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Solar Radio-Frequency Reflectivity and Localization of FRB from Solar Reflection

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ABSTRACT

The radiation of a Fast Radio Burst (FRB) reflects from the Moon and Sun. If a reflection is detected, the time interval between the direct and reflected signal constrains the source to a narrow arc on the sky. If both Lunar and Solar reflections are detected these two arcs intersect, narrowly confining the location. Galactic FRB like FRB 200428 may be bright enough to be detected by a 25 m diameter radio telescope staring at the Moon or Sun. A previous paper calculated reflection by the Moon. Here we calculate the reflectivity of the Sun in the "flat Sun" approximation as a function of angle of incidence and frequency. At grazing incidence the reflectivity is high at frequencies $\lessapprox 200\,$MHz but low at higher frequencies; for near-normal incidence the reflectivity is high only for grequencies $\lessapprox 100\,$MHz.

Key words: radio continuum, transients: fast radio bursts, Sun: atmosphere

1 INTRODUCTION

The all-sky FRB rate, above a threshold ~ 1 Jy-ms at 1400 MHz, is $\sim 10^6$/sky-year (Cordes & Chatterjee 2019; Petroff, Hessels & Lorimer 2022). Despite this, until recently only ~ 100 distinct FRB sources had been observed (Petroff *et al.* 2016; Transient Name Server) because most radio telescopes have very limited fields of view. For example, an individual Parkes beam has a width of about 10^{-5} sterad at this frequency; its 13 beams together cover about 10^{-5} of the sky. CHIME/FRB (Ng *et al.* 2017; CHIME/FRB Collaboration 2021a) has the comparatively large field of view of 200 square degrees and discovered 536 distinct FRB sources in about a year at a fluence threshold of about 5 Jy-ms at 600 MHz (CHIME/FRB Collaboration 2019b; Fonseca *et al.* 2020; CHIME/FRB Collaboration 2021b). STARE2, consisting of a network (providing interferometric localization information) of choke-ring (essentially dipole) feeds (Bochenek *et al.* 2020a), has a field of view of about 3.6 sterad, about 30% of the sky, at the price of the very high L-band detection threshold of ~ 300 kJy-ms.

It has long been realized (Katz 2014) that a "cosmological" FRB in our Galaxy would be bright enough to be observed by a single half-wave dipole antenna, and that a small network of such dipoles could localize it. STARE2 observed (Bochenek *et al.* 2020b) the first (at the time of writing, only) Galactic FRB 200428, even though it was less energetic than any observed extra-Galactic FRB. It was also, more fortuitously, observed by CHIME/FRB (CHIME/FRB Collaboration 2020a). More FRB with accurate positions, as well as observations with full-sky sensitivity, could identify future Galactic FRB.

A radio telescope whose beam is matched to the angular size of the Moon or the Sun (telescope diameter about 25 m in L-band) and staring at that object could detect reflected radiation from a FRB anywhere in the sky, with sensitivity about one order of magnitude less than that of a dipole or a single element of STARE2 (Katz 2020). Greater sensitivity could be provided by a larger telescope with a multi-beam feed covering the Moon or Sun. Comparing the phases of the signals from such telescopes with that from STARE2 or a similar instrument would provide two very long interferometric baselines, one equal to the projected Earth-Moon separation and one equal to the projected Earth-Sun separation, and therefore enable precise localization on the sky. At the lower frequencies at which the Solar reflectivity is high, the resolution-matched telescope would be much larger than 25 m and its sensitivity higher, but even a 25 m telescope would have useful sensitivity to events like FRB 200428.

This paper calculates the reflectivity of the Sun as a function of frequency and angle of incidence using a known model of the Solar atmosphere and corona. The reflectivity must be known to evaluate the feasiblity of observing FRB reflected by the Sun. The geometry is shown in Fig. 1.

