Constraints on long-lived remnants of neutron star binary mergers from late-time radio observations of short duration gamma-ray bursts

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ABSTRACT

The coalescence of a binary neutron star (NS) system (a ‘NS merger’ or NSM) may in some cases produce a massive NS remnant that is long-lived and, potentially, indefinitely stable to gravitational collapse. Such a remnant has been proposed as an explanation for the late X-ray emission observed following some short duration gamma-ray bursts (GRBs) and as possible electromagnetic counterparts to the gravitational wave chirp. A stable NS merger remnant necessarily possesses a large rotational energy \(\sim > 10^{52}\) erg, the majority of which is ultimately deposited into the surrounding circumburst medium (CBM) at mildly relativistic velocities. We present Very Large Array (VLA) radio observations of 7 short GRBs, some of which possessed temporally extended X-ray emission, on timescales of \(\sim 1–3\) years following the initial burst. No radio sources were detected, with typical upper limits \(\sim 0.3\) mJy at \(\nu = 1.4\) GHz. A basic model for the synchrotron emission from the blast wave is used to constrain the presence of a long-lived NSM remnant in each system. Depending on the GRB, our non-detections translate into upper limits on the CBM density \(n \sim < 3 \times 10^{-2} - 3 \times 10^{-3}\) cm\(^{-3}\) required for consistency with the remnant hypothesis. Our upper limits rule out a long-lived remnant in GRB 050724 and 060505, but cannot rule out such a remnant in other systems due to their lower inferred CMB densities based on afterglow modeling or the lack of such constraints.

Key words: stars: magnetars, neutron – surveys – gamma-ray burst: general – gravitational waves

1 INTRODUCTION

The coalescence of binary neutron star [NS] (hereafter ‘neutron star mergers’, or NSMs) are promising central engines for powering short-duration gamma-ray bursts (GRBs) (Paczynski 1986; Eichler et al. 1989). NSMs are also the primary source of gravitational waves for upcoming ground-based interferometric detectors such as Advanced LIGO and Virgo (Abadie et al. 2010a).

Numerical simulations of the merger process (e.g. Ruffert & Janka 1999; Uryū et al. 2000; Rosswog & Liebendörfer 2003; Oechslin & Janka 2006; Chawla et al. 2010; Rezzolla et al. 2010; Hotokezaka et al. 2011) show that the end product of a NSM is typically a hyper-massive NS remnant, which is (at least temporarily) stable to gravitational collapse as the result of support by thermal pressure and/or differential rotation (Morrison et al. 2004; O’Connor & Ott 2011; Paschalidis et al. 2012; Lehner et al. 2012). In the past it has generally been assumed that the neutron star collapses to form a black hole within a relatively short timescale \(\sim < 100\) ms. The newly created black hole is surrounded by a thick remnant torus of mass \(M_t \sim 10^{-2} M_\odot\), the subsequent accretion of which may power the transient relativistic jet responsible for the GRB (e.g. Narayan et al. 1992; Rezzolla et al. 2011).

One of the biggest uncertainties in predicting the outcome of a NSM results from our incomplete knowledge of the equation of state of high density matter (Hebeler et al. 2013). The recent discovery of massive \(\sim 2 M_\odot\) neutron stars (Demorest et al. 2010; Antoniadis et al. 2013) indicates that the EoS is not as soft as predicted by some previous models. This increases the likelihood that NSMs could not only produce hyper-massive NSs, but also NSs which are indefinitely stable to gravitational collapse (e.g. Özel et al. 2010; Bucciantini et al. 2012; Giacomazzo & Perna 2013). Due to the high angular momentum of the merging binary, such a NS remnant will necessarily be rotating extremely rapidly, with a rotation period \(P \sim 1\) ms close to centrifugal break-up. The NS remnant may also acquire a strong magnetic field \(\geq 10^{14} - 10^{15}\) G similar to those of Galactic ‘magnetars’, since the initially weak field will be amplified by shear instabilities at

