The quest for particle-accelerating colliding-wind binaries across the electromagnetic spectrum

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Outline

- Scientific context
- The catalogue of particle-accelerating colliding-wind binaries
- The fraction of PACWBs among CWBs
- Multiwavelength observations
- Concluding remarks

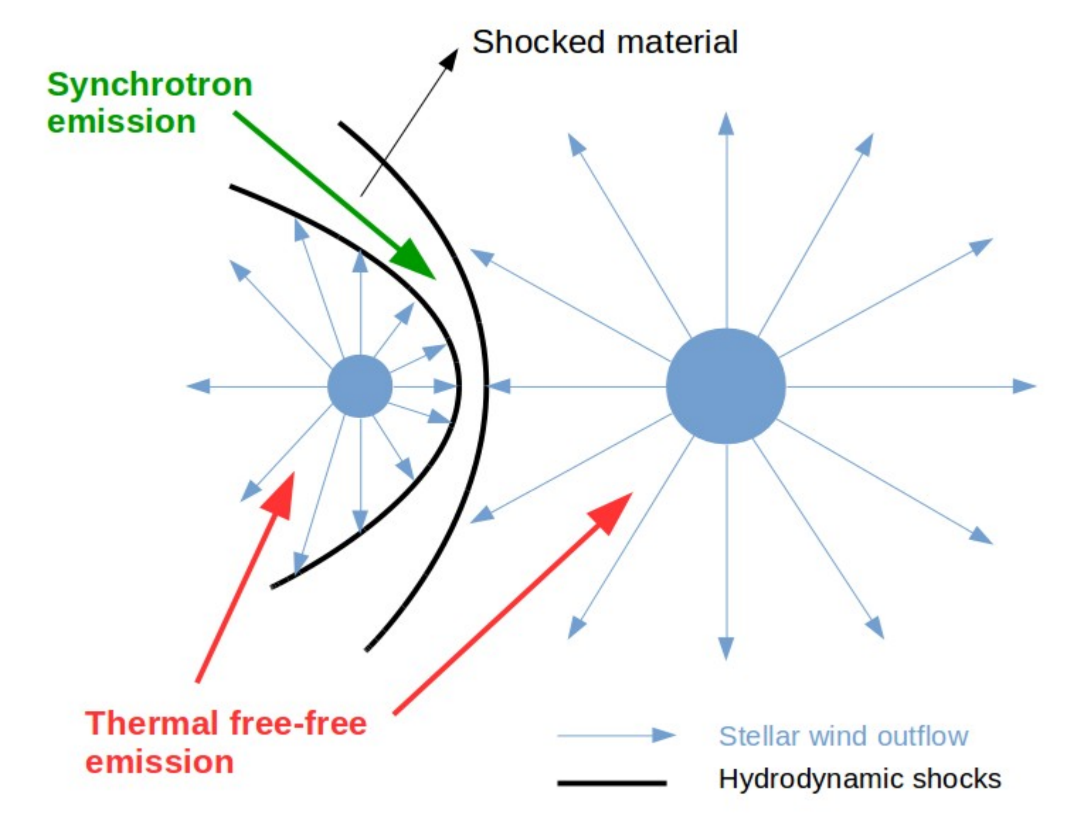
Scientific context

Massive stars are typically O-type, early B-type stars, along with their evolved counterparts known as WR star. It includes also transition objects.

A crucial aspect is their strong, dense stellar winds.

A large fraction of these stars are found in binary – or higher multiplicity – systems.

In this configuration, colliding winds are responsible for strong shocks where many physical processes can operate, including particle acceleration through Diffusive Shock Acceleration.



At least a few tens of colliding-wind binaries are able to accelerate particles up to relativistic energies. Most of them are identified through synchrotron radiation in the radio domain. The presence of high energy particles calls upon dedicated studies in the high energy domain.

