LOCAL CIRCUMNUCLEAR MAGNETAR SOLUTION TO EXTRAGALACTIC FAST RADIO BURSTS

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Received 2015 April 6; accepted 2015 May 19; published 2015 July 9

ABSTRACT

We synthesize the known information about fast radio bursts (FRBs) and radio magnetars, and describe an allowed origin near nuclei of external, but non-cosmological, galaxies. This places them at \( z \ll 1 \), within a few hundred megaparsecs. In this scenario, the high dispersion measure (DM) is dominated by the environment of the FRB, modeled on the known properties of the Milky Way center, whose innermost 100 pc provides 1000 pc cm\(^{-3}\). A radio loud magnetar is known to exist in our galactic center, within \( \sim 2 \) arcsec of Sgr A*. Based on the polarization, DM, and scattering properties of this known magnetar, we extrapolate its properties to those of Crab-like giant pulses and SGR flares and point out their consistency with observed FRBs. We conclude that galactic center magnetars could be the source of FRBs. This scenario is readily testable with very long baseline interferometry measurements as well as with flux count statistics from large surveys such as CHIME or UTMOST.

Key words: Galaxy: center – pulsars: general – stars: magnetars

1. INTRODUCTION

The phenomenon of fast radio bursts (FRBs) has generated excitement in the astronomical community as well as speculation regarding the origin of the events (Lorimer et al. 2007; Thornton et al. 2013). FRBs are millisecond radio transients with flux densities between 0.2 and 1.5 Jy. They are also highly dispersed, with dispersion measures (DMs) far exceeding the expected contribution from our own galaxy in their direction (DM \( \sim 500–1200 \) pc cm\(^{-3}\)). Theories of their distance vary from atmospheric to solar system, galactic, and cosmological; however, the high DMs have led a number of people to believe that they are extragalactic. This is also partly due to their location on the sky, since the high galactic latitudes cast doubt on a galactic or solar system origin (Thornton et al. 2013). If the extragalactic dispersion is caused by the intergalactic medium (IGM), then the sources would be cosmological, found between redshifts 0.45–1. However, it is possible that the dispersion could be due to dense regions in more nearby galaxies, as noted by Thornton et al. (2013) and Luan & Goldreich (2014). These galaxies would be within a few hundred megaparsecs, which we will consider noncosmological.

Perhaps more mysterious than their location are their progenitors and emission mechanisms. A wide range of ideas have been proposed, from blitzars (Falcke & Rezzolla 2014) to superconducting cosmic strings (Yu et al. 2014), compact object mergers (Kashiyama et al. 2013) to nearby flaring main-sequence stars (Loeb et al. 2014).

In this paper, we provide yet one more allowed interpretation consistent with current data: giant pulses (GPs) or outbursts from magnetars in the nuclear regions of external galaxies. The idea that FRBs could be radio-emitting magnetars was explored by Kulkarni et al. (2014) and Lyubarsky (2014), where the high brightness temperatures are explained by shock-induced maser emission. We do not focus on the emission mechanism nor do we favor pulsar-like emission (GPs) versus SGR flares; we are simply putting forth an explanation for FRBs based on magnetars near the centers of external galaxies that is consistent with the existing data, which make falsifiable predictions. The noncosmological (i.e., local) extragalactic nuclear FRB can naturally explain the observed large DMs and scattering (SM) and could help explain their polarization properties.

2. GALACTIC CENTER PULSARS

2.1. Nuclear Properties

Our own galactic center region has a high measured electron density, and the recently discovered pulsar and magnetar SGR J1745-2900 has a measured DM \( \sim 1778 \) (Eatough et al. 2013), most of which is thought to originate from the inner few parsecs of the galaxy. Seen from a typical extragalactic line of sight, this magnetar would have a DM \( \sim 1000 \). It is scattered by a few seconds at \( \sim \) GHz, which is a thousand times longer than the observed scattering timescales of FRBs. However, very long baseline interferometry (VLBI) measurements indicate that this scattering is dominated by a screen closer to our Sun than the galactic center (Bower et al. 2014), in which case a typical extragalactic line of sight would see a much smaller scattering time, perhaps a few milliseconds.

