From GRBs to BH Binaries

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Outline

• Collapsar model (and its requirements)
• Binary evolution
• Energetics (Blandford-Znajek)
• BH binaries
• GRB relics & energies
• Massive BH binaries
• SASIs
• Conclusions
Collapsars
GRBs from Collapsars

- $E_{HN} \geq 30$ bethes
- $V_{HN} \sim 30,000$ km/sec
- Type Ic (bl) HN assoc. to GRBs
- Wolf-Rayet progenitor
- High angular momentum (to form accretion disk)
- Strong magnetic field
Binary evolution
Binary evolution

- BH Progenitor (primary): $20 \text{ Msun} < M_{\text{zams}} < 40 \text{ Msun}$
- Let the star evolve as a single star, to guarantee a massive core $\Rightarrow$ BH.

Case C mass transfer!
Roche Lobe Overflow

RLOF occurs when material from the star reaches the equipotential where the star’s gravity is balanced by the companion’s gravity and the centrifugal force.
Case C mass transfer

• RLOF $\Rightarrow$ Common Envelope:

\[ a_i \sim 1,500 \, R_{\text{Sun}} \Rightarrow a_f \sim \text{few} \, R_{\text{Sun}}. \]

• H envelope removed very late $\Rightarrow$ Massive WR star.

• Tidal synchronization provides a large amount of angular momentum late enough so it will not be lost to winds.

• Lower mass companions will fit in tighter orbits $\Rightarrow$ more J into primary $\Rightarrow$ large $a^*$ BH.
Energetics
Energetics

- Spinning BHs contain a large reservoir of energy:
  \[ E_{\text{rot}} = f(a_*) M_{\text{BH}} c^2, \]
  \[ f(a_*) = 1 - \sqrt{\frac{1}{2} \left(1 + \sqrt{1 - a_*} \right)} \]

- GRBs, HNe, Jets can tap this energy through Blandford-Znajek mechanism:
  \[ E_{\text{BZ}} = \epsilon_\Omega \frac{E_{\text{rot}}}{M_\odot c^2} \times 1,800 \text{ bethes} \]
Blandford-Znajek

Rotating Black Hole

Accretion Disc

Current $J$

Load $R_L$

Magnetic Field $B$

Accretion $d l$
Blaauw-Boersma Kicks

\[ P_2 = \left(1 + \frac{\Delta M}{M_{BH} + m}\right)^2 P_1 \]

\[ V_{Sys} = \left(\frac{\Delta M}{M_{BH} + m}\right) V_{He} \]
BH binaries
BH binaries

• ~ 15 “well known” Galactic sources.
• 3 extragalactic sources.
• 8 have Mstar < 1-Msun companions (hard to model).
• 7 have ~2-Msun companions (good candidates).
• 3 have Mstar > 10-Msun companions (little J).
Post SN Binary evolution

- Reconstructing the pre-explosion orbits in BH binaries allows for an estimation of the Kerr parameter of the BH at the time it was formed.

- Angular momentum extracted to power a GRB/HN may reduce this value.

