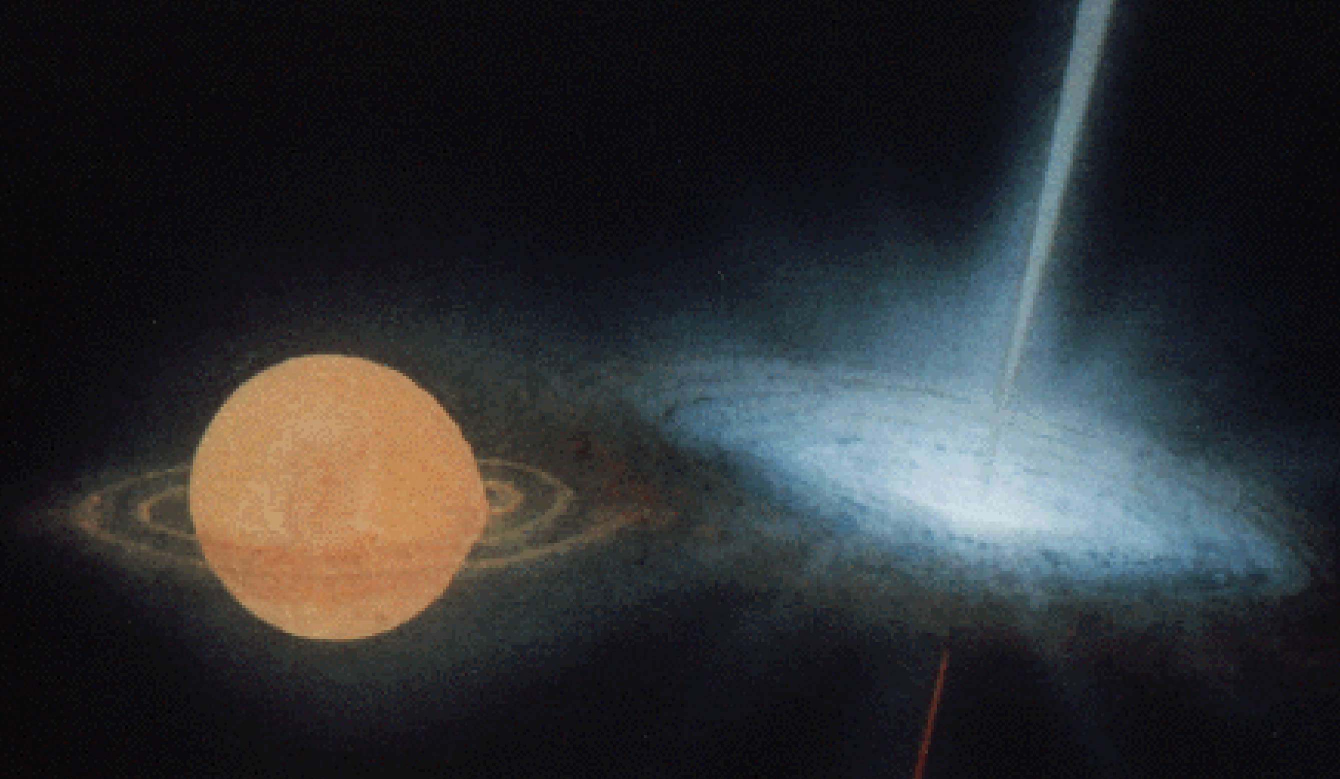
Making Wolf-Rayet X-ray Binaries and double black holes through stable Roche-lobe overflow (without Common Envelope Evolution)



Ed van den Heuvel, KITP Massive Star Program, 14 March 2017

(with: S.Portegies Zwart and S. De Mink,

(ArXiv: 1701.02355v1)

Presented earlier at MIAPP NS Program,Garching Aug. 2015

Overview:

- The OLD problem of the "missing Wolf-Rayet X-ray Binaries", as evolution products of HMXBs with O,B donor stars / Cyg X-3
- SS433: not all HMXBs later in life go into CE-evolution: some spiral-in by stable Roche-lobe overflow and survive
- Condition for O,B-HMXB for avoiding CE evolution and suvive as WR X-ray binary: : accretor MUSTBE a BLACK HOLE
- WR X-ray binaries CAN ONLY CONTAIN BLACK HOLES
- Their later evolution products can be: close double BH binaries (*Belczynski et al. 2013; Maccarone et al. 2014, Esposito et al. 2015*)

EVOLUTION OF MASSIVE CLOSE BINARIES

Nautsnie Informatsie 27,70T, 1973

A.Tutukov, L.Yungelson.

Summary

The evolution of a massive close binary is discussed, starting from main sequence up to the formation of two relativistic objects and disruption of the system. The following general scheme of evolution is outlined: two main-sequence stars (S + S stage) — mass exchange — Wolf-Rayet star or blue supergiant plus main sequence star (WR + S stage) — explosion of WR star, appearing as a supernova event — collapsed or neutron star plus main sequence star, which may be observed as "runaway star" (R + R stage) — mass exchange — collapsed or neutron star plus WR star (R + WR stage)

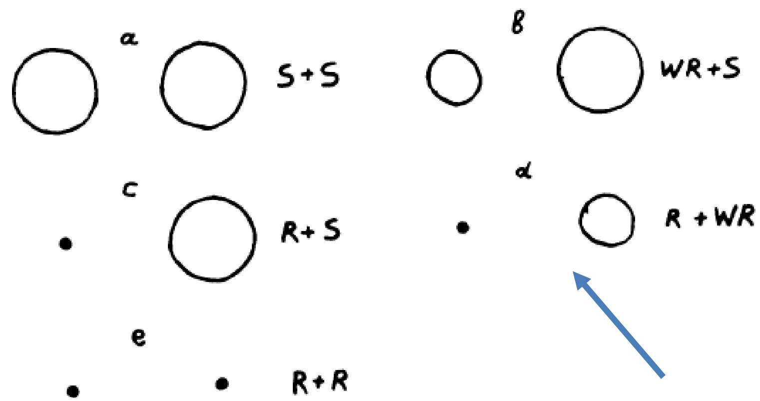
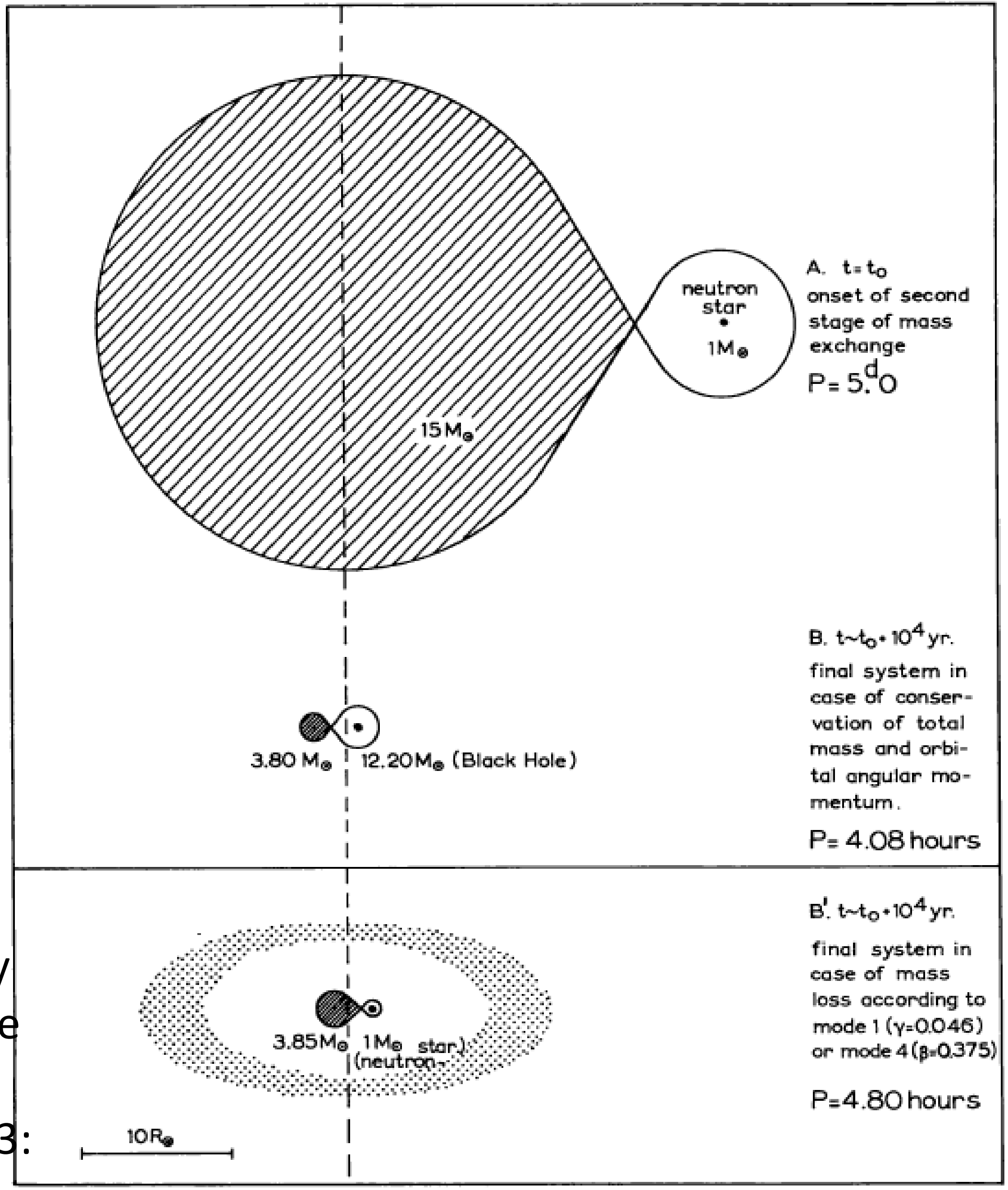


Рис. 1. Последовательность эволюционных стадий тесной двойной звезды большой массы.

E. P. J. van den Heuvel and C. De Loore A&A 1973 Roche-lobe overflow



Suggested:
Cyg X-3 (P = 4.8h) is outcome :
Helium star + compact star

Van Kerkwijk et al. (1992, Nature):
UKIRT IR-spectra:
Companion of Cyg X-3 is WR Star = Helium star
(≥ 8 MΘ for WR star, type WN4/5)

Considered as most likely outcome, due to Shakura& Sunyaev 1973:

The He I lines during outburst suggest WN7

In quiescence: WN4-5, which corresponds to WN mass at least 10 Msun

(Fender et al. 1999 MNRAS 308,473)