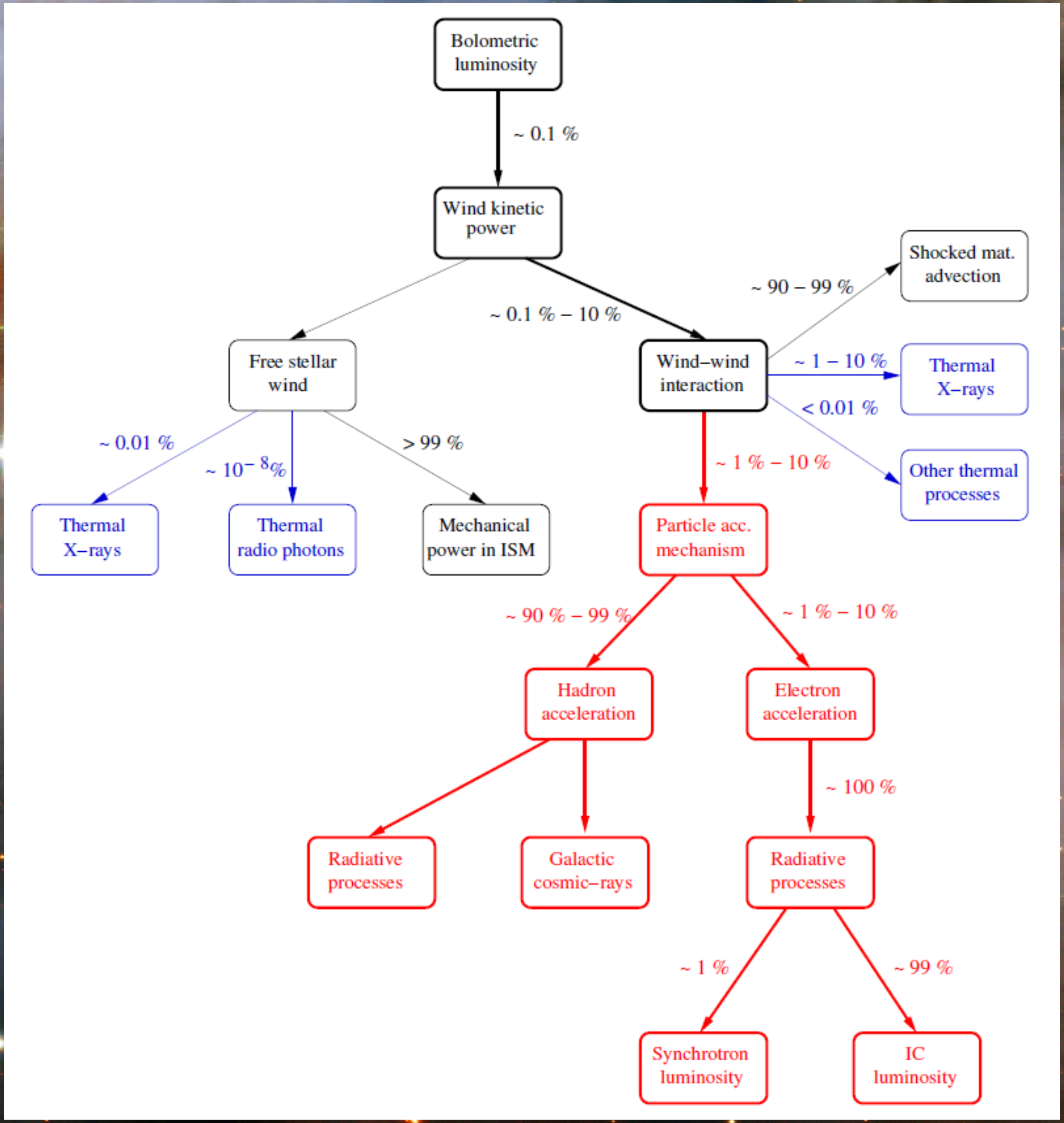
This subset of Colliding-Wind Binaries (CWB) is now referred to as Particle-Accelerating Colliding-Wind Binaries (PACWB)

Scientific context

Let's take a look at the big picture !
→ Energy budget

(De Becker & Raucq 2013, A&A, 558, A28)

Where does the energy come from ?



Mixture of thermal and non-thermal processes, likely to be investigated in various spectral domains !

Scientific context

Closer look at the radio emission

→ **radio spectra of PACWB are composite, with thermal and non-thermal contributions**

Thermal emission :

Free-free emission with a spectral index of the order of 0.6

(Wright & Barlow, 1975, MNRAS, 170, 41 ; Panagia & Felli, 1975, A&A, 39, 1)

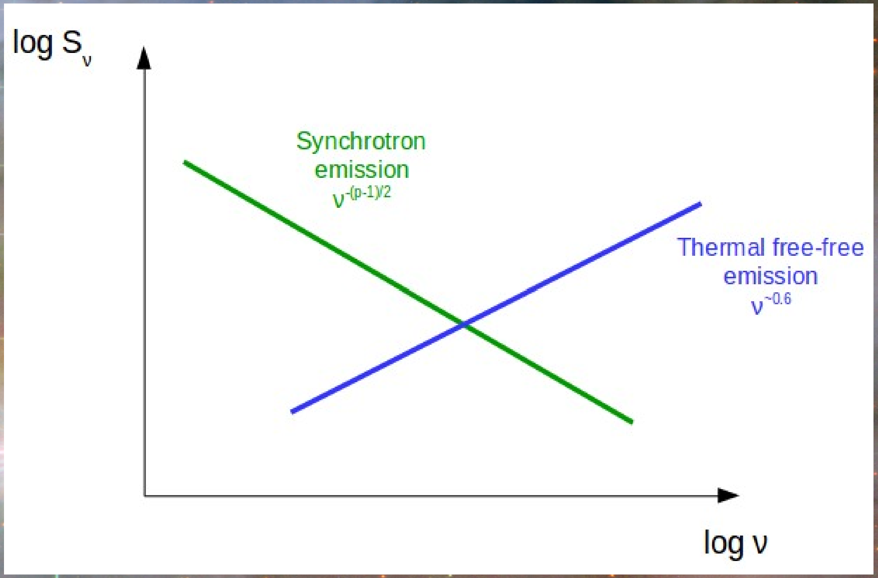
Non-thermal emission :

Synchrotron radiation with a spectral index that should be negative

$\alpha = -(p-1)/2$

with p known as the electron index

(Blumenthal & Gould, 1970, Rev. Mod. Phys, 42, 237 ; White 1985, ApJ, 289, 698)

