

On the origin of a highly dispersed coherent radio burst

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Accepted 2012 June 14. Received 2012 June 13; in original form 2012 April 10

ABSTRACT

We discuss the possible source of a highly dispersed radio transient discovered in the Parkes Multibeam Pulsar Survey (PMPS). The pulse has a dispersion measure of $746 \text{ cm}^{-3} \text{ pc}$, a peak flux density of 400 mJy for the observed pulse width of 7.8 ms and a flat spectrum across a 288-MHz band centred on 1374 MHz . The flat spectrum suggests that the pulse did not originate from a pulsar, but is consistent with radio-emitting magnetar spectra. The non-detection of subsequent bursts constrains any possible pulsar period to $\gtrsim 1 \text{ s}$, and the pulse energy distribution to being much flatter than typical giant pulse emitting pulsars. The burst is also consistent with the radio signal theorized from an annihilating mini black hole. Extrapolating the PMPS detection rate provides a limit of $\Omega_{\text{BH}} \lesssim 5 \times 10^{-14}$ on the density of these objects. We investigate the consistency of these two scenarios, plus several other possible solutions, as potential explanations to the origin of the pulse, as well as for another transient with similar properties: the Lorimer burst.

Key words: black hole physics – surveys – pulsars: general – Galaxy: stellar content – cosmological parameters.

1 INTRODUCTION

There are many known and proposed sources of transient radio wave emission in the Universe – from well-known terrestrial, Solar system and Galactic sources to a menagerie of hypothesized sources covering a broad range in terms of potential detectability and plausibility. Many of the known sources recur, e.g. solar radio bursts occur every day (Nita et al. 2002), and the pulses from some radio pulsars repeat so reliably that they can be used as ‘cosmic clocks’ to detect the stochastic gravitational wave background (Hobbs et al. 2010). Some bursts, however, are less regular in their recurrence, and indeed several radio transients have never been observed to repeat. This latter group is of particular interest, especially as a number of the postulated sources are one-time-only events which would never repeat, and as the numbers detected should rise dramatically with the onset of the ‘all-sky transient monitoring’ capabilities of Low Frequency ARray (LOFAR; Stappers et al. 2011), the Very Large Array (VLA; Perley et al. 2011), MeerKAT (Booth et al. 2009), Australian SKA Pathfinder (ASKAP; Johnston et al. 2008) and ultimately the Square Kilometre Array (SKA; Colegate & Clarke 2011).

The numerous radio pulsar surveys constitute a rich, and perhaps the best available, data archive for exploring the parameter space of potential radio transients – especially at millisecond to second scales. Many have never been searched for transient bursts. In one such search of the Parkes Multibeam Pulsar Survey (PMPS;

Manchester et al. 2001), a highly dispersed single burst of radio emission was discovered (Keane et al. 2010, 2011). This burst, which was detected, in a beam with 7-arcmin half-power radius, in the direction of $\text{RA} = 18:52:05$, $\text{Dec.} = -08:29:35$, i.e. $l = 25^\circ:43:42$, $b = -4^\circ:00:42$, is the subject of this paper. In Section 2 we describe the properties of the pulse. In Section 3 we consider possible solutions as to its origin. Throughout, we present the corresponding discussion for the ‘Lorimer burst’ (LB) reported by Lorimer et al. (2007). In Section 4 we present our conclusions and a discussion on these matters.

2 THE PULSE

The pulse in question was received in the PMPS on 2001 June 21 (MJD 52081) in observation PM0141_017A1, i.e. in beam A (the 10th beam, in the outer hexagonal ring of the receiver) in the 17th pointing recorded on survey tape 141. The observation started at $12:57:32 \text{ UTC}$ (MJD 52081.539 953 703 701 UTC) and the pulse was detected 278.795 s into the observation, i.e. at $13:02:10.795 \text{ UTC}$ (MJD 52081.543 180 497 682 UTC). The SIMBAD astronomical data base lists only seven sources within a radius of 7 arcmin : six are optical/infrared stars and one is an X-ray source. There are no $\text{H}\alpha$ or H I anomalies at this position.