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The possibility that some mergers could leave stable magnetar remnants has recently received heightened attention as a possible explanation for the X-ray activity observed after some short GRBs, such as the ‘extended emission’ observed on timescales of minutes after the GRB [Metzger et al. 2008; Metzger et al. 2011; Bucciantini et al. 2012] and the X-ray ‘plateaux’ observed on longer timescales (Rowlinson et al. 2013; Gompertz et al. 2013). Acranon of the remnant torus cannot readily explain this emission, since the torus is not expected to be present at such late times due to powerful outflows that occur on timescales of seconds or less (e.g. Fernández & Metzger 2013). Prolonged energy injection from a magnetar remnant has also been proposed as a potential electromagnetic counterpart to the gravitational wave signal (Zhang 2013; Fig. 2, top panel), calculated for $\epsilon_g = 0.1(0.01)$. A stable neutron star remnant formed by a NSM possesses a significant magnetic field strength $B_\text{st}$, as occurs on a timescale $t_\text{dec}$, as occurs in similar physical contexts such as GRB afterglows and radio supernovae.

Table 1. Late-Time Radio Upper Limits on Short GRBs

| GRB    | $\tau$ (d) | $T_{\text{dec}}$ (h) | $V_{\text{lim}}$ (mJy) | $\epsilon_{\text{B}}^{\text{st}}$ (cm$^{-3}$) | $\Omega_{\text{ns}}^{\text{st}}$ (s$^{-1}$) | $n_{\text{CBM}}$ (cm$^{-3}$) | $E_{\text{lim}}^{\text{st}}$ (cm$^3$) |
|--------|-------------|------------------------|-------------------------|-------------------------------------------|----------------------------------------|---------------------------------|-------------------------------|
| 050709 | 0.16        | 924                    | 0.35                    | $\sim 10^{-4} - 0.1$                      | 0.03(0.1)                              | 1(3)$ \times 10^{-3}$           |                               |
| 050724 | 0.258       | 913                    | 0.24                    | $\sim 0.1 - 10^3$                        | 0.05(0.2)                              | 2(5)$ \times 10^{-3}$           |                               |
| 051221A | 0.5465      | 759                    | 0.21                     | $0.5 - 2.4 \times 10^{-3}$               | 0.2(0.5)                               | 5(10)$ \times 10^{-3}$          |                               |
| 051227T | 0.80        | 753                    | 0.24                    | $\sim 0.0 - 10^{-3}$                     | 0.3(0.9)                               | 8(20)$ \times 10^{-3}$          |                               |
| 060313N | 0.75        | 677                    | 0.51                    | $\sim 10^{-4}$                          | 0.6(2)                                 | 0.01(0.04)                      |                               |
| 060505O | 0.089       | 624                    | 0.33                    | $\sim 1$                                | 0.03(0.08)                             | 6(20)$ \times 10^{-4}$          |                               |
| 070714B | 0.9230      | 189                    | 0.19                     | -                                       | 4(12)                                  | 0.01(0.04)                      |                               |

(§) Flux density upper limit based on our radio non-detections, estimated as 3 times the rms noise level at the GRB position. (b) Density of the circumburst medium based on GRB afterglow modeling from the literature. (c) Maximum CBM density in remnant neutron star scenario allowed so as not to exceed radio upper limit based on our VLA observations using our fiducial blastwave model (Fig. 2, top panel), calculated for $\epsilon_g = 0.1(0.01)$. (d) Maximum CBM density in remnant neutron star scenario allowed so as not to exceed radio upper limit based on hypothetical observations taken with the upgraded VLA (Falcke et al. 2013) in the near future (September 2014) using our fiducial blastwave model (Fig. 2, bottom panel), calculated for $\epsilon_g = 0.1(0.01)$. References for the redshifts and CBM density constraints are given in the text.

In this paper we present radio observations of several short GRBs taken on timescales of $\sim 1$-3 years following the burst. Our search revealed no detections, which as we will show begins to place interesting constraints on the presence of a long-lived NS remnant in these systems. In §2 we present our observations. In §3 we describe a simple model for the expected radio light curve of the neutron star remnant ejecta, which we compare to the radio upper limits. In §4 we summarize our conclusions.

