Background
GW150914 + GRB

- Generally, do not expect EM counterpart for BBH merger: no matter by disruption of binary.
- GW150914 was BBH merger $M_1 = 35^{+5}_{-3} M_\odot$, $M_2 = 30^{+3}_{-4} M_\odot$
- Fermi detected transient lasting 1 s starting 0.4 s after GW signal (Connaughton et al., 2016). $L_{iso} \sim 2 \times 10^{49}$ erg/s.
- No INTEGRAL/AGILE detections though, generally considered coincidence.
Background
Isolated BBH Formation and Disk Probability

- Two pathways to BBH formation: common envelope and dynamical effects in globular clusters.
- Dynamical BBHs involve close encounters, stripping circumbinary material (Mink and King, 2017).
- CE (and other scenarios) may produce disk.
- Key is long-lived disk, need to be cool else MRI-driven $\alpha$ viscosity kills disc. (Janiuk et al., 2017a).

Figure: Common Envelope BBH (Belczynski et al., 2016).

Key Questions

- What matter, if any, surrounds an isolated BBH at merger?
- How is the matter heated?
- For reasonable values, luminosity & characteristic spectrum?
One of earliest papers and very adventurous (Loeb, 2016).

Core of extremely massive star fragments into two BH during collapse and recombine ~ minutes.

Consider total core/BH mass $65M_\odot$, star must $\gtrsim 100M_\odot$.

To avoid [pulsational] pair instability (sets in around He core $\gtrsim 35M_\odot$) and to increas rotation, merge two stars each of which is stable. Unsurprisingly, run into difficulties.

He cores $\gtrsim 35M_\odot$ begin pulsing immediately and cannot form BH $\gtrsim 45M_\odot$ (Woosley, 2016).

Shows can use stellar binary, would expect pulsational pair instability in one of two stars, eject much of envelope.

Assume disk exists (if $a_0 \sim R_\odot$ then BBH lifetime shorter than disk lifetime), inner radius set when $\tau_{GW}(a) \sim \tau_{\nu}(r_{in})$, where $r_{in} = 2a \sim 10^{10}$ cm.

Two perturbations, instantaneous mass loss and recoil of nascent BH due to anisotropic GW emission.
Timescale:
\[ t_{\text{dyn}} \sim \frac{G M}{v^3} \sim 2.2 \left( \frac{M}{60 M_\odot} \right) \left( \frac{10^3 \text{ km/s}}{v} \right)^3 \text{ hr.} \]

\( v \) is recoil velocity.

Luminosity should \( \sim f \frac{M_d v^2}{t_{\text{dyn}}} \) for some efficiency \( f \sim 0.1 \), gives
\[ L \sim 5 \times 10^{42} \left( \frac{f}{0.1} \right) \left( \frac{v}{10^3 \text{ km/s}} \right)^5 \left( \frac{M_d/M_{\text{BH}}}{10^{-3}} \right) \text{ erg/s} \]

Energy scales bound by black body emission and shock temperature
\[ T_b = \left( \frac{L}{2\pi \sigma R_\odot^2} \right)^{1/4} \sim 3 \times 10^8 \text{ K}, \]
\[ T_S \sim \frac{\mu m_H v^2}{2k_B} \sim 2 \times 10^7 \text{ K}. \]

These correspond to medium X-rays, \( \sim \text{KeV} \).

Martin et al., 2018 closely extends de Mink, introduces disk lifetime estimates.

BBH inspiral, disk viscous lifetime \( (\text{CE} \gtrsim 10R_\odot) \):
\[ \tau_{GW} \sim 10^8 \left( \frac{a_b}{10R_\odot} \right)^4 \text{ yr}, \]
\[ \tau_{BH} \sim 5 \times 10^5 \frac{0.1}{\alpha} \text{ yr}. \]

Need \( T_d \lesssim 800 \text{ K} \) to be unionized, no MRI, “dead zone” in midplane
\[ R_{dz} = 417 \left[ \frac{H}{0.01} \right]^2 \left( \frac{M}{60 M_\odot} \right) R_\odot. \]

Dead zone accretes through surface, still \( \sim 10 \times \) lifetime.

Consider only natal kick effect.

Disk up to some radius \( R_{ub} \) becomes unbound by kick, extremely small \( \sim 5 \times 10^{-7} M_\odot \), \( \sim 2 \times 10^{38} \text{ erg/s} \).

Decreting disk (strong binary torque) slowly pushes material outwards by viscosity + torques by binary.

