Millisecond-duration bright radio pulses at 1.4 GHz with high dispersion measures (DMs) were reported by Lorimer et al., Keane et al., and Thornton et al. Their all-sky rate is $\approx 10^4$ day$^{-1}$ above $\sim 1$ Jy. Related events are “Perytons”—similar pulsed, dispersed sources, but most certainly local. Suggested models of fast radio bursts (FRBs) can originate in Earth’s atmosphere, in stellar coronae, in other galaxies, and even at cosmological distances. Using physically motivated assumptions combined with observed properties, we explore these models. In our analysis, we focus on the Lorimer event: a 30 Jy, 5 ms duration burst with DM $= 375$ cm$^{-3}$ pc, exhibiting a steep frequency-dependent pulse width (the Sparker). To be complete, we drop the assumption that high DMs are produced by plasma propagation and assume that the source produces pulses with frequency-dependent arrival time (“chirped signals”). Within this framework, we explore a scenario in which Perytons, the Sparker, and the FRBs are all atmospheric phenomena occurring at different heights. This model is ad hoc in that we cannot explain why Perytons at higher altitudes show greater DMs or exhibit narrower pulses. Nonetheless, we argue that the Sparker may be a Peryton. We end with two remarks. First, the detection of a single FRB by an interferometer with a kilometer (or longer) baseline will prove that FRBs are of extraterrestrial origin. Second, we urge astronomers to pursue observations and understanding of Perytons since they form (at least) a formidable foreground for the FRBs.

Key words: galaxies: individual (SMC) – ISM: general – pulsars: general – radio continuum: general

Online-only material: color figures

1. INTRODUCTION

The subject of radio transients seems to have finally come of age. The Galactic list starts with GCRT J1745−3009, an erratic source in the meter-wave band (Hyman et al. 2005), and is followed by neutron stars that produce strong pulses occasionally, the so-called rotating radio transients (RRATs; McLaughlin et al. 2006). Radio afterglows appear to routinely follow giant flares from soft gamma repeaters (SGRs; Frail et al. 1999). Recently, an entirely new type of radio source (Zauderer et al. 2011) was unexpectedly discovered first in the hard X-ray band, Swift J164449.3+573451 (Burrows et al. 2011). To within the exquisite astrometric precision afforded by radio very long baseline interferometry, the radio counterpart coincides with the nucleus of a small star-forming galaxy at $z = 0.35$ (Levan et al. 2011). The Lorentz factor of this relativistic explosion, $\sim 10$, is smaller by an order of magnitude than those inferred in gamma-ray bursts. A plausible model for the source is blazar activity initiated by feeding a tidally disrupted star to a nuclear black hole (Bloom et al. 2011). A recent summary of the rates of extragalactic radio transients can be found in Frail et al. (2012).

Lorimer et al. (2007) reported the discovery of an intense (30 Jy) and short-duration (5 ms) burst in the decimeter band (1.4 GHz). This transient was found as a result of the archival analysis of the Parkes multibeam pulsar data obtained toward the Magellanic Clouds. The dispersion measure (DM) of this burst, 375 cm$^{-3}$ pc, considerably exceeded the sum of the estimated DM contributed by the interstellar medium (ISM) of our own Galaxy and that contributed by the Magellanic Clouds. Follow-up observations did not show any repeating burst.

Lorimer and colleagues proposed that most of the DM arose from electrons in the intergalactic medium (IGM). Using currently accepted values for the density of the IGM, they estimated the redshift to this event—which, hereafter, we call the Sparker—to be about 0.12 ($\sim 500$ Mpc).

The Sparker would be the first impulsive radio transient event seen from outside the Local Group. If so, this discovery assumes a seminal stature. Specifically, the sharp pulse will enable astronomers to probe the column density, magnetic field, and turbulence of the IGM (Macquart & Koay 2013; Cordes 2013). The discovery appeared timely given that several countries have undertaken massive investments in radio astronomy in the meter and decimetric bands—the Low Frequency Array (LOFAR; Falcke et al. 2007), the Murchison Wide Field Array (MWA; Bhat et al. 2007), and the Australian Square-Kilometre-Array Pathfinder (ASKAP; Johnston et al. 2008). In short, in the parlance so popular with funding agencies, the discovery motivated further archival searches. Additional transients were found with some features similar to those of the Sparker (Burke-Spolaor et al. 2011). Some of these bursts exhibited a trajectory in a plane of arrival time ($t$) and frequency ($\nu$) as follows: $t(\nu) \propto \nu^{−n}$, but with $n \approx 2$. We remind the reader that for a pulse traveling through cold plasma, $n$ is exactly 2 (Rybicki & Lightman 1979). Furthermore, some of the bursts showed “lumpy” emission (that is, the broadband spectrum could not be described by a simple power law). Most troubling was that these events were detected in many beams. These sources were dubbed “Perytons” by the discoverers. Burke-Spolaor and colleagues argue that Perytons are atmospheric phenomena and explain the detection in all (most) beams to pickup by distant sidelobes. Kocz et al. (2012) found additional Perytons in a second reanalysis and noted...
that a cluster of Perytons was separated by about 22 s and suggested that Perytons are artificial signals. Regardless, it is now accepted that Perytons are terrestrial in origin. The DM of the Sparker was noted to be similar to that inferred for Perytons and as a result, some doubt was cast on the extragalactic nature of the Sparker.

Another archival search of the Parkes Galactic Plane Survey data found a transient event in a single beam and with a DM of 746 cm\(^{-3}\) pc (Keane et al. 2012). Earlier this year, Thornton et al. (2013) reported the finding of four short-duration bursts. One of these events showed a frequency-dependent arrival time with \(n = 2\) to within the precision offered by the measurements. These bursts with peak fluxes of about 1 Jy also showed DMs (ranging from 553 cm\(^{-3}\) pc to 1104 cm\(^{-3}\) pc) in considerable excess of that expected from the Galactic ISM. Unlike the Perytons, these four events were found in only one beam. This archival analysis drew data from the “High Time Resolution Universe” (HTRU) survey, which in turn used a digital filter bank (Keith et al. 2010), whereas the older Parkes data were obtained with an analog filter bank. Thornton and colleagues, like Lorimer et al. (2007) before, argue that the excess dispersion arose primarily in the IGM and infer redshifts ranging from \(z = 0.45\) to 0.96. These authors quote an all-sky rate of \(\dot{N} \approx 10^4\) events day\(^{-1}\). This is a remarkably high rate for an extragalactic population (assuming no repetitions).

Curiously, the brightest burst in Thornton et al. (2013) exhibits an asymmetric pulse shape, with a rise time smaller than the decay time. Furthermore, for this event and the Sparker, the observed pulse width is frequency dependent with the pulse width, \(\Delta \tau \propto v^{-m}\) and \(m \approx 4\). Such a characteristic pulse frequency-dependent broadening is also seen in pulsars with large DMs and attributed to multipath scattering as the radio pulse traverses through inhomogeneous structures in the ISM. In contrast, the Perytons show symmetrical pulse profiles.

To summarize, analysis of the Parkes multibeam data with two different pulsar backends (one analog and the other digital) taken during the course of pulsar searches in the 1.4 GHz band at the Parkes Observatory has shown three types of impulsive radio bursts: Perytons (Burke-Spolaor et al. 2011), the Sparker (Lorimer et al. 2007), and fast radio bursts (FRBs; Keane et al. 2012; Thornton et al. 2013). There is agreement that Perytons are of terrestrial origin. In contrast, the Sparker and FRBs have been argued to arise from extragalactic sources.

2. THE RATIONALE AND LAYOUT OF THE PAPER

The inference that the Sparker and FRBs are of extragalactic origin is not unreasonable. However, great claims need great proofs. It is important to explore whether there are plausible explanations of the excess electron column density arising either in our own Galaxy or in its extended environs. It is this exploration of alternative frameworks that is the primary purpose of this paper.

We focus on three observational clues for FRBs.

1. The arrival times of the pulses vary as \(v^{-2}\), where \(v\) is the sky frequency of the pulse.
2. For two events the width of the pulse scales as \(v^{-4}\).
3. The all-sky rate of the FRBs is \(\dot{N} \approx 10^4\) events day\(^{-1}\).

Other clues include the DM, the peak flux, the pulse duration, and limits on the repetition rate. We have a preliminary measure of how the source count scales with flux from Thornton et al. (2013). However, we have little information about their angular distribution (isotropic versus Galactic).

The first version of this paper was completed and submitted (to the Astrophysical Journal) a few months after the Lorimer et al. (2007) paper was published. The primary result of that manuscript was that, if the frequency-dependent arrival time was due to propagation, then the Sparker had to be located beyond the Local Group. However, after inspection of the raw data of the Sparker (kindly provided by D. Lorimer), we developed some doubts about the celestial nature of the event, and so we withdrew the manuscript. Subsequently, the emergence of Perytons further questioned the celestial origin of the Sparker. The publication by Thornton et al. (2013) showed that the Sparker was not unique. Furthermore, the rash of papers attempting to explain the origin of FRBs shows the general interest in exploring the extragalactic nature of FRBs. Our interest was revived—whence this paper.

The paper is quite long, and so a summary of the goals is likely to help prepare the reader as she/he gets ready to read the rest of the paper. The goals of this paper are threefold.

1. Accepting that the \(v^{-2}\) arrival time pulse sweep arises from propagation in cold plasma, we attempt to constrain the size (\(L\)) and distance (\(d\)) to the nebula that contains this cold plasma. Clearly, \(d\) is smaller than the distance to the source, \(D\).
2. The events, by virtue of being impulsive, must arise in compact regions. We investigate whether the proposed models would allow for decimetric radio pulses to propagate freely from the explosion site.
3. Given the difficulty of an extragalactic origin for the Sparker and FRBs, we consider the possibility that the trajectory of the pulse in the arrival-time–frequency plane is a property of the source itself\(^6\) and that Perytons, the Sparker, and FRBs are all local sources. We confront this “unified” model with the observations.

The outline is as follows. The Sparker, by its sheer brilliance, by having the lowest DM of the proposed FRB family, and by having a DM similar to Perytons, still claims an important position in this discussion. As such, we review this event in considerable detail. In Section 3, we summarize the basic observations of the Sparker. In Section 4, we posit an intervening nebula that can account for the excess DM inferred for the Sparker. Using H\(\alpha\) surveys, Galaxy Evolution Explorer (GALEX) ultraviolet (UV) data, and the fact that the decimetric signal from the Sparker cannot be heavily absorbed by the ionized nebula, we exclude portions of the \(L-d\) phase space. We conclude that the Sparker cannot be located in our Galaxy, in the Small Magellanic Cloud (SMC), or even in the Local Group. We investigate potential caveats to this important conclusion: a porous nebula (Section 5), a nebula ionized by shocks instead of UV photons (Section 6), and the possibility that the hot corona of a star can provide the excess DM (Section 7).

In Section 8, we conclude that the simplest explanation is that the Sparker, and by implication the FRBs, is located well outside the Local Group. In Sections 9 and 10, we review the proposed models for FRBs. We check whether the models allow for successful propagation of decimetric radiation from the site of the explosion, and separately we check whether the large daily rate of FRBs can be accommodated by the proposed models. We find that several proposed models fail on the first test.

\(^6\) A “chirped signal” in the parlance of electrical engineering.
and all but one physically motivated model is severely challenged by the large daily rate of FRBs. We find that a model in which the radio pulses arise from giant flares from young extragalactic magnetars is attractive on both counts (Section 10). In Section 11, we investigate the frequency-dependent broadening seen in one FRB and the Sparker and conclude that this broadening (if due to propagation) is best explained as due to multipath propagation in dense ISM in the vicinity of the progenitor star.

In Section 12, we abandon the assumption that the $v^{-2}$ arrival time pulse sweep is due to propagation, but instead attribute the frequency sweep as a property of the source itself. We investigate plausible man-made, solar, and stellar sources. The Perytons are undeniably local phenomena and yet share many features with the Sparker and the FRBs. In Section 13, we present a plausible model unifying these three phenomena with the Perytons taking place close to the Parkes telescope, the FRBs the farthest away, and the Sparker in between. We readily admit that our model for “unifying” the Perytons, the Sparker, and the FRBs is not based on a physically motivated model.

We summarize in Section 14. In short, there is little doubt that Perytons are terrestrial signals. We are struck by and troubled by the DM of the Sparker being the same as the mode of the DMs of the Perytons. It is not unreasonable to conclude that the Sparker is a Peryton that occurred in the first (or so) Fresnel zone for the Parkes telescope. It is not a great leap to conclude that FRBs are simply distant versions of the Sparker. Of the extragalactic models, we favor the model in which FRBs result from giant flares from young magnetars. The model can explain the high daily rate of FRBs.

We end this section by noting that unlike in 2007, we now have the Sparker and at least four FRBs. Given this situation, a reader, at first blush, may wonder why it is important to discuss one specific case (the Sparker) in some detail. In our opinion, when one is confronted by a new and astonishing phenomenon, it is almost always useful to approach the observations with elementary but robust analyses. In some cases it may well be that a simpler explanation would suffice (e.g., the event of Keane et al. 2012 and other claimed FRBs at low Galactic latitudes are arguably RRATs hiding behind H II regions). Second, while we are not able to make concrete progress (establish or reject an extragalactic hypothesis), we are open to the idea that astronomers at Parkes have indeed uncovered a most fantastic phenomenon—brilliant sparks at extragalactic distances. Consistent with our (currently) agnostic view, we detail in Zheng et al. (2014) the potential use of FRBs to probe intergalactic matter.

3. THE SPARK

The event reported by Lorimer et al. (2007) was found in a reanalysis of data obtained with the 13 beam system mounted at the Cassegrain focus of the Parkes 64 m radio telescope. The data from which this pulse was discovered were originally obtained to look for pulsars in the SMC. For each of the two linear polarizations, the signal from each of the 13 beams (sky frequency 1.28–1.52 GHz; Staveley-Smith et al. 1996) was fed into a filter bank with 96 channels, each 3 MHz wide, and followed by square-law detection. The detected signal from the two polarization signals was summed, filtered, and digitally sampled at the rate of 1 kHz (Manchester et al. 2001). The authors searched the data stream for single pulses in the range from 1 ms to 1 s and DMs between 0 and 500 cm$^{-3}$ pc.

A single intense burst of short duration (<5 ms; epoch, UTC 2001 August 24, 19:50:01) with best-fit DM of 375 ± 1 cm$^{-3}$ pc was identified. The burst was so intense that it saturated one of the beams (signal-to-noise ratio [S/N] reported as ≳23 (Lorimer et al. 2007); for simplicity we adopt S/N > 100) and was readily detected in two adjacent beams (see Appendix A for further analysis). The peak flux was estimated to be $S ≳ 30 ± 10$ Jy. The high precision with which the DM was inferred means that the data are consistent with a cold plasma dispersion model to equally good precision.

Our attempts to better localize the position of the Sparker by accounting for the measured signal levels in different beams with the (far-field) Parkes multibeam response function (updated by L. Staveley-Smith following Staveley-Smith et al. 1996) did not converge to a well-defined region. In order to make progress, we adopt a localization that makes use of approximate circular symmetry of the beams. This localization region is a polygon (aka “kite”) and is displayed graphically in Figure 1 and numerically in Table 5 (Appendix A). When a single position is needed (e.g., to compute foreground extinction), we use the position of the beam in which the signal was saturated: R.A. = 01h18m06s, decl. = −75°12′19″ (J2000).

3.1. Energetics

We adopt the following values for the Sparker at the fiducial frequency, $v_0 = 1.4$ GHz: peak flux density $S_0 = 30$ Jy, measured pulse width of $\Delta t_0 = 5$ ms, and intrinsic pulse width $\Delta t = 1$ ms. The broadband spectrum of the Sparker appears not to be well determined (D. Lorimer 2007, private communication, and our own analysis). The usable data for the Sparker are from the unsaturated beams, and since the response is a function of frequency, one can expect the data to suffer from chromatic effects.

In contrast to the Sparker, the four events reported by Thornton et al. (2013) are found only in one beam. Thus, the broadband spectrum of these events can be expected to be less prone to chromatic problems discussed above. The four events show reasonably good S/N across the entire 1.28–1.52 GHz range. This rough uniformity suggests that a power-law spectrum is adequate to describe the broadband spectrum and the power-law index, $\alpha$, is not too far from zero. We assume a power-law model for the fluence spectrum, $F(\nu) \propto \nu^\alpha$. When a specific value is called for, we use $\alpha = -1$.

The broadband fluence of the Sparker is

$$F \approx - \frac{S_0 \tau_0 v_0}{\alpha + 1} \left( \frac{v_0}{v_f} \right)^{\alpha+1}, \quad \text{for } \alpha < -1, \quad (1)$$

$$= S_0 \tau_0 N \tau_0 \ln \left( \frac{v_u}{v_f} \right) \quad \text{for } \alpha = -1; \quad (2)$$

where $\tau_0$ is the optical depth at $v_0$, $v_u$ and $v_f$ are the upper and lower cutoff frequencies of the broadband spectrum, and we assume that $v_0 \ll v_u$. A conservative estimate of the bolometric fluence is obtained with $\alpha = -1$ and setting the log factor to 10. With these two assumptions we find $F \approx 2.1 \times 10^{-14}$ erg cm$^{-2}$.
Thus, the isotropic radiated energy in the radio band alone is
\[ E_R \approx 2.5 \times 10^{30} D_{\text{kpc}}^2 \text{erg}, \]  
where \( D_{\text{kpc}} \) is the distance to the source.8

3.2. Constraints from Brightness Temperature

The brightness temperature can be computed from the Rayleigh–Jeans formula, 
\[ S_0 = 2kT_B\frac{\nu_0^2}{c^2} \pi (R/D)^2, \]
where \( R \) is the radius of the source. Provided that there are no relativistic flows, \( R < c\Delta t \), and the minimum brightness temperature is
\[ T_B(\nu_0) \lesssim 1.6 \times 10^{24} D_{\text{kpc}}^{-2} \Delta t_{\text{ms}}^{-2} \text{K}. \]
The emission mechanism is either incoherent or coherent. We will consider the first option. It is well known that brightness temperatures in excess of \( 10^{12} \text{K} \) lead to severe Compton losses (Kellermann & Pauliny-Toth 1969). If, however, there is a relativistic outflow (with a bulk Lorentz factor, \( \Gamma \)), then the observed duration is compressed by the forward motion (toward us) and also the flux is enhanced (for the same reason). As a result, the inferred brightness temperature (Equation (4)) is \( \approx \Gamma^3 \) larger than that in the rest frame of emission (Padmanabhan 2002, p. 490). Limiting the brightness temperature in the source frame to \( 10^{12} \text{K} \) then leads us to
\[ D_{\text{kpc}}^2 \lesssim \frac{\Gamma^3}{10^{12}}. \]

Gamma-ray bursts (GRBs), cosmic explosions with the most relativistic bulk outflows, have inferred values of \( \Gamma \) as high as \( 10^3 \). In this scenario, \( D \lesssim 100 \text{pc} \). Thus, the observed excess DM must clearly arise from the source (or its circumstellar medium). We investigate this possibility in Section 7. Conversely, should we find incontrovertible evidence that the Sparker is located

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8 We use the convention that a particular quantity is normalized with the appropriate physical unit displayed as a subscript in roman font. Thus, \( D_{\text{kpc}} \) is the distance to the source in units of kiloparsecs.
at great distances (say, even 1 kpc), then the emission process must be coherent. In principle, coherent processes can produce (almost) arbitrarily high brightness temperature radiation—provided that the emitting region consists of highly relativistic matter.