2.1 Characteristics

The pulse was detected in only one of the 13 beams of the receiver, with a peak signal-to-noise ratio (S/N) of 16.3. Fig. 1 shows the pulse as a function of observing time and sky frequency.

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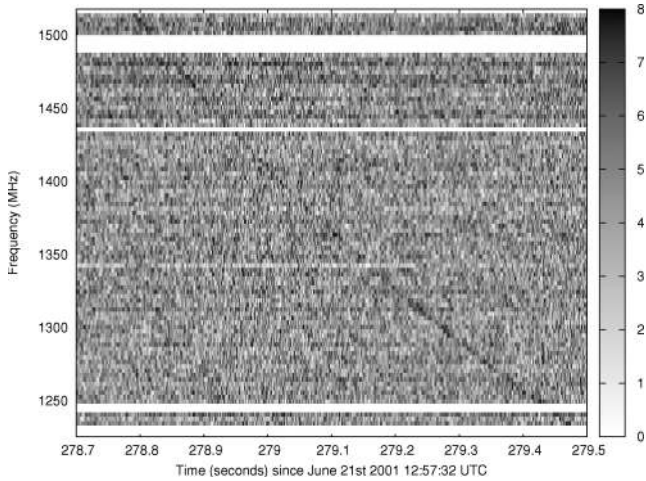


Figure 1. The pulse from J1852–08, as a function of sky frequency and observing time, with amplitude represented by a grey-scale. Here eight 250- μ s samples have been added together to produce the grey-scale (0 = white, 8 = black) from the original 1-bit data. Nine of the 96 channels contain no information and have been set to zero. The frequency-dependent delay is proportional to $f^{-2.02 \pm 0.01}$, and the best-fitting DM is $746 \text{ cm}^{-3} \text{ pc}$.

A frequency-dependent delay is evident. The dispersion measure (DM) which produces the highest S/N, when dedispersed with respect to the standard relation for a cold ionized interstellar medium $t_{\text{delay},s} = 4150 \text{ DM} / f_{\text{MHz}}^2$, is $746 \pm 1 \text{ cm}^{-3} \text{ pc}$. Testing how well such a law is obeyed by fitting for a frequency-dependent delay function which is proportional to f^α gives $\alpha = -2.02 \pm 0.01$. This is robust to dividing the 96-channel data into as many as 16 parts, before obtaining a time of arrival (using standard pulsar timing methods) at each sub-band and then fitting. For 16 sub-bands, the average S/N per sub-band is ≈ 4 . Finer frequency resolution results in unacceptably low S/N in the sub-bands.

The observed pulse width, when the data are dedispersed to 1516.5 MHz (the top of the band) using a DM of $746 \text{ cm}^{-3} \text{ pc}$, is 7.8 ms (the PMPS time resolution is 250 μ s). The pulse width is 7.7 ms in the top-half of the band (dedispersed to 1516.5 MHz) and 8.4 ms in the bottom-half of the band (dedispersed to 1372.5 MHz). Finer frequency resolution shows the pulse width to be constant (within the limits of what can be determined for the S/N) as a function of frequency across the entire 288-MHz band. The pulse is barely resolved (if at all), as the dispersive smearing time within the 3-MHz frequency channels is 7.1 ms (9.9 and 5.7 ms) at the middle (bottom and top) of the band. Removing this contribution from the observed pulse width reveals that any intrinsic width, combined with any scatter broadening, amounts to no more than 3 ms. A steep power law, e.g. the Kolmogorov scenario with $W \propto f^{-4.4}$, can be ruled out, as can the predicted scatter broadening time of ~ 130 ms from the empirical estimate of Bhat et al. (2004), although the latter is known to be uncertain to at least two orders of magnitude.

