ショートガンマ線バースト中心動力源の数値モデリング

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研究会「ガンマ線バースト研究の新機軸」
GW170817 as a BNS merger event

Aug. 17th 2017, 74 sec. signals detected by LIGO-Hanford.

S/N is 32.4!
Real Multimessenger Astronomy Era

GW $\Rightarrow$ $\gamma$-ray $\Rightarrow$ UV, Optical, IR $\Rightarrow$ X-ray $\Rightarrow$ Radio

Host galaxy (NGC4993) was identified by the optical telescope (SSS17A)
Mass measurement of NSs.

$m_1$: 1.36-1.60 $M_\odot$, $m_2$: 1.17-1.36 $M_\odot$ (low spin prior)
$m_1$: 1.36-2.26 $M_\odot$, $m_2$: 0.86-1.36 $M_\odot$ (high spin prior)

Luminosity distance is $40^{+8}_{-14}$ Mpc
Tidal deformability measurement of NSs
LSC and Virgo collaboration PRL 119, 161101 (2017)

- Tidal deformation $\Lambda$ is related to a NS radius $\Rightarrow$ Information of the NS equation of state.
- Soft EOS is favored ($\Lambda \leq 800$)
Detected UV-Optical-Infrared emission

Arcavi et al. Nature 24291, 2017

Drout et al. Science (aaq0049) 2017

- Rapid reddening from UV to IR
- Spectrum is quasi-black body
- Long-duration IR component & short-duration UV-Optical component (see also Tanaka kun’s talk)
Science target of GWs from BNS merger

Revealing the central engine of SGRBs
► Merger hypothesis (Narayan, Paczynski, and Piran 92)

Exploring the equation of state of neutron star matter
► Determination of NS radius (NS tidal deformability) (Flanagan & Hinderer 08 etc.)

Origin of the heavy elements
► R-process nucleosynthesis site (Lattimer & Schramm 76)

Electromagnetic counterpart of GW sources
► Optical-near infrared emission due to the radioactive heating source of r-process elements (Li & Paczynski 98, Metzger et al. 10)
**GW170817 as a central engine of GRB170817A?**

Metzger 17

- **Off-axis GRB?** (Ioka San’s talk)
- **Rapid Blue Kilonova/Slow Red Kilonova**

Uncertainty of heating rate: factor 2-3 (blue), < 2 (red), Thermalization efficiency: Uncertain (blue), Robust (red), Geometry factor $\approx 2 \Rightarrow$ factor of 2-3 (blue), 3-10 (red) in estimated $M_{\text{ej}}$
GW170817 as a central engine of GRB170817A?

- SGRB rate observed on-axis: \( f_{\text{on}} R_{\text{SGRB}} \approx 2 - 6 \ \text{Gpc}^{-3} \ \text{yr}^{-1} \)
- Merger rate of BNS: \( R_{\text{BNS}} \approx 1540^{3200}_{-1220} \ \text{Gpc}^{-3} \ \text{yr}^{-1} \)

⇒ beaming fraction \( f_{\text{b}} \approx f_{\text{on}} R_{\text{SGRB}} / R_{\text{BNS}} \approx 10^{-4} - 2 \times 10^{-2} \)

⇒ jet half-opening angle \( \theta_j = (2 f_{\text{b}})^{1/2} \approx 0.02 - 0.2 \)
An inferred remnant of GW170817

**Given EOS**

\[ \Delta T: \text{Maximum released rotational energy for HMNS} \Rightarrow \text{Rigidly rotating NS} \]

\[ \text{Observed kinetic energy of the ejecta} \quad E_{\text{kin}} = \frac{1}{2} (M_{\text{blue}} v_{\text{blue}}^2 + M_{\text{red}} v_{\text{red}}^2) \approx 10^{51} \text{ erg} \]

**Margalit & Metzger 17**

- Baryon mass constant

- \( \Delta T \): Maximum released rotational energy for HMNS ⇒ Rigidly rotating NS