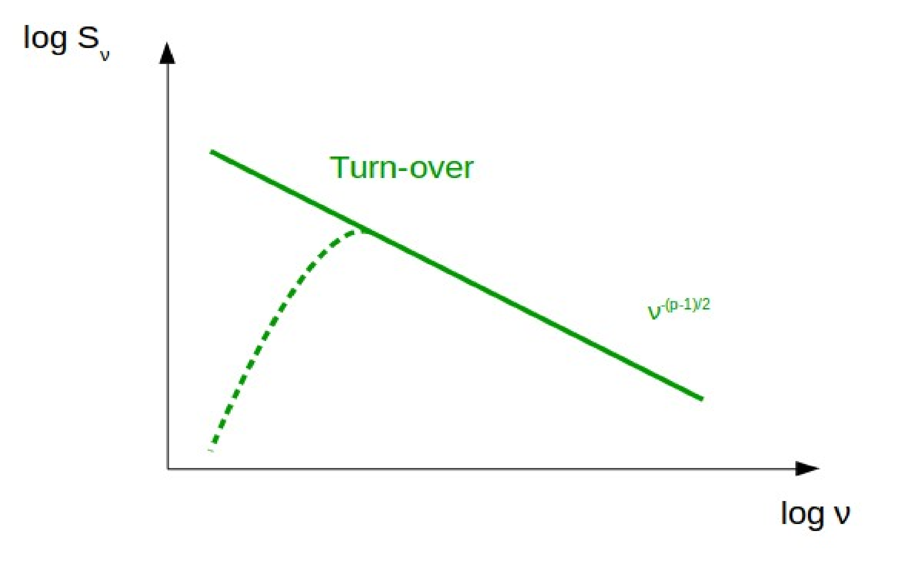


T + NT → the resulting spectral index depends on the waveband

As a conservative criterion :

NT if the spectral index is < 0.3

Scientific context



<u>The synchrotron spectrum</u>

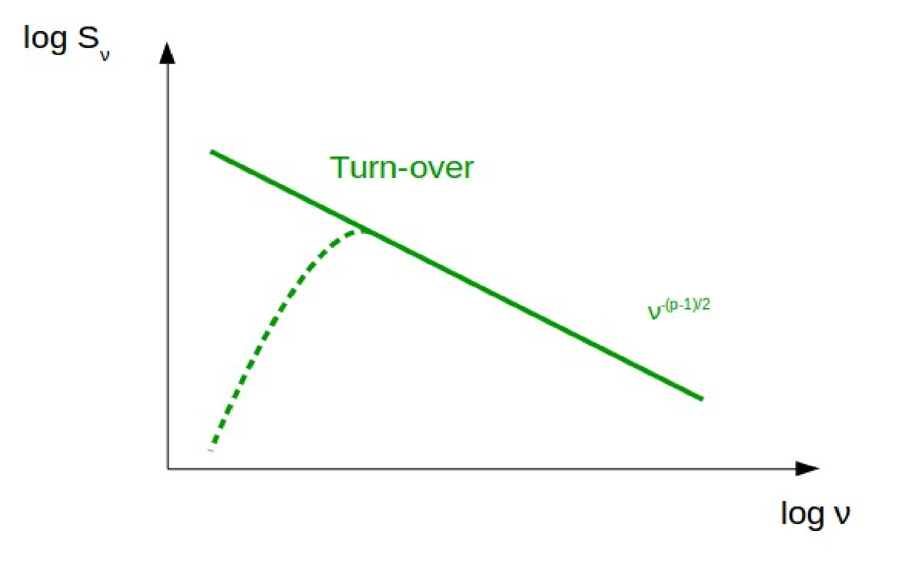
→ which turn-over process(es) could be at work for the synchrotron component?

Free-Free Absorption ?

Synchrotron Self Absorption ?

Razin-Tsytovitch Effect ?

Scientific context



The synchrotron spectrum

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Scientific context

Closer look at the X-ray emission

→ X-ray spectra of PACWB are dominated by thermal emission in the soft part (below 10 keV)

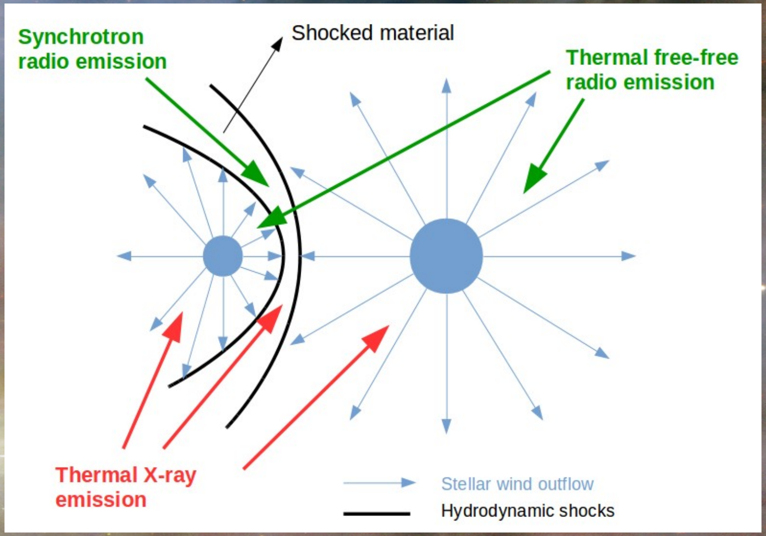
Individual stellar winds :

→ thermal X-ray emitters , with typical plasma temperatures of a few 10^6 K

Wind-wind collision region :

→ thermal X-ray emitter, with typical plasma temperature up to a few 10^7 K

The soft X-ray spectrum is made up by all these components !