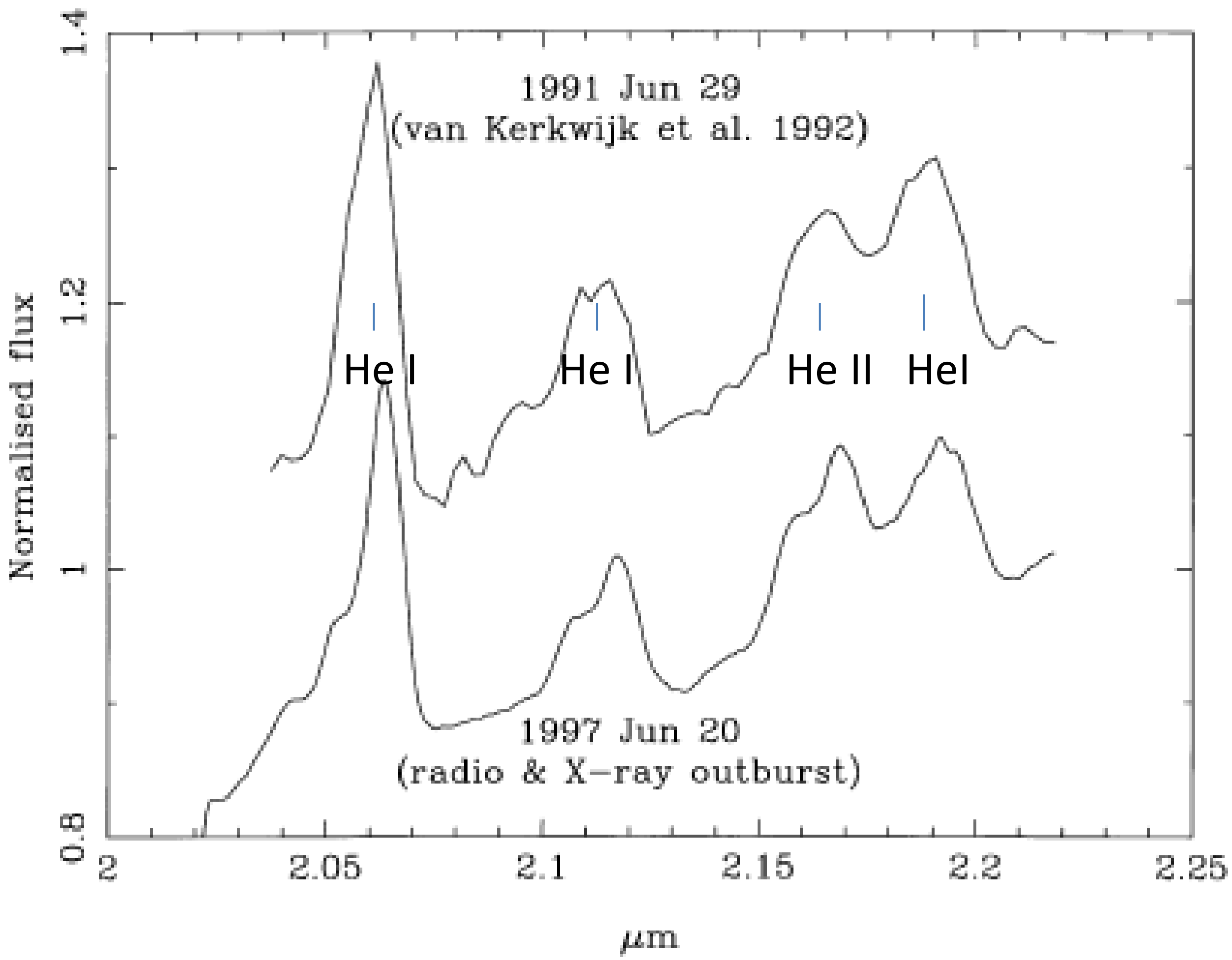


Figure 6. A comparison of the 1991 June 29 spectrum of van Kerkwijk et al. (1992) with our spectrum of 1997 June 20, obtained during a radio and X-ray outburst. The similarity of the two spectra (contrast with the quiescent spectra in Figs 1 and 2) indicates that the initial WN7 classification based upon van Kerkwijk's spectrum was not representative of the underlying spectral type of the companion, but instead a result of enhanced He I emission during outburst.

Cyg X-3, one of the most spectacular X-ray sources in our Galaxy

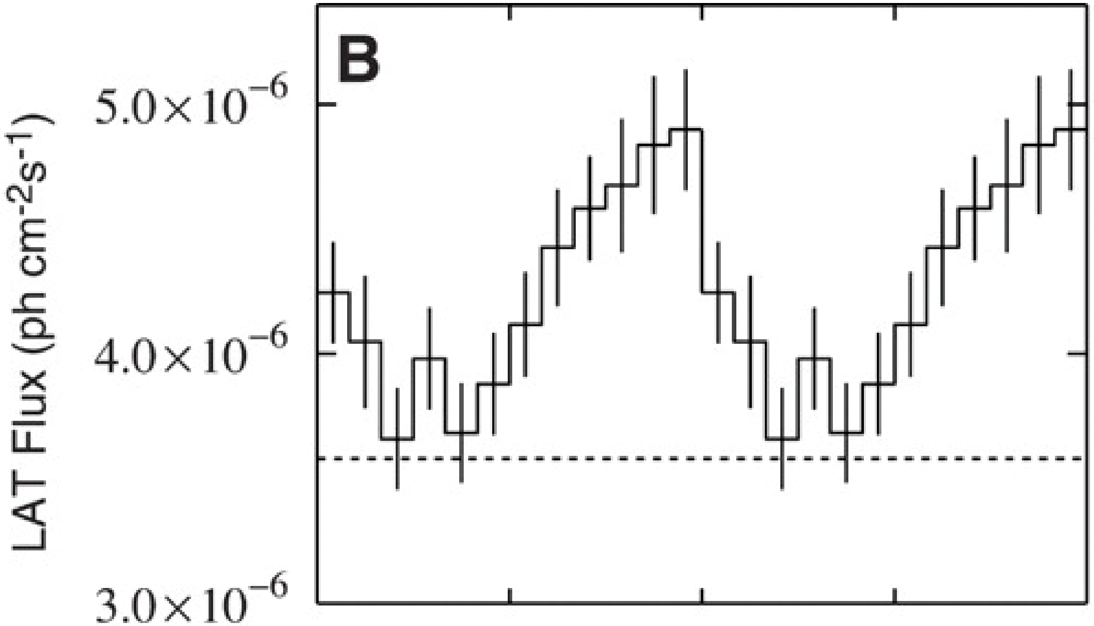
Giant Radio outbursts September 2-11 and 18-25 1972: for a few weeks the brightest radio source in the sky.

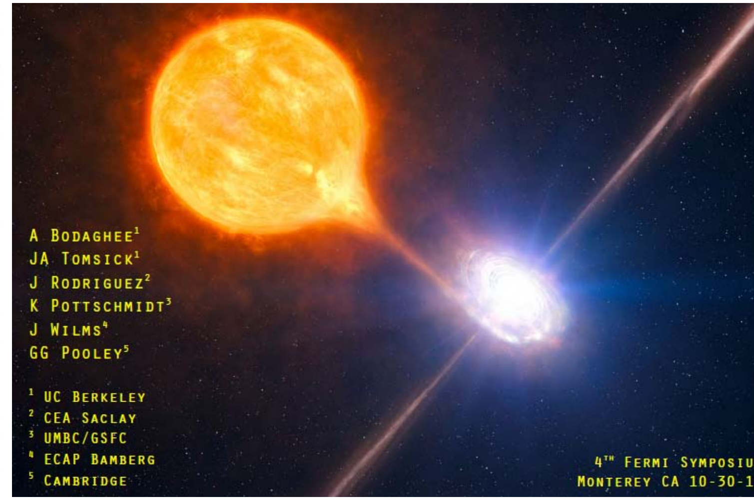
AN ENTIRE VOLUME OF NATURE PHYSICAL SCIENCES (VOL.239, OCTOBER 1972) WAS DEVOTED TO CYG X-3

The radio spectral evolution exactly resembled that of a quasar outburst: expanding bubble of highly relativistic electrons +magnetic fields. (Hjellming and collaborators, 3 Nature papers october 1972)

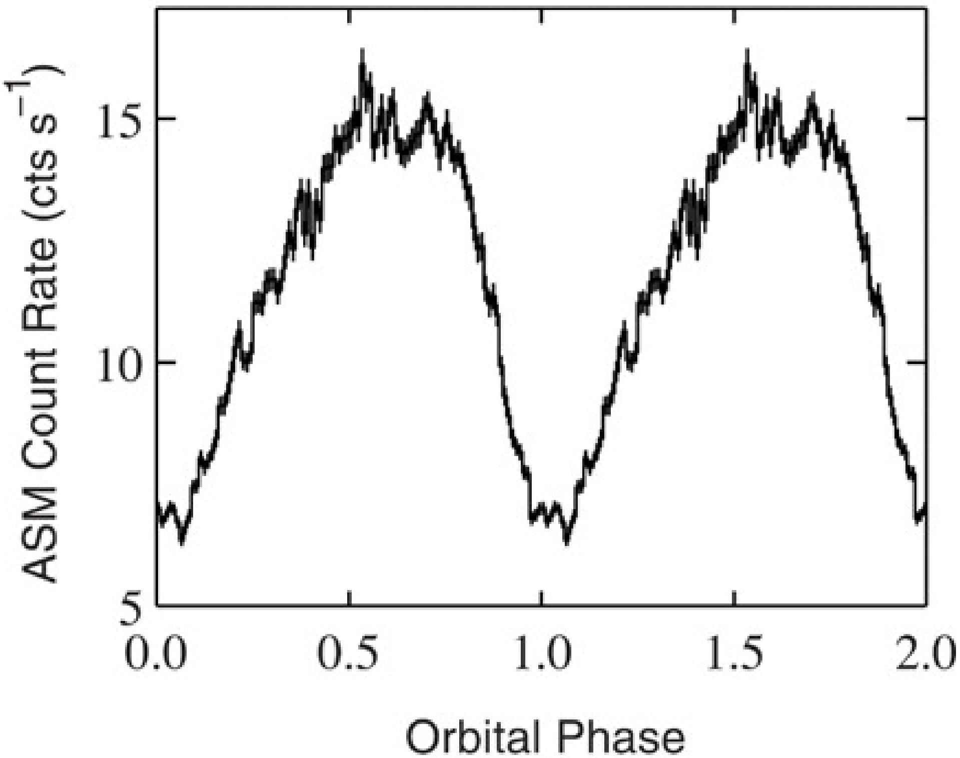
Becklin et al. (Nature Phys.Sc. 239, 130) discovered its huge IR radiation

From HI absorption: behind 3 spiral arms: d ~ 10 kpc in gal. plane





Gamma Rays are due to jets



Cyg X-3 X-ray lightcurve by RXTE; Phase 0.0: Compact star behind WR star;
X-rays scattered around in WR wind.

The Wolf-Rayet X-ray Binaries and M33 X-7

(N.B.: Wolf-Rayet stars are Helium stars)

Name	P(orb)	L_X (ergs/s)	L_{IR} (erg/s)	M_{WR} (Msun)	M_{accr} (Msun)	Reference
Cyg X-3	4.8h	10^{38}	$3x10^{39}$	8-12	?	*Hanson et al.(2000ApJ)*
IC 10 X-1	34.4h	10^{38}		32.7(2.6)	23.1(2.1)?	*Silverman & Filippenko (2008ApJ)*
NGC 300 X-1	32.3h	$1{,}5.10^{38}$		15 (3)	14.5(2.5)?	*Carpano et al.(2007ApJ)*
				(if half opt. continuum from WR)		
NGC 253 CX-	14.5h	~ 10^{38}		?	*?*	*Maccarone e.a.(2014 MN)*
NGC 4490 CX-	6.4 h	~ 10^{38}		?	?	*Esposito et al. (2015 MN)*
Circinus CG X-1	7.2h	~ 10^{38}		?	?	*Esposito et al. (2015 MN)*
M33 X-7 (O7-8III)	3.45d			M_O =70(6.9)	15.65(1.45)	*Orosz et al. (2007Nature)*

All the external galaxies have low metallicity: 0.1 to 0.3 solar

X-ray lightcurve of
CG X-1 is quite similar to
that of Cyg X-3:
Produced by scattering
in dense WR wind.
P= 7.2 hours

