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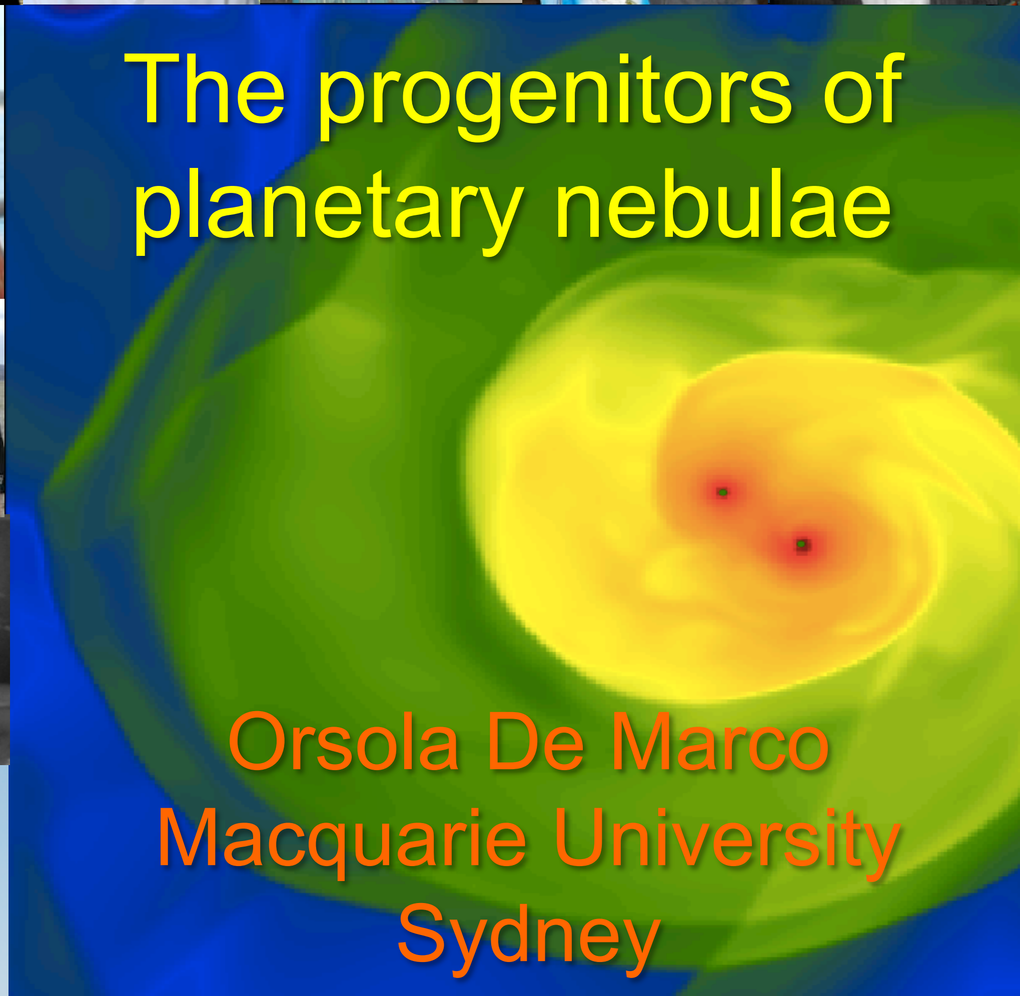


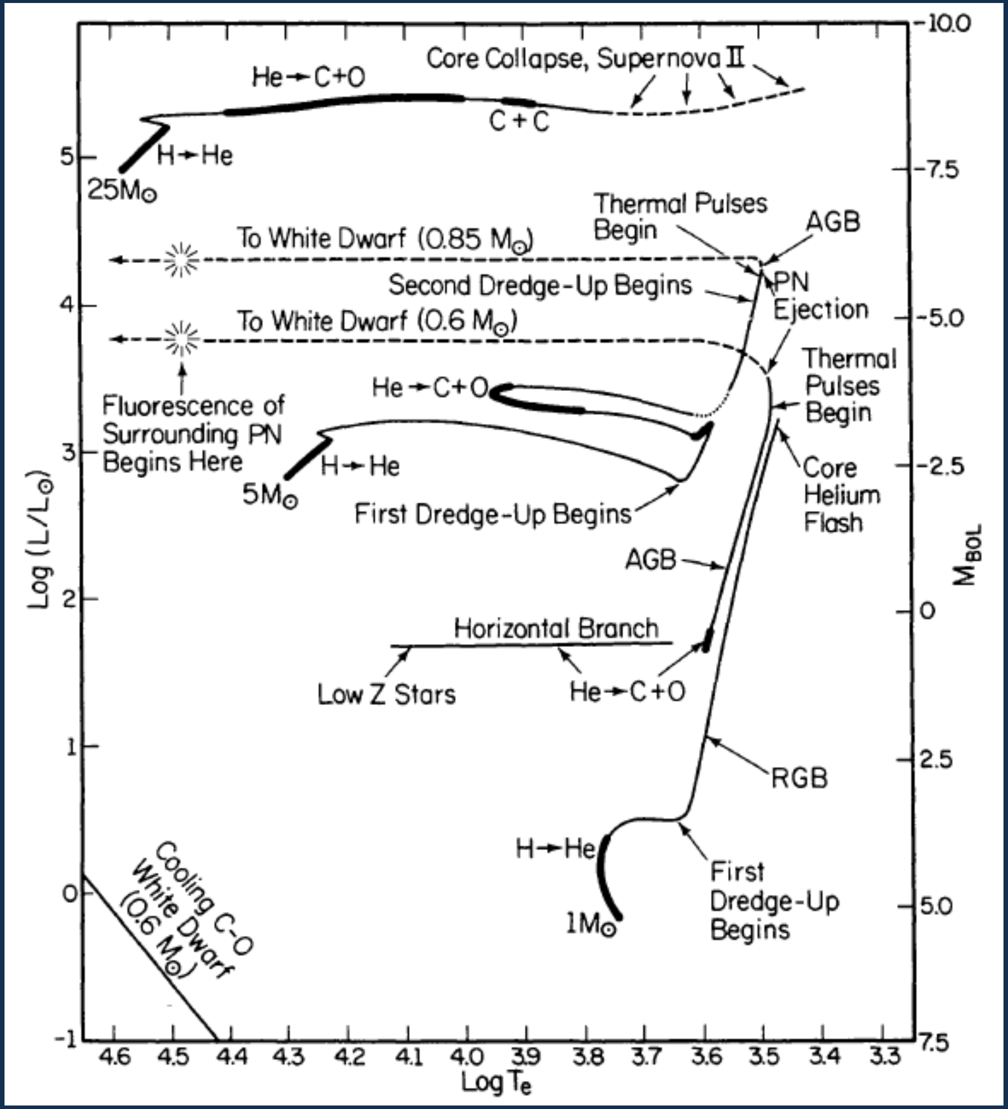
The progenitors of planetary nebulae

Orsola De Marco
Macquarie University
Sydney

Outline

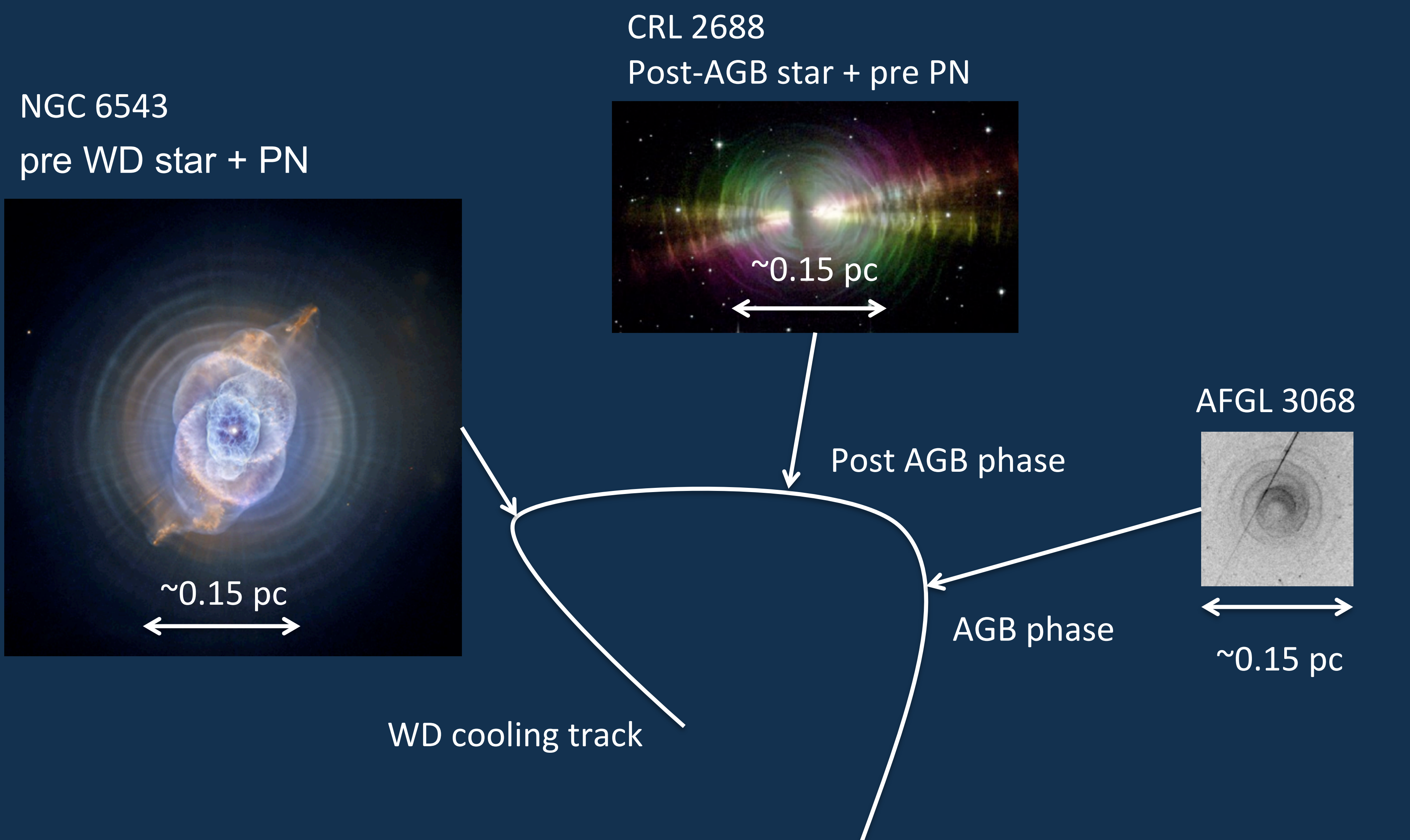
- The textbook path to PN-hood
- Part #1: no theoretical understanding of how to make collimated PN with single stars
- Part #2: the PPN momentum and morphology problem
- Part #3: expectations from MS binary fraction and period distribution: too many short period binary central stars of PN
- A revised framework for the evolution to PN
- To-do list

Intermediate mass evolution on the HR diagram



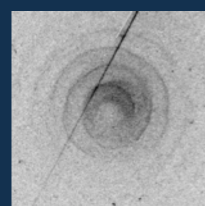
Iben 1995

The progenitors of PN: the simplistic picture



Part #1: a theoretical shortcoming

How can spherical AGB mass-loss turn into collimated PN?