- Observed kinetic energy of the ejecta \( E_{\text{kin}} = \frac{1}{2} (M_{\text{blue}} v_{\text{blue}}^2 + M_{\text{red}} v_{\text{red}}^2) \approx 10^{51} \text{ erg} \)
Probability distribution of the baryon mass of merger remnant

\[
P \left( M_{\text{rem}}^b | \mathcal{O}, \text{EoS} \right) = \int dM_1^b \int dM_2^b \, \delta(M_1^b + M_2^b - M_{\text{ej}} - M_{\text{rem}}^b) \times P \left( g_{\text{EoS}}(M_1^b) ; g_{\text{EoS}}(M_2^b) | \mathcal{O} \right) \left| g_{\text{EoS}}(M_1^b) \right| \left| g_{\text{EoS}}(M_2^b) \right|
\]

Posterior from GW170817, gEoS:M_b->M_g

- \( M_{\text{ej}} = 0.02 \, M_\odot \)
- Consistency check of the probability of the baryon mass and \( \Delta T < 10^{51} \text{erg} \Rightarrow M_{g,\text{max}} < 2.17 M_\odot \)
- No significant post-merger signal (LSC collaboration 17)

\( \Rightarrow \) BH is an inferred remnant of GW170817
Exploring a realistic picture of NS-NS mergers

(Bartos et al. 13)

- **Time axis**
- **Total mass vs Maximum mass of NSs (EOS)**
  - EOS produces a systematic error for modeling the central engine ⇒ Constraining a tidal deformability of NS
  - MHD effect: Effective turbulent viscosity and/or large scale dynamo
  - Neutrino reaction: Pair annihilation

B-field and neutrino play an essential role

B-field and neutrino are irrelevant
From inspiral to late inspiral phase

Tidal deformation: NS just before the merger could be deformed by a tidal force of its companion.

Tidal deformability depends on NS constituent, i.e., EOS.

Tidal deformation

Stiff EOS (large R)

Easily tidally deformed

Soft EOS (small R)

Hard to be tidally deformed
Tidal deformability imprinted in GWs

\[ h = A(t)e^{i\Phi(t)} \]

Amplitude

Phase

Tidal force is attractive force ⇒
Tidal deformation accelerates the phase evolution

Theoretical template of GWs

Data + noise

Template

Strain (10^{-21})

Hanford

Time (s)
To measure a tidal deformability:

Large tidal deformability $\Rightarrow$ Rapid phase evolution
Numerical diffusion $\Rightarrow$ Rapid phase evolution

Requirement:

Red: Larger tidal deform.
Cyan: Small tidal deform.

$\Delta \Phi_{\text{error}} < \Delta \Phi_{\text{tidal}}$

Merger
Toward a theoretical template bank

We construct a phenomenological waveform template (Kawaguchi, KK et al. in prep.). ⇒ Data analysis of released LIGO data.
Importance of MHD

Effective turbulent viscosity

\[ \partial_t \langle \rho j \rangle + \partial_R (\langle \rho j v^R \rangle + RW_{R\varphi}) = 0 \]

\[ W_{R\varphi} = \langle \delta v^R \delta v^\varphi \rangle - \frac{B^R B^\varphi}{4\pi \rho} \]

- Angular momentum transfer by the stress
- Energy dissipation due to the effective turbulent viscosity

Generation of large scale field

- Coherent poloidal field is necessary for a jet launch via the Blandford-Znajek process (BH formation case) / Magnetar model (dipole radiation)
Magnetization of the remnant massive NS
Kelvin-Helmholtz instability (KK et al. 14, 15)

Fine resolution \((\Delta x=17.5\text{m})\)

- Small scale vortices develop rapidly ⇒ Efficient amplification of the B-field
- Low res. run cannot reproduce vorticity formation

Low resolution \((\Delta x=150\text{m})\)
The growth rate shows the divergence. c.f. $\sigma \propto$ wave-number for KH instability.

