Searching for Galactic Micro-FRB with Lunar Scattering

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ABSTRACT

Does the Galaxy contain sources of micro-FRB? The answer to this question is essential to determining the nature of FRB sources. At typical (10 kpc) Galactic distances a burst would be about 117 dB brighter than at a “cosmological” (z = 1) distance. Even very low energy Galactic micro-FRB would be detectable, if they exist, or a useful upper bound on their rate set, by a modest (20 m at 1.4 GHz) radio telescope staring at the Moon to detect their reflected radiation. Such a system would have all-sky sensitivity to FRB. The interval between detection of direct and Lunar-scattered radiation would restrict a burst’s position to a narrow arc.

Key words: radio continuum: transients, Galaxy: general, instrumentation: miscellaneous

1 INTRODUCTION

The sources of Fast Radio Bursts (FRB) remain a mystery. If associated with stars or their remnants, the distribution of FRB fluence on the sky would be expected to be concentrated in the Galactic plane, as is the distribution of other radiation associated with stars 1. This is a consequence of the domination of the distribution of stars in the Universe, weighted by the -2 power of their distance, by the Galactic disc.

Yet FRB are isotropically distributed. Are FRB are associated with stars or with some unrelated class of objects? If the former, concentration of micro-FRB, such as may be produced by repeating FRB, in the Galactic plane would be expected. Empirical confirmation or contradiction of that prediction would help decide the question of the origin of FRB.

Some FRB repeat, requiring a non-catastrophic origin, but it is not known if apparently non-repeating FRB actually repeat at long intervals or are the results of catastrophic non-repeating processes. Phenomenological arguments for the distinct nature of the sources of repeating and and apparently non-repeating FRB have been recently presented by Katz (2019a); Li et al. (2019), while Ravi (2019) has argued on statistical grounds that apparent non-repeaters must actually repeat because the rates of known catastrophic events are insufficient.

There are may be two contributors to a population of Galactic micro-FRB: Repeaters that, like FRB 121102, have large numbers of weak bursts but that are much weaker or less active than FRB 121102 (which, if at Galactic distances, would have been detected in side-lobes of unrelated radio observations), and possible weak non-repeaters. If FRB are produced by comparatively common objects like neutron stars, of which there are many in the Galaxy with a broad range of parameters, then a minority with optimal parameters (such as very young neutron stars) may be detectable at cosmological distances while the much greater number with less favorable parameters might produce micro-FRB detectable only at Galactic distances.

Most natural events that leave their sources fundamentally unchanged repeat, with a spectrum of outburst sizes that increases rapidly towards weaker outbursts. Examples include earthquakes, Solar and stellar flares, giant pulsar pulses, lightning and SGR outbursts. Most of these processes appear to have no natural size scale, but rather a power law distribution of event sizes. In contrast the largest SGR outbursts and recurrent novae (from a specific star) appear to be exceptions, with characteristic sizes. Catastrophic events that destroy their sources, such as supernovae and gamma-ray bursts, generally also have characteristic sizes.

FRB energetic enough to be observed at cosmological distances are detected at a rate ~ 10⁶/sky·y. With ~ 3 × 10⁹ L* galaxies with z ≤ 1 their rate is ~ 10⁻⁸–10⁻⁹/galaxy·y. Less energetic bursts of repeating FRB, detectable at Galactic distances, may be frequent enough to occur in feasible observing times (Bochenek et al. 2020). Some constraints on those FRB, with energies between those detectable only at Galactic distances and those detectable at cosmological distances, were set by observations of the Virgo cluster (Agarwal et al. 2019). Detection of Galactic micro-FRB would establish that the Galaxy contains many

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sources, consistent with the popular hypotheses (Katz 2018; Cordes & Chatterjee 2019) that these sources are neutron stars. The absence of Galactic micro-FRB would point to sources rare enough that there are none in the Galaxy (Katz 2019a,b), likely excluding neutron star origin.

In this paper I suggest a method of monitoring the entire Galaxy for micro-FRB. Its sensitivity would be about 73 dB less than that of pointed observations with a Parkes-class telescope, but this is more than made up by the \( \approx 117 \) dB inverse-square law ratio of intensity of Galactic sources in comparison to those at “cosmological” distances \( (z = 1); \) luminosity distance \( 7 \) Gpc). The survey would probe the FRB luminosity function about 44 dB deeper than is possible at cosmological distances. The proposed observations would be sensitive to bursts over almost the entire sky, and the hypothesis of a numerous population of Galactic micro-FRB could be confirmed or excluded.

The Moon reflects, mostly as a specular glint but partly diffusely, radio radiation that illuminates it. Radiation from a FRB in any direction (except for the narrow cone eclipsed by the Earth) is reflected in every direction and can be detected at the Earth (except for sources in the narrow cone eclipsed at the Earth by the Moon). The intensity at the Earth is much less than the incident intensity at the Moon, but the great brightness of a Galactic FRB, in comparison to the same event at cosmological distances, more than compensates for this.