We thought we had the solution to the formation of non-spherical PN …

SHAPING BIPOLAR AND ELLIPTICAL PLANETARY NEBULAE: EFFECTS OF STELLAR ROTATION, PHOTOIONIZATION HEATING, AND MAGNETIC FIELDS

GUILLERMO GARCÍA-SEGURA,[1] NORBERT LANGER,[2] MICHAŁ RÓŻYCZKA,[3,4] AND JOSÉ FRANCO[5]

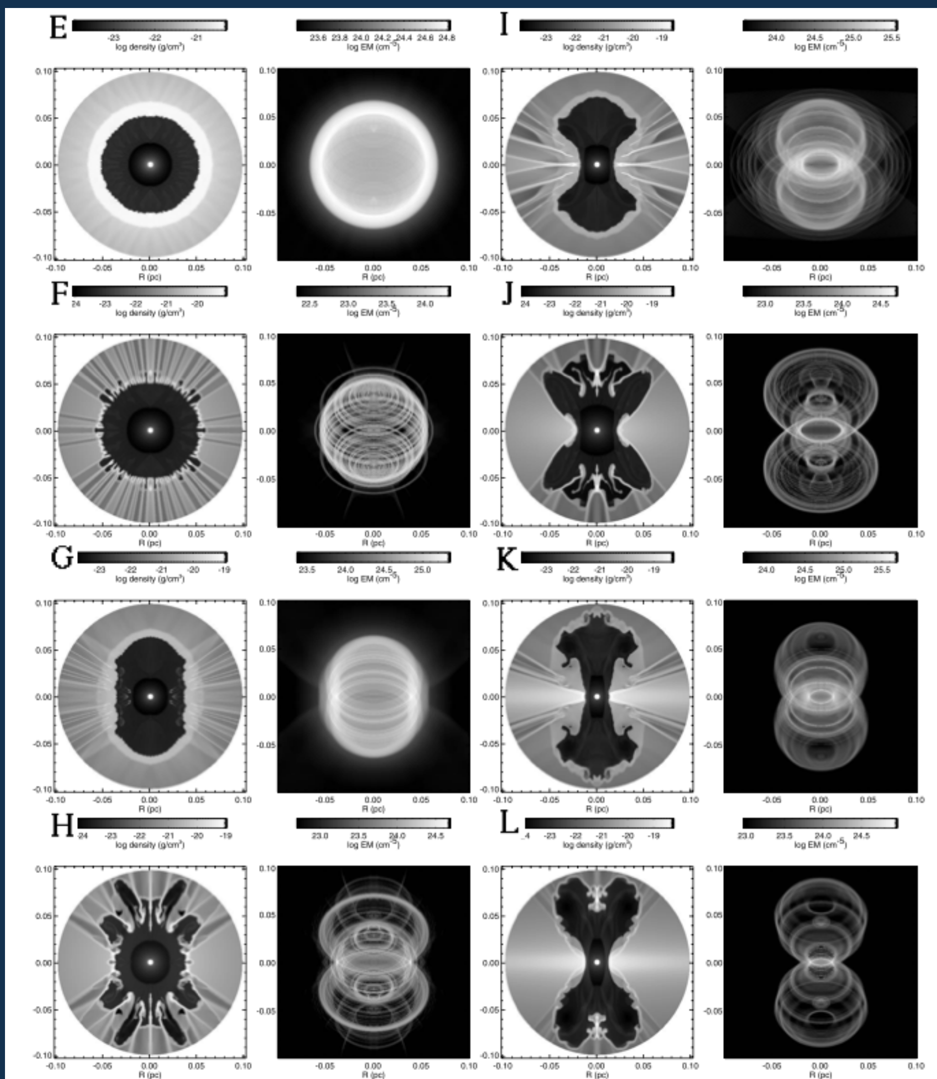
Received 1998 February 27; accepted 1999 January 4

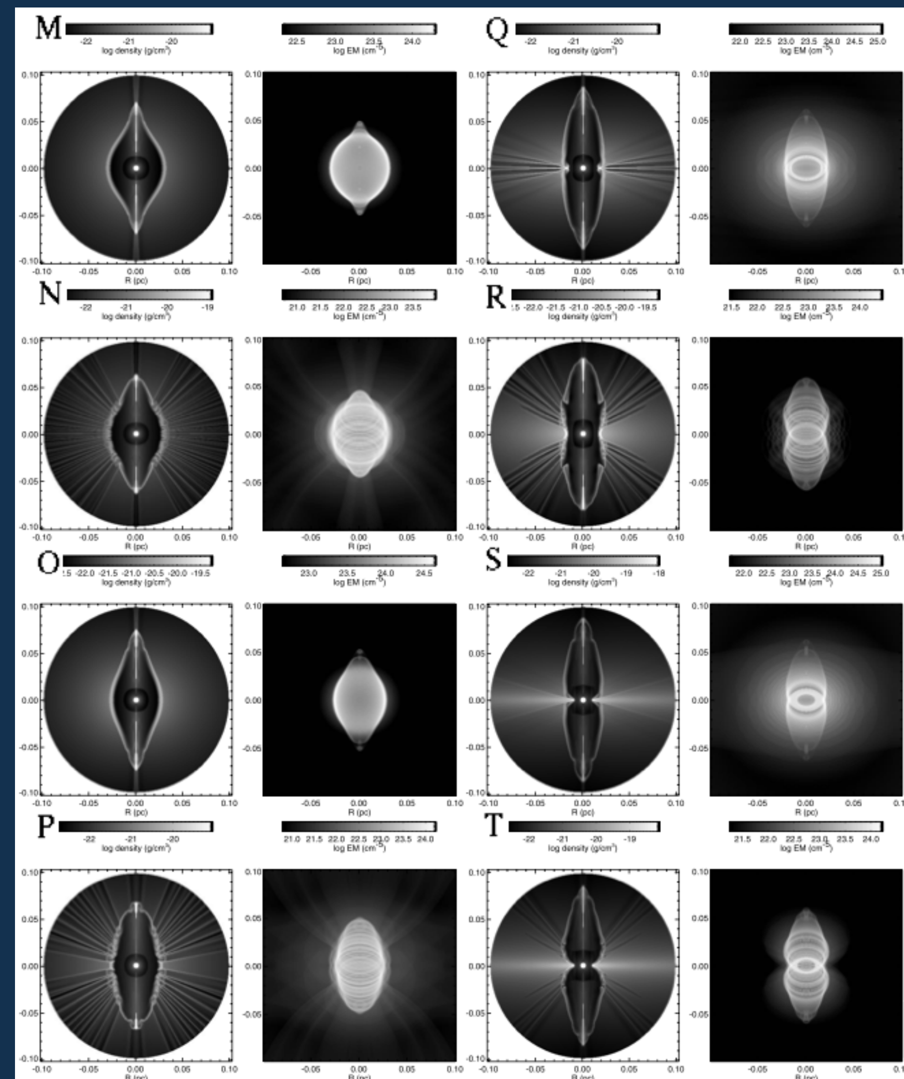
ABSTRACT

We present two-dimensional hydrodynamical and magnetohydrodynamical simulations of the evolution of planetary nebulae formed through the interaction of two succeeding, time-independent stellar winds. Both winds are modeled according to a consistent physical prescription for the latitudinal dependence of their properties. We propose that single stars with initial masses above $\sim 1.3\ M_\odot$ can achieve near-critical rotation rates during their "superwind" phase at the tip of the asymptotic giant branch (AGB). We show that the resulting equatorially confined winds and their subsequent inflation to a double lobe structure by the post-AGB wind leads to the typical hourglass shape found in many planetary nebulae, such as MyCn 18. Following Chevalier & Luo and Różyczka & Franco, we then combine the effect of a magnetic field in the post-AGB wind with rotating AGB winds. We obtain highly collimated bipolar nebula shapes, reminiscent of M2-9 or He 2-437. For sufficiently strong fields, ansae and jets, similar to those observed in IC 4593 are formed in the polar regions of the nebula. Weaker fields are found to be able to account for the shapes of classical elliptical nebulae, e.g., NGC 6905, in the case of spherically symmetric AGB winds, which we propose for single stars with initial masses below $\sim 1.3\ M_\odot$. Photoionization, via instabilities in the ionization-shock front, can generate irregularities in the shape of the simulated nebulae. In particular, it leads to the formation of cometary knots, similar to those seen in the Helix nebula (NGC 7293). This effect may also be responsible for large-scale irregularities like those found in Sh 2-71 or WeSb 4. We arrive at a scenario in which the majority of the planetary nebula with their diverse morphologies is obtained from single stars. This scenario is consistent with the Galactic distribution of the different nebula types, since spherical and elliptical nebulae—which have a distribution with a large scale height above the Galactic plane—are ascribed to progenitor masses below $\sim 1.3\ M_\odot$, with magnetic effects introducing ellipticities. Bipolar nebulae, on the other hand—which are on average closer to the Galactic plane—are found to stem from progenitors with initial masses above $\sim 1.3\ M_\odot$.

Subject headings: ISM: magnetic fields — ISM: structure — MHD — planetary nebulae: general — stars: AGB and post-AGB — stars: mass loss

… all shapes are accounted for…





A spanner in the works

Why Magnetic Fields Cannot Be the Main Agent Shaping Planetary Nebulae

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ABSTRACT. An increasing amount of the literature reports the detection of magnetic fields in asymptotic giant branch (AGB) stars and in central stars of planetary nebulae (PNe). These detections lead to claims that the magnetic fields are the main agent shaping the PNe. In this paper, I examine the energy and angular momentum carried by magnetic fields expelled from AGB stars, as well as other physical phenomena that accompany the presence of large-scale fields, such as those claimed in the literature. I show that a single star cannot supply the energy and angular momentum if the magnetic fields have the large coherent structure required to shape the circumstellar wind. Therefore, the structure of nonspherical planetary nebulae cannot be attributed to dynamically important large-scale magnetic fields. I conclude that the observed magnetic fields around evolved stars can be understood with respect to locally enhanced magnetic loops, which can have a secondary role in the shaping of the PN. The primary role, I argue, rests with the presence of a companion.

… and …

Isolated versus common envelope dynamos in planetary nebula progenitors

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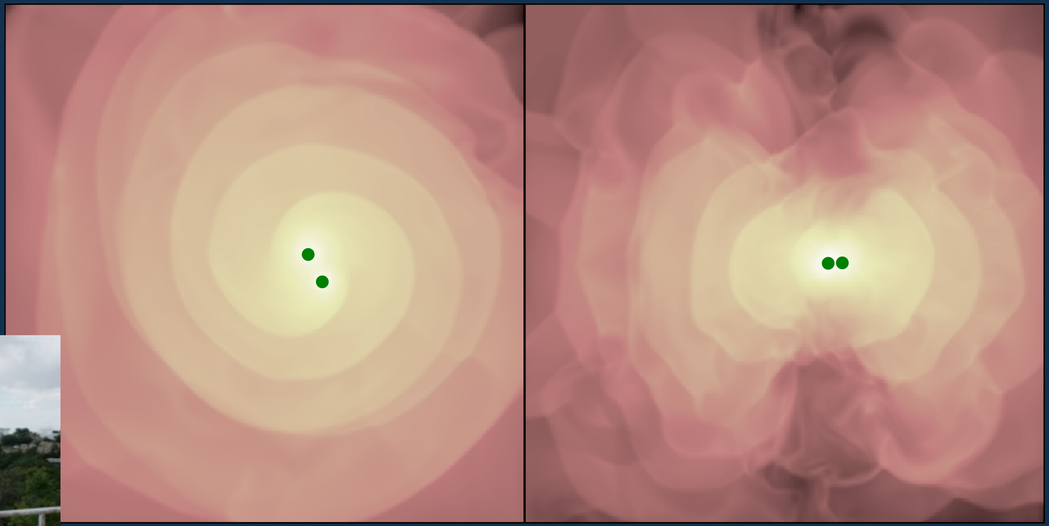
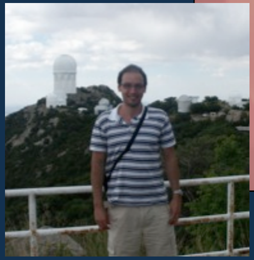
ABSTRACT

The origin, evolution and role of magnetic fields in the production and shaping of proto-planetary nebulae (PPNe) and planetary nebulae (PNe) are a subject of active research. Most PNe and PPNe are axisymmetric with many exhibiting highly collimated outflows; however, it is important to understand whether such structures can be generated by isolated stars or require the presence of a binary companion. Towards this end, we study a dynamical, large-scale $\alpha - \Omega$ interface dynamo operating in a 3.0 $M_{\odot}$ Asymptotic Giant Branch (AGB) star in both an isolated setting and a setting in which a low-mass companion is embedded inside the envelope. The back reaction of the fields on the shear is included and differential rotation and rotation deplete via turbulent dissipation and Poynting flux. For the isolated star, the shear must be resupplied in order to sufficiently sustain the dynamo. Furthermore, we investigate the energy requirements that convection must satisfy to accomplish this by analogy to the Sun. For the common envelope case, a robust dynamo results, unbinding the envelope under a range of conditions. Two qualitatively different types of explosion may arise: (i) magnetically induced, possibly resulting in collimated bipolar outflows and (ii) thermally induced from turbulent dissipation, possibly resulting in quasi-spherical outflows. A range of models is presented for a variety of companion masses.