It had been thought that the GC harbored a large number of pulsars, but that they were difficult to observe at low frequencies due to a scattering screen within \( \sim 200 \) pc of Sgr A* (Lazio & Cordes 1998; Wharton et al. 2012). However, after the discovery of the radio-loud magnetar, J1745-2900, just \( \sim 2 \) arcsec from Sgr A*, it now seems that there really is a dearth of regular pulsars and an over-representation of magnetars. Though hundreds to thousands of ordinary pulsars were predicted to exist within \( \sim 0.2 \) pc of the galactic center, none have yet to be found (Pfahl & Loeb 2004). Dexter & O’Leary (2014) show that this implies that the region is an effective environment for magnetar formation, whose short lives could explain the lack of such radio-loud objects in the central parsec. The GC would then be a graveyard of highly magnetized massive stars, some of which became magnetars and emitted in the radio for \( \sim 10^4 \) years before spinning down sufficiently to cross the death line.

It is worth pointing out that J1745-2900 is one of just four known radio-loud magnetars. Within 2.2 arcsec of Sgr A*, it
occupies a volume that is $\sim 10^{-9}$ of our galaxy’s volume and $\sim 5 \times 10^{-5}$ of its mass, and where there is an anomalous absence of ordinary pulsars. This suggests not only that radio-loud magnetars can form in such environments, but preferentially do. External nuclear regions could therefore also harbour magnetars and could provide both the dispersion and the scattering observed in FRBs.

In the cosmological picture, it is difficult to explain the scattering tails seen in several bursts from the IGM. Luan & Goldreich (2014) point out that if it is due to turbulence, then the length scale of plasma scattering in the IGM at a distance of 1 Gpc for approximately millisecond tails is impossibly small. In other models, the IGM is an equally unlikely place for the scattering to occur (Pen & Levin 2014). However, we do point out that McQuinn (2014) has shown that cosmological FRBs could be scattered at approximately milliseconds by intervening galactic disks if their electron distribution were more extended than is currently believed.

### 2.2. Possible Sources

A dozen or so pulsars are known to exhibit GPs, which are of very short durations and can be many orders of magnitude brighter than their average pulse flux (Mickaliger et al. 2012). A rare tail of supergiant pulses (Cordes et al. 2004) has also been identified, with brightness temperatures reaching up to $10^{32}$–$10^{37}$ K (Hankins et al. 2003). They tend to be short enough (<16 ns) that their pulses are consistent with a pure scattering profile, which is also the case for the observed FRBs. It is worth noting that the only FRB for which there is polarization information is FRB 140514, which was found to have $\sim 20\%$ circular polarization and very little linear polarization (<10\% (Petroff et al. 2014). Considering the rotation measure of the GC magnetar, J1745-2900, is RM $= -6.7 \times 10^5$ rad m$^{-2}$, if other galactic centers were like our own, then nuclear pulsars and magnetars could become linearly depolarized due to multi-path Faraday rotation from a scattering screen (Petroff et al. 2014). It is also possible that the sources themselves are circularly polarized. At 2 GHz, J1745-2900 is also observed to be $\sim 20\%$ circularly polarized, with no detected linear polarization. At higher frequencies, this magnetar is strongly linearly polarized. GPs are known to often be highly circularly polarized, for example, over half of the peaks from B1937+21 are in a pure Stokes V state.

Though none of the known pulsars that exhibit GPs are radio-loud magnetars, the energetics of FRBs are not difficult to accommodate and one could imagine high-luminosity radio outbursts from such objects; some magnetars are soft gamma-ray repeaters (SGR), which have episodic outbursts emitting $10^{36}$ erg in a fraction of a second. At distances of $\sim 100$ Mpc, the inferred energy of an FRB is $\sim 10^{36}$ erg, a tiny fraction of known SGR burst energies. Magnetars that emit in the radio can also have non-negligible circular polarization and the GC object J1745-2900 seems to have a typical circular fraction of $20\%$, though this increases when the pulse flares up (Lynch et al. 2014).

