The Evolution of Close Binaries

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The case of RS Ophiuchi

- as a test of binary stellar evolution
- as a potential Type Ia supernova (SN Ia) progenitor

I. Testing Binary Evolution: the Case of sdB Stars

II. Problems in Binary Evolution

III. The Progenitors of SNe Ia

III. The Origin of Symbiotic Binaries

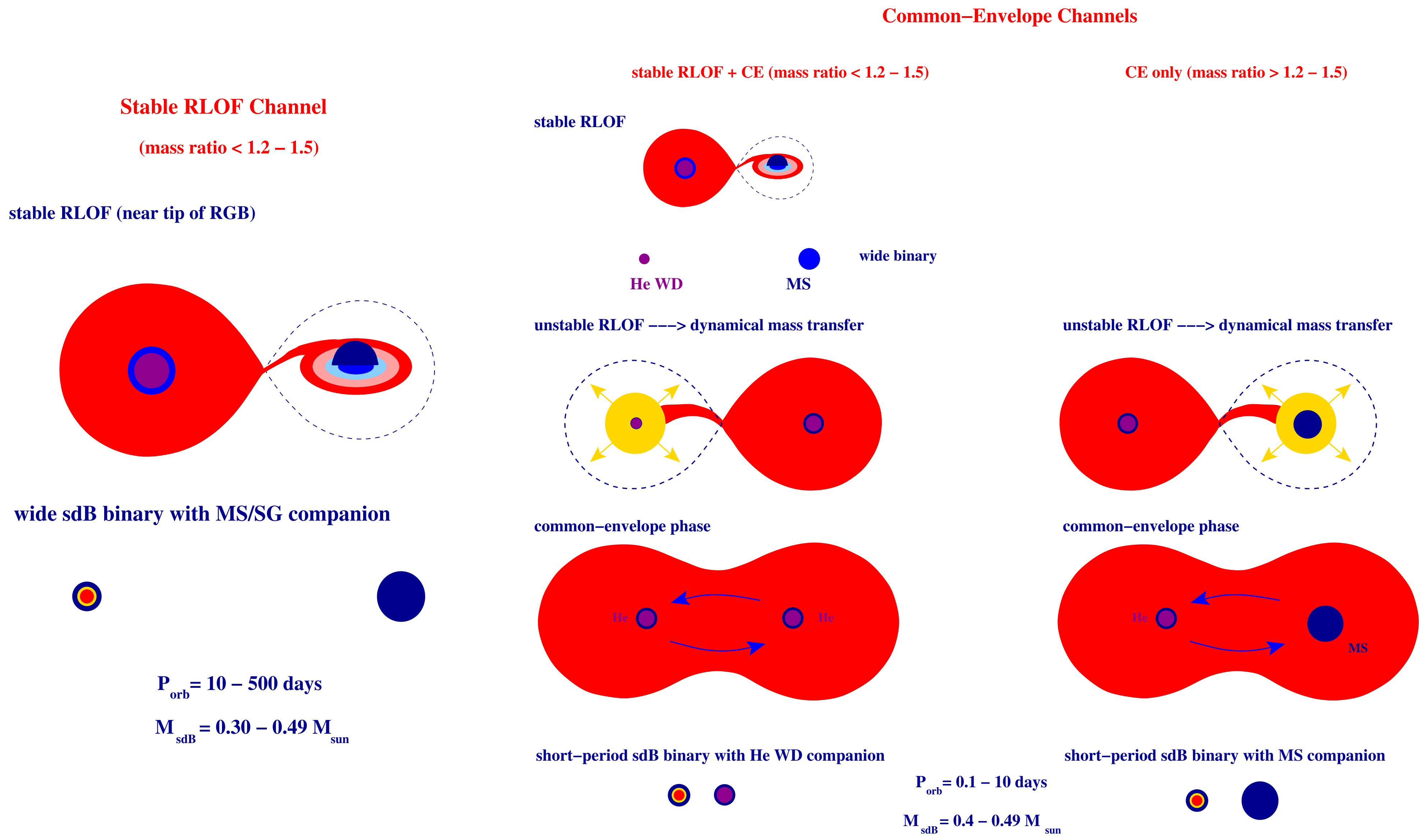
IV. The Status of RS Ophiuchi

Testing Binary Evolution: sdB Stars

(Han et al. 2002, 2003)

