Binary Interactions and the Shaping of Planetary Nebulae
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- the majority of stars are in binary systems
- binary interactions affect the shaping of planetary nebulae

Question: are all/most asymmetric planetary nebulae affected by binary interactions?

I. Physical Causes of Asymmetry
II. Review of Binary Interactions
III. The Role of Wide Binaries (Mira AB)
IV. Overall Assessment
The Origin of PN Asymmetries

- Shaping by the external medium
  - interacting wind model (Kwok, Volk, Balick)
  - due to asymmetric AGB wind (equatorially enhanced)
  - very successful in describing observed morphologies

- Asymmetric ejection
  - common-envelope (CE) ejection, binary merging

- The role of rotation (axi-symmetry!)
  - ‘true’ single stars are slowly rotating in the AGB phase (angular-momentum conservation!), including their cores (slow rotation of young white dwarfs)

- Magnetic Fields
  - strong required B fields require dynamo → rapid rotation (CE phase, merger?)

- Binary interactions are the most natural cause of the observed asymmetries
Binary Interactions

• most stars are members of binary systems

• a large fraction are members of interacting binaries

• rule of thumb: each decade of $\log P$ contains 10% of all stars (for $P$ from $10^{-3} - 10^7$ yr)

→ 50% of all stars are in binaries with $P_{\text{orb}} < 100$ yr

• mass-ratio distribution:
  ▷ for massive stars: masses strongly correlated
  ▷ for low-mass stars: uncertain/controversial
    (if masses correlated → more asymmetric PNe for more massive stars)

• binary interactions
  ▷ common-envelope (CE) evolution
  ▷ stable Roche-lobe overflow
  ▷ binary mergers
  ▷ wind focusing
Common-Envelope (CE) Ejection

- at least $10 - 15\%$ of PNe are ejected common envelopes (Bond, De Marco)
- most known post-CE binaries have $P_{\text{orb}} \lesssim 3\, \text{d}$
- the real numbers could be much larger (De Marco, Afsar & Bond, Sorensen & Pollaco)
- binary population synthesis [BPS]: (Han et al. 1995)
  - $> 10 - 15\%$ from FGB
  - $> \sim 5\%$ from AGB
  - constrains CE ejection efficiency

Han et al. (1995)
Stable Roche-Lobe Overflow

- A tidally locked, Roche-lobe filling AGB star is rapidly rotating

\[ \frac{v_{\text{rot}}}{v_{\text{break}}} = (1 + q)^{1/2} \left( \frac{R_1}{a} \right)^{3/2} \]

\(0.33 \ [q = 1], \ 0.41 \ [q = 0.2]\)

- Many post-AGB stars are in circular binaries with \(P_{\text{orb}} > 100 \text{ d}\) (Van Winckel)

**but:** Evolution presently unclear (see talk by Frankowski)

- Quasi-dynamical mass transfer? (PhP 1992)
- With or without temporary CE?

→ Binary mass loss: yes; PN formation: not necessarily (no dynamical ejection or superwind phase!)
Binary Mergers

• one of the most important, but not well studied binary interactions

• **BPS:** $\sim 10\%$ of all stars are expected to merge with a companion star

• efficient conversion of orbital-angular momentum to spin orbital-angular momentum

• if mergers occur early in the evolution $\rightarrow$ subsequent spin-down just as for single stars

• need late mergers or

• late merger with a planet? (Livio, Soker)

  (planetary systems common, enough angular momentum to moderately spin up envelope $\rightarrow$ elliptical PNe?)

The Triple-Ring Nebula around SN 1987A

SN 1987A: an anomalous supernova

- progenitor (SK $-69^\circ 202$): blue supergiant with recent red-supergiant phase ($10^4$ yr)
- chemical anomalies
- the triple-ring nebula
  - not a limb-brightened hourglass, but physically distinct rings
  - axi-symmetric, but highly non-spherical
- supernova is at the centre, but outer rings are slightly displaced
- dynamical age: $\sim 20,000$ yr

all anomalies linked to a single event a few $10^4$ yr ago, most likely the merger of two massive stars
Figure 2
Formation of the Triple-Ring Nebula
(Morris and Podsiadlowski 2007)

- **3-dim SPH simulations**
  (GADGET; Springel)

- simulate mass ejection during merger and subsequent blue-supergiant phase

- **angular momentum of orbit → spin-up of envelope**

  → flattened, disk-like envelope

- **energy deposition in rapid spiral-in phase** ($\approx 1/3E_{\text{bind}}$)

  → partial envelope ejection → outer rings, bipolar lobes

- **equatorial mass shedding during red-blue transition → inner ring**
Gravitational Focusing
(Morris, Fabian, Pilyugin)

• companion gravitationally focuses wind from AGB star

→ equatorially enhanced wind

• focusing fraction (Morris)

\[ \alpha_f \equiv \frac{\dot{M}_{\text{focus}}}{\dot{M}_{\text{outflow}}} = \frac{0.8}{V_w} \left[ \frac{M_2}{a} \right]^2 \left[ V_w^2 + 0.9 \frac{M_1+M_2}{a} \right]^{-3/2} \]