Only a tiny fraction of the burst energy needs to come out to power an FRB. In order to explain the common large DM of FRBs, these GPs would require preferential properties of circumnuclear magnetars. Events would be expected to repeat after several years, making a direct search challenging. An all-sky search with a telescope such as CHIME (Bandura et al. 2014) over a year could discover $\sim 10^5$ events, of which $\sim 10^4$ would repeat in a year and a few would be lucky enough to be caught in the same CHIME beam a second time. The long integrations at known FRB locations have not resulted in repeat events, which is consistent with this picture.

Given the small number of radio-loud magnetars in the Milky Way, one cannot comment on their distribution in other galaxies. However, in this picture, there could be a sizeable fraction of sources that exist outside of their galaxy’s nuclear regions, in which case there should be a commensurate number of FRBs with modest DMs, perhaps $70$–$100$ pc cm$^{-3}$ for an object at 100 Mpc. The apparent lack of sources with such DMs could be explained by a selection effect: radio bursts whose DMs are not extraordinary may simply not get identified as FRBs. These may be missed or ignored given the large ensemble of radio transients with an apparent $\nu^{-2}$ sweep, including RRAT’s and perytons (Bagchi et al. 2012).

### 3. Predictions

This scenario is readily testable: at redshifts less than unity $z < 1$, the flux distribution is given by a Euclidean universe, with $N(>S) \propto S^{-3/2}$, only weakly dependent on DM, assuming that the bursts are nearly standard candles. This is not necessarily expected for high redshift objects, where cosmological expansion and source population evolution are expected to change.

A VLBI detection would find a spatial coincidence to within a few parsecs of a galactic nucleus, which is approximately milliarcseconds at distances of $\sim 100$ Mpc. The current non-coincidence with nearby galaxies constrains the typical distance to be larger than $\sim 100$ Mpc. This is still an order of magnitude closer than if the DM is primarily accounted for by the IGM.

The galactic center magnetar is linearly depolarized at frequencies below $\sim 4$ GHz, consistent with multi-path Faraday depolarization from the scattering screen (Petroff et al. 2014). Circular polarization is not affected and has indeed been observed in FRBs.

### 4. Applications

Substantial interest has developed for cosmology, should FRB be at cosmological distances. These are summarized in McQuinn (2014). Should the DM be dominated by the host galaxy, these applications would be difficult to materialize. The expected scattering size of such events would be microarcseconds, which could be detectable with galactic scintillation (Pen et al. 2014).

In a large survey, such as CHIME, the closest event could be at approximately megaparsec distances. Continuous monitoring of neighboring galactic centers, e.g., M31, for years, could detect pulses many kJy bright, requiring only a small receiver to monitor. Similarly, long-term continuous monitoring of the GC magnetar may uncover rare super-giant pulses. All-sky telescopes, such as the FFTT (Tegmark & Zaldarriaga 2009), may be well suited for finding close, bright sources.

Extrapolating from the one known nuclear magnetar, a sample of $10^5$, as might be found by CHIME, could result in the closest projected impact angle of $\sim 7$ mas. This would place it near the Einstein Ring radius, within $\sim 1000$ Schwarzschild radii, such that it could be gravitationally lensed by the central black hole. Assuming its projected proximity to the black hole does not increase the FRBs DM or SM too significantly, this
would be seen as an echo separated by the black hole Schwarzschild time, approximately seconds. The echo would be fainter and the combination of delay and flux constrains the central black hole mass.

5. CONCLUSIONS

We have described an FRB scenario based on circumnuclear magnetar phenomena. In this scenario, FRBs are bright bursts or GPs from magnetars at the centers of nearby external galaxies, within a few 100 Mpc. The dominant DM contribution is due to the nuclear medium, which is sufficient for galaxies similar to the Milky Way whose innermost 100 pc provides ~1000 pc cm\(^{-3}\).