Pre-shock velocities within the ('unstable') stellar winds → a few 100 km/s

Pre-shock velocities for the colliding stellar winds → a few 1000 km/s

Scientific context

<u>Closer look at the X-ray emission</u>

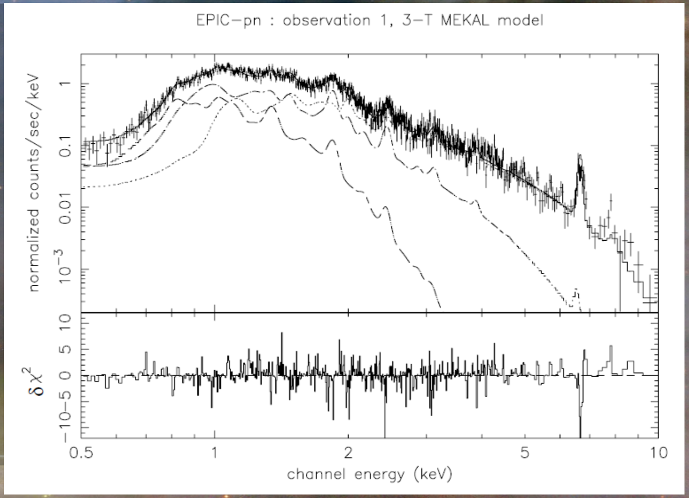
Spectra are made of many emission lines, on top of a free-free continuum.

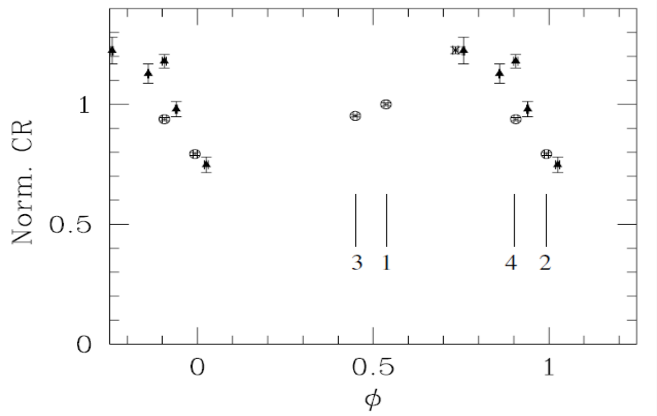
The strong iron line at about 6.7 keV is the signature of a dominant thermal component produced by a plasma at a few 10^7 K.

The X-ray spectrum is expected to vary as a function of orbital phase

- eccentric orbit (variation of the emission measure for the CW component
- orientation effects (absorption by the stellar winds material)

XMM-Newton soft X-ray spectrum of the O-type binary Cyg OB2#8A (P ~22 days)
(De Becker et al. 2006, MNRAS, 371, 1280)

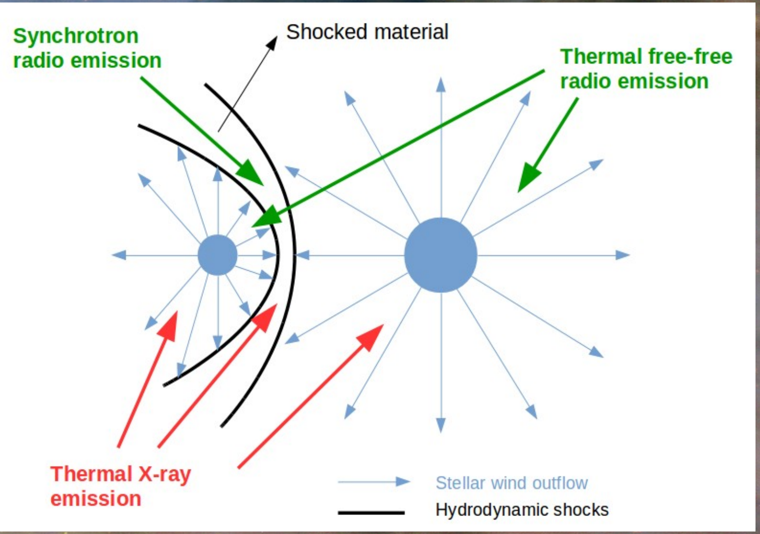




X-ray light curve of Cyg OB2#8A combining measurements made with several observatories
(De Becker et al. 2006, MNRAS, 371, 1280)

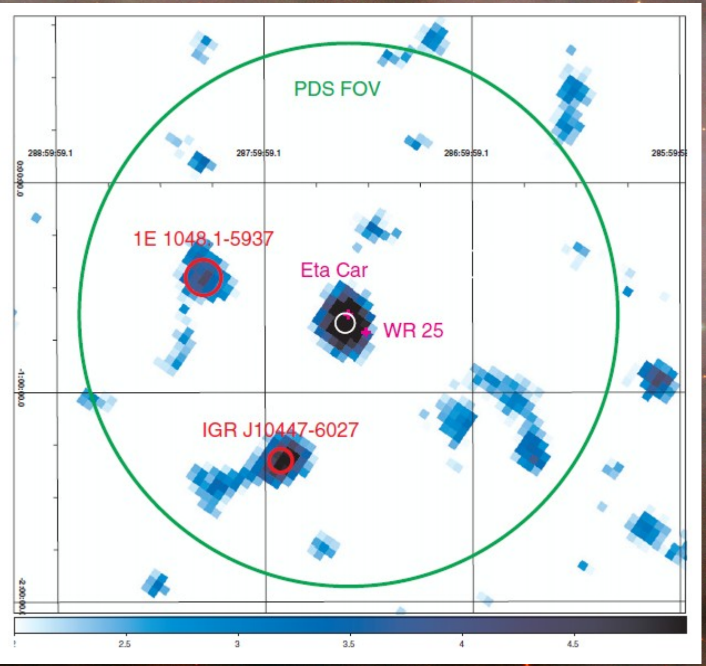
Scientific context

What about non-thermal X-rays ?
Relativistic electrons in the presence of the strong photospheric radiation from the stars
→ inverse Compton scattering should operate
→ a power law (NT) X-ray component is expected.