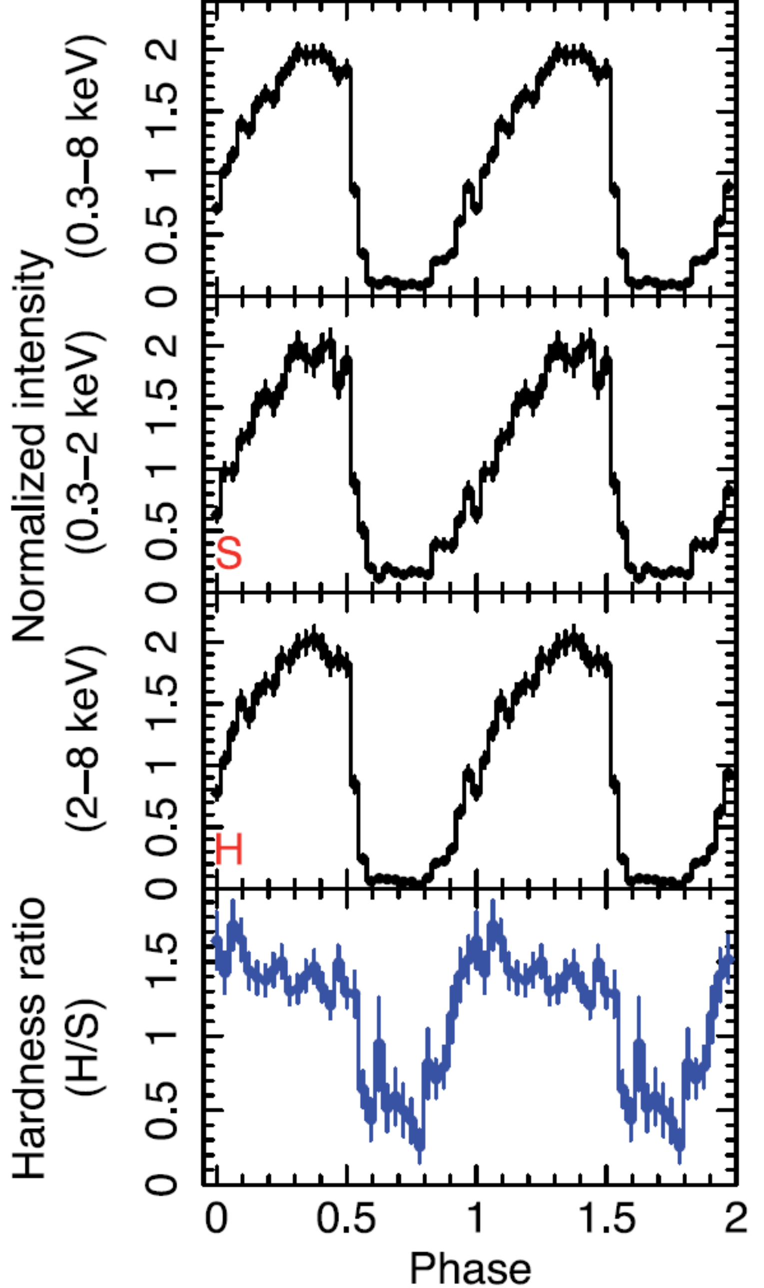


Figure 6. Background-subtracted folded profile of CG X-1 (observation 12823/4) in different energy bands. The hardness ratio between the hard and soft bands is also plotted at the bottom.

The problem of the missing WR stars

- If indeed all HMXBs produce WR X-ray Binaries, one would, since WR stars live ~ 400 000 years, and HMXBs live less than ~100 000 years, expect a large number of WR X-ray Binaries in the Galaxy.

- But: we know only ONE: Cygnus X-3

- Important point: only He-stars more massive than ~ 10 (± 2) M_{sun} show WR spectrum (*Crowther, 2007*, Annual Rev. A&A, masses from spectroscopic binaries).

- Our and Tutukov & Yungelson's original idea: all Helium stars > 3-4 M_{sun} are WR stars: **too simplistic**

Common Envelope evolution

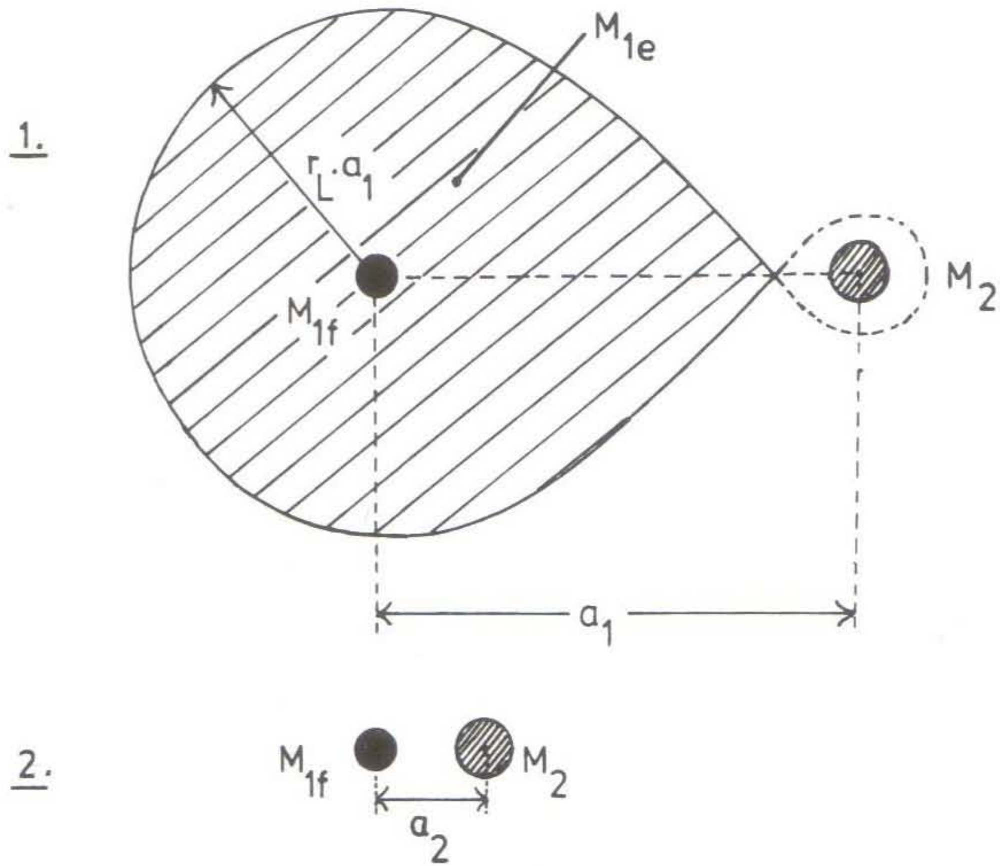


Fig. 69. Outline of the various system parameters at the onset of Common Envelope evolution. After CE evolution the system consists of stars with masses M_2 and M_{1f} with separation a_2 (further description in the text).

Orbital change in CE Evolution (Webbink 1984 formalism; see also Taam 1996, and Taam and Sandquist, 2000, Ann. Rev. A&A):

$$\frac{a_f}{a_i} = \frac{M_{core} M_1}{M_{donor}} \frac{1}{M_1 + 2M_{env}/(\alpha_{CE}.\lambda\, r_L)}$$

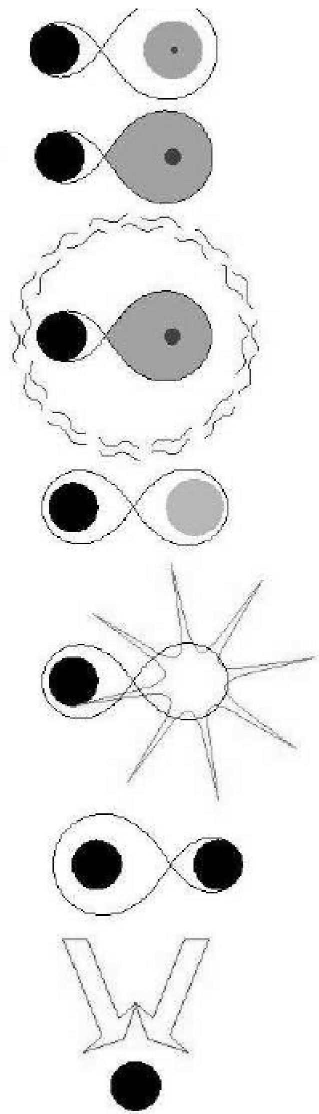
Numerical hydrodynamic calculations of CE by Terman (1994, see Taam ,1996), for donor stars with *convective envelopes*, and dense He-exhausted cores, yields:

$\alpha_{CE}.\lambda \sim$ 0.3 to 0.5; further: $r_L \sim 0.5$.

For example, with $M_{donor} = 20$, $M_{core} = 6$, $M_1 = 1.4$, $\alpha_{CE}.\lambda = 0.5$ one obtains: $a_f / a_i = 1/270$, leading to survival only for $P \geq 2$ years ($a_f > 2{,}5 R_{sun}$).

However, if the core is still He-burning, the density profile of the envelope makes value of ($\alpha_{CE}.\lambda$) much smaller and CE leads to merger.

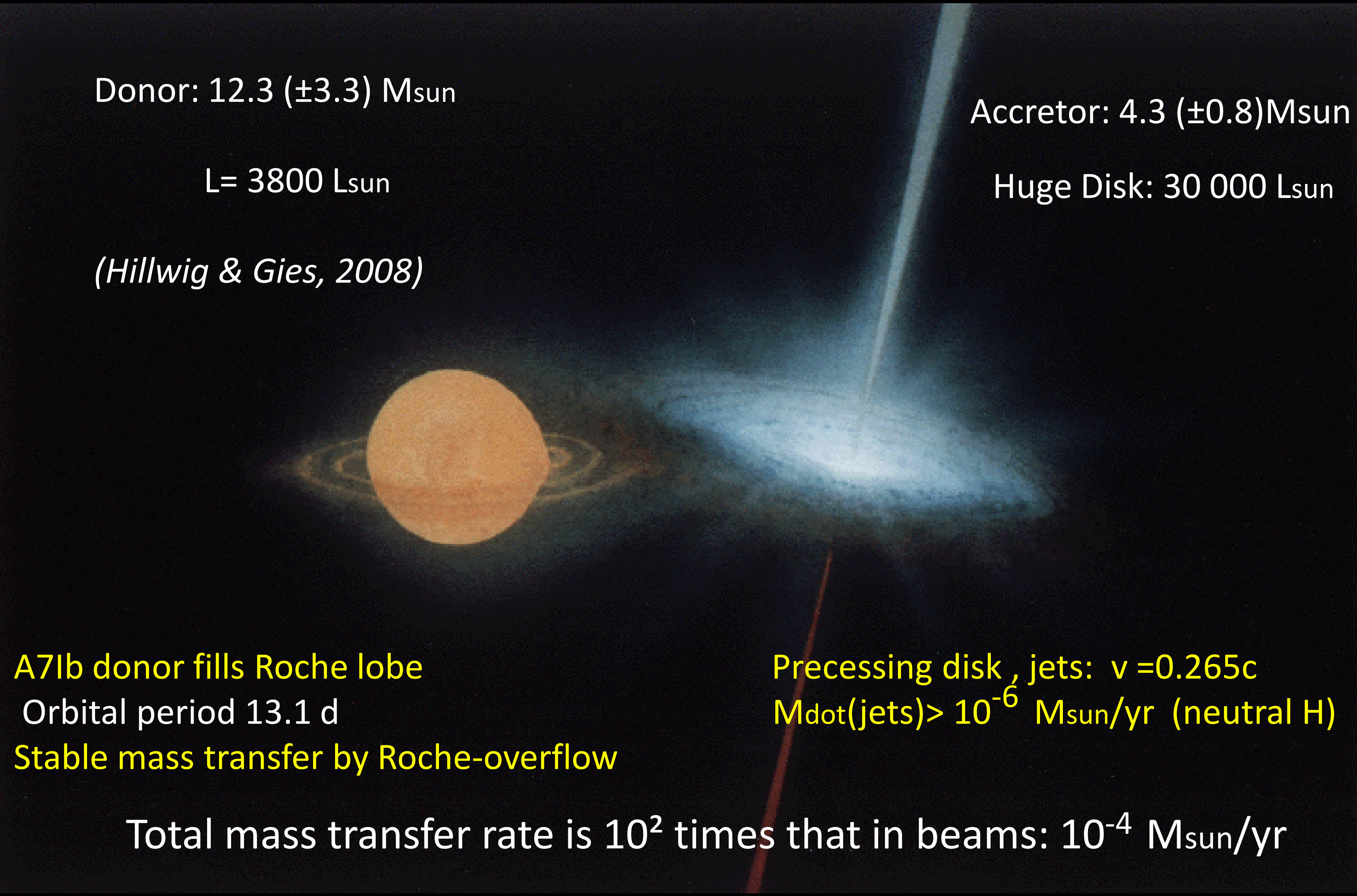
Scenario for making a WR XRB and double BH through CE-Evolution (Bogomazov 2014, Astron.Rep.), using “Scenario Machine” PopSynProgr.



