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

Jim Fuller$^{1,2}$, Christian D. Ott$^1$

$^1$TAPIR, Walter Burke Institute for Theoretical Physics, Mailcode 350-17, California Institute of Technology, Pasadena, CA 91125, USA
$^2$Kavli Institute for Theoretical Physics, Kohn Hall, University of California, Santa Barbara, CA 93106, USA

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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. Our scenario predicts that FRBs are localized to galactic centers, and that our own galactic center harbors a large population of NS-mass ($M \sim 1.4 M_\odot$) 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 (FRB) 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 at $\sim \text{GHz}$ frequencies. They exhibit a frequency dependent delay time, $\Delta t \propto \nu^{-2}$, indicative of radio wave propagation through a cold, diffuse plasma. Their large dispersion measures ($D_M \sim \text{several} \times 100 \text{ cm}^{-3} \text{pc}$) indicate that they have traversed through a considerable column density of electrons. However, most FRBs have been discovered at high galactic latitudes, indicating that their $D_M$ is not produced within our galaxy. The estimated event rate of FRBs is large, up to $10^4$ per sky per day (Thornton et al. 2013). If FRBs are produced by astronomical sources, they likely originate at cosmological distances. Several authors (Luan & Goldreich 2014; Dennison 2014; Katz 2014b,a) have shown that the observed $D_M$ must accumulate over large distances, and if it originates from the intergalactic medium, the distances to the sources must be large ($D \sim 2 \text{Gpc}$). The large distances imply large energies, with typical bursts emitting $10^{38}$ to $4 \times 10^{40}$ erg (Thornton et al. 2013; Kulkarni et al. 2014; Dolag et al. 2014) at radio wavelengths. Conversely, these authors showed that the width of the scattering tails (produced by density inhomogeneities in the ISM/IGM) in some FRBs cannot be explained by scattering within the IGM, and likely originates within the host galaxy of the source. This may indicate that at least some FRBs originate near galactic centers (Luan & Goldreich 2014). Typical comoving distances of $D \sim 2 \text{Gpc}$ and an event rate of $10^9 \text{day}^{-1}$ 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.

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; Deneva 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.

The missing pulsar problem has no obvious solution. 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. The discovery of a magnetar near the GC provides circumstantial evidence in support of this hypothesis, but 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.

2 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 in depth by Bramante & Linden 2014; see also Kouvaris & Tinyakov 2011; Kouvaris 2012; McDermott et al. 2012 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. The virialized DM particles sink to the center of the NS (this typically occurs even for low-mass DM particles) where they accumulate within a small volume. Bosonic DM can then form a Bose-Einstein condensate, while fermionic DM will form a degenerate Fermi gas. When the DM agglomeration exceeds a critical mass, the DM forms a black hole (BH) at the NS center that (provided it is massive enough to avoid evaporation on timescales shorter than it takes the NS material to accrete) consumes the NS.

The NS collapses into the BH on a dynamical time scale ($t_{\text{dyn}} \sim 1\text{ ms}$), and a $\sim 1.4M_\odot$ BH remnant is left behind. During the collapse, the magnetosphere must suddenly detach from the BH horizon and dissipate. The rapid reconfiguration and reconnection of the field lines generates a burst of electromagnetic energy. If some 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 several papers (Kouvaris & Tinyakov 2011; Kouvaris 2012; McDermott et al. 2012; Bramante & Linden 2014), here we simply restate their basic results. First, there is only a narrow (2-3 orders of magnitude) range of DM collapsing cross sections $\sigma$ that allows for rapid DM accumulation within GC NSs while allowing more local NSs to survive for several Gyr. This range is dependent on the DM particle mass but generally lies in the region $10^{-53}\text{ cm}^2 \lesssim \sigma \lesssim 10^{-40}\text{ cm}^2$ for a NS core temperature of $10^9\text{ K}$. 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 $t_c \propto \rho_{\text{DM}}^{-1}$. Therefore, GC DM densities must be orders of magnitude larger than the DM density in the solar neighborhood. 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 be enhanced by at least a factor of $10^4$. Such enhancement is not unreasonable if the DM density profile resembles a Navarro-Frenk-White (NFW) profile where the density within the inner $\sim 10\text{ kpc}$ roughly scales as $\rho_{\text{DM}} \propto r^{-1}$. However, DM-induced collapse may not be able to occur in dwarf galaxies that exhibit cored DM density profiles, i.e., central DM densities are lower because the DM density profile flattens near the GC. The observation of many old millisecond pulsars in globular clusters (e.g., Heinke et al. 2005) would require low DM densities in globular clusters, which is consistent with current observational constraints (e.g., Conroy et al. 2011; Ibata et al. 2013) unless the DM density profile deviates far from NFW in globular clusters.

3 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 a supramassive NS collapse scenario in which a massive, centrifugally supported rigidly rotating NS spins down until it collapses to a BH.