However, soft X-rays are dominated by thermal processes
→ investigations in hard X-rays are needed !

- Several PACWB in the Cygnus region → no detection with INTEGRAL (De Becker et al. 2007, A&A, 472, 905)
- Eta Carinae (very massive transition object) → detected with BeppoSax (Viotti et al. 2004, A&A, 420, 527), with INTEGRAL (Leyder et al. 2008, A&A, 477, L29), and with Suzaku (Sekigushi et al. 2009, PASJ, 61, 629)
- WR140 potentially detected with Suzaku, but might be a contamination by a background Seyfert galaxy (Sugawara et al. 2015, PASP, 67, 121)



Scientific context

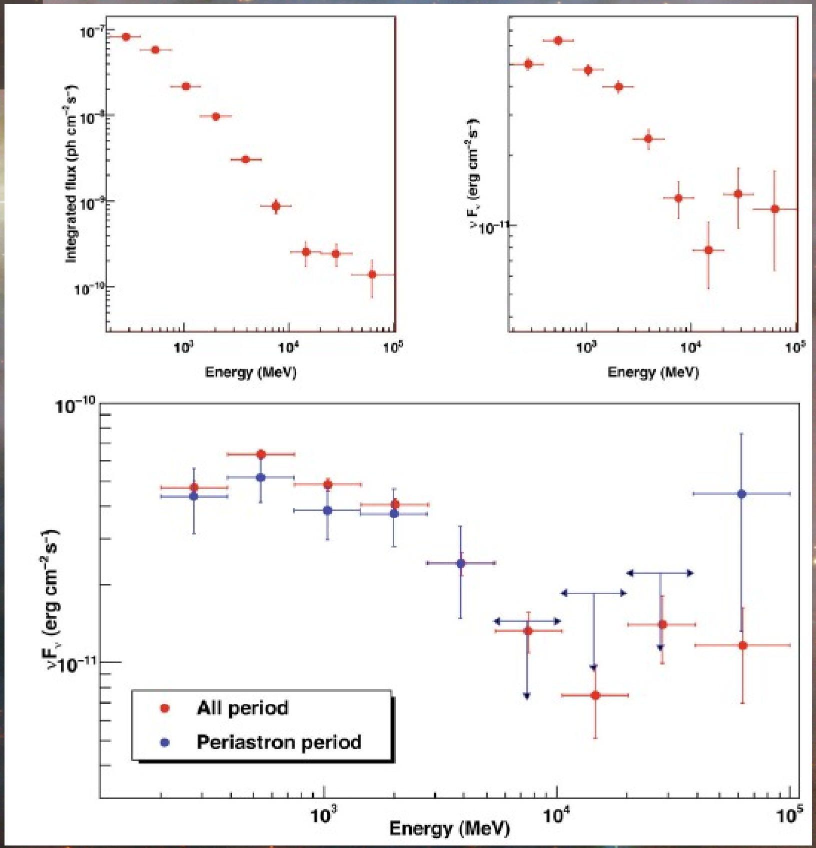
What about gamma rays ?

Non-thermal processes at work in the gamma-ray domain

- inverse Compton scattering ?
- hadronic processes ?

- **Eta Carinae → detected with AGILE (Tavani et al. 2009, ApJ, 698, L142) and with Fermi (Abdo et al. 2010, ApJS, 187, 460)**
- **WR11 potentially detected with Fermi (Pshirkov 2016, MNRAS, 457, L99)**
- **A sample of WR-type CWB investigated after many years of observations with Fermi → no detection ! (Werner et al. 2013, A&A, 555, A102)**

Gamma-ray emission from Eta Car
(Farnier et al. 2011, A&A, 526, 57)



The catalogue of PACWBs

So far, about 40 systems identified to be particle accelerators among CWBs
- O-type stars
- Wolf-Rayet stars
- a few 'transitional' objects

Now unified in only one list!

(De Becker & Raucq 2013, A&A, 558, A28)

http://www.astro.ulg.ac.be/~debecker/pacwb/

Previous censuses used to separate systems of different evolution stages, e.g. Dougherty & Williams 2000, De Becker 2007, Benaglia 2010...

→ strong need to unify these objects into a unique class, occupying a rather wide parameter space.

The catalogue of PACWBs

So far, abou... ...ators among CWB...
- O-type sta...
- Wolf-Raye...
- a few 'tran...

...ker & Raucq 2013, ...8, A28)

...er/pacwb/

Previous ce... ...t evolution stages, e.g. ... ...aglia 2010...