- sdB stars are helium-core-burning stars (with $M \simeq 0.5\,M_\odot$) that have lost most of their envelopes by binary interactions
- prototypical evolution for forming compact binaries
  - ▷ stable Roche-lobe overflow
  - ▷ common-envelope (CE) evolution
  - ▷ binary mergers
- all channels appear to be important ($\gtrsim 50\,\%$ are short-period, post-CE binaries; Maxted, Heber, Napiwotzki)
- mass transfer must have started near the tip of the red-giant branch (helium burning!)

$\rightarrow$ ideal systems to test/constrain binary evolution



Common−Envelope Channels
stable RLOF + CE (mass ratio < 1.2 − 1.5)
CE only (mass ratio > 1.2 − 1.5)
Stable RLOF Channel
(mass ratio < 1.2 − 1.5)
stable RLOF (near tip of RGB)
stable RLOF
He WD
MS
wide binary
unstable RLOF −−−> dynamical mass transfer
unstable RLOF −−−> dynamical mass transfer
wide sdB binary with MS/SG companion
common−envelope phase
common−envelope phase
He
He
He
MS
P orb = 10 − 500 days
M sdB = 0.30 − 0.49 M sun
short−period sdB binary with He WD companion
short−period sdB binary with MS companion
P orb = 0.1 − 10 days
M sdB = 0.4 − 0.49 M sun

Problems in Binary Evolution (Selection)

Common-envelope evolution and ejection

- dynamical mass transfer leads to a CE and spiral-in phase
- if envelope is ejected → short-period binary (Paczyński 1976)
- CE ejection criterion?
  - ▷ qualitatively: $\alpha_{\rm CE}\,|\Delta E_{\rm orb}| > E_{\rm env}$
  - ▷ the role of recombination energy (Han et al. 2002/03)?
  - ▷ $\alpha_{\rm CE}\,|\Delta E_{\rm orb}| > |E_{\rm grav} + \alpha_{\rm therm} E_{\rm therm}|$
  - ▷ sdB binaries: $\alpha_{\rm CE} = 0.75$, $\alpha_{\rm therm} = 0.75$
  - ▷ CE ejection efficient, recombination energy important

The criterion for dynamical mass transfer

- dynamical mass transfer is caused by a mass-transfer runaway (giant expands, Roche lobe shrinks)
  - ▷ for n = 1.5 polytrope: $q > q_{\rm crit} = M_{\rm donor}/M_{\rm accretor} = 2/3$
  - ▷ real stars: $q_{\rm crit} \gtrsim 1.1 - 1.3$
- problem:
  - ▷ many S-type symbiotics (with $q > 2 - 3$) appear to fill their Roche lobes (Mikołajewska)
  - ▷ sdB binaries: best fit: $q_{\rm crit} \simeq 1.5$
- the role of 'near-RLOF'?
- tidally enhanced mass loss (Eggleton, Tout)

The role of non-conservative mass transfer

- mass transfer is often very non-conservative
- angular-momentum loss affects orbital evolution
  - ▷ different prescriptions give very different outcomes (e.g. can stabilize/destabilize mass transfer)
  - ▷ no good theoretical model, weak observational constraints
- sdB binaries: mass transfer in stable systems has to be very non-conservative to produce short-period sdB binaries with WD companions

Binary mergers

- poorly understood/constrained
- $\sim 10\,\%$ of all stars are expected to merge with a companion star
- responsible for many eruptive events?