With a measure of S/N as a function of frequency, we can, with a knowledge of the sensitivity of the instrument, determine the radio spectrum of the pulse. This results in peak flux densities, for the observed pulse width, ranging from as low as 360 to as high as 510 mJy across the band, with a slight dip in flux density in the middle of the band (see Fig. 1). Within the error in this estimation (expected to be at least 30 per cent) and the limits of the available S/N, this is consistent with a flat spectrum. Another factor, potentially the dominant source of uncertainty, is the angular and frequency dependence of the telescope gain. The pulse is unlikely

to have been detected along the central axis of the beam corresponding to maximum sensitivity, where the gain is 0.581 K Jy^{-1} (Manchester et al. 2001). The beam responses are well described as Gaussian, with half-power beam widths (HPBW) of 14.5 arcmin at the central frequency of 1374 MHz. In addition to this angular dependence, the HPBW will scale linearly with frequency so that at the top of the band, at 1518 MHz, it will be narrower than at the bottom of the band, at 1230 MHz, in proportion to the ratio of these frequencies. Clearly, the spectrum of any incident astrophysical signal will be made steeper by this effect if detected off-axis. Burke-Spolaor et al. (2011) discuss empirical measurements of this effect where a positive intrinsic spectral index β can appear as steep as $\beta - 3$. Thus, there is an extra (perhaps very large) uncertainty in the spectrum of the source, and the spectrum is likely to be flatter than observed. Below we take the peak flux density of the pulse (at the observed pulse width) to be 400 mJy. The intrinsic fluence, \mathfrak{F} , of the 7.8-ms burst is thus

$$\mathfrak{F} = 1.2 \times 10^{13} (D/20 \text{ kpc})^2 \text{ J Hz}^{-1}. \quad (1)$$

2.2 Distance

The distance to the source of the pulse, whatever it may be, is uncertain. The only available estimate is to invert the relationship between DM and distance: $\text{DM} = \int_0^D n_e dl$. This requires a model of the free electron density. The current best model is NE2001 (Cordes & Lazio 2002) which predicts that a maximum of $533 \text{ cm}^{-3} \text{ pc}$ of the DM is contributed by the Galaxy towards the total value of $746 \text{ cm}^{-3} \text{ pc}$. The six pulsars within a radius of 2° of this line of sight have DMs of no more than $282 \text{ cm}^{-3} \text{ pc}$. To estimate the distance, there are two options: (i) assume that the NE2001 model is incorrect along this line of sight, so that all of the DM contribution is due to Galactic material, and the source is then within our Galaxy at a distance of $\lesssim 20 \text{ kpc}$ (this being where the ‘Galaxy ends’ according to the NE2001 model); (ii) take the NE2001 estimate to be correct, in which case the excess DM of $223 \text{ cm}^{-3} \text{ pc}$ would be due to the intergalactic medium and any putative host galaxy for the source. In the second scenario, repeating the analysis of Lorimer et al. (2007), an extremely large distance of $\approx 500 h^{-1} \text{ Mpc}$ results.

2.3 Re-observations

Deciding between these two possibilities is crucial as the implied luminosities, and therefore likely progenitors, depend on it. Motivated by this we performed follow-up observations using the Parkes Telescope to test the hypothesis that the source is Galactic (i.e. NE2001 is incorrect) and a pulsar which emits giant pulses (GPs; the most likely Galactic solution). In this scenario, many more weaker pulses would be expected to be easily detected. We used analogue filter banks, the same backend as was used in the original survey (Manchester et al. 2001), with 0.5-MHz and 100- μ s frequency and time resolution, respectively, recording Stokes I with 1-bit digitization. Concurrently, we recorded Stokes $IQUV$ data, with the digital filter banks with 8-bit digitization, with the aim of looking more closely at these data, with polarization information and with more dynamic range, if a second event was detected in the total intensity data. In 15 h of follow-up only two events were detected which were inconsistent with radiometer noise, both of which were clearly due to narrow-band radio frequency interference (RFI). No further pulses from J1852–08 were seen in a total of 15.5 h of observation. In the following section, we investigate the implications of this.