2 OBSERVATIONS

Seven short GRBs (Table 1) were chosen to be observed based on favorable northern hemisphere sky positions, with a preference for those showing evidence for temporally extended X-ray emission (Norris & Bonnell 2006), since one motivation for these observations was to test the hypothesis that these events are produced by a long-lived magnetar remnant (Metzger et al. 2008).

Observations of the selected GRBs were obtained on 19 and 23 January 2008 with the Very Large Array (VLA). The radio frequency was 1.425 GHz. The correlator was configured for wide-band continuum observations with a total of 100 MHz bandwidth in each of right and left circular polarization. The VLA was in B configuration producing synthesized beams with a minimum of 3
arcsec in one axis and ranged from 5 to 18 arcsec in the second axis, depending on declination and the hour angle of the source. Targets were observed for approximately 20 minutes bracketed by phase calibrator sources. 3C 48 was used as an absolute amplitude calibration source. Standard interferometric calibration and imaging techniques were applied with the AIPS package (Greisen 2003). No sources were detected at the positions of the optical afterglows for the GRBs. In Table 1, we provide a 3σ upper limit for the flux density of the sources. Thresholds were higher than expected from thermal statistics due to the presence of bright sources in the primary beam and, in some cases, extended galactic emission.

We now briefly summarize the relevant properties of each GRB. When available, the observed X-ray, optical, and radio afterglow emission from each burst have in some cases been used to constrain the CBM density, assuming the afterglow is synchrotron radiation produced by the collimated GRB outflow. In our picture the jet responsible for the GRB is either (1) independent of the merger remnant (e.g. it is powered by accretion onto the central object immediately following the merger), or (2) is also powered by the spin-down of the remnant, but contains only a small fraction of its total rotational energy, due e.g. to the difficulty of collimating the magnetar wind into a bipolar jet given the low quantity of mass surrounding the merger site (Bucciantini et al. 2012).

### GRB 050709

GRB 050709 was one of the first short GRBs to have its host galaxy identified (Fox et al. 2005; Hjorth et al. 2005; Villasenor et al. 2005), with redshift of \( z = 0.16 \). Panaitescu (2006) modeled the early optical afterglow, constraining the CBM density to be \( 10^{-4} < n < 0.1 \) cm\(^{-3} \). This burst was accompanied by temporally extended X-ray emission (e.g. Barthelmy 2007).

### GRB 050724

GRB 050724 had an early-type host galaxy at redshift \( z = 0.258 \) (Berger et al. 2005). The radio afterglow was detected with a flux density \( \sim 0.2 - 0.5 \) mJy over the first ~1 day (Berger et al. 2005), before decaying to a undetectable level over the next week. Afterglow modeling by Panaitescu (2006) constrained the CBM density to be \( 0.1 < n < 10^{-2} \) cm\(^{-3} \).

### GRB 051221A

GRB 051221A (Cummings et al. 2005) occurred in a star-forming galaxy at redshift \( z = 0.5465 \) (Berger & Soderberg 2005). The GRB radio afterglow was detected at \( t \sim 1 \) day at \( ~0.1 \) mJy, but then decayed to an undetectable level over the next couple weeks (Soderberg et al. 2006). Afterglow modeling by Soderberg et al. (2006) constrained the CBM density to the range to be \( n \sim 0.5 - 2.4 \times 10^{-3} \) cm\(^{-3} \).

### GRB 051227

GRB 051227 was a short GRB with extended emission (Barthelmy et al. 2005) and no radio detection on a timescale of a few days with an upper limit \( < 0.1 \) mJy (Frail 2005). The redshift of the host galaxy identified by D’Avanzo et al. (2009) is uncertain, but D’Avanzo et al. (2009) suggest a redshift \( z \sim 0.8 \) (which we adopt) based on matching the colors of the host to the expected luminosity of a similar galaxy type. To our knowledge no detailed modeling of the optical afterglow or resulting constraints on the CBM density are available.