• requires fairly close companion

• BPS:
  - strong focusing (\(\alpha_f > 0.5\)): \(\sim 3\%\)
  - mild focusing (\(\alpha_f > 0.1\)): \(\sim 10\%\)

but: the case of Mira AB: gravitational focusing even in fairly wide binaries
The Symbiotic Binary Mira AB

- wide binary \((P_{\text{orb}} \gtrsim 1000 \text{ yr})\), consisting of Mira A \((P_{\text{puls}} \simeq 330 \text{ d})\) and an accreting white dwarf
- \(\dot{M} \sim 10^{-7} \text{M}_\odot \text{yr}^{-1}\)

Recent Observations:

- soft X-rays (Chandra, Karovska et al. 2005) from both components (shocks in the wind of Mira A and from accretion disk)
- the envelope of Mira is resolved in X-rays and the mid-IR (Marengo et al. 2001)
  - the slow wind from Mira A fills its Roche lobe \((R_{\text{RL}} \sim 40 \text{ AU})\)
  - but: radius of Mira A: 1 – 2 AU
- a new mode of mass transfer(?): wind Roche-lobe overflow
- important implications for D-type symbiotics
Mass Loss from Mira Variables in Binaries (Mohamed, P.)

The atmosphere of an AGB star

- large-amplitude Mira pulsations lift matter of the atmosphere (but not to escape speed)
- pumping mechanism $\rightarrow$ till gas reaches low temperatures for dust formation
- radiation pressure on dust accelerates matter to escape speed

Mira variables in binaries

- if dust-formation radius ($R_{dust}$) is a significant fraction of the Roche-lobe radius ($R_{RL}$) $\rightarrow$ binary effects affect the mass-loss geometry

- transition from
  - spherical wind for $R_{dust} \ll R_{RL}$
  - disk-like outflow
  - wind Roche-lobe overflow for $R_{dust} \sim R_{RL}$
  - unstable mass transfer? for $R_{dust} > R_{RL}$

- formation of circumbinary disk possible plus bipolar component from accreting source

NB: Application to WR binaries?

- where $R_{RL}$ less than the outer wind acceleration radius (Gräfener & Hamann 2005)
Wind Roche-Lobe Overflow

- a new mass-transfer mode for wide binaries
- high mass-transfer fraction (compared to Bondi-Hoyle wind accretion) \(\rightarrow\) more efficient accretion of s-process elements for the formation of barium stars (without circularization)
- accretion rate in the regime where WDs can accrete? \(\rightarrow\) increase the range for SN Ia progenitors (but may not be efficient enough)
- asymmetric system mass loss \(\rightarrow\) formation of circumstellar disks and bipolar outflows from accreting component (e.g. OH231.8+4.2)
  \(\rightarrow\) shaping of (proto-)planetary nebulae
  \(\triangleright\) binaries with longer orbital periods important

Case D Mass Transfer

- extension of case C mass transfer, but potentially more important (possibly larger orbital period range)
- also: massive, cool supergiants with dynamically unstable envelopes (e.g. Yoon & Langer)
- large mass loss just before the supernova?
- possible implications for Type II-L, IIb supernovae (increases rate estimates), SN 2002ic
- delays onset of dynamical mass transfer
  \(\rightarrow\) produces wider S-type symbiotic binaries (i.e. solve orbital period problem)
  \(\rightarrow\) solve the problem of black-hole binaries with low-mass companions
Implications for PN Shaping

- even in fairly wide binaries, gravitational focusing is important.
- asymmetric system mass loss $\rightarrow$ formation of circumstellar disks and bipolar outflows from accreting component (e.g. OH231.8+4.2)
  $\rightarrow$ shaping of (proto-)planetary nebulae
- depends on $v_{\text{wind}}$ and $v_{\text{orb}}$
- as star climbs AGB $\rightarrow$ Mira phase: expect transition from spherical wind to equatorial wind
  gravitational focusing is much more important than previous estimates suggested
## The Importance of Binary Interactions

- results from *binary population synthesis* (Han)

<table>
<thead>
<tr>
<th>Process</th>
<th>Percentage</th>
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<tbody>
<tr>
<td>CE ejection</td>
<td>15 – 20%</td>
</tr>
<tr>
<td>Binary mergers</td>
<td>~ 10%</td>
</tr>
<tr>
<td></td>
<td>– 5%</td>
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<tr>
<td></td>
<td>+ 10%?</td>
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<td>Gravitational focusing</td>
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*35 – 50% + 25%*
Discussion

• binary interactions likely to be the dominant cause for asymmetric planetary nebulae

• probably all bipolar/butterfly PNe

• elliptical PNe: only need moderate asymmetry: planets, early mergers, distant companions, single stars

• Are all PNe caused by binary interactions (Iben, Paczyński, De Marco)?

  ▶ Personal judgement: necessity of binarity is unproven/unclear
  ▶ single stars should also be able to produce PNe