The formation of single sdB stars through common-envelope mergers

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Mike Politano, Ron Taam, Bart Willems

September 29, 2009
Outline

1. The formation of single sdB stars
   - Properties of sdB stars
   - Population-synthesis models
   - Population-synthesis results
   - Conclusions and future work

2. GW binary inspirals with LIGO/Virgo
   - LIGO/Virgo
   - Binary inspirals
   - Markov-chain Monte Carlo
   - Conclusions
sdB stars

Basic properties:

- Core helium burning stars with very thin ($\lesssim 0.02 \, M_\odot$) hydrogen-rich envelope
- In the field $\sim 40$–$70\%$ are found in binaries
- In GCs mostly observed as **single** sdB stars
- Masses observed $\sim 0.39 \, M_\odot$ – $0.7 \, M_\odot$ (e.g. asteroseismology)
Possible formation channels:

**In wide binaries:**
- One or two phases of stable Roche-lobe overflow

**In close binaries:**
- One or two CE/spiral-in phases

**Single sdB stars:**
- He-WD–He-WD mergers ($M \gtrsim 0.4 \, M_\odot$)
- Strong mass loss at tip of RGB (e.g. capture of planet; Soker & Harpaz, 2000, 2007; Livio & Siess, 1999a,b)
- **CE merger on the RGB** (Soker 1998, Soker & Harpaz 2000, 2007)
Eggleton code TWIN:

- 116: single-star models: 0.5, 0.6, \ldots, 10.0, 10.5, \ldots, 20.0 \, M_\odot
- Solar composition
- Core mass: \( M_c \equiv \text{central region where } X < 0.1 \)
- Envelope binding energy: \( E_{\text{bind}} \equiv \int_{M_c}^{M_s} \left( E_{\text{int}}(m) - \frac{Gm}{r(m)} \right) \, dm \)
- Convective mixing: \( l/H_P = 2.0 \)
- Convective overshooting: none for \( M < 1.2 \, M_\odot \), \( \delta_{\text{ov}} = 0.12 \) for \( M \geq 1.2 \, M_\odot \)
- Stellar wind: Reimers-like (\( \eta = 0.2 \)), De Jager
- *Helium-flash-avoidance routine*
Randomly select $10^7$ binaries:

- $M_p$: Miller-Scalo IMF
- $q \equiv M_s / M_p$: $g(q) \, dq = \{1, q, q^{-0.9}\} \, dq$

Follow the evolution of track closest in mass to primary

When mass comes closer to next track, jump with conservation of $M_c$

Assume synchronous, rigid rotation on RGB, AGB

If $v_{\text{rot}} > v_{\text{crit}}$: lose additional mass and AM until $v_{\text{rot}} \leq v_{\text{crit}}$

$v_{\text{crit}} \equiv \{0.1, 1/3, 1.0\} \cdot v_{\text{br}}$
CE and spiral-in

- CE occurs if:
  - $R_p > R_{RL,p}$ and $q > q_{\text{crit}}(M_p, M_c)$ (Hurley et al.)
  - Darwin instability

- Classical energy formalism to determine post-CE orbit:
  \[
  E_{\text{bind}} = \alpha_{\text{CE}} \left( \frac{GM_p M_s}{2 a_i} - \frac{GM_c M_s}{2 a_f} \right)
  \]
  \[
  \alpha_{\text{CE}} = \{0.1, 0.5, 1.0\}
  \]

- Merger occurs if: $R_{RL,s,\text{postCE}} < R_{s,\text{postCE}}$
Merger product

The merged object has:

- the core mass of the original primary
- the maximum mass for which the star is spinning subcritically (and $M \leq M_p + M_s$)
- the evolutionary state of the primary, or later

The merged object does:

- evolve in the same way as a single star
- lose additional mass to ensure that $v_{\text{rot}} \leq v_{\text{crit}}$
### Population-synthesis results

<table>
<thead>
<tr>
<th>Category</th>
<th>Number</th>
<th>Fraction of previous group</th>
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<td>100%</td>
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<td>No MT</td>
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<td>71%</td>
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<tr>
<td>Stable MT</td>
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<td>16%</td>
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<td>RGB</td>
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<td>AGB</td>
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<tr>
<td>Critically rotating HB stars</td>
<td>4,504</td>
<td>31%</td>
<td>0.05%</td>
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</table>
The formation of single sdB stars through common-envelope mergers

HRD with merger population

All merged objects:

Merged objects on HB:

$v_{\text{crit}} = \frac{1}{3} v_{\text{br}}$

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\[ v_{\text{crit}} = \frac{1}{3} v_{\text{br}} \]
Rotational velocities

\[ \frac{v_{\text{rot}}}{v_{\text{crit}}} : \]

\[ v_{\text{rot}} (\text{km/s}): \]

Merged objects, single stars, \( v_{\text{crit}} = \frac{1}{3} v_{\text{br}} \)
Core and envelope masses

**Helium-core masses:**

- Fraction of objects
- Helium-core mass at present epoch ($M_\odot$)

**Envelope masses:**

- Fraction of objects
- Envelope mass at present epoch ($M_\odot$)