#### GRB 060313

Roming et al. (2006) obtain a photometric redshift \( z = 0.75 \) (\( z < 1.1 \) with 90% confidence) for GRB 060313, which we adopt. Roming et al. (2006) also model the afterglow, finding a low CBM density \( n \sim 10^{-4} \) cm\(^{-3} \). No radio emission was detected at \( t \sim 2 \) days, with an upper limit of \( 0.11 \) mJy (Soderberg & Frail 2006).

#### GRB 060505

GRB 060505 occurred in a star forming galaxy at \( z = 0.089 \) (Fynbo et al. 2006; Ofek et al. 2007). Based on the stellar population near its position in the host galaxy (Thöne et al. 2008) and spectral lag (McBreen et al. 2008), GRB 060505 has been argued to be a member of the long GRB class (although see Levesque & Kewley 2007), despite its short duration and lack of an observable supernova. Here we adopt the standard assumption that GRB 060505 was indeed a short burst. Afterglow modeling by Xu et al. (2009) indicates a CBM density \( n \sim 1 \) cm\(^{-3} \).

#### GRB 070714B

GRB 070714B has one of the highest spectroscopically confirmed redshifts \( z = 0.9230 \) of any short GRB (Graham et al. 2009). No radio afterglow was detected, with an upper limit \( < 0.1 \) mJy on a timescale of ~2 weeks (Chandra & Frail 2007). This burst was accompanied by temporally extended X-ray emission (e.g. Ibrahim et al. 2008).

### 3 CONSTRAINTS ON STABLE MERGER REMNANT

#### 3.1 Blast Wave Model

We model the late-time radio emission due to energy injection by a long-lived stable remnant using the synchrotron blast wave model of Nakar & Piran (2011). Accounting for the early free-coasting phase, and the subsequent Sedov-Taylor expansion, the blast wave velocity \( v = c \beta \) evolves as

\[
\beta = \begin{cases} \\
\beta_0, & (r < R_{\text{dec}}) \\
\beta_0 (r/R_{\text{dec}})^{-3/2}, & (r \geq R_{\text{dec}}),
\end{cases}
\]

where \( \beta_0 \) is the initial velocity and \( R_{\text{dec}} \) is the deceleration radius (eq. (1)). We adopt a value of \( \beta_0 = 0.8 \) corresponding to mildly relativistic ejecta (bulk Lorentz factor \( \Gamma_0 = (1 - \beta_0^2)^{-1/2} \approx 1.5 \). This value is motivated by our expectation that the majority of the energy is coupled to the relatively massive ejecta (eq. (2)), resulting in a mildly relativistic quasi-spherical outflow. Note that since the mass ejected by a NSM is unlikely to exceed ~ few \( 10^{-5} M_\odot \) (e.g. Hotokezaka et al. 2013), equation (2) requires that the ejecta be at least mildly relativistic, \( \beta_0 \sim 1 \) for \( E_{\text{ej}} \sim 3 \times 10^{52} \) erg. If, on the other hand, a large fraction of \( E_{\text{ej}} \) were instead channeled into a collimated ultra-relativistic jet with \( \Gamma_0 > 1 \), this would produce extremely bright bremsstrahlung radio emission peaking at earlier times, which is incompatible with the modest radio flux densities of short GRBs measured on timescales of ~ days-weeks after the burst (eq. (2)).