Though we do not know to what extent magnetars preferentially form at the GC, the fact that one of just four radio loud magnetars is within 2" of Sgr A* tells us that such objects are over represented in these environments. There are also physical arguments that could explain the lack of pulsars and the apparent tendency to form magnetars: Dexter & O’Leary (2014) suggest that efficient formation could be due to highly magnetized progenitors or a top-heavy initial mass function. Given the large energy released in the episodic outbursts of SGR magnetars and the tendency for some pulsars to emit GPs, we have shown that FRBs could be nuclear events. This picture also alleviates the difficulty of producing 1 ms scattering tails from the diffuse IGM, which has been shown to be problematic by Macquart & Koay (2013) and Luan & Goldreich (2014). Though we do not quantify scattering from galactic nuclei, we think temporal broadening from such regions at ~0.1−100 ms is reasonable. Our explanation is also consistent with the polarization properties of FRB 140514, which had no detectable linear polarization and ~20% circular polarization. This could be caused by linear depolarization at low frequencies due to phase randomization from multiple paths through a scattering screen. Such polarization properties are seen in the galactic center magnetar and GPs from other pulsars.

This model is readily testable with expected upcoming surveys. With either a precise VLBI localization, or a large sample as expected from UTMOST\(^4\) and CHIME Bandura et al. (2014), this model makes quantitative predictions.

We thank NSERC for support.

REFERENCES

Bagchi, M., Nieves, A. C., & McLaughlin, M. 2012, MNRAS, 425, 2501
Bandura, K., Addison, G. E., Amiri, M., et al. 2014, Proc. SPIE, 9145, 22
Bower, G. C., Deller, A., Demoerost, P., et al. 2014, ApJL, 780, L2
Cordes, J. M., Bhat, N. D. R., Hankins, T. H., McLaughlin, M. A., & Kern, J. 2004, ApJ, 612, 375
Dexter, J., & O’Leary, R. M. 2014, ApJL, 783, L7
Eatough, R. P., Falcke, H., Karuppusamy, R., et al. 2013, Natur, 501, 391
Falcke, H., & Rezzolla, L. 2014, A&A, 562, A137
Hankins, T. H., Kern, J. S., Weatherall, J. C., & Eilek, J. A. 2003, Natur, 422, 141
Kashiyama, K., Ioka, K., & Mészáros, P. 2013, ApJL, 776, L39
Kulkarni, S. R., Ofek, E. O., Neill, J. D., Zheng, Z., & Juric, M. 2014, ApJ, 797, 70
Lazio, T. J. W., & Cordes, J. M. 1998, ApJ, 505, 715
Loeb, A., Shvartzvald, Y., & Maoz, D. 2014, MNRAS, 439, L46
Lorimer, D. R., Bailes, M., McLaughlin, M. A., Narkevic, D. J., & Crawford, F. 2007, Sci, 318, 777
Luan, J., & Goldreich, P. 2014, ApJL, 785, L26
Lynch, R. S., Archibald, R. F., Kaspi, V. M., & Scholz, P. 2014, arXiv:1412.0610
Lyubarsky, Y. 2014, MNRAS, 442, L9
Macquart, J.-P., & Koay, J. Y. 2013, ApJ, 776, 125
McQuinn, M. 2014, ApJL, 780, L33
Mickaliger, M. B., McLaughlin, M. A., Lorimer, D. R., et al. 2012, ApJ, 760, 64
Pen, U.-L., & Levin, Y. 2014, MNRAS, 442, 3338
Pen, U.-L., Macquart, J.-P., Deller, A. T., & Brisken, W. 2014, MNRAS, 440, L36
Petroff, E., Bailes, M., Barr, E. D., et al. 2014, arXiv:1412.0342
Pfahl, E., & Loeb, A. 2004, ApJ, 615, 253
Tegmark, M., & Zaldarriaga, M. 2009, PhRvD, 79, 083530
Thornton, D., Stappers, B., Bailes, M., et al. 2013, Sci, 341, 53
Wharton, R. S., Chatterjee, S., Cordes, J. M., Deneva, J. S., & Lazio, T. J. W. 2012, ApJ, 753, 108
Yu, Y.-W., Cheng, K.-S., Shiu, G., & Tye, H. 2014, ICAP, 11, 40

\(^4\) http://www.caastro.org/news/2014-utmost