ELECTROMAGNETIC COUNTERPARTS OF NS$^2$ MERGERS: SGRBs, Macronova, Cocoon Emission and Radio Flares

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Outline

• A side remarks on BBH mergers and Long GRBs
• Why EM counterparts?
• Rates
• GRBs - excellent but beamed
• Mass ejection in NS mergers
• Evidence for mass surrounding short (non-Collapsar) GRBs.
• Consistency with r-process Nucleosynthesis.
• Short GRB cocoons and their signature - the brightest quasisotropic EM counterpart.
• Jets in SNe - the observational signature.
Long GRBs

Wanderman & TP 2011
Long GRBs vs BBH merges

Hotokezaka & TP 2017

- LGRB observed rate \(\sim 1 \text{ Gpc}^{-3} \text{ yr}^{-1}\)
- With beaming \(\sim 50 \text{ Gpc}^{-3} \text{ yr}^{-1}\)
- Comparable to BBH merger rate!

- LGRBs arise from the death of massive stars
- LGRBs arise in low metallicity Galaxies
- Massive BBH require low metallicity

\[\Rightarrow\] LGRBs signal the formation of the BHs of the BBH

(the merger takes place, of course Gyrs later)
The expected $\chi_{\text{eff}}$ (Hotokezaka & TP 17a,b)

From a WR population that follows the LGRB rate
Why EM Counterparts?

(Kochanek & TP 1993)

Where?
What?
How?
Short vs. Long and Mergers vs. Collapsars

Eichler, Livio, TP, Schramm, 88

MacFadyen & Woosley 98

NS mergers
Indirect Evidence

Direct Evidence

Collapsars

Direct Evidence

Indirect Evidence
The Rate of short GRBs
(Wanderman & TP 2015)

- Current observed rate
  \( \sim 5 \text{ Gpc}^{-3} \text{ yr}^{-1} \sim 0.5 \text{ Myr}^{-1} \)
- Higher z rate is larger
- Uncertainties
  - Short delay mergers (need high redshift sGRBs) can be \( \sim 20 \text{ Myr}!!! \)
  - Lowest energy (rate can be higher)
  - Beaming factor \( \times 10^{-70} \)
    (Very uncertain)
- Galactic rate from binary pulsars \( 21_{-14}^{+28} \text{ Myr}^{-1} \) (Kim + 15)
- Most pop synthesis estimate ignore low kick channel
Short GRBs as EM counterparts

- GRBs are beamed and the probability for a joint observations is rather small (about 1 in 20)
- Joint GW + GRB detection - once in ~10 years
Mergers ejects $0.01-0.04 M_{\text{sun}}$ with $E_k \sim 10^{50}-10^{51}$ ergs

Stephan Rosswog
Mergers ejects $0.01-0.04 M_{\text{sun}}$ with $E_k \sim 10^{50}-10^{51}$ ergs

Stephan Rosswog
Different ejecta components

$10^9 - 10^{10}$ cm.

GRB jet

Merger shock breakout

Cocoon

Dynamical ejecta

Wind

$\sim 0.01 \, M_{\text{Sun}}$

From Hotokezaka & TP 2015
Macronova* (Li & Paczynski 1997)

- Radioactive decay of the neutron rich matter.
- $E_{\text{radioactive}} \approx 0.001 \text{ Mc}^2 \approx 10^{50}$ erg
- A weak short Supernova like event.

*Also called Kilonova
Macronova* (Li & Paczynski 1997)

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*Also called Kilonova, Hektanova, Decanova*
Supernova

Photosphere  Photons escape

Powered by radioactive decay of $^{56}\text{Ni} \rightarrow ^{56}\text{Co} \rightarrow ^{56}\text{Fe}$

Ni 6.1 days  Co 77 days
Supernova

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luminosity  time
Supernova

Photosphere

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luminosity

Ni 6.1 days

Co 77 days

time
After a second $\frac{dE}{dt} \propto t^{-1.3}$ (Freiburghaus et al. 1999; Korobkin et al. 2013)
Macronova emission

\[ \tau = \frac{c}{\nu} \]