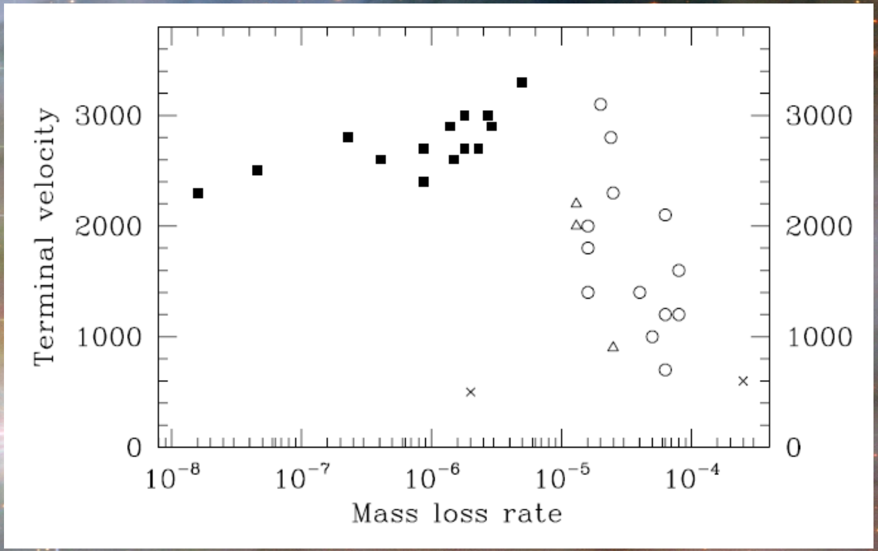
→ strong ne... ..., occupying a rather wi...

#	Usual ID	Status	Sp. type(s)	P
1	HD 15558	B (T?)	O5.5III(f) + O7V	442 d
2	δ Ori A	T	(O9.5II + B0.5III) + B?	5.733 d/> 100 yr
3	σ Ori AB	M	O9.5V + B0.5V (+ OBs?)	?
4	15 Mon	B	O7V(f) + O9.5Vn	25.3 yr
5	WR 8	B	WN7 + WC(?)	38 d, 115 d
6	WR 11	B	WC8 + O7.5	78.53 d
7	WR 14	B?	WC7	?
8	CD–47 4551	U	O5If	–
9	WR 21a	B	O3f*/WN6ha + O4	32.673 d
10	HD 93129A	B	O2If* + O3.5V?	?
11	HD 93250	B	O4III + O4III	> 100 d
12	η Car	B	? + ?	2022.7 d
13	WR 39	B?	WC7	?
14	WR 48	T	(WC5 + O6-7V) + OI?	19.138 d/?
15	HD 124314	B?	O6V(n)((f))	?
16	HD 150136	T	(O3-3.5V((f*)) + O5.5-6V((f))) + O6.5-7V((f))	2.675 d/8.2 yr
17	HD 151804	U	O8Iaf	–
18	WR 78	U	WN7h	–
19	WR 79a	B	WN9ha + ?	many years
20	HD 152623	T	(O7V((f)) + OB?) + OB?	3.9 d/?
21	WR 89	B	WN8h + OB	?
22	WR 90	U	WC7	–
23	WR 98	B	WN7/WC + O8-9	48.7 d
24	WR 98a	B	WC9 + OB?	565 d
25	WR 104	B	WC9 + B0.5V	220 d
26	WR 105	U	WN9h	–
27	9 Sgr	B	O3.5V((f*)) + O5V	~ 8.6 yr
28	WR 112	B?	WC9 + ?	?
29	HD 167971	T	(O6-7V + O6-7V) + O8I	3.321 d/~ 20 yr
30	HD 168112	B?	O5.5III(f*) (+ OB?)	> 1 yr
31	CEN 1a	B	O4 + ?	?
32	CEN 1b	B	O4 + ?	?
33	WR 125	B	WC7 + O9III	> 15 yr, ~20–22 yr
34	HD 190603	U	B1.5Ia	–
35	WR 133	B	WN5 + O9I	112.4 d
36	WR 137	B	WC7 + O9V-III	13.05 yr
37	WR 140	B	WC7 + O5	7.9 yr
38	Cyg OB2 #5	Q	(Ofpe/WN9 + O6–7Ia) + OB? + B0V	6.598 d/6.7 yr/> 9000 yr
39	Cyg OB2 #9	B	O5I + O6-7I	2.35 yr
40	Cyg OB2 #8A	B	O6If + O5.5III(f)	21.908 d
41	Cyg OB2-335	B	O7V + O9V	a few days(?)
42	WR 146	B (T?)	WC6 + O8?	many years ?
43	WR 147	B	WN8 + B0.5V	many years ?

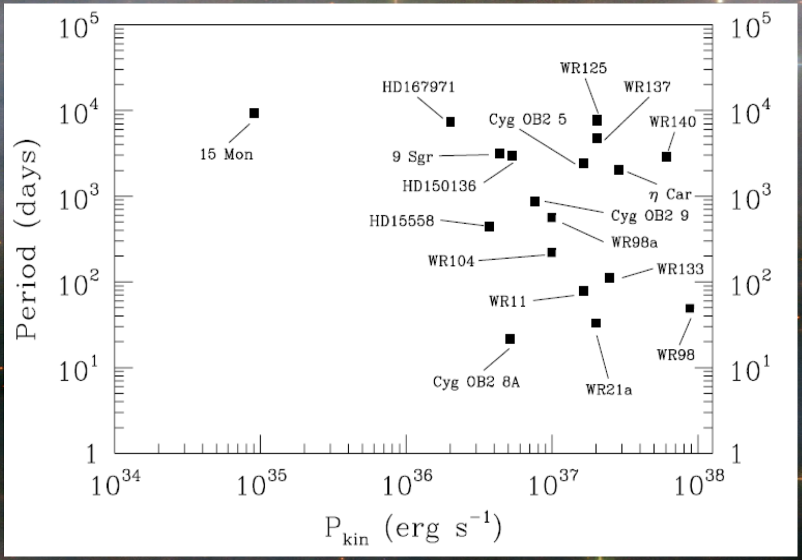
The catalogue of PACWBs

Positions of the dominating star of each system, in the wind parameter space (mass loss rate in solar mass per year, and terminal velocity in km/s).