If anyone can, binaries can: scenario A

- Common envelope interactions:
- AGB star + companion within 3-4 AU
- Promote equatorially-enhanced mass loss, magnetic fields and jets



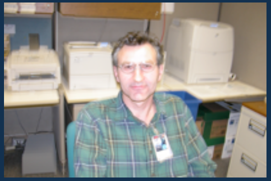


Passy et al. 2012

Boffin et al. 2012

If anyone can, binaries can: B

- Companions can act directly on the envelope and promote equatorially-enhanced outflows for *a* = 6-10 AU (e.g., Mastrodemos & Morris 1998)



Edgar et al. 2008

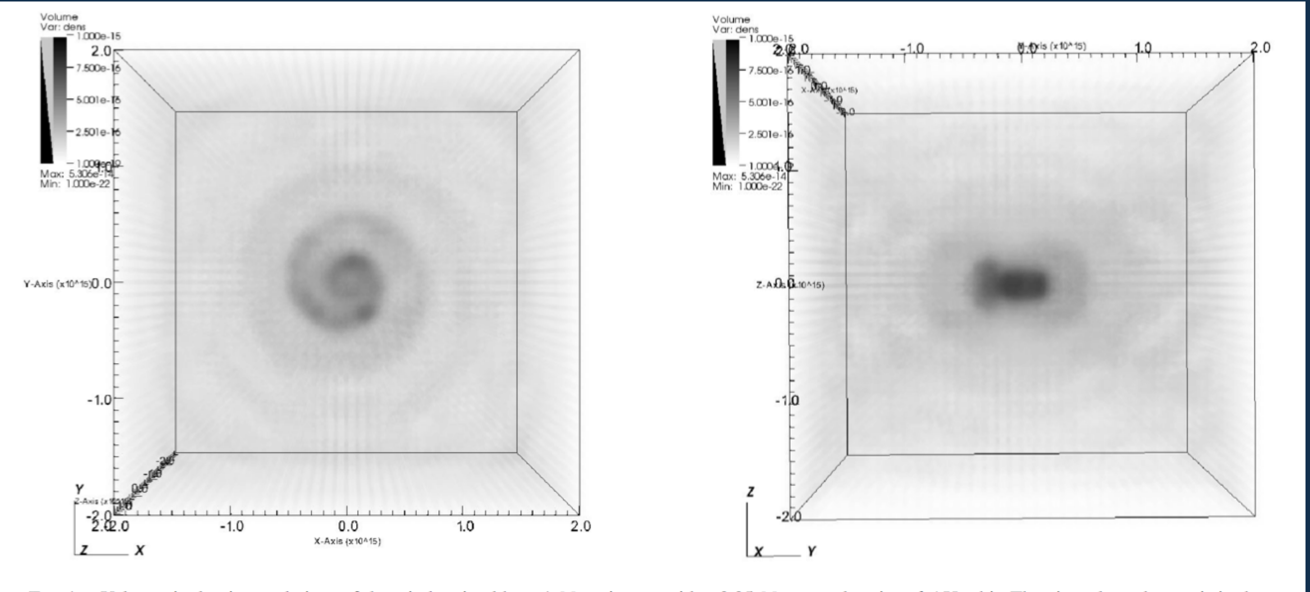
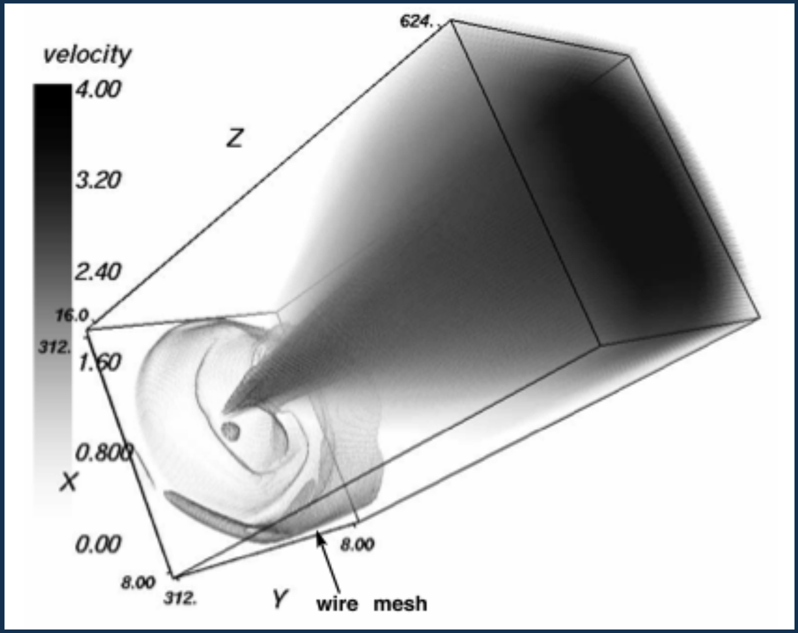


FIG. 1.—Volumetric density renderings of the wind emitted by a 1 $M_{\odot}$ primary, with a 0.25 $M_{\odot}$ secondary in a 6 AU orbit. The view along the *z*-axis is shown on the left, and that along the *x*-axis on the right. The binary orbits in the $z = 0$ plane.

If anyone can, binaries can: C

- If companions can accrete and form jets, they can blow lobes and form compression disks which subsequently shape the nebulae (e.g., Garcia-Arredondo & Frank 2004)



Part #2: observational conundrums about post-AGB stars

What is accelerating and collimating these outflows?

The momentum problem in PPN…

Mass, linear momentum and kinetic energy of bipolar flows in protoplanetary nebulae

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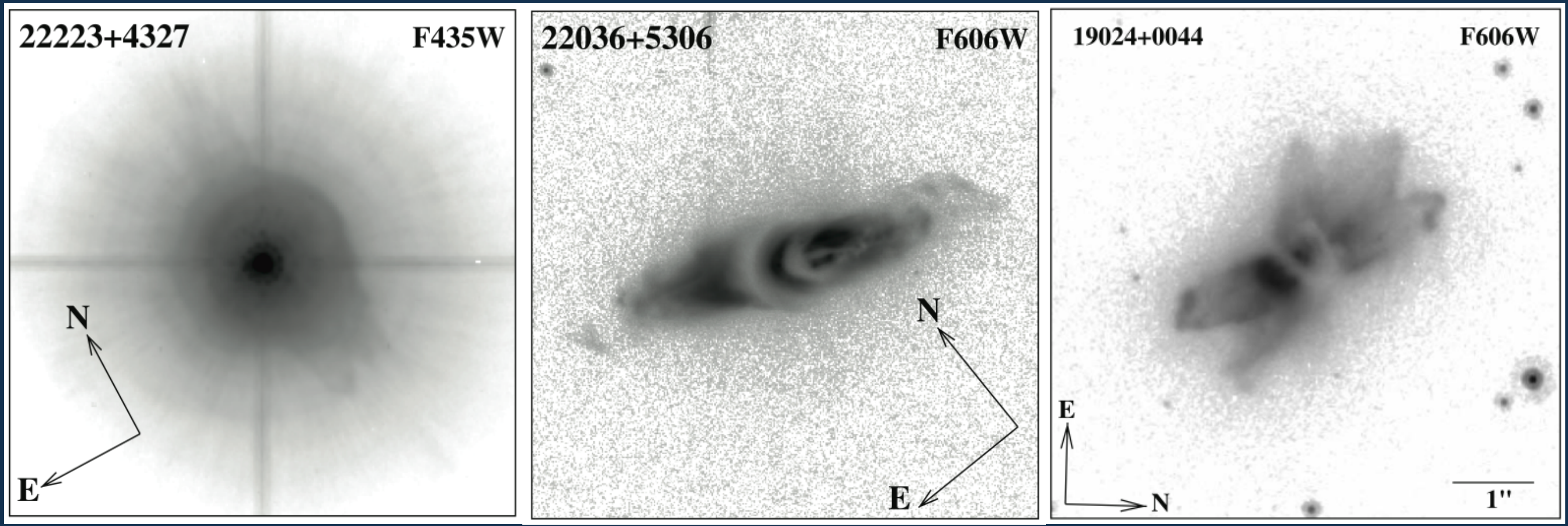
Abstract. We have studied the CO emission from protoplanetary nebulae (PPNe). Our sample is composed of 37 objects and includes, we think, all well identified PPNe detected in CO, together with the two yellow hypergiants emitting in CO and one young PN. We present a summary of the existing CO data, including accurate new observations of the ^{12}CO and ^{13}CO $J = 1$–0 and $J = 2$–1 lines in 16 objects. We identify in the nebulae a slowly expanding shell (represented in the spectra by a central core) and a fast outflow (corresponding to the line wings), that in the well studied PPNe is known to be bipolar. Excluding poor data, we end up with a sample of 32 sources (including the 16 observed by us); fast flows are detected in 28 of these nebulae, being absent in only 4. We present a method to estimate from these data the mass, "scalar" momentum and kinetic energy of the different components of the molecular outflows. We argue that the uncertainties of our method can hardly lead to significant overestimates of these parameters, although underestimates may be present in not well studied objects. The total nebular mass is often as high as $\sim$1 $M_\odot$, and the mass-loss rate, that (presumably during the last stages of the AGB phase) originated the nebula, had typical values $\sim$$10^{-4}$ $M_\odot$ yr^{-1}. The momentum corresponding to this mass ejection process in most studied nebulae is accurately coincident with the maximum momentum that radiation pressure, acting through absorption by dust grains, is able to supply (under expected conditions). We estimate that this high-efficiency process lasts about 1000–10 000 yr, after which the star has ejected a good fraction of its mass and the AGB phase ends. On the other hand, the fast molecular outflows, that have probably been accelerated by shock interaction with axial post-AGB jets, carry a significant fraction of the nebular mass, with a very high momentum (in most cases between 10^{37} and 10^{40} g cm s^{-1}) and very high kinetic energy (usually between 10^{44} and 10^{47} erg). In general, yellow hypergiants and post-AGB objects with low initial mass show nebular masses and momenta that are, respectively, higher and lower than these values. We compare the momenta of the fast outflows with those that can be supplied by radiation pressure, taking into account the expected short acceleration times and some effects that can increase the momentum transfer. We find that in about 80% of PPNe, the fast molecular flows have too high momenta to be powered by radiation pressure. In some cases the momentum of the outflow is $\sim$1000 larger than that carried by radiation pressure; such high factors are difficult to explain even under exceptional conditions. Wind interaction is the basic phenomenon in the PN shaping from the former AGB envelopes; we conclude that this interaction systematically takes place along a dominant direction and that this process is not powered by radiation pressure. Due to the lack of theoretical studies, the possible momentum source remains a matter of speculation.

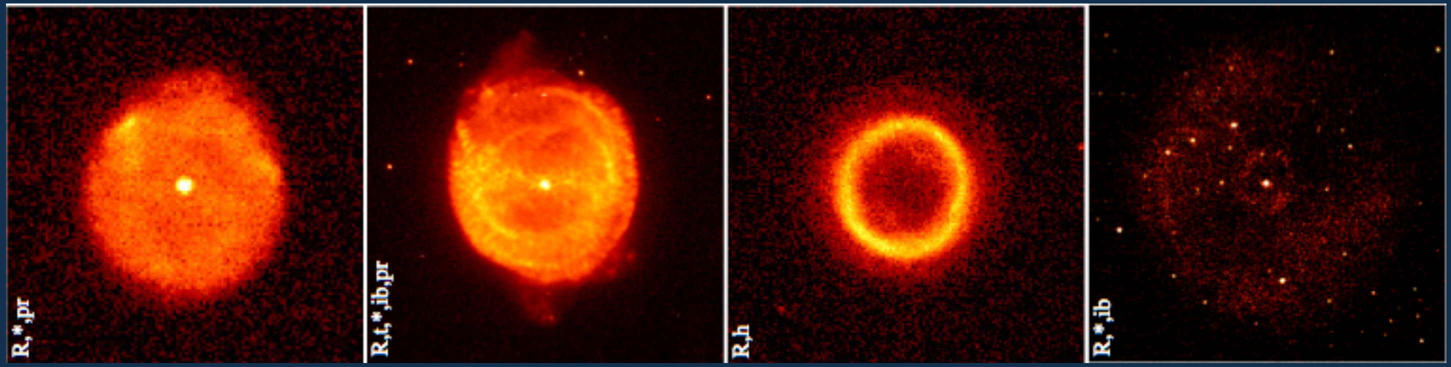
The shapes of PPN and young PN

- Collimated nebulae
- Jet sculpting (Sahai & Trauger 1998, Sahai et al. 2007, 2011)



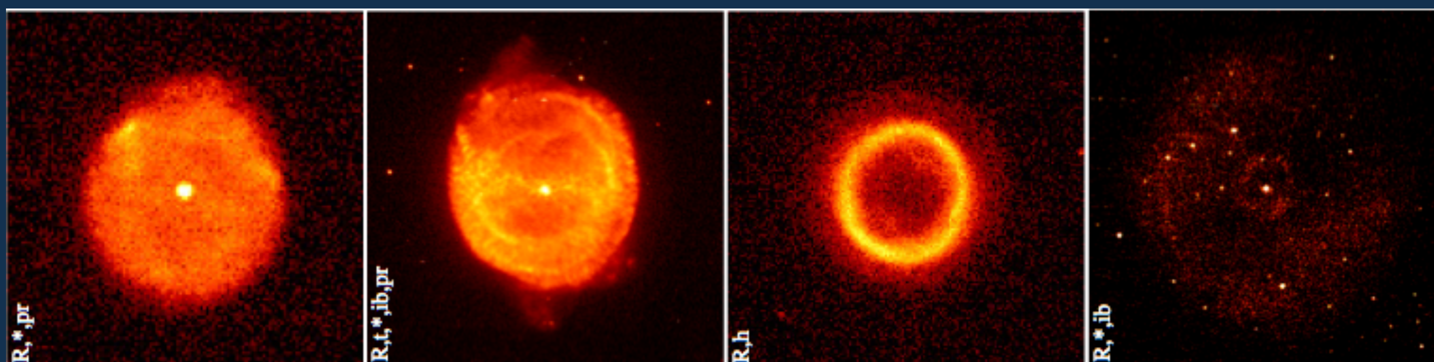
The shapes of PPN and young PN

- No round PPN
- 4 “round” young PN out of ~120 objects



The shapes of PPN and young PN

- But are they spherical or are they pole-on?

