LETTER

doi:10.1038/nature10365

Detectable radio flares following gravitational waves from mergers of binary neutron stars

Ehud Nakar[1] & Tsvi Piran[2]

Mergers of neutron-star/neutron-star binaries are strong sources of gravitational waves[1–3]. They can also launch subrelativistic and mildly relativistic outflows[4–8] and are often assumed to be the sources of short γ-ray bursts[9]. An electromagnetic signature that persisted for weeks to months after the event would strengthen any future claim of a detection of gravitational waves[10]. Here we present results of calculations showing that the interaction of mildly relativistic outflows with the surrounding medium produces radio flares with peak emission at 1.4 gigahertz that persist at detectable (submillijansky) levels for weeks, out to a redshift of 0.1. Slower subrelativistic outflows produce flares detectable for years at 150 megahertz, as well as at 1.4 gigahertz, from slightly shorter distances. The radio transient RT 19870422 (ref. 11) has the properties predicted by our model, and its most probable origin is the merger of a compact neutron-star/neutron-star binary. The lack of radio detections usually associated with short γ-ray bursts does not constrain the radio transients that we discuss here (from mildly relativistic and subrelativistic outflows) because short γ-ray burst redshifts are typically $>$0.1 and the appropriate timescales (longer than weeks) have not been sampled.

Gravitational-wave detectors, and in particular the advanced LIGO and Virgo interferometers, are being constructed now with the goal of detecting gravitational waves from binary neutron-star coalescence at distances up to a few hundred megaparsecs (redshift $z \approx 0.1$)[12]. The detection of an accompanying electromagnetic signal would complement these efforts, providing an independent confirmation of the discovery and increasing the detectors' effective sensitivity. The search for such an electromagnetic signal has therefore attracted much interest. The radioactive decay of ejected debris from the merger would drive a short-lived supernova-like event[13]. For example, ejection of 0.01 solar masses ($0.01 M_\odot$) from a merger at a distance of 300 Mpc would result in a faint optical flare that peaks after ~1 day (ref. 14). Finding, and especially identifying, such rare and faint events in the crowded variable optical sky is an extremely challenging task. Other authors have speculated on the production of low-frequency radio signals from the interaction of the neutron stars' magnetic fields[15–17]. These attempts focused on electromagnetic signals that are contemporaneous with, or follow quickly, the merger and the gravitational waves. Unfortunately, these predictions are highly uncertain.

Here we predict a robust radio signal that peaks several weeks after the merger. Numerical simulations show that compact binary mergers launch energetic subrelativistic and mildly relativistic outflows[4–8]. Ejection sources include unbound tidal tails, and winds driven by neutrino heating, nucleosynthesis and electromagnetic processes[18–21], emerging from the proto-neutron star or from an accretion disk. Overall, almost all merger models find a significant ejection of mass and energy. In binary neutron-star mergers, an ejection of about 10^{50} erg at (0.1–0.2)c (where c is the speed of light) and about 10^{49} erg as faster ejecta is a fairly robust prediction. The outflow from black-hole/neutron-star mergers is less certain, but it is possibly more energetic and faster[18] (~10^{52} erg at 0.5c).

The interaction of this outflow with the surrounding tenuous matter generates a blast wave. Although the outflow may be highly non-uniform initially, it becomes spherical rather quickly. We therefore consider a spherical outflow with energy E and an initial velocity $c\beta_i$ that propagates into a medium with a constant density, n. If the outflow is not ultrarelativistic, it propagates at a constant velocity until time t_{dec}, when, at a radius R_{dec}, it collects a mass comparable to its own. Time t_{dec} (in days) is given by

$$t_{dec} = \frac{R_{dec}}{c\beta_i} \approx 30\, E_{49}^{1/3} n_0^{-1/3} \beta_i^{-5/3} \qquad (1)$$

Here and in the following, unless stated otherwise, q_x (where q is any parameter) denotes the value of $q/10^x$ in c.g.s. units. At a radius $R > R_{dec}$, the flow decelerates, assuming a Sedov–Taylor blast wave: $\beta \approx \beta_i (R/R_{dec})^{-3/2}$.