Key: longer lived, luminosity \( \sim 5 \times 10^{40} \text{ erg/s} \).
**Scenarios**

**Bisikalo, 2018: Mass Loss Shock**

- Consider actively accreting Shakura-Sunyaev disk $\dot{m} \sim 0.05 \dot{m}_{CR}$ (Bisikalo, Zhilkin, and Kurbatov, 2018).
- Implies initial temperatures at inner radius $T \sim 10^7$ K. Inner radius set $r_{in} = 2a_{merge} \sim 10^8$ cm.
- Instantaneous $m \rightarrow 0.95m$, shock $Ma \sim \sqrt{\frac{GM}{r_{in}c^2}}$
- 2D hydrodynamical simulation. Try $Ma = [100, 150, 200]$.
- Shocks gas, optically thick so black body emission $\sim 10^8$ K $\sim 10$ keV.

**Invariant luminosity**

$$\frac{T_2}{T_1} = \frac{P_2/\rho_2}{P_1/\rho_1} \propto Ma^2 \propto \frac{GM}{r_{in}AT_1}$$

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**Scenarios**

**Perna, 2016: Restarted Accretion**

- SNe fallback can produce disks $\sim 10^5$ yr (Perna, Lazzati, and Giacomazzo, 2016).
- Weak explosion leaves initial disk $\sim 0.5M_\odot$, accretes until cool/dead, $M_d \sim 5.5 \times 10^{-4} M_\odot$.
- Argue when $t_{visc} \gtrsim t_{GW}$, heating, accretes cold buildup.
- Emission timescale $\sim 0.2$ s, $\lesssim$ luminosity, doesn’t really predict the delay.
Scenarios
Janiuk, 2017: Kicked into CB Torus

BBH merger kicks into envelope ~300 km/s, accretion powers GRB (Janiuk et al., 2017b).
GR simulations to get kick velocity, 2D MHD.

- Uses $M_{\text{torus}} = 0.25M_{\text{BH}}$. Torus is taken to be comparable to BH mass, maybe can happen if CCSNe quick succession.
- $\nu$-luminosity $\sim 5 \times 10^{52}$ erg/s at $t \sim 0.6$ s, duration $\sim 2$ s.

Summary

What matter, if any, surrounds an isolated BBH at merger?
~$10^{-4}M_{\text{BH}}$ mass can remain in a cool disk unless CE phase puts BH very close together.

- How is the matter heated?
  **Many scenarios: bursts of accretion, shocked black body.**
  - Not discussed, in AGN disks can give better chance (brighten optically thick AGN disk, (Bartos et al., 2017)).

- For reasonable values, luminosity & characteristic spectrum?
  **Accretion-driven emission can $\sim 10^{45}$ erg/s as required, dynamical $\lesssim 10^{40}$ erg/s.**
Slightly more in detail (sometimes) and hardly formal overview of each paper:

- **Loeb, 2016** “The adventurous paper.”
  
  - Suggested the merger of two \( \gtrsim 50 M_\odot \) helium stars to produce a single massive star with total mass \( \gtrsim 100 M_\odot \) and rapidly spinning core. The core then collapses to two separate BH that merge on the order of minutes inside the not-yet-ejected envelope, which then produces a supernova and observable signal.

- **Woosley, 2016** and other papers significantly discount this proposal, arguing that the pulsational pair instability breaks apart the resultant star too quickly, at best creating a core \( \lesssim 45 M_\odot \), insufficient for the \( M_1 + M_2 = 65 M_\odot \) GW150914.

- **Pair instability** sets in for stars \( \gtrsim 130 M_\odot \). Large stars are primarily supported by radiation pressure. So if a highly energetic photon from the highly luminous core of an exceedingly massive star has a high probability of pair production, then the radiation luminosity is suppressed and the star collapses under its own weight to a pair-instability supernova.

- The **pulsational pair instability** sets in for smaller stars \( M \sim [90 M_\odot, 130 M_\odot] \), where instead of the star going kaput immediately, it pulses and ejects material until it settles into a smaller mass star.

- **Mink and King, 2017** “Order of magnitudes.”

  - In the circumbinary disk of a BBH, the inner cavity opened has radius \( R_{in} \sim 2a \) the orbital separation. Argue that the circumbinary disk at merger must have radius \( 2a_{decouple} \) where \( t_{visc}(a_{decouple}) \gtrsim t_{GW}(a_{decouple}) \), then derive order of magnitude estimates.

  - Gravitational inspiral timescale is given by classic Peters 1964 equation

    \[
    t_{GW} \simeq 1.1 \times 10^4 \left( \frac{a}{R_\odot} \right)^4 \left( \frac{M}{60 M_\odot} \right)^{-3} \text{ yr.} \tag{1}
    \]

    - Setting this equal to \( t_{visc}(a) \) (formula not given here) gives decoupling radius (notated \( R_{in} \) as Equation 2 of the paper, I renamed to avoid confusion)

      \[
      a_{decouple} \simeq 3 \times 10^{10} \left( \frac{a}{0.1} \right)^{-2/5} \left( \frac{H/R}{10^{-3}} \right)^{-4/5} \left( \frac{M}{60 M_\odot} \right)^{-4/5} \left( \frac{M}{60 M_\odot} \right)^{-4/5} \text{ cm.} \tag{2}
      \]

      This happens “shortly before the merger”, a timescale is not cited. The separation is \( \sim 300 \times \) the merger separation though, or \( \sim 3 \times 10^4 \) km, which corresponds to \( \sim 10 \) s orbital periods I think, about a day before merger?