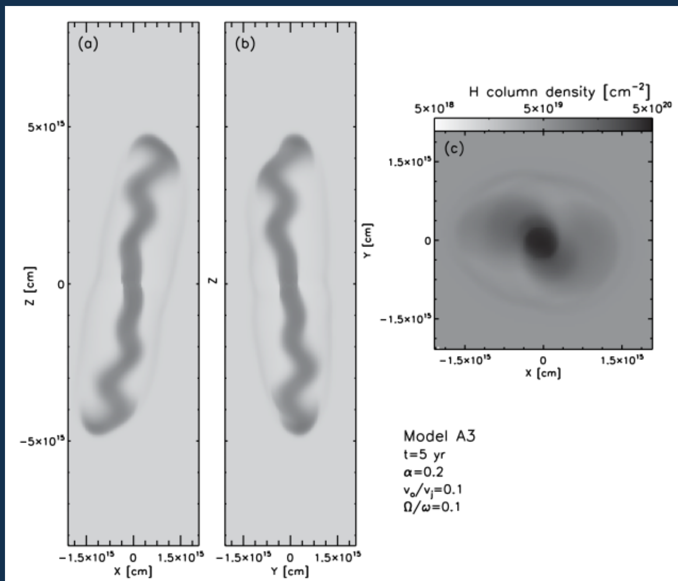


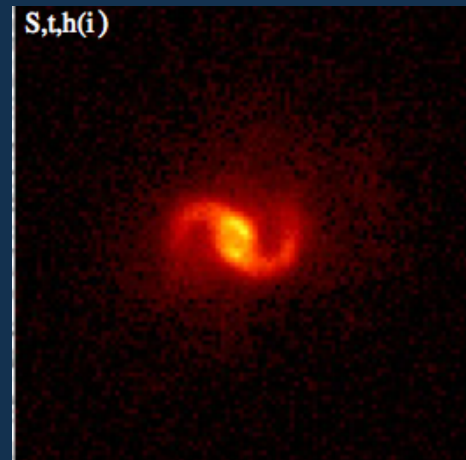
Sp 1: pole-on ring PN

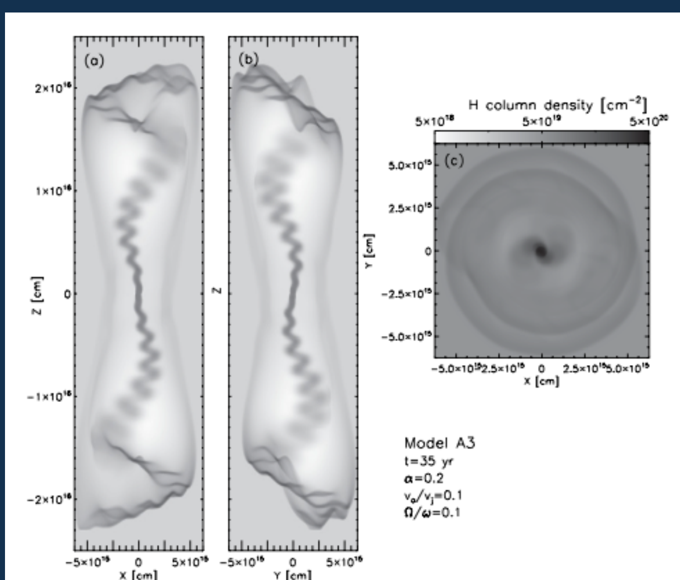
Abell 39: spherical PN

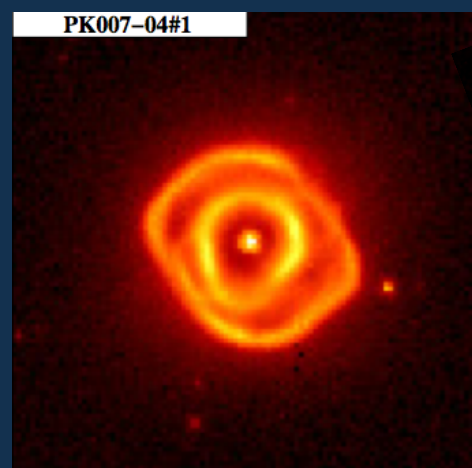
Simulations of jets in PPN

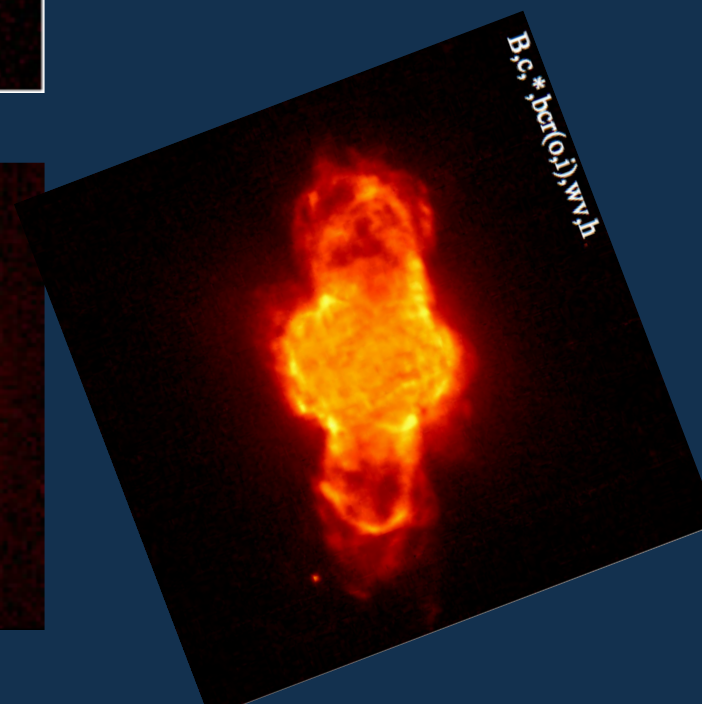
Raga et al. 2009





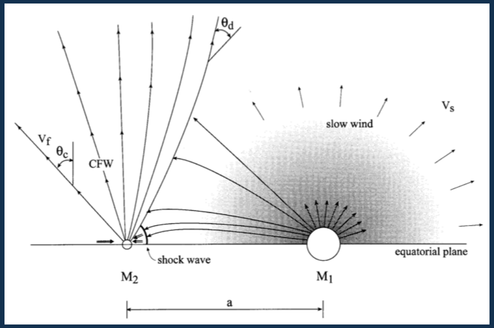




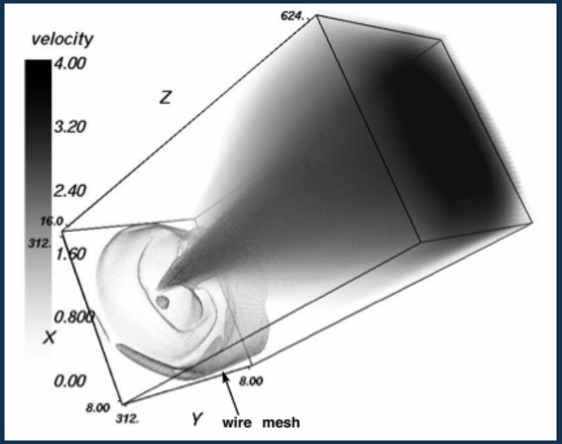


Jet shaping and disk compression

- Soker & Rappaport 2000: jets from accretion disks around the secondary in binaries with a=few-200 AU cause compression disks and bipolar nebulae.

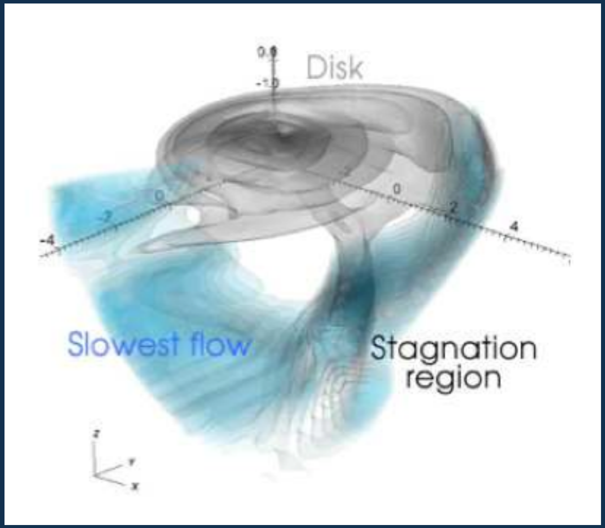
- Garcia-Arredondo & Frank 2004: hydrodynamic models (a=10AU, M1=1.6, M2=0.4) to confirm formation of compression disk and shaping action.



Accretion disk formation

Huarte-Espinosa et al. 2012

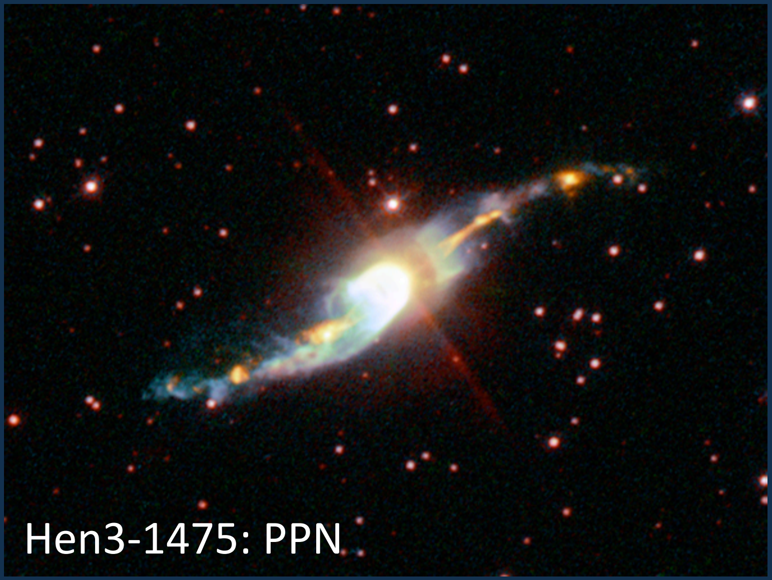
- Model the formation of a disk around a companion that accretes from the AGB wind
- *a* = 10,15, 20 AU
- Accretion rates insufficient for if companion is a MS star, ok for WD at 10AU
- But other accretion modes possible? (Mohamed & Podsiadlowski 2007)



Jet-Lag in PPN

Huggins 2007

- 7 PPN, jet lags disk by ~100 years
- Superwind creates the PPN and accretes onto companion making jet that slightly lags the main PPN?



Hen3-1475: PPN

The "naked" pAGB stars

van Winckel et al. 2009

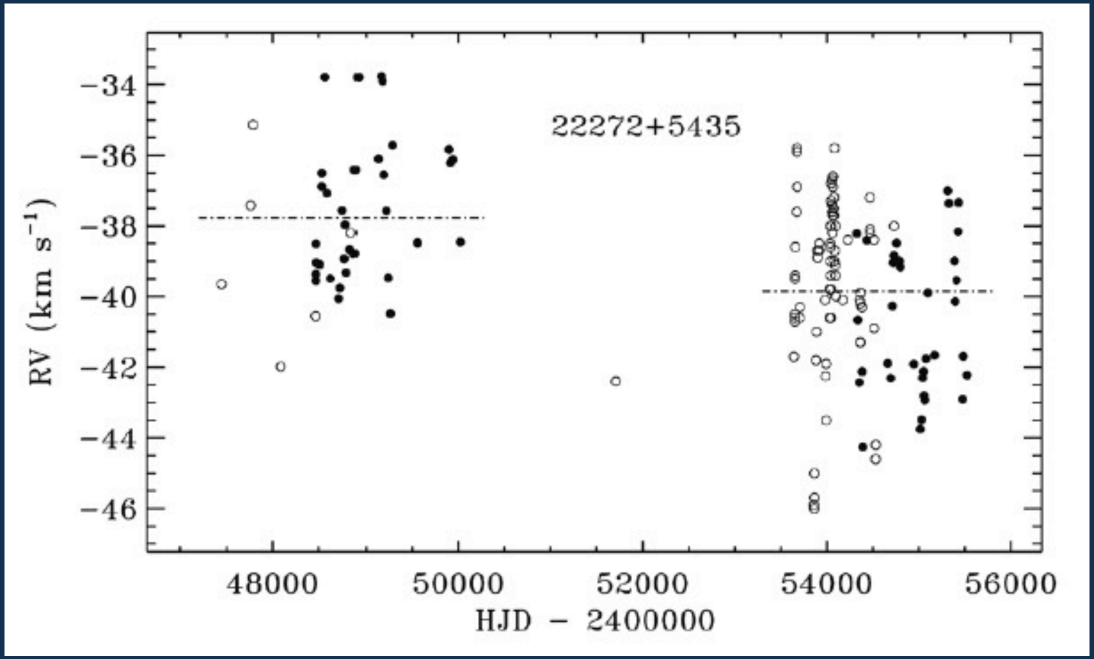
- Binary separations 0.5-3 AU
- Dusty Keplerian disks r~10AU
- No visible nebula (couple of exceptions)
- PPN vanished because star stalled from accretion?
- Origin?