Photons escape from this region
Macronova emission

$\tau = \frac{c}{\nu}$

Photons escape from this region
Energy Generation

Hotokezaka, Sari & TP + 16

\[
\begin{align*}
\gamma \\
N + p \\
\nu_e \\
e \\
GF \\
N + n
\end{align*}
\]

\[
t_f = \frac{2\pi^3}{G_F^2 m_e c^4} \frac{\hbar^7}{m_e c^4} \approx 10^4 \text{sec}
\]

\[
\dot{E} = \epsilon_e \frac{m_e c^2}{t_f} \left( \frac{t}{t_F} \right)^{-\alpha}
\]

\[
\frac{1}{\tau} \propto \frac{d}{dE} \int d^3 p_e \int d^3 p_\nu
\]

\[
\begin{align*}
E^3 & \quad \text{or} \quad E^{3/2} \\
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\end{align*}
\]

Relativistic \quad \frac{1}{\tau} \propto E^5 \quad \rightarrow \alpha = 6/5

Newtonian \quad \frac{1}{\tau} \propto E^{7/2} \quad \rightarrow \alpha = 9/7

Macronova
Photons escape from this region.

Opacity

\[ \tau = \frac{c}{v} \]

Diffusion time

\[ t_{\text{diff}} = \frac{\tau (v_{\text{max}} - v) t}{c} = \frac{mk}{4\pi c vt} \]

Optical depth

\[ \tau \approx \frac{mk}{4\pi (vt)^2} \]
Photons escape from this region. Decrease due to radioactive decay. 

Increase as we see a large fraction of the matter.

Decrease due to radioactive decay.
\[ \tau = \frac{c}{v} \]

Photons escape from this region

Decrease due to radioactive decay

Increase as we see a large fraction of the matter.

Decrease due to radioactive decay

Macronova
Peak time and peak luminosity

Diffusion time = expansion time $\leftrightarrow$
Mass of the "emitting region"

Luminosity

Radioactive heating rate

The peak time

The peak luminosity

Macronova
Lanthanides dominate the opacity
(Kassen & Barnes 13, Tanaka & Hotokezaka 13)

- $\kappa = 10 \text{cm}^2/\text{gm}$
- $t_{\text{max}} \propto \kappa^{1/2}$ => longer
- $L_{\text{max}} \propto \kappa^{-0.65}$ => weaker
- $T \propto \kappa^{-0.4}$ => redder
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\( \text{uv or optical} \Rightarrow \text{IR} \)
Bolometric light curves
neutrino driven winds

Different $Y_e$, different nucleosynthesis, different opacity: $\kappa = 1\text{cm}^2/\text{gm}$
neutrino driven winds - lightcurves
Combined macronova signal
The short Gamma-Ray Burst (GRB) 130603B

GRB 130603B

\( z = 0.356 \leftrightarrow 1 \text{ Gpc} = 3 \text{ Glyr} \)
At 15:49:14 UT, the Swift Burst Alert Telescope (BAT) triggered and located GRB 130603B (trigger=557310). Swift slewed immediately to the burst.

The BAT on-board calculated location is

RA, Dec 172.209, +17.045 which is

RA(J2000) = 11h 28m 50s
Dec(J2000) = +17d 02' 42"

with an uncertainty of 3 arcmin (radius, 90% containment, including systematic uncertainty).

The BAT light curve showed a single spike structure with a duration of about 0.4 sec.

The peak count rate was 60000 counts/sec (15-350 keV), at ~0 sec after the trigger.

A short burst

z=0.356 <=> 1 Gpc = 3 Glyr
GRB130603B @ 9 days AB
(6.6 days at the source frame)

HST image (Tanvir + 13)
Swift

Macronova?

0.01–0.05 $M_\odot$

Tanvir + 13 (see also Berger + 13)

GRB 130603B
GRB 060614

Need $M \approx 0.1 M_{\odot}$

$\Rightarrow$ BH-NS ?