  - The only available dynamical timescale is

    \[
    t_{dyn} \sim \frac{GM}{V^3} \sim 2.2 \left( \frac{M}{60 M_\odot} \right) \left( \frac{10^3 \text{ km/s}}{V} \right)^{-3} \text{ hr.} \tag{3}
    \]
Here, $V$ is the maximum available velocity by dimensional analysis, usually the recoil velocity of the central black hole upon merger $v_{rec}$.

- The remaining disk’s dimensions are calculated by asserting $R_D : v_K(R_D) \sim V$, setting the recoil velocity equal to the Keplerian velocity at the outer edge of the disk; the exterior disk is unbound since its kinetic energy is greater than its gravitational binding energy. This is used to determine the brightness temperature.

- The peak luminosity is some fraction of the total disk kinetic energy divided by the dynamical time, so

$$L \sim f \frac{M_d V^2}{t_{dyn}}.$$ (4)

Using $M_d \sim 0.001 M_{BH}$ the total mass of the binary gives

$$L \sim 5 \times 10^{42} \left( \frac{f}{0.1} \right) \left( \frac{V}{10^3 \text{ km/s}} \right)^5 \left( \frac{M_d/M_{BH}}{10^{-3}} \right) \text{ erg/s.}$$ (5)

- The temperature of the emission must be bound from below by the black body temperature (brightness temperature, optically thick limit) or the shock temperature (the maximum energy scale accessible to the phenomenon). Thus,

$$T_b < T < T_S,$$

$$T_b = \left( \frac{L}{2 \pi \sigma R_d^2} \right)^{1/4},$$ (6)

$$T_S = \frac{3 \mu m_H V^2}{16 k_B}.$$ (7)

In the slides, I just used $k_B T_S \sim \frac{mV^2}{2}$; the extra factor of $3/8$ comes from a full treatment of the disk radiative flux:

$$F_z = -\frac{16 \sigma T^3}{3} \frac{\partial T}{\partial z},$$

$$= \frac{4 \sigma T_c^4}{3} \frac{1}{\kappa_R \rho H},$$

$$= \frac{8 \sigma T_c^4}{3} \frac{1}{\kappa_R \Sigma}.$$ (8)

I’ve seen this result but couldn’t find it in my lecture notes, so I Googled for it\footnote{https://arxiv.org/pdf/1505.02172.pdf}. Then setting $F_z \kappa_R \Sigma \sim \frac{mV^2}{2}$ kinetic energy recovers the desired shock temperature expression.

Plugging in numbers, $T \in [3 \times 10^6, 2 \times 10^7]$ K.

- Martin et al., [2018] extends the above analysis a bit:
- α viscosity is \[ v = a (\frac{H}{R})^2 R^2 \Omega, \] and so the viscous timescale is

\[ t_\nu = 6.5 \times 10^5 \left( \frac{\alpha}{0.1} \right)^{-1} \left( \frac{H/R}{0.01} \right)^{-2} \left( \frac{M}{60M_\odot} \right)^{-1/2} \left( \frac{R}{10^4 R_\odot} \right)^{3/2} \text{yr.} \] (8)

- For a more realistic \( a_{in} = 10R_\odot \), \( t_{GW} \gg t_\nu \). Thus, we must consider the evolution of the disk.

- By setting \( T(R) \) the temperature of the disk equal to the temperature where the MRI shuts off, we can obtain the minimum radius \( R_{dz} \) where the disk is sufficiently cool to not have MRI-driven viscosity, the “dead zone.”

- We can compute the mass of the disk outwards of \( R_{dz} \) up to where the disk is unbound by the recoil velocity \( R_{ub} \) (the same as the previous article). This produces a mass \( \sim 5.6 \times 10^{-7} M_\odot = 2 \times 10^{-7} M_{BH} \), and so we predict \( \sim 2 \times 10^{38} \text{erg/s} \), significantly lower than Mink and King, 2017 owing largely to a less massive disk.

- There's also the possibility of a circumbinary decretion disk: if the binary torque is strong at the inner radius of the circumbinary disk, material may fail to accrete. In such a disc, torques cause \( -M \) decretion by torquing the disk outwards; enforcing steady state and constant disk mass (expanding disk) gives \( \Sigma(R) \), from which the mass contained within the \( R_{ub} \) can be computed.