Accurate determination of the stellar parameters of the companions is still lacking in several systems.



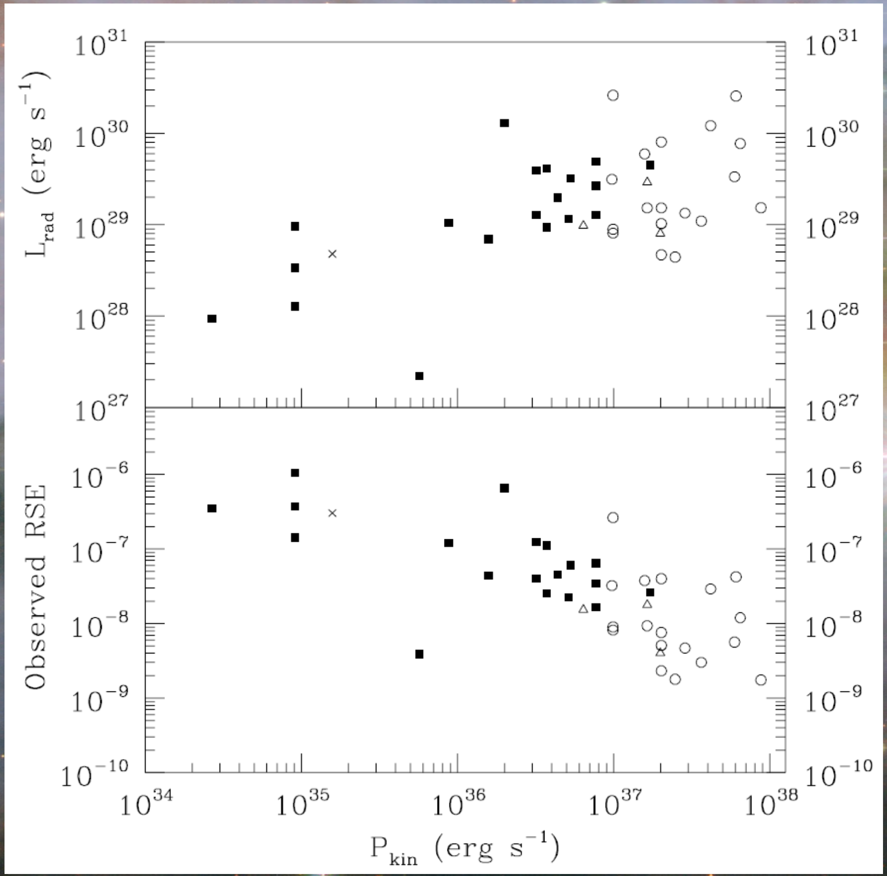
(De Becker & Raucq 2013, A&A, 558, A28)



Plot of the period of the system expressed (when available!) as a function of the kinetic power.

The lower limit on the period seems to be located at 'a few weeks'

The catalogue of PACWBs



(De Becker & Raucq 2013, A&A, 558, A28)

Estimates of the radio luminosity, dominated by synchrotron emission, present a rather wide dispersion.

Radio Synchrotron Efficiency (RSE) : **Defined as the fraction of the kinetic power of the system converted into synchrotron radiation (see the energy budget)**

A trend is suggested by the plot, but more data points are needed to clarify this trend : RSE decreases as a function of kinetic power, certainly due to the highest optical depth of the strongest winds.

Outline

Scientific context

The catalogue of particle-accelerating colliding-wind binaries

The fraction of PACWBs among CWBs

Multiwavelength observations

Concluding remarks

The fraction of PACWBs among CWBs

Why is it relevant to raise the question of this fraction ?

1. Important aspect of the physics of colliding-wind massive binaries

2. Connection with the question of the production Galactic cosmic rays

The fraction of PACWBs among CWBs

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1. Important aspect of the physics of colliding-wind massive binaries

2. Connection with the question of the production Galactic cosmic rays

What is the feedback of particle acceleration on the hydrodynamics of colliding winds ? What can be learned about shock physics in massive binaries, and how does it compare with similar physics in other environments (supernova remnants...)

The fraction of PACWBs among CWBs

Why is it relevant to raise the question of this fraction ?

1. Important aspect of the physics of colliding-wind massive binaries

2. Connection with the question of the production Galactic cosmic rays

If this fraction is not so weak, the total population of PACWBs in the Milky Way could provide a not so negligible contributon to the population of 'low energy' cosmic rays.