			M2	a(Rsun)	t(Myr)	e	
HMXB	BH+I	20.83	53.09	140	2.7	0.3	
	BH+III	20.83	52.31	140	4.3	0.3	
CE- Evol.	SBH+III	20.83	47.70	110	4.3	0.2	
→	BH+WR	20.83	26.06	4.9	4.3	0	WR-XRB
	SN	20.84	18.24	5.9	4.6	0	
	BH+BH	20.84	9.12	8.5	4.6	0.3	
	BH	29.96			90		

Figure 4: Evolutionary track for NGC 300 X-1. The notation is described in Section 3.

SS 433 (Micro Quasar) tells us: CEE is not the whole story



Donor: 12.3 (±3.3) M_{sun}

L= 3800 L_{sun}

(Hillwig & Gies, 2008)

Accretor: 4.3 (±0.8)M_{sun}

Huge Disk: 30 000 L_{sun}

A7Ib donor fills Roche lobe

Orbital period 13.1 d

Stable mass transfer by Roche-overflow

Precessing disk , jets: v =0.265c

M_{dot}(jets)> 10^{-6} M_{sun}/yr (neutral H)

Total mass transfer rate is 10^2 times that in beams: 10^{-4} M_{sun}/yr

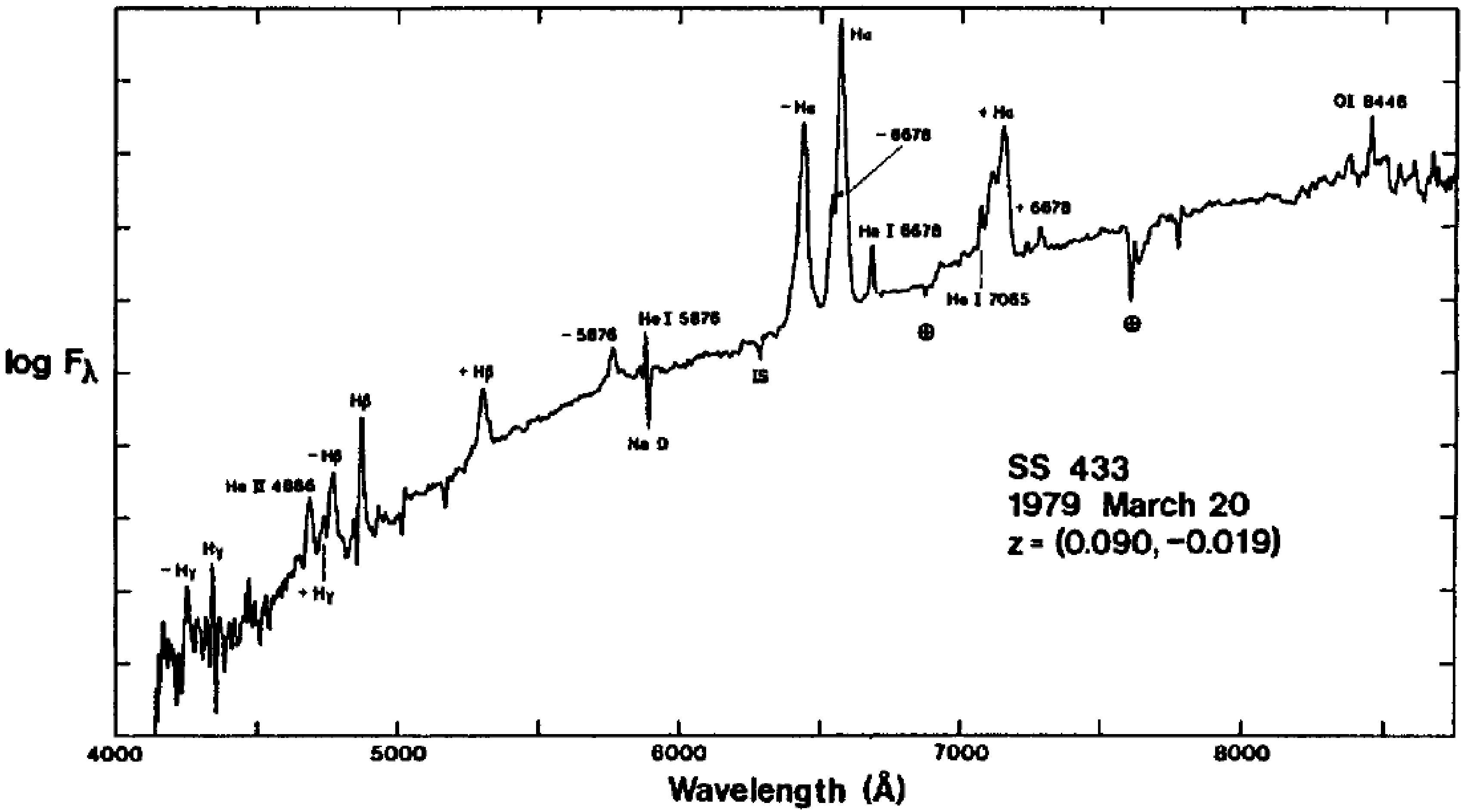


Fig. 32. The spectrum of SS 433 on March 1979, when the pattern of multiple red-and blueshifted emission lines is particularly obvious. Emission lines prefixed with a 'plus' are redshifted features, and the 'minus' prefix denotes blueshifted features. This spectrum was obtained with the Lick 3m Shane reflector. Note the very strong stellar absorptions of Fe II λ 5169 and O I λ 7773, as well as P-Cygni absorption components to Balmer and He I lines in the "stationary" spectral line system. Each division on the ordinate is 0.83 mag (adapted from Margon [164]).

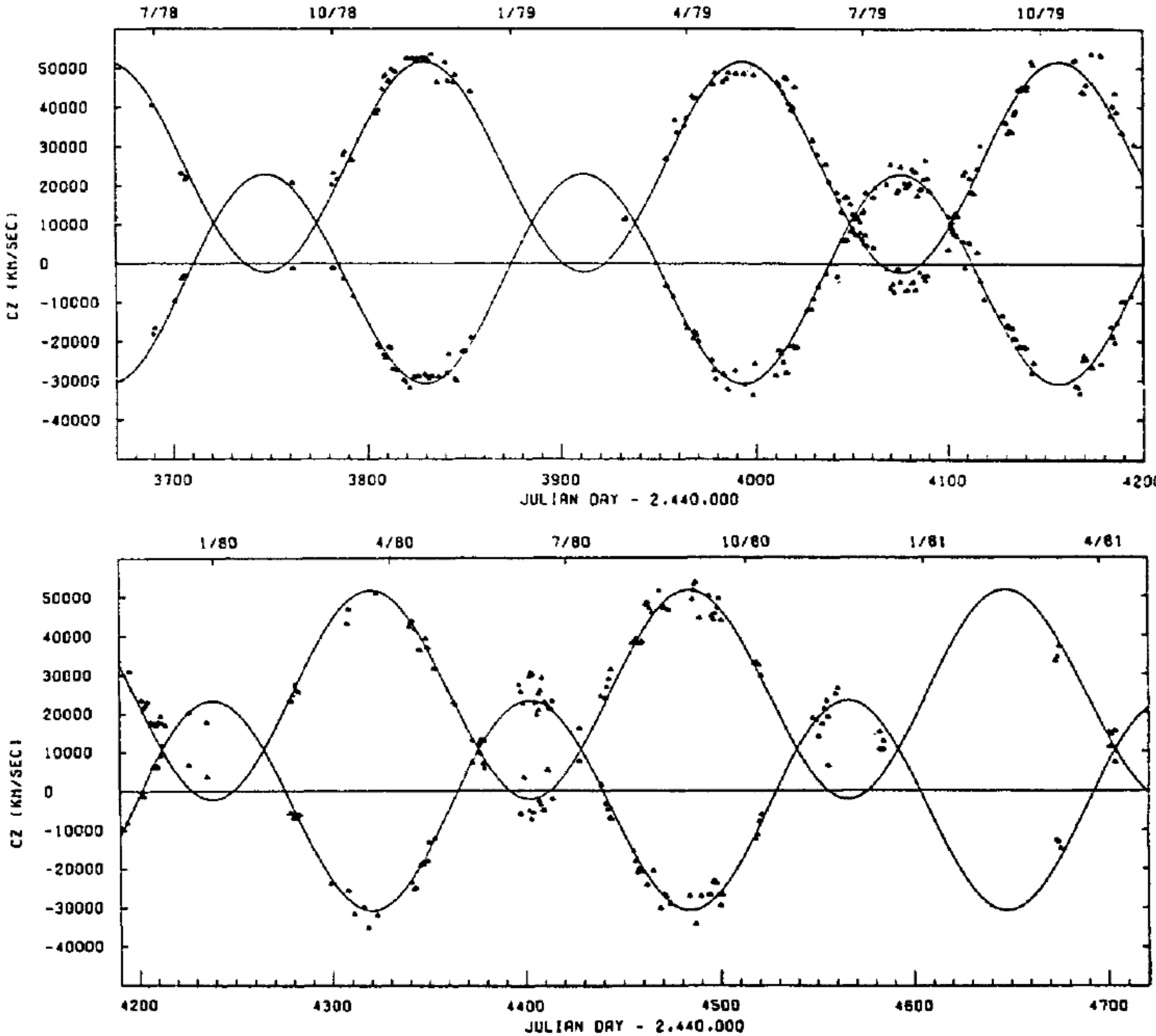
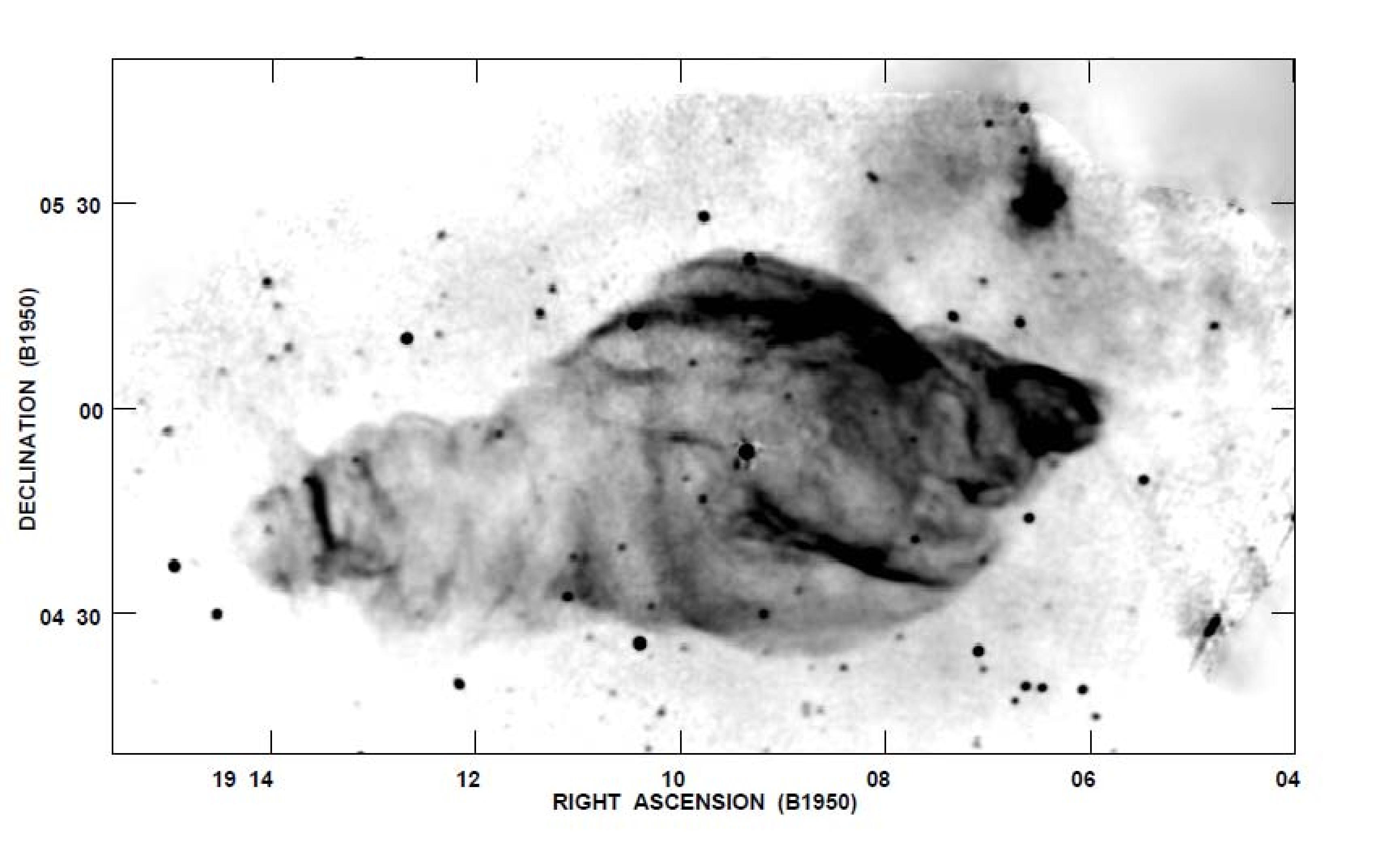