The blast wave generates magnetic fields and accelerates particles that emit synchrotron radiation. The same microphysics used successfully to model radio emission of type Ibc supernovae[22,23], where $\beta \approx 0.2$, and to model late radio emission of γ-ray bursts[24,25], where the flow is mildly relativistic, is applicable here. In both cases, the electrons and the magnetic field are found to carry significant fractions of the total internal energy of the shocked gas, $\varepsilon_e \approx \varepsilon_B \approx 0.1$. The observed spectra reveal a power-law distribution of the electrons' Lorentz factor, γ: $dN/d\gamma \propto \gamma^{-p}$ for $\gamma > \gamma_m = [(p-2)/(p-1)](m_p/m_e)\varepsilon_e \beta^2$, where m_p and m_e are the proton and electron masses, respectively, γ_m is the minimal Lorentz factor of the electron's distribution and $p \approx 2$–3.

The radio spectrum is determined by ν_m, the synchrotron frequency of electrons with Lorentz factor γ_m, and by ν_a, the synchrotron self-absorption frequency (Supplementary Information). The specific flux, F_ν, at a given frequency is strongly suppressed below ν_a, and it decreases as $\nu^{-(p-1)/2}$ above ν_m and ν_a. The signal across the whole spectrum increases at $t < t_{dec}$. Its behaviour after t_{dec} depends on the relation between the observed frequency, ν_{obs}, and ν_m and ν_a. The signal peaks at t_{dec} if $\nu_{obs} > \nu_{a,dec}$, $\nu_{m,dec}$, where $\nu_{a,dec} \equiv \nu_a(t_{dec})$ and $\nu_{m,dec} \equiv \nu_m(t_{dec})$. Otherwise the signal peaks when $\nu_{obs} = \nu_m$ or when $\nu_{obs} = \nu_a$, whichever is latest.

The flare characteristics are most sensitive to the initial velocity of the outflow, β_i. Because the brightest radio emission is observed at t_{dec}, a lower value of β_i implies a longer rise time of the radio emission after the merger. Additionally, $\nu_{m,dec}$, $\nu_{a,dec}$ and the peak flux at any observed frequency depend strongly on β_i. As mergers are expected to eject an outflow over a range of velocities, we discuss separately below the observed signature of mildly relativistic ($\beta_i \approx 1$) and subrelativistic ($\beta_i \approx 0.2$) ejecta.

A mildly relativistic blast wave with canonical parameters produces a synchrotron spectrum with $\nu_{a,dec} \le \nu_{m,dec} \approx 1$ GHz. The strongest signal is then expected at time t_{dec} (a few weeks after the merger) and around 1.4 GHz (Supplementary Information): the peak of the observed specific flux at ν_{obs} in units of millijanskys is

$$F_{\nu_{obs},peak}[\nu_{obs} > \nu_{m,dec},\ \nu_{a,dec}] \approx 0.3 E_{49} n_0^{\frac{p+1}{4}} \varepsilon_{B,-1}^{\frac{p+1}{4}} \varepsilon_{e,-1}^{p-1} \beta_i^{\frac{5p-7}{2}} d_{27}^{-2} \left(\frac{\nu_{obs}}{1.4}\right)^{-\frac{p-1}{2}} \qquad (2)$$

---

[1] Raymond and Beverly Sackler School of Physics & Astronomy, Tel Aviv University, Tel Aviv 69978, Israel. [2] Racah Institute of Physics, The Hebrew University, Jerusalem 91904, Israel.

where d is the distance to the merger (here $\nu_{\rm obs}$ is in GHz). The peak flux at lower frequencies (<1 GHz) is significantly lower and it is observed at a later time. If the outflow is subrelativistic ($\beta_{\rm i} \approx 0.1$–$0.2$), then $\nu_{\rm a,dec}$, $\nu_{\rm m,dec} \leq 150$ MHz and equation (2) is applicable also in the frequency range of low-frequency radio detectors. The flux peaks at $t_{\rm dec}$, which is of the order of years, and it is brighter at 150 MHz than at 1 GHz by about an order of magnitude. Note that over the whole expected range of blast wave parameters, $\nu_{\rm a} \leq 1$ GHz at all times and the spectrum above 1 GHz is optically thin during the entire evolution. We stress that in radio supernovae, the surrounding dense winds lead at early time to an optically thick spectrum at $\nu_{\rm obs} > 1$ GHz, and the transition $\nu_{\rm a} = \nu_{\rm obs}$ determines the time and flux at the peak. As discussed below, this different spectral signature enables us to distinguish between merger flares and radio supernovae.

