapse and could not resolve the missing pulsar problem, although they may still allow for relatively large FRB rates. A much smaller DM cross section (red line in Figure 1) would not allow for timely NS collapse and could not resolve the missing pulsar problem nor generate enough FRBs. A much larger DM cross section (blue line) would cause NSs to quickly collapse even outside of GCs, and can be ruled out by existing observations of old NSs.

To compute an approximate FRB rate, we assume a constant star formation rate and galaxy age of \( t_G = 10^{10} \) yr, such that the star formation rate within a radius \( r \) is simply \( \dot{M}_* = M(r)/t_G \). Star formation rates peaking at early times will yield older populations of NSs and will increase the FRB rate. Given a current star formation rate of \( \dot{M}_{*,0} \approx 1.6 \, M_\odot \) yr\(^{-1}\) (Licquia & Newman 2014) and a galactic core-collapse supernova rate of \( \dot{R}_{SN} \approx 2 \times 10^{-2} \) yr\(^{-1}\) (Li et al. 2011), we calculate a NS creation rate of \( \dot{M}_{NS} \approx 1.5 \times 10^{-2} \dot{M}_* \), assuming each supernova generates a NS of mass \( M_{NS} \approx 1.4 \, M_\odot \). Finally, we set the FRB rate per unit volume equal to

\[
\frac{dR_{FRB}}{dV} = \frac{1}{\dot{M}_{NS}} \frac{dM_{NS}}{dV} \quad \text{if} \ t_c < t_G, \\
\frac{dR_{FRB}}{dV} = 0 \quad \text{if} \ t_c > t_G. \tag{5}
\]

The FRB rate within a radius \( r \), \( R_{FRB} \), is simply the volume integral over equation (5) and is shown in the bottom panel Figure 1. This demonstrates that a Milky Way-like galaxy is capable of producing a total FRB rate of \( R_{FRB} \sim 10^{-2} \) yr\(^{-1}\) gal\(^{-1}\).

In comparison, the core-collapse supernova rate is \( \dot{R}_{SN} \sim 2 \times 10^{-2} \) yr\(^{-1}\) gal\(^{-1}\) for a Milky-Way-like galaxy (Li et al. 2011). In our simple model, only about one tenth of galactic NSs (those born within roughly 1 kpc of the GC) can collapse within a Hubble time. However, the current FRB rate is comparable to the current supernova rate because the average galactic past star formation rate (\( \dot{M} \sim 10 \, M_\odot \) yr\(^{-1}\)) is larger than the current star formation rate. Given a volumetric core-collapse supernova rate (at \( z = 0 \)) of \( \dot{R}_{SN} \sim 10^{−3} \) Mpc\(^−3\) yr\(^−1\) (Li et al. 2011), a plausible FRB rate is then

\[
R_{FRB} \sim 5 \times 10^{−5} \text{ Mpc}^−3 \text{ yr}^{-1}. \tag{6}
\]

The observed FRB rate is somewhat debated, but may be as large as \( 10^4 \) day\(^−1\) (Thornton et al. 2013). This corre-

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transient associated with FRB 140514 (Petroff et al. 2014a). FRBs will not ever repeat, although multiple FRBs could arise from the same galaxy as long as its GC is DM-rich. We hope the exciting implications of these scenarios will reinvigorate searches for FRBs and GC pulsars, and we anticipate that future observations will elucidate the nature of these enigmas.

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4 DISCUSSION AND PREDICTIONS

There are several reasons why the DM-induced collapse scenario may not occur. The most likely is that DM properties are simply not compatible with this scenario, for the multitude of possibilities discussed in Bramante et al. (2013). On the contrary, if DM-induced collapse is observed to occur, it would provide constraints on DM properties. Below, we list several predictions of the DM-induced collapse scenario and its relation to the GC missing pulsar problem and FRB generation. If these predictions can be falsified, we can discount the scenario. However, if the predictions hold up, the scenario must be regarded seriously.

1. Dark matter mass, scattering cross sections, and self-interaction properties are in accordance with the limits discussed in Bramante & Linden (2014).

2. There is no GC X-ray or γ-ray excess due to DM annihilation.

3. Large galaxies contain cusped DM density profiles, with central DM densities exceeding ∼1 M⊙pc−3.

4. Long-lived NSs do not exist near most GCs, i.e., there should be no observed NSs with ages much larger than the collapse time shown in Figure 1. The discovery of an old millisecond pulsar or low mass NS X-ray binary within the inner ∼50 pc of the GC would disfavor the NS-induced collapse scenario.

5. There exists a large population of NS-mass (M ≈ 1.4 M⊙) BHs near GCs. The discovery of a low mass X-ray binary containing a M ≤ 2 M⊙ BH near the GC would reinforce the DM-induced NS collapse scenario.

6. FRBs are localized near (within ∼1 kpc of) GCs of massive galaxies or central cluster galaxies where DM densities are large. A magnetar flare FRB scenario (Kulkarni et al. 2014) Lyubarsky 2014, Pen & Connor 2015 may entail that many FRBs occur near GCs, but also allows FRBs to arise from young stellar populations in dwarf galaxies. In contrast, dwarf galaxy hosts (where DM densities are low) are unlikely in the DM-induced collapse scenario.

7. FRBs exhibit little or no associated optical or X-ray transient, in agreement with the recent non-detection of any transient associated with FRB 140514 (Petroff et al. 2014a). FRBs will not ever repeat, although multiple FRBs could arise from the same galaxy as long as its GC is DM-rich.

We hope the exciting implications of these scenarios will reinvigorate searches for FRBs and GC pulsars, and we anticipate that future observations will elucidate the nature of these enigmas.

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