4. THE DISTANCE TO AND THE SIZE OF THE DM NEBULA

The excess DM inferred toward the Sparker requires that there be an intervening ionized nebula. Our goal in this section is to derive some constraints on the size (or diameter), \( L \), and the distance, \( d \), to the nebula. We will assume the following values for Galactic ionized gas: DM and emission measure (EM; see below) toward the Galactic pole of 25 cm\(^{-3}\) pc and 2 cm\(^{-6}\) pc, respectively (Cox 2000; Section 21.1).

For simplicity, we assume that the nebula is a sphere of hydrogen with uniform electron density, \( n_e \). Such a nebula will manifest itself via H\(\alpha\) recombination radiation and free–free absorption. Separately, provided that the nebula is photoionized, the UV continuum from the ionizing source may be detectable. Absorption. Separately, provided that the nebula is photoionized, the UV continuum from the ionizing source may be detectable. We will accept the IGM solution only if our exploration rules out Galactic or near-Galactic possibilities.

The primary parameter that determines the strength of the H\(\alpha\) emission and free–free absorption is the EM. The DM of the intervening nebula is \( \text{DM} = L_{pc} n_e \text{ cm}^{-3}\text{ pc} \), and the corresponding EM (in the usual units) is

\[
\text{EM} = \text{DM}^2 L_{pc}^{-1} \text{ cm}^{-6}\text{ pc},
\]

where \( L_{pc} = L/(1\text{ pc}) \).

4.1. Free–Free Absorption

The free–free optical depth is given by

\[
\tau_{ff}(v) = 4.4 \times 10^{-7} \text{EM} \left( \frac{T_e}{8000\text{ K}} \right)^{-1.35} \left( \frac{v}{1\text{ GHz}} \right)^{-2.1},
\]

where \( T_e \) is the electron temperature and \( v \) is the frequency in GHz (Lang 1974, p. 47). The temperature normalization is appropriate for a photoionized nebula. Combining Equations (6) and (7), we find

\[
\tau_{ff}(v) = 2.7 \left( \frac{v}{v_0} \right)^{-2.1} \left( \frac{T_e}{8000\text{ K}} \right)^{-1.35} \left( \frac{L}{0.01\text{ pc}} \right)^{-1},
\]

where we have set DM = 350 cm\(^{-3}\) pc (accounting for a Galactic contribution of 25 cm\(^{-3}\) pc). From this equation, we immediately see that invoking very compact nebulae, \( L < 0.01 \text{ pc} \), is problematic owing to producing high optical depths. The observed fluence spectrum, \( \mathcal{F}(v) \), is related to the true fluence spectrum, \( \mathcal{F}(v) \), as follows:

\[
\mathcal{F}(v) \propto \mathcal{F}(v) \exp \left[ -\tau_{ff} \left( \frac{v}{v_0} \right)^{-2.1} \right],
\]

As discussed earlier (Section 3.1), the fluence spectrum is not well measured. In the vicinity of frequency \( v \), we can make an expansion

\[
\alpha' = \frac{d \ln \mathcal{F}(v)}{d \ln v} \bigg|_v = \beta + 2.1 \tau_0 \left( \frac{v}{v_0} \right)^{-2.1},
\]

where the intrinsic spectrum in the vicinity of \( v_0 \) is assumed to be a power law, \( \mathcal{F}(v) \propto v^\beta \) with \( \beta = -1 \). Thus, even a modest amount of optical depth (\( 2 < \tau_0 < 4 \)) can result in an extraordinarily steep spectrum (\( \alpha' = 3.2–7.4(v/v_0)^{-2.1} \)) for the underlying spectrum. There are two consequences.

First, an intrinsic spectrum as steep as the values discussed above would be remarkable. Millisecond pulsars possess a reputation for having the “steepest” spectra. Examples include PSR 1937+21 (\( \alpha = -2.7 \); Backer et al. 1982; Erickson 1983) and PSR 1957+20 (\( \alpha = -3 \); Fruchter et al. 1990). A perusal of the literature shows two sources that are even steeper: the Sun (Giménez de Castro et al. 2006) and GCRT J1745–3009 (Hyman et al. 2007).

For the latter source, a weak burst was found to have a spectral index of \( \alpha = -13.5 \pm 3 \). This was measured over a limited frequency range from 310 to 338 MHz. The Sun is much better studied. For some spiky bursts from the Sun, the spectrum is exponential, consistent with the spectrum emitted by a monoenergetic electron gyrating in a uniform field (see Appendix B). An exponential spectrum can give an arbitrarily high power-law index for frequency (see Appendix B).

A steep intrinsic spectral index would thus favor (based on the fact that all the steepest sources are fit with exponentials) an exponential distribution for \( \mathcal{F}(v) \propto \exp(-v/v_c) \), where \( v_c \) is the characteristic frequency. In this case, Equation (10) becomes

\[
\alpha' = -\frac{v}{v_c} + 2.1 \tau_0 \left( \frac{v}{v_0} \right)^{-2.1}.
\]

It is clear from this equation that a large value of \( \tau_0 \gg 1 \) would result in \( \alpha' \) varying rapidly even over the 1.2–1.5 GHz band of the Parkes pulsar spectrometer. We see no evidence for such strong spectral curvature for either the Sparker or the FRBs.\(^9\)

Next, the bolometric fluence in the exponential model is

\[
\mathcal{F} = S_0 \tau_0 v_c \exp\left(\frac{v}{v_c} + \tau_0\right).
\]

Let us consider the implication of invoking significant free–free absorption. For instance, setting \( \tau_0 = 5 \) in Equation (11), we find \( v_c \approx v_0/12 \). Propagating this choice of \( v_c \) to Equation (12) results in an isotropic emission of nearly \( 5 \times 10^{35} D_{\text{pc}}^2 \) erg. Even at 100 pc the inferred energy loss in the radio band would severely challenge what is observed from the most active stars, whose radio emission is typically measured in hundreds of millijanskys (Güdel 2002).

Continuing with this theme and setting \( \tau_0 < 5 \), we find, from Equation (8),

\[
L > L_{\text{eff}} = 5.6 \times 10^{-3}\text{ pc}.
\]

Note that this severe constraint on \( L \) has no dependence on \( d \). It also has no dependence on the angular size of the nebula since by assumption the angular size of the Sparker is assumed to be smaller than that of the putative nebula. The nebula size, \( L_{\text{eff}} \) (Equation (13)), corresponds to \( 2 \times 10^3 R_\odot \).

\(^9\) Parenthetically we note that should a pulse be found with positive and large observed spectral index (that is, \( \alpha \gg 1 \), but not so high that the pulse is entirely absorbed), then a plausible explanation is that \( \tau_0 \gtrsim 1 \).
Figure 2. Tangential projection of the known pulsars (marked by squares; the number next to each square is the DM of the pulsar) in the vicinity of the SMC with north up and east to the left. The Sparker is marked by a circle. The background is the diffuse H\textalpha\ emission obtained from the Southern H\textalpha\ Sky Survey (Gaustad et al. 2001). The grid marks the right ascension (R.A.) and the declination (decl.), both in units of degrees. The South Celestial Pole is toward the bottom of the figure. The pulsar-rich globular cluster, 47 Tucanae, is located at R.A. $\approx 6^\circ$ and decl. $\approx -72^\circ$ (square box; the mean DM of the pulsars in this cluster is 24 cm$^{-3}$ pc$^{-1}$). The LMC (not marked) is located to the north and east of the SMC and lies outside this map.

(A color version of this figure is available in the online journal.)

From Equation (13), we conclude that Sparker cannot arise from a terrestrial phenomenon. The reader may find it instructive to read Appendix C to appreciate typical DM and EM in any reasonable stellar context (including compact binaries with a main-sequence companion and so on). Luan & Goldreich (2014) arrived at the same conclusion independently. The only way to avoid a stellar model for FRBs is to invoke high temperatures—a possibility that we treat in depth in Section 7.

4.2. Dispersion Measure: Galactic Contribution

In Figure 2, we present a wide-field overview of the region of the Sparker. The Sparker is about three degrees south of the center of the SMC (see Figure 2). The projected transverse distance is 3.1 kpc, assuming a distance of 60 kpc to the SMC (Storm et al. 2004). In Figure 3, we present a zoom-in of the field centered around the SMC. As noted by Lorimer et al. (2007), the Sparker lies outside the bright H\textalpha\ and the bright H\textalpha\ boundaries of the SMC.

In the region of the sky containing the Sparker and the SMC there are six pulsars\footnote{http://www.atnf.csiro.au/research/pulsar/psrcat} (Manchester et al. 2005) and one magnetar (McGarry et al. 2005). One pulsar (PSR J0057$-$7201) has a DM of 27 cm$^{-3}$ pc (Crawford et al. 2001)—consistent with being a Galactic pulsar located above the warm ionized medium (WIM) layer. The DMs of the remaining five pulsars range from 70 to 205 cm$^{-3}$ pc (McConnell et al. 1991; Crawford et al. 2001; Manchester et al. 2006). These five pulsars are generally thought to be associated with the SMC. As a matter of reference, the pulsars in the Large Magellanic Cloud (LMC) have an excess (over the Galactic value) of about 100 cm$^{-3}$ pc. Five degrees away and located at a distance of 4 kpc (in the inner halo of our Galaxy), the globular cluster 47 Tucanae hosts a hive of pulsars with typical DMs of about 24 cm$^{-3}$ pc.

Thus, the first conclusion is that the Galactic contribution to the observed DM of the Sparker (assuming, say, a halo location) is no more than 25 cm$^{-3}$ pc. As can be gathered from discussion at the beginning of this section, the Galactic contribution to the EM is negligible.

Next, the angular size of the DM-inducing nebula for the Sparker cannot be larger than, say, $\theta_{DM} \sim 5^\circ$. Otherwise, we would expect a larger DM for the pulsars in the neighborhood. This conclusion is true whether the Sparker is located in the halo or the SMC. Thus, we obtain our first constraint:

$$L < d\theta_{DM},$$

provided that $D < 60$ kpc (the distance to the SMC).
4.3. Dispersion Measure: SMC Contribution

With respect to Figure 3 and noting the DMs of PSR J0045–7042 (70 cm$^{-3}$ pc) and PSR J0111–7131 (76 cm$^{-3}$ pc), we suggest that the SMC has an extended (diameter of 4 deg) ionized halo that contributes about 50 cm$^{-3}$ pc (which, when added to the Galactic DM, yields a total of 75 cm$^{-3}$ pc). Assuming a spherical geometry and a diameter of 4 kpc, this extended diffuse halo of the SMC has a mean electron density of 0.0125 cm$^{-3}$, and the corresponding EM contribution is 0.63 cm$^{-6}$ pc. Incidentally, we note that the H$_{\alpha}$ column density toward PSR J0045–7042 (DM = 70 cm$^{-3}$ pc) is 2.1 × 10$^{20}$ cm$^{-2}$ (Figure 4) and is comparable to the column density arising from the ionized SMC halo.

We conclude that the Galactic+SMC DM contribution is about 75 cm$^{-3}$ pc. Thus, were the Sparker to be located in or behind the SMC, the excess DM would be 300 cm$^{-3}$ pc and correspondingly the EM would be

\[ \text{EM}^S = 9 \times 10^4 L_{\text{pc}}^{-1} \text{cm}^{-6} \text{pc}. \] (15)

The superscript “$S$” (“$G$”) is used to indicate the expected EM assuming an origin for the Sparker at the distance of the SMC or beyond (or in the Galaxy). For the Galactic case, the excess DM corresponds to 350–375 cm$^{-3}$ pc.

4.4. Recombination Radiation: H$\alpha$

An ionized nebula emits recombination radiation (e.g., the Balmer series). The H$\alpha$ brightness is determined by the recombination rate and the fraction of recombinations that result in H$\alpha$ emission (see Reynolds 1984). For $T \sim 8000$ K and assuming case B, we find $I = 1.09 \times 10^{-7} \times \text{EM} \text{erg cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$, whence the usual statement that 1 Rayleigh of photon intensity corresponds to an EM of 2.2 cm$^{-6}$ pc.

The Southern H$\alpha$ Sky Survey (SHASSA; see Figure 3) imaged the entire southern sky in a narrow band ($\Delta \lambda_{\text{SHASSA}} = 16$ Å; this corresponds to a velocity width of ±365 km s$^{-1}$) centered on the rest wavelength of H$\alpha$ (6563 Å) and at an angular resolution of 0:8 (Gaustad et al. 2001). The rms per pixel is about 2 Rayleigh. When dealing with surface brightness, it helps to divide the discussion into two parts: objects with a size bigger (“resolved”) or smaller (“compact”) than the angular size of the beam(s) of the survey(s).

We first consider the resolved case. We determined that the SHASSA 5$\sigma$ detection limit for a 1 deg diameter nebula is about 0.5 Rayleigh. The upper limit at a scale of 1$''$ is naturally larger

\[ \text{See Equation (9) of Valls-Gabaud (1998).} \]

\[ \text{We adopt the following recombination coefficient: } \alpha_B = 8.7 \times 10^{-14} T_4^{-0.89} \text{cm}^3 \text{s}^{-1}, \text{ where } T_4 \text{ is the temperature in units of } 10^4 \text{K} \text{ (Osterbrock & Ferland 2006).} \]

\[ \text{A unit of surface brightness commonly used in aeronomy. One Rayleigh is } 10^9/(4\pi) \text{ photons per square centimeter per steradian per second. For the H$\alpha$ line, the intensity in cgs units is } 2.41 \times 10^{-7} \text{ erg cm}^{-2} \text{s}^{-1} \text{ sr}^{-1}. \]
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Figure 4. Neutral hydrogen (H\textsubscript{i}) column density integrated over the heliocentric velocity range 88.5–215.5 km s\textsuperscript{−1} in the direction toward the Sparker. The data were obtained with the ATCA (beam FWHM of 98′′) supplemented by the Parkes 64 m single-dish images. The polygon at the bottom of the image represents the Sparker localization (Appendix A), while the circle shows the position and FWHM size of the beam in which the Sparker saturated the detector (Table 3). The grayscale intensity range is $-3 \times 10^{19}$ to $8.4 \times 10^{21}$ atom cm\textsuperscript{−2}. Boxes (white and black) show the positions of known SMC and Galactic pulsars, while the number accompanying each box shows the pulsar measured DM. At the position of the Sparker, the H\textsubscript{i} column density is $3.5 \times 10^{20}$ cm\textsuperscript{−2}. From Stanimirovic et al. (1999).

and was found to be 6 Rayleigh. We thus find

$$\frac{\text{EM}}{2.2 \text{ cm}^{-6} \text{ pc}} = 0.45 \text{ DM}^2 L_{\text{pc}}^{-1} \lesssim R_{\text{SHASSA}},$$

where $R_{\text{SHASSA}}$ is the surface brightness (on the relevant angular scale). Using Equation (15), we obtain our second constraint:

$$L \gtrsim 82 \text{ kpc} \quad \text{for } \theta \sim 1^\circ,$$

$$L \gtrsim 6.8 \text{ kpc} \quad \text{for } \theta \sim 1'. \quad (17)$$

Here $\theta = L/d$ is the angular diameter of the nebula. Note that the size constraint is independent of $d$, provided that the nebula has an angular size $\gtrsim 1^\circ$ or $\gtrsim 1'$, respectively.

Next, consider the case of a nebula whose angular size is smaller than that of the resolution of the SHASSA. The expected H\textalpha flux is

$$F_{\text{H\alpha}} = h \nu_{\text{H\alpha}} R_{\text{SHASSA}} \frac{\pi \theta^2}{4}, \quad (18)$$

where $h \nu_{\text{H\alpha}}$ is the energy of an H\textalpha photon. Combining this equation with Equation (15) (and likewise for a Galactic location), we find

$$F_{\text{H\alpha}}^G = 10.5 \times 10^{-9} L_{\text{pc}} d_{\text{kpc}}^{-2} \text{ erg cm}^{-2} \text{ s}^{-1}, \quad (19)$$

$$F_{\text{H\alpha}}^S = 7.8 \times 10^{-9} L_{\text{pc}} d_{\text{kpc}}^{-2} \text{ erg cm}^{-2} \text{ s}^{-1}. \quad (20)$$

The point-source limit for a single pixel of SHASSA is $R_{\text{SHASSA}} \Delta \Omega$, where $\Delta \Omega \sim 5.4 \times 10^{-5}$ sr (corresponding to one SHASSA pixel). Given that $R_{\text{SHASSA}} = 6$ Rayleigh (see above), we find

$$F_{\text{H\alpha}} \lesssim 7.8 \times 10^{-14} \text{ erg cm}^{-2} \text{ s}^{-1}. \quad (21)$$

Combining the inequality (Equation (21)) with Equations (19) and (20), we derive the following constraints:

$$L_{\text{pc}} d_{\text{kpc}}^{-2} \lesssim 0.75 \times 10^{-5} \quad \text{(Galactic)} \quad (22)$$

$$L_{\text{pc}} d_{\text{kpc}}^{-2} \lesssim 1 \times 10^{-5} \quad \text{(SMC and Beyond).} \quad (23)$$

Combining Equation (22) with Equation (13), we find that the nebula cannot be located any closer than

$$d_{\text{min}}(H\alpha) \sim 27 \text{ kpc}. \quad (24)$$

Parenthetically, we note that, in principle, a similar exercise can be carried out for the two-photon emission, traced by UV observations.
4.5. UV Continuum

A nebula ionized by one or more hot stars would be accompanied by a strong underlying stellar continuum. Here we explore archival data to see whether suitable ionizing stars exist within the Sparker region. We then match the rate of recombination for the nebula (which is a function of $L$ and hence of $d$), $N_R$, to the rate of ionization by possible ionizing sources, $N_I$. The strongest plausible ionizing source or the most distant ionizing source then provides the largest $d$. It is important to understand that this exercise will only constrain ionizing sources within (at best) the Local Group. The exercise does not constrain very distant ionizing sources (e.g., the IGM).