3 POSSIBLE SOLUTIONS

3.1 Radio frequency interference

The strongest signals detectable by any radio telescope are often of terrestrial origin. In searches for isolated astrophysical bursts, there are several steps we can follow to minimize the effects of RFI. For instance, the zero-DM subtraction technique can be used to remove broad-band RFI, using the fact that it will be strongest at a DM of zero (Eatough, Keane & Lyne 2009). Narrow-band RFI can be removed by keeping an account of the bandpass as a function of time and excising anomalously high or variable channels. Furthermore, for pulsar surveys performed at Parkes using the 13-beam 21-cm receiver, boresight sources are not expected to appear in more than four beams at once. Most astrophysical signals are detected in only one beam, and many RFI signals are detected in several beams, i.e. they are detected in the sidelobes of the beams' gain patterns, so that a multibeam coincidence test can be used to discriminate against these undesired signals. This can take the form of a post-facto comparison of detected events (Keane et al. 2010) or, as has recently been implemented by Kocz et al. (2012), a full cross-correlation of the signals from each beam. The pulse under consideration here survives all of these checks which leads us to conclude that it is astrophysical in origin. As stated in Section 2 the pulse follows the theoretical f^{-2} dispersion law without deviation and is detected in only one beam of the 21-cm receiver. This clearly contrasts not only with typical RFI signals, but also with less commonly encountered RFI signals such as the 'periton' signals (Burke-Spolaor et al. 2011; Kocz et al. 2012). These signals are detected in most/all beams, but with atypical frequency-dependent delay. This delay is somewhat quadratic, but with 'kinks' where $dt/df \approx 0$. These authors also noted that the inferred DM for these signals, if one fits for the theoretical quadratic dispersion law, is, in the case of 15 of the 21 peritons reported, within 10 per cent of $375 \text{ cm}^{-3} \text{ pc}$, the DM for the LB. Other curious characteristics of the periton signals include the following: they all occur in the UTC range 0–3, have a tendency to appear in the latter ~ 20 per cent of each second and are separated by gaps of ~ 22 s. In the light of the dissimilarity between these signals and the burst discussed in this paper, we are confident that the two phenomena are not linked. Furthermore, we agree with the conclusion of Burke-Spolaor et al. (2011) that the LB originated from a boresight astrophysical source, as originally concluded by Lorimer et al. (2007).

3.2 Pulsar giant pulse

Pulsar spectra are typically steep: their mean spectral index is -1.8 , with values steeper than -1 being very uncommon (Maron et al. 2000). Nevertheless, despite the flat spectrum of the pulse, we consider this possibility as, on a pulse-by-pulse basis, pulsar spectra can vary dramatically (Kramer et al. 2003) and because the radio-emitting magnetars show flat spectra (e.g. Levin et al. 2010, and references therein). This scenario presupposes that the NE2001 model is sufficiently uncertain, i.e. the free electron content is underestimated by more than 50 per cent along the line of sight to the source. This is possible; see e.g. Gaensler et al. (2008) who showed errors of a factor of 2 at high Galactic latitudes, and Deller et al. (2009) for a comparison with VLBI-derived distances. The most likely Galactic source to consider is that of a 'giant pulse' from a pulsar at the edge of the Galaxy. GPs are sometimes (arbitrarily) defined to be those pulses where the pulse 'energy' (i.e. the product of the peak flux density and the effective pulse width) is more than 10 times the

mean (Knight 2006). There are at least 14 pulsars known to exhibit GPs, the most notable being the Crab pulsar, which we will use as a template below. The pulse energy distributions for GPs follow power laws such that the number of GPs with energy $E > E_{\text{thresh}}$ is proportional to $E_{\text{thresh}}^{-\alpha}$. The measured value of α in the most recent analysis of the main pulse GPs of the Crab is 2.1 (Karuppusamy, Stappers & van Straten 2010). The lowest measured value is 1.4 for the millisecond pulsar B1937+21 (Soglasnov et al. 2004) and the highest is 4.5–4.8 for the 0.9-s pulsar B0031–07 (Kuzmin & Ershov 2004).