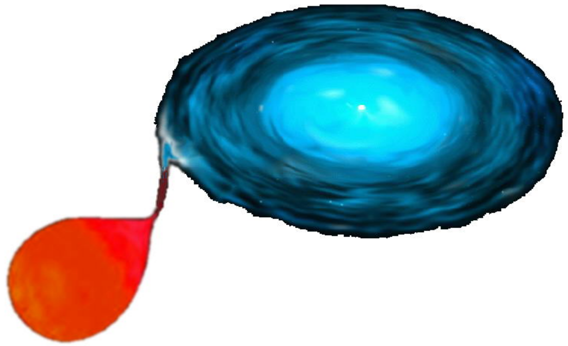
The Progenitors of Type Ia Supernovae

- SNe Ia are thermonuclear explosions in CO white dwarfs approaching the Chandrasekhar mass
- typical rate: a few $10^{-3}\,\mathrm{yr}^{-1}$ (Galaxy)
- occur in young and old populations (Branch 95)
  - ▷ but: low level star formation even in many elliptical galaxies (e.g. Schawinski, Kaviraj)
  - ▷ relative ratio of young to old unclear (see poster on time delays by Förster)
- the nature of their progenitors is still not resolved
  - ▷ numerous progenitor models
  - ▷ more than one (two, three?) channels

The double-degenerate (DD) channel

- two CO WDs with a combined mass $> 1.4\,\mathrm{M}_\odot$ merge (driven by gravitational radiation)
- Pros:
  - ▷ theoretically predicted rate is high (Yungelson, Nelemans, Han, etc.)
  - ▷ probably consistent with observations of DDs (SPY [Napiwotzki])
  - ▷ can produce systems with short and long time delays
- Cons:
  - ▷ CO WD mergers are more likely to lead to core collapse (i.e. neutron stars) (Nomoto, Iben)
  - ▷ but: situation presently unclear (see Yoon et al. 2007); some DD mergers may produce SNe Ia?

Single-degenerate models



- accretion from non-degenerate companion
- supersoft channel
  - ▷ mass donor: late main-sequence star, early subgiant ($M > 1.8\,\mathrm{M}_\odot$; $P_{\mathrm{orb}} \lesssim$ d)
- Pros:
  - ▷ observed systems (e.g. U Sco)
  - ▷ rate close to the needed rate (but binary assumptions; Yungelson)
- Cons:
  - ▷ model requires fine-tuning of $\dot{M}$
  - ▷ uncertain accretion efficiency
  - ▷ supersoft channel does not produce systems with time delays $\gtrsim 1.5$ Gyr

→ second channel: red-giant channel

  - ▷ RS Oph prototype progenitor?

Symbiotic Binaries as SN Ia Progenitors
(Hachisu, Kato, Nomoto)