The rate of recombinations is $N_R = \pi/6n_e^2\alpha_p L^3$, where $\alpha_p$ is the recombination coefficient (see footnote 12). Consistent with the spirit of this section (namely, a photoionization model), we assume $T = 8000$ K. For a given distance, $d$, we derive a maximum nebular diameter, $L$, using the constraints provided in the previous section and thence $N_R$. The calculations are summarized in Table 1. We find that $N_R$ is as small as $2 \times 10^{35}$ s$^{-1}$ and as large as $2.7 \times 10^{38}$ s$^{-1}$ (at 1 Mpc). The corresponding minimum luminosity in ionizing photons (assuming photons with energy just above the Lyman continuum) is $L_R h v_L$, where $h v_L$ is the energy of a photon at the Lyman edge. This luminosity ranges between $4.4 \times 10^{34}$ erg s$^{-1}$ and $5.9 \times 10^{35}$ erg s$^{-1}$. The inferred ionizing rates should be compared with that expected from O and B stars (Schaerer & de Koter 1997): log$(N_I) = 49.85$ for an O3V star ($T_{\text{eff}} = 51230$ K and log$(L_{\text{bol}}/L_\odot) = 6.0$) and log$(N_I) = 47.77$ for a B0.5V star ($T_{\text{eff}} = 32060$ K and log$(L_{\text{bol}}/L_\odot) = 4.7$).

The Galaxy Evolution Explorer (GALEX) UV space telescope (Martin et al. 2005) is well suited to search for and characterize potential hot (and thus ionizing) sources. The GALEX images are shown in Figure 5 and have exposure times of 135 s in both the far-UV (FUV) channel (center wavelength, 1538 Å; FWHM = 226 Å) and the near-UV (NUV) channel (2289 Å; FWHM = 794 Å).

Only hot stars with $T_{\text{eff}} \gtrsim 2 \times 10^4$ K are capable of ionizing hydrogen atoms. The extinction-corrected GALEX color–magnitude diagram (CMD; assuming that all sources are outside the Galaxy) for detected sources in the Sparker region is shown in Figure 6. The extinction was corrected using the Galactic color excess in the direction of the Sparker (Schlegel et al. 1998), a total-to-selective extinction ratio derived from the Cardelli et al. (1989) extinction law (see Section 2.3 of Wyder et al. 2007), and assuming $R_V = 3.08$. As can be seen from Bianchi et al. (2007, Figure 7), the GALEX color, $\Delta_{\text{UV}} \equiv \text{FUV} - \text{NUV}$, of stars with $T_{\text{eff}} \gtrsim 2 \times 10^4$ K is $\Delta_{\text{UV}} < 0$.

Although some objects in the polygon region (Figure 6) have $\Delta_{\text{UV}} < 0$, we argue that these stars are too faint to be the ionizing sources responsible for the DM nebula. The brightest object (labeled star A in Figures 5 and 6) with $\Delta_{\text{UV}} < 0$ within the polygon region has FUV AB magnitude of 20.5 mag and NUV = 21.4 mag. Here, following standard convention, the GALEX magnitudes are defined in the AB system (Oke 1974). CD-75 38 is a useful comparison star with $V = 10.35$, $B = 10.98$, $NUV = 15.310 \pm 0.001$, and $FUV = 22.23 \pm 0.08$. Star A is the hottest star within the polygon. See Section 4.5 for more discussion.
foreground white dwarf, then its ionizing capacity is negligible. Should star A be a young star in the outskirts of our Local Group (530 kpc), then it has the ability to power a nebula with $L = 0.69$ pc (see Table 1) and this nebula could account for the excess DM. However, the Sparker will either have to arise in this nebula or, if behind, be closely aligned with this star (recall that the angular size of the nebula is 0′.4; see Table 1).

Using the same arguments as above, we conclude that all the other blue objects with fainter FUV magnitudes are not consistent with being hot main-sequence stars in the SMC or closer according to the models in Bianchi et al. (2007). These objects are more likely to be foreground white dwarfs or background unresolved star-forming galaxies.

To summarize, we did not find any suitable ionizing source capable of maintaining a DM = 350 cm$^{-3}$ pc (Galactic origin) or DM = 300 cm$^{-3}$ pc (SMC or beyond location) nebula. We translate this constraint as follows. We equate the Lyman continuum flux of the hottest and brightest star in the localization region to the recombination rate of a photoionized nebula of diameter $L$. Since this is the maximum possible luminosity, we derive our fifth constraint:

$$L_{pc}d_{kpc}^{-2} \lesssim 6 \times 10^{-8}. \quad (25)$$

When Equation (25) is combined with the free–free constraint (Equation (13)), we find $d \gtrsim 303$ kpc. This demand is marked by an open square in Figure 7. The minimum distance estimate can be further improved by determining the luminosity class of star A (via spectroscopic observations). In any case, even if star A is indeed a young main-sequence B star in the outskirts of the Local Group, then the Sparker is located at a distance of 530 kpc. This is shown by the inverted triangle in Figure 7. In this framework, star A cannot supply any more ionizing photons than those required for the minimum-size nebula (at this distance; see Table 1); we can exclude any nebula with a size larger than that of the minimum nebula at 530 kpc or larger distance—therefore the vertical line in Figure 7.

4.6. A Large Ionized Galactic Corona?

At this point one can imagine a location for the Sparker at the edge of our Local Group (though the progenitor population

![Figure 6. GALEX CMD around the Sparker region. The colors and magnitudes were derived from the GALEX All-sky Imaging Survey image of this field.](image)

![Figure 7. Parameter space of the size of the nebula ($L$ in parsecs) and the distance to the nebula ($d$ in kiloparsecs) based on the DMs of pulsars in the vicinity of the Sparker (Equation (14)), the lack of radio free–free absorption of the burst itself (Equation (13)), the surface brightness limit from SHASSA (Equation (17)), and the point-source limit obtained from SHASSA (Equation (22)). The dashed line marks the lower edge of the phase space excluded by the lack of a suitably powerful ionizing source (Section 25). The constraint on the mass of the interstellar halo leads to the top rectangle (marked as Equation (26)). The circle ($d = d_{\text{min}}$ (H$_\alpha$) $\sim$ 27 kpc) and square ($d = 303$ kpc) mark the minimum allowed distance based on the absence of H$_\alpha$ and Lyman continuum (GALEX) data. The SHASSA constraint is limited to a distance of several megaparsecs owing to the small width of the SHASSA H$_\alpha$ filter ($\pm$8 Å). For this reason, the plot cuts off at 5 Mpc.](image)
beyond 303 kpc (marked by an open square). However, there is no reason to believe that the outer reaches of our Galaxy are peppered with any dense interstellar clouds \( n_e \sim 435 \text{ cm}^{-3} \); see Table 1) or stars capable of ionizing such compact nebulae. Given the paucity of stars at such distances, postulating such a nebulae routinely (not only for the Sparker but for each FRB) is most artificial. On the other hand, a host galaxy located well outside the Local Group would be entirely allowed by the observations.

Next, let us consider the upper right region in Figure 7. Here we are allowed to have large nebulae \( (L \gtrsim 20 \text{ kpc}) \) but at great distances \( (d > 2 \text{ Mpc}) \). This requirement is easily met by the IGM.

We conclude that the circumstantial evidence is not consistent with a Galactic or SMC origin or even a Local Group origin. The following possibilities are allowed: the excess DM arises in the IGM, or in a galaxy well outside the Local Group, or both. In Sections 5 and 6, we discuss possible loopholes in reaching this conclusion.

5. A POROUS NEBULA?

The discussion thus far in this section is based on the assumption of a homogeneous intervening nebula. We now consider the implications of a porous nebula. Specifically, we assume that the nebula is composed of \( N \) ionized clumps of size \( L \). For mathematical simplicity, we assume that both the nebula and the clumps are cubes. We define the volume filling factor as \( \phi_V = N^{1/3}/L^3 \). Let \( n_e = N/L^3 \) be the number density of clumps. Since the cross section of the clumps is \( l^2 \), on average we encounter \( n_e l^2/L \) clumps along a given line of sight. The average DM is then

\[
DM = n_e l^2 L \times n_e L = \phi_V n_e L \quad (27)
\]

and the average EM is

\[
EM = n_e l^2 L \times n_e^2 L = \phi_V n_e^2 L, \quad (28)
\]

where \( n_e \) is the electron number density in the clumps. Therefore,

\[
\frac{DM^2}{EM} = \phi_V L. \quad (29)
\]

That is, the size of the nebula inferred from the DM and EM is the filling factor times the physical size of the region.

In the previous section, a unity volume filling factor is assumed (i.e., no clumps). All constraints related to the nebula size inferred from the DM and EM are affected if the filling factor is not unity, with some strengthened and some weakened. Mathematically, the effect is to replace \( L \) in the relevant constraint equations with \( \phi_V L \).

Apparentely, the constraint from the spatial range of the nebula limited by the DM of pulsars (Equation (14)) is not affected. The constraint from free–free absorption (Equation (13)) becomes \( \phi_V L > L_{\alpha} \), and the corresponding line in Figure 7 moves up by a factor of \( 1/\phi_V \). Similarly, \( L \) in Equation (17) is also replaced by \( \phi_V L \), and the corresponding line in Figure 7 moves up. Constraints from Equations (14) and (17) are thus strengthened by requiring a larger size of the nebula region and shrinking the allowed region (that above the line) in the parameter space. Replacing \( L \) by \( \phi_V L \) in Equations (22) and the UV constraints (Section 4.5) also moves up the corresponding lines in Figure 7, but this change expands the allowed region (region below each line) and thus weakens the constraints. We note, however, that because the relevant lines move up by the same factor, the minimum distance set by combining Equations (13) and (22) (or that by Equations (13) and (23)) remains unchanged.

In summary, a porous nebula does not change the minimum distance to the nebula. The free–free constraint increases the minimum size of the nebula. Thus, on both grounds Galactic models are excluded even more strongly.

6. CAVEAT: A NEBULA NOT POWERED BY PHOTOIONIZATION

In the previous section, the strongest constraint on the minimum distance to the Sparker came from examining the GALEX UV data. This constraint is meaningful only if the DM nebula is photoionized. However, one could think of free electrons being produced by other mechanisms. Three mechanisms come to mind: cosmic-ray ionization, radiative shocks, and a flash-ionized nebula. The GALEX limits would be rendered useless should we be able to develop a plausible case for any of these mechanisms. Separately, dust extinction would attenuate UV photons and also potentially dilute the GALEX constraints.

Historically, cosmic rays were the first to be suggested as ionizing sources for the diffuse ISM (see Spitzer 1978). The ionization cross section is dominated by low-energy (nonrelativistic) protons and ions (see Webber 1998). The estimated cosmic-ray ionization rate lies in the range \((3–300) \times 10^{-17} \text{s}^{-1} \) per H atom (Wolfire et al. 2003; Le Petit et al. 2004). We can easily show that matching the recombination time to any of the nebular parameters listed in Table 1 to the ionization timescale would require a cosmic-ray flux \(10^7 \text{ times larger} \) than the above value.

6.1. Ionization by Shocks

Shocks, usually the product of supernova blast waves or stellar winds, provide an alternative ionization mechanism. The amount of DM generated depends on the properties of the medium (most notably, the ambient particle density \( n_0 \)), the energy carried by the shock, and the fraction transferred to the ISM. Here and below, unless stated otherwise, when computing the \(\text{H}\alpha \) flux a nominal temperature of \(10^4 \text{ K} \) is assumed.

On one side of the energy spectrum are strong, high-velocity shocks such as those originating in supernova blast waves (e.g., Heng & McCray 2007). For example, an \( E = 10^{51} \text{ erg} \) supernova that expends, say, \( f = 10\% \) of the total energy on ionization of the surrounding ISM requires an ambient \(\text{H}\) density of

\[
n_0 = 8.5 f^{-1/2}E_{51}^{-1/2}DM_{300}^{1/2} \text{ cm}^{-3} \quad (30)
\]

to produce the expected levels of DM. The size \((\sim 35 \text{ pc}) \) and the EM \((\text{EM} \sim 2600 \text{ cm}^{-6} \text{ pc}) \) of the resulting nebula would make it easily detectable by SHASSA, even if located within the SMC or beyond.

On the low-energy side, we find that typical (e.g., Raymond et al. 1988) fully developed radiative shocks are incapable of producing the required levels of DM. As reviewed by Draine & McKee (1993), the extent of the radiative zone is solely determined by the column density, \( N_{\text{rad}} \), of the shocked material. For typical shock speeds of \( 60 < v_s < 150 \text{ km s}^{-1} \) and the Alfvén Mach number \( M_A \gg 1 \), the shocked column is

\(14 M_A \) is the Alfvén Mach number, \( M_A = v_s/v_A \), and \( v_A \) is the Alfvén velocity.
The shock must move forward fast enough to accumulate the shock propagation speed. Essentially, the leading edge of function and timescales in the radiative zone, compared to timescale for the development of the full radiative shock is \( \sim 10^5 \). The Astrophysical Journal

Increasing the ambient density, constraints to beyond the SMC. The timescale is rather long—a result from a cataclysmic event.

Therefore, this possibility requires a highly elongated radiative shock with an almost edge-on viewing geometry. It is within the realm of possibilities that such a situation may take place for an RRAT located in the Galactic plane. However, the requirements of a supernova shock and edge-on geometry mean that we cannot routinely invoke this explanation for most FRBs.

6.2. Flash-ionized Nebula?

In the previous section, we assumed that the DM-causing nebula was already present when the \textit{Sparker} event took place. We now consider the possibility that the \textit{Sparker} was accompanied by a soft X-ray flash (\textit{Flasher!}) and this flash resulted in the ionization of the nebula.

The soft X-ray flash has to be powerful enough to produce a nebula with electron density of DM = 300 cm\(^{-3}\) pc or 1.16 \times 10\(^{15}\) cm\(^{-2}\), and there has to be enough circumburst gas to provide the necessary number of electrons. The number of electrons within the flash-ionized nebula is

\[
N_e = \frac{4\pi}{3} \left( \frac{L}{2} \right)^3 n_e = 4.6 \times 10^{53} \frac{DM}{300 \text{ cm}^{-3} \text{ pc}} \left( \frac{L_{pc}}{10^{-2} \text{ pc}} \right)^2.
\]  

(31)

The timescale for ionization at radius \( r \) is

\[
\tau_{ion} = \left[ \sigma_1 \left( \frac{\nu}{v_1} \right)^{-3} \frac{N_e}{\Delta \tau X} \frac{4\pi r^2}{\Delta \nu \Delta \tau} \right]^{-1},
\]  

(32)

where \( \Delta \tau X \) is the duration of the soft X-ray flash, \( \sigma_1 \left( \frac{\nu}{v_1} \right)^{-3} \) is the photoelectric absorption at frequency \( \nu \), and \( \sigma_1 = 6 \times 10^{-18} \text{ cm}^2 \) is the cross section at the Lyman edge (\( h v_1 = 13.6 \text{ eV} \)). At the edge of the nebula (\( r = L/2 \)) the ionization time is determined by the luminosity and ionization cross section (which is dominated by the photoionization of hydrogen) and is

\[
\tau_{ion} = 0.001 \Delta \tau X \left( \frac{\nu}{v_1} \right)^3.
\]  

(33)

Provided that \( \Delta \tau X \sim \Delta \tau \), we find that \( \tau_{ion} \) is much smaller than the delay between the propagation in the decimeter band (say, 1.4 GHz) and that by a photon at high energies. This justifies assuming an instantaneous creation for the flash-ionized nebula. The energy of the X-ray flash is

\[
E_{ion} > N_e h v_1 = 1 \times 10^{43} \left( \frac{DM}{300 \text{ cm}^{-3} \text{ pc}} \right) \left( \frac{L_{pc}}{10^{-2} \text{ pc}} \right)^2 \text{ erg}.
\]  

(34)

The (isotropic) energy budget is quite impressive even for the smallest allowed value of \( L \). In particular, the isotropic bolometric yield of the rare hyperflares from SGRs can be as high as 10\(^{37}\) erg—but with most of the release in the hard X-ray band. Furthermore, the estimate of Equation (34) does not account for radiation at energies lower or higher than \( h v_1 \). Should the nebula be a few parsecs in size, then the \textit{Sparker} results from a cataclysmic event.

The \textit{Sparker} took place about 13 yr ago. Given the recombination timescale of

\[
\tau_R = \left( \frac{n_e \alpha R}{\frac{DM}{300 \text{ cm}^{-3} \text{ pc}}} \right)^{-1} \left( \frac{L}{10^{-2} \text{ pc}} \right) \text{ yr},
\]  

(35)

there still exists an opportunity to search for the flash-ionized nebula. The flux level is the same as that estimated for the \( \text{HII} \) region model (Section 4.4).

We note, however, that if a comparable amount of the required energy for the “flasher” is emitted as X-rays or \( \gamma \)-rays, then it would be readily detectable by the interplanetary network\(^{15} \) (IPN) up to the SMC distance. Lorimer et al. (2007) reported that the IPN, which has almost full-sky coverage, did not detect any GRBs or SGR hyperflares temporally associated with the \textit{Sparker}.

As in the previous section, we can probably invoke this framework for a single source such as the \textit{Sparker}. However, it would be difficult to do so for an entire population with a daily rate of 10\(^4\) and not have the expected EUV/X-ray flashes remain undetected by past and existing missions.

7. STELLAR CORONAL MODEL

Taking a contrarian view, Loeb et al. (2014) propose a scenario in which a stellar corona provides the observed DM. This means that the actual electromagnetic pulse (EMP) takes place somewhere inside the corona and the radio pulse propagates the DM as it propagates toward the observer. In this section we use EMP to indicate the predispersed pulse as distinct from the \textit{Sparker}, which we use to indicate the observed, dispersed pulse.

The simplest expectation for this model is that FRBs should be concentrated toward the Galactic plane. The reported events are all at high latitudes, which is obviously not a good omen for the model (unless they are all very nearby). We eagerly await the analysis of low-latitude fields from Parkes and Arecibo. Robust detection of FRBs in these data sets would certainly boost this model.

\(^{15}\) http://heasarc.gsfc.nasa.gov/docs/heasarc/missions/ipn.html
The emission mechanism is via either coherent or incoherent processes. Coherent emission within a corona (which consists of dense nonrelativistic plasma) may be problematic. On the other hand, it is possible to imagine a sudden deposition of energy (e.g., magnetic reconnection) that results in ultrarelativistic shock. A radio pulse can plausibly be produced in the postshock gas via incoherent synchrotron emission (see Blandford 1977).

From Equation (5) we find $\gamma \sim 10^4$. The size of the emitting region is $2\gamma^2 c \Delta t$. For $\Delta t = 1$ ms, the size of the emitting region is $6 \times 10^{15}$ cm, which is much larger than any plausible corona. Independent of this concern, it would be useful to investigate possible modifications of the spectrum of the radio pulse as it propagates through the coronal plasma and coronal photon field.

Now let us return to some basic considerations of the model (independent of how the EMP was generated). We start with a simple model: a corona with a homogeneous electron density $n_e$ and radius $L$. We assume that the EMP is generated at radius $R_*$ (which is not necessarily the photospheric radius). Then $\text{DM} = n_e (L_{\text{pc}} - R_{\text{pc}})$, where $R_{\text{pc}} = R_*/(1 \text{ pc})$ and $L_{\text{pc}} = L/(1 \text{ pc})$.