Deroo et al. (2006) IRAS08544-4432 10 um VLTI

So, are CSPPN all binaries?

Hrivnak et al. 2010,2011

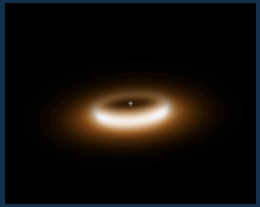
- 7 CSPPN studied
- One has a 22 yr period
- Light variability hard to detect or not expected for such wide binaries
- RV variability hard to detect
- If ALL PPN are wide binaries (P>20 years, a>10AU and/or M2<0.25Mo) we would not easily know



A combined hypothesis for the pAGBs

(Bright et al. 2013)

- Orbital separation main driver of the difference
- Naked pAGBs: closer binaries, failed CE, re-accretion, stalled evolution, fading of the PPN



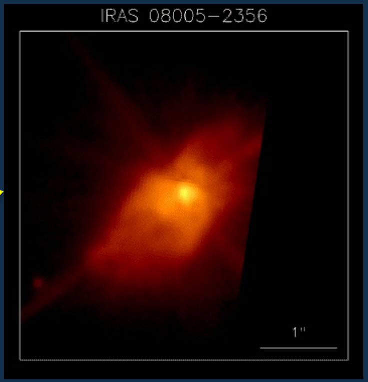
- pAGBs with PPN: wider binaries, no re-accretion, PPN + PN phase.

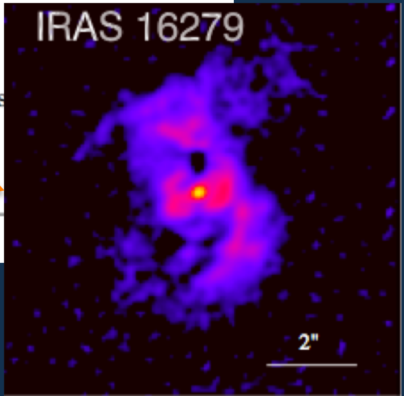
A combined hypothesis for the pAGBs: a test (Bright et al. 2013)

- Compact, fatter, Keplerian disks in naked pAGBs
- Large, flat, expanding disks in PPN

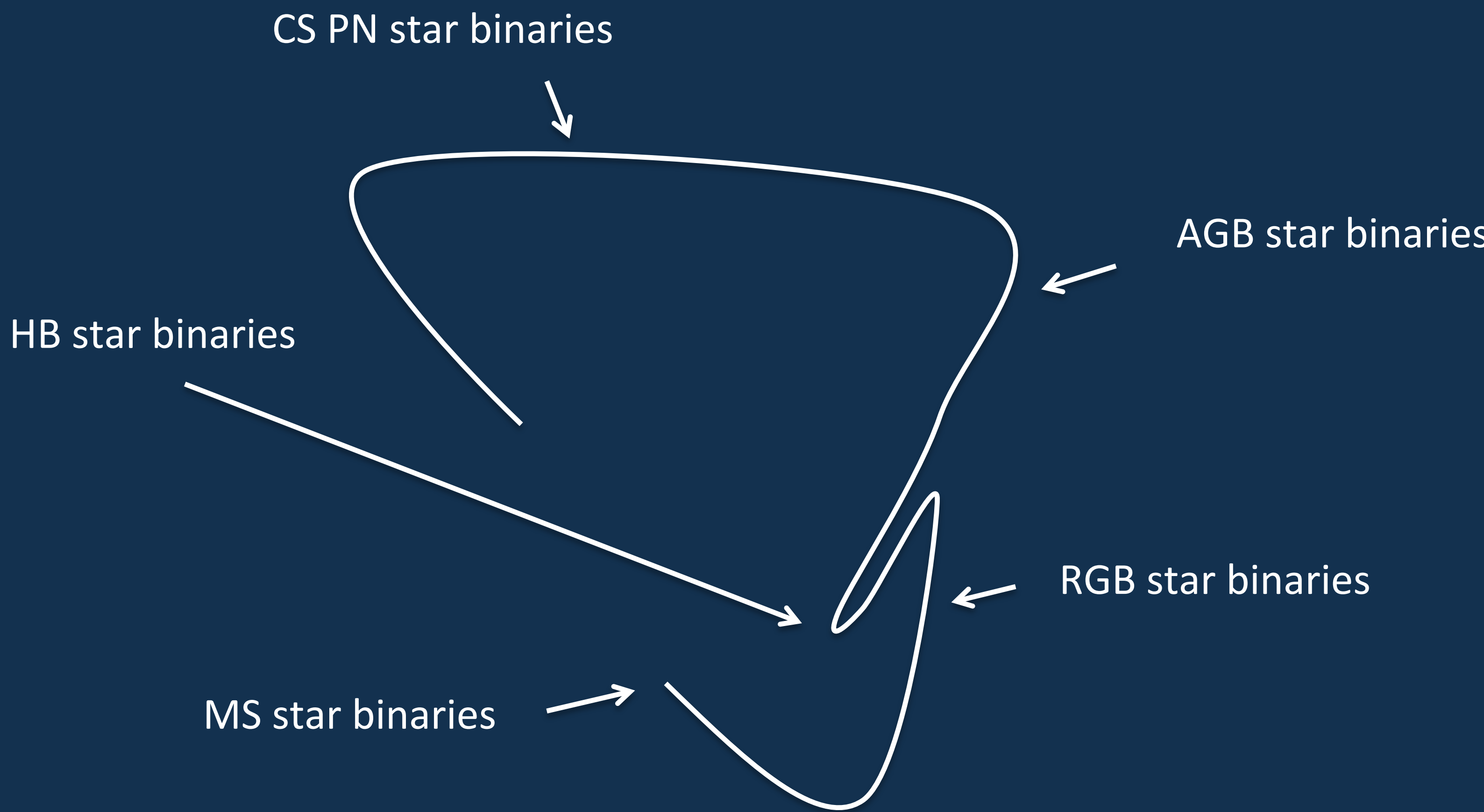
TABLE 6.12: pre-PNe Targets; Results

Star	Fringes Tracked?	Disk?	Inner Radius (AU)	Mass ($M_\odot$)	Chemistry	Other Characteristics
IRAS 05341+0852	slight	?	<329 ± 94	-	-	-
IRAS 07134+1005	no	?	<400	-	-	-
IRAS 07430+1115	slight	?	<329 ± 94	-	-	-
IRAS 08005-2356	yes	yes	5	1.5×10^{-5}	silicate	
IRAS 16279-4757	yes	yes	60	2.0×10^{-3}	carbon	flared,
IRAS16333-4807	no	yes	-	-	-	dis
IRAS 17150-3224	slight	?	140 or <753check this!	-	-	
IRAS 17347-3139	slight	yes	62	-	-	



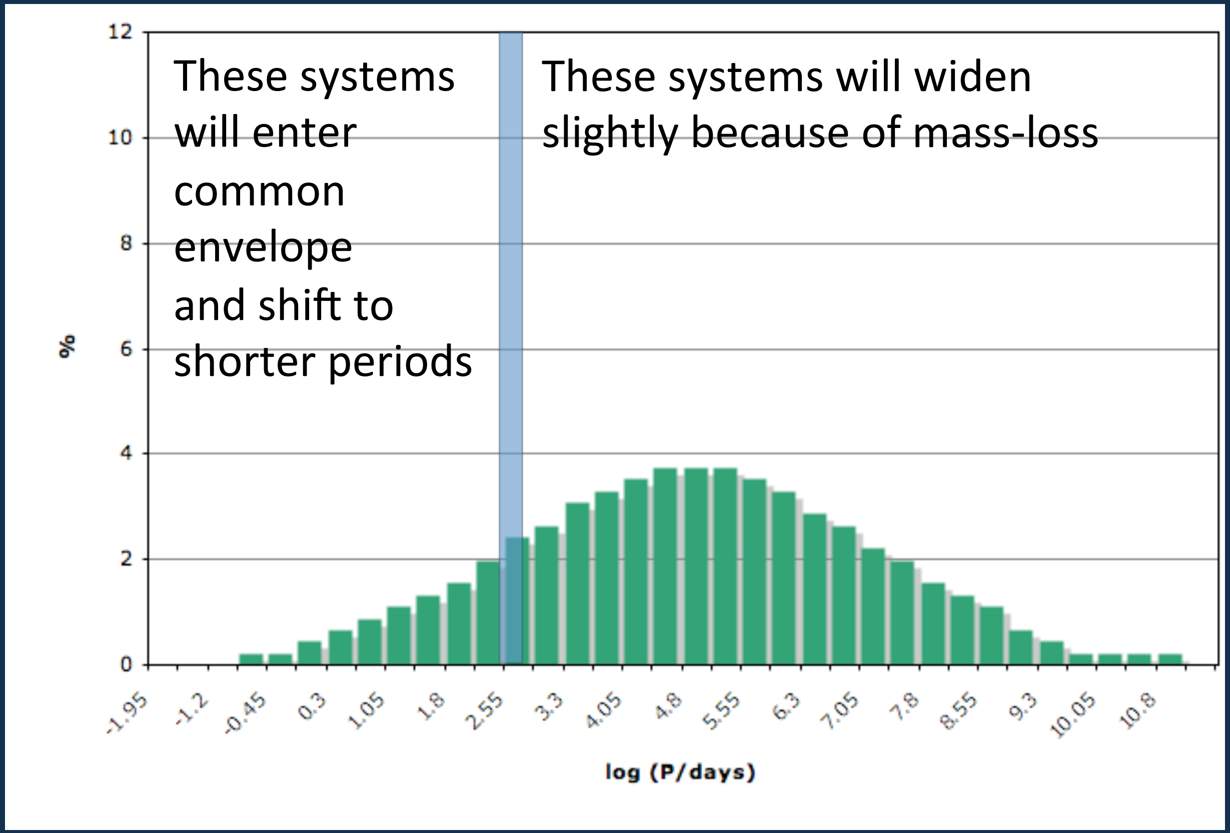


Part #3: How does the binary component of the MS population evolve from the MS to the WD?



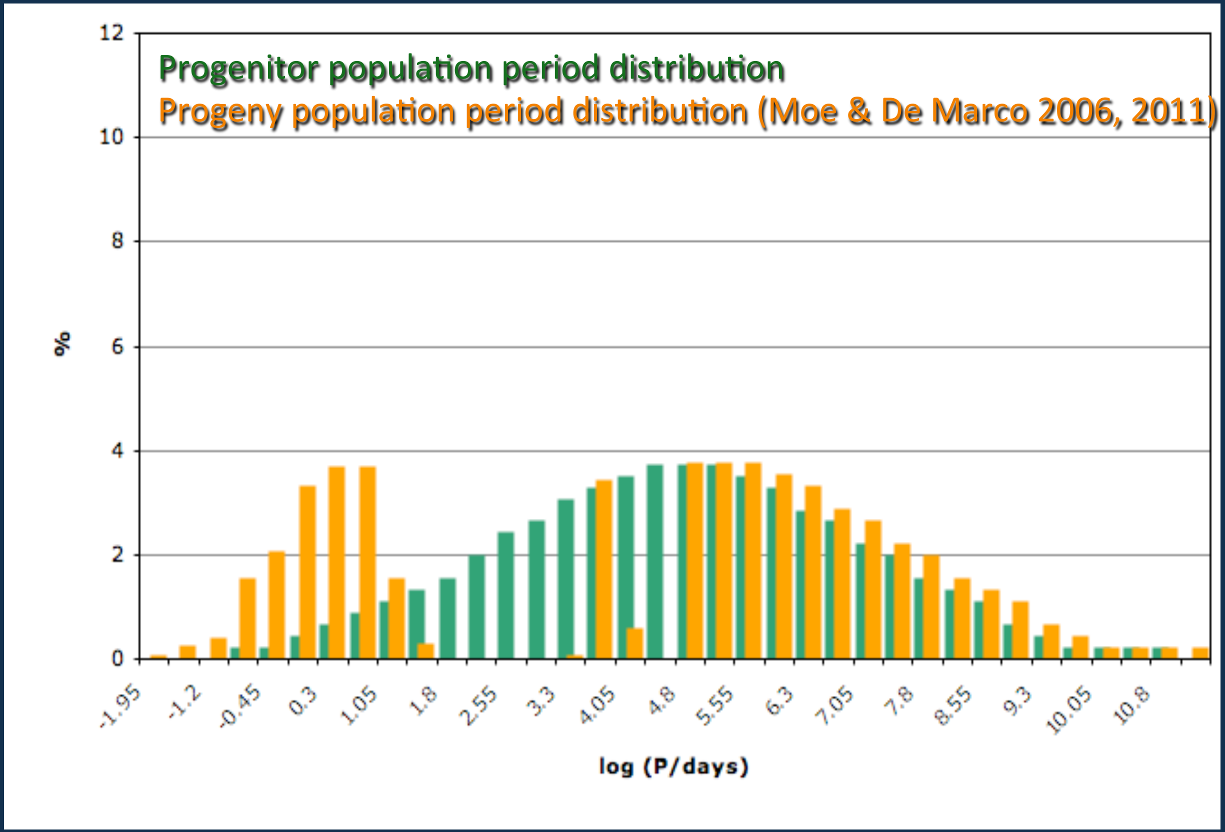
F-K star main sequence period distribution