2 REFLECTIVITY

Katz (2020) estimated that the radio-frequency reflectivity of the Sun is low at frequencies $\gtrapprox 200\,$MHz, but high at lower frequencies. FRB have not generally been observed at low frequencies, in part because dispersion delays and scattering broadening are much greater at low frequencies, the former scaling $t_{dispersion} \propto \nu^{-2}$ (and the derivative that measures the differential arrival time across a channel

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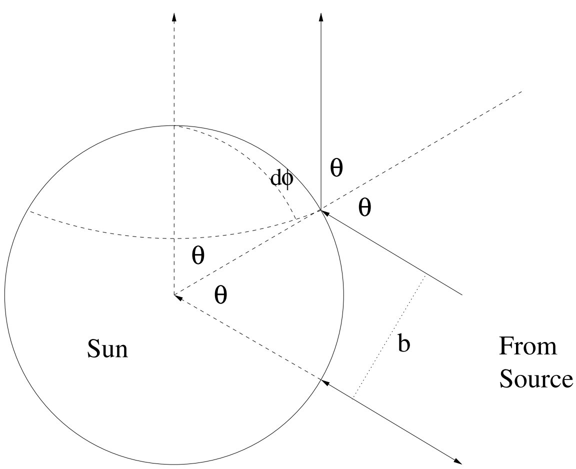

Figure 1. Scattering of FRB radiation by the Sun (after Fig. 1 of Katz (2020)). The angle of incidence is θ

$dt_{dispersion}/d\nu \propto \nu^{-3}$), and $dt_{scatter}/d\nu \gtrapprox \nu^{-4}$. However, FRB 20180916B was detected by LOFAR at frequencies as low as 120 MHz (Pastor-Marazuela *et al.* 2020), demonstrating that at least some FRB may be observed at these low frequencies at which the Solar reflectivity is expected to be high.

Radar measurements of the Solar reflectivity only measure it at normal incidence, but most FRB specularly reflected by the Sun to the Earth will have angles of incidence far from normal, so their rays do not penetrate the denser and more absorptive lower layers of the Solar atmosphere.

Radio telescopes operating at lower frequencies ($<$ 300 MHz), such as the Murchison Widefield Array (Tingay *et al.* 2013; Wayth *et al.* 2018), LOFAR (van Haarlem *et al.* 2013) and the planned SKA LFAA (de Lera Acedo *et al.* 2020), are generally phased arrays of dipoles. Focusing is electronic (beams are synthesized) so the telescope can effectively "stare" at the Sun without imposing a focussed heat load on the receiving elements. The older Giant Metrewave Radio Telescope (Ananthakrishnan 1995) uses parabolic dishes to focus radio waves, but its dishes are made of an open (7% filled) wire mesh that does not efficiently focus visible light because the wires are cylindrical and much thicker than the wavelength of visible light. If necessary, the receiver can be protected from focussed sunlight with a thin sheet of opaque (to visible and infrared light) plastic.

Synthesized beams have complex angular structure, rather than being simply matched to the angular size of the Sun, as would be possible for a parabolic dish at shorter wavelengths and proposed for parabolic reflectors staring at the Moon at higher frequencies. Despite this, they are sensitive to FRB scattered by the Sun; aside from radio frequency interference (generally narrowly confined in frequency), there is little radiation with the temporal characteristics of FRB in any direction, other than FRB themselves. At low frequencies the dispersion and scatter broadening characteristic of FRB are large, making them easy to discriminate against any other transients in a synthesized beam. Solar-scattered FRB would be distinguishable from unscattered FRB simultaneously observed in other lobes of the beam by different dispersion measures and by the possible earlier direct path observation of flux from the FRB by instruments like STARE2.

The reflectivity

$$\mathcal{R}(\nu,\theta) = \exp\left(-\tau(\nu,\theta)\right), \tag{1}$$

where ν is the wave frequency and θ is determined by the direction to the FRB. The absorption optical depth along the ray path

$$\tau(\nu,\theta) = \int \kappa(\nu, n_e(\vec{r}), T(\vec{r}))\, ds, \tag{2}$$

where $\kappa(\nu, n_e, T)$ is the opacity, the electron density $n_e = n_e(\vec{r})$ and the temperature $T(\vec{r})$ are found from a model (Avrett & Loeser 2008) of the Solar atmosphere.