The circum-merger density also strongly affects the flare signature. For example, if the surrounding particle density is $\sim 10^{-3}$ cm^{-3}, the peak flux from a mildly relativistic ejecta decreases to the microjansky level at a distance of 300 Mpc, and the timescale increases by a factor of ten, to a year. A merger taking place in such a density can be detected only up to distances of ~100 Mpc (Table 1.) The density is expected to vary significantly, from $n \approx 1$ cm^{-3}, in galactic disks, to $n \approx 10^{-6}$ cm^{-3}, for mergers taking place outside their host galaxies. Because all observed Galactic neutron-star binaries reside within the Galactic disk, where the average density is $n \approx 1$ cm^{-3}, a significant fraction of the cosmological mergers are expected also to take place in rather dense environments. We therefore use $n = 1$ cm^{-3} as the canonical density value. If mergers produce short γ-ray bursts, then observations of their afterglows support this value (Supplementary Information).

An intriguing possibility is that compact merger events also eject ultrarelativistic jets that produce short γ-ray bursts[9] (SGRBs). It is important to examine the relationship between SGRBs and the radio flares discussed here, assuming that mergers are producing SGRBs. An SGRB beamed towards us will be observed in coincidence with the gravitational-wave signal, providing a clear electromagnetic counterpart. Even if the SGRB itself is missed, owing to partial sky coverage, its afterglow will be easily detectable. However, SGRBs are expected to be beamed, and only rarely will one point towards us. A beamed SGRB observed off-axis produces, once it has slowed down, a long-lasting radio 'orphan' afterglow[26], similar in its characteristics to the mildly relativistic signal discussed above. However, the total energy (corrected for beaming) in the ultrarelativistic jet is at most comparable to—and probably lower than—that of the mildly relativistic ejecta. Consequently the latter will dominate the radio emission.

The radio remnant signals that we consider here, which are generated by subrelativistic and mildly relativistic outflows, could not have been detected in the radio afterglow searches that were carried out following SGRB triggers. The reasons are twofold. First, SGRBs are typically detected at distances of 1–3 Gpc, far beyond the detection horizon of gravitational-wave detectors. Hence the signals are much weaker than those associated with detected gravitational-wave events. Second, SGRB afterglow searches are optimized to detect the emission from ultrarelativistic ejecta pointing towards the observer. Such emission peaks at higher frequencies and on shorter timescales than the emission from mildly and subrelativistic ejecta discussed here. SGRB afterglow searches are done at a sensitivity of ~0.1 mJy at 4.8–8.5 GHz during the first week or two after the bursts (see, for example, refs 27–29). Equation (2) implies that over the distance range 1–3 Gpc, the radio signal of mildly relativistic ejecta with energy 10^{50} erg that propagate into a medium of density $n = 1$ cm^{-3} peaks after ~60 days at a flux of ~0.01–0.1 mJy at 5 GHz. The flux before the peak rises as $(t/t_{\rm dec})^3$ (Supplementary Information). Therefore, these early radio afterglow searches could not have detected the radio signal, even if the mildly relativistic ejecta had an energy of 10^{51} erg. Thus, the paucity of detected SGRB radio afterglows has no direct implication for the nature of the remnants we discuss here.

A new wave of radio detectors is now coming online. The most sensitive operate at frequencies of 1.4 GHz and higher. Table 1 summarizes the relevant properties of these facilities and their detection horizons. The best facility for a targeted search, following a detection of a candidate gravitational-wave source, is clearly the EVLA. A deep, ~50 μJy, localized EVLA search of the 10–100 deg^2 error box of a gravitational-wave trigger[30] can detect mildly relativistic ejecta (with an energy of even ~10^{48} erg) out to the horizon of advanced gravitational-wave detectors. The upcoming lower-frequency LOFAR sensor array will be more effective in searches for subrelativistic outflows, whose signals peak at LOFAR's frequencies, thus compensating for LOFAR's lower sensitivity. LOFAR is also relatively more effective when searching for flares in a low-density medium.

Even before the completion of the advanced gravitational-wave detectors, blind searches can identify radio flares from compact binary mergers. Identification of radio emission from any merger type (binary neutron star or black hole/neutron star) would determine the merger rate, which is a parameter of utmost importance for the design and operation of advanced detectors. With a merger rate of 300 Gpc^{-3} yr^{-1}, we expect these facilities to detect ~20 remnants from mildly relativistic outflows with an energy of $E = 10^{49}$ erg (and ~1,000 remnants if $E = 10^{50}$ erg), in a single whole-sky snapshot. LOFAR may detect a dozen transients in a whole-sky survey, even if only a subrelativistic outflow with an energy of 10^{50} erg is ejected (see Supplementary Information for details, as well as for a discussion of ways to distinguish these flares from other possible radio transients).