The detected pulse had a S/N of 16.3, whereas we would have been capable of easily detecting pulses at S/N values as low as 5. For a GP-emitting pulsar this means that we might have expected $(16.3/5)^\alpha$ weaker pulses (this is ~ 10 for the Crab's $\alpha = 2.1$) assuming similar pulse widths, or that the probability we get a pulse $> 5\sigma$ in a given (unknown) pulse period P is $(16.3/5)^\alpha/N$, where $N = (T_{\text{obs}}/P)$ is the total number of periods observed and T_{obs} is the observation time. Thus the probability of not seeing a single weaker pulse for N periods in a row is $[1 - (16.3/5)^\alpha/N]^N$, which (assuming $N \gg 1$, which it no doubt will be for any reasonable pulsar period) is just $\exp[-(16.3/5)^\alpha]$. This has the (perhaps counter-intuitive) implication that the limit on α is independent of the duration of the follow-up, as long as $N \gg 1$ and there are no redetections. Therefore, a probability of $< 10^{-5}$ implies $\alpha \gtrsim 2$ (such as for the Crab) is ruled out, and for a probability of $< 10^{-2}$, the range $\alpha \gtrsim 1.2$ is ruled out. Very flat distributions with $\alpha \lesssim 1$ are not ruled out.

Although the limit on α is no better for the 15.5 h of follow-up as compared to the 35-min PMPS observation alone, the limit on the GP rate is much stronger. The rate per period is $< 6 \times 10^{-7} (P/P_{\text{Crab}})$, whereas pulses with the same energy ($400 \text{ mJy} \times 7.8 \text{ ms} = 3.1 \times 10^3 \text{ Jy } \mu\text{s}$) occur with a much higher probability of $\approx 2 \times 10^{-3}$ in the case of the Crab's main-pulse GPs (see the top panel of fig. 5 in Karuppusamy et al. 2010). However, we should consider the intrinsic fluence, SWD^2 , for a fair comparison. Taking 20 kpc as the distance to J1852–08, and recalling that the distance to the Crab is 2 kpc, we see that we must consider the rate of pulses with energy $3.1 \times 10^5 \text{ Jy } \mu\text{s}$ which is $2 \times 10^{-3} (100)^{-2.1} \approx 10^{-7}$ for the Crab. This is not excluded by our rate limit; however, we know $\alpha < 1.2$, not 2.1 as for the Crab. Also, this implicitly assumes that the GP rate is identical to the Crab at an intrinsic fluence of $3.1 \times 10^5 \text{ Jy } \mu\text{s} \times (20 \text{ kpc})^2$. If we consider the rates to be identical at an intrinsic fluence 100 times lower and utilize our α limit, we get a rate of $\geq 2 \times 10^{-3} (100)^{-1.2} \approx 8 \times 10^{-6}$. Choosing a lower intrinsic energy as a reference point gives an even more constraining limit, although it is unclear where this point should be chosen.

We can see that a long-period pulsar with (say) $P \gtrsim 1$ s, or one with a GP burst rate 10–100 times less than the Crab, or, equivalently, a source with a high nulling fraction, is not ruled out. In the past 6 years a number of long-period pulsars have been discovered which might fit these criteria. The first group are the three radio-emitting magnetars. These sources show large modulation in single pulse flux density and flat radio spectra (Lazaridis et al. 2008). However, unlike the J1852–08 pulse, they are seen to be 'on' for very long time-scales and have been tracked over several years. The so-called 'RRATs' emit detectable pulses at a rate per period of between 10^{-3} and 10^{-1} . It is unclear, in most cases, whether or not these sources null, but the lower limit on the ratio of peak to average flux densities can be > 100 (e.g. Keane & McLaughlin 2011). The pulse energy distributions of these sources are not yet well studied, although some seem to show lognormal distributions (Keane et al. 2010), whereas the two sources with power-law distributions show $\alpha = 2$ and 3, respectively (Miller et al., in preparation). With

a single pulse, it is impossible to pass comment on the likelihood of a log normal (or any other two-parameter) distribution.