Input to the radio model include the fraction of the blast wave energy going into relativistic electrons \( \epsilon_{\text{e}} \) and the magnetic field \( \epsilon_B \), respectively. We adopt a value of \( \epsilon_{\text{e}} = 0.1 \), as...
motivated by the similar values found by modeling GRB afterglows (Panaitescu & Kumar 2002) and mildly relativistic blast waves from jetted tidal disruption events (Metzger et al. 2012; Berger et al. 2012). We adopt a fiducial value of $\epsilon_B = 0.1$, although we explore the sensitivity of our upper limits on the density to the value of $\epsilon_B$ by also considering a lower value $\epsilon_B = 0.01$ in some of our models. The power-law index of the relativistic electrons is assumed to be $p = 2.3$. We assume a blast wave energy equal to the rotational energy of the pulsar $E = E_{\text{rot}} = 3 \times 10^{52}$ erg, since a rotation period near centrifugal break-up appears to be a robust property of stable merger remnants (Giacomazzo & Perna 2013). We include corrections to the late radio emission based on the recent work by Sironi & Giannios 2013, although in practice this has little effect on our conclusions. Our model also includes the effects of synchrotron self-absorption, as described in Nakar & Piran (2011).

If the observing frequency is above both the peak synchrotron frequency and the self-absorption, as is usually satisfied at $\nu = 1.4$ GHz, then the peak flux density achieved at $t = t_{\text{dec}}$ is given by (Nakar & Piran 2011)

$$F_{\text{peak}} \approx 3 \text{mJy} \left( \frac{E_{\text{rot}}}{10^{52} \text{erg}} \right)^{0.83} \left( \frac{n}{10^3 \text{ cm}^{-3}} \right)^{0.83} \left( \frac{\epsilon_e}{0.7} \right)^{1.3} \beta_0^{2.5} d_{33}^2, \hspace{1cm} (6)$$

where $d = d_{33} 10^{33}$ cm is the luminosity distance, normalized to a value characteristic of the typical redshift $z \approx 0.5$ of short GRBs. Thus, for typical parameters $E_{\text{rot}} = 3 \times 10^{52}$ erg, $\epsilon_e = \epsilon_B = 0.1$, $\beta = 0.8$, $d_{33} = 1$, a stable remnant NS should be detectable by the old VLA[upgraded VLA] at $t \sim t_{\text{dec}}$ for a CBM density $n \geq 0.02[0.001]$ cm$^{-3}$, where we have assumed a flux density sensitivity of $0.2[0.02]$ mJy for the old and upgraded VLA, respectively.

### 3.2 Comparison to Upper Limits

Figure 1 shows the luminosity of synchrotron emission $\nu L_\nu$ at frequency $\nu = 1.4$ GHz as a function of time (rest frame) after the merger, shown for several values of the CBM density $n$ and calculated assuming $\epsilon_e = \epsilon_B = 0.1$. Shown with black solid triangles are the upper limits from our VLA observations of short GRBs. In most cases the observing band is above the characteristic synchrotron peak frequency, such that the light curve rises to a peak flux density $\sim F_{\text{peak}}$ (eq. 4) on a timescale $\sim t_{\text{dec}}$ (eq. 3). The different light curve shape in the high density cases $n = 1, 10$ cm$^{-3}$ arises due to the effects of synchrotron self absorption, which is important because the self-absorption frequency is comparable to the observing frequency, especially at early times.

Figure 1 shows that we can rule out a long-lived remnant for those short GRBs that occur in a reasonably high density environment $n \geq 0.01 - 1$ cm$^{-3}$ characteristic of the ISM of star-forming galaxies. Figure 2 provides a different perspective on the data by showing the ratio of the predicted radio flux density of the blast wave at the time of our observations to our radio upper limits for $\epsilon_B = 0.1$. Horizontal bars show the range of allowed CBM densities for each burst (colored accordingly), based on modeling of the GRB afterglow from the literature (no afterglow modeling was available for GRB 051227 or 070714B). The maximum CBM density allowed for each GRB so as not to exceed radio upper

- **Figure 1.** Luminosity of synchrotron emission $\nu L_\nu$ at $\nu = 1.4$ GHz due to the blast wave produced by the remnant NS as a function of time (rest frame) after the merger, shown for several values of the CBM density $n$ and calculated assuming $\epsilon_e = \epsilon_B = 0.1$. Shown with black solid triangles are the upper limits from our VLA observations of short GRBs. In most cases the observing band is above the characteristic synchrotron peak frequency, such that the light curve rises to a peak flux density $\sim F_{\text{peak}}$ (eq. 4) on a timescale $\sim t_{\text{dec}}$ (eq. 3). The different light curve shape in the high density cases $n = 1, 10$ cm$^{-3}$ arises due to the effects of synchrotron self absorption, which is important because the self-absorption frequency is comparable to the observing frequency, especially at early times.
limit based on our VLA observations is given in Table 1 for both $\epsilon_B = 0.01$ and $\epsilon_B = 0.1$.