Nomoto, Umeda, Hachisu, Kato, Kobayashi, Tsujimoto: *SN Ia* 7

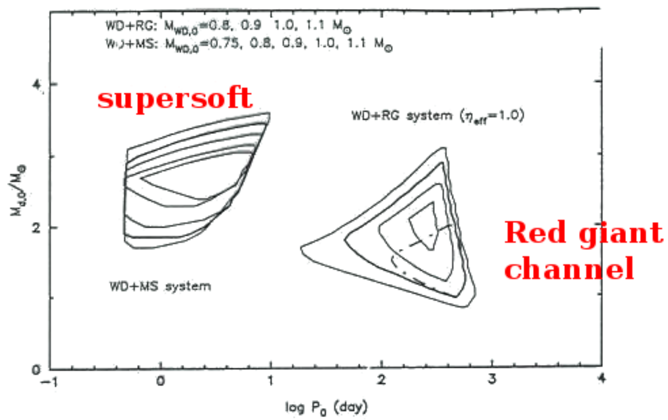


FIGURE 4. The region to produce SNe Ia in the $\log P_0 - M_{d,0}$ plane for five initial white dwarf masses of $0.75 M_\odot$, $0.8 M_\odot$, $0.9 M_\odot$, $1.0 M_\odot$ (heavy solid line), and $1.1 M_\odot$. The region of $M_{WD,0} = 0.7 M_\odot$ almost vanishes for both the WD+MS and WD+RG systems, and the region of $M_{WD,0} = 0.75 M_\odot$ vanishes for the WD+RG system. Here, we assume the stripping efficiency of $\eta_{eff} = 1$. For comparison, we show only the region of $M_{WD,0} = 1.0 M_\odot$ for a much lower efficiency of $\eta_{eff} = 0.3$ by a dash-dotted line.

Post-CE WD binaries

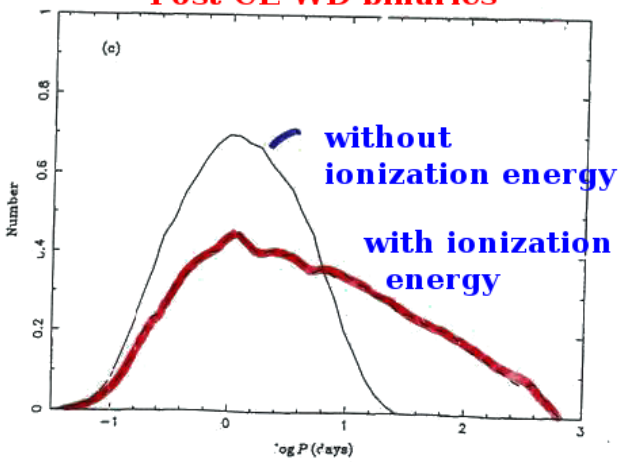


Figure 4 – continued

Han et al. (1995)

- two islands in $P_{orb} - M_2$ diagram where WDs can grow in mass
- red-giant channel: $P_{orb} \sim 100\,d$, M_2 as low as $1\,M_\odot$
- may explain SNe Ia with long time delays

Problem: binary population synthesis simulations do not produce many systems in the red-giant island ($10^{-5}\,yr^{-1}$ for optimistic assumptions (Han))

- ▷ stable RLOF → wide systems with $P_{orb} \gtrsim 10^3\,d$
- ▷ CE evolution → close systems with $P_{orb} \lesssim 10^2\,d$

→ gap in period distribution for systems with $P_{orb} \sim 200 - 1000\,d$ (e.g. Han, Frankowski)

→ importance of RS Oph

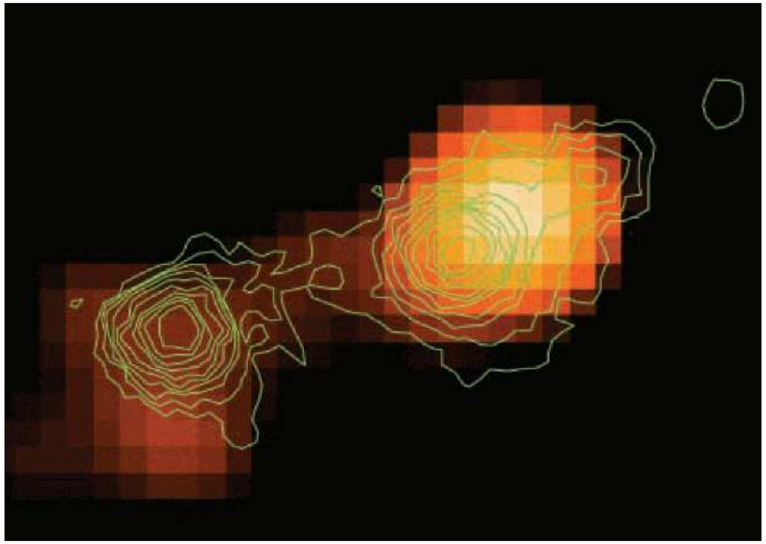
→ suggests problem with binary evolution model

Quasi-dynamical mass transfer?