Merged objects, single stars
The formation of single sdB stars through common-envelope mergers

Rotational velocity vs. envelope mass

\[ v_{\text{crit}} = \frac{1}{3} v_{\text{br}} \]

\[ v_{\text{crit}} = v_{\text{br}} \]
The formation of single sdB stars through common-envelope mergers

Rotational velocity vs. envelope mass

$$v_{\text{crit}} = \frac{1}{3} v_{\text{br}}$$

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The formation of single sdB stars through common-envelope mergers
Losing the envelope

Detailed model of an HB star with initial parameters $M \approx 0.59 \, M_\odot$, $M_{\text{env}} \approx 0.11 \, M_\odot$ and $v_{\text{rot}} \approx 25 \, \text{km/s}$:

- $M_{\text{env}}$ vs. $\log R$:
  - $M_{\text{env}}$ vs. $\log R_\odot$:
  - $M_{\text{env}}$ vs. $T_{\text{eff}}$:
    - $T_{\text{eff}}$ vs. $M_{\text{env}}$:
  - $M_{\text{env}}$ vs. $v_{\text{rot}}$:
    - $v_{\text{rot}}$ vs. $M_{\text{env}}$:
Conclusions

- Common-envelope mergers on the RGB lead to rapidly rotating merger products.
- Contraction of such a merged object due to helium ignition provides a natural way for the star to spin up and experience enhanced mass loss.
- This leads to a population of rapidly rotating HB stars.
- A small fraction of these HB stars have thin envelopes.
- With some additional mass loss, these stars may become single sdB stars.
Future work

- Use more flexible implementation for mass loss due to winds and rotation
- Include magnetic braking for merged object
- Look for mechanism to remove last bit of HB-star envelope (perhaps on RGB?)
- Combine population synthesis and entropy sorting:
  - do population synthesis to get the mergers
  - use entropy sorting to get a merged object
  - interpolate to create an evolution model
  - evolve it with a detailed stellar-evolution code (including rotation)
And now for something completely different...
How to measure gravitational waves from quite a long way away

Marc van der Sluys
University of Alberta, Edmonton, AB, Canada
Vivien Raymond, Ilya Mandel, Vicky Kalogera

September 29, 2009
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Laser Interferometer GW Observatory (LIGO)
### Predicted detection rates

#### Realistic estimate:

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<td>Advanced</td>
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#### Plausible, optimistic estimate:

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<td>1.5</td>
<td>1.4</td>
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<td>Advanced</td>
<td>200</td>
<td>190</td>
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</table>

Estimates assume $M_{NS} = 1.4 M_{\odot}$ and $M_{BH} = 10 M_{\odot}$

CBC group, rates document
## Goals of this project

### LIGO
- Show that Markov-Chain Monte Carlo (MCMC) with a large number of parameters (12–15) on LIGO data can be done
- Automated parameter estimation on detected inspiral signal:
  - Confirm spinning inspiral nature of signal
  - Determine *physical* parameters (masses, spin, position, ...)

### Astrophysics
- BH/NS mass distributions, BH spins and spin alignments
- Association of GW and EM events, *e.g.* GRB
- Merger rates, NS-NS/BH-NS/BH-BH merger ratios
- Evolution of massive stars (in binaries), CEs
- Initial-mass range for BH progenitors
Inspiral waveforms with increasing spin

\[ a_{\text{spin}} \equiv \frac{S}{M^2} = 0.0, 0.1 \text{ and } 0.5 \]
Signal injection into detector noise

- Using 2 4-km detectors \( H1, L1 \)
- Gaussian, stationary noise
- Do 1.5-pN software injections
- Retrieve physical parameters with 1.5-pN template

Here, \( \Sigma \text{SNR} = 17 \)
Compute posterior distribution

- Find posterior density of the model parameters
- Bayesian approach
- The likelihood for each detector $i$ is:
  \[
  L_i(d|\vec{\lambda}) \propto \exp\left(-2 \int_0^\infty \frac{\left|\tilde{d}(f) - \tilde{m}(\vec{\lambda}, f)\right|^2}{S_n(f)} df \right)
  \]

- Coherent network of detectors:
  - PDF($\vec{\lambda}$) $\propto$ prior($\vec{\lambda}$) $\times$ $\prod_i L_i(d|\vec{\lambda})$

- Use Markov-Chain Monte Carlo to sample the posterior
Markov chains

- Choose starting point for chain: $\tilde{\lambda}_1$
- Compute its likelihood: $L_j \equiv L(d|\tilde{\lambda}_j)$ and prior: $p_j \equiv p(\tilde{\lambda}_j)$
- do $j = 1, N$
  - draw random jump size $\Delta \tilde{\lambda}_j$ from Gaussian with width $\tilde{\sigma}$
  - consider new state $\tilde{\lambda}_{j+1} = \tilde{\lambda}_j + \Delta \tilde{\lambda}_j$
  - calculate $L_{j+1} \equiv L(d|\tilde{\lambda}_{j+1})$ and $p_{j+1} \equiv p(\tilde{\lambda}_{j+1})$
  - if($\frac{p_{j+1}}{p_j} \frac{L_{j+1}}{L_j} > \text{ran}_\text{unif}[0, 1]$ ) then
    - Accept new state $\tilde{\lambda}_{j+1}$
    - Increase jump size $\tilde{\sigma}$
  - else
    - Reject new state; $\tilde{\lambda}_{j+1} = \tilde{\lambda}_j$
    - Decrease jump size $\tilde{\sigma}$
  - end if
- save state $\tilde{\lambda}_{j+1}$
- end do ($j$)
The formation of single sdB stars
GW binary inspirals with LIGO/Virgo