- Accreting mass from the companion may increase the observed value.
<table>
<thead>
<tr>
<th>Name</th>
<th>$M_{BH,2}$</th>
<th>$M_d,2$</th>
<th>$M_{BH,now}$</th>
<th>$M_{d,now}$</th>
<th>Model $a_*$</th>
<th>Measured $a_*$</th>
<th>$P_{Orbit,now}$</th>
<th>$E_{BZ}$</th>
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<tr>
<td></td>
<td>$[M_\odot]$</td>
<td>$[M_\odot]$</td>
<td>$[M_\odot]$</td>
<td>$[M_\odot]$</td>
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<td></td>
<td>[days]</td>
<td>$[10^{51} \text{ ergs}]$</td>
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<td>J1118+480</td>
<td>$\sim 5$</td>
<td>$&lt; 1$</td>
<td>$6.0 - 7.7$</td>
<td>$0.09 - 0.5$</td>
<td>0.8</td>
<td>-</td>
<td>0.169930(4)</td>
<td>$\sim 430$</td>
</tr>
<tr>
<td>Vel 93</td>
<td>$\sim 5$</td>
<td>$&lt; 1$</td>
<td>$3.64 - 4.74$</td>
<td>$0.50 - 0.65$</td>
<td>0.8</td>
<td>-</td>
<td>0.2852</td>
<td>$\sim 430$</td>
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<tr>
<td>J0422+32</td>
<td>6 – 7</td>
<td>$&lt; 1$</td>
<td>$3.4 - 14.0$</td>
<td>$0.10 - 0.97$</td>
<td>0.8</td>
<td>-</td>
<td>0.2127(7)</td>
<td>500 $\sim$600</td>
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<tr>
<td>1859+226</td>
<td>6 – 7</td>
<td>$&lt; 1$</td>
<td>$7.6 - 12$</td>
<td>0.8</td>
<td>-</td>
<td>0.380(3)</td>
<td>500 $\sim$600</td>
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<tr>
<td>GS1124–683</td>
<td>6 – 7</td>
<td>$&lt; 1$</td>
<td>$6.95(6)$</td>
<td>0.56 – 0.90</td>
<td>0.8</td>
<td>-</td>
<td>0.4326</td>
<td>500 $\sim$600</td>
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<tr>
<td>H1705–250</td>
<td>6 – 7</td>
<td>$&lt; 1$</td>
<td>$5.2 - 8.6$</td>
<td>0.3 – 0.6</td>
<td>0.8</td>
<td>-</td>
<td>0.5213</td>
<td>500 $\sim$600</td>
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<tr>
<td>A0620–003</td>
<td>$\sim 10$</td>
<td>$&lt; 1$</td>
<td>$11.0(19)$</td>
<td>0.68(18)</td>
<td>0.6</td>
<td>0.12±0.19</td>
<td>0.3230</td>
<td>$\sim 440$</td>
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<tr>
<td>GS2000+251</td>
<td>$\sim 10$</td>
<td>$&lt; 1$</td>
<td>$6.04 - 13.9$</td>
<td>$0.26 - 0.59$</td>
<td>0.6</td>
<td>-</td>
<td>0.3441</td>
<td>$\sim 440$</td>
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<tr>
<td>Nu: with evolved companion</td>
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<tr>
<td>GRO J1655–40</td>
<td>$\sim 5$</td>
<td>1 – 2</td>
<td>5.1 – 5.7</td>
<td>1.1 – 1.8</td>
<td>0.8</td>
<td>0.65 – 0.75</td>
<td>2.6127(8)</td>
<td>$\sim 430$</td>
</tr>
<tr>
<td>4U 1543–47</td>
<td>$\sim 5$</td>
<td>1 – 2</td>
<td>2.0 – 9.7</td>
<td>1.3 – 2.6</td>
<td>0.8</td>
<td>0.75 – 0.85</td>
<td>1.1164</td>
<td>$\sim 430$</td>
</tr>
<tr>
<td>XTE J1550–564</td>
<td>$\sim 10$</td>
<td>1 – 2</td>
<td>9.68 – 11.58</td>
<td>0.96 – 1.64</td>
<td>0.5</td>
<td>0.49±0.13</td>
<td>1.552(10)</td>
<td>$\sim 300$</td>
</tr>
<tr>
<td>GS 2023+388</td>
<td>$\sim 10$</td>
<td>1 – 2</td>
<td>10.3 – 14.2</td>
<td>0.57 – 0.92</td>
<td>0.5</td>
<td>-</td>
<td>6.4714</td>
<td>$\sim 300$</td>
</tr>
<tr>
<td>XTE J1819–254</td>
<td>6 – 7</td>
<td>$\sim 10$</td>
<td>8.73 – 11.69</td>
<td>5.50 – 8.13</td>
<td>0.2</td>
<td>-</td>
<td>2.817</td>
<td>10 $\sim$12</td>
</tr>
<tr>
<td>GRS 1915+105</td>
<td>6 – 7</td>
<td>$\sim 10$</td>
<td>14(4)</td>
<td>1.2(2)</td>
<td>0.2</td>
<td>$&gt; 0.98$</td>
<td>33.5(15)</td>
<td>10 $\sim$12</td>
</tr>
<tr>
<td>Cyg X–1</td>
<td>6 – 7</td>
<td>$\geq$ 30</td>
<td>$\sim$ 10.1</td>
<td>17.8</td>
<td>0.15</td>
<td>$&gt; 0.97$</td>
<td>5.5996</td>
<td>5 $\sim$6</td>
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<tr>
<td>Extragalactic</td>
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<td></td>
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<tr>
<td>LMC X–1</td>
<td>$\sim 40$</td>
<td>$\sim$ 35</td>
<td>8.96 – 11.64</td>
<td>30.62±3.22</td>
<td>$&lt; 0.05$</td>
<td>0.81 – 0.94</td>
<td>3.91</td>
<td>$&lt; 2$</td>
</tr>
<tr>
<td>LMC X–3</td>
<td>7</td>
<td>4</td>
<td>5 – 11</td>
<td>6 $\pm$ 2</td>
<td>0.43</td>
<td>$\sim$ 0.3</td>
<td>1.70</td>
<td>$\sim$155</td>
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<tr>
<td>M33 X–7</td>
<td>$\sim 90$</td>
<td>$\sim$ 80</td>
<td>14.20 – 17.10</td>
<td>70.0±6.9</td>
<td>$\sim 0.05$</td>
<td>0.72 – 0.82</td>
<td>3.45</td>
<td>3 $-$ 11</td>
</tr>
</tbody>
</table>
GRB relics & energies
### Some Galactic BHs