For high temperatures ($T > 3 \times 10^9$ K), the free–free absorption coefficient per unit length (Lang 1974, p. 47) is

$$\alpha(v) = 9.79 \times 10^{-3} \frac{n_e n_i T}{v^2 T^{3/2}} \ln \left( \frac{4.7 \times 10^{10} T}{v} \right) \text{ cm}^{-1}. \quad (36)$$

Normalizing $v = v_0 = 1.4 \times 10^9$ Hz and setting $T = 10^8 T_8$, we find

$$\tau(v) \approx 3.4 \times 10^{-7} \left( \frac{v}{v_0} \right)^{-2} T_8^{-3/2} \left( \frac{\text{DM}^2}{L_{\text{pc}}} \right), \quad (37)$$

where $\text{DM} = 10^3 \text{DM}_3 \text{ cm}^{-3} \text{ pc}$. Let us say that $\tau(v_0) \lesssim 3$ (see Equation (10) and subsequent discussion). Thus, we have

$$L_{\text{pc}} - R_{\text{pc}} \gtrsim 1 \times 10^{-7} T_8^{-3/2} \text{DM}_3^2 \left( \frac{v}{v_0} \right)^{-2}. \quad (38)$$

This length scale corresponds to about $4 R_\odot$. Going forward, we will set $v = v_0$.

The mean density, the mass, and the thermal content of the corona is

$$n_e = 1 \times 10^{10} T_8^{3/2} \text{DM}_3^{-1} \text{ cm}^{-3},$$
$$M_e = 1 \times 10^{-12} \text{DM}_3^2 T_8^{-3} M_\odot,$$
$$Q_e = 5.1 \times 10^{37} \text{DM}_3^5 T_8^{-3} \text{ erg}. \quad (39)$$

For the corona to be in approximate hydrostatic equilibrium, we must have the thermal energy (in each of electrons and protons) be less than the gravitational potential energy (per H atom) or $3k_BT < GM m_H/L$; here $m_H = m_p + m_e$. This is clearly violated, and so we must assume that there is outflow. The characteristic thermal velocity that matters is

$$v = \sqrt{\frac{3k_BT}{m_H}} = 1580 T_8^{1/2} \text{ km s}^{-1}, \quad (40)$$

and the mass flux is

$$\dot{M} = 4\pi L^2 n_e m_H \sqrt{\frac{3k_BT}{m_H}},$$
$$\approx 5 \times 10^{-8} T_8^{-3} \text{DM}_3^3 M_\odot \text{ yr}^{-1}. \quad (41)$$

So even though we started with a static model for the corona, we find that the corona is not dynamically stable and has a strong outflow. If so, the assumption of a homogeneous density in the corona is not correct. Therefore, we need to adopt a wind equation: $n_e \propto r^{-2}$. As noted in Appendix C, as long as $L$ is even modestly larger than $R_*$, we can approximate $\text{EM} \approx \text{DM}^2/R_{\text{pc}}$, which is similar to the homogeneous case, provided that we identify $R_*$ with $L$.

The free–free luminosity per unit volume is ($\text{Lang 1974, p. 46}$)

$$\epsilon_{\text{ff}} = 1.4 \times 10^{-27} T_8^{1/2} n_e^2 \text{ erg cm}^{-3} \text{ s}^{-1}, \quad (42)$$

where we have assumed a pure hydrogen plasma ($n_e = n_i$). The luminosity (assuming that the plasma is optically thin) and the bolometric flux density are, respectively,

$$L_{\text{ff}} = \frac{4\pi}{3} L_3 \epsilon_{\text{ff}} = 1.7 \times 10^{32} T_8^{-1} \text{DM}_3^3 \text{ erg s}^{-1},$$
$$f_{\text{ff}} = 1.3 \times 10^{-12} D^{-2}_{\text{kpc}} T_8^{-1} \text{DM}_3^3 \text{ erg cm}^{-2} \text{ s}^{-1}. \quad (43)$$

The cooling and the hydrodynamical timescales are

$$t_{\text{ff}} = 3k_BT n_e/\epsilon_{\text{ff}},$$
$$= 3.43 T_8^{-1} \text{DM}_3 \text{ day}. \quad (44)$$

and

$$t_h = L/v = 0.5 T_8^{-2} \text{DM}_3^2 \text{ hr}. \quad (45)$$

Since the corona is optically thin and $t_h < t_{\text{ff}}$, we expect to see a bright X-ray source with typical photon energy of $2.7k_BT = 23 T_8$ keV lasting for $0.5 T_8^{-2}$ hours (after the radio burst). However, we note that X-ray emission will be seen for at least a similar duration as the corona inflates to provide the necessary DM. Thus, we will have X-ray emission, preceding and succeeding the EMP, with a fluence of

$$F_{\text{ff}} = 2.3 \times 10^{-9} D_{\text{kpc}}^{-2} T_8^{-3} \text{DM}_3^6 \text{ erg cm}^{-2}. \quad (46)$$

X-ray missions are more sensitive at lower energies, and so better constraints on this model can be obtained by considering missions that operated primarily in the classical X-ray band or the soft X-ray band. In order to compute the X-ray light curve, we would need to know the boundary conditions at the base of the corona. Since the proposed model is not sufficiently developed, any further calculation of this sort is premature. We can reasonably assume that the duration of the X-ray emission at lower energies (keV range) is longer than the $1T_8^{-2} \text{DM}_3^2$ hr discussed above.

In summary, an expectation of the coronal class of models is $\text{precursor}$ hard X-ray emission followed by an X-ray afterglow that becomes softer with time. Given a daily FRB rate of $\dot{N} \approx 10^4 \text{ day}^{-1}$, the number of X-ray sources we expect to see is $\dot{N} t_{\text{fx}}$, where $t_{\text{fx}}$ is the duration over which the X-ray signal is above the detection level. For $T = 10^8$ K we expect about $10^3$ cm$^{-3}$ pc is Compton thin; the plasma is also thin for free–free absorption for $h\nu$ comparable to $k_BT$. $^{16}$
400 sources at any given time in the sky. According to Kanner et al. (2013), at any given time, there are $4 \times 10^{-8}$ X-ray transients per square degree on the sky with a flux threshold greater than $3 \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$ (0.2–2 keV band), or about 16 sources over the entire sky. Most of these are identified with sources that are expected to be variable from other considerations (e.g., known flare stars primarily; see Vikhlinin 1998). Clearly, coronal models with $T = 10^8$ K are not favored on observational grounds.

Let us consider even hotter coronas, say, $T = 3 \times 10^8$ K. Relative to the $T = 10^8$ K coronal model, the duration of the event is reduced by a factor of 10 (from an hour to 6 minutes) and the flux decreased by a factor of three. With a mean temperature of 70 keV, this short-lived object may even be mistaken for a long-duration GRB! Given $\dot{\nu}$, we would expect 10 nearby (100 pc) events every day, each with a fluence of $10^{-3}$ erg cm$^{-2}$. The Burst Alert Telescope (BAT) can detect GRBs with fluence (15–150 keV) brighter than $10^{-8}$ erg cm$^{-2}$ (though most of the GRBs are considerably brighter). A search through the BAT catalog (Sakamoto et al. 2011) would provide observational feedback to the coronal model.

8. AN EXTRAGALACTIC ORIGIN

In Section 4, using basic theory and archival Hα and GALEX data, we attempted to constrain the size ($L$) and the location (distance, $d$) to an intervening ionized nebula that could account for the excess (over Galactic value, if the Sparker was located in our Galaxy or in the vicinity of the Magellanic Clouds) of the DM inferred from the frequency-dependent arrival time of the pulse from the Sparker. The allowed phase space for $L$ and $d$ is summarized in Figure 7. We concluded that the nebula cannot be located in our own Galaxy or the SMC and is not even allowed to be on the periphery of our Galaxy. After investigating possible caveats (Sections 5 and 6), we concluded that the excess of DM arises in another galaxy, or in the IGM, or both. Having reached this conclusion, the only issue is to apportion the DM between the IGM and ionized gas within the host galaxy. For the Sparker, in accord with Lorimer et al. (2007), a redshift range $0.1 \lesssim z \lesssim 0.3$ is reasonable.\(^{17}\)

A similar analysis can be applied to the four FRBs reported by Thornton et al. (2013), but that is not educational. What is useful is to take the best constraints from the whole set of the Parkes events. In particular, the $L_d$ scales as DM$^2$ (see Equations (6) and (7)). The larger DMs of Thornton et al. (2013) therefore provide the strongest constraints on compact intervening nebulae and for stellar models (Section 7).

We conclude that the Sparker and the four Parkes events have to be extragalactic—provided that the frequency-dependent arrival time is a result of propagation through cold plasma. In this section we investigate the consequences of the Sparker being located in a distant galaxy. Anticipating the later discussion to include FRBs, we set the nominal distance to 1 Gpc. We will now revisit the issue of energetics and brightness temperature (see Sections 3.1 and 3.2).

Switching now to parameters typical of FRBs (peak flux of 1 Jy at 1.4 GHz and $\Delta t = 1$ ms), we find that the isotropic energy release in the radio band is

$$\mathcal{E}_S \sim 4 \times 10^{50} D_{\text{Gpc}}^2 \text{ erg},$$

(47)

assuming $\alpha = -1$ with a low-frequency cutoff of $v_0/10$ (see Section 3.1). However, if the intrinsic spectrum is an exponential (see Section 4.1), then the isotropic energy release is larger by $\approx \exp(x_0)/(x_0 \ln(x_0))$, where $x_0 = v_0/v_c$.

The brightness temperature at $v_0$ is $6 \times 10^{34} D_{\text{Gpc}}^2 K$ and is larger by the factor $v_0^2 \exp(x_0)$ at $\nu = v_c$. We compare the Sparker to Galactic RRATs and giant pulses from pulsars. The brightest RRAT known to date has a peak flux of 3 Jy in the 21 cm band. For the RRAT sample of McLaughlin et al. (2006), we derive brightness temperatures as high as $10^{23}$ K. Next, the highest brightness temperature event to date is a 15 ns wide giant pulse from PSR 1937+214 with $T_B > 5 \times 10^{20}$ K (in the 1.65 GHz band; after correction for interstellar scintillation and scattering; Soglasnov et al. 2004). Thus, apparently, pulsars can produce the high brightness temperatures that we are inferring for the Sparker.

We draw the reader’s attention to the dual-frequency (2.7 and 3.5 GHz) studies of PSR J1824−2452A (Knight et al. 2006). The authors report that the spectral index of $\sim -5.4$ was observed over the frequency range 2.7–5.4 GHz. Furthermore, it was noted that the giant pulse phenomenon is not necessarily broadband (i.e., the spectrum could be quenched at lower frequencies). Finally, many of the giant pulses are 100% elliptically polarized.

Despite the apparent agreement of brightness temperature and potential spectral similarity, there is one big difference between giant pulses from pulsars and the Sparker: the size of the emitting region. The high brightness temperatures exhibited by pulsars are on nanosecond timescales. This translates into sizes for the emitting regions from a few meters and up. In contrast, the size of the Sparker emitting region is $R = c \Delta t \lesssim 300$ km. This is an upper limit due to possible dispersion and scattering broadening.

Before we discuss the proposed models, it is useful to discuss the most general constraint(s) that can be obtained from the observations. Clearly, the high brightness temperatures of FRBs stand out. As first discussed by Wilson & Rees (1978), the high brightness temperature inferred in the Crab pulsar requires two conditions: an extremely clean region to prevent severe losses due to induced Compton scattering, and an ultrarelativistic flow that would then boost the inferred brightness temperature by $\gamma^3$. Separately, matter, if present, would be accelerated by the strong electromagnetic field and rapidly dissipate energy. Propagation will also be impeded. Were the Sparker to be an RRAT or a pulsar, albeit at cosmological distances, then $\gamma \sim 10^4$ to $10^6$ would be needed in order to prevent induced Compton scattering from significantly attenuating the radio emission. In this spirit we draw the reader’s attention to a recent paper by Katz (2014), where he argues that $\gamma > 10^3$ and notes that a compact source and an expanding highly relativistic source are both possible.

In summary, suitable progenitor models are those that have an ultraclean emitting region and, in addition, a low-density circumstellar medium so that external absorption is not significant. This means, almost always, that the free–free optical depth should not be large (for usual parameters, the plasma frequency is usually well below the GHz band).

9. PROGENITORS

Even more remarkable than their inferred extragalactic nature is the all-sky rate of Sparker and associated Parkes events. Lorimer et al. (2007), noting that the Sparker would have been

\(^{17}\)As can be seen from Figure 1, there is no distinctive galaxy within the localization region. The most notable galaxy lies outside the polygon beyond the northwestern tip.


Table 2
Volumetric Rates of Selected Cosmic Explosions

| Class | Type     | \( \Phi \) (Gpc\(^{-3}\) yr\(^{-1}\)) | Ref |
|-------|----------|----------------------------------|-----|
| LSB (low) | BC | 100–1800 | (1,2) |
| LSB(high) | Obs | 1 | (1) |
| SHB | BC | 100–550 | (1) |
| In-spiral | Th | \( > 10 \times \) | (3a) |
| SGR | BC | 500–2000 | (3b) |
| Core Collapse | BC | \( > 10 \times \) | (3a) |
| FRB | Obs | \( > 10 \times \) | (3a) |

Notes. “Obs” is the annual rate inferred from observations. “BC” is the observed rate corrected for beaming. “Th” is the rate deduced from stellar models. LSB stands for GRBs of the long duration and soft spectrum variety. A gamma-ray luminosity of 10\(^{49}\) erg s\(^{-1}\) divides the “low” and “high” subclasses (see Guetta & Della Valle 2007). SHB stands for GRBs of the short duration and hard spectrum class. SGR stands for soft gamma repeaters. Here we only include those giant flares with isotropic energy release \( > 4 \times 10^{40}\) erg.

References. (1) Guetta & Della Valle 2007; (2) Soderberg et al. 2006; (3a) Nakar et al. 2006; (3b) Coward et al. 2012; (4) Kalogera et al. 2004; (5) Ofek 2007; (6) Scannapieco & Bildsten 2005; (7) Li et al. 2011; (8) Lorimer et al. 2007; (9) Thornton et al. 2013.


detected to \( z \sim 0.3 \) \( (D \sim 1 \) Gpc\), derived a local volumetric rate of 90 Gpc\(^{-3}\) day\(^{-1}\). For the four Parkes events, Thornton et al. (2013) quote an all-sky-rate of 1.0\(^{0.5} \times 10^{4}\) d\(^{-1}\) (for fluence above a few Jy ms in the 1.4 GHz band). The comoving distances for these events, if most of the DM is attributed to the circumstellar density (see Appendix C). Even for Type Ib/C supernovae, the velocity of the mass-losing wind, determines the run of the circumstellar density (see Appendix C). Even for Type Ib/C supernovae (which have the fastest winds and the smallest mass-loss rate) \( A_\star \) is in the range of 0.01–1; here \( A_\star \equiv A/5 \times 10^{11} \) cm\(^{-1}\). As argued in Appendix C, this value is sufficient to cause free–free absorption (in the decimeter band) at a radius of 10\(^{14}\) cm. Thus, for a successful radio burst, the radio-emitting region must be located beyond this radius. For this reason we reject all ordinary core-collapse supernovae and their more exotic variants: long-duration GRBs, low-luminosity GRBs, and the model of Egorov & Postnov (2009).

9.2. The Blitzar Model

To circumvent the fundamental problem of absorption by either the ejecta or the circumstellar medium, Falcke & Rezzolla (2014) propose a novel scenario: the desired fraction of core-collapse supernovae explode and leave massive neutron stars that are rotating sufficiently rapidly that they can exceed the maximum mass of a stable but static neutron star. The neutron star spins down via the pulsar mechanism. Meanwhile, the SN debris and circumstellar medium are slowly cleared up. At some point the massive neutron star can no longer support itself and collapses to a black hole. During this transmutation, a strong radio pulse is emitted (Blitzar!). We agree that the Blitzar model is a clever scenario, but below we argue that the ramifications of the model are not in accord with what we know about the demographics of pulsars and the energetics of supernovae and supernova remnants.

We consider a simple and hopefully illustrative example. Let us say that at the end stage of a supermassive neutron star’s life, just before it collapses into a black hole, it has a spin period of \( P_1 = 1.5 \) ms, a value that is typical of the faster-spinning millisecond pulsars. Now let us make the simplifying assumption that this pulsar was born with a spin period that is half its final spin period, that is, with \( P_0 = 0.75 \) ms. With \( P_0 \) and \( P_1 \) fixed, the only free parameter is the time, \( \tau \), it takes for the supermassive neutron star to spin down to \( P_1 \). The magnetic field strength prior to the collapse can be computed in the vacuum dipole framework and is \( B = 5.2 \times 10^{10} \tau_4^{-1/2} \) G, where \( \tau = 10^4 \tau_4 \) yr. The spin-down luminosity of the pulsar, prior to the transmutation, is extraordinary: \( \dot{E} = 2 \times 10^{40} \tau_4^{-1} \) erg s\(^{-1}\). The spin-down luminosity at birth is \( (P_1/P_0)^3 = 16 \) times higher.

Now we work out the ramifications of the Blitzar hypothesis. First, (1), in a typical late-type galaxy, given the putative birth rate of FRBs (1 per 10\(^3\) yr), we should expect 10\( \tau_4 \) such bright young pulsars with magnetic field strengths significantly above those of millisecond pulsars (\( B \lesssim 10^8 \) G). Next, (2), given the ratio of the FRB rate to that of core-collapse supernovae, 1 in 10 supernovae should exhibit evidence of an underlying long-lived powerful source of energy. Let us consider a specific case and set \( \dot{E} = 10^{46} \) erg s\(^{-1}\). Assuming a mean expansion speed of \( 5 \times 10^8 \) cm s\(^{-1}\) (at late times), the radius of a supernova two years after the explosion is \( R_5 = 3 \times 10^{16} \) cm. It is safe to assume that this power input is rapidly thermalized. Equating the blackbody luminosity, \( 4\pi R_5^2 \sigma T_5^4 \), to \( \dot{E} \) yields \( T \sim 10^5 \) K. A search with WISE and Spitzer missions for mid-IR emission from nearby and decade-old core-collapse supernovae would provide useful upper limits on the rate of Blitzars (see Helou et al. 2013).

 Decreasing the typical time to collapse from 10\(^4\) yr to 10\(^3\) yr would alleviate the issue raised in (1) but exacerbate the concern raised in (2) but lead to a large population (10\(^3\)) of millisecond young (10\(^6\) yr) pulsars—a hypothesis that can be immediately refuted given the known demographics of Galactic pulsars. Finally, (3), by constructions these events would release, over a timescale of \( \tau \), an energy of \( \Delta E = 1/2 (I_0\omega_0^2 - I\omega_4^2) \), which is comparable to the typical initial rotation energy of the neutron star or 10\(^52\) erg; here \( I \) is the moment of inertia, \( \omega = 2\pi / P \), and the subscripts are as in the previous paragraph. There is little evidence that the inferred energy release in any Galactic supernova remnant, including those associated with magnetars, exceeds 10\(^51\) erg (Vink & Kuiper 2006).
9.3. Short Hard Bursts

Short hard bursts are well suited as possible progenitors. After all, these systems are clean: no supernova ejecta, and no rich circumstellar medium. However, as has been noted earlier, the rates of the Parkes events far exceed those of the short hard bursts (see Table 2). Additionally, we offer the following line of simple reasoning. The very large rate for the Parkes events suggests that they are not beamed. The five Parkes events have \( z < 1 \). In contrast, the redshift distribution of short hard bursts is wider. Bearing this in mind, we note that the all-sky rate of short hard bursts is \( \approx 0.5 \text{ day}^{-1} \) (Nakar 2007). Thus, concordance between these two estimates would require an inverse beaming factor in excess of \( 2 \times 10^{41} \). There is no evidence for such a large inverse beaming factor (Berger 2014).\(^{18}\) In order to preserve the connection between FRBs and coalescence events, we have to conclude that only a small fraction of coalescence events produce short hard bursts.