Yang et al., 2015
FIG. 1. The optical observations of sGRB 050709. The $R$-band emission (green dashed line) decreases as $t_{1.63 \pm 0.16}$, consistent with the $V$-band data. On the other hand the $I$-band (VLT $I$-band data as well as the first two HST F814W-band data points decrease much slower as of $t_{1.12 \pm 0.09}$. This is strongly suggesting an additional optical emission component emerging at $t_{2.5}$ days that is characterized by a low-luminosity and a soft spectrum. In the insert we show the SED of the afterglow of sGRB 050709 measured by VLT on July 12, 2005 compared with a possible Iron line-like spectral structure adopted from Kasen et al. 

An uncertainty of $\pm 0.75$ mag has been adopted following Hotokezaka et al.

The late F814W-band emission (see Fig. 2) is very similar to the $I$/F814W-band excess observed in GRB 060614. The latter is consistent with a macronova expected days after a compact binary merger, provided that a significant mass ($\approx 0.1 M_\odot$) was ejected.

The VLT $I$/F814W-band emission light curve can be reasonably reproduced with a macronova following a black hole-neutron star merger with $M_{ej} \approx 0.05 M_\odot$ and $V_{ej} \approx 0.2 c$, where $c$ is the speed of light and $V_{ej}$ is the ejecta velocity (see Fig. 3). This is comparable but slightly smaller than the parameters used for fitting the $I$-band excess observed in the afterglow of GRB 060614. Such a large amount of $r$-process material is consistent with a black-hole neutron star mergers and it also supports the hypothesis that compact object mergers are prime sites of significant production of $r$-process elements.

The weak $I$-band emission at $t \approx 2.5$ days together with the almost simultaneous $R$ and $V$ observations, imply a puzzling broad line-like structure. A speculative interpretation is that this signal arises from a wind-macronova. A strong line feature can be produced by a macronova dominated by Iron. Such an Iron-group dominated macronova may arise from an accretion disk wind in which the heavier $r$-process elements are depleted because strong neutrino irradiation from a remnant neutron star can increase the electron fraction of the disk material. For this interpretation to hold there must have been an early jet break, corresponding to a narrow jet as seen in other sGRBs. In this case only the first observation at $t \approx 1.4$ days after the burst is a clear afterglow signal. Hence this interpretation cannot be verified due to the unavoidable uncertainties in the afterglow subtraction.

Need $M \approx 0.05 M_\odot$

$\Rightarrow$ BH-NS ?

Jin et al., 2016
Are Macronova Frequent?

- There are 3 (6) possible (nearby) historical candidates with a good enough data
- In 3/3 (3/6) there are possible Macronovae
r-process consistency

Hotokezaka & TP 17
If correct

- Confirmation of the GRB neutron star merger model (Eichler, Livio, TP & Schramm 1989).

- Confirmation of the Li-Paczynski Macronova.

- Confirmation that compact binary mergers are the source of heavy (A>130) r-process material (Gold, Silver, Platinum, Plotonium, Uranium etc...).
Radio Flares  (Nakar & Piran 2011)

A long lasting radio flare due to the interaction of the ejecta with surrounding matter may follow the macronova.
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A long lasting radio flare due to the interaction of the ejecta with surrounding matter may follow the macronova.
Supernova
Months

Macronova
Weeks

Supernova remnant
a few x $10^4$ years

Radio Flare
months – years
Radio Flare light curves

Nakar, TP 2011; TP+13; Hotokezata + TP, 15; Hotokezaka et al., 16
A flare from GRB 130603B should be detected by the EVLA (if the external density is not too small)
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The Cocoon signature

From Hotokezaka & TP 2015
Jet Propagation

(MacFayden & Woosley 1998; Aloy+ 1999; Matzner 2003; Lazzati and Begelman, 05; Bromberg + 2011....)
Jet Propagation

(MacFayden & Woosley 1998; Aloy+ 1999; Matzner 2003; Lazzati and Begelman, 05; Bromberg + 2011....)
3D Simulations by Ore Gottlieb using Pluto.
Breakout time \( \sim 0.2 \) sec
Ejecta from the simulations of Nakagura et al 2014
3D Simulations by Ore Gottlieb using Pluto.

