Birthrates of accretion-induced collapse neutron stars from binary evolution models

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Some previous studies of accretion-induced collapse of WD -> NS

- Miyaji; Nomoto, Saio, Kondo (e.g. accretion in merging CO WDs)
- Colgate, Fryer (rate estimates, explosion models, NS EOS)
- Ivanova+ (formation mechanisms; globular clusters)
- Dessart (radiation-hydro collapse models of massive WDs)
- Darbha, Metzger+ (using Dessart collapse models; post-collapse nucleosynthesis and light curves)
- Wickramasinghe+ (rates, properties)
- Bhattacharya, Yoon, Janka, Woosley, Abdikamalov, Schwab, & others.
Motivation: why learn about neutron stars formed via collapse of a WD?

• If we can predict rates, delay time distribution (DTD) & physical properties (e.g. donor star type), **detection probability** is higher.

• Rates (vs. SNe Ia) \(\leftarrow\rightarrow\) effect on **chemical evolution**: How much synthesized material is locked up in the remnant? How much is expelled into the ISM? The **r-process**, neutron-rich isotopes.

• Rates are estimated to be higher than was previously assumed (e.g. Hurley et al. 2010; binary MSPs).
**Basic Recipe for Binary Evolution**

Population Synthesis Code

- **adopted prescriptions** (not all processes are relevant for all systems).
- IMF distribution; mass ratio q
- distribution $\sim 1/a$
- metallicity, stellar wind mass-loss rates, common envelope formalism, magnetic braking, natal kicks (NS/BH)
- distribution $\sim 2e$
- adopted initial distributions which describe the orbit.
- M1, M2, a, e
- tidal interactions: calculate change in binary orbital parameters: $\dot{a}, \dot{e}, \dot{\omega}_1, \dot{\omega}_2$
- change in orbital angular momentum: $\dot{J}_{\text{tid}}, \dot{J}_{\text{RLOF}}, \dot{J}_{\text{MB}}, \dot{J}_{\text{GR}}$
- output: SNe, GR sources, CVs, GRBs (post-processing: star formation rates; calibration)

**StarTrack** BPS code (e.g. Belczynski et al. 2008).
Orbital equations evolved in tandem with stellar evolution.

Orbital separation ‘a’, eccentricity ‘e’, Initial Mass Function (IMF) of stars: chosen via Monte Carlo from probability distribution functions that are based on observational data.
Angular Momentum Loss (AML) through Roche-lobe overflow (RLOF), Common Envelope (CE), magnetic braking, gravitational radiation → $\dot{J}_{\text{orb}}$

On what timescale does mass transfer proceed? $\rightarrow \dot{M}_{\text{nuc}}$ or $\dot{M}_{\text{th}}$, ?

Non-degenerate vs. degenerate?

CE: $\dot{M}_{\text{dyn}}$, two formalisms we use in BPS: Webbink ($\alpha$); Nelemans ($\gamma$):

$$\alpha \left( -\frac{G M_{\text{rem}} M_2}{2a_f} + \frac{G M_{\text{giant}} M_2}{2a_i} \right) = -\frac{G M_{\text{giant}} M_{\text{env}}}{\lambda R_{\text{giant}}}$$

$$\gamma \frac{J_i}{M_{\text{giant}}+M_2} = \frac{J_i-J_f}{M_{\text{env}}}$$

Binding energy parameter “$\lambda$” may have metallicity dependence (Xu & Li, 2010).
Adopt two CE models
lower value of \( \alpha \times \lambda \) -> closer post-CE orbits

- `Classic` Webbink (1984) prescription where binding energy parameter \( \lambda \) is constant for all H-rich stars: \( \alpha \times \lambda = 1 \).

- `New` prescription with variable \( \lambda \) based on Xu & Li (2010) employs evolutionary stage-dependent \( \lambda \), and \( \alpha = 1 \). Example:, \( \lambda \) is \( \sim 1 \) for sub-giants, can be \( \sim 3-10+ \) for AGB.

- Run BPS model (burst of SF at t=0, 40,000 binaries each) for each CE prescription: `old’ & `new’. 
Neutron stars formed from intermediate-mass stars

• **In a binary**: either via *(i)* merger (runaway accretion), **or** through *(ii)* non-dynamical Roche-lobe overflow or wind accretion.

• Specific nomenclature for different evolutionary scenarios (see Ivanova et al. 2008). If NS is formed:

Through **merger** of WD binary: **merger-induced** collapse (**MIC**).

Through **stable accretion** in a binary: **accretion-induced** collapse (**AIC**). Here I include this in wind-accretion scenarios.