Remarkably, the observed 5 GHz transient RT 19870422 (ref. 11) shows all the expected properties of the radio remnant of a compact binary merger. At 1 Gpc distance and with a duration of two months, this transient is what we would expect from a mildly relativistic outflow with an energy of ~10^{50} erg. The inferred rate of similar transients[11], 80–20,000 Gpc^{-3} yr^{-1}, is fully consistent with the estimates of compact binary mergers. This transient is therefore an excellent candidate to be the first observed radio remnant of a merger. Unfortunately, we cannot rule out the possibility that this is an especially bright radio supernova[11]. We note, however, that this latter interpretation requires a supernova brighter by an order of magnitude than any radio supernovae previously observed. Simultaneous optical observations or multiwavelength radio observations could have easily distinguished

Table 1 | Observing radio flares

Radio facility	Observing frequency (GHz)	Field of view (deg^2)	One-hour r.m.s.* (μJy)	One-hour detection horizon†			Ten-hour detection horizon‡
				$\beta_{\rm i} \approx 1$, $E_{49} = 1$, $n_0 = 1$	$\beta_{\rm i} \approx 1$, $E_{49} = 10$, $n_0 = 1$	$\beta_{\rm i} = 0.2$, $E_{49} = 10$, $n_0 = 1$, $p = 2.5$	$\beta_{\rm i} \approx 1$, $E_{49} = 1$, $n_0 = 10^{-3}$, $p = 2$
EVLA	1.4	0.25	7	1 Gpc	3.3 Gpc	370 Mpc	140 Mpc
ASKAP	1.4	30	30	500 Mpc	1.6 Gpc	180 Mpc	70 Mpc
MeerKAT	1.4	1.5	35	500 Mpc	1.6 Gpc	165 Mpc	65 Mpc
Apertif	1.4	8	50	400 Mpc	1.25 Gpc	140 Mpc	50 Mpc
LOFAR	0.15	20	1,000	35 Mpc	90 Mpc	70 Mpc	20 Mpc

Shown are properties and detection horizons (neglecting cosmological corrections) for an observation at different radio facilities of blast waves with various values of $\beta_{\rm i}$, E_{49}, n_0 and p (in all cases, $\varepsilon_{\rm e} \approx \varepsilon_{\rm B} \approx 0.1$; see text for definitions of these symbols). Information on facilities is available as follows: EVLA (http://www.aoc.nrao.edu/evla); ASKAP (http://www.atnf.csiro.au/projects/askap/technology.html); MeerKAT (http://www.ska.ac.za/meerkat); Apertif (http://www.astron.nl/general/apertif/apertif); and LOFAR (http://lofar.org).

* The root mean squared value of the background noise for one hour of observation.

† The distance at which the observed peak flux is four times the one-hour r.m.s.

‡ The distance at which the observed peak flux is four times the root mean squared value of the background noise for ten hours of observation.

between the two possibilities. Unfortunately, no such observations are available. However, the detection rate implied by this event is very high, indicating that similar events could easily be detected by a relatively small-scale survey and that their nature should be easily probed.

Received 11 February; accepted 11 July 2011.