- need a different mode of mass transfer (Webbink, Podsiadlowski)
- very non-conservative mass transfer but without significant spiral-in
- may also be needed to explain the properties of double degenerate binaries (Nelemans), υ Sgr, etc.
- transient CE phase or circumbinary disk (Frankowski)?

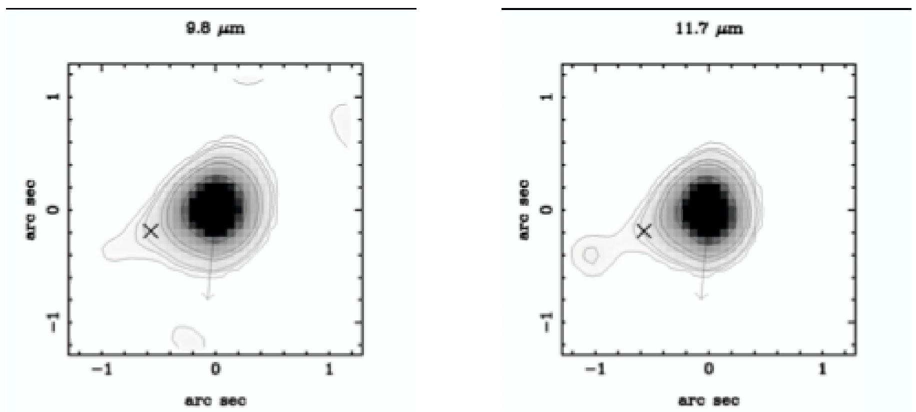
The Symbiotic Binary Mira AB

- wide binary ($P_{orb} \sim 400\,yr$), consisting of Mira A ($P_{puls} \simeq 330\,d$) and an accreting white dwarf
- $\dot{M} \sim 10^{-7}\,M_{\odot}\,yr^{-1}$



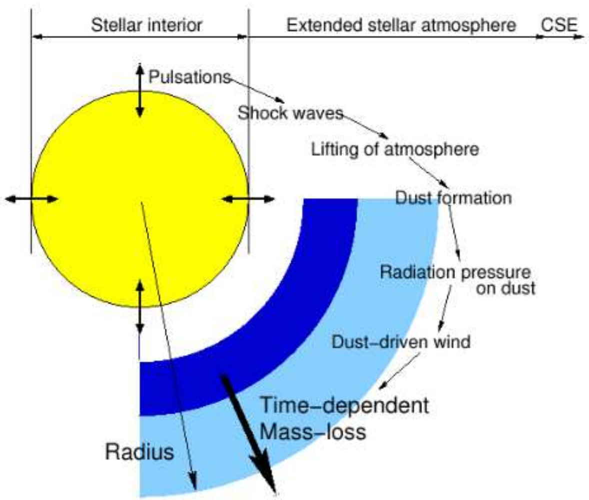
Recent Observations:

- 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 ($R_{RL} \sim 25\,AU$)
  - ▷ 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 → 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})→ 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) → more efficient accretion of s-process elements for the formation of barium stars (without circularization)
- accretion rate in the regime where WDs can accrete? → increase the range for SN Ia progenitors (but may not be efficient enough)
- asymmetric system mass loss → formation of circumstellar disks and bipolar outflows from accreting component (e.g. OH231.8+4.2)

  → shaping of (proto-)planetary nebulae

  ▷ 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

  → produces wider S-type symbiotic binaries (i.e. solve orbital period problem)