For a radio telescope beam matched to the angular size of the Moon the loss in sensitivity, aside from a contribution \( \sim 13 \text{ dB} \) attributable to the Lunar reflectivity and a trigonometric factor, equals the gain in acceptance solid angle \( (4\pi \text{ sterad} \times \text{ beam solid angle}) \). In addition, the required telescope would be modest \( (\approx 20 \text{ m in L band}) \) and perhaps possible to dedicate to these observations whenever the Moon is above the horizon, thousands of hours per year. At this frequency, a larger telescope (or one observing at higher frequency) would have greater sensitivity, at the price of requiring multiple beams to cover the Moon.

\section{Lunar Scattering}

Scattered radiation can be detected by a radio telescope staring at the Moon. The glint is not significantly spread in time (diffraction broadens it very slightly from a geometrical glint) while Fermat’s Principle implies that in the limit of geometrical optics the diffuse scattering is not temporally broadened.

On scales \( \gtrsim 20 \text{ m} \) median Lunar slopes are \( \sim 10^5 \) (Rosenburg et al. 2011). Most direct measurements (Thompson & Dyce 1966) of Lunar radio-wave reflection have been monostatic and are not directly applicable to the bistatic problem of scattering towards the Earth from general directions of incidence. The measured electromagnetic properties (Olhoeft & Strangway 1975) of the Lunar surface can be used to estimate the bistatic scattering. At the L-band frequencies of most FRB observations the properties in the upper 1–3 cm of soil are applicable: the density is about \( 1.55 \text{ g/cm}^3 \) and the empirical relation of Olhoeft & Strangway (1975) indicates a dielectric constant \( K' \approx 2.77 \) and refractive index \( n = \sqrt{K'} \approx 1.66 \).

Here we treat the Moon as a specularly reflecting sphere of radius \( R \) at a distance \( D \) from the observer. For an observer on the Earth \( D/R \approx 220 \) and \( D/RE \approx 60 \) so that both source and observer may be considered to be at infinity. The geometry is shown in Fig. 1.

If the FRB signal is \( F \) per unit area on a surface perpendicular to its direction, it delivers \( F \cos \theta \) per unit area of the surface of the Moon at the specular point, where \( \theta \) is the angle between the specular point and the direction to the Earth (Fig. 1). The signal may be the flux, the fluence or the integral of the product of flux with an arbitrary function of time. The signal integrated over the portion of the Lunar surface in an interval \( d\theta \) about \( \theta \) and \( d\phi \) about the azimuthal angle \( \phi \) (around the direction to the Earth) is \( F \cos \theta R^2 \sin \theta d\theta d\phi \). This is reflected into a solid angle \( d\Omega = \sin \theta 2d\theta 2d\phi \) because the change in direction on reflection is twice the angle of incidence \( \theta \).

The reflected signal per unit solid angle is

\[ \frac{1}{4}FR^2 \cos \theta. \]  

At a distance \( D \) the observed signal is

\[ F_{obs} = \frac{R}{D} \frac{R^4}{4} \cos \theta, \]  

where \( R \) is the reflection coefficient. For polarizations perpendicular and parallel to the plane of incidence

\[ R_\perp(\theta) = \left( \frac{\cos \theta - \sqrt{n^2 - \sin^2 \theta}}{\cos \theta + \sqrt{n^2 - \sin^2 \theta}} \right)^2; \]

\[ R_\parallel(\theta) = \left( \frac{n^2 \cos \theta - \sqrt{n^2 - \sin^2 \theta}}{n^2 \cos \theta + \sqrt{n^2 - \sin^2 \theta}} \right)^2. \]  

The products \( R(\theta) \cos \theta \) are shown in Fig. 2.

There are two important consequences of Eqs. 2 and 3 and Fig. 2:

(i) As a rough approximation

\[ \frac{F_{obs}}{F} \sim 0.025 \frac{R^2}{D^4} \sim 5 \times 10^{-7}; \]  

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the scattered signal is about 63 dB weaker than the direct signal\(^2\).

(ii) Scattering is strongly polarizing.

The optimal diameter of a single-beam telescope is \(d_{opt} \approx \lambda D/(2R) \approx 22 \text{ m at } 1400 \text{ MHz}\). Many such telescopes exist, and would provide nearly 4\pi sky coverage for FRB during the 0.5 duty factor of the Moon above the horizon. The telescope gain near the center of its beam

\[
g_{tel} \approx 20 \log_{10} \left( \frac{\pi d_{tel}}{\lambda} \right)^2 \approx 20 \log_{10} \left( \frac{\pi D}{2R} \right)^2 \approx 50 \text{ dB}. \tag{5}
\]

Combining Eqs. 4 and 5 leads to a system gain

\[
g_{sys} \approx 20 \log_{10} \left[ 0.02 \left( \frac{\pi}{2} \right)^2 \right] \approx -13 \text{ dB}, \tag{6}
\]

independent of \(D/R\).

