Constraining the Long-living Supramassive Neutron Stars by Magnetar-boosted Kilonovae

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**Kilonovae**

**Background**

Neutron star merger

Merger ejecta: heavy elements

Radioactive heating

Thermal radiation: kilonova

- Peak luminosity: $\sim 10^{41}$ erg/s
- Peak time: $\sim 1$ day
- Waveband: $\sim$ optical
- (Regular)
Magnetar-boosted Kilonovae

Active merger remnant
Continuous outflow
Energy injected to ejecta
Boosted luminosity

Types central engines:
BH accretion / magnetar spin-down

Magnetars:
highly magnetized neutron stars
Supramassive Neutron Stars

- SMNS are magnetars
- Rotational energy: $10^{52} - 10^{53}$ erg!
- Boosted luminosity: $10^{2} - 10^{3}$ brighter!
Supramassive Neutron Stars: sGRB

Why magnetars

Magnetars are also used to model X-ray plateau in sGRB afterglow
Bright Nature vs. Absence of Detection

Simple estimation

**Theory**

- Maximum luminosity: $>> 10^2$ times
- Detectable distance: $>> 10^1$ times
- Detectable volume: $>> 10^3$ times
- Expected detection number: Magnetar-boosted KNe $> \text{regular KNe}$!

**Observation: sky survey**

- Zwicky Transient Facility (ZTF), Panoramic Survey Telescope and Rapid Response System (Pan-STARRS), ...
- Time: $> 4$ years
- No detection!

Constraint on boosted kilonova model or SMNS
**Model**

Basic ingredients

- Neutral ejecta
- Ionized ejecta
- X-ray ionization front
- Magnetic wind nebula
- Ejecta
- Spindown power
- X-ray ionization
- Thermal radiation
- Boosted Kilonova
**Model: Magnetar**

spindown power

Magnetar has limited survival timescale:

\[
\eta = \frac{\int_0^{t_c} L_{sd} dt}{E_{ini}} = \frac{t_c}{t_c + t_{sd}}
\]

Dipole power:

\[
L_{sd} = L_{sd,0}(1 + t/t_{sd})^{-2}
\]

\[
L_{sd,0} \approx 10^{50} \left( \frac{E_{ini}}{10^{53} \text{erg}} \right)^2 \left( \frac{B}{10^{15} \text{G}} \right)^2 \text{erg/s}
\]

\[
t_{sd} = 0.01 \left( \frac{E_{ini}}{10^{53} \text{erg}} \right)^{-1} \left( \frac{B}{10^{15} \text{G}} \right)^{-2} \text{d.}
\]
Model: Pulsar Wind Nebula

pair cascade

Saturated pair cascade: balance

\[ n_\pm = \sqrt{\frac{16YL_{sd}}{3\sigma_T m_e c^3 V_n}}. \]

Optical depth: Thomson scattering

X-ray luminosity:

\[ L_n \sim \frac{E_n}{\tau_n} = \frac{cE_n}{R_n(1 + \tau_n)}. \]
**Model: Ejecta**

Photoionization

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Ionization balance:

\[
f^i \int \frac{4\pi J_\nu}{h\nu} \sigma^i_\nu d\nu = n_{Fe} \alpha_{rec} f^{i+1} \sum_{i=1}^{i=27} (i-1) f^i
\]

\[
\sum_{i=1}^{i=27} f^i = 1
\]

Bound-free opacity:

\[
\kappa_{bf,\nu} = \frac{1}{56m_p} \sum_{i=1}^{26} f^i \sigma^i_\nu
\]

Photoionization Heating
Observational Features

features

![Graph of observational features with legend showing different energy bands and parameters.]
Observational Expectation

We expect way more KNe than we really have!

But it’s not easy to estimate the number of detection...

Model-independent study:

Explore the parameter space

Model-dependent study:

EoS and sky survey strategy

One more possibility:

Rayleigh-Taylor Instability?
Model-independent Study: detectable distance

Detectable distance

Explore the Parameter space

\[ D_{i,\text{max}} = \frac{E_{\text{inj}}}{E_{\text{ini}}} \]

\[ \eta = \frac{E_{\text{inj}}}{E_{\text{ini}}} \]
Model-dependent Study

Monte Carlo simulation

- Equation of States: UU ($M_{TOV} = 2.0 \, M_{\text{sun}}$), SLy ($M_{TOV} = 2.2 \, M_{\text{sun}}$)

- From BNS population (galactic) to remnant population

- Evolve the remnant by “RNS code”

- Mimic ZTF sky survey strategy

- A free parameter: $E_{\text{ini}} / E_{\text{kep}}$
Model-dependent Study: detection number

result

UU ($M_{TOV} = 2.0 \, M_{\odot}$)

SLy ($M_{TOV} = 2.2 \, M_{\odot}$)

Upper limit

SMNS formation rate
Model-dependent Study

Constraint

Significance of rejection ($\sigma$)
Rayleigh-Taylor Instability

Isotopic blastwave

- Acceleration of ejecta leads to RT instability.
- The PWN matter can leak away from the ejecta and forms blastwave!
- We assume the blastwave is like GRB afterglow
- We don’t see so many orphan afterglow!
Implications

- SMNS are likely to be rare

- Boosted-kilonovae candidates (e.g., GRB 200522A): too faint

- Orphan GRB afterglow: a new class of orphan afterglow

- sGRB plateau: unlikely from magnetars

- FRB: dispersion measure is too high

- Multimessenger observation: will place further constraint to our model
Summary & Conclusion

- Magnetar-boosted kilonovae are extremely bright optical transients yet not discovered so far.

- The absence of detection places strict constraint on the “magnetar” model.

- SMNS must be rare and can’t be “long-living”
Thank You

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