Fig. 33. The values of red- and blueshifts of SS 433 over an almost 3 yr period; displayed are 500 separate Doppler-shift values obtained on 300 separate nights. Most of the data have been obtained by Margon and University of California colleagues, and a few points are from the literature. The solid line is the best-fit to the simple kinematic model, with free parameter values given by table 17 (Margon [165]).



Westerhout 50, the"beam bag" produced by the precessing beams and disk-wind of SS433: The beams have been going on for many thousands of yrs.

Andrew King (2014), after King,Taam and Begelman, ApJL (2000):

If the donor star has a **radiative envelope**, then even for

huge mass transfer rates $-\dot{M}_2 \sim \frac{M_2}{t_{\rm thermal}} \sim 10^{-4} {\rm M}_\odot\, {\rm yr}^{-1}$

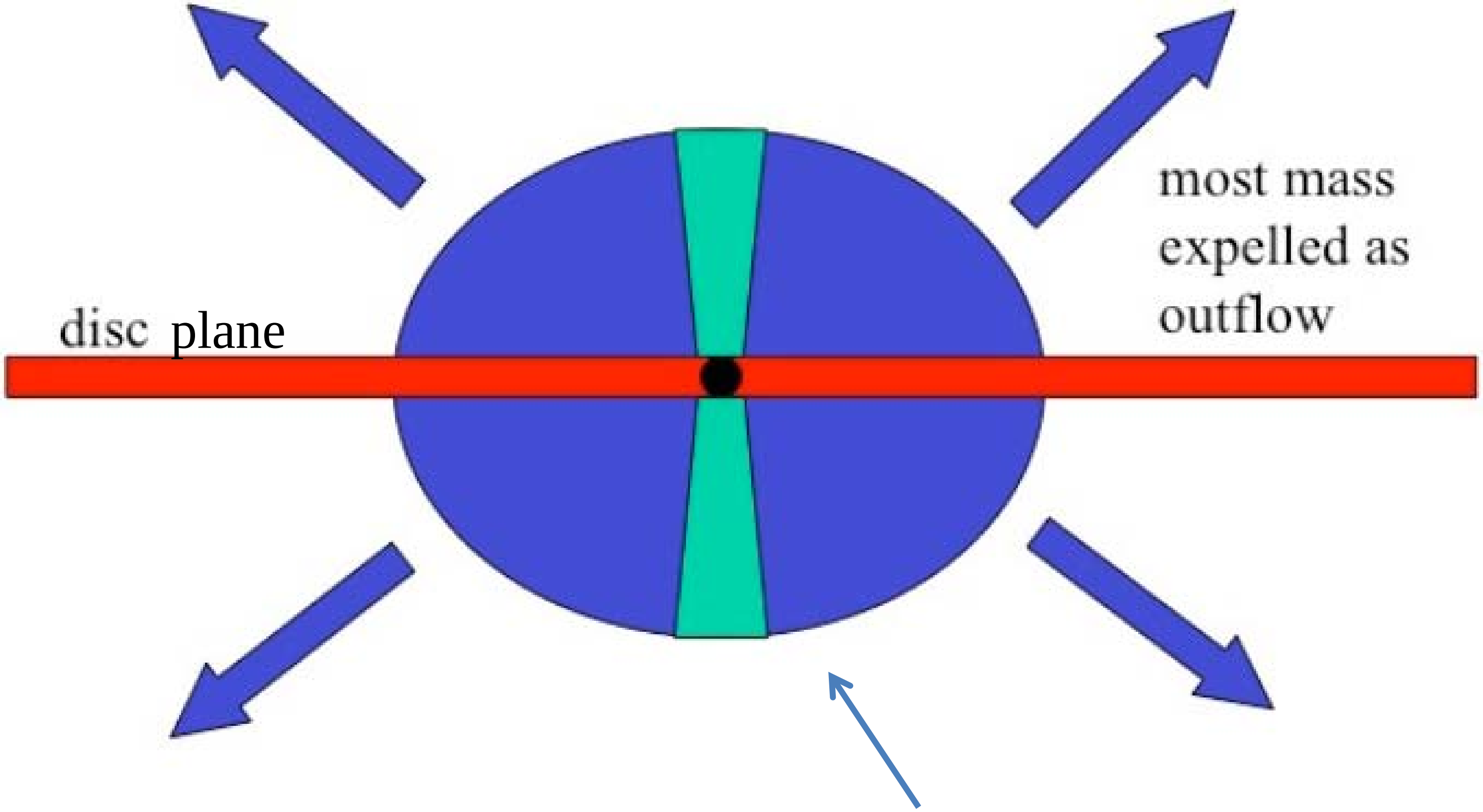
common-envelope evolution avoided provided `spherization radius'

$$R_{\rm sph} \sim \frac{-\dot{M}_2}{\dot{M}_{\rm Edd}} R_s$$

where R_s is Schwarzschild radius, is smaller than companion's Roche lobe radius R_L , ~ binary separation (K & Begelman, 1999):

Consider for this the picture of super-Eddington accretion proposed by Shakura & Sunyaev (1973)

Super-Eddington Accretion



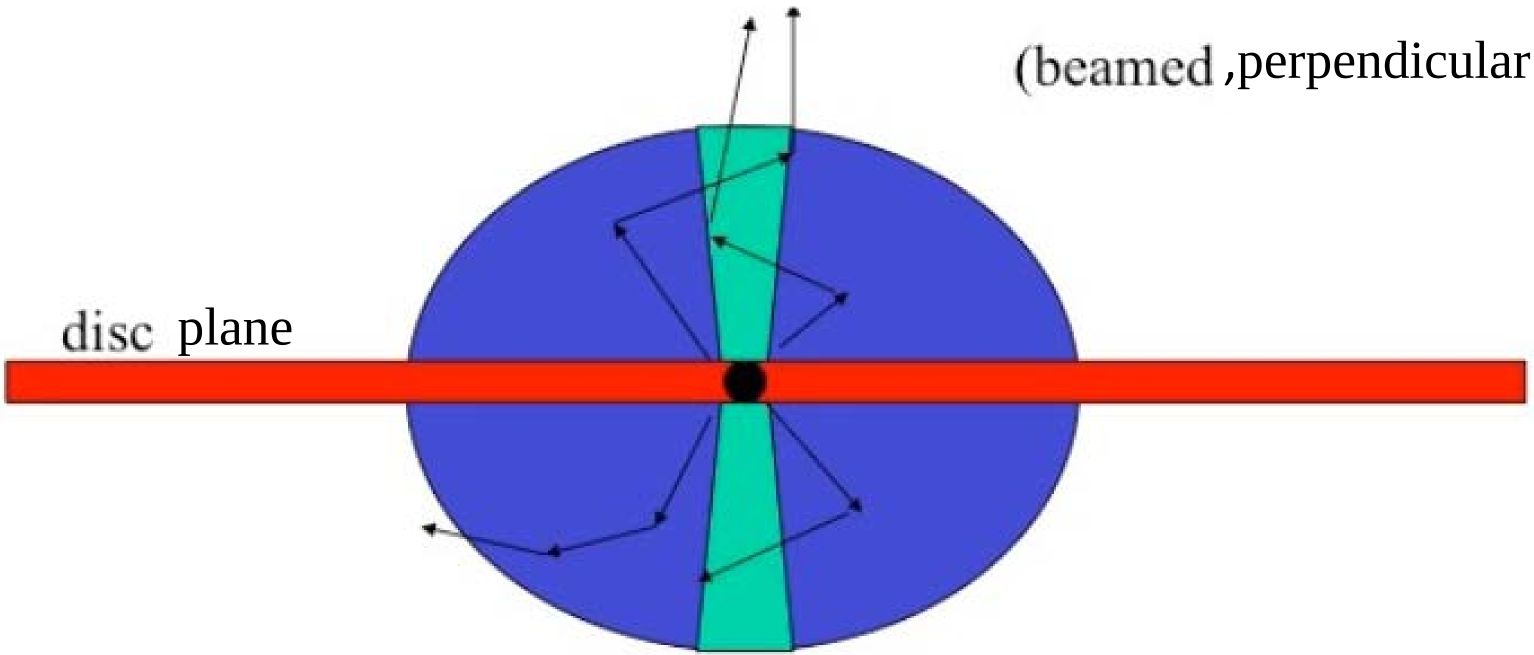
Spherization radius (inside disc) most matter is expelled here, as local L_{rad} (accr) = L_{Edd}

From King, 2014

Super-Eddington Accretion

$L_X \simeq [1 + \ln(\dot{M}/\dot{M}_{\rm Edd})]L_{\rm Edd}$ *(Shakura and Sunyaev 1973)*

(beamed ,perpendicular to disc)



$R_{\rm sph} \sim (\dot{M}/\dot{M}_E)R_s$ (most matter expelled here, as here local $L_{rad} = L_{edd}$)

From King, 2014

Additional condition for stability of Roche-lobe overflow from a radiative envelope (not realized by King et al. 2000):

Roche-lobe overflow from a radiative envelope becomes unstable when the mass ratio of Donor star and Compact star

$$q = M_{donor}/M_{compact} > q_{crit} \sim 3.5$$

This follows from binary evolution calculations of Tout et al. (1997), Tauris et al. (2000) and Hurley et al. (2000).

CONCLUSION: Roche-lobe overflow from donor with radiative envelope for $q < 3.5$ is stable, and leads to spiral-in by “SS433-type” mass transfer followed by mass loss from vicinity of compact star.