<table>
<thead>
<tr>
<th>Name</th>
<th>$M_{BH}$</th>
<th>$M_{Sec}$</th>
<th>$P_{orb}$</th>
<th>$a^*$</th>
<th>$E_{BZ}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>4U 1543-47 II Lupi</td>
<td>2-9.7</td>
<td>1.3-2.6</td>
<td>1.12</td>
<td>0.75-0.85</td>
<td>~430</td>
</tr>
<tr>
<td>GRO J1655-40 Nova Sco 94</td>
<td>5.1-5.7</td>
<td>1.1-1.8</td>
<td>2.61</td>
<td>0.65-0.75</td>
<td>~430</td>
</tr>
<tr>
<td>XTE J1550-564</td>
<td>9.7-11.7</td>
<td>0.96-1.64</td>
<td>1.55</td>
<td>0.3-0.6</td>
<td>~300</td>
</tr>
<tr>
<td>LMC X-3</td>
<td>5-11</td>
<td>4-8</td>
<td>1.70</td>
<td>~0.3</td>
<td>~150</td>
</tr>
</tbody>
</table>

3 BHs where the spin has been measured and matches the predictions. Mass is expressed in Solar masses, orbital period in days, the Kerr parameter is unitless and the available Blandford-Znajek energy is in Bethes.
Massive BH binaries
When the stars don’t fit in their orbit!

<table>
<thead>
<tr>
<th>Name</th>
<th>$M_{BH}$</th>
<th>$M_{Sec}$</th>
<th>$P_{orb}$</th>
<th>$a^*$</th>
<th>$E_{BZ}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cyg X-1</td>
<td>14.8(1)</td>
<td>19.2(1.9)</td>
<td>5.60</td>
<td>&gt;0.97</td>
<td>5-6</td>
</tr>
<tr>
<td>LMC X-1</td>
<td>10.8(.84)</td>
<td>30.6(3.2)</td>
<td>3.91</td>
<td>0.91(6)</td>
<td>&lt;2</td>
</tr>
<tr>
<td>M33 X-7</td>
<td>15.6(1.4)</td>
<td>70(6.9)</td>
<td>3.45</td>
<td>0.84(5)</td>
<td>3-11</td>
</tr>
</tbody>
</table>
$P_{\text{orb}}$ vs $a^{*}$
Alternative?
Kick the BH off center!

- A series of kicks? (Seems to work for NSs)
- A long single kick: SASI with $m=1$
- Conservation of $E, J$ (It’s a massive BH!)

Does it solve the problem?
However...

- We’re still missing $E_{\text{ring}}$.
- $E_{\text{ring}}$ depends on $l_{\text{ring}}$ and $\omega^2$.
- Material in the ring easily becomes relativistic if (a) the ring has little mass and if (b) its radius is small.
However #2

- So far we have assumed 100% energy conversion efficiency!

- Unlikely.
Furthermore...

Furthermore...

O’Connor & Ott, 2011

R_sasi~100 km, not a large lever arm

Further mass accretion lowers a*
Alternate alternatives...
Accretion onto the BH

- Hypercritical accretion?
- Super-Eddington accretion?
- We need wRLOF mass transfer.

![Graph showing BH spin versus mass transfer](image)
Wind RLOF

- If $M_{\text{comp}} > M_{\text{BH}}$, mass transfer shrinks $a_{\text{orb}}$. Also as the star loses mass, $R_{\text{comp}}$ grows. RLOF leads to unstable mass transfer.

