Short gamma-ray bursts from binary neutron star mergers: the “time-reversal” scenario

RICCARDO CIOLFI

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Introduction: SGRBs

leading model of short gamma-ray bursts (SGRBs) central engine is a black hole surrounded by hot thick torus → end result of a binary neutron star (BNS) or mixed binary (NS-BH) merger

Paczynski 1986, Eichler et al. 1989

BNS and NS-BH binary mergers are among the most promising sources of gravitational waves likely of rate ~40/yr for Advanced LIGO and Virgo possibility of combined GW-EM detection!
**X-ray afterglows of SGRBs**

- SWIFT revealed that most SGRBs are accompanied by long-duration ($\sim 10^2 - 10^5$ s) and high-luminosity ($10^{46} - 10^{51}$ erg/s) X-ray afterglows
- total energy can be higher than the SGRB itself
- hardly produced by BH-torus system - they suggest ongoing energy injection from a long-lived NS

**Magnetar Model**

- X-ray emission $\rightarrow$ spindown of a uniformly rotating NS with a strong surface magnetic field
  \[ L_{sd}(t) \sim B^2 R^6 \Omega_0^4 \left(1 + \frac{t}{t_{sd}}\right)^{-2} \]

- Zhang & Meszaros 2001
- Metzger et al. 2008
- Gompertz et al. 2013
- Rowlinson et al. 2013
LONG-LIVED NS IS A LIKELY OUTCOME OF THE MERGER

- observation of $\sim 2 \, M_\odot$ NSs
  - Demorest et al. 2010
  - Antoniadis et al. 2013
- progenitor masses peak around $1.3 - 1.4 \, M_\odot \rightarrow$ BMP mass likely $< 2.5 \, M_\odot$
  - Belczynski et al. 2008
- stable NS obtained in GR BNS merger simulations
  - Giacomazzo & Perna 2013
Product of BNS mergers

PROBLEM OF THE LONG-LIVED NS MODEL:

- strong baryon pollution can choke the formation of a relativistic jet

\[\rightarrow\] HARD TO EXPLAIN THE SGRB PROMPT EMISSION

- e.g., Dessart et al. 2009, Hotokezaka et al. 2013, Siegel et al. 2014
The SGRB dichotomy

- Numerical relativity picture: prompt BH-torus formation
  
  → can explain prompt SGRB emission ✓
  
  → cannot explain X-ray afterglows ✗

- Observational picture: magnetar model

  → cannot explain prompt SGRB emission ✗
  
  → can explain X-ray afterglows ✓

Possible solution: “time-reversal” scenario

Ciolfi & Siegel 2015a
"Time-reversal" phenomenology


I) The differentially rotating, supramassive NS (SMNS) ejects a baryon-loaded and highly isotropic wind

Siegel et al. 2014
(see also Siegel & Ciolfi 2015a)

Dessart et al. 2009
“Time-reversal” phenomenology

60 ms evolution for 3 geometries
dipole 60

dipole 6

random
differential rotation
powers baryon-loaded and magnetized outflow

for all MF geometries the outflow has an isotropic component

collimation depends strongly on MF geometry

Siegel et al. 2014
Siegel & Ciolfi 2015a
(I) The differentially rotating, supramassive NS (SMNS) ejects a baryon-loaded and highly isotropic wind

(II) The cooled-down and uniformly rotating NS emits spin-down radiation inflating a photon-pair nebula that drives a shock through the ejecta
“Time-reversal” phenomenology II

- **uniformly rotating NS** emits **spin-down radiation** and inflates a **photon-pair nebula**

  \[ L_{sd} \approx 1.5 \times 10^{49} B_{p,15}^2 R_6^3 P_{in,-3}^{-4} (1 + t/t_{sd})^{-2} \text{ erg s}^{-1} \]

  \[ t_{sd} \approx 2.7 \times 10^3 B_{p,15}^{-2} R_6^{-3} P_{in,-3}^2 \text{ s} \]

- **high photon pressure** drives a strong **shock** through the ejecta, sweeps up material into a **thin shell**

- **nebula energy rapidly heats up and accelerates** the ejecta shell (up to mildly relativistic speeds)

  [Metzger & Piro 2014]

  analogies with PWNe
  (see talk by D. Siegel)
(I) The differentially rotating, supramassive NS (SMNS) ejects a baryon-loaded and highly isotropic wind

(II) The cooled-down and uniformly rotating NS emits spin-down radiation inflating a photon-pair nebula that drives a shock through the ejecta

(III) The NS collapses to a black hole (BH), a relativistic jet drills through the nebula and the ejecta shell and produces the prompt SGRB, while spin-down emission diffuses outwards on a much longer timescale, producing the X-ray afterglow
• at $t_{\text{coll}} \sim t_{\text{sd}}$ the NS collapses to a BH-torus system