We now discuss specific models related to short hard bursts. Totani (2013) revives erstwhile models in which the neutron stars are reactivated as they approach coalescence. This is an attractive model from the point of view of radio pulse generation, as well as the fact that the radio emission takes place prior to the coalescence. However, as noted above, in this scenario nature is bountiful with coalescence events. We should expect to see an event within 100 Mpc every 3 days once Advanced LIGO turns on. We admit that we find this scenario to be positively Panglossian (see, e.g., Belczynski et al. 2012).

Next, it has been noted in Zhang (2014) and Lasky et al. (2014) that in some short hard bursts the X-ray light curve shows a plateau. The authors interpret the cessation of this X-ray plateau as marking the transmutation of the coalescence product—a supermassive neutron star—into a black hole. Inspired by the Blitzar model, Zhang (2014) suggest that the transmutation results in an intense radio burst. On general grounds one expects that the merger will be followed by the ejection of a relatively small amount (\( 10^{-4} M_{\odot} \) to \( 10^{-5} M_{\odot} \)) of subrelativistic matter (see Hotokezaka et al. (2013)). Appendix C, we construct a simple toy model with spherical ejection, constant shell thickness, and a coasting velocity and find that decimetric radiation will be absorbed, via the free–free process (Appendix C). Calculation of \( \Phi_{GF}(E_{\gamma} \lesssim E_{\gamma}^*) < 2.5 \times 10^4 \text{ Gpc}^{-3} \text{ yr}^{-1} \) (49) and stated in Table 2). This upper limit is compatible with the inclusion of recent giant flares in nearby galaxies: GRB 051103 (Ofek et al. 2006) and GRB 070201 (Ofek et al. 2008). Comparison of the Galactic rate (discussed below) with the inferred extragalactic rate implies a gradual cutoff (or steepening) of the flare energy distribution at \( E_{\gamma} \approx 5 \times 10^5 \text{ erg} \) to 10 times this value. This energy release is sufficient to account for a typical FRB at, say, 1 Gpc.

We now proceed to compute the volumetric rate of SGR flares. We do so in two different ways. Ofek (2007) combined the observations of Galactic SGR giant flares with the limits on giant flares in nearby galaxies. Based on these observations, Ofek finds that the rate of giant flares with energy above \( E_{\gamma} \gtrsim 3 \times 10^{56} \text{ erg} \) is about \((0.4-5) \times 10^{-4} \text{ yr}^{-1} \) per SGR with an upper limit on the volumetric rate\(^{19}\) of

\[
\Phi_{GF}(E_{\gamma} \lesssim E_{\gamma}^*) < 2.5 \times 10^4 \text{ Gpc}^{-3} \text{ yr}^{-1} \]

An entirely new class of models is speculated by Kasai et al. (2013). These authors propose that a fraction of the mergers of two white dwarfs lead to a highly magnetized white dwarf rotating rapidly and that such an object may produce a strong radio pulse. These authors make the implicit assumption that the merger takes place with no ejection of material. However, the merger is not a clean process (e.g., Marsh et al. 2004; Raskin et al. 2014). The less massive white dwarf, having the lower density, is disrupted first. The disrupted material forms an accretion disk, which then feeds the more massive star (primary). Accretion power heats up the primary star as well as the disk itself. As a result, one expects a strong stellar wind to accompany accretion. As noted in Section 8, the production of high-temperature beams of radiation requires a very clean environment, and the few baryons that are present have to be relativistic. Leaving this general comment aside, we argue that the resulting wind cannot be any less strong than that seen for Wolf–Rayet stars and thus \( A_{\gamma} \approx 1 \). If so, the radio pulse will be absorbed by the free–free process (Appendix C). Calculation of \( A_{\gamma} \) for merger models is beyond the scope of this paper, but proponents are advised to look into this issue.

10. GIANT FLARES FROM SOFT GAMMA-RAY REPEATERS

We finally come to giant flares from SGRs, which have been speculated to be the FRB progenitors by Popov & Postnov (2010) and Thornton et al. (2013). What makes this suggestion worthwhile is a plausible physical model (Lyubarsky 2014). In this model, following the giant flare, an EMP (Poynting vector) is formed and propagates outward. The pulse eventually shocks the magnetized plasma that constitutes the plerion (inflated by steady power from the magnetar during the course of its life). Lyubarsky provides plausible arguments for strong radio emission from either the reverse shock or the forward shock. Specifically, the model supports an efficiency of \( 10^{-5} \) to \( 10^{-6} \) in converting the energy released to bolometric radio emission. Next, the high brightness temperature is elegantly accounted for by synchrotron maser emission.

The most spectacular and energetic Galactic giant flare was observed on 2004 December 27 from SGR 1806–20 (Hurley et al. 2005; Palmer et al. 2005). We will use this event as the benchmark for giant flares from SGRs, and as such its distance enters into our calculations. For simplicity, we assume a distance of 15 kpc (Svirski et al. 2011) for SGR 1806–20 in all our analyses in this work. This event, at our assumed distance, had a characteristic energy release of \( E_{\gamma} = 3.6 \times 10^{46} \text{ erg} \) in the X-ray band (Boggs et al. 2007). If we assume that the isotropic energy release in \( \gamma \)-rays, \( E_{\gamma} \), was approximately equal to this characteristic value, then in Lyubarsky’s model, this event could explain FRBs with radio emission of \( E_{\gamma} \approx 3 \times 10^{40} \text{ erg} \) to 10 times this value. This energy release is sufficient to account for a typical FRB at, say, 1 Gpc.

We now proceed to compute the volumetric rate of SGR flares. We do so in two different ways. Ofek (2007) combined the observations of Galactic SGR giant flares with the limits on giant flares in nearby galaxies. Based on these observations, Ofek finds that the rate of giant flares with energy above \( E_{\gamma} \gtrsim 3 \times 10^{56} \text{ erg} \) is about \((0.4-5) \times 10^{-4} \text{ yr}^{-1} \) per SGR with an upper limit on the volumetric rate\(^{19}\) of

\[
\Phi_{GF}(E_{\gamma} \lesssim E_{\gamma}^*) < 2.5 \times 10^4 \text{ Gpc}^{-3} \text{ yr}^{-1} \]

(49)
Active SGRs are a youthful population. For instance, the true age of the BAT of 19(\tau_{\text{GF}}/30 \text{yr})^{-1} \text{yr}^{-1}, where \tau_{\text{GF}} is the mean time between Galactic giant flares as energetic as 2004 December 27. During the period 2005–2013, BAT discovered a total of 70 short-duration events. Most of these are genuine short hard gamma-ray bursts (Berger 2014). The only short hard event in this sample that has been claimed to be an extragalactic giant flare is GRB 050906 [and associated with the starburst galaxy IC 328 (distance of 130 Mpc; Levan et al. 2008)]. After discounting securely identified and strong candidate short hard bursts in the BAT sample, we are led to the conclusion that \tau_{\text{GF}} easily exceeds 100 yr. We thus reaffirm the primary conclusion of the Ofek (2007) analysis: there is a break in the luminosity function of giant flares, and the mean time between flares as bright as the 2004 December 27 event is in excess of a century.

A second approach is to use the statistics of Galactic (including satellite galaxies) giant flares, including those fainter than \mathcal{E}_{\gamma}. The lifetime of the field of X-ray astronomy is, say, 40 yr. During this period, we have observed three giant flares with energy above \approx 10^{44} \text{erg} (1979 March 5, 1998 August 27, and 2004 December 27). Thus, we can plausibly assume that the mean time between giant flares is \tau_{\text{GF}} \approx 25 \text{yr}. The g-band luminosity of the Milky Way is 1.8 \times 10^{10} L_{\odot} (Licquia & Newman 2013). The local density in B band is 1.8 \times 10^3 L_{\odot} Mpc^{-3} (Cross et al. 2001). Thus, the volumetric rate of giant flares is

\[ \Phi_{\text{GF}}(\mathcal{E}_{\gamma} \gtrsim 3 \times 10^{44} \text{erg}) \approx 4 \times 10^5 (\tau_{\text{GF}}/25 \text{yr})^{-1} \text{Gpc}^{-3} \text{yr}^{-1}. \] (50)

This rate applies to events that are brighter than the event of 1998 August 27 (which was approximately 100 times fainter than the event of 2004 December 27). This simple determination of the volumetric rate and the upper bound of Ofek discussed above (which we remind the reader applies to bursts with \mathcal{E}_{\gamma} \lesssim \mathcal{E}_s) are consistent with each other.

10.1. Dense Interstellar Medium

We draw the reader’s attention to an important issue. We have looked into the environments of several magnetars in our Galaxy. Almost all of them, not surprisingly, are star-forming regions (which are rich in both ionized and neutral interstellar gas) or embedded in a supernova remnant. We find DMS ranging from 100 cm to nearly 10^3 \text{cm}^3 \text{pc}^{-3}. Furthermore, the X-ray flash could additionally ionize neutral matter (see Section 6.2). Indeed, this causal association of young SGRs with dense ISM regions provides the most reasonable explanation for scattering tails seen in one FRB and in the Sparker (and discussed in Section 11).

Consistent with this giant flare hypothesis, it follows that a significant contribution to the inferred DM arises from the vicinity (distance comparable to star-forming regions, say, \lesssim 100 \text{ pc}) of the young magnetar. We advocate 400 cm^3 pc as a representative value. In this case, the effective volume of FRBs is reduced. However, the significant Poisson error in Equation (50) shows that we can easily tolerate a reduction in the true volume by a factor of a few. In summary, it is not unreasonable to claim a good match between the true volumetric rate of FRBs and that of giant flares from SGRs.

Additionally, it may well be that for some FRBs the local ISM is dense enough that the decimetric signal is attenuated by free–free absorption. These may further increase the volumetric rate of FRBs. Another consequence is that low-frequency (meter wavelength) searches would find fewer FRBs compared to L-band searches as pointed out in Hassall et al. (2013).

10.2. Efficiency of Radio Emission

An important test for self-consistency of the giant flare model for FRBs is whether giant flares can support the required energetics. In order to correctly evaluate the isotropic bolometric energy release of the FRBs, we need to know the radio spectrum of FRBs and in particular whether there is significant emission in bands outside the 1.4 GHz band. At present, we have no constraints on this, and so we will assume that \mathcal{F} = \ln(10)\nu\tilde{S}_\nu\Delta t is a good measure of the true fluence of the source (see Equation (2)). Here \tilde{S}_\nu is the observed peak flux density. The bolometric isotropic energy release is then \mathcal{F}(1+z)4\pi D^2, where D is the comoving source distance. For the four FRBs, we find that the radio bolometric energy, \mathcal{E}_R, ranges from 10^{49} \text{erg} to 10^{41} \text{erg}. After accounting for the local DM contribution, the distances are smaller, and as a result the isotropic release is smaller by a factor of a few. According to Lyubarski (2014), bolometric radio emission can be produced with an efficiency of \eta_R = \mathcal{E}_R/\mathcal{E}_\gamma = 10^{-6} to 10^{-3}. Thus, working backward, this model would demand energy releases for the four FRBs to range from 10^{44} \text{erg} to 10^{46} \text{erg} (where we have adopted \eta = 10^{-5}). This energy range is well matched to the assumptions made in computing the volumetric rate (see comments following Equation (50)).

To conclude, radio emission arising from giant flares of young magnetars offers the most plausible physical model that can account for the high brightness temperature of FRBs (while not suffering from free–free absorption) and also account for the scattering tails seen in some FRBs. Furthermore, we find good agreement between the rates of giant flares and of FRBs.

11. FREQUENCY-DEPENDENT PULSE WIDTH

The Sparker and the brightest FRB in the Thornton et al. (2013) sample show a pulse width that is frequency dependent, \Delta(\nu) \propto \nu^m with \nu \approx -4. The simplest explanation (as has been noted by the discoverers) is that this broadening of the pulse is due to multipath propagation (“Interstellar Scintillation and Scattering” or ISS). The observations of the Sparker with its low DM (relative to the FRBs) are the most difficult to explain—whence the focus in this section on the Sparker. Given our postmortem of extragalactic models, we focus, in this section, only on the young magnetar model.

First, we summarize the minimum background to understand the basic physics of multipath propagation. The spectrum of the density fluctuations is usually modeled as a power law with exponent \eta_Hk, between spatial frequency q_1 = 2\pi/l_1 and q_0 = 2\pi/l_0. Here l_1 is the so-called inner scale (at which energy is dissipated) and l_0 is the outer scale (at which energy is injected). For the electrons in the diffuse ISM, it appears that the Kolmogorov spectrum (\beta_K = 11/3) describes the density fluctuations quite well. The normalization of the power law is

22 Those sources with a free–free optical depth of, say, a few would show up with a strongly positive spectral index; see Equation (11) and the discussion that follows.
In particular, for the case of one can derive the spatial coherence scale,  

\[ ds \]

\[ \text{Figure 8. Geometry of the scattering screen. In the "thin-screen" approximation the scattering is confined to an intervening "thin" screen located at } d_s. \]

The screen scatters an incoming ray by the scattering angle, \( \theta_s \) (whose value is directly related to the scattering strength of the screen). In this example, rays from the source can reach the observer via a direct path and by a scattered path. The difference between the two arrival paths results in pulse broadening (among other effects).

described by the “scattering measure” (SM). For a given SM one can derive the spatial coherence scale.  

We adopt the “thin-screen” approximation (Figure 8), with the distance to the screen being \( d_s \). With reference to Figure 8, the rms angle by which a ray is bent is \( \theta_s = 1/(kr_0) \); here \( k = 2\pi/\lambda \). From Figure 8, we deduce that \( \theta_s = \theta_1 + \theta_0 \). In the small-angle approximation, \( \theta_1 = \theta_0d_s/(D-d_s) \), and thus

\[ \theta_0 = \theta_1 D/d_s. \]

A burst of radiation can reach the observer via two extreme paths: a straight line or a scattered ray. The time difference between the two rays gives rise to an exponential scattering tail whose width is given by

\[ \Delta \tau \approx \frac{d_s}{2c} \theta_s^2 \left( 1 - \frac{d_s}{D} \right). \]

Equation (52) suggests three locales: (1) \( d_s \ll D \) (screen close to the observer), (2) \( d_s \approx D/2 \) (screen midway to the observer and source), and (3) \( d_s \approx D \) (screen close to the source). Note that cases (1) and (2) require the same scattering properties but have very different observational manifestations.

We begin by first estimating the contribution to ISS by the Galactic ISM. To this end, we apply the NE2001 model (Cordes & Lazio 2002) to this line of sight and find that the Galactic ISM contributes an SM, in the usual mongrel and horrific units of \( 3 \times 10^{-4} \text{ m}^{-20/3} \text{ kpc} \). The associated Galactic ISS pulse broadening is 0.05 \( \mu s \) at 1.4 GHz. Clearly, the Galactic ISM cannot account for the 5 ms pulse width of the Sparkler.

Luan & Goldreich (2014) provide good arguments why the IGM is unlikely to have the necessary level of turbulence to result in \( \Delta t \approx 5 \text{ ms} \) (at 1.4 GHz). We find the explanation convincing and so now focus on the last locale. In this case, we have

\[ \theta_s^2 \approx 2c\Delta t/1. \]

where \( l = D - d_s \). For \( \Delta t = 5 \text{ ms} \) we find \( \theta_s = 2.04 \text{ pc}^{1/2} \) arcsecond. The inferred scattering angle, \( \theta_s \), can be converted to SM using the standard formulation (Goodman 1997):

\[ \theta_s(\nu) = 0.22 \text{ mas} \left( \frac{\nu}{1.4 \text{ GHz}} \right)^{-11/5} \left( \frac{SM}{10^{-3.5} \text{ m}^{-20/3} \text{ kpc}} \right)^{3/5}, \]

where mas stands for milliarcseconds. From this, we deduce

\[ \log(SM) = 3.1 - 5 \frac{1}{6} \log(l_0). \]

The most turbulent regions known to date are the following: the H II region NGC 6334, \( \log(SM) \sim 3.3 \) (Morgan et al. 1990); the Galactic center, \( \log(SM) \sim 1.2 \) (Lazio et al. 1999); and the star-forming Cygnus region, \( \log(SM) \sim 1.2 \) (Molnar et al. 1995). These three regions are rich in gas and stars. Highly turbulent screens are usually found at the interfaces of H II regions, stellar wind bubbles, and the ISM. This is precisely the sort of locale where young magnetars are located.

It is important to check that the scattering medium is not so dense as to absorb the decimetric pulse. Turbulence in the nebula results in variations in density of the electrons, \( \langle \delta n^2 \rangle \). The EM from the rms variations alone is (Cordes et al. 1991)

\[ \text{EM}_{\text{SM}} = 544 \text{ cm}^{-6} \text{ pc} \left( \frac{SM}{\text{ kpc}^{-20/3}} \right) \left( \frac{l_0}{1 \text{ pc}} \right)^{2/3}; \]

here \( l_0 \) is the outer scale length of the turbulence spectrum. This EM should not exceed our previous constraints of \( 2.7 \times 10^7 < \text{EM} < 6.4 \times 10^7 \text{ cm}^{-6} \text{ pc} \) (see Table 1). It is reasonable to assume that the outer scale length will be a fraction of the size of the nebula (see NGC 6334 and the Galactic center; see Lazio et al. 1999). Bearing this in mind, an SM even as large as \( \log(SM) \sim 3 \) can be accommodated. However, in this extreme case the scattering screen is not only dense but also very turbulent. Parenthetically, we wonder whether some FRBs are not detected because of free–free absorption within the host galaxy (and exacerbating the all-sky rates of FRBs).

In summary, we can explain in the young magnetar model why some FRBs may exhibit frequency-dependent pulses. The radio pulse is broadened by dense ISM structures that likely form the interface between the magnetar plerion (or star-forming complex) and molecular clouds illuminated by young stars. This hypothesis nicely explains why scattering tails are not seen in all FRBs (namely, it is seen in only those cases where the magnetar is embedded in highly turbulent structures). In contrast, in the framework where multipath propagation takes place in the IGM one would expect scattering tails to be seen in all FRBs.

12. NONDISPERSED SIGNAL

The assumption that the frequency-dependent arrival time is due to propagation through an ionized medium provides the underpinnings of the discussions in Sections 4–6. These considerations led us to reject a stellar, a Galactic, and even a Local Group origin for the Sparkler and the four Parkes events. We were led to the conclusion that the Sparkler and associated events must arise in other galaxies and propose in Section 10 that giant flares from SGRs are the most plausible progenitor. The
range of models we have considered is quite comprehensive, yet we must leave no stone unturned.