LIGO/Virgo
Binary inspirals
Markov-chain Monte Carlo
Conclusions

MCMC example

\[ \mathcal{M} \left( M_\odot \right) \]

Signal: 2.994
Median: 2.967
\[ \Delta_{95\%} \]: 2.71%

Iteration: 4.63E+06
Data points: 3.09E+05

Chain:

log(L):

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MCMC runs

MCMC parameters

Masses: \( M \equiv (M_1 + M_2) \eta^{3/5} \) & \( \eta \equiv \frac{M_1 M_2}{(M_1 + M_2)^2} \), distance: \( \log d_L \), time and phase at coalescence: \( t_c \) & \( \varphi_c \), position: R.A. & sin Dec, spin magnitude: \( a_{\text{spin}1,2} \), spin orientation: \( \cos \theta_{\text{spin}1,2} \) & \( \varphi_{\text{spin}1,2} \), orientation: \( \cos(\iota) \) & \( \psi \)

MCMC set-up

- 5 serial chains per run, starting from the true parameter values
- Chain length: \( 5 \times 10^6 \) states, burn-in: \( 5 \times 10^5 \) states
- Run time: 10 days on a 2.8 GHz CPU for 1.5-pN waveform (\( \sim 2.5 \times \) longer for 3.5-pN)

- Signals injected in simulated noise for H1L1V @ SNR \( \approx 17.0 \)
- Fiducial binary: \( M_{1,2} = 10 + 1.4 M_\odot \), \( d_L = 16-21 \text{ Mpc} \)
- Spin: \( a_{\text{spin}} = 0.0, 0.1, 0.5, 0.8 \), \( \theta_{\text{SL}} = 20^\circ, 55^\circ \)
Spinning MCMC results

Parameters:
- H1 & L1
- $M = 10, 1.4 \, M_\odot$
- $d_L = 18.7 \, \text{Mpc}$
- $a_{\text{spin}} = 0.5$, $\theta_{\text{SL}} = 20^\circ$
- $\sum\text{SNR} \approx 17.0$
- Black dashed line: true value
- Red dashed line: median
- $\Delta$'s: 90% probability

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Spinning MCMC results

**Spinning BH, non-spinning NS:**

$10 + 1.4 \, M_\odot$, 16–22 Mpc, $\Sigma \text{SNR}=17$

- 2 detectors, $a_{\text{spin}} = 0.0$
- 2 detectors, $a_{\text{spin}} = 0.5$
- 3 detectors, $a_{\text{spin}} = 0.5$

van der Sluys et al., 2008; Raymond et al., 2009
### Accuracy of parameter estimation

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<th>2 detectors (H1 &amp; V):</th>
<th>a_{spin}</th>
<th>θ_{SL}</th>
<th>d_L</th>
<th>M_1</th>
<th>M_2</th>
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<th>a_{spin}</th>
<th>θ_{SL}</th>
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<td>(Mpc)</td>
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<td>(%)</td>
<td>(%)</td>
<td>(%)</td>
<td>(ms)</td>
<td>(%)</td>
<td>(%)</td>
<td>(°)</td>
<td>(°²)</td>
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<td>27.2</td>
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</tbody>
</table>

90%-probability ranges, injection SNR = 17.0

| a | the true value lies outside the 90%-probability range |
| b | idem, outside the 99%-probability range, but inside the 100% range |

van der Sluys et al., 2008

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How to measure gravitational waves from quite a long way away
MCMC with two spins

- 3.5-pN waveform
- 3 detectors
- $M = 3.0 \, M_\odot$, $\eta = 0.22$
- $a_{\text{spin}} = 0.5, 0.8$
- $\Sigma \text{SNR}=20$
Conclusions GW parameter estimation

MCMC code:

We have developed an MCMC code that can recover the 12–15 parameters of a binary inspiral, including one or two spins

Accuracies:

- Detection with only 2 detectors can produce astronomically relevant information when spin is present, with typical accuracies for low/higher spin:
  - individual masses: $\sim 32\%/39\%$
  - dimensionless spin: $0.17 - 0.18$
  - distance: $\sim 55\%/45\%$
  - sky position: $\sim 500^2 / 40^2$
  - binary orientation: $\sim 2500^2 / 175^2$
  - time of coalescence: 11ms / 6ms

- Combination of the above can lead to association with an electromagnetic detection (e.g. gamma-ray burst)
The formation of single sdB stars
GW binary inspirals with LIGO/Virgo

LIGO/Virgo
Binary inspirals
Markov-chain Monte Carlo
Conclusions

End...