Our upper limits rule out a magnetized remnant NS in GRB 050724 and 060505. However, the low values of $n$ for the other GRBs or the lack of such information, preclude similarly definitive constraints. Figure 1 makes clear that a NSM remnant cannot GRBs or the lack of such information, preclude similarly definitive constraints. Figure 1 makes clear that a NSM remnant cannot

\[
\frac{B}{n} \lesssim 3 \times 10^{21} \text{G cm}^{-3}.
\]

This implies that later observations will be more constraining. The red triangles in Figure 1 show what constraints could be placed by a hypothetical observation in the near future (September 2014) with an instrument such as the upgraded VLA, with a sensitivity assumed to be 10 times greater than the (original) VLA observations. These same constraints are shown in the bottom panel of Figure 2 and in the last column of Table 1.

### 4 DISCUSSION AND CONCLUSIONS

A long-lived magnetized NSM remnant has received recent attention as a possible source of X-ray emission following short GRBs and as possible gravitational wave counterparts. Any NS remnant that indeed avoids collapse is necessarily born rapidly rotating due to the substantial angular momentum of the initial binary. Although a minimum rotation period of $P \sim 1$ ms may be enforced by gravitational radiation due to non-axisymmetric (e.g. bar mode) instabilities (e.g. Ott et al. 2013), this still places a robust minimum on the reservoir of rotational energy of $E_{\text{rot}} \gtrsim 3 \times 10^{52}$ erg (eq. 1). This enormous energy must eventually be injected into the surrounding CBM. Unless the magnetic dipole field of the remnant neutron star is relatively low $< 3 \times 10^{12}$ G, its spin-down time will be shorter than the time required for the blast wave to decelerate via its interaction with the CBM $t_{\text{dec}}$ (eq. 1). The full value of $E_{\text{rot}}$ must thus be used as the energy of the blast wave to compute the expected radio emission.

Motivated by the potential for such luminous radio emission, we undertook VLA observations of several short GRBs, three of which possessed temporally extended X-ray emission. Although we find no detections, our upper limits are nevertheless constraining on the presence of NSM remnants in these systems. We can already rule out long-lived NSM remnants in a few short GRBs (050724, 060505) with known high CBM densities, and are placing upper limits on the allowed range of CBM densities in other systems consistent with the NSM remnant hypothesis (Figs. 1, 2). One of these bursts, GRB 050724, showed temporally extended X-ray emission; thus our observations are already tension with the CBM densities inferred based on independent afterglow modeling for GRB 050709 (Panaitescu 2006), GRB 050724 (Panaitescu 2006), GRB 051221A (Soderberg et al. 2006), GRB 060313 (Roming et al. 2006), and GRB 060505 (Xu et al. 2006). Bottom Panel: Same as top panel, but calculated based on hypothetical observations in the near future (September 2014) with the VLA at 1.4 GHz. The upgraded VLA is assumed to achieve a flux density sensitivity which is a factor of 10 lower than for our (original) VLA observations.