Motivated thus, in this section, we abandon this central assumption. We will assume that the frequency-dependent arrival time is due to a property of the source itself. We start the discussion by noting that the following three equations denote the same phenomenon: \( t \propto \nu^{-\alpha}, \dot{\nu} \propto \nu^{\alpha+1}, \) and \( \nu \propto t^{-1/\alpha}. \)

12.1. Artificial Signals

The ultra-high-frequency (UHF) band covers the frequency range 0.3–3 GHz (aka the “decimetric” band). Starting from 1.24 GHz, the frequency allocations are as follows: amateur radio, military, mobile phone (many blocks), and cordless phone. The band 1.4–1.427 MHz is exclusively allocated to radio astronomers to undertake passive observations. Perytons are seen in this band. If Perytons are artificial signals, then the radio astronomy allocation is being (illegally) infringed upon.

It is important to understand that it does not take much for nearby sources to produce Jy-level signals. In appropriate units, the isotropic emitted power of the Sparker, \( 1 \times 10^6 (D/100 \text{ km})^2 \text{ erg s}^{-1}, \) is easily emitted by an orbiting satellite or a terrestrial transmitter.\(^{27}\) In a similar vein, the signal strength of the GPS signal at a typical location on the surface of Earth\(^{28}\) is \(-138 \text{ dBW m}^{-2} \text{ MHz}^{-1},\) corresponding to \(1.6 \times 10^6 \text{ Jy at the primary carrier frequency (L1) of GPS (1575 MHz; 2 MHz wide).}\) Next, the leisurely drift (half a second to traverse 300 MHz of bandwidth) and the quadratic chirp of the Perytons bear no similarity to artificial signals. Incidentally, this discussion also shows that it will take some effort to ex post facto detect (from musty archives at various radio observatories and monitoring facilities) radio bursts expected from the past giant flares of SGR 1900+14 and SGR 1806–20.

12.2. Solar Flares

A search of the literature revealed Type III solar radio bursts (Bastian et al. 1998) as examples of drifting signals. Of specific interest are decimetric Type III bursts (“Type IIIdm bursts”): short pulses of radiation in the 1–3 GHz range. The characteristics of a typical Type III burst are (1) a duration of \( \nu/(220 \text{ MHz})^{-1} \text{ s}, \) (2) a frequency drift of \( \nu_{\text{GHz/s}} \sim \nu_{\text{GHz}}^{1.84} \) (3) a strength of 10–100 sfu,\(^{29}\) and (4) a brightness temperature in excess of \( 10^5 \) K indicating that the emission is due to a coherent process. Type IIIdm bursts usually appear in a series of hundreds to thousands of bursts, but single bursts have been observed as well (see Figure 7 of Isliker & Benz 1994).

While their physics is poorly understood, Type IIIdm bursts are thought to be caused by downw ard (or upward) directed beams of nonthermal electrons in the solar corona. The frequency drift is believed to be caused by the change in the plasma frequency, \( \omega_p^2 = 4\pi n_e(\nu)^2/m_e, \) a result of the gradient of the ambient electron density \( n_e(\nu) \) felt by the moving beam.

Except for the weak energetics, the characteristics of the Sparker event fit to an order of magnitude the description of a Type IIIdm burst. However, at the time of observation (2001 August 24, 19:50:01 UT, or 05:50 local time), the Sun was \( \sim 7^\circ \) below the horizon at the Parkes radio telescope site, and the angular distance from the Sun (with respect to the pointing of the telescope) was \( \sim 111^\circ. \) This excludes the Sun as the direct origin of the event. The hypothesis could still be saved by assuming that emission from a solar burst was reflected off an orbiting reflector (e.g., a satellite, or a piece of debris) or the Moon.\(^{30}\) This would explain the relative weakness of the event, since, depending on the characteristics of the reflector and the flare, the signal may be attenuated at will. However, it would require a series of very fortunate events to have a very fine-tuned Sun–reflector–Earth configuration occurring at precisely the right time to reflect a \( v^{-2} \) Type IIIdm burst\(^{31}\) toward the telescope antenna. All of the above makes this hypothesis highly implausible. Additionally, a search of the Virtual Solar Observatory\(^{32}\) revealed no flares around the time of the Sparker event.

Other than the Sun, the planet Jupiter is the only significant source of bursty radio emission in the solar system. Jupiter’s emission is dominated by strong \( (10^7–10^8 \text{ Jy}) \) bursts, but primarily in the decameter band. Furthermore, at the time of observation, Jupiter was at R.A. = 6\(^{h}\)37\(^{m}\), decl. = 22\(^\circ\)56\(^{m}\), more than 120\(^\circ\) away from the location of the event.

12.3. Stellar Flares

A promising source of drifting signals similar to the Sparker are the stellar analogs of Type III dm bursts. Flaring at GHz radio wavelengths has been observed in late-type main-sequence stars (Bastian et al. 1990), and, as discussed in the previous section, Type IIIdm flares are particularly good candidates for a Sparker-like signal. For example, a Type III-like burst has recently been observed in AD Leonis (Osten & Bastian 2006), a young, nearby \( (D = 4.9 \text{ pc}) \) dM4e star. Its quiescent 1.2 GHz radio luminosity is \( 5.5 \times 10^{13} \text{ erg s}^{-1} \text{ Hz}^{-1} \) (Jackson et al. 1989), equivalent to flux density levels of \(~ 2 \text{ mJy},\) with transient flux density enhancements of up to 1 Jy.

Despite the superficial similarities, the details of stellar flares and the Sparker event are in qualitative disagreement. First, decimetric bursts observed in flare stars show evidence for substructures (a series of smaller sub-bursts) not observed in the Sparker event (e.g., compare the dynamic spectra in Figures 1 and 5 of Osten & Bastian 2006 with Figure 2 in Lorimer et al. 2007). Second, the drifts of coronal radio bursts are typically well fit with a simple linear dependence or a \( t \propto \nu^{-0.84} \) power law in the case of the Sun, significantly different from the observed \( t \propto \nu^{-2} \) drift. A stellar radio burst compatible with the Sparker would need to be one of a kind and unusually fine-tuned, in addition to coming from a yet unknown nearby flare star.\(^{33}\) We therefore consider this explanation unlikely.

We next consider neutron-star analogs of solar Type III dm bursts, recently proposed to exist in magnetar magnetospheres (Lyutikov 2002). Observationally seen as SGRs and anomalous X-ray pulsars (AXPs), magnetars are young, strongly magnetized \( (B \gtrsim 10^{14} \text{ G}) \) and slowly spinning \( (P \sim 1–10 \text{ s}) \) neutron stars. By extrapolating the scales known for solar flares and magnetically active T Tauri stars, Lyutikov (2002) proposed that magnetars should exhibit short \( (<1 \text{ s}) \), coherent, strong \( (\sim 0.1–100 \times D^{-2} \text{ kpc Jy}) \), drifting \( (\nu_{\text{max}} \propto t^{\pm 2}) \) decimetric radio power

\(^{26}\) In communications, a frequency-dependent arrival time is referred to as a “chirp.” Propagation through a cold plasma has a specific chirp signature, \( t \propto \nu^{-2}. \)

\(^{27}\) For comparison, the power emitted by an active typical cell (mobile) phone is 0.5 W or \(~ 3 \times 10^6 \text{ erg s}^{-1}. \)

\(^{28}\) http://gpsinformation.net/main/gpspower.htm

\(^{29}\) Here “sfu” is the solar flux unit, 1 sfu = 10^4 Jy.

\(^{30}\) Such an event may have been detected during nighttime at the Bleien Observatory; see Saint-Hilaire et al. (2014).

\(^{31}\) This in itself would be unusual given the \( t \propto \nu^{-0.84} \) dependence for typical solar Type III dm bursts.

\(^{32}\) http://virtualsolar.org

\(^{33}\) A Simbad search reveals no known flare stars in the vicinity of the Sparker.
bursts. The expected signal drift of $t \propto \nu^{-1/2}$ is in disagreement with the strongly constrained observation of $t \propto \nu^{-2}$, but this may or may not be a serious problem given the heuristic derivation of the burst properties that Lyutikov (2002) employs.

However, the known magnetars are all in the Galactic plane, whereas the Sparker and the FRBs are found at high-latitude regions, and so we do not consider the Galactic magnetar model to be reasonable. Parenthetically, as can be gleaned from this discussion, it would be useful to search for chirped bursts with different chirp signals ($t \propto \nu^n$ with values other than $n = -2$) in archival pulsar data, especially at low Galactic latitudes.

13. UNIFYING PERYTONS AND FRBs

In this section, we attempt to unify Perytons and FRBs. We are motivated by the fact that Perytons that are a $\nu^{-2}$ chirped signal are somehow produced either in our atmosphere or by an artificial source or sources. Perytons must be nearby because they are seen in almost all beams. FRBs are also chirped signals, but since they appear almost always in single beams, they must be located in the far field. Naturally, it is tempting to unify the two classes of chirped signals by putting Perytons nearby and FRBs farther away. It is the exploration of this simple idea that constitutes the primary focus of this section.

We submit that examining the detailed properties of radio telescope optics is helpful in our quest for unification. Since Perytons are generally considered to be “nearby,” it is possible that the events are not sufficiently far away to assume that they are in the Fraunhofer regime, as would normally be the case for celestial events. In addition to helping unify these phenomena, these details inform us that some care is needed in interpreting Peryton rates.

This section is organized as follows. In Section 13.1, we summarize what we know about Perytons. The necessary background of the Fresnel–Fraunhofer regimes in optical theory is given in Section 13.2. We then summarize searches for Perytons at other observatories (Sections 13.3–13.6). We end the section by constructing a unified model for Perytons and FRBs (Section 13.7).

13.1. A Primer on Perytons

To date Perytons have been reported from two observatories: Parkes (Section 13.5) and the Blein Observatory (Section 13.3). Kocz et al. (2012) provide a succinct description: “Perytons are signals with swept-frequency characteristics that mimic the dispersion of a pulsar, are detected in multiple receiver beams with approximately the same signal-to-noise ratio, and cannot be traced to an astronomical source.” It is worth noting that some of the Perytons show a $\nu^{-2}$ arrival time delay to within experimental errors (e.g., Peryton 12 and 13 listed in Table 1 of Burke-Spolaor et al. 2011) and that others show an approximate quadratic sweep. The DMs inferred from the frequency sweeps lie in the range 200–400 cm$^{-3}$ pc with a mode at about 380 cm$^{-3}$ pc (Figure 9).

Perytons show symmetric pulses with pulse widths that are tens of milliseconds. The widths remain the same across the 1.28–1.52 MHz band of the Parkes pulsar spectrometer. In contrast, the pulse widths of FRBs are less than 10 ms, with many being unresolved at the millisecond scale. The brightest FRB exhibits an exponential decay that is also frequency dependent. The Sparker shows a frequency-dependent width but not an exponential tail.

**Figure 9.** Histogram of the Perytons observed at Parkes. The Sparker with a DM = 375 cm$^{-3}$ pc is shown by a plus sign. The four daytime Perytons found at the Bleien Observatory (Section 13.3) span the range 350–400 cm$^{-3}$ pc (this range is shown by light shading).

Perytons show a strong propensity to occur during daytime, and many occur during clear days (Bagchi et al. 2012). Furthermore, some Perytons occur closely spaced in time: five Perytons within a two-minute interval (Kocz et al. 2012), and two Perytons within a minute of each other (Bagchi et al. 2012). In contrast, FRBs are not seen to recur despite several hour-long stares at the same position (Lorimer et al. 2007; Thornton et al. 2013). We defer the discussion of the rates of Perytons to later subsections.

13.2. Fresnel and Fraunhofer Regimes

There are two considerations that matter when observing nearby objects with large aperture telescopes. First, the beam response of a large aperture (diameter, $D$) telescope depends strongly on whether the source is “near-field” (Fresnel regime) or “far-field” (Fraunhofer regime; Fourier optics). Next, the angular resolution of a telescope is $\theta_D = \lambda/D$, where $\lambda$ is the wavelength of the radio signal. We have no knowledge of the angular sizes of Perytons, and it may well be that Perytons will be resolved by sufficiently large telescopes (and this may account for their presence in several beams).

The Fresnel scale and Fresnel zone number are, respectively, $a_F = D^2/\lambda$ and $n_F = a_F/D$, where $D$ is the distance to the source. The Fraunhofer approximation is applicable when $n_F \rightarrow 0$. The Fresnel formulation is applicable when $n_F$ is in the vicinity of unity (with ray optics applicable when $n_F \rightarrow \infty$). As a matter of reference, at $\lambda = 21$ cm, the Fresnel scales for a 6 m (ATA), 25 m (VLRA antennas), 64 m (Parkes), and 305 m telescope (Arecibo) are 0.18 km, 3 km, 20 km, and 440 m, respectively. This wide variation in $a_F$ means that care must be taken when comparing Peryton detections and statistics at the various facilities.

The response, at wavelength $\lambda$, of a telescope with a circular aperture (diameter, $D$) to a point source located at distance $r$ is given by

$$I_\lambda(\theta|n_F, \theta_D) = \left| \int_0^1 J_0[\pi \rho(\theta/\theta_D)] \exp(i n_F \pi \rho^2) 2 \rho d\rho \right|^2. $$

(58)
Here \( \theta \) is the angular offset of the receiving beam with respect to the boresight. This response is graphically summarized in Figure 10 for a range of \( n_F \). As can be seen from this figure, even with a modest Fresnel number, a point source will appear even with a modest Fresnel number, a point source will appear like extended for a telescope that is focused for observing sources at infinity.

In the Fraunhofer regime, the only way a distant compact source can be seen in multiple beams is by sidelobe "pickup." For an unobscured circular aperture, the beam response in the Fraunhofer regime is given by

\[
I_\lambda(\theta) = \left[ \frac{2J_1(\pi \theta/\theta_D)}{\pi \theta/\theta_D} \right]^2, \\
\approx \frac{2}{\pi^4} \left( \frac{\theta}{\theta_D} \right)^{-3} \text{ for } \theta/\theta_D \gg 1. \tag{59}
\]

As before, here \( I(\theta) \) is normalized to unity for a point source at infinity and located on axis.

However, structures that obscure the aperture cause additional sidelobes (and in some cases result in sidelobes with responses greater than expected from Equation (58)). Let \( \eta_m \) be the beam response obtained by integrating from, say, \( \theta = 0 \) to a few \( \theta_D \) ("main beam response"). Then \( 1 - \eta_m \) must account for the integrated response of the these wayward sidelobes. The smallest response by these sidelobes is obtained by spreading \( 1 - \eta_m \) uniformly over a solid angle \( \Omega_{SL} \), which can reasonably account for most of the sidelobes. With these two simplifying assumptions the sidelobe response is

\[
I_{SL} = (1 - \eta_m) \frac{\theta_D^2}{\Omega_{SL}}. \tag{60}
\]

For the Parkes telescope, we find \( I_{SL} = 2 \times 10^{-6} \Omega_{SL}^{-1} \), where we assume \( \eta_m = 0.8 \) and \( \Omega_{SL} \) has the units of steradian.

13.3. Perytons from Bleien Observatory

An important very recent development is the detection of Peryton-like events at the Bleien Observatory located 50 km west of Zurich, Switzerland (Saint-Hilaire et al. 2014). These authors recorded the radio spectrum of the sky with a log-periodic antenna in the band 1.15–1.74 GHz. The spectrometer channel width and dump time were 1 MHz and 10 ms, respectively. The beam of the antenna was 110 \( \phi \) in the north–south direction and 70 \( \phi \) in the east-west direction. Over 288 days (from 2009 June 3 to 2010 March 18), the authors found four daytime pulsed events with pulse widths of about 20 ms and peak fluxes ranging from 250 to 840 kJy, exhibiting a trajectory in the frequency-time plane consistent with a \( v^{-2} \) sweep.

The inferred DMs are in the range 350–400 cm\(^{-3}\) pc, even though the search covered the range 50–2000 cm\(^{-3}\) pc. The DM determinations are necessarily crude, being limited by coarse time binning and low S/N (8–16). Apart from their apparent brilliance, these events appear to share all the properties of Perytons, including the strong clustering of the inferred DMs around 300 cm\(^{-3}\) pc. It is not unreasonable to conclude that these events are also Perytons. With this independent detection at an observatory far away from Parkes, we can reasonably conclude that Perytons are truly a worldwide phenomenon.\(^{34}\)

The mean time between the bright Perytons detected at the Bleien Observatory is 72 days. Next, the beam of the log-period antenna is 1.75 sr. Thus, the daily all-sky rate of the bright Bleien Perytons is 0.1 per day, or 36 per year.

13.4. Search for Perytons at ATA

A search for FRBs was undertaken at the Allen Telescope Array (ATA; Siemion et al. 2012). This array consists of 42 dishes each of 6 m diameter and operates in the 1.4 GHz band. We note that the Fresnel radius for the ATA antennas is 0.18 km. According to Figure 10, the ATA antennas are focused for daylight pulsing events (Siemion et al. 2012). The resulting instantaneous field

\(^{34}\) The Parkes data certainly required Perytons to be of local origin (the Shire of Parkes). The observations of Saint-Hilaire et al. (2014) elevate Perytons to worldwide or terrestrial status.
of view was an impressive 150 deg$^2$, and the experiment lasted 450 hr. The authors state, “This wide-field search yielded no detections, allowing us to place a limiting rate of less than 2 sky$^{-1}$ hr$^{-1}$ for 10 ms duration pulses having mean apparent flux densities greater than 44 Jy.” Apparently, despite a gain of nearly $10^4$ in peak flux sensitivity, the ATA experiment could not detect Perytons.

Adopting a mean peak flux of 440 kJy for the Bleien sample, we deduce that the all-sky daily rate of Perytons as a function of peak flux ($S$), $N_P(\lesssim S) \propto S^q$, would require that $q \gtrsim -0.67$. We appreciate that this inference is subject to Poisson errors, but nonetheless we are intrigued by the fact that the value of $q$ hints at a disk or even a curved atmosphere geometry for the distribution of Perytons (Appendix D).

We now estimate whether a typical bright Bleien Peryton could have been detected by the ATA dishes via sidelobes (Equation (59)). Thus, a 440 kJy compact source would be detectable to a single ATA antenna via off-axis response provided that $\theta/\theta_D < 6$. In this case, the effective field of view of the Fly’s Eye can be as large as 5400 deg$^2$. The product of the solid angle (where all sky is set to unity) and the exposure time of the Fly’s Eye experiment is 2.53 day-sec. The mean Poisson expectation is 0.25. Thus, the lack of detection of a single bright Peryton ($S \gtrsim 440$ kJy) via a sidelobe does not violently violate the Bleien rate.

13.5. Perytons from Parkes

Burke-Spolaor et al. (2011) and Kocz et al. (2012) report Perytons found in the analysis of the high-latitude data, while Bagchi et al. (2012) report events found in the Galactic plane survey. In both cases, the same (analog-filter bank) backend that was used to detect the Sparker was used with the multibeam receiver. Perytons have been found with the new digital filter bank55 (S. Burke Spolaor & M. Bailes 2013, private communication).