We applied the same analysis to the LB, where 40 h of follow-up observation has been reported without a further detection (Lorimer et al. 2007). In this case, we rule out $\alpha \gtrsim 1.0$ with a probability of 10^{-7} (and $\alpha \gtrsim 0.5$ with a probability of 10^{-2}), where we have adopted the Lorimer et al. S/N of 100. The limit on the GP rate per period is $< 2 \times 10^{-7} (P/P_{\text{Crab}})$. In the case of the LB, where the DM in excess of the NE2001 value is so much larger than in the J1852–08 case, and hence the distance is apparently $\gg 10$ kpc, this rate can be easily scaled to 1. However, using the nominal distance of 500 Mpc, the inferred radio luminosity is ~ 8 orders of magnitude brighter than the brightest pulse ever detected from the Crab, which seems much too luminous to be due to the same mechanism. For both bursts, we note that the above calculation of the limit for α implicitly assumes a rate of 1 per T_{obs} , whereas the best estimate for the rates, in both cases, can be taken to be $1.0^{+2.3}_{-0.8}$ per T_{obs} (Gehrels 1986), with corresponding probability of $\exp[-X(16.3/5)^\alpha]$, where $X \in (0.2, 3.3)$. If the true rate were lower than the nominal rate used, the α limit would be less constraining than stated above, whereas if the rate is in fact higher, the α limit would be even stronger.

3.3 Annihilating black holes

One theorized source of ‘single event’ radio signals are annihilating mini black holes. Evaporating black holes with $M_{\text{BH}} < 10^{13}$ kg can create electron–positron pairs (as $kT_{\text{BH}} > 2m_e c^2$). If evaporation can only proceed down to a mass M_{crit} , at which point the energy of $E = M_{\text{crit}} c^2$ is released, then pairs with (initial) Lorentz factors of $\gamma = 10^{13} \text{ kg}/M_{\text{crit}}$ are created. As first pointed out by Rees (1977), such a ‘fireball’ of relativistic pairs, which would have energy $E = 10^{30}/\gamma$ J and contain $E/(\gamma m_e c^2) = 10^{43}/\gamma^2$ pairs, expanding into the surrounding magnetic field of the interstellar medium, will produce surface currents and a radio burst. Blandford (1977) showed that the pairs will be sufficiently energetic to do this, while avoiding annihilation, in the range $10^5 < \gamma < 10^7$, and calculated the energy spectrum of the radio pulse to be

$$I_{\nu\Omega} = 6.7 \times 10^{-13} \frac{E^{4/3} |F(\nu/\nu_c)|^2}{(B \sin \theta)^{2/3} \gamma^{8/3}} \text{ J Hz}^{-1} \text{ sr}^{-1}, \quad (2)$$

where $F(\nu/\nu_c)$ describes the shape of the spectrum, a power law with spectral index -0.6 up to ν_c , a critical frequency ~ 10 GHz, above which the spectrum steepens significantly. Substituting in the earlier expression for E and parametrizing $b = (B \sin \theta)/(5 \mu\text{G})$ and $\gamma_5 = \gamma/10^5$, this becomes

$$I_{\nu\Omega} = 1.1 \times 10^{14} b_5^{-2/3} \gamma_5^{-4} |F(\nu/\nu_c)|^2 \text{ J Hz}^{-1} \text{ sr}^{-1}. \quad (3)$$

Such a pulse occurs in a single radio frequency cycle (and so is broad-band) at a frequency of ~ 1 GHz. The observed pulse width τ_{obs} is smeared with respect to the intrinsic width, so that the *inferred* ‘radio pseudo-luminosity’ of the radio pulse $L \approx (4\pi I_{\nu\Omega})/\tau_{\text{obs}}$ is simply

$$L_{\text{BH}} \approx \frac{140}{\tau_{\text{obs}}} b_5^{-2/3} \gamma_5^{-4} |F(\nu/\nu_c)|^2 \text{ Jy kpc}^2. \quad (4)$$