  ➔ transient jet is formed in $\lesssim 0.01 - 1\text{ s}$ drills through the ejecta and generates the SGRB

• nebula and ejecta represent an optically thick environment

  ➔ large fraction of spin-down energy is still trapped and diffuses outwards on much longer timescale

  ➔ spin-down energy acquires substantial delay before emerging and producing the X-rays
Electromagnetic emission

I

II

III

The spin-down emission is **given off before but (in part) observed after** the prompt SGRB radiation
Discussion: evidence

• proposed new scenario to solve SGRB-X-ray afterglow dichotomy → “time-reversal” scenario

• delay times can explain observed X-ray afterglow durations → attractive alternative to current models

Evidence:

• potential observation of X-ray plateau with SGRB in between → indication of time reversal

• potential observation of an orphan event without SGRB → isotropy of afterglow
Implications:

• SGRBs with X-ray afterglows (majority of observed events) originate from BNS mergers → no BH-NS progenitors

• SMNS constraints on EOS in combination with a mass estimate

Ciolfi & Siegel 2015b

• peak amplitude of GW emission separated from SGRB by lifetime of the NS
GW and EM observations

- GW observations ideal trigger for EM observations
- peak amplitude of GW emission separated from SGRB by lifetime of the NS
  → very precise measurement of the NS lifetime!
Following steps

- **GRMHD simulations of BNS mergers**
  long post-merger evolution
  SMNS properties
  mass ejection, winds
  (Ciolfi, Kastaun, Giacomazzo, Siegel)

- **1D dynamical model** to describe
  phase II and phase III
  realistic light curves and spectra
  (see talk by D. Siegel)

  Siegel & Ciolfi 2015b, 2015c

much larger spatial scales and time scales
NOT covered by GRMHD simulations
References

Short gamma-ray bursts in the ‘time-reversal’ scenario

Short gamma-ray bursts from binary neutron star mergers: the time-reversal scenario

Magnetically driven winds from differentially rotating neutron stars and X-ray afterglows of short gamma-ray bursts

Siegel D.M. & Ciolfi R. (2015a), in “Swift: 10 Years of Discovery”, PoS(SWIFT 10)169
Magnetically-induced outflows from binary neutron star merger remnants

Electromagnetic emission from long-lived binary neutron star merger remnants I: formulation of the problem

Electromagnetic emission from long-lived binary neutron star merger remnants II: light curves and spectra
BACKUP SLIDES
Baryon-loaded wind

- rest-mass density of the wind $\rho \sim 10^8$ g/cm$^3$
- ejection speed $v \lesssim 0.1$ c
- mass loss rate $\dot{M} \sim 10^{-3}$ $M_\odot$/s
- mostly isotropic!

rest-mass density evolution ↓
SGRB precursors

Troja et al. 2010

Fig. 1.—Swift/BAT mask-weighted light curves (15–150 keV) of short GRBs with possible precursor activity. Dashed vertical lines mark the precursor duration. The precursors of GRB080702A and GRB050724 are shown in greater detail in the insets. For comparison, we also show the background-subtracted light curves of Fermi/GBM (090510 and 081024A) and Suzaku/WAM (091117).

2.2. Imaging analysis

In order to further check whether the excess in the light curve is related to the GRB, we produced a background-subtracted sky image in the interval of the candidate precursor and searched for a source at the GRB position.
Timing argument

The scenario cannot hold unless the maximum delay is at least as large as the observed afterglow duration

• from observations: \( t_{\text{coll}} \gtrsim t_{\text{sd}} \)

• typically: \( t_{\text{sd}} \gg t_{\text{dr}} + \Delta t_{\text{shock}} \)

\[ \rightarrow \quad \text{at } t_{\text{coll}} \quad \text{ejecta matter is swept up into thin shell} \]

• delay for a photon emitted just before collapse (“last spin-down photon”):

\[ t_{\text{delay}}^{\text{NS}} = \Delta t_{\text{diff}} - \frac{R_{\text{ej}}(t_{\text{coll}} + \Delta t_{\text{diff}})}{c} \]

• Delay of jet is negligible (very low densities at \( t_{\text{coll}} \))

Timing criterion

\[ t_{\text{delay}}^{\text{NS}} \sim t_{\text{NS}} - t_{\text{delay}}^{\text{jet}} \gtrsim \Delta t_{\text{afterglow}} \]
**Diffusion timescales**

- for static ejecta:
  \[
  t_{\text{diff}, \text{stat}}(t) = \frac{\Delta \rho_{\text{ej}}}{c} (1 + \kappa \rho_{\text{ej}}(t) \Delta \rho_{\text{ej}}) \propto t^{-2}
  \]