The observed rate of Perytons appears to be dependent on which survey the search (and analysis) was based on. Burke-Spolaor et al. (2011) spent 45 days of observing and found 16 Perytons (or 6 if those that occurred in a short period count as only one Peryton). Thus, their observed rate is 0.36 (0.13) per day where the quantity in brackets refers to “independent” Perytons. The typical peak flux density for this sample is 0.1 Jy. Bagchi et al. (2012) analyzed the Galactic plane data and found four Perytons over 75 days. The typical flux density is higher, 0.5 Jy. The daily observed rate is thus 0.05 (0.04) per day. At low Galactic latitudes the system temperature ($T_{sys}$) is higher than at high latitudes. So one expects a higher limiting flux and thus fewer Perytons, but the large difference between the rates of the two surveys (admittedly subject to severe Poisson errors) needs careful investigation.

The above rates are observed rates. Translation of these rates to all-sky rates depends on the location of Perytons (near-field or far-field). Burke-Spolaor et al. (2011) assume that Perytons are via pickup of bright sources by sidelobes that are severely off-axis: $\theta \gg 5^\circ$ from the principal pointing axis. Burke-Spolaor et al. (2011) go further and assume that the instantaneous field of view for the Perytons is the visible sky ($\Omega = 2\pi$ sr). This would, via Equation (60), require a pickup level of about $10^{-7}$,

55 From which FRBs were found and reported by Thornton et al. (2013).

56 Bagchi et al. (2012) quote a rate that is smaller than those quoted here because they treat each beam as an independent stream. Perytons are found in all beams, and thus the beams should not be counted as being independent.

57 We give the radius in units of degrees, but when computing solid angles, we switch to radians.
value of $\alpha$.\textsuperscript{38} Third, as can be seen from Figure 10, it is difficult (in the absence of high S/N) to distinguish a Peryton with $n_F = 1/2$ from that located at infinity ($n_F = 0$).

### 13.6. Searches for Perytons at Other Observatories

Currently, a search for FRBs is being carried out at the Expanded Very Large Array (EVLA).\textsuperscript{39} The array has 27 antennas with $D = 25$ m. The Fresnel scale for a single antenna, at a wavelength of 21 cm, is 3 km. Likely most Perytons will be in the far-field regime. A search for Perytons in the signal streams from each antenna would be useful. Perytons as nearby objects, given the spatial width of the B-array, will have substantial parallax. For instance, the sky angular position of a Peryton hypothetically located at 5 km will vary by $\pm 45^\circ$ as we go from one end of the array to the other. Thus, curiously enough, for the study of Perytons, the instant field of view of the VLA is 27 times that of a single 25 m telescope. This total field of view exceeds that of the Parkes multibeam system. Furthermore, given a smaller $a_F$, Perytons are likely to be in “focus” (relative to the situation at Parkes), and thus the Perytons will be brighter. Going forward, it appears to us that it would be quite promising to undertake commensal or archival analysis of \textit{L}-band data. A single detection of a Peryton will immediately inform us of its parallax.

The same comments apply to the search for FRBs with the Very Long Baseline Array (VLBA) system—the V-FASTR experiment (Wayth et al. 2012). An additional advantage of the V-FASTR experiment is that it can simultaneously search for Perytons in 10 different weather regions.

The Arecibo \textit{Sparker} radio telescope is also equipped with a multibeam pulsar receiver and signal processing system.\textsuperscript{40} For the Arecibo telescope, the $a_F = 443$ km at $\lambda = 21$ cm. Thus, relative to Parkes, the Perytons will be considerably out of focus (see Figure 12), and it may well be that Arecibo, despite its larger collecting area, will not detect any Perytons.

### 13.7. A Working Hypothesis

We propose a working hypothesis aimed at unifying Perytons, the \textit{Sparker}, and FRBs. The underpinnings are the following.

1. Perytons are atmospheric phenomena that are detected essentially on-axis (and not via sidelobes located a radian or two away from the boresight).
2. Perytons are seen in many beams for the Parkes multibeam receiver. Ergo, we deduce that they be located in the near field (“out of focus”). Thus, we infer that Perytons are located at distances not beyond the first Fresnel zone for the Parkes telescope at 21 cm wavelength.
3. The \textit{Sparker} is a Peryton that probably occurred close to the Fresnel radius of the telescope, $a_F$ (Equation 57). The higher distance ensures that the \textit{Sparker} will appear more or less in good focus. Our primary motivation for claiming that the \textit{Sparker} is a Peryton is that the DM of the \textit{Sparker} coincides with the peak of the DM distribution for Perytons (see also Bagchi et al. 2012).
4. The FRBs appear to be in good focus and therefore in this hypothesis have to occur beyond the Fresnel radius of the Parkes telescope at $\lambda = 21$ cm. As can be seen from Figure 10, the beam response for a source with $n_F \ll 1$ is not different from that of cosmic sources ($n_F \rightarrow 0$).

In this framework, for Perytons, the effective field of view is the larger of the circumscribed circle discussed above (5.3 deg$^2$) and the solid angle covered by the Fresnel point-spread function. The all-sky Peryton rate is then $(4\pi/\Delta\Omega)\nu_p$, where $\Delta\Omega$ is the larger of 5.3 deg$^2$ and the apparent angular size of Perytons (as seen by the Parkes telescope in the 20 cm band). The bulk of the Perytons in this hypothesis would be intrinsically weak signals, perhaps $100$ Jy to a few kJy.

We are acutely aware that our working hypothesis glosses over many key issues. To start with, we have provided no strong reasons for a natural, or atmospheric, origin for Perytons as opposed to a man-made origin. Next, we have not provided any physical model for the Perytons, nor have we even suggested why Peryton-like phenomena (the \textit{Sparker} and FRBs), occurring at supposedly larger heights\textsuperscript{41} in the atmosphere, should exhibit narrower pulses or show a $v^{-2}$ sweep of arrival time, nor why the \textit{Sparker} and one of the FRBs exhibit a frequency-dependent pulse width. In our defense, we note that Perytons are accepted to be local events and some of them show a $v^{-2}$ sweep of arrival time (within experimental errors; see above). So our suggestion has some basis in reality.

We end this section with two observations. In the proposed framework, for the Arecibo telescope, the Perytons, the \textit{Sparker}, and the FRBs will be deeply into the Fresnel region. Assigning nominal heights\textsuperscript{42} of 5 km, 20 km, and 40 km for Perytons, the \textit{Sparker}, and FRBs, respectively, we find Fresnel zone numbers of 86, 21, and 11. As can be seen from Figure 12, the pickup of Perytons by the giant Arecibo reflector, relative to the Parkes telescope, is diminished severely. Next, we note that a source even at a height of 100 km has $n_F \approx 4$, and the Fresnel beam would be quite out of focus (see Figure 11). Our proposed working hypothesis would have great difficulty (perhaps even to a fatal level) in explaining a single beam detection of an FRB by the Arecibo multibeam system. We do note that no Peryton—and for that matter no robust FRB—was reported from the archival analysis of the Arecibo data described in Deneva et al. (2009). Since the submission of the paper, we became aware of a detection of an FRB candidate at Arecibo (Spitler et al. 2014). We will assume that this Arecibo event is not a local artificial signal. In that case, the event must originate above the atmosphere (see discussion in Section 13.2 and also above). We point out that the broadband spectrum of the event is extremely unusual, having a spectral index, $\alpha$, ranging from 7 to 11! Spitler and coworkers explain this spectral index by positing that the event was seen in the sidelobe. This is a plausible explanation. However, we note that the event is located close to the Galactic equator. A small intervening ionized nebula (e.g., compact HI region) could also produce such a strong positive spectral index. Referring to Equation (10), we find that a free–free absorption of $\tau_0 \approx 4$ would be sufficient to convert an intrinsic spectral index of $-1$ to the observed spectral index. In this case, the Arecibo event would be an RRAT with an intervening compact nebula.

We conclude this section by noting that the Fresnel scale for the VLBA is $3 \times 10^3$ AU and that for the VLA is approximately the distance to the Moon. In that sense, a single detection of

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\textsuperscript{38} Conversely, we note that strong spectral indices, positive or negative and with large magnitudes, can also be obtained.

\textsuperscript{39} Principal Investigator: Casey Law.

\textsuperscript{40} http://www.naic.edu/alfa/pulsar/

\textsuperscript{41} We caution that what matters is the distance to the Peryton as opposed to the height. A Peryton at an altitude of, say, 3 km can be beyond the first Fresnel zone if viewed at low elevation angles.

\textsuperscript{42} Arecibo is a transit instrument, and so the sources are observed over head.
an FRB by the VLA will immediately establish an extralunar origin and one by the VLBA, an extra-solar-system origin.

14. CONCLUSIONS

From analysis of archival pulsar data obtained at the Parkes Observatory, astronomers have reported radio pulses with millisecond duration and with a frequency-dependent arrival time that, if interpreted as due to propagation, would require DMs considerably exceeding that expected from the Galactic ISM (Lorimer et al. 2007; Thornton et al. 2013). The short durations of these events require a high brightness temperature, even if their origin is Galactic, let alone extragalactic. The all-sky rate of FRBs is an astounding $10^4$ per day. In this paper we have explored a wide range of scenarios capable of explaining the properties and suggested progenitors of the Sparker (which has the lowest inferred DM; Lorimer et al. 2007) and FRBs (Thornton et al. 2013). Complicating this discussion is the presence of “Perytons,” which share the properties of FRBs but are conclusively identified as arising locally (terrestrial origin). The inferred DMs of the Perytons are strongly clustered in the range $300–400$ km.

We started our investigation of these sources by accepting that the large inferred DM for the Sparker is indeed a result of a signal propagating through a cold plasma. We arrived at the following conclusions.

1. Based on available archival imaging, the nebula that produces the large DM for the Sparker can be no closer than $300$ kpc. The minimum distance for the four FRBs (with their larger inferred DMs) would be higher. This conclusion led us to investigate extragalactic models for the sources.

2. We consider a host of plausible extragalactic progenitors, including supernovae, blazars, short hard bursts, white dwarf mergers, and SGRs. The models either are physically inconsistent (lack a suitable clean and relativistic environment to produce high brightness temperature bursts or suffer from free–free absorption in the general vicinity of the progenitor) or are unable to account for the high all-sky FRB rate ($10^4$ day$^{-1}$).

3. Of all the possible progenitors, giant flares from young magnetars present the most attractive physical model. This model has the advantage of naturally explaining why some FRBs show frequency-dependent pulse widths. The model can also account for the rates provided that an efficiency of $10^{-5}$ can be achieved in converting the energy release in giant flares into radio emission.

We believe that we have explored all reasonable stellar models for FRBs. Thus, should it turn out that FRBs are not of stellar origin, then nonstellar models (e.g., quasars, E. S. Phinney 2012, private communication; cosmic superconducting strings, Vachaspati 2008) have to be considered.

Consistent with our agnostic exploration of the FRB phenomenon, we drop the requirement that the Sparker’s large DM was produced by propagation through a cold plasma. In this framework the source produce a “chirped” signal (frequency-dependent arrival time). Chirped signals are used by the military (radar) and by communications (spread spectrum) and also arise from natural phenomena (e.g., bursts from the Sun, atmospheric events). We propose an empirical model unifying Perytons with FRBs, with the Perytons being in the near field of the Parkes telescope (where the Fresnel approximation holds) and FRBs being in the far field (where the traditional Fourier optics assumed by radio astronomers holds).

The inferred DM for the Sparker is similar to the mode of the Peryton distribution (Figure 9). Next, it is not obvious to us (from the signal level in different beams) that the Sparker has to be a source at a very large distance (Appendix A). Economy of hypotheses leads us to suggest that the Sparker itself is a Peryton that occurred at a height of about $20$ km (the Fresnel scale for the Parkes 64 m telescope at a wavelength of $21$ cm). In order to explain FRBs as Perytons, we require that the chirp rate of Perytons must scale proportionally with their distance (height). We offer no explanation for this requirement.

Perytons form a formidable foreground for FRBs. As such, further progress will require astronomers to understand the distribution of and distances to Perytons. Perytons show clearly that nature can produce chirped signals in the $21$ cm band, and so a thorough understanding of the Perytons will only help astronomers distinguish local sources from cosmic sources. Since Perytons are local sources with as yet unknown distances, some care is needed prior to comparing the rates of Perytons from different telescopes (with differing Fresnel scales).
In summary, there is no compelling evidence to support an extraterrestrial origin for FRBs. A plausible argument can be made to relate giant flares from SGRs to FRBs. In this picture, the typical redshift of an FRB is $z \approx 0.5$. An interferometric localization of FRBs will immediately rule out a local origin. The same data will show either a host galaxy (which would then revive stellar models or quasar models) or no host galaxy (which will favor truly exotic origins). A modest investment in several clusters of simple dipoles tuned to the 1–2 GHz band and separated moderately (tens to hundreds of kilometers) would be a worthwhile investment (if only to explore strong decimetric pulses not only from Galactic giant flares but from the gamut of Galactic sources).

Despite the current murky situation, it is tempting to think of bountiful diagnostics that can be provided by millisecond bursts of extragalactic origin. In Zheng et al. (2014) we review a couple of these diagnostics. In particular, we drew the reader’s attention to a unique way by which astronomers can search for solar-mass intergalactic MACHOs through FRBs.

We conclude by noting that in the title of the paper, “Giant Sparks at Cosmological Distances?,” the adjective “giant” refers to the nominal length scale of the emitting region (300 km; Section 8), and the word “spark” has the same meaning as in pulsar phenomenology. We point out that the traditional outcome of papers that pose a question in their title is generally in the negative. Nonetheless, one could take some comfort from the history of GRBs. This was an exotic phenomenon even for astronomers. The history of GRBs started generally in the negative. Nonetheless, one could take some comfort from the history of GRBs. This was an exotic phenomenon even for astronomers. The history of GRBs started with searches for possible terrestrial (artificial) signals. Since their discovery in 1967, the diversity of observed phenomenons has grown tremendously. Bursts of gamma-rays are now seen from atmospheric events (Fishman et al. 1994), from the Sun (Third Orbiting Solar Observatory; Kraushaar et al. 1972), from compact stellar sources in our Galaxy (Mazets et al. 1979; Cline et al. 1980; Kasliwal et al. 2008), from cosmological distances (Metzger et al. 1997), and from at least two distinct populations (Kouveliotou et al. 1993). So, at early times, what one could have considered to be a single phenomenon literally spans terrestrial to cosmological scales. It may well be that astronomers are on a similar adventure in the radio band.

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APPENDIX A

A BETTER LOCALIZATION OF THE SPARKER

With a single detection of a pulse by a single beam, the localization is necessarily poor—no better than the area of sky illuminated by the main beam. However, the Sparker was detected in 3 out of the 13 beams, with S/Ns of >100, ~21, and ~14; a summary can be found in Table 3. This pattern of detections, in principle, should allow us to improve the position of the Sparker. To this end, we need the location of the beams and the response of the beams. We tried several assumptions, which we briefly summarize. First, as a zero-order approximation, we assume that the beam shapes are Gaussian, with the widths and gains specified in Table 3, and that the ratios in intensities in the different beams are provided by the square of the S/N. We also assumed that the relative intensities are known to precision of about 5% and that the real S/N of the saturated beam is smaller than about 1000. Given these assumptions, we find that the Sparker localization is within the error region specified in Table 4. However, it is well known that the beam shapes of radio instruments are non-Gaussian. Therefore, next we attempt to use an electromagnetic model of the beam response supplied to us by L. Staveley-Smith (updated from Staveley-Smith et al. 1996; see Figure 13). The response function is valid for point sources located well beyond the first Fresnel zone.

We adopted the S/Ns given above for beams 6, 7, and 13, and $<5$ in the rest of the beams (Table 3). Since the S/N values are subject to Poisson errors, we allow for 3σ uncertainties in the S/N values that we used. However, we were not able to find any position within the Parkes multibeam field of view that can reproduce the observed detections. This failure could be due to the fact that (1) the electromagnetic model is not adequate to model responses at large angles (2θD to 3θD) or (2) the Sparker is not located at a great distance (in which case our use of the multibeam pattern is incorrect).

Burke-Spolaor et al. (2011) used an empirical beam response (by scanning the multibeam receiver across a bright pulsar) and found a best-fit position: R.A. = 19h44m4 ± 0.08 and decl. = $-75^\circ 17\pm 0^\circ 08$ (J2000). This position almost coincides with beam 6 (see Figure 1 and also Table 3). The Sparker is detected in beam 7 (due northwest) and beam 13 (due west). However, given the claimed location, we would have expected the Sparker to be detected by the beams due southeast, due east, and due northeast with S/Ns similar to those seen in beams 7 and 13, or at least with S/N > 5. The lack of detection in these three beams is troubling.
Figure 13. Parkes multibeam relative response pattern, based on electromagnetic modeling, as a function of position in degrees relative to the center of the field of view (L. Staveley-Smith 2013, private communication; updated from Staveley-Smith et al. 1996). The response function is valid for point sources located well beyond the first Fresnel zone.

(A color version of this figure is available in the online journal.)

The entry in boldface is the beam in which the Sparker signal is saturated (S/N > 100). FWHM stands for full width at half maximum of the beam. The adopted FWHM values are 14', 14.5', and 15' for the central beam, inner-ring beams, and outer-ring beams, respectively (see Manchester et al. 2001). The gain is the mean aperture efficiency of each beam (Manchester et al. 2001). The positions of the beams were provided to us by M. Bailes and D. Lorimer.

In order to deduce the most conservative localization of the Sparker, we adopted an approach based primarily on symmetry. We assumed that the beam pattern has circular symmetry. Since the Sparker was detected in three beams, but not in all the other beams, we conclude that the Sparker should be in the region between the three beams. Beams 7, 6, and 12 are on a straight line; therefore, the lower part of the localization region is perpendicular to the line connecting these beams. We assumed that the region is symmetric, mostly because beam 6 had the strongest detection. These considerations led us to a polygon (aka “kite”). The vertexes of this polygon are listed in Table 5. The northeast side of the polygon is defined by the centers of beams 6 and 7 (see Table 3), while the northwest side is defined by the centers of beams 7 and 13. The southeast side is perpendicular to the line joining beams 6 and 7, and the southwest side is the intersection of the line joining beams 13 and 12 and the southeast side.