Breakout time $\sim 0.2$ sec

Ejecta from the simulations of Nakagura et al 2014
The “short” plateau
Moharana & TP 17  arXiv170502598

$t_b \sim 0.4$ Sec

There are mergers in which the jet don’t break out!
While propagating in the ejecta, the jet dissipates its energy (~$10^{49}$ ergs) in a cocoon.

Can we see this energy?

Yes.
The cocoon breakout

Ore Goettlib, Ehud Nakar & TP 17

arXiv170510797G

Cooling + Radioactivity

=> short lived bright signal
The brightest counterpart

Bolometric Luminosity

Temperature

g Magnitude

Multiwavelengths

cooling emission

cocoon macronova
g band light curve

Observational strategy: look for a rapid (hour) bright blue signal and followup in IR (Grossman, Korobkin, Rosswog, TP, 14)
Cocoon Afterglow
Teboul & TP 17

• The relativistic part of the cocoon’s ejecta may lead to an afterglow emission due to the interaction of the ejecta with the surrounding matter.
Detectability

aLIGO will provide a 100 deg$^2$ error box

• The Dynamical ejecta IR signal
  • @ 300 Mpc -> $M_H \approx 23.5-24.5$ (-1 at optimal viewing angle) on a time scale of a few days
  • Rapid follow up is impossible in the IR.

• Neutrino driven wind UV/Blue signal
  • @ 300 Mpc -> $M_H \approx 23.7-24.2$ on a time scale of a < day
  • Possible with SHC on subaru or continuous cover with ZTF or equivalent or LSST

• Cocoon signature
  • @ 300 Mpc -> $M_H \approx 22-23$ on a time scale of an hour
  • Possible with SHC on subaru or continuous cover with ZTF or equivalent or LSST
Detection strategy

• Deep search in the optical using HSC or multiple exposures on a very wide field telescope (ZTF).

• With detection deep localized search in the near IR

• Blind searches in Optical and clearly in IR are hopeless (a few single event detections per year with the LSST).
Conclusions

- Short GRBs are the best EM counterparts - but the rate of a sGRB+GW signal is small ~ 1 in 10 years.
- NS$^2$ ejecta produces a weak “supernova” first a supernova like optical/IR signal (Macronova/kilonova) and then a SNR like Radio Flare.
- Consistently of numerous observations pointing out to NS$^2$ mergers as sources of r-process.
- The GRB jet deposits $\sim 10^{49}$ ergs in a cocoon.
- Cocoon cooling emission + radioactivity => a bright (22-23 mag) blue short (hours) signal.
- Observational strategy: look for a rapid bright blue signal and follow up in IR.
1) Physical Processes in Astronomical Transients
Jerusalem winter school
27/12/2017 - 4/1/2018

2) Several Postdoc positions under the ERC grant TReX
A remark about binary neutron stars
TP & Shaviv 2005; Dall’Osso, TP & Shaviv 2013, Beniamini & TP 2015; Beniamini, Hotokezaka & TP 16

Most observed Galactic binary neutron stars have almost circular orbits and a low proper motion

- Very low mass ejection (<0.1 $M_{\odot}$ for J0737-3039B)
- NOT formed in a regular SNe

This is not taken into account in most (e.g. Cote + ) Pop synthesis calculations.
GBM counterpart (p=0.002)
The BHBH (GW150914) EM counterpart problem

- $>10^{49}$ ergs $\Rightarrow > 10^{-5} m_{\text{sun}}$

- Life time of a BHBH binary
  $\sim 1$ Gyr (from minimal separation)

- Cannot keep so much mass from formation for 1 Gyr.

- Need to link (in time) the mass accumulated to the merger.
A short distance capture + matter injection

=> A 3 body interaction in a globular cluster?

=> Maybe possible but extremely rare