(Duquennoy & Mayor 1991; Raghavan et al. 2010)

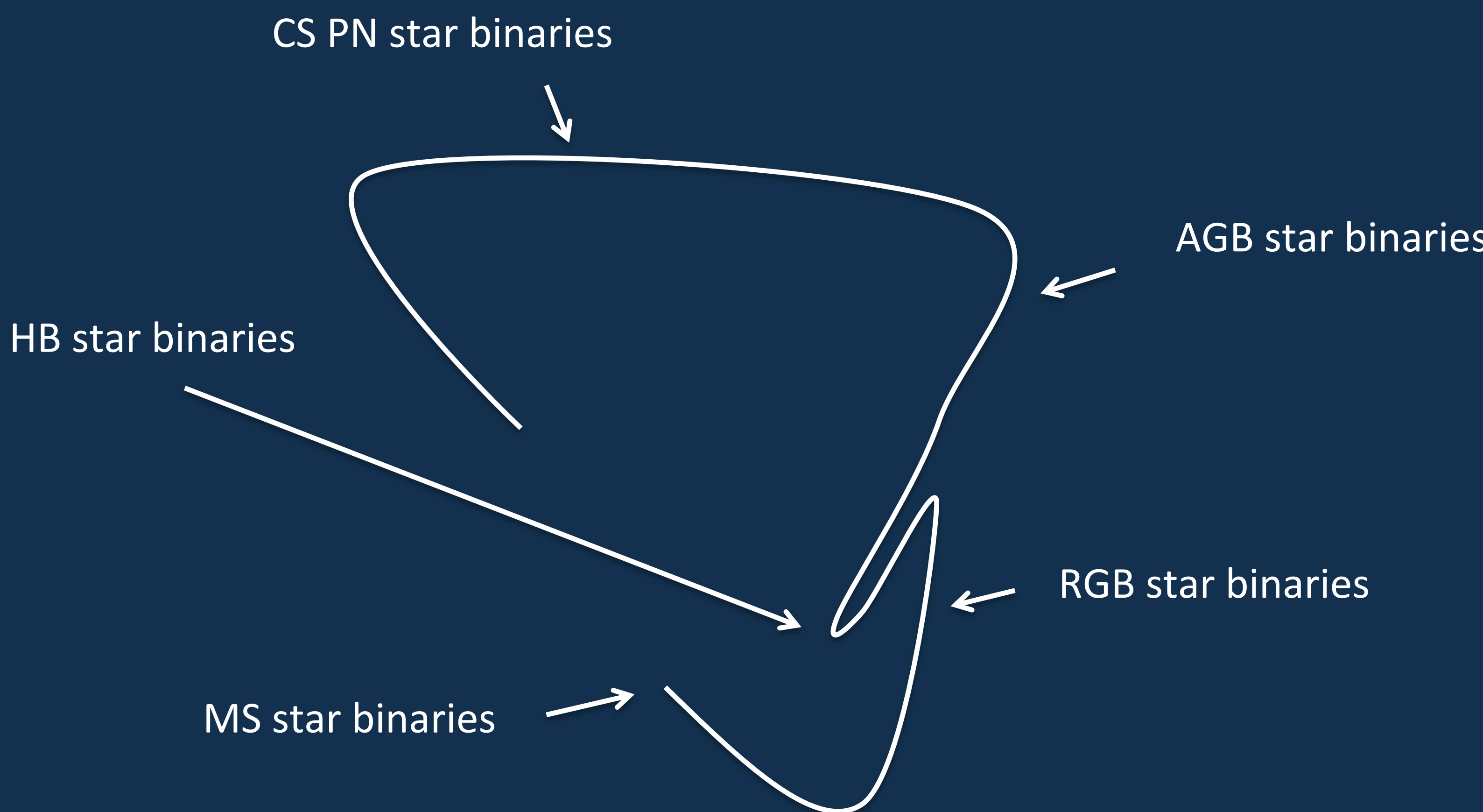


Binary fraction: ~50%

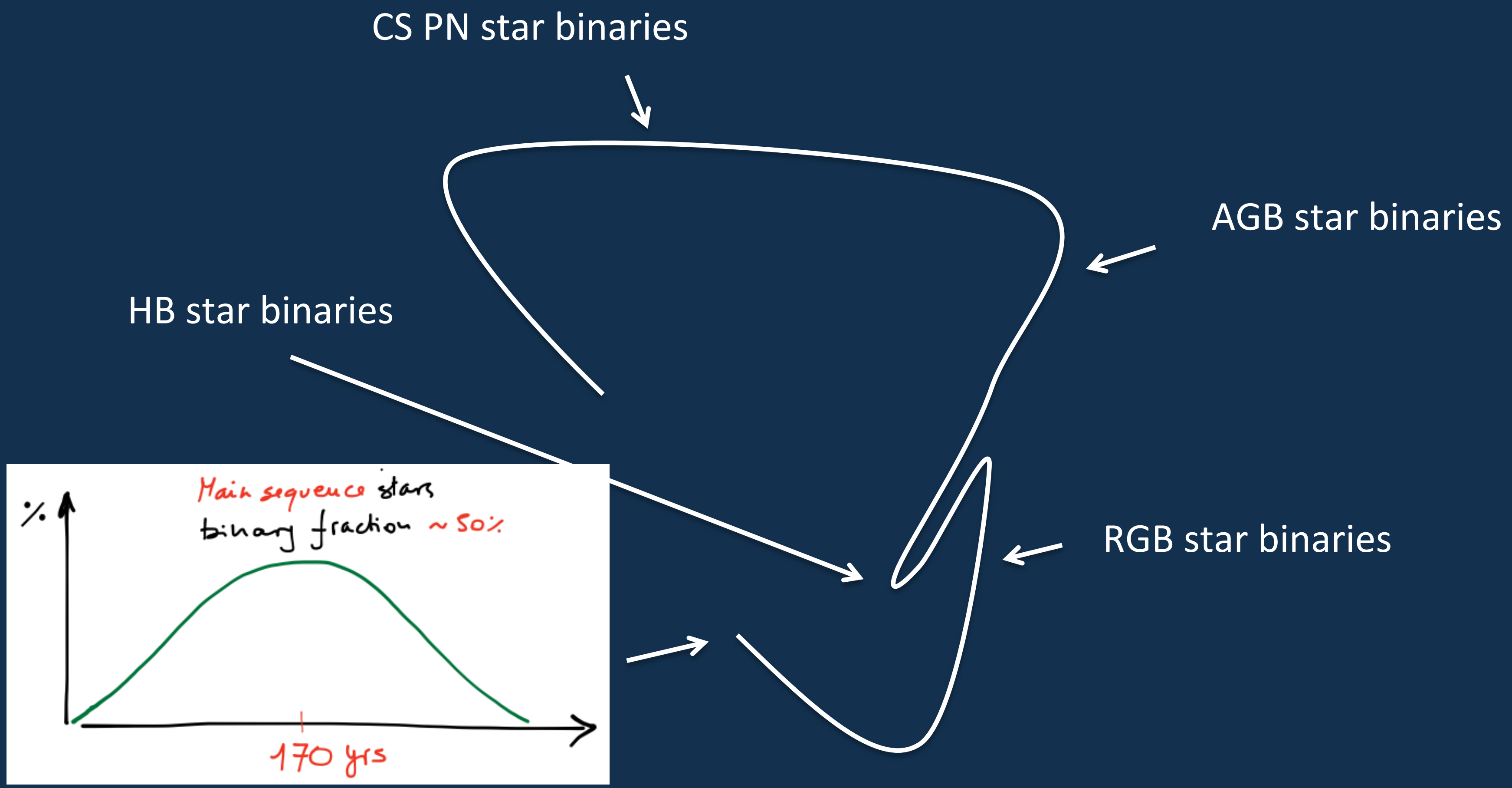
“Evolved” star period distribution



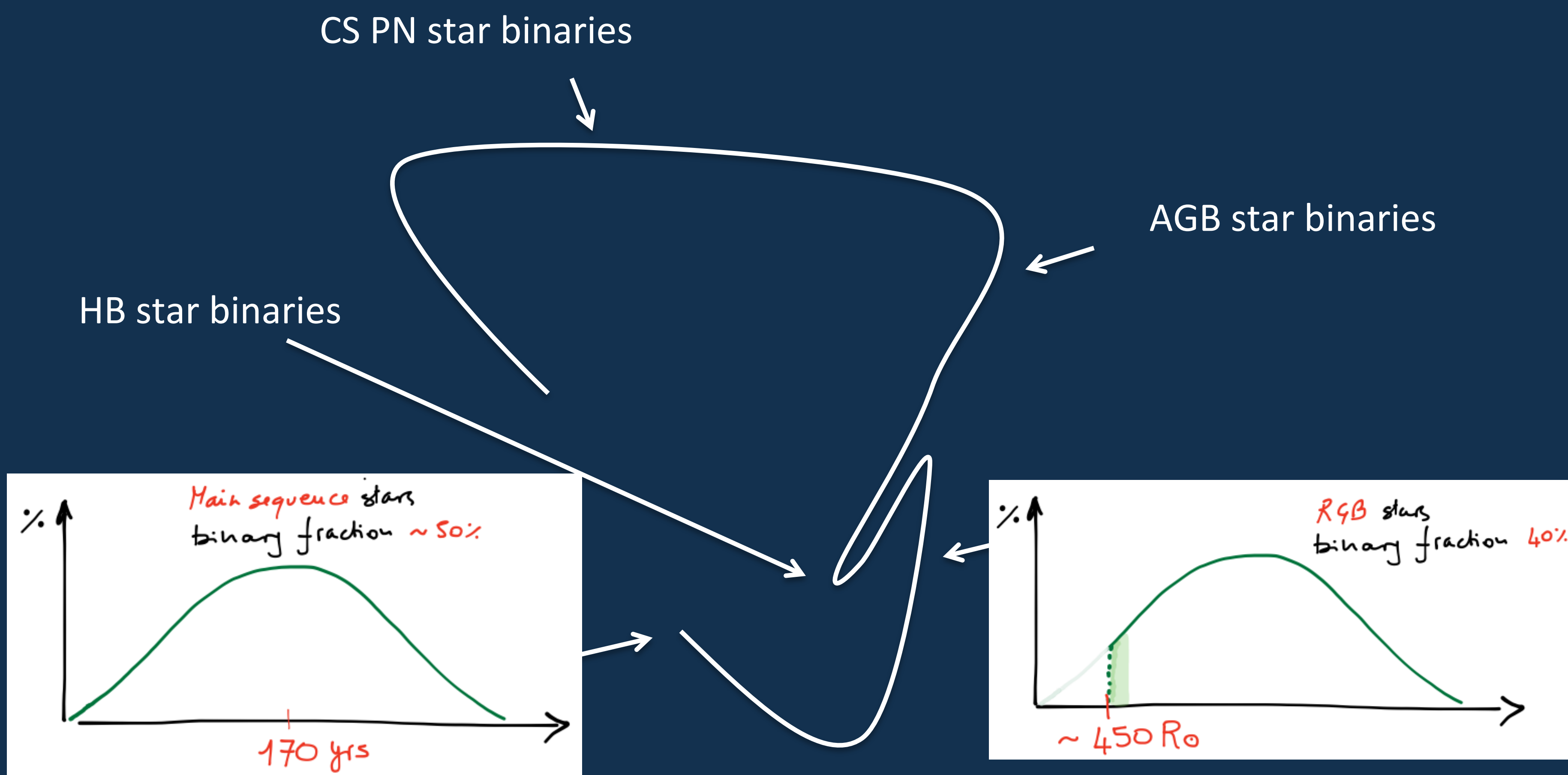
The evolution of the binary fraction and period distribution