At $\nu/\nu_c \approx 0.1$, $|F(\nu/\nu_c)|^2 \approx 1$, so in our parametrization we have $L_{\text{BH}} \sim 140/\tau_{\text{obs}}$. However, we know that, by definition, $L = SD^2$, where S is flux density and D is distance. Thus, assuming the burst under consideration here is due to such an annihilating black hole, we can infer a distance from the observed S , τ_{obs} and expected L_{BH} value. This yields a distance of $\lesssim 200$ kpc. Both larger values of γ_5 and the lower sensitivity of an off-axis detection lower the distance.

In theory, this estimate for distance in the black hole scenario can be compared with the DM estimate for the distance as a check of consistency. We again have two scenarios: (i) if the NE2001 model is correct, then the distance is much too short and inconsistent with the DM distance; (ii) if the NE2001 model is sufficiently incorrect, so that we can attribute essentially all the dispersion to the ~ 20 kpc of Galactic material along the line of sight, then the scenario is not inconsistent. In the case of the LB, repeating this analysis we infer a distance of $\lesssim 25$ kpc, which is, regardless of whether or not NE2001 is hugely incorrect along that particular line of sight, much too short. Thus, this scenario is not a consistent explanation for the LB.

3.4 Other solutions

In double neutron star systems, one star will be recycled to millisecond periods, whereas the second will have a longer period (e.g. Lorimer 2008, and references therein). Hansen & Lyutikov (2001) consider such a binary, on the verge of merging due to the emission of gravitational waves, where the longer period star has a magnetic field of $\sim 10^{15}$ G and a period of $\gtrsim 10$ s. The millisecond pulsar fuels a flow of plasma in the light cylinder of the long-period pulsar, within which it is completely enclosed, resulting in the loss of orbital and spin energy to a broad-band coherent millisecond radio burst. The flux density detected at Earth for such an event, occurring at a distance D , is $S \approx 1 \text{ mJy} (\epsilon/0.1)(100 \text{ Mpc}/D)^2 B_{15}^{2/3}$, where ϵ is an efficiency factor and B_{15} is the magnetic field strength of the long-period neutron star in units of 10^{15} G. Applying this to the pulse under consideration here implies a distance of ~ 5 Mpc (~ 500 kpc) for magnetic field strengths of 10^{15} G (10^{12} G), which is not inconsistent with the observed dispersion, for a sufficiently incorrect NE2001 estimate along this line of sight. In the case of the LB, this yields a distance of ~ 600 kpc (~ 60 kpc), which is too small a distance to be consistent, regardless of the correctness of NE2001 for the line of sight. However, it is highly uncertain as to whether the signal could propagate through the ‘plasma shroud’ of the system, and the volumetric merger rate suggests that these events are unlikely to occur at distances $\ll 100$ Mpc (Hansen & Lyutikov 2001). A confirmation would necessarily require a detection of the gravitational wave counterpart signal, but as both pulses under discussion here occurred before the LIGO and GEO600 detectors came online, no such check is possible.

Colgate & Noerdlinger (1971) and Colgate (1975) considered the case of a supernova shell expanding into the magnetic field of the pre-existing star. The shell ‘combs’ the magnetic field into the radial direction, producing a current sheet and an associated coherent radio burst. As for the merger scenario, given the expected rates, the distance such events are expected to occur at is ~ 100 Mpc. Furthermore, for a volumetric supernova rate of $9 \times 10^{-5} \text{ Mpc}^{-3} \text{ yr}^{-1}$ (Horiuchi et al. 2011), the number of supernovae expected in the PMPS would be just ~ 0.1 assuming it would be sensitive out to 500 Mpc in all directions, which itself is highly optimistic given the effects of dispersion and scattering on sensitivity. The predicted allowable pulse energies cover a large range: $10^{27} - 10^{35}$ J, with the 1970s limits just probing the upper end of this range for sources at 100 Mpc (Meikle & Colgate 1978). Taking the pulse under consideration here to be due to such an event, the implied energy at 100 Mpc is $\approx 10^{29}$ J. The same calculation for the LB gives $\sim 5 \times 10^{30}$ J for the same distance. The wide (and therefore unconstraining) range of allowable energies mean that a distance consistent with the dispersion can easily be found.