The nature of the companion of SS433:

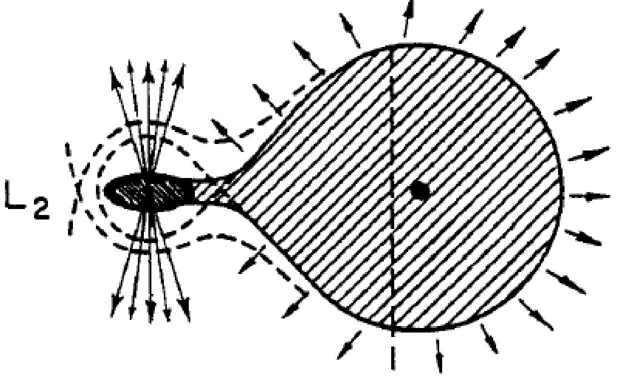
A7I Supergiant companion (Hillwig & Gies 2008): T_{eff} =8500K, R= Roche-lobe with P_{orb} = 13,1 d gives L ~ 3800 L_{sun}.

This fits with M = 12.3 (± 3.3) M_{sun} . $M_{compact}$ = 4.3 (±0.8)M_{sun}. The initial mass of the donor was probably 14 -15M_{sun}

Donor mass and orbital period resemble a Be/X-ray binary progenitor, although the mass of the compact star is too large for a neutron star:

It must be a black hole (Nauenberg & Chapline 1973; Kalogera and Baym 1996).

The > 200 known Be/X-ray binaries in Galaxy all have NS accretors. SS433 had therefore **a very rare type** of Be/X-binary progenitor



At very high mass transfer rates, if over 99.9 per cent of the transferred mass lost from the disc of the compact star (as is the case in SS433) one has $\beta = 1$ (β= fraction of transferred matter that is ejected from vicinity of compact star; $(1-\beta)$ = amount accreted).

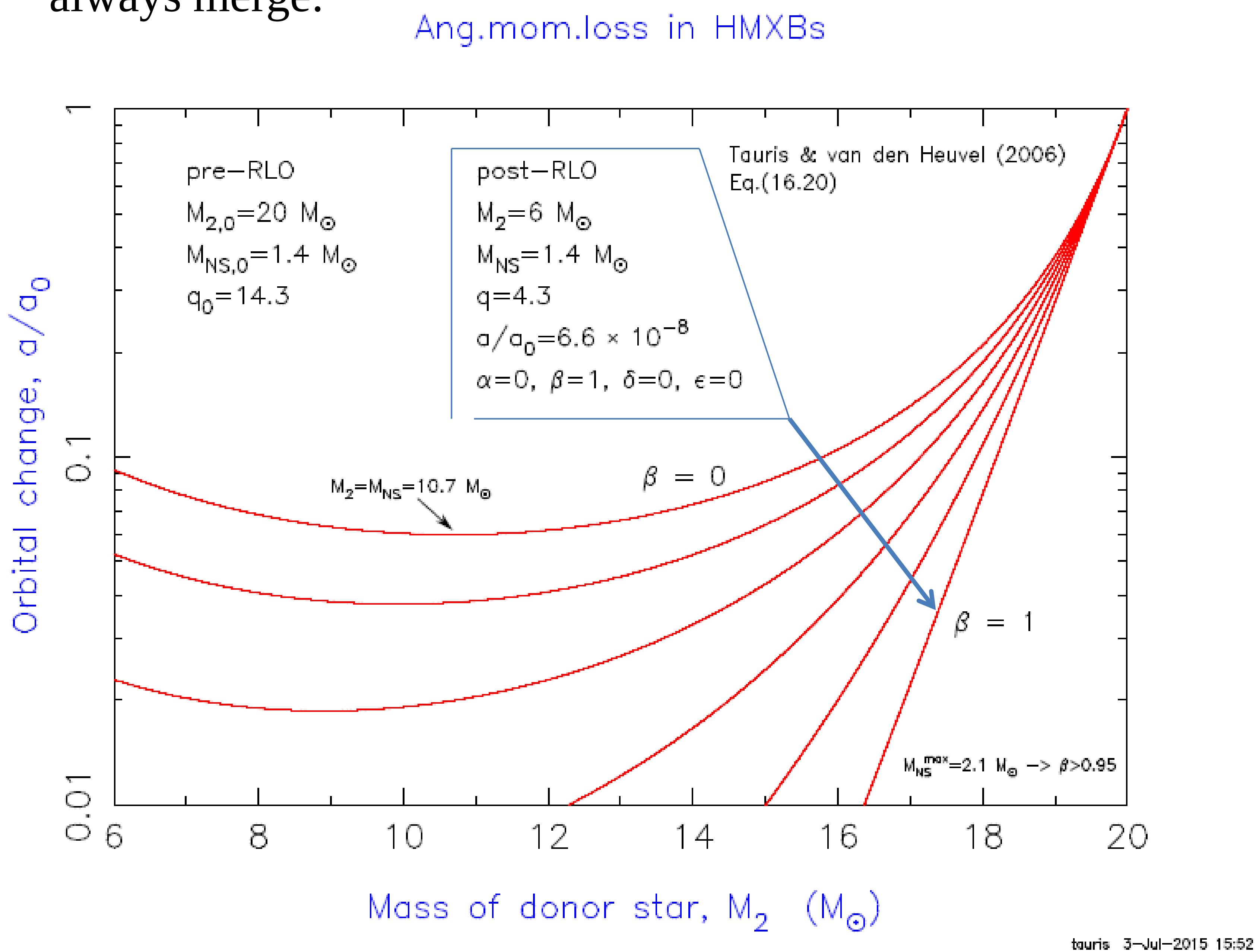
In that case, one simply has (e.g. Soberman et al., 1997):

$$a/a_o = [(q_o + 1)/(q + 1)](q_o/q)^2 .\exp(-2(q_o - q)) \qquad \text{(A)}$$

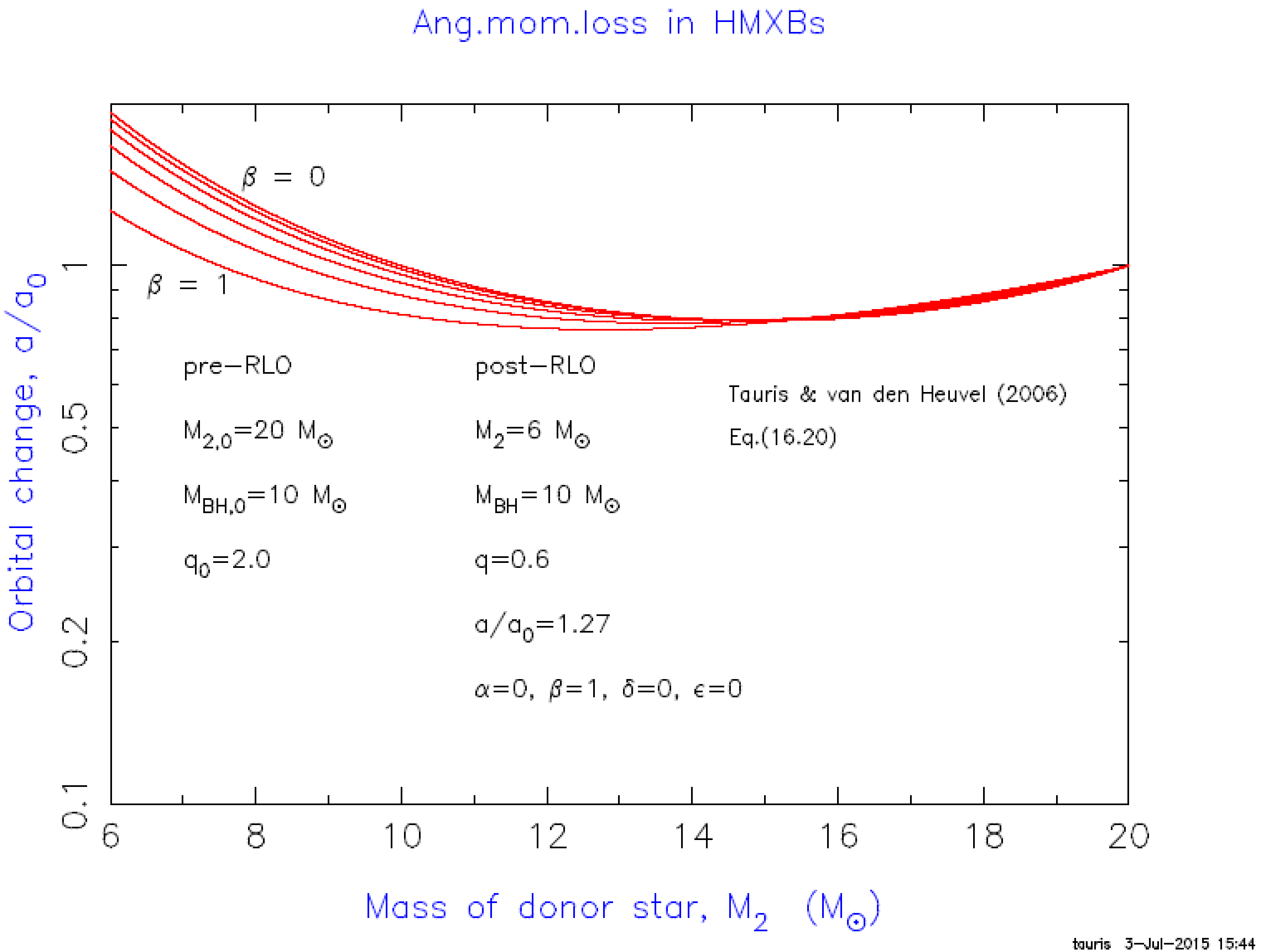
and:

$$P/P_o = [(q_o + 1)/(q + 1)]^2 (q_o/q)^3 . \exp(-3(q_o - q)) \qquad \text{(B)}$$

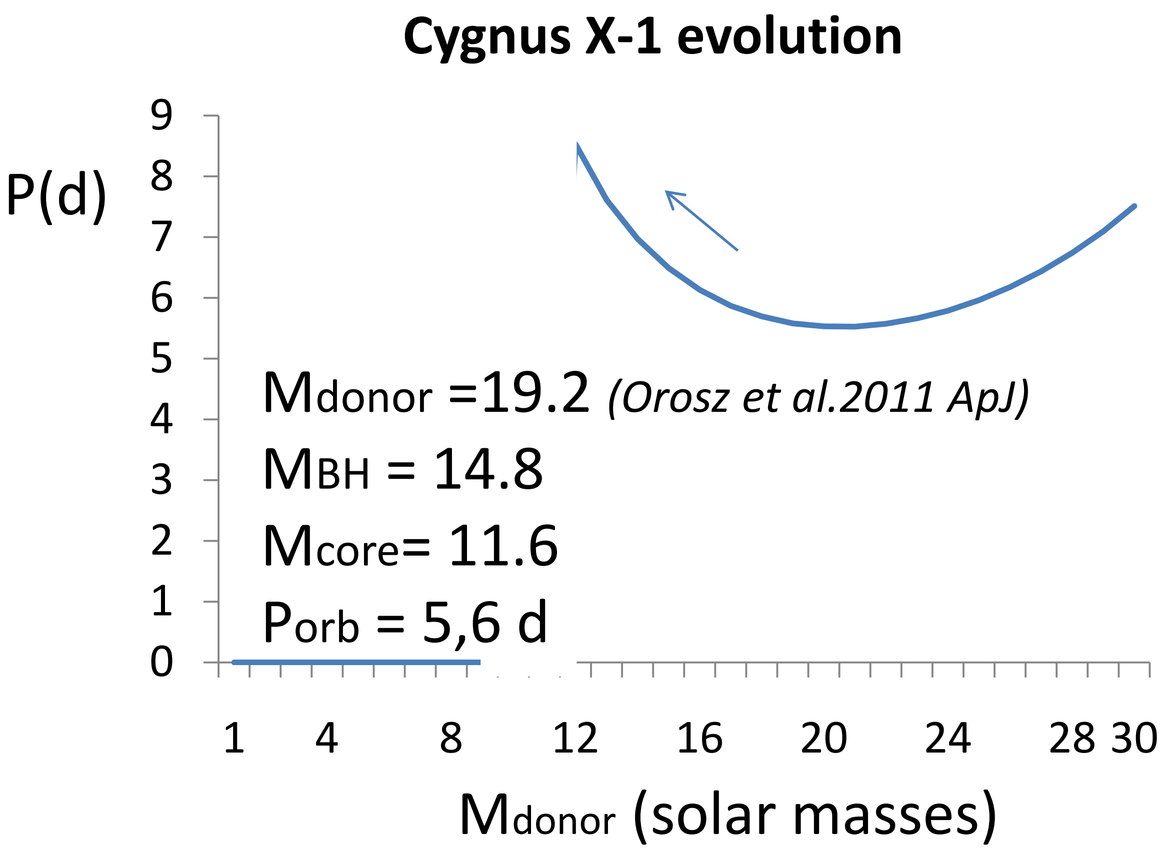
Supergiant HMXBs with a neutron star accretor (1.4 Msun) will always merge:



Systems with a BH accretor with mass ~ 10Msun will survive:



Evolution with Roche overflow and mass loss from disk of BH



Core mass of donor derived from L_{donor} which indicates *initial mass 30M_{sun}*

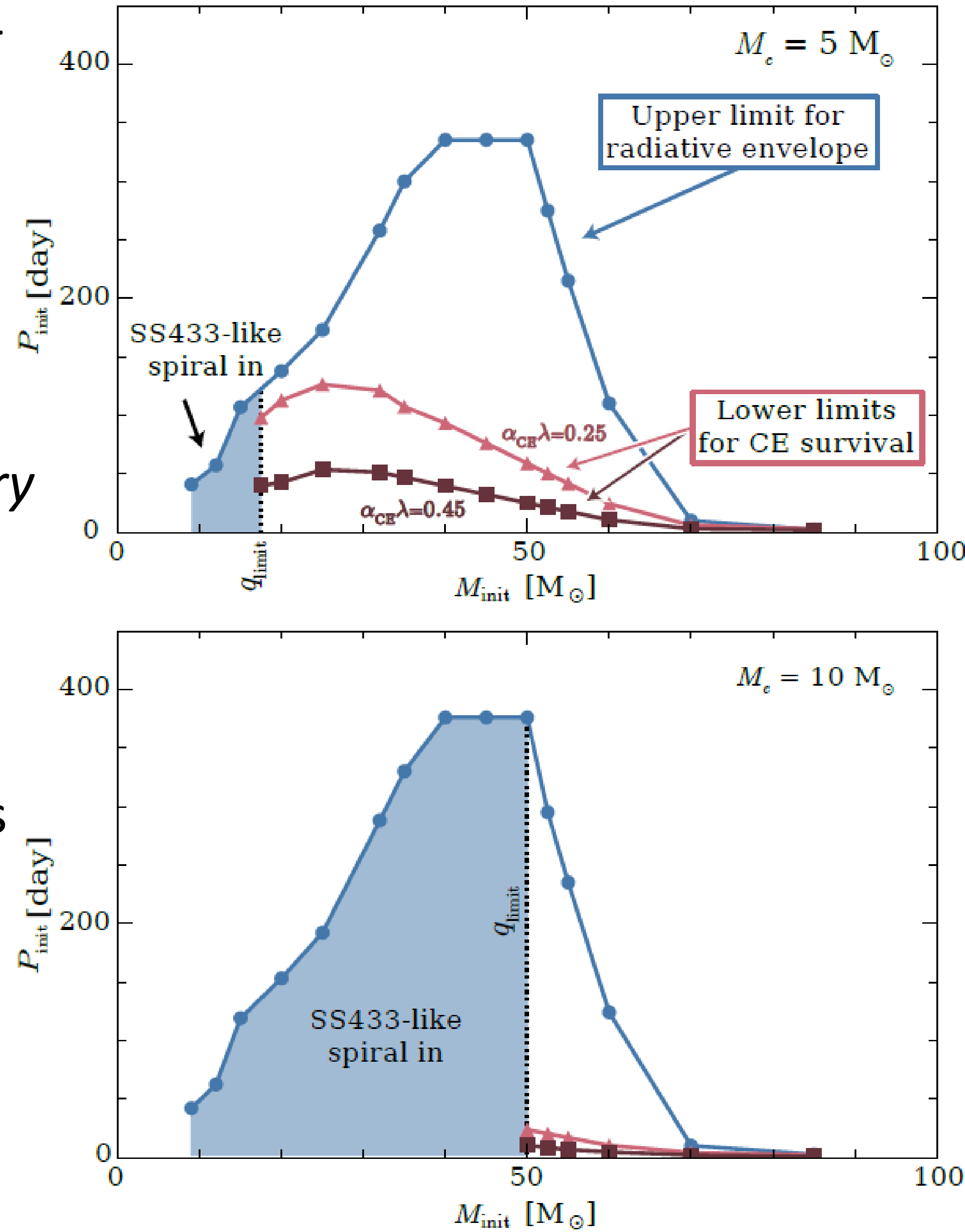
Initial period 7,5 d, Final period 8,5 d *Present system near minimum period!* (Is this reason for present stability of the mass transfer?)

With "*standard*" *CE evolution* and ($\alpha_{CE}.\lambda$) = 0.3, P(final) = 3,26h and a(final) = 3.33R_{sun}; Roche lobe WR star = 1,2R_{sun}, is just possible

Conditions for survival of SS433-like spiral-in by stable Roche-lobe overflow, and of CEE with a 5 and a 10 M_{sun} black hole companion, as a function of initial donor mass.

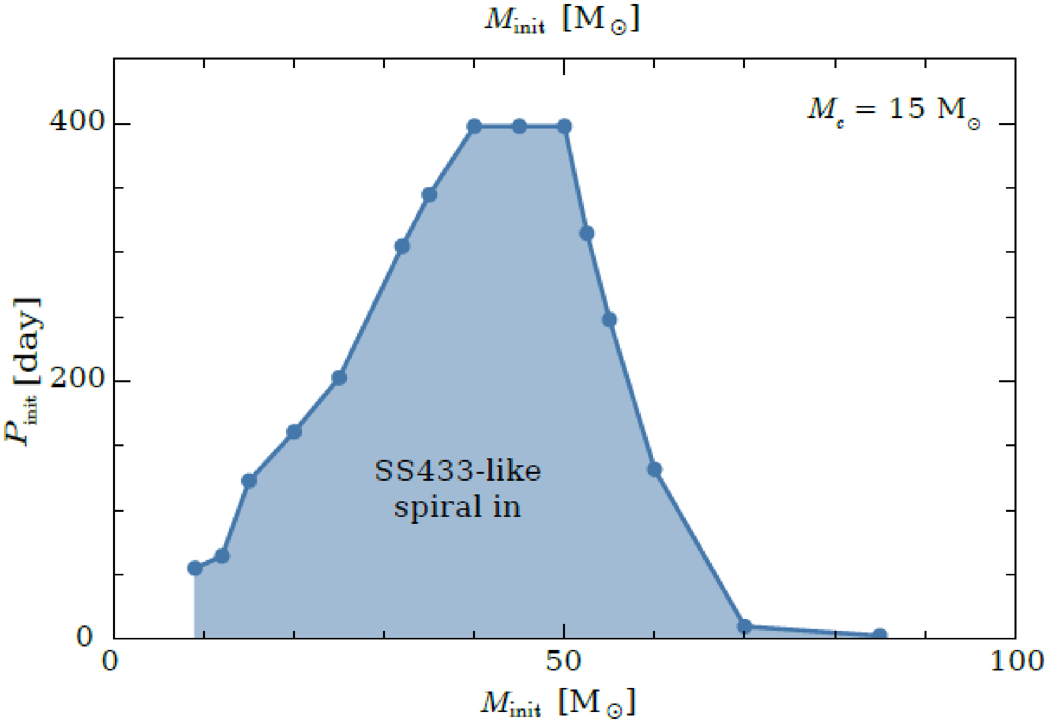
We used the rotating evolutionary models of Ekström et al. (2012). For Teff > 8100 K envelopes were assumed to be radiative.

Above the blue curves envelopes of donors are convective and CEE is unavoidable.



The same with a 15 Msun black hole companion:

All systems in the blue region spiral-in by stable Roche-lobe overflow



Calculated future evolution of 7 well-observed galactic WR+O binaries, based on "Conti-scenario": WN ⟶ WC/WO ⟶ Collapse :

Name	Spectrum	Observed		HMXB at RLOF	WR X-ray binary		Double black hole	
		P [day]	Masses [$M_\odot$]	Masses [$M_\odot$]	Masses [$M_\odot$]	P [day]	Masses [$M_\odot$]	P [day]
WR 127	WN3 + O9.5V	9.555	17 + 36	**9.6 + 33**	**9.6** + 13.6	1.54:	**9.6 + 7.0**	1.71
WR 21	WN5 + O4-6	8.255	19 + 37	**10.2 + 34**	**10.2** + 14.1	1.64:	**10.2 + 7.9**	1.77
WR 62a	WN5 + O5.5	9.145	22 + 40.5	**10.8 + 37**	**10.8** + 16.1	1.45:	**10.8 + 8.8**	1.61
WR 42	WC7 + O7V	7.886	14 + 23	**10.4 + 22**	**10.4** + 8.0	13.75	**10.4 + 4.5**	14.71
WR 47	WN6 + O5V	6.2393	51 + 60	**18.1 + 46**	**18.1** + 25.8	7.96	**18.1 + 10.4**	8.59
WR 79	WC7 + O5-8	8.89	11 + 29	**9.0 + 27.4**	**9.0** + 10.1	2.44	**9.0 + 5.4**	2.64
WR 11(CE)	WC8 + O7.5III	78.53	9.0 + 30	**7.8 + 28.5**	**7.8** + 10.5	0.90	**7.8 +5.6**	0.98

3 more WR+O systems evolve to periods similar to WR 42 and WR 47.

Problem: still too many WR X-ray binaries are produced:

- Galactic Nr. of WR stars: 1200 (± 200) (Rosslowe and Crowther, 2015),
 ~ 80 (O+WR) double-lined spectroscopic binaries with
 orbital periods suitable to make WR X-binaries. Half of these will have
 short orbital periods < 2 days.

- 40 short-period WR X-ray systems expected in a steady state of star formation, in the Galaxy (first and second WR phase: equal durations)

- WR X-binary X-ray luminosity (:) $V_w^{-4} \cdot a^{-2}$, where V_w = wind velocity near the orbit, and a = orbital radius.
 In Cyg X-3 the compact star *in low-velocity part of wind: very high L_x* .
 If orbital period > 1 day, L_x easily 100 to 1000 times lower.

- Still: unlikely > 10 short-P WR X-binaries in Galaxy, without being found within 5 kpc from Sun.

Possible solutions of high birthrate problem

- Perhaps half of massive star core collapses give neutron stars (Sukhbold et al 2016). Systems with NSs will coalesce. And:
- Perhaps q-limit for massive binaries is lower than 3.5. (What does Fe-bump convection do to radiative envelope?) If limit is 3, only one short-period system in the Table remains (the CE product of WR11): factor 5 reduction of predicted 40 systems.
- Combined expected Galactic number then reduced by factor 10: 4 short-P WR X-ray systems.
- If in half of these, second SN would produce a BH: formation rate of close double BHs from these systems: 2 in 400 000 years.