The evolution of the binary fraction and period distribution

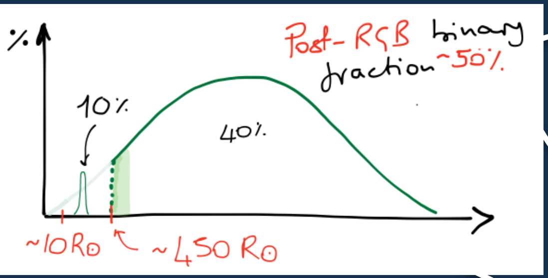


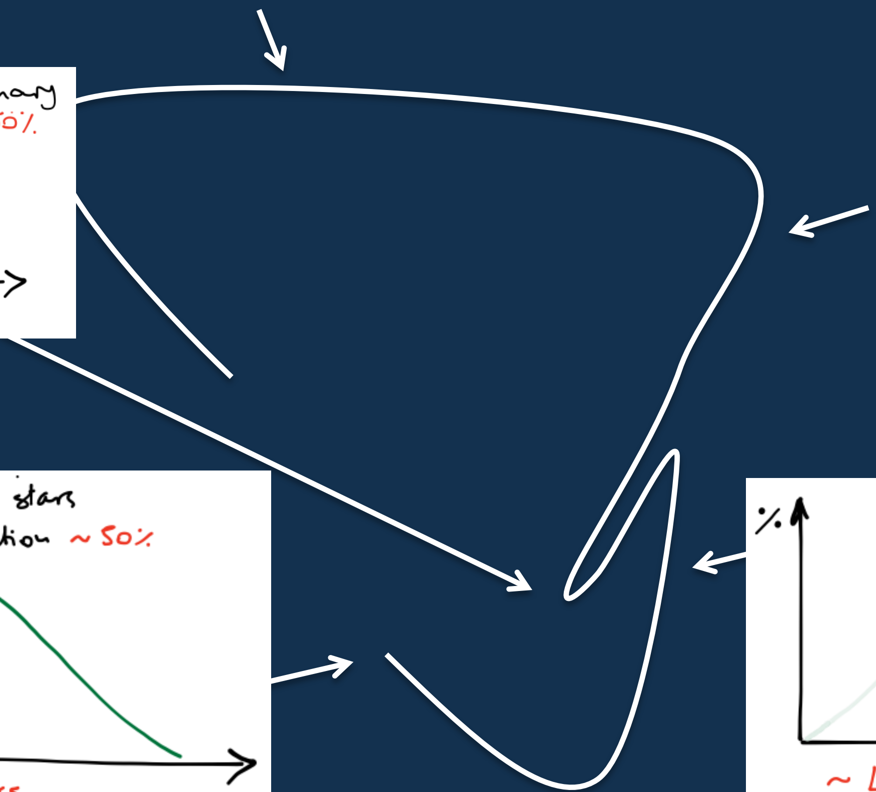
The evolution of the binary fraction and period distribution



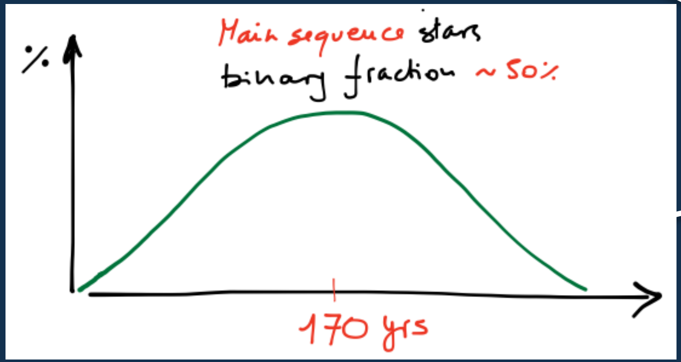
The evolution of the binary fraction and period distribution

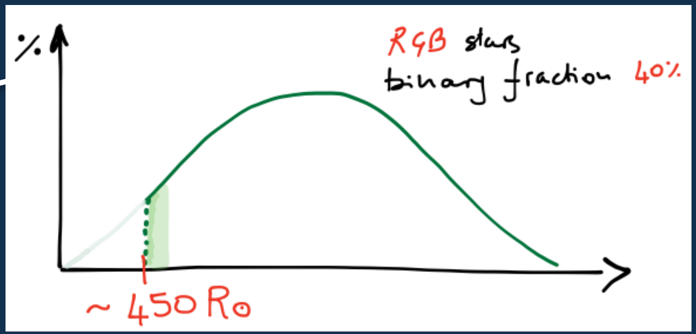
CS PN star binaries



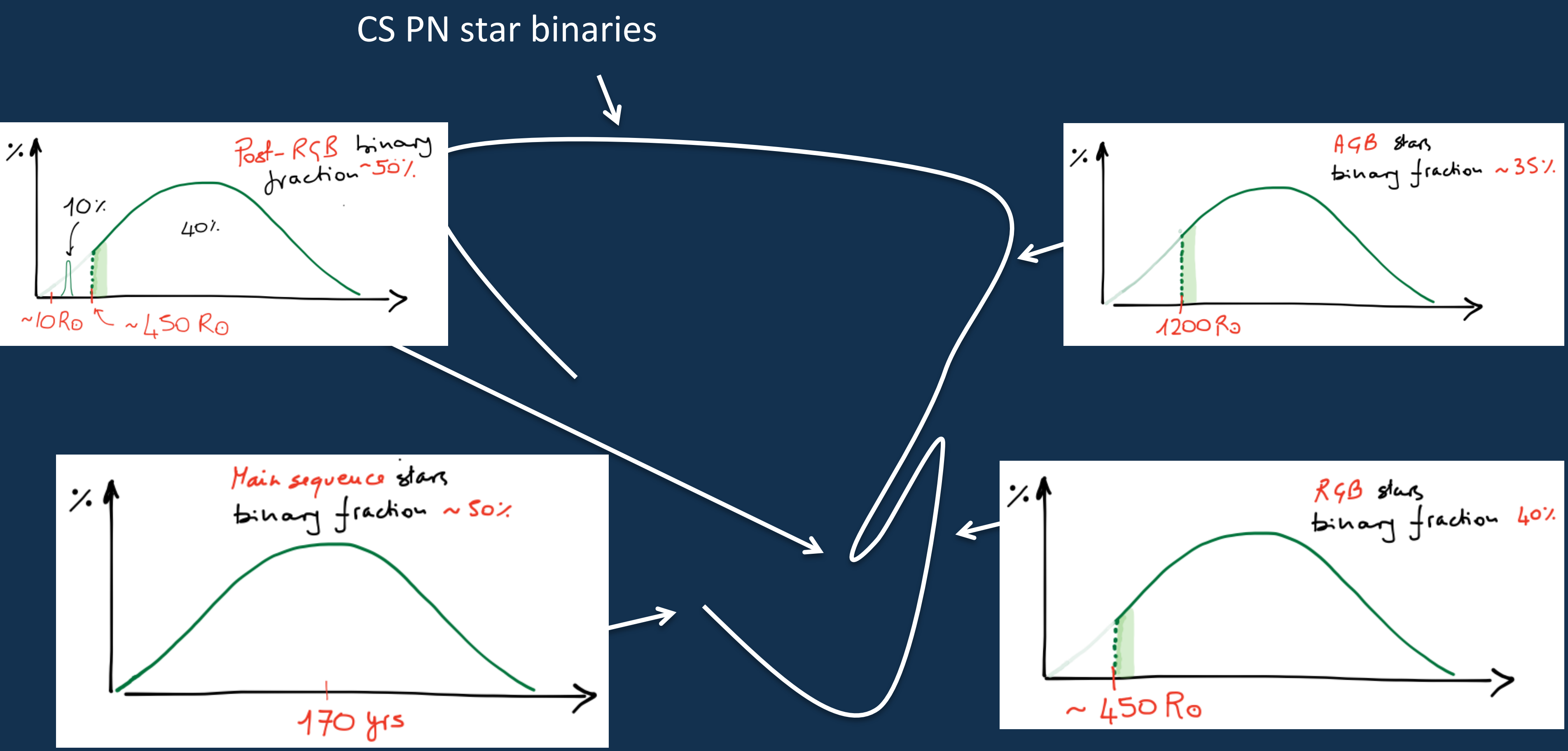


AGB star binaries

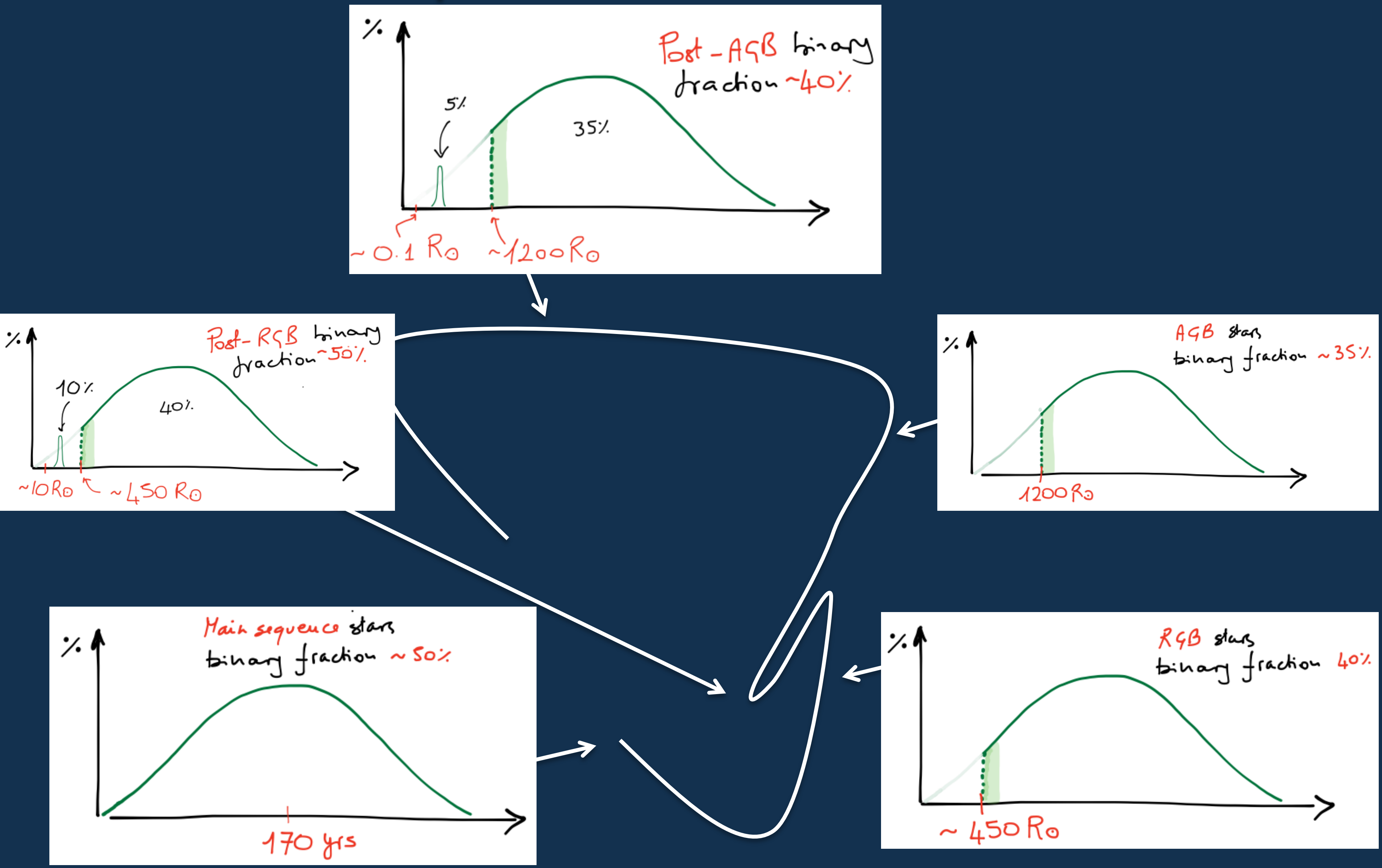




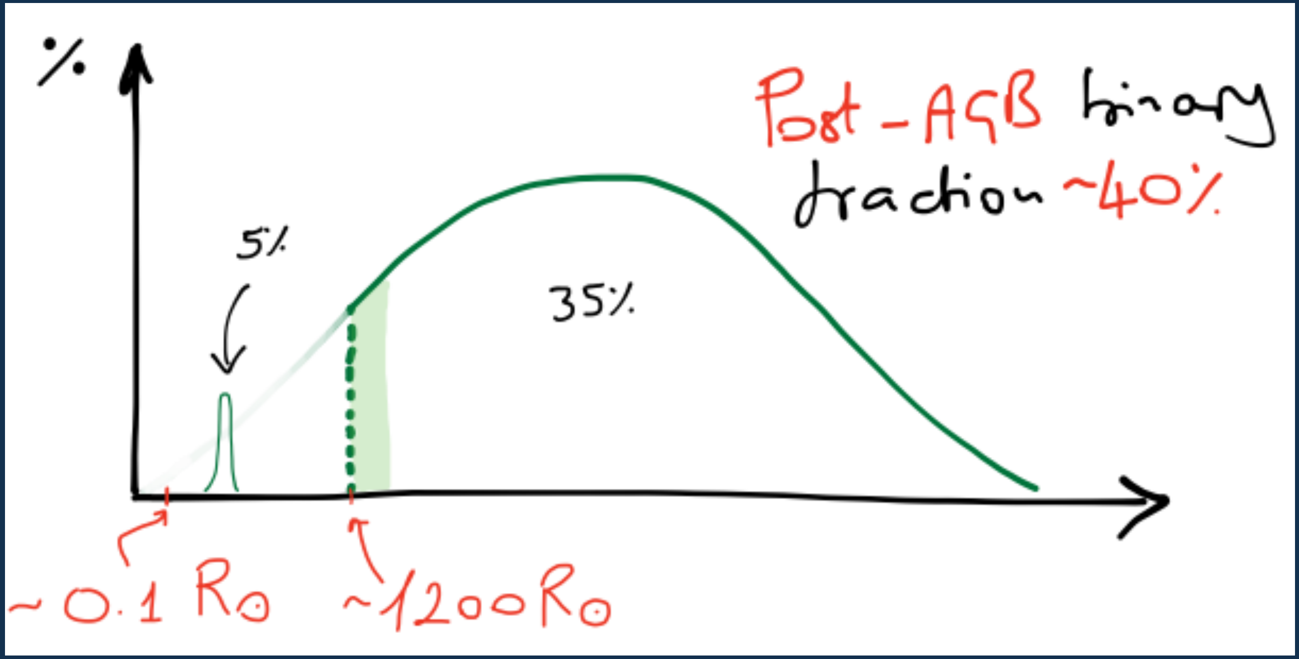
The evolution of the binary fraction and period distribution