The path $\vec{r}(s)$ of a ray of radiation is found, in the geometrical optics limit, from the eikonal equation (Brau 2004)

$$\frac{d}{ds}\left(n\frac{d\vec{r}}{ds}\right) = \nabla n, \tag{3}$$

where ds is an element of path length, the refractive index

$$n = \sqrt{1 - \frac{\omega_p^2}{\omega^2}}, \tag{4}$$

$\omega = 2\pi\nu$ and the plasma frequency

$$\omega_p = \sqrt{\frac{4\pi n_e e^2}{m_e}}. \tag{5}$$

For a specified $n_e(\vec{r})$, we integrate Eq. 3 numerically to find the path. This integration requires knowing the relation $b = b(\theta)$, where b is the impact parameter. In general this relation is non-trivial, but in a "flat Sun" approximation $b = R\sin\theta$, where R is the Solar radius and $\vec{r}$ is replaced by an altitude z. This approximation is justified because in the chromosphere and transition (to the corona) zone where the ray is bent and absorption is significant the scale height of the Solar atmosphere is small compared to its radius R.

The opacity (Spitzer 1962), including the effect of stimulated emission,

$$\begin{aligned}\kappa(\nu, n_e, T) =& \frac{4}{3}\sqrt{\frac{2\pi}{3k_BT}}\frac{n_e\sum_Z n_Z Z^2 e^6}{hcm_e^{3/2}\nu^3} \\ & \left\{1 - \exp\left[-\left(\frac{h\nu}{k_BT}\right)\right]\right\} g_{ff} \\ \approx & \frac{4}{3}\sqrt{\frac{2\pi}{3}}\frac{n_e\sum_Z n_Z Z^2 e^6}{(k_BTm_e)^{3/2}c\nu^2} g_{ff},\end{aligned} \tag{6}$$

where n_Z is the density of ions with charge Z (allowing for multiply ionized atoms in the hotter regions), k_B is the Boltzmann constant and g_{ff} is the Gaunt factor. The Gaunt factor depends only logarithmically on the parameters, except where $\omega \to \omega_p$ and the group velocity is significantly less than c (Spitzer 1962), and is typically about 15. Rays whose angles of incidence are not small do not closely approach $\omega = \omega_p$. Eqs. 1, 2 are then used to find the reflectivity. The results for several angles of incidence are shown as functions of the frequency in Fig. 2.

3 DISCUSSION

Fig. 2 shows that for frequencies $\nu \gtrapprox 150\,\mathrm{MHz}$ the reflectivity the reflectivity is substantial only for angles of incidence $\theta \gtrapprox$

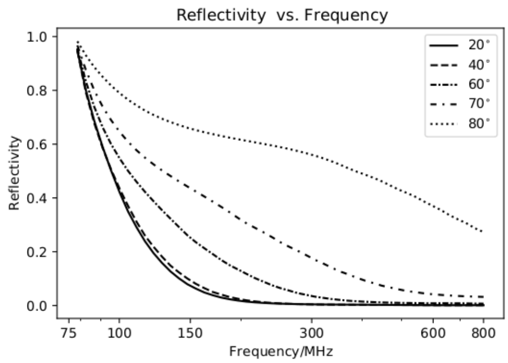

Figure 2. Solar reflectivity *vs.* frequency at several angles of incidence θ.

60°. The fraction of the sky with angles of incidence $\geq \theta$ is $(1+\cos 2\theta)/2$, which is 0.25 for $\theta = 60^\circ$ but only 0.12 for $\theta = 70^\circ$. Unlike the Moon, the Sun is a far-from-isotropic reflector at those frequencies and effectively reflects only a fraction of isotropically distributed sources, such as FRB.

However, at lower frequencies $\nu \lessapprox 100\,$MHz, the Sun is a good reflector, better than the Moon (Katz 2020), at all angles of incidence. In addition, detection of the delay of Solar-scattered FRB provides much sharper localization than does detector of Lunar-scattered FRB, although the combination of these localizes in two angles rather than only one. A system to detect and localize very bright Galactic FRB would use two telescopes, one staring at the Moon and one staring at the Sun, in addition to direct detection by an instrument like STARE2.

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