- Companion star filling large part of its RL.

- BH at $a_{\text{orb}} \lesssim 2 R_{\text{comp}}$.

- Winds, not fully accelerated at RL surface ($V_w \lesssim 500 \text{ km/s}$ as opposed to $V_w \sim 3000 \text{ km/s}$), become focused in L1 towards BH.

- $V_w \sim V_{\text{orb}}$ efficient wind RLOF mass transfer.
Eddington Limited Accretion

• Eddington luminosity for Bondi accretion (spherically symmetric):

\[ L_{Edd} = \frac{4\pi G M_{BH} m_p \mu \varv \epsilon c}{\sigma_T} \]

Thus, a maximum accretion rate can be identified:

\[ \dot{M}_{Edd} = \frac{L_{Edd}}{c^2} = \frac{4\pi c R}{\kappa_{es}} \]

In general, if the accretion rate grows, L increases and self-regulates the accretion rate to a value below the Eddington limit.

• Hence, for a 10 M\(_{\text{Sun}}\) black hole we obtain:

\[ \dot{M}_{BH,Edd} \approx \frac{10^{18} \text{ cm}^2 \text{ s}^{-1}}{0.4 \text{ cm}^2 \text{ g}^{-1}} \approx 3 \times 10^{-8} \frac{M_{\text{Sun}}}{\text{yr}} \]
Hypercritical Accretion

- Dump material on desired BH.
- Trap photons emitted at $R_{ph}$.
- Form Standing Accretion Shock at $R_{sw} < R_{ph}$ with $T \sim 1$ MeV.
- Photons are advected with matter, neutrinos remove energy.
- Accretion rate above: $\dot{m} \equiv \frac{\dot{M}}{M_{Edd}} \approx 3 \times 10^3$
Conclusions (1)

• Case C mass transfer seems to be essential for producing Collapsar GRBs (however see Case M).

• Tidal locking & strong B fields are necessary.

• BH binaries seem likely candidates of long GRBs (subluminous & cosmological)
Conclusions (2)

• 14 Galactic sources of subluminous IGRB / HN explosions.

• LMC X-3 likely formed from a cosmological IGRB / HN.

• 3 likely sources of “dark explosions”.
Conclusions (3)

- SASIs do not seem to explain known spins of BHs in HMXBs.
- Neither do binary pre-BH-formation stellar evolution models.
- Evidence points to post-BH-formation spin up scenario.
Selected references

- Moreno Méndez, E & Cantiello, M.  Submitted.
Measuring $a^*$

During the earlier post-bounce phase (see bottom panel of Fig. 11), we observe the presence of light nuclei in the heating region between the neutrinospheres and the standing bounce shock. There, the abundance of light nuclei in the heating region does not exceed that found in the free nucleons. Hence, light nuclei are not expected to have a very strong impact on neutrino heating. However, already at 50 ms (Fig. 11(a)) during the later post-bounce phases, we observe a dissocation of light nuclei into nucleons. At 200 ms post bounce, above the neutrinospheres only few light nuclei are found in comparison to the free nucleons. Hence a very strong impact on neutrino heating is not expected.

Impact on neutrino heating and cooling

The presence of light nuclei can modify neutrino heating and cooling. The heating region is located between the neutrinospheres and the standing bounce shock, whereas cooling occurs around the neutrinospheres. To identify the abundances of light nuclei in the two regions, a dissolution of light nuclei into nucleons is interesting because it modulates the neutrino signal, than more heating. Additionally, an impact on cooling mechanisms. For example, less cooling has a similar potential for the 15 M⊙ progenitor model from Woosley and Weaver (1995) using the HS (TM1) EOS. The most dramatic at this distance close to the shock. The most impact on explosion mechanics between the neutrinospheres and the standing bounce shock. There, the inclusion of weak processes with light nuclei may enhance the abundances directly below the shock have decreased. The slight compression increases further on the long term. The slight compression

Radial profiles of the baryon density (solid lines) and the temperature (dashed lines) in the top panels and the corresponding NSE composition (bottom panels) at two selected post-bounce times for the 15 M⊙ progenitor model from Woosley and Weaver (1995) using the HS (TM1) EOS. The green vertical lines denote the position of the neutrinospheres for νe (solid lines) and for νe (dashed lines).

Hempel, Fischer, Schaffner-Bielich & Lienendoerfer 2011