Through **single star evolution**: **evolutionary-induced** collapse (**EIC**). I will not discuss these in this talk.
Modelling **Progenitors**: overlap between SNe Ia and AIC/MIC

- We assume if **ONe WD accretes to MCh** -> AIC (but see Marquardt et al. 2015).
- Donors can be MS stars, giants (including AGB), stripped helium-burning stars, or WD (rare).

**AIC cf. SDS**

- As for **WD mergers**: How do we delineate between “SN Ia” and “collapse to NS”? This is unclear.
- Previously it was thought MOST mergers of two CO WDs would form a neutron star. This is no longer the standard assumption (SN Ia gained favour).
- We assume any double **WD merger with ONE OR MORE ONe WD** -> MIC.

**MIC cf. DDS**
Results: AIC for ‘old’ CE model

• Events with delay times $> 1000$ Myr have red giant or sub-giant donors. ZAMS mass range of donor $1.3 - 1.8 \, M_{\text{Sun}}$. 

• Events with delay times $< 1000$ Myr have a variety of donors: main sequence, giants, AGB, and helium-burning stars.

• Most prompt delay time events ($< 100$ Myr) all have AGB donors (via wind accretion, not RLOF).
Results: AIC for ‘new’ CE model (main differences in *mauve*)

- Events with delay times $> 1000$ Myr have red giant, sub-giant, or *white dwarf* donors. Thus mostly similar to old CE model.

- Events with delay times $< 1000$ Myr have mostly helium-burning star donors. Some AGB donors, but no *sub-giants or red giants*. Very different results from old CE model!

- Most prompt delay time events ($< 100$ Myr) have AGB or *helium-burning* star donors.
Progenitor properties for **AIC** from StarTrack:
x-axis: ZAMS mass of collapsing star (primary)

**Lower-mass primaries:**
Encounter first MT event when donor is AGB star.

**Higher-mass primaries:**
Encounter first MT event when donor is sub-giant or red giant.

At time of collapse the donor star is a:
- He-burning or HeWD
- helium-burning star
- sub-giant
- MS star
- helium-burning star
- RG range
- AGB range
Results: MIC for both CE models (WD mergers)

- Delay times **span wider range for mergers**; more likely in older populations compared to AIC.

- Merger most often between **ONe + CO WD**. Rarely double ONe WD.

- Shorter delay time events (<1000 Myr) tend to involve two CE phases, whereas >1000 Myr systems typically have encounter 1 CE.
Delay times for AIC vs. MIC

MIC:
- wider DTD
Summary
Galactic rate estimates

- Assume Galaxy has stellar mass $6.4 \times 10^{10} \, M_{\text{sun}}$.

- Remember: we assume all $CO+CO$ mergers make $SNe \, Ia$ or something else; not MIC.

- Actual rate for MW including AIC & MIC together: $5 \times 10^{-5} < \text{AIC+MIC} < \sim 10^{-4}$ per year.
Summary

delay times (ages), donors

• Most AIC/MIC occur **shortly after star formation** (delay times < 300 Myr). **Components** are either:
  - ONeWD + COWD (MIC)
  - ONeWD + AGB star donor (AIC)

• MIC systems predicted to be born out to $t_{\text{Hubble}}$. AIC extremely rare >5000 Myr (for field evolution).

• So what about young radio pulsars observed in (old) **globular clusters**? (e.g. Boyles et al. 2011).
Binaries can explain young radio pulsars in Galactic globular clusters

• At least 3 isolated, 1 binary pulsar seen in Galactic globular clusters (metal-rich).

• EIC have low natal kicks, but unlikely progenitors in old globular clusters.

• The 3 isolated pulsars could be formed via MIC (long enough delay times) without invoking N-body interactions. AIC could explain the pulsars if stellar dynamics are invoked.

NGC 6624: metal-rich GC. Known to host at least 3 YOUNG pulsars. http://www.naic.edu/~pfreire/GCpsr.html
Conclusions

- Notable differences (donor star type) in AIC progenitor properties depending on adopted common envelope formalism. (Reason: different evolution due to wider post-CE orbit in ‘new’ model).

- MIC can occur at very long delay times; both MIC & AIC produce prompt progenitors. Rates ~1-2 orders of mag below SNe Ia.

- We see many AIC events with delay times < 100 Myr (AGB donors) only if we allow for wind RLOF in BPS model (Abate et al. 2013).

- Can we draw a line between thermonuclear SNe and AIC production? This will set limits on event rates, thus nucleosynthesis yield estimates, including r-process site investigations (e.g. Qian & Wasserburg 2007).