- for static nebula:
  \[
  t_{\text{diff}, \text{stat}}(t) = \frac{R_{\text{n}}(t)}{c} \left(1 + \sqrt{\frac{4Y_{\text{T}} L_{\text{sd}}(t)}{\pi R_{\text{n}}(t) m_{\text{e}} c^3}}\right) \propto t^{-1/2}
  \]

\[
\begin{align*}
  t_{\text{delay}} & \lesssim t_{\text{diff, stat}}(t_{\text{coll}}) + t_{\text{diff, stat}}(t_{\text{coll}}) - R_{\text{ej}}(t_{\text{coll}}) / c \\
  t_{\text{delay}} & \gtrsim t_{\text{diff, stat}}(t_{\text{coll}}^*) + t_{\text{diff, stat}}(t_{\text{coll}}^*) - R_{\text{ej}}(t_{\text{coll}}^*) / c
\end{align*}
\]

solve iteratively for \( t_{\text{coll}}^* \):
\[
  t_{\text{coll}}^* = t_{\text{coll}} + t_{\text{diff, stat}}(t_{\text{coll}}^*) + t_{\text{diff, stat}}(t_{\text{coll}}^*) \]

→ use lower limit to check the timing criterion
Results on delay estimation

• for parameter ranges considered:
  \[ t_{\text{delay}}^\text{NS} > 3 \times 10^4 \text{ s} \]
  \[ t_{\text{delay}}^\text{NS} \gtrsim 10^5 \text{ s} \quad (B_p \lesssim 10^{15} \text{ G}) \]

  generally: \[ t_{\text{delay}}^\text{NS} \gtrsim \Delta t_{\text{afterglow}} \]

  “time-reversal” scenario compatible with observations

parameter ranges:

\[ B_p \sim 10^{14} - 10^{16} \text{ G} \]
\[ P_{\text{in}} \sim 0.5 - 5 \text{ ms} \]
\[ t_{\text{dr}} \sim 0.1 - 10 \text{ s} \]
\[ \dot{M} \sim 10^{-4} - 10^{-2} M_\odot \text{ s}^{-1} \]
\[ \Delta t_{\text{shock}} \sim 0 - 100 t_{\text{dr}} \]
\[ v_{\text{ej}}^0 \sim 0.01 - 0.1 c \]
**EOS constraint for a SMNS**

Ciolfi & Siegel 2015b

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**most likely progenitor mass combination**

\[ 1.3 - 1.4 \, M_\odot \]

Belczynski et al. 2008

\[ M \sim 0.9(M_1 + M_2 - 0.1) \]

\[ M \sim 2.34 \, M_\odot \]

\[ (M_b \sim 2.87 \, M_\odot) \]

**APR4 ✓**

**H4 ✓**

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**Graph**

- **APR4** No rotation
- **APR4** Maximal rotation
- **H4** No rotation
- **H4** Maximal rotation

**Axes**

- \( \rho_c \, [10^{15} \text{ g/cm}^3] \)
- \( M \, [M_\odot] \)
progenitor mass combination

\[ 1.4 - 1.4 \, M_\odot \]

\[ M \sim 0.9(M_1 + M_2 - 0.1) \]

\[ M \sim 2.43 \, M_\odot \]

\( M_b \sim 2.98 \, M_\odot \)

EOS constraint for a SMNS

Ciolfi & Siegel 2015b
progenitor mass combination

$1.5 - 1.5 \, M_{\odot}$

$M \sim 0.9(M_1 + M_2 - 0.1)$

$M \sim 2.61 \, M_{\odot}$

($M_b \sim 3.2 \, M_{\odot}$)

APR4 $\times$

H4 $\times$
EM emission from long-lived BNS merger remnants

Siegell & Ciolfi 2015b, 2015c

- **1D dynamical model** to describe phase II and phase III on large time and spatial scales

  ideal EM counterpart to the GW signal

- bright (up to $L_X \sim 10^{48}$ erg/s)
- long-lasting (typically $10^4$ s)
- isotropic
- associated with a large fraction of BNS merger events
- clear distinction NS-NS vs NS-BH
EM emission from long-lived BNS merger remnants
Siegel & Ciolfi 2015b, 2015c

- **1D dynamical model** to describe phase II and phase III on large time and spatial scales

![Graphs showing light curves and spectra](image)

- **NO SMNS collapse**
  - SGRB prompt emission @ merger

- **SMNS collapse**
  - $t_{\text{coll}} = t_{\text{spin-down}}$
  - SGRB prompt emission @ merger

- **SMNS collapse**
  - $t_{\text{coll}} = t_{\text{spin-down}}$
  - SGRB prompt emission @ SMNS collapse (time-reversal scenario)
EM emission from long-lived BNS merger remnants

Siegel & Ciolfi 2015b, 2015c