Given the wide range of Lorentz factors possible ($\sim 10\text{--}10^6$), one might also devise a relativistic source to fit the observed distance and flux density, e.g. a precessing jet from a microquasar (R. Spencer, private communication). All of the other known types of radio transient signals can be dismissed due to either their time-scales or their lack of dispersion (as nearby sources) or both (Keane 2010).

4 CONCLUSIONS AND DISCUSSION

The pulse discussed here is consistent with a number of scenarios. It is consistent with a ‘giant pulse’ from either a young pulsar with a burst rate perhaps 10–100 times less than the Crab, or a long-period pulsar, albeit with quite a steep cumulative pulse energy distribution with $\alpha \lesssim 1$ and a flat radio spectrum more like those of the radio-emitting magnetars. A second scenario involving the radio signal from an annihilating mini black hole is also consistent. It is interesting that the two possibilities can only apply if the NE2001 model is sufficiently incorrect along the line of sight to the source that all of the dispersion is due to the Galaxy. It is also noteworthy that neither of these two scenarios gives a consistent solution for the LB, regardless of NE2001’s precision. We can use the lack of other detections in the PMPS to set an upper limit on Ω_{BH} , the cosmological density of mini black holes which produce radio bursts (i.e. primordial black holes within a certain mass range). From one event within a (say) 20-kpc radius, detected during the PMPS, whose duration was 0.21 yr and field of view was 0.55 deg^2 , we can extrapolate to obtain a limit of $\Omega_{\text{BH}} \lesssim 5 \times 10^{-14}/\gamma_5$. Although, amongst other things, this assumes that all such black holes produce radio bursts at the end of their lives, the implication is that annihilating black holes are an insignificant contribution to the matter density of the Universe.

Next we considered radio bursts from NS–NS mergers, which, although the rate is uncertain, can be consistent with an extragalactic source for the pulse, although again not for the LB. A burst associated with an expanding supernova shell allows solutions for both pulses, although the predicted energy range for the pulse (which spans eight orders of magnitude) means a meaningful comparison with DM-derived distances is not possible. An important point is that the intrinsic time-scale is unknown for the pulses discussed here. In both cases, the pulse widths are of the order of, and just slightly larger than, the dispersion smearing time within a single 3-MHz frequency channel. We cannot account for any contribution due to scattering in the intervening medium, as our knowledge of this effect along specific lines of sight through the Galaxy is very poor. However, this could be used to decide between the consistent solutions. For instance, if there is zero (or very little) scattering, then we would know that the intrinsic pulse time-scale is ~ 1 ms and the annihilating mini black hole (and supernova) scenarios would be ruled out. All we can say is that for the pulsars closest to the line of sight monitored by the Lovell Telescope, it is difficult to decipher scattering from intrinsic profile features, although the recent successful work by Hassall et al. (2012) in this area provides cause for optimism. Transient signals detected in the future with LOFAR, and other next-generation wide field-of-view telescopes, where rapid localization, classification, multiwavelength follow-up and the detection of any associated gravitational wave signal (e.g.

with Advanced LIGO) will be possible, lead us to believe that unambiguous identification of the sources of such energetic events will become routine in the SKA era.

ACKNOWLEDGMENTS

EFK acknowledges the FSM for support. The authors thank R. P. Eatough and the anonymous referee for useful discussion and helpful comments which have improved the quality of this paper.

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