(with just Cyg X-3 in our Galaxy, and the 5 other WR-BH systems, the predicted LIGO detection rate of BH+BH mergers from the observed WR -X systems is ~ 16 events per year (cf. Belczynski et a. 2013, Maccarone et al. 2014, Esposito et al. 2015)

Conclusions:

- If Donor star has radiative envelope, HMXB can survive Roche-lobe overflow and produce a Wolf-Rayet X-ray binary (that is: with $M_{He} > 8M_{sun}$) if compact star is sufficiently massive, $\geq$ 5-10 M_{sun}.

- If the compact star is ~ 1,4 M_{sun} Neutron star, O,B-HMXBs will merge, (unless orbital period > several years: Be/X-binaries)

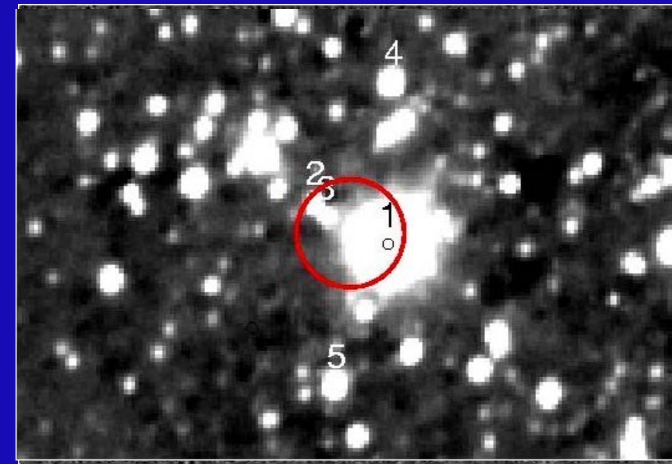
- Only HMXBs with Black Hole accretors will produce WR X-ray Binaries. (So: Cyg X-3 must harbor a Black Hole).

- The same is still true if the WR X-ray binary formed by CE Evolution.

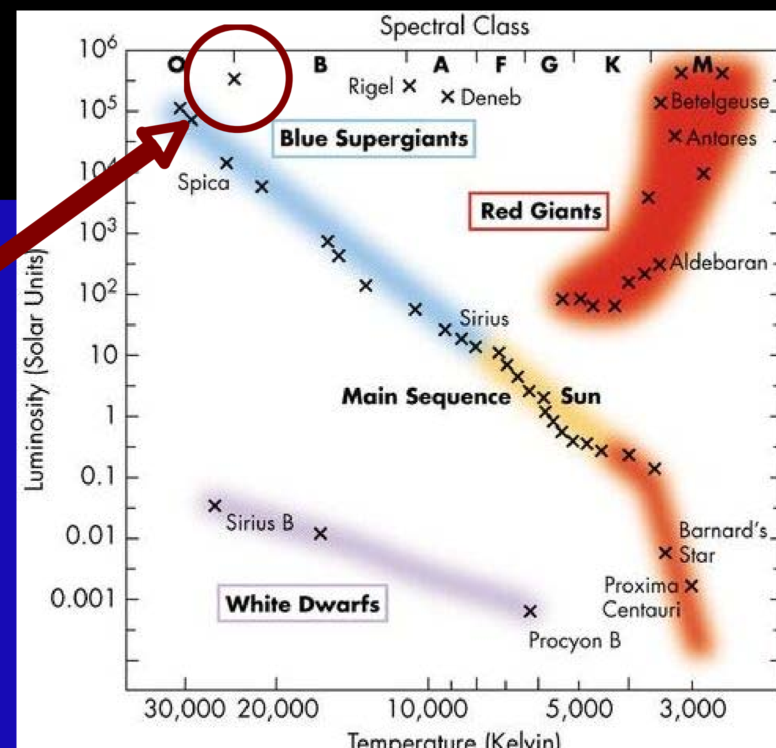
- The galactic formation rate of close double BHs originating from WR X-ray binaries is of order 10^{-5} per year.

A possible X-ray binary in the phase of CE evolution: IRG 16318-4848

Highly Obscured source: IGRJ16318-4848

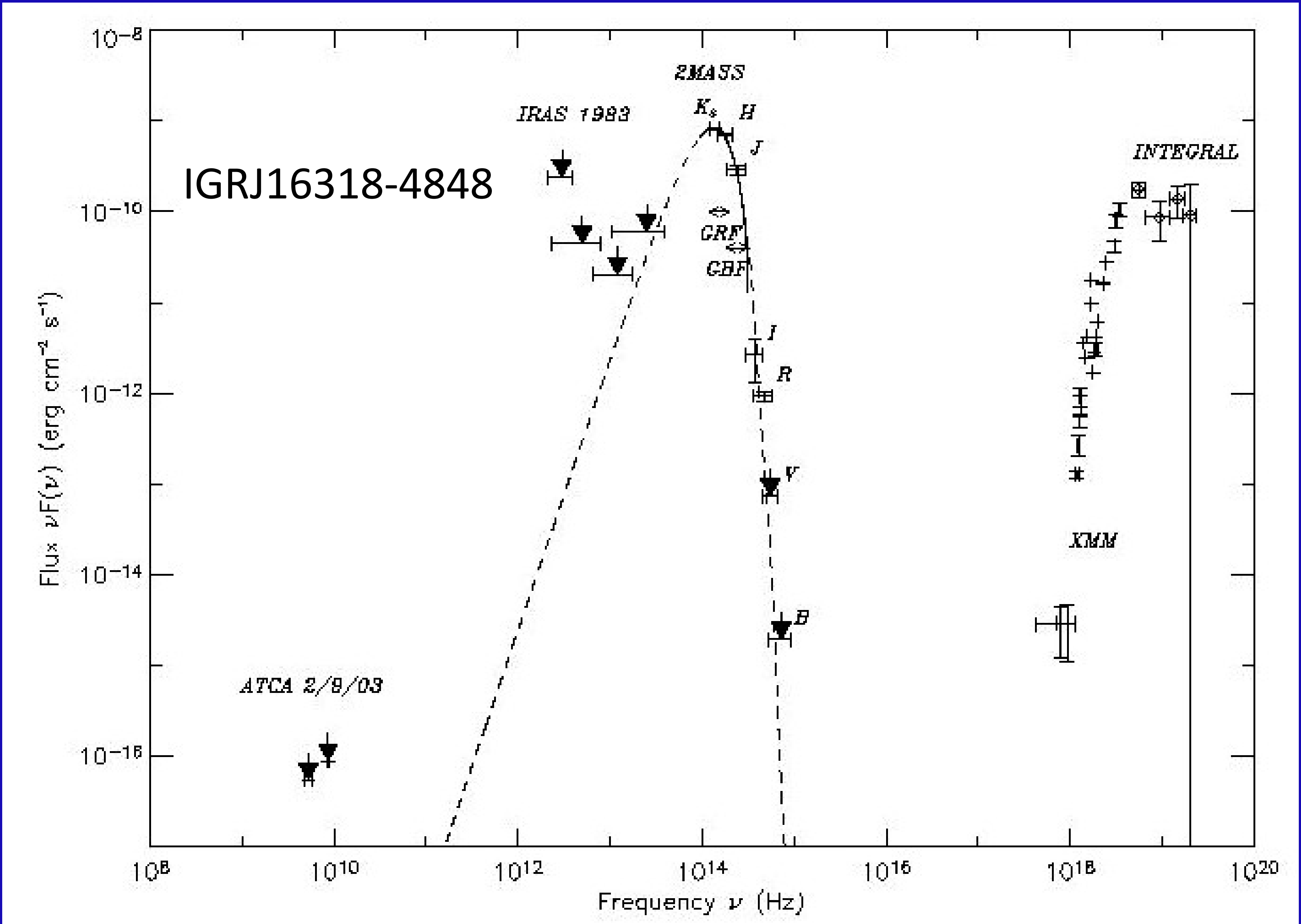


- 1st source discovered by INTEGRAL (Walter et al. 2003); bright IR counterpart
- Unusual absorption Av=17 mag, 100x>IS, but 100x<X
- NIR spectrum: stratified/complex circumstellar envelope, wind...
- Luminous sgB[e] star, HMXB, $\sim 10^6 L_\odot$, > $20 M_\odot$, 22200K, $20 R_\odot$=0.1au



Filliatre & Chaty 2004

Slide: courtesy Chaty

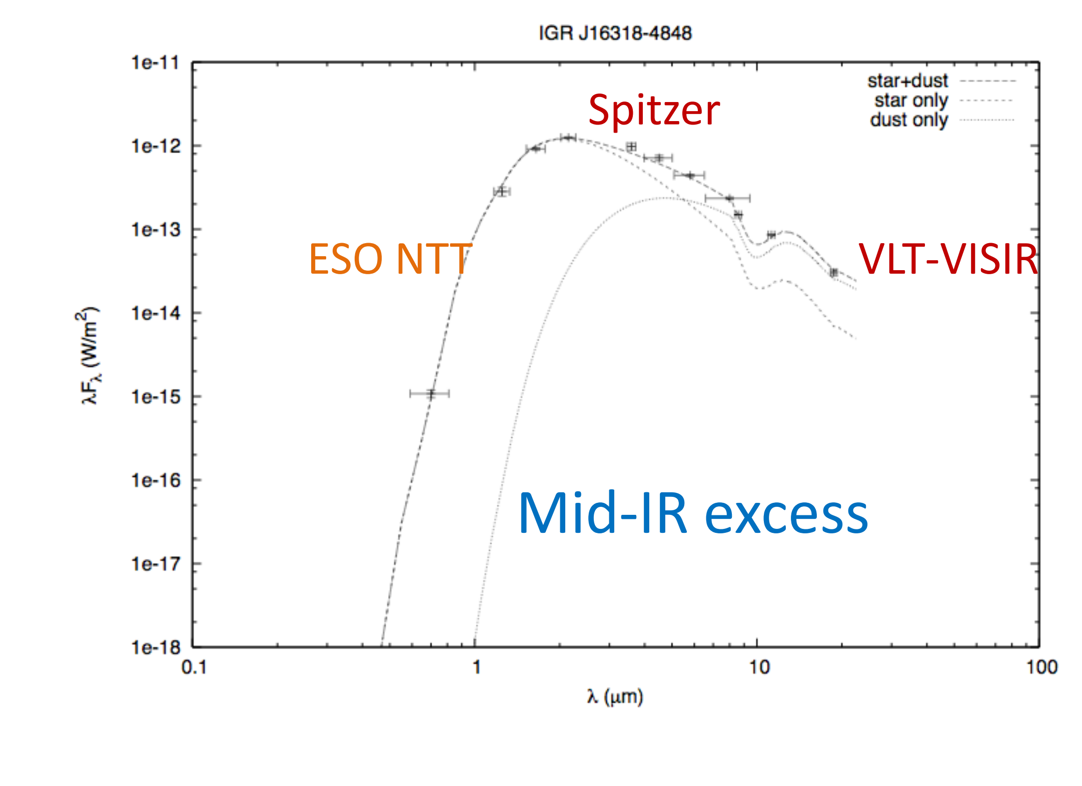


Filliatre and Chaty 2004

- Extremely obscured Source: What is origin of the large absorption?

- VLT Observations: Large MIR excess (T_{dust} =1100 K, R_{dust} = 12 R* = 240R_{sun} ~ 1 AU) + strong Si, PAH em. Lines

(Chaty and Rahoui, 2010)



- If a NS orbiting in 10 days a ~20 M_{sun} star, then *a* ~50 R_{sun}

Dust cocoon (or disk?)enshrouds the entire binary system

Is this begin of CE phase of HMXB?