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 \( \nu \sim 1/\Delta t_{\text{dyn}} \sim \text{kHz} \). 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

\[
\nu_p \sim 2 \text{ GHz } B_{12}^{1/2} P_1^{-1/2},
\]

where \( B_{12} \) is the field strength in units of \( 10^{12} \) G, and \( P_1 \) is the spin period in seconds. Following their analysis, we calculate an emitted power near GHz frequencies of

\[
P_R \sim 2 \times 10^{41} \text{ erg s}^{-1} B_{12}^{13/6} P_1^{-13/6}. \tag{3}
\]

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 \( E_R \sim 2 \times 10^{36} \text{ erg} \), 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 should not be taken too seriously.

The radiative power of equation 3 can be compared to the simulation of the non-rotating collapse of a NS by Lehner et al. (2012) (see also [Palenzuela 2013; Dionysopoulos et al. 2013]), who find \( P_{\text{rad}} \sim 10^{42} - 10^{43} B_{12}^2 \text{ erg s}^{-1} \) over a duration of roughly a millisecond, implying \( E_{\text{rad}} \sim 10^{39} - 10^{40} B_{12}^2 \text{ erg} \). Most of the magnetic field energy is swallowed by the BH, accounting for the low radiative efficiency. Unfortunately, these authors do not compute a radiation spectrum, so it is unclear how much energy is emitted in 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 X-ray/\( \gamma \)-ray wavelengths, however, any optical/UV/X-ray/\( \gamma \)-ray transient produced is unlikely to be detected. Its maximum luminosity is \( L \lesssim 10^{43} \text{ erg s}^{-1} \), and its duration is expected to last \( t \lesssim 1 \text{ ms} \), preventing even very rapid follow-up observations. Finally, [Lehner et al. 2012] find that the radiative power is slightly beamed along the magnetic equator.

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. Of course, it is possible that FRB emission is somewhat beamed, meaning the radiated energy is smaller than the estimates of [Kulkarni et al. 2014] and [Dolag et al. 2014]. Beamed emission would also require larger volumetric collapse rates in order to account for observed volumetric FRB rates.

The observed FRB scattering tails are also consistent with the DM-induced collapse scenario, which requires that FRBs occur near GCs where lots of intervening material is available to boost the dispersion measure or produce scattering. Indeed, [Luan & Goldreich 2014] and [Katz 2014a] have shown that the scattering is unlikely to arise from the IGM, and is most likely generated deep within the host galaxy. Similarly, our scenario entails that FRBs occur near GCs where the scattering could be produced. Moreover, at least some of the observed \( D_M \sim 100 \text{ cm}^{-3} \text{ pc} \) may be contributed by the host galaxy, depending on the exact source location and galaxy inclination. This implies FRBs could be somewhat closer (perhaps by tens of percent) than estimated by assuming the observed \( D_M \) is generated in the IGM.

### 4 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 \( (M_{\text{acc}} \lesssim 10^{-10} M_\odot) \) is accreted before collapse. The most salient detail of the process is that the collapse time scales as \( t_c \propto \rho_{\text{DM}}^{-1} \), 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 [Sefusatti 2013]. 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 include a DM component with an NFW profile, with scale radius \( R_s = 12 \text{ kpc} \) and density normalization \( \rho_0 = 1.1 \times 10^{-2} M_\odot \text{ pc}^{-3} \). Figure 1 shows the density profile and enclosed mass of our model. For simplicity, we assume a constant DM velocity dispersion of \( v_{\text{DM}} = 200 \text{ km s}^{-1} \) at all radii. If the DM has an adiabatically contracted profile, GC DM densities may be even larger (and NS collapse times proportionally smaller) than those calculated below.

As a matter of demonstration, we choose a bosonic DM particle mass of \( m = 1 \text{ TeV} \) and nucleon scattering cross section \( \sigma = 4 \times 10^{-53} \text{ cm}^2 \), which permits NS survival in the solar neighborhood but allows NS collapse near the GC. Using the DM properties and density profile described above, we compute the NS collapse time \( t_c \) as a function of radius, shown in Figure 1. In the solar neighborhood, the collapse time is \( t_c \sim 10^{11} \text{ yr} \), while in the central parsec, \( t_c \lesssim \text{few } 10^{6} \text{ yr} \). DM-induced collapse could thus substantially reduce the number of detectable radio pulsars within

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1 The DM mass needed to create a BH can depend on the NS internal temperature [Bramante & Linden 2014]. In our calculations, we use an NS core temperature \( T_c = 10^8 \text{ K} \), which is reasonable for old NSs in the photon-cooling phase (see, e.g., [Yakovlev & Petrich 2004] and cooling tracks obtained with the NSCool code: [http://www.astroscu.unam.mx/neutrones/NSCool](http://www.astroscu.unam.mx/neutrones/NSCool)). Young NSs (with ages less than \( \sim 2 \times 10^6 \text{ yr} \)) may be substantially warmer, which may raise the DM mass required for BH formation and therefore increase collapse times. Changing \( T_c \) from \( 10^8 \text{ K} \) does not invalidate our analysis, it simply shifts the allowed range of DM scattering cross sections \( \sigma \).
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 \( \dot{M}_* = \frac{M(r)}{t_G} \). Given a current star formation rate of \( \dot{M}_{\star,0} \approx 1.6 M_\odot \) yr\(^{-1} \) (Liquiura & Newman 2014) and a galactic core-collapse supernova rate of \( R_{\text{SN}} \approx 2 \times 10^{-2} \) yr\(^{-1} \) (Li et al. 2011), we calculate a NS creation rate of \( \dot{N}_{\text{NS}} \approx 1.5 \times 10^{-2} \) \( \dot{M}_* \), assuming each supernova generates a NS of mass \( 1.4 M_\odot \). Finally, we set the FRB rate per unit volume equal to:

\[
\frac{dR_{\text{FRB}}}{dV} = \begin{cases} 
\frac{1}{\dot{N}_{\text{NS}}} \frac{d\dot{M}_{\text{NS}}}{dV} & \text{if } t_c < t_G, \\
0 & \text{if } t_c > t_G,
\end{cases}
\]

(4)

where \( \dot{M}_{\text{NS}} = 1.4 M_\odot \) is a typical NS mass. The FRB rate within a radius \( r \), \( R_{\text{FRB}} \), is simply the volume integral over equation [4] and is shown in the bottom panel Figure [4]. This demonstrates that a Milky Way-like galaxy is capable of producing a total FRB rate of \( R_{\text{FRB}} \approx 10^{-2} \) yr\(^{-1} \) gal\(^{-1} \).

In comparison, the core-collapse supernova rate is \( R_{\text{SN}} \approx 2 \times 10^{-2} \) 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 \( R_{\text{SN}} \approx 10^{-4} \) Mpc\(^{-3} \) yr\(^{-1} \) (Li et al. 2011), a plausible FRB rate is then

\[
R_{\text{FRB}} \approx 5 \times 10^{-5} \text{ Mpc}^{-3} \text{ yr}^{-1}
\]

(5)

The observed FRB rate is somewhat debated, but may be as large as \( 10^3 \) day\(^{-1} \) (Thornton et al. 2013). This corresponds to a volumetric rate of

\[
R_{\text{obs}} \approx 10^{-4} \text{ Mpc}^{-3} \text{ yr}^{-1} \left( \frac{D}{2 \text{ Gpc}} \right)^{-3}
\]

(6)

where \( D \) is the comoving distance out to which most FRBs are observed. The lack of FRB detections in lower galactic latitude surveys (Petroff et al. 2014b) indicates the FRB rate may be substantially lower than that quoted by Thornton et al. 2013. It is also possible that the DM-induced collapse rate is dominated by other types of galaxies (e.g., early type galaxies, galaxies in clusters) with larger DM densities. We argue that the DM-induced collapse rate may be high enough to account for most FRBs (within the uncertainties), although we defer a more thorough FRB rate analysis to future studies.

5 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, either because the DM-nucleon scattering cross section is too small, or because DM particles self-annihilate. The shaded region of Figure 1 in Bramante & Linden (2014) displays the approximate DM parameter space where DM-induced collapse is allowed. Since the allowed parameter space for NS collapse is quite small compared to the total possible space, it seems unlikely that DM-induced NS collapse commonly occurs in nature. On the contrary, if DM-induced collapse can be shown to occur, it would provide the tightest constraints to date 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 masses, 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 $\gamma$-ray excess due to DM annihilation.

3. Large galaxies contain cusped DM density profiles, with central DM densities exceeding $\sim 1 M_\odot$ 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 recently discovered magnetar near our own GC (Eatough et al. 2013) is likely very young (Dexter & O’Leary 2014), and cannot have collapsed yet. The discovery of an old millisecond pulsar within the inner $\sim 30$ pc of the GC would likely invalidate the NS-induced collapse scenario.

5. There exists a large population of NS-mass ($M \approx 1.4 M_\odot$) BHs near GCs. The discovery of a low mass X-ray binary containing a $M \lesssim 2 M_\odot$ BH near the GC would re-inforce the DM-induced NS collapse scenario. The discovery of a low mass NS X-ray binary near the GC would disfavor the scenario and rule out some DM parameter space.

6. FRBs are localized near (within $\sim 1$ kpc of) GCs of massive galaxies where DM densities are large. Note that a magnetar flare FRB scenario (Kulkarni et al. 2014, Lyubarsky 2014) also predicts that many FRBs occur in star forming regions near GCs. However, the magnetar flare model predicts that FRBs arise from young stellar populations, and that dwarf galaxy hosts are possible. In contrast, the DM-induced collapse scenario entails that FRBs will not commonly originate from dwarf galaxies (where DM densities are low), although they may occur in old stellar populations, such as central regions of elliptical galaxies and spiral galaxy bulges.

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.

Finally, we note that the DM-induced NS collapse scenario is not necessarily mutually exclusive with other FRB scenarios (e.g. Kulkarni et al. 2014 and Lyubarsky 2014) and that there are other possible sources of FRBs (e.g. Kulkarni et al. 2014). It is entirely possible (although perhaps unlikely) that FRBs have multiple sources or that the missing pulsar problem stems from both efficient magnetar formation and DM-induced collapse. In any case, the exciting implications of these scenarios should reinvigorate searches for FRBs and GC pulsars, and we anticipate that future observations will elucidate the nature of these enigmas.

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