1. Taylor, J. H. & Weisberg, J. M. A new test of general relativity — gravitational radiation and the binary pulsar PSR 1913+16. *Astrophys. J.* **253,** 908–920 (1982).
2. Esposito, L. W. & Harrison, E. R. Properties of the Hulse-Taylor binary pulsar system. *Astrophys. J.* **196,** L1–L2 (1975).
3. Wagoner, R. V. Test for the existence of gravitational radiation. *Astrophys. J.* **196,** L63–L65 (1975).
4. Rosswog, S., Davies, M. B., Thielemann, F. & Piran, T. Merging neutron stars: asymmetric systems. *Astron. Astrophys.* **360,** 171–184 (2000).
5. Ruffert, M. & Janka, H. Coalescing neutron stars — a step towards physical models. III. Improved numerics and different neutron star masses and spins. *Astron. Astrophys.* **380,** 544–577 (2001).
6. Yamamoto, T., Shibata, M. & Taniguchi, K. Simulating coalescing compact binaries by a new code (SACRA). *Phys. Rev. D.* **78,** 064054 (2008).
7. Rezzolla, L., Baiotti, L., Giacomazzo, B., Link, D. & Font, J. A. Accurate evolutions of unequal-mass neutron-star binaries: properties of the torus and short GRB engines. *Class. Quantum Grav.* **27,** 114105 (2010).
8. Kiuchi, K., Sekiguchi, Y., Shibata, M. & Taniguchi, K. Exploring binary-neutron-star-merger scenario of short-gamma-ray bursts by gravitational-wave observation. *Phys. Rev. Lett.* **104,** 141101 (2010).
9. Eichler, D., Livio, M., Piran, T. & Schramm, D. N. Nucleosynthesis, neutrino bursts and gamma-rays from coalescing neutron stars. *Nature* **340,** 126–128 (1989).
10. Kochanek, C. S. & Piran, T. Gravitational waves and gamma-ray bursts. *Astrophys. J.* **417,** L17–L20 (1993).
11. Bower, G. C. *et al.* Submillijansky transients in archival radio observations. *Astrophys. J.* **666,** 346–360 (2007).
12. Smith, J. R. & LIGO Scientific Collaboration. The path to the enhanced and advanced LIGO gravitational-wave detectors. *Class. Quantum Grav.* **26,** 114013 (2009).
13. Li, L. & Paczyński, B. Transient events from neutron star mergers. *Astrophys. J.* **507,** L59–L62 (1998).
14. Metzger, B. D. *et al.* Electromagnetic counterparts of compact object mergers powered by the radioactive decay of r-process nuclei. *Mon. Not. R. Astron. Soc.* **406,** 2650–2662 (2010).
15. Hansen, B. M. S. & Lyutikov, M. Radio and X-ray signatures of merging neutron stars. *Mon. Not. R. Astron. Soc.* **322,** 695–701 (2001).
16. Moortgat, J. & Kuijpers, J. Gravitational waves in magnetized relativistic plasmas. *Phys. Rev. D* **70,** 023001 (2004).
17. Pshirkov, M. S. & Postnov, K. A. Radio precursors to neutron star binary mergings. *Astrophys. Space Sci.* **330,** 13–18 (2010).
18. Rosswog, S. Mergers of neutron star-black hole binaries with small mass ratios: nucleosynthesis, gamma-ray bursts, and electromagnetic transients. *Astrophys. J.* **634,** 1202–1213 (2005).
19. Levinson, A. General relativistic, neutrino-assisted magnetohydrodynamic winds-theory and application to gamma-ray bursts. I. Schwarzschild geometry. *Astrophys. J.* **648,** 510–522 (2006).
20. Metzger, B. D., Piro, A. L. & Quataert, E. Time-dependent models of accretion discs formed from compact object mergers. *Mon. Not. R. Astron. Soc.* **390,** 781–797 (2008).
21. Dessart, L., Ott, C. D., Burrows, A., Rosswog, S. & Livne, E. Neutrino signatures and the neutrino-driven wind in binary neutron star mergers. *Astrophys. J.* **690,** 1681–1705 (2009).
22. Chevalier, R. A. Synchrotron self-absorption in radio supernovae. *Astrophys. J.* **499,** 810–819 (1998).
23. Chevalier, R. A. & Fransson, C. Circumstellar emission from Type Ib and Ic supernovae. *Astrophys. J.* **651,** 381–391 (2006).
24. Frail, D. A., Waxman, E. & Kulkarni, S. R. A 450 day light curve of the radio afterglow of GRB 970508: fireball calorimetry. *Astrophys. J.* **537,** 191–204 (2000).
25. Frail, D. A. *et al.* Accurate calorimetry of GRB 030329. *Astrophys. J.* **619,** 994–998 (2005).
26. Rhoads, J. E. How to tell a jet from a balloon: a proposed test for beaming in gamma-ray bursts. *Astrophys. J.* **487,** L1–L4 (1997).
27. Soderberg, A. M. & Frail, D. A. GRB060313: radio observations. *GCN Circ.* **4884** (2006).
28. van der Horst, A. J. GRB 060801: WSRT radio observations. *GCN Circ.* **5390** (2006).
29. Wieringa, M. H., Chandra, P. & Frail, D. A. ATCA radio observations of short hard burst GRB 071112B. *GCN Circ.* **7095** (2007).
30. Wen, L. & Chen, Y. Geometrical expression for the angular resolution of a network of gravitational-wave detectors. *Phys. Rev. D* **81,** 082001 (2010).

Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

Acknowledgements We thank D. Frail, S. Kulkarni, A. Levinson, A. MacFadyen, E. Ofek and S. Rosswog for discussions. This research was supported by an ERC advanced research grant, by the Israeli Center for Excellence for High Energy Astrophysics, by the ISF (grant No. 174/08) and by an IRG grant.

Author Contributions Both authors contributed equally.

Author Information Reprints and permissions information is available at www.nature.com/reprints. The authors declare no competing financial interests. Readers are welcome to comment on the online version of this article at www.nature.com/nature. Correspondence and requests for materials should be addressed to T.P. (tsvi@phys.huji.ac.il) or E.N. (udini@wise.tau.ac.il).