Double Black Holes: Recent Observations and Predictions

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Rates (empirical): Bulik, Belczynski, Prestwich (2011)
Observations: known BH masses

- **4 – 15$M_\odot$:** Galactic BHs ($Z \sim Z_\odot$)
  - 17 transients: low mass companion
  - 3 persistent: massive companion
  (Casares, Bailyn, Orosz, Charles, Greiner, ......)

- **8, 11$M_\odot$:** LMC X-3, X-1 ($Z \sim 30\%Z_\odot$)
  - HMXBs: massive companions (Orosz 02, Orosz et al. 09)

- **16$M_\odot$:** M33 X-7 ($Z \sim 5 – 40\%Z_\odot$)
  - massive $70M_\odot$ close companion (Orosz et al. 07)

- **$\sim 20M_\odot$:** NGC300 X-1 ($Z \sim 60\%Z_\odot$)
  - massive $26M_\odot$ close WR companion – (Crowther et al. 2010)

- **$\sim 30M_\odot$:** IC10 X-1 ($Z \sim 30\%Z_\odot$)
  - massive $17M_\odot$ close WR companion (Prestwich et al. 07)

Stars at low metallicity form massive BHs: How massive can a BH get?
Predictions: calculation of a BH mass

1) update on Hurley et al. stellar winds
   - single star models
   - new wind mass loss rates (Vink et al.)
   - estimate BH mass (SN hydro)

2) new BH mass estimates:
   - systematically higher BH mass
   - steep increase of BH mass with decreasing metallicity (smaller winds)

\[ Z = 1.0 \ Z_\odot: \ max. \ BH \ mass: \sim 15 M_\odot \]
\[ Z = 0.3 \ Z_\odot: \ max. \ BH \ mass: \sim 30 M_\odot \]
\[ Z = 0.01 \ Z_\odot: \ max. \ BH \ mass: \sim 80 M_\odot \]

Observations: chemical composition of stars

Panter et al. 2008:

- SDSS sample: $\sim 30,000$ galaxies
- recent star formation: $\lesssim 1 \text{Gyr}$
  - 50%: solar metallicity ($Z_\odot$)
  - 50%: sub-solar metallicity ($0.1 Z_\odot$)

Stellar observations/models:

- solar metallicity:
  - max BH mass: $\sim 15 M_\odot$ (GRS 1915)
  - large stellar radii -> messy interactions
- sub-solar metallicity:
  - max BH mass: $\sim 30 M_\odot$ (IC10 X-1)
  - small stellar radii -> clean interactions
Predictions: merger/detection rates

1) common envelope (CE) required in the BH-BH formation: orbital contraction
   - high metallicity: many progenitors do not survive CE -> stellar mergers
   - low metallicity: many progenitors survive CE -> BH-BH formation

   **BH-BH birth rates: increase by ~ 100 from high to low metallicity**

2) consider 2 CE models: major factor (and unknown) in the BH-BH formation
   - model A: rather liberal CE treatment -> many systems survive
   - model B: more strict physical treatment -> most systems die in CE

   **BH-BH birth rates: decrease by ~ 100 from model A to B**

LIGO/VIRGO detection rates:

- **Initial LIGO:** model A excluded
- **Advanced LIGO:** model B
  - NS-NS small contribution (1/30)
  - BH-BH dominate (the first source)

\[ d_{0, \text{nsns}} = 50-100 \text{ Mpc}: 1-10 \text{ detections} \]


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**Population Synthesis Detection Rates [yr\(^{-1}\)]**

<table>
<thead>
<tr>
<th>Sensitivity</th>
<th>Type</th>
<th>Rate A (B)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>NS-NS</td>
<td>0.01 (0.002)</td>
</tr>
<tr>
<td>18 Mpc (Initial)</td>
<td>BH-NS</td>
<td>0.02 (0.01)</td>
</tr>
<tr>
<td></td>
<td>BH-BH</td>
<td>4.9 (0.05)</td>
</tr>
<tr>
<td>300 Mpc (Advanced)</td>
<td>NS-NS</td>
<td>45.1 (9.5)</td>
</tr>
<tr>
<td></td>
<td>BH-NS</td>
<td>85.8 (42.8)</td>
</tr>
<tr>
<td></td>
<td>BH-BH</td>
<td>21425 (242)</td>
</tr>
</tbody>
</table>
IC10 X-1/NGC300 X-1: evolution and fate

1) Close massive binaries: BH + WR
   - $P_{\text{orb}} \sim 30$ h ($V_{\text{orb}} \sim 600$ km/s)
   - $M_{\text{WR}} \sim 15 - 35 \, M_{\odot}$
   - $M_{\text{BH1}} \sim 15 - 30 \, M_{\odot}$

2) Very simple evolution:
   - WR: heavy mass loss
   - WR: core collapse/supernova
   - BH-BH: formed ($t_{\text{merger}} \sim 1$ Gyr)

3) GR detection rate:
   - Evolution: short lifetime 0.5 Myr
   - Discovery: X-ray binary upto 2 Mpc
   - Initial LIGO/VIRGO: upto 200 Mpc

   GR detection rate: $\sim 3 \, \text{yr}^{-1}$!!!

why don’t we see BH-BH inspirals???

For the smallest masses (largest $i$):

    (IC) BH-BH: $23 \, M_{\odot} - 13 \, M_{\odot}$ ($M_c=15 \, M_{\odot}$)

    (NGC) BH-BH: $15 \, M_{\odot} - 11 \, M_{\odot}$ ($M_c=11 \, M_{\odot}$)