Our upper limits are unconstraining for low CBM densities not because the peak luminosity $F_{\text{peak}}$ (eq. 3) is too low, but instead because the observations were taken before the light curve has peaked at $t_{\text{dec}} \sim n_{\text{dec}} \propto n^{-1/3}$ (Fig. 1). Since our observations were taken over 5 years ago, additional data taken in the present epoch with more sensitive instruments such as the upgraded VLA or LOFAR could substantially tighten the constraints. The bottom panel of Figure 2 shows the constraints on the predicted flux density as a function of CBM density that could be placed by upgraded VLA ($\nu = 1.4$ GHz) by observations taken in September 2014. Unfortunately, given the low or uncertain CBM densities in the remaining GRBs in our sample, it does not appear that additional nondetections would allow us to rule out a remnant merger in events beyond those already constrained (GRB 050724 and 060505). We nevertheless expect that additional, more recent, short GRBs could be added to our sample for future observations, prioritized by systems with known high densities.

Although particularly low CBM densities hinder our ability to constrain NSM remnants in individual systems, such low densities should not be ubiquitous among the population of binary neutron star mergers. Although some NSMs are predicted to occur outside of their host galaxies due to the natal kicks received by the NS at birth (e.g. Belczynski et al. 2006; Kelley et al. 2010), this is unlikely to always be the case. In fact, the low mass NSs most likely to leave stable remnants are produced in electron capture supernovae, for which the expected kicks are much smaller (e.g. Buras et al.)
Thus, most mergers leaving long-lived remnants should occur within the confines of their host galaxies, where the CBM density is relatively high.

The constraints our upper limits place on the presence of temporarily stable (‘hyper-massive’) neutron star remnants are much less strict than those on indefinitely stable remnants. This is because a hyper-massive neutron star is unlikely to live longer than a few seconds, as set by the time required for thermal support to be removed via neutrino cooling and for differential rotation to be eliminated by magnetic torques. Only if the dipole magnetic field of the remnant is extremely high ($B_d > 10^{12}$ G) could a substantial fraction of its rotational energy be extracted prior to collapse. Separately, another caveat is that our radio upper limits are also only constraining on stable remnants that possess a moderately strong dipole magnetic field ($B_d \gtrsim 10^3$ G), since otherwise the spin-down timescale is too long to power a substantial blast wave luminosity.

It is uncertain theoretically whether a system leaving a NSM remnant can produce a GRB at all due to the substantial baryon loading of the jet expected from the neutrino-driven wind of the NSM remnant (e.g. Dessart et al. 2009). However, independent of their association with GRBs, the formation of long-lived remnants in NS mergers is also constrained based on the current absence of such radio transients in blind radio surveys.

Frail et al. (2012) present updated limits on the rates of transients based on past radio surveys. They predict that that number of NSM transients per square degrees is approximate two orders of magnitude below the limits of current surveys (Frail et al. 2003; de Vries et al. 2004; Croft et al. 2010). However, the blast wave energy they assume, $E = 10^{50}$ erg (Nakar & Piran 2011), is more than two orders of magnitude lower than that produced by a long-lived NSM remnant. The peak flux density of the resulting radio transient will thus be approximately two orders of magnitude brighter (eq. 1), increasing the expected rate of detected events at fixed flux density by a factor $\sim 10^3$.

Using Figure 6 of Frail et al. (2012) we estimate that one can exclude the possibility that a majority of NSMs leave stable remnants based on the upper limits placed by past radio surveys, if one assumes a rate of binary neutron star mergers $\sim 300$ Gpc$^{-3}$ yr$^{-1}$ near the middle of the estimated range (Abadie et al. 2010). This illustrates the power of upcoming radio surveys, combined with future gravitational wave observations, to constrain the fraction of mergers leaving stable remnants and hence indirectly constrain the equation of state of nuclear density matter. On a related note, the much higher radio luminosities produced in the case of a remnant NS, as compared to the normal case of prompt black hole formation, can often make radio observations a much more promising electromagnetic counterpart to the gravitational wave source than previously assumed (Nakar & Piran 2011; Metzger & Berger 2012).

As a final remark, note that our upper limits, and also those placed by radio surveys, place similarly strong constraints on the proposed long-lived electromagnetic spin-down of black holes produced by NSMs (Lyutikov 2013). This suggests that such newly-formed black holes indeed rapidly shed their ‘hair’ (Lyutikov & McKinney 2011).

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