Compact Object Mergers

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Rosswog 2007
Overview

- Diversity of Mergers & Outcomes
- WD-WD:
  - R Cor Bor *s? Type Ia SNe? AIC of WD→NS?
- NS-NS, NS-BH
- Gamma-ray Bursts & Gravitational Wave Astrophysics
Stability of Mass Transfer

- Mass transfer begins when stellar $R \sim R_L \equiv$Roche Lobe
- Subsequent evolution depends on how $R^* \& a$ of orbit change
  - stable mass transfer? ... or ... merger on $\sim a$ dynamical time?
- If $M_{\text{tot}} \& J_{\text{tot}}$ conserved:
  - unstable transfer (merger!): $M_2 \geq M_1$
- GR: Close Binaries w/ Compact Objects:
  - $\gamma = 5/3$ polytropes: unstable if $M_2 \geq (2/3) M_1$ but ... mass loss, direct impact, tides, ...
  - NS-NS, BH-NS? unstable for plausible mass ratios
Diversity of Mergers & Why We Care

- **WD-WD**
  - $M \gtrapprox M_{CH}$: Type Ia supernovae? AIC of WD $\rightarrow$ NS?
  - $M \lesssim M_{CH}$: weird stars (e.g., R Cor Bor, extreme He *)

- **NS-NS & NS-BH**
  - most likely kHz gravitational wave source (LIGO, VIRGO)
  - short duration gamma-ray bursts
  - source of some n-rich heavy nuclei in nature (r-process)

- **WD-NS**
  - unusual GRB? unusual SNe? less well explored/constrained
WD-WD Mergers: What do we Know Empirically?

SPY

Rates uncertain (~ la from pop synthesis); no several σ detection of system w $M_{\text{tot}} > M_{\text{CH}}$

SWARMS
WD-WD Mergers: $M \approx M_{\text{CH}}$

(the story due to Ken Shen ....)

Key Evolutionary Phases (C/O WDs)

1. Dynamical Disruption (~ min)
   (C ignition possible in some cases?)
   If *'s survive merger ...

2. Viscous evolution of remnant (~hrs-year)

3. Cooling of the remnant (~$10^{4-5} \text{ yr}$)

Key Physics (pre-explosion): MHD, EOS, Opacity, ...
Computational Challenge: Merger, then ~ Multi-D Stellar Structure
WD-WD Mergers: \( M \approx M_{\text{CH}} \)

(the story due to Ken Shen ....)

2. Viscous evolution (~hours-year) \( \rightarrow \) spherical remnant w/ significant thermal support at large radii

3. Cooling of the remnant (~10^{4-5} yr): **AIC or Ia?**
NS-NS Mergers: What do we Know Empirically?

3 known NS-NS binaries in our galaxy will merge in a Hubble time (no BH-NS systems known)

\[ \dot{N}_{\text{merge}} \approx 10^{-5} - 3 \times 10^{-4} \text{ yr}^{-1} \text{ per MW galaxy} \]

(Kalogera et al. 2004)
NS-NS & NS-BH Mergers

Key Evolutionary Phases

1. Dynamical Disruption + Tidal Tails (~ ms)
2. Possible hypermassive NS; \( < \)-mom transport (B-fields) \( \rightarrow \) collapse to BH (\( \sim \) 10s ms)
3. Viscous evolution of disk (\( \sim \) 0.1-1 sec)
4. Disk ‘Explosion’ + Fallback (\( \approx \) sec)

Key Physics: GR, MHD, weak interactions, \( \nu \) transport, nuclear htg, ....
The Evolution of the Remnant Disk

Angular momentum conservation $\rightarrow$ disk spreads ($\&$ cools)

$\dot{M} \sim M_\odot \, s^{-1}$

$\tau_{\text{photons}} \gg 1 ; \tau_{\nu} \sim 1$

$\rightarrow$ only neutrino cooling impt

Accretion onto a Central BH

red = high density
blue = low density

multi-D MHD but no realistic physics for NS debris

ID time-dependent Models
($\alpha$-viscosity; realistic EOS, $\nu$-microphysics)
The Little Bang: Late-time Disk ‘Explosion’

Initially $T \sim$ few MeV; disk mostly free neutrons
After $\sim$ sec, $R \sim 500$ km & $T \lesssim 0.5$ MeV
free n & p recombine to He
fusion ($\sim 7$ Mev/nucl) unbinds disk

Ejected Mass $\sim 1/2$ Initial Disk $\sim 10^{-2} M_{\odot}$, at $v \sim 0.1$ c
Neutron-rich matter ($Y_e \sim 0.3$)

Metzger et al. 2008
Late-Time Activity from Fall-back Accretion?