The sensitivity of the proposed system should be compared to that of a single dipole, which is near 0 dB (except in its narrow nulls), and to that of the Parkes telescope (\(d_{tel} = 64 \text{ m}\)) in the center of one of its beams, which is about 60 dB. The proposed system would be about 13 dB less sensitive than a single dipole and 73 dB less sensitive than Parkes. In a search for Galactic micro-FRB this lesser sensitivity would be compensated by the fact that at Galactic distances (10 kpc) a given burst would be about 117 dB brighter than at luminosity distance 6.7 Gpc \((z = 1)\) and about 100 dB brighter than at luminosity distance 1.0 Gpc \((z = 0.193\), the distance of FRB 121102). The proposed system would probe the FRB luminosity function 44 dB fainter than Parkes at \(z = 1\) and 27 dB fainter than Parkes at \(z = 0.193\).

### 3 LOCALIZATION

If a burst were detected by the proposed system, localization would be necessary to confirm the burst’s Galactic nature and to permit further investigation. There are two methods of localization, both of which require simultaneous detection with another instrument.

One such instrument would be a dipole or array of dipoles. Even a single dipole would be more sensitive than the proposed system, but would suffer from a high rate of electromagnetic interference because of a dipole’s roughly isotropic sensitivity. A dipole would detect a Galactic FRB with the same energy as the Parkes FRB at \(z \sim 1\) with signal-to-noise ratio roughly 50 dB higher than the detections of the cosmological FRB (Katz 2014). A phased array of dipoles would provide higher sensitivity over the entire visible hemisphere, and also directional information to discriminate against interference, whether through the antenna or “back-door” into the electronics. STARE2 (Bochenek et al. 2020) has somewhat lower angular acceptance (3.6 sterad) than dipoles and a sensitivity of 300 kJy for 1 ms bursts, roughly 55 dB less than that of Parkes but about 5 dB better than that of a dipole.

#### 3.1 Temporal

Comparing the arrival times of a burst at a Lunar-staring telescope and at another receiver, such as a dipole or an array of dipoles, would constrain the position of the burst. Radiation reflected by the Moon arrives later than that observed directly by

\[
\Delta t = \frac{D}{c} \left( 1 - \cos \left( \pi - 2\theta \right) \right) = \frac{D}{c} \left( 1 + \cos \left( 2\theta \right) \right) \sim 1 \text{ s}, \tag{7}
\]

where \(D\) is the distance to the Moon. Bursts are typically 1–10 ms long but contain temporal structure as fine as \(\Delta t \sim 30 \mu\text{s}\). On the basis of the time difference of arrival between the Lunar-reflected signal and the direct signal detected by a dipole array, a burst could be localized to an arc of width

\[
\Delta \theta \sim \frac{\Delta t}{|d\Delta t/d\theta|} \sim 5 \times 10^7. \tag{8}
\]

If phase coherence can be maintained between the detectors, \(\delta t\) in Eq. 8 would be replaced by \(\Delta t/(2\pi c)\). This narrow, albeit one-dimensional, localization of bursts from anywhere on the sky is the chief advantage of observation of Lunar-scattered bursts.

Less sharp localization \(\delta \theta \sim c\delta t/L \sim 5(6000 \text{ km}/L)'\) transverse to the narrow arc can be provided by comparing arrival times at two dipole arrays separated by a distance \(L\). Very large separations reduce the probability that a burst is above the horizon at both locations, so \(\sim 6000 \text{ km} \) may be a practical upper limit on useful values of \(L\).

\(\text{Figure 2. The angle-dependent factors in Eq. 2 of the two polarization states for a Lunar dielectric constant } K' = 2.77 (n = 1.66). Lower x-axis gives angle of incidence } \theta \text{ in radians, upper in degrees.}\)
3.2 Polarization

Fig. 2 shows that the polarization of reflected radiation depends on its angle of incidence. Combining the measured polarization of a Lunar-reflected burst with that measured directly by a dipole or dipole array would constrain the direction of origin of the burst. Because of the limited accuracy of polarization measurements this could not be a tight constraint, probably no more accurate than $\sim 0.2$ rad, but its intersection with a temporal arc of localization would be sufficient to establish whether a burst originated within, or outside, the Galactic plane.

3.3 No Solar Reflection

If reflection from the Sun could be observed, it would provide an independent and precise second temporal localization arc intersecting that of Lunar reflection. Unfortunately, the Sun’s temperature is not steep. Solar reflection is likely not intersecting that of Lunar reflection. If reflection from the Sun could be observed, it would provide an independent and precise second temporal localization arc of localization would be obtained. In particular, detection of Galactic micro-FRB would establish that their sources are comparatively common in the stellar population, while non-detection would tend to exclude sources, like neutron stars, that are present in the Galaxy in large numbers.

Non-repeating FRB may be produced with catastrophic events with a natural scale (so that at low energy $\alpha < 0$). Repeating phenomena, such as earthquakes, meteorite impacts, pulsar pulses, and stellar flares, generally have more weak events than strong ones, typically with a power law distribution that grows rapidly towards small amplitude ($\alpha > 0$). This appears to be true for FRB 121102, the only well-studied repeater, although this has not been well quantified and extrapolation to weaker bursts detectable only at Galactic distances is uncertain. Despite this, the existence of repeating FRB with a broad distribution of intrinsic strengths suggests that if any such sources were present in the Galaxy their weaker bursts might be observable.

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