### Table 3

| Beam | R.A. (J2000) | Decl. (J2000) | S/N | FWHM | Gain |
|------|--------------|---------------|-----|------|------|
| 1    | 01:21:18.0   | -74:46:01     | <5  | 14.0 | 0.74 |
| 2    | 01:17:09.8   | -74:22:04     | <5  | 14.1 | 0.69 |
| 3    | 01:24:19.5   | -74:19:33     | <5  | 14.1 | 0.69 |
| 4    | 01:28:37.7   | -74:43:00     | <5  | 14.1 | 0.69 |
| 5    | 01:25:39.1   | -75:09:40     | <5  | 14.1 | 0.69 |
| 6    | 01:18:06.0   | -75:12:19     | >100| 14.1 | 0.69 |
| 7    | 01:13:55.8   | -74:48:09     | 14  | 14.1 | 0.69 |
| 8    | 01:09:53.4   | -74:23:32     | <5  | 14.5 | 0.58 |
| 9    | 01:20:13.1   | -73:55:27     | <5  | 14.5 | 0.58 |
| 10   | 01:31:30.8   | -74:15:57     | <5  | 14.5 | 0.58 |
| 11   | 01:33:14.5   | -75:06:15     | <5  | 14.5 | 0.58 |
| 12   | 01:22:30.3   | -75:36:34     | <5  | 14.5 | 0.58 |
| 13   | 01:10:25.8   | -75:14:34     | 21  | 14.5 | 0.58 |

Notes. The entry in boldface is the beam in which the Sparker signal is saturated (S/N > 100). FWHM stands for full width at half maximum of the beam. The adopted FWHM values are 14', 14.5', and 15' for the central beam, inner-ring beams, and outer-ring beams, respectively (see Manchester et al. 2001). The gain is the mean aperture efficiency of each beam (Manchester et al. 2001). The positions of the beams were provided to us by M. Bailes and D. Lorimer.

### Table 4

Sparker Error Region

| R.A. (J2000) | Decl. (J2000) |
|--------------|---------------|
| 18.85619     | -75.12665     |
| 19.34551     | -75.18275     |
| 19.37912     | -75.19694     |
| 19.34551     | -75.20249     |
| 18.83199     | -75.14258     |
| 18.83064     | -75.13011     |

### Table 5

The Vertices of the Polygon that Encloses All Possible Positions of the Sparker

| R.A. (J2000) | Decl. (J2000) |
|--------------|---------------|
| 19.5250      | -75.2053      |
| 18.4825      | -74.8025      |
| 17.6075      | -75.2372      |
| 18.5900      | -75.3647      |

### APPENDIX B

**MONOENERGETIC PARTICLE SYNCHROTRON SPECTRUM**

The simplest model for producing an arbitrarily steep spectrum radio emission is to have monoenergetic electrons gyrating in a magnetic field. Starting at lower frequencies, the spectrum rises as $x^{1/3}$, peaking at $x = 0.29$ and declining as

$$S(x) = A\sqrt{x}\exp(-x), \quad x \gg 1.$$  \hspace{1cm} (B1)

Here $A$ is a normalization factor, $x = \nu/\nu_c$, and

$$\nu_c = \frac{3}{4\pi}\gamma^3\omega_B\sin(\alpha)$$ \hspace{1cm} (B2)

is the so-called gyro-synchrotron frequency. Here $\omega_B = eB/(\gamma m_c)$ is the gyro-frequency of an electron with Lorentz factor $\gamma$ and gyrating in a magnetic field of strength $B$ and moving in the mean at an angle $\alpha$ with respect to the field lines (Rybicki & Lightman 1979, Chapter 6).

For $x \gg 1$, the power-law slope is given by

$$\alpha = \frac{d\ln S_c}{d\ln \nu} = \frac{3}{2} - \frac{\nu}{\nu_c}.$$ \hspace{1cm} (B3)

At high frequencies, an arbitrarily large spectral index can be obtained by invoking a smaller value of $\nu_c$.

### APPENDIX C

**STARS AND SUPERNOVAE: DM AND EM**

Consider a star with a mass loss rate of $\dot{M}$ and radius $R_*$. In a steady state, this leads to a wind with a density radial distribution, $\rho(r)$, given by

$$\dot{M} = 4\pi r^2 \rho_w \rho(r).$$ \hspace{1cm} (C1)
Here \( v_p \) is the radial velocity of the wind many stellar radii away from the star. The DM, EM, and plasma frequency \( v_p \) are then given by

\[
DM = \int_{R_e}^{\infty} \frac{\rho(r)}{\mu m_H} \frac{d \rho(r)}{dr} = \frac{M}{4\pi v_p \mu m_H} R_e^{-1}, \tag{C2}
\]

\[
EM = \int_{R_e}^{\infty} \left( \frac{\rho(r)}{\mu m_H} \right)^2 \frac{d \rho(r)}{dr} = \left( \frac{\dot{M}}{4\pi v_p \mu m_H} \right)^2 R_e^{-3} \tag{C3}
\]

\[
v_p = \frac{1}{2\pi} \sqrt{\frac{4\pi n_e e^2}{m_e}} \text{ Hz}, \tag{C4}
\]

where \( \mu \) is the mean molecular weight of electrons.

The stellar wind velocity is clearly greater than the escape velocity. For stars on the lower main sequence, the escape velocity is constant since \( R \propto M \). We set \( v_w = 10^3 \text{ km s}^{-1} \) and for simplicity let \( \mu = 1 \). Then we find

\[
DM = 17 B^2 \left( \frac{R_e}{R_\odot} \right)^{-1} \text{ cm}^{-3} \text{ pc},
\]

\[
EM = 4 \times 10^9 B^2 \left( \frac{R_e}{R_\odot} \right)^{-3} \text{ cm}^{-6} \text{ pc},
\]

\[
v_p = 223 B^{1/2} \left( \frac{R_e}{R_\odot} \right)^{-1} \text{ MHz}, \tag{C5}
\]

where \( B = \dot{M}_{-10}/(v_w/10^3 \text{ km s}^{-1}) \) and \( \dot{M}_{-10} = M/10^{-10} \text{ M}_\odot \text{ yr}^{-1} \). These equations show why stellar models cannot produce sufficient DM without producing a very large EM leading to free–free absorption in the decimetric band.

In the model of Loeb et al. (2014), the radio pulse is produced at some radius within an extended corona and the DM results from the pulse propagating to the surface. Such an extended corona cannot be stably bound to the star, and it is reasonable to assume a wind solution as above. However, we will not assume a steady state. Let the radio pulse be emitted at radius \( R_e \) and the edge of the corona be at \( L \). In this case, the DM and EM are

\[
DM = n_e R_e \left[ 1 - \left( \frac{R_e}{L} \right) \right],
\]

\[
EM = \frac{n_e^2 R_e^3}{3} \left[ 1 - \left( \frac{R_e}{L} \right)^3 \right],
\]

\[
= \frac{DM^2 \left[ 1 - \left( \frac{R_e}{L} \right)^3 \right]}{3 R_p \left[ 1 - \left( \frac{R_e}{L} \right)^2 \right]}, \tag{C6}
\]

where \( n_e = n_e(R_e) \) and \( R_p = R_e/(1 \text{ pc}) \). Even if \( L \) is greater than \( R_e \), by as little as a factor of 1.3, we have \( EM \approx DM^2/R_p \).

One of the models suggested for the Parkes events is the merger of two white dwarfs that eventually forms a magnetar (Levan et al. 2006). Our current understanding of the merger is as follows: the lower-mass white dwarf is tidally disrupted and accretes onto the other (“primary”) white dwarf. During the mass buildup of the primary white dwarf, a fraction of the accretion energy drives a very strong stellar wind. The relevant outflow velocity is the escape velocity of the primary star, and so \( v_w \approx 5 \times 10^8 \text{ cm s}^{-1} \). Using the convention from supernovae, we have \( A_s = M/(4\pi v_w^2) \times 5 \times 10^{11} \text{ gm cm}^{-1} \) (Chevalier & Fransson 2006). \( A_s = 1 \) for \( v_w = 5 \times 10^8 \text{ km s}^{-1} \) and \( M = 5 \times 10^{-5} \text{ M}_\odot \text{ yr}^{-1} \). Rescaling from Equation (C5)

\[
\tau_\text{ff}(v_0) = 1.9 A_s^2 r_{15}^{-3} \cdot \tag{C7}
\]

\[
v_p = 5 A_s^{1/2} r_{15}^{-1} \text{ MHz}, \tag{C8}
\]

These two equations inform us that only radio emission emitted after the blast wave has crossed the radius at which the free–free optical depth is sufficiently small will reach the observer. For instance, even if the stellar wind lasts for a day, the circumstellar medium will be optically thick to decimetric radiation (provided that \( A_s \) is comparable to unity).

Next, we consider the case of a merger product transmuting to the next level of compactness: merged white dwarfs to magnetar, or merged neutron stars to a rapidly spinning black hole. We will assume that a mass \( \Delta M \) is ejected at subrelativistic velocities \( v \) in a spherical geometry. Numerical simulations suggest \( 10^{-4} \lesssim \Delta M \lesssim 10^{-2} \text{ M}_\odot \) (Hotokezaka et al. 2013). Let us assume that the debris is a shell of radius \( R = \rho t \) and has a width \( \Delta R = f R \), with \( f \) being assumed to be a constant (with time). Then

\[
n_e = 9.5 \times 10^9 f_{-1} \Delta M_{-2} V_{10}^{-1} v_{10}^{-3} \text{ cm}^{-3},
\]

\[
v_p = 878 \left( f_{-1} \Delta M_{-2} V_{10}^{-3} v_{10}^{-3} \right)^{1/2} \text{ MHz}, \tag{C9}
\]

\[
DM = 3.1 \times 10^5 \Delta M_{-2} V_{10}^{-2} \nu_{10}^{-2} \text{ cm}^{-3} \text{ pc},
\]

\[
EM = 3 \times 10^{15} f_{-1} \Delta M_{-2} V_{10}^{-5} \nu_{10}^{-5} \text{ cm}^{-6} \text{ pc}, \tag{C10}
\]

where \( \Delta M = 10^{-2} \text{ M}_\odot, v = 10^{10} \text{ km s}^{-1} \), and \( f = 0.1 \). Thus, for these nominal parameters one would have to wait many months before any radio emission from the central source can successfully propagate to the outside world.
Table 6
Table of Frequently Used Symbols

| Symbol | Meaning | Units/Value | Section |
|--------|---------|-------------|---------|
| DM     | Dispersion Measure | cm$^{-1}$ pc | Section 1 |
| $t$    | Arrival time of radio signal | sec | Section 1 |
| $v$    | Frequency of radio signal | GHz | Section 1 |
| $n$    | Exponent of relation between $t$ and $v$, $t(v) \propto v^{n}$ | | Section 1 |
| $N'$  | All-sky daily event rate | day$^{-1}$ | Section 1 |
| $\Delta t$ | Measured pulse width at frequency $v$ | ms | Section 1 |
| $L$   | Thickness (size) of nebula causing most of DM | pc | Section 2 |
| $d$   | Distance to the nebula | pc | Section 2 |
| $D$   | Distance to the source ($>d$) | pc | Section 2 |
| $v_0$ | Center frequency of observing band | 1.4 GHz | Section 3 |
| $S_0$ | Spectral flux density at frequency $v_0$ | Jy | Section 3.1 |
| $\Delta t_0$ | Measured pulse width at $v_0$ | ms | Section 3.1 |
| $\Delta t$ | Intrinsic pulse width at $v_0$ | 1 ms | Section 3.1 |
| $S(v)$ | Spectral flux density at frequency, $v$ | Jy | Section 3.1 |
| $F(v)$ | Fluence, $S(v)\Delta t(v)$ | Jy ms | Section 3.1 |
| $\alpha$ | Spectral index of the spectrum of the fluence, $F(v) \propto v^{\alpha}$ | -1 | Section 3.1 |
| $\tau_0$ | Free–free optical depth at frequency $v = v_0$ | | Section 3.1 |
| $v_0$ | The lowest frequency of source emission | GHz | Section 3.1 |
| $v_0'$ | The highest frequency of source emission | GHz | Section 3.1 |
| $\dot{E}_R$ | Isotopic total (integrating from $v_1$ to $v_0$) energy release | erg | Section 3.1 |
| $D_{nc}$ | Distance to the source in units of kiloparsecs | kpc | Section 3.1 |
| $R$ | Radius of the source | pc | Section 3.2 |
| $T_{B}(v)$ | Brightness temperature at frequency $v$ | K | Section 3.2 |
| $\Gamma$ | Bulk Lorentz factor of the expanding source | | Section 3.2 |
| $\text{EM}$ | Emission Measure of the nebula | cm$^{-6}$ pc | Section 4 |
| $n_e$ | Mean electron density in nebula | cm$^{-3}$ | Section 4 |
| $L_{pc}$ | The thickness of nebula in parsec units | pc | Section 4 |
| $\tau_{ff}(v)$ | Free–free optical depth of the nebula at frequency $v$ | | Section 4.1 |
| $T_e$ | Temperature of nebula | K | Section 4.1 |
| $\alpha'$ | The log-derivative of $F(v)$ | | Section 4.1 |
| $\nu_0$ | The characteristic frequency of an exponential spectrum | GHz | Section 4.1 |
| $L_{II}$ | The size of the nebula for which $\tau(v_0) = 5$ | pc | Section 4.1 |
| $F_\text{bol}$ | Bolometric Fluence | erg cm$^{-2}$ | Section 4.1 |
| $\theta_{\text{sm}}$ | Maximum angular size of nebula | deg | Section 4.2 |
| $\text{Superscript}^S$ | Object located in Milky Ways | | Section 4.3 |
| $\text{Superscript}^G$ | Object located in SMC | | Section 4.3 |
| $F_{\text{Hz}}$ | Line-integrated Hz emission | erg cm$^{-2}$ s$^{-1}$ | Section 4.4 |
| $d_{\text{min}}$ | Minimum distance to the nebula | pc | Section 4.4 |
| $N_I$ | Rate of ionization within the nebula | s$^{-1}$ | Section 4.5 |
| $N_{RI}$ | Rate of recombinination within the nebula | s$^{-1}$ | Section 4.5 |
| $u_B$ | Case-B recombinination rate | cm$^{-1}$ s$^{-1}$ | Section 4.5 |
| $h\nu_1$ | Energy of a photon at the Lyman edge | 13.6 eV | Section 4.5 |
| $\Delta \nu_{\text{UV}}$ | $GALEX$ color: FUV–NUV | AB mag | Section 4.5 |
| $\phi_{\nu}$ | Volume filling factor of the nebula | | Section 5 |
| $n_0$ | Particle density of ambient medium | cm$^{-3}$ | Section 6.1 |
| $v_1$ | Velocity of shock into the ambient medium | cm s$^{-1}$ | Section 6.1 |
| $N_e$ | Total number of electrons in (flash-ionized) nebula | | Section 6.2 |
| $\tau_{\text{ion}}(v)$ | Timescale for ionization of a neutral atom at the edge of the nebula | yr | Section 6.2 |
| $\Delta t_{\text{soft}}$ | Duration of the soft X-ray flash | ms | Section 6.2 |
| $E_{\text{soft}}$ | Energy release of the soft X-ray flash | erg | Section 6.2 |
| $\tau_{\text{re}}$ | Recombination timescale within the nebula | s | Section 6.2 |
| $R_s$ | Radius of the stellar corona | pc | Section 7 |
| $R_{pc}$ | Radius of the stellar corona in units of parsecs | pc | Section 7 |
| $\alpha(v)$ | Free–free absorption coefficient per unit length | cm$^{-1}$ | Section 7 |
| $\tau(v)$ | Free–free optical depth at frequency $v$ | | Section 7 |
| $M$ | Mass loss from corona | $M_\odot$ yr$^{-1}$ | Section 7 |
| $\epsilon_{\text{ff}}$ | Free–free luminosity per unit volume | erg cm$^{-3}$ s$^{-1}$ | Section 7 |
| $\epsilon_{\text{ff}}$ | Free–free luminosity | erg s$^{-1}$ | Section 7 |
| $f_{\text{fit}}$ | Bolometric flux density from corona | erg cm$^{-2}$ s$^{-1}$ | Section 7 |
| $F_{\text{m}}$ | Bolometric flux from corona | erg cm$^{-2}$ | Section 7 |
| $\tau_{\text{in}}$ | Duration of hard X-ray emission | s | Section 7 |
| $\epsilon_{\text{is}}$ | Isotropic energy release from FRBs in the radio band | erg | Section 8 |
| $\Phi_{\text{FRB}}$ | Volumetric annual rate of fast radio bursts (FRBs) | Gpc$^{-3}$ yr$^{-1}$ | Section 9 |
| $A$ | Mass loss parameter, $A = M/(\dot{E}_R v_0)$ | g cm$^{-1}$ | Section 9.1 |
| $A_\nu$ | Mass loss parameter, $A$, in units of $5 \times 10^{11}$ g cm$^{-1}$ | | Section 9.1 |
| $P_\text{t}$ | Period of neutron star just prior to collapse into a black hole | ms | Section 9.2 |
Appendix D

Source Counts

Here we review the source count for several geometries (in particular curved atmosphere). This section may be useful in inferring the geometry of Perytons (from observations).

Spherical Geometry. Consider the following case: a homogeneous population of sources, density \( s \) per unit volume, with identical luminosity, \( L \), in Euclidean geometry. Then the volume within distance \( r \) is \( V(<r) = (4/3)\pi r^3 \). The flux density at Earth is \( S = L/(4\pi r^2) \). Thus number of sources with flux density less than \( S \) is

\[
N(<S) = \frac{4\pi}{3} r^3 \propto S^{-3/2} \tag{D1}
\]

with \( p = 3/2 \).

Plane-parallel Geometry. Now consider a slab of height \( h \) and extending indefinitely along its length as shown in Figure 14. For \( r < h \), we have the same scaling as in the spherical case. For \( r > h \) the volume of the atmosphere is the difference between the volume of the hemisphere of radius \( r \) and the volume of the polar cap whose height is \( r-h \). This volume is

\[
V(<r) = \pi h^3 \left[ \frac{r^2}{h^2} - \frac{1}{3} \right]. \tag{D2}
\]

Thus, in this case \( V(<r) \) asymptotically approaches \( r^2 \) (as \( r \gg h \)) and \( N(S) \propto S^{-p} \) with \( p \to 1 \).

Curved Atmosphere Geometry. Now consider an atmosphere enclosing a sphere (as in the case of our atmosphere). In this case, as can be seen from Figure 15, \( V(r) \) has a maximum value. For \( r \lesssim h \), a sphere of radius \( r \) will be within the atmosphere and thus \( p \approx 3/2 \). Next, the maximum value for \( r \) is \( w = \sqrt{2Rh + h^2} \). Clearly, we run out of volume, \( V(<r) \), when \( r > w \). Thus, \( p = 0 \), asymptotically. Thus, a flat power-law index (especially \( p \lesssim 1/2 \)) would indicate a population within a curved atmosphere.

An elegant derivation of the differential and the integral was obtained by E. S. Phinney:

\[
\frac{dV}{dr} = 2\pi r^2 \left[ \frac{(R+h)^2 - R^2 - r^2}{2R} \right] = \frac{\pi r}{R} [2Rh + h^2 - r^2]
\]

\[
V(<r) = \frac{2\pi}{3} h^3 + \frac{\pi}{2R} [2Rh + h^2] + \frac{\pi}{4R} (h^4 - r^4), \tag{D3}
\]

which is valid for \( h < r < w \). In the limit of \( h \ll R \) the formula for plane-parallel distribution is recovered (Equation (D2)). The differential formula is well suited for computing the population distribution with a specified vertical dependence for the density of the sources.