Tidal Tails

1.1 & 1.6 M⊙ NS merger

Rosswog 2007

But at least partially suppressed by r-process heating in ejecta
NS-NS & NS-BH Mergers

Key Evolutionary Phases

1. Dynamical Disruption + Tidal Tails (\(\sim\) ms)
2. Possible hypermassive NS; \(\times\)-mom transport
   (B-fields) \(\rightarrow\) collapse to BH (\(\sim\) 10s ms)
3. Viscous evolution of disk (\(\sim\) 0.1-1 sec)
   (consistent w/ short GRB durations)
4. Disk ‘Explosion’ + Fallback (\(\approx\) sec)

Short(ish)-Duration GRB

![Graph showing time from BAT trigger vs. counts (pc.)](image)
~ kHz GWs: a New Frontier in Compact Object Astrophysics

• Direct detection of GWs: unique insights into compact objects
  • masses, spins, orientation to line of sight, ...
  • no bias re. photons escaping to observer!
  • probes of nuclear physics, relativity, ....

• Critical to connect these GW detections to wealth of EM data on similar (same?) sources

LIGO reached design sensitivity in ~ 2006: \( h \sim \Delta L/L \sim 10^{-21} \)
(no detections; as expected)
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Advanced LIGO & Virgo in ~ 2015
~10x sensitivity → $10^3$ x volume/rate

worldwide effort: Geo600 (Germany), LCGT (Japan), LIGO Australia (??), ...
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Advanced LIGO/VIRGO:
NS-NS Mergers at \( \sim 200 \text{ Mpc} \)
BH-BH Mergers at \( \sim \text{Gpc} \)

(Kalogera et al. 2004)
Most Promising Isotropic EM Counterpart

Heating of NS Debris in Compact Object Mergers

\(~ 10^{-3} - 10^{-2} M_\odot\) unbound during dynamical phases of merger & disk explosion (v~0.1c)

Initial thermal energy lost to adiabatic expansion

Luminosity of Unbound Ejecta Depends on Heating

Heating due to decay of n-rich nuclei created via r-process

emission peaks when \( t_{\text{diff}} \approx t_{\text{exp}} \)

\( t \sim 1 \text{ day} \) for NS ejecta

Heating Rate (log)

~2 hrs  1 day  10 days

Late-time R-process heating

Ni decay (for comparison)
Most Promising Isotropic EM Counterpart

**R-process Powered Transient**

**Observational Diagnostics**

- Few day “kilonova”:
  - \( L \sim 3 \times 10^{41} \text{ ergs s}^{-1} \)
  - \( M_V \sim -15 \)
  - \( T \sim 10^4 \text{ K at peak: optical} \)

- Spectroscopic: all n-rich elements (no Ni, Fe, C, O, He, Si, H, Ca, ...)

- Colors, etc. hard to predict because insufficient atomic line info for relevant nuclei!

**Graphical Representation:**

- Bolometric luminosity vs. time (days)
- Luminosity in units of ergs s\(^{-1}\)
- Different lines represent different thermality factors: \( \epsilon_{\text{therm}} = 1 \), \( \epsilon_{\text{therm}} = 0.5 \), and \( \text{LP98; } I = 3 \times 10^{-6} \)

**Spherical RT with SEDONA:** \( 10^{-2} M_\odot \)
NS-NS & NS-BH Mergers: Computational Challenges

Astrophysical Observable

**GWs:** GR (M?)HD Sims of Merger & Collapse to BH; Realistic EOS; r-process htg to correctly model ejecta

**GRB:** GR MHD Sims of disk & jet; weak interactions; nuclear heating; ν transport;

**EM Counterpart to GW:** 3D RT problem given ejecta mass, kinematics from merger & disk sims

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