- Finally, considering that the outer edge’s expansion spreads the disk, this also lowers \( \Sigma \) globally, so accounting for all this gives luminosity \( \sim 10^{40} \text{erg/s} \).

- Bisikalo, Zhilkin, and Kurbatov, 2018
  - Only consider instantaneous \( \Delta M_{BH} \), no recoil upon merger.
  - Consider actively accreting Shakura-Sunyaev disk accreting at 0.05 the critical rate. Assume that at merger, \( r_{in} = 2a \) (so no disk decoupling). This gives a disk that is roughly 100 times closer in than the de Mink model, \( \sim 10^8 \text{cm} \).
  - Numerical simulation for three Mach numbers \( \mu^2 = \frac{GM}{r_{in} c_{in}^2} \) the ratio of the Keplerian velocity (\( \sim \) shock velocity, though the treatment in the paper is a BVP solution so a bit more careful) to the thermal velocity. Varying the Mach number is done by varying the initial temperature and thus \( c_{in} \).
    Find that the disk is fully shocked (up to the simulation domain, which is really just the interior of the disk) within \( \sim 30 \text{s} \).
  - Assert disk is radiatively inefficient with such a fast shock, so luminosity is just set by shocked gas temperature. Find that the final luminosity \( \sim 10^{45} \text{erg/s} \) for all Mach numbers.

\[ \text{Typical CE evolution produces } a_0 \sim [30,50]R_\odot \text{ I think, e.g. GW150914 is thought to have begun at an orbital separation of } \sim 50R_\odot \text{ (Belczynski et al., 2016)} \]
That $c_{in}$ does not change the shocked gas temperature is not surprising: the Rankine-Hugoniot conditions tell us
\[
\frac{T_2}{T_1} = \frac{P_2/P_1}{\rho_2/\rho_1} \propto M^2,
\]
and the Mach number was defined above $\mu^2 \propto c_s^{-2} \propto T_1^{-1}$, and so $\frac{T_2}{T_1} \propto \frac{1}{T_1}$ and $T_2$ does not depend on $T_1$ the pre-shocked gas temperature.

Furthermore, the extremely close-in disk means that the Keplerian orbit time is much shorter than $t_{dyn}$ in Eq. 3. This must be the new $t_{dyn}$ that sets the dissipation/shock timescale. If we use $P^2 \propto a^3$, then the disk inner edge of Mink and King, 2017 corresponds to a Keplerian rotation period $P \sim 8$ hr, well longer than $t_{dyn}$ set by a typical recoil velocity. Thus, unsurprisingly, the choice of disk starting condition changes what physical timescale limits the luminosity timescale, and the two results are not in conflict. It appears to me that Mink and King, 2017 and Martin et al., 2018 have a better disk treatment.

- Perna, Lazzati, and Giacomazzo, 2016

  - Considers that a circumbinary disk will accrete until dead, $\sim 5.5 \times 10^{-4} M_\odot$ where the disk is no longer ionized and the MRI is suppressed.

  - As $t_{GW}$ sweeps through $t_v(R)$ the viscous timescale that varies as a function of radius, the outer edge of the disk will begin to heat up as $t_{GW} \lesssim t_v$. But since the inner edge of the disk is still cool, the outer edges will simply pile up inwards at $t_{GW}T = t_v(R_c)$ critical radius, where

\[
R_c = 3.45 \times 10^7 \left( \frac{R}{H} \right)^{4/5} \frac{M}{30 M_\odot} \left( \frac{0.1}{\alpha} \right)^{2/5} \text{cm.} \tag{9}
\]

  - Owing to the accumulation of matter at $R_c$, the final disk decoupling should result in a large body of matter heated (and accreted) all at once. Accretion and sGRB theory predict that an initial disk of $\sim 10^{-4} M_\odot$ piled into a close orbit would be consistent with a $\sim 10^{49} L_{iso}$ isotropic luminosity sGRB.

  - A brief analysis discusses whether the compacting disk can produce ionizing radiation to reheat the inner disk; the answer seems to be weakly unlikely for hand-wavy parameter choices.

- Janiuk et al., 2017

  - The only other numerical paper that I read, Considers massive torus around recoiling BH. Numerical relativity simulations were used to get a wide range of recoil velocities\footnote{They obtained $\sim [300,700]$ km/s, which is roughly in line with those used by the other studies.}, and then 2D MHD was used to identify neutrino luminosity of sudden accretion of BH impacting torus.

  - For an enormous torus $M_{torus} = 0.25 M_{BH}$ (justifiable if short lived binary, two supernovae happen close together so infall of one interacts with ejection of other), get neutrino luminosity $\sim 5 \times 10^{52}$ erg/s lasting $\sim 2$ s starting $\sim 0.6$ s after the merger.
References