  → solve the problem of black-hole binaries with low-mass companions

Testing the red-giant channel for SN Ia progenitors

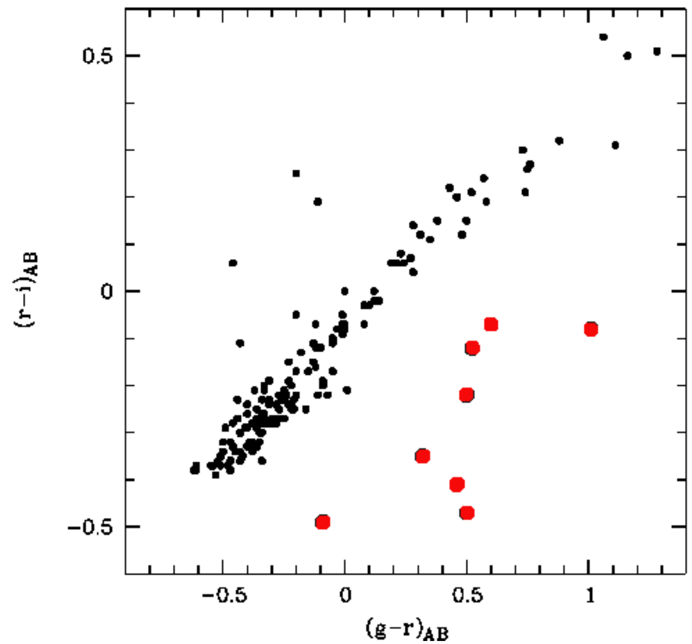
- Identifying the surviving runaway companions after a SN Ia (cf. claim of Tycho-G [Ruiz-Lapuente])
- Identification of circumstellar matter in normal SNe Ia (Patat et al. 2007)

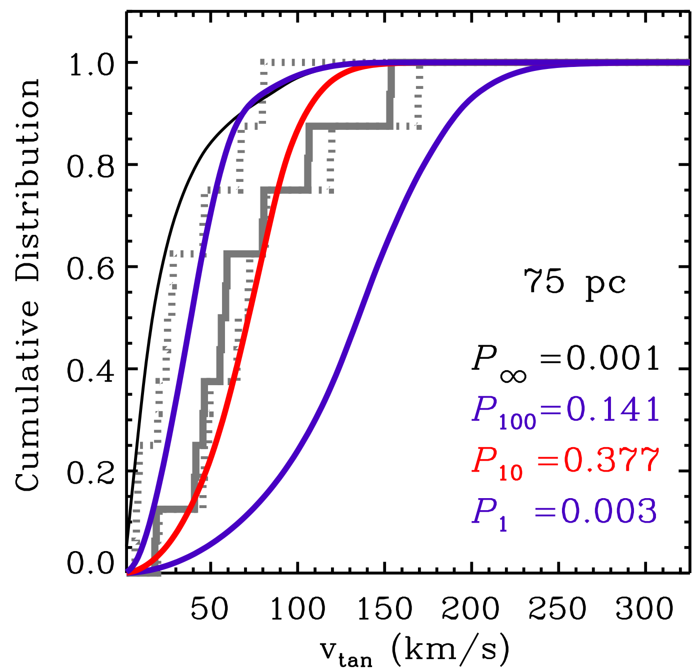
The Origin of Ultra-Cool Helium White Dwarfs (Justham et al. 2007 [poster])

- ultra-cool white dwarfs ($T_{\rm eff} < 4000\,$K)

$\rightarrow$ implies very low-mass white dwarfs (cooling timescale! $\lesssim 0.3\,M_\odot$)

- can only be formed in binaries
- some may have pulsar companions, most appear to be single
- most likely origin: surviving companion after a SN Ia
- kinematics: pre-SN period $10 - 100\,$d (short end of red-giant island?)





The Status of RS Ophiuchi

- $P_{orb} = 456\,d \rightarrow M_{core} = 0.4\,M_{\odot}$

$\rightarrow$ $R_{RL} \gtrsim 90\,R_{\odot}$ (cf. Zamanov et al. 2006)

$\rightarrow$ late stage of the mass-transfer phase?

Some questions for the workshop:

- What is the mass of the giant?
- Is RS Oph a SN Ia progenitor (CO or ONeMg WD?)?
- What is the formation rate of systems like RS Oph
  - ▷ to constrain binary evolution?
  - ▷ to assess the importance as a SN Ia channel?