The evolution of the binary fraction and period distribution



Comparison with the observations: the short period CS binary fraction

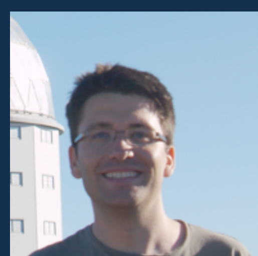


Expectation ~5%

Comparison with the observations: the short period CS binary fraction

Observation >~15-20%

(Bond 2000; Miszalski et al. 2009)



Prediction ~5%

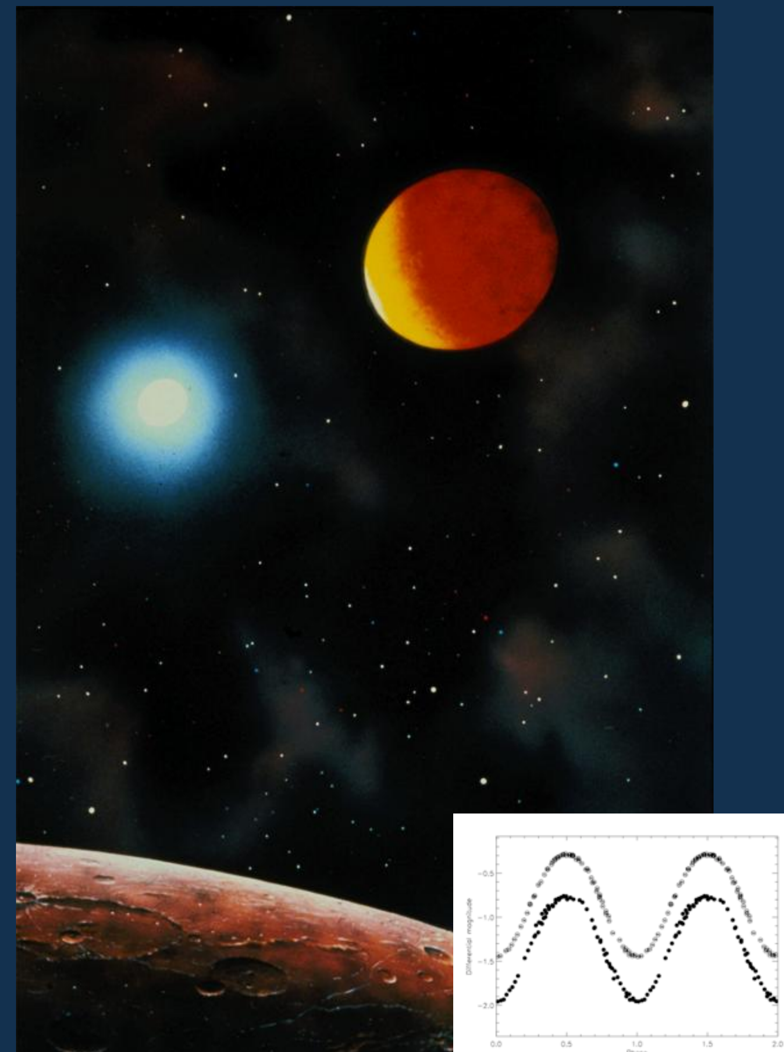
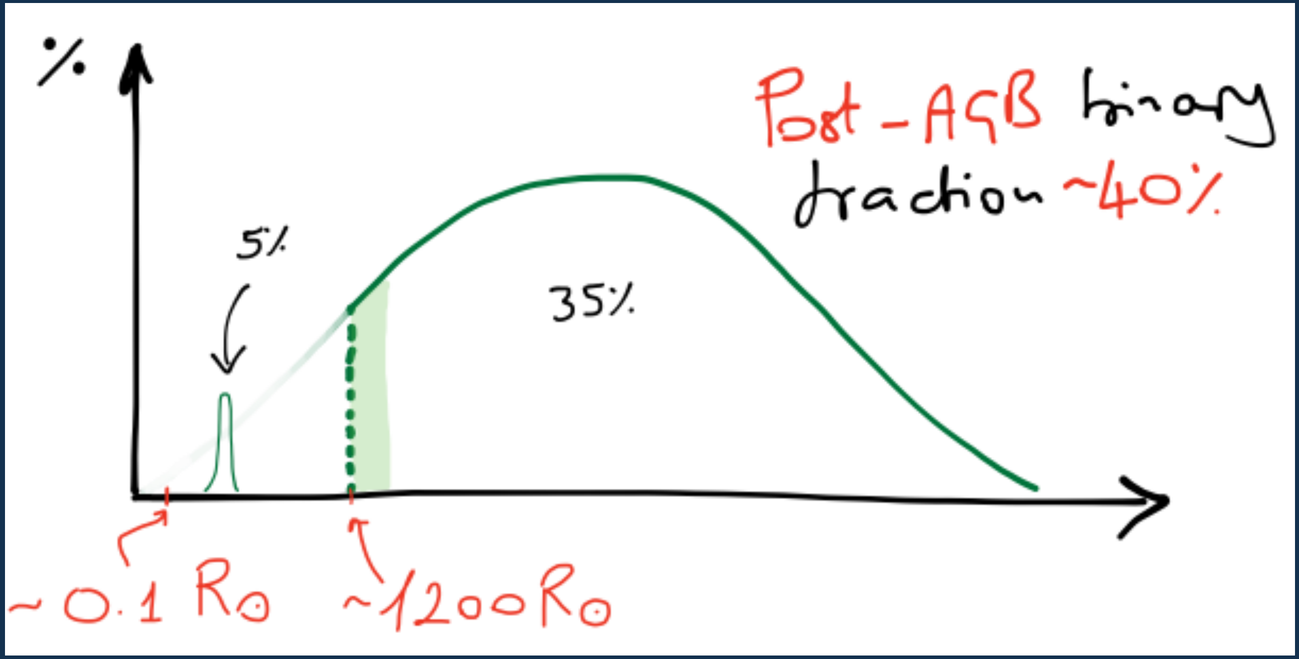


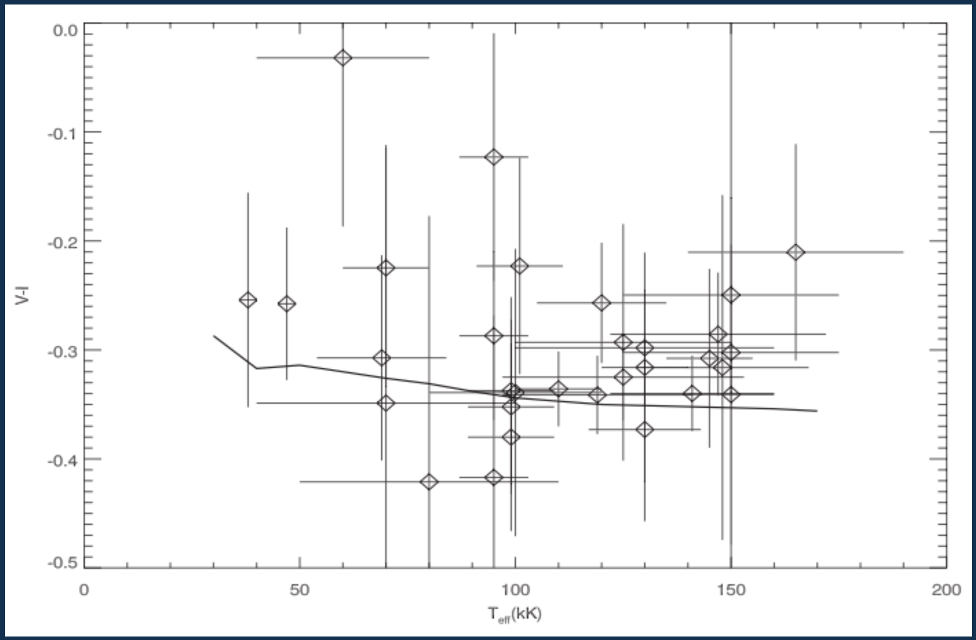
Figure 7. The *I*-band (filled symbols) and *V*-band (unfilled symbols) light curves for V664 Cas, plotted in differential magnitudes such that the system is brightest at $\Phi = 0.5$.

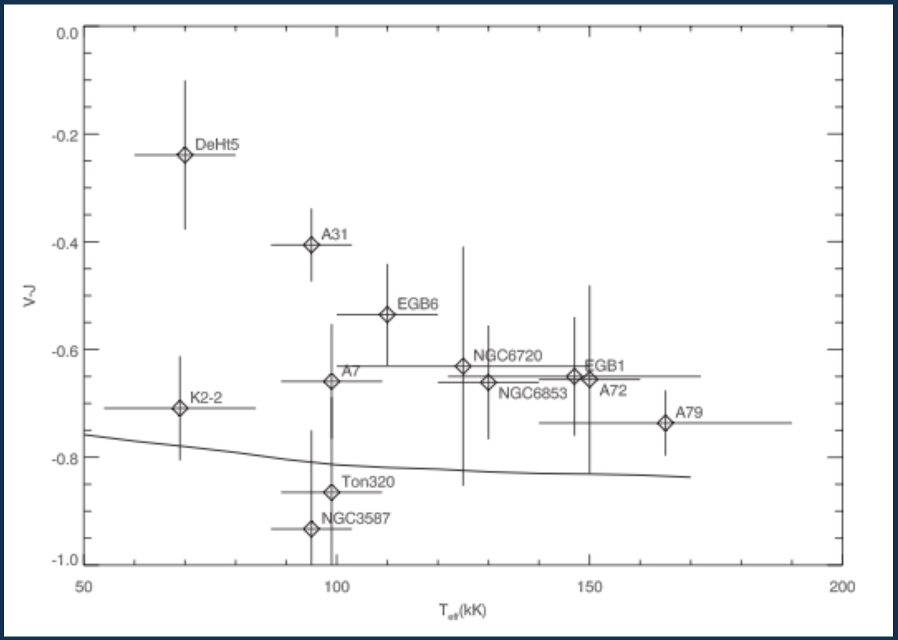
Comparison with the observations: the overall CS binary fraction



Expectation ~40%

Comparison with the observations: the overall CS binary fraction

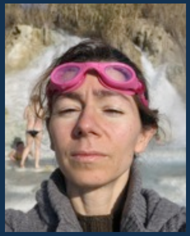




27 objects
~70-80% binary fraction (debiased)

11 objects
~100% binary fraction (debiased)

Prediction ~40%
Statistics are been improved upon



De Marco et al. 2013

PN and galaxies

- If PN represent the evolved byproduct of *all* 1-8 Mo stars:
- Chemical (e.g., C) yields from PN can be converted to galactic yields.
- If PN represent a subgroup then the yields will not be representative of the entire population.

Summary: a revised, testable framework

1. Single stars form round or mildly elliptical PN, or may not form a PN at all, which would explain how 50% MS binary fraction grows in CSPN sample

2. A PPN denotes the presence of jets. This type of jets require intermediate separation binaries (a=10-20AU). Circumbinary disks should be flat and expanding.

3. Closer separations (5-10 AU) cause re-accretion of material which leads to “naked” pAGB phase (+ Keplerian circumbinary disk) after the PPN phase. No PN arises

4. Closer separations still (<5AU) lead to a capture and a CE leading to a post-CE PN (no PPN phase). Bipolar PN sometimes with jets

The to-do list: tests

1. CSPN binary fraction and period distribution
2. Binary detection in PPNe. Disk characterisation.
3. Masses and momenta in jets and tori not only in PPN but in post-CE PN and PN in general (optical and Radio kinematics)
4. Models (semi-analytical and hydro) tailored to individual systems

Thank you!