Strong, but randomly oriented B-field energy evolution $B_0 = 10^{13} \text{G}$.
Effective turbulent viscosity in merger remnants

Space time diagram of merger remnant (KK et al. 17)

Dense core

Envelope

MRI unstable

MRI stable

$\alpha$ inside a core $\approx 5 \times 10^{-3}$

$\alpha$ inside an envelope $\approx 0.01 - 0.02$

$\alpha = \left\langle \frac{W_{R\phi}}{P} \right\rangle$

$W_{R\phi}$: Reynolds + Maxwell stress
Power spectrum evolution of B-fields

- Early phase: KH instability amplifies the small scale magnetic field efficiently
- Late phase: Inverse cascade of MRI?
- No prominent signal of the generation of coherent field
What we learn from these numerical experiments

- **Non-linear phase** of the MRI is essential: Magneto-turbulent state should be sustained to generate effective turbulent viscosity
  ⇒ Fate of a remnant of BNS mergers

It generally requires much finer resolution.
What we learn from these numerical experiments

- Large scale dynamo is still challenging problem. In particular, poloidal B-field

- A magnetized SN simulation suggests a generation of coherent toroidal field via large scale dynamo.
What we learn from these numerical experiments

- After a BH formation case, jet launch is still non-trivial problem

Jet launch is not found in our simulation;

\[ P_{\text{ram}} \approx 10^{29} \text{dyn cm}^{-2} \left( \frac{\rho}{10^9 \text{g cm}^{-3}} \right) \left( \frac{v}{0.3c} \right)^2 \quad \gg \quad P_{\text{mag}} \approx 10^{27} \text{dyn cm}^{-2} \left( \frac{B}{10^{14} \text{G}} \right)^2 \]
Jet launch is found at $t \approx 10$ ms after a BH formation
MRI is not resolved
No fall back matter
No clear explanation of a jet launch
Jet launch for delayed collapse, no jet for prompt collapse; small disk mass (EOS depend)
Negligible amount of fall back matter (?)
Condition for a generation of poloidal field via only MHD process: $t_{\text{fall}} < t_{\text{vis}}$
Long-lived remnant case

\[ \beta = \frac{P}{P_{\text{mag}}} \] on x-z plane for a long-lived remnant

Force free condition is hard to be built in a short time scale after merger
Long-lived remnant case

Pair annihilation heating drives an outflow to a polar direction

Fujibayashi et al. 17a

\[ \Gamma_f \approx 1.1 \left( \frac{Q/\rho}{10^{24} \text{ erg g}^{-1} \text{ s}^{-1}} \right) \left( \frac{\tau_{\text{heat}}}{1 \text{ ms}} \right) \]

\[ \tau_{\text{heat}} = \frac{z}{v_{\text{eje}}} \approx \frac{30 \text{ km}}{0.1c} \approx 1 \text{ms} \]

\[ \rho \downarrow \text{is necessary with keeping the heating rate, c.f.} \]
\[ \rho \sim 10^5 \text{ g cm}^{-3} \text{ with } Q \sim 10^{31} \text{ erg cm}^{-3} \text{ s}^{-1} \text{ is for } \Gamma \sim 100 \]

⇒ Still difficult even with a viscous heating (Just et al. 15, Fujibayashi et al. 17b)
Long-lived remnant case

Pair annihilation-driven wind may help to generate a coherent field

For instance,

\[ \left( \frac{B^2}{8\pi \rho c^2} \right) \approx 1 \left( \frac{B}{10^{13.5} \text{ G}} \right)^2 \left( \frac{\rho}{10^5 \text{ g cm}^{-3}} \right)^{-1} \]

Force-free magnetic field could be build with the assist of neutrino pair annihilation.

Ultimately, NR-neutrino Radiation transfer MHD simulation is necessary (e.g., Siegel & Metzger 17).
Summary

▶ Opening of the real multi messenger astronomy of compact binary merger (rich information!)

▶ Equation of state of neutron star matter (tidal deformability) is constrained for the first time.
⇒ We build a template band based on NR simulations and data analysis is on going.

▶ Numerical modeling of a central engine is still on the way.

Pure MHD or neutrino pair annihilation is not likely to be sufficient to launch a relativistic jet.
GRRMD simulation is awaited.