The fraction of PACWBs among CWBs

What can we tell about that fraction ?

$$F_{PACWB} = \frac{N_{PACWB}}{N_{CWB}}$$

The fraction of PACWBs among CWBs

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Massive star population in the Milky Way : ~ a fraction of about 10^{-6} of the stellar population
→ ~ 10^5 objects
Fraction of binaries : more than 50 %
Fraction of systems with adequate periods : several 10 %
→ N_{CWB} in the range of 1 – 5 X 10^4

The fraction of PACWBs among CWBs

What can we tell about that fraction ?

$$F_{PACWB} = \frac{N_{PACWB}}{N_{CWB}}$$

To date, only ~ 40 objects
→ Actual measurement of the scarcity of PACWBs ? Or a biased census due to difficulties to identify them notably because of strong observational biases ?

No clear identification of a special feature likely to restrict PACWBs to only a tiny fraction of the massive star population
→ where are the missing members ?
→ a huge observational effort is needed to clarify this question !

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The fraction of PACWBs among CWBs

If one has to focus on a list of targets to identify new PACWBs, how should we select candidates ?

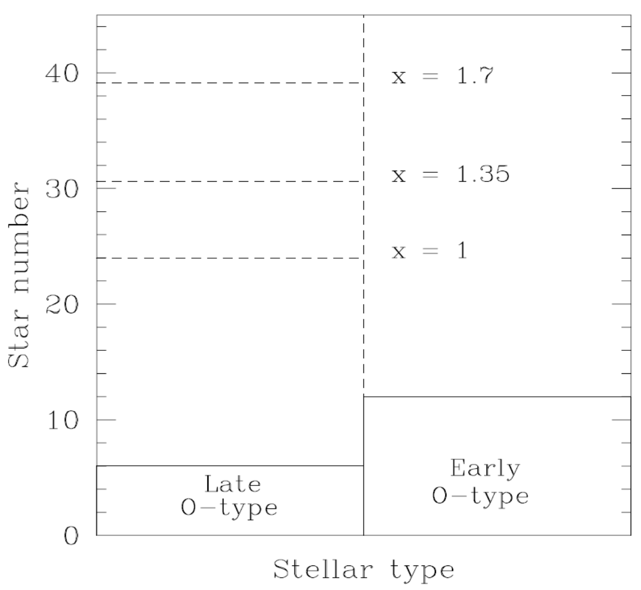
<u>1. Should we privilege some stellar categories ?</u>

The present catalogue includes stars from all O-type categories, WR stars from all classes, and transition objects.

However, late-type objects are under-represented. This can be explained by a lower kinetic power likely to feed non-thermal processes (below detection limit?).

Assuming a 'standard Initial Mass Function' (with different indices x), the actual number of early O-type members allows to predict numbers of late O-type objects much larger than the actual number in the catalogue
→ **the PACWB population does is not representative of a standard stellar**

→ early type objects should be a priori privileged, though late type objects should not completely be rejected



(De Becker, Benaglia, Romero,& Peri 2017, A&A, in press)

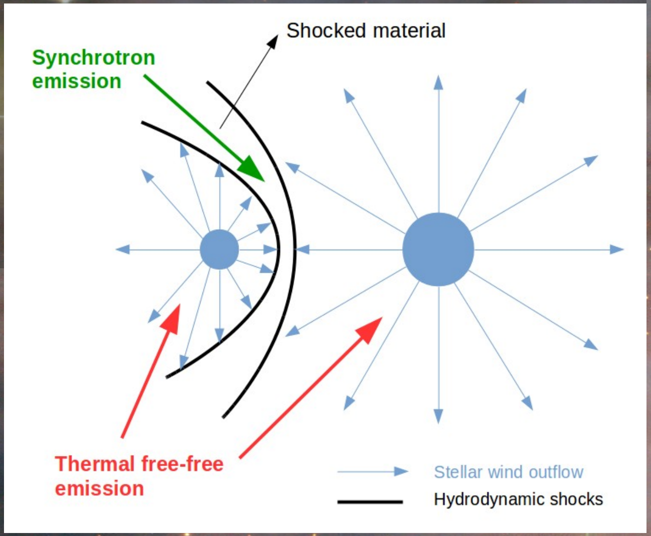
The fraction of PACWBs among CWBs

If one has to focus on a list of targets to identify new PACWBs, how should we select candidates ?

2. Should we privilege a range of orbital periods ?

The present catalogue includes systems with periods ranging between a few weeks and several decades. The shortest periods are notably affected by a strong FFA of the synchrotron spectrum because of a shorter stellar separation.

In addition, significant cooling of relativistic electrons through IC scattering limits the capability of DSA to sustain a significant relativistic electrons population



→ It is more likely to identify PACWBs among CWBs whose period is at least a few weeks (though it will depend on the stellar category)

The fraction of PACWBs among CWBs

If one has to focus on a list of targets to identify new PACWBs, how should we select candidates ?

3. Should we focus on highly magnetic objects ?

As the main tracer of particle acceleration is synchrotron radio emission, one may wonder whether these detections could be favored for stars with strong magnetic fields

Attempts to measure the surface magnetic field of a sample of PACWBs
→ no detection at the level of ~1 Gauss
(Neiner et al. 2015, A&A, 575, A66)

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Not a surprise ! One knows that the magnetic field strength required to account for the measured synchrotron spectra (assuming equipartition) in the synchrotron emission region is of the order of a few mG.

(e.g. Dougherty et al. 2003, A&A, 409, 217)

Considering the dependence on the distance (assuming a stellar origin), this turns into a surface magnetic field strength of the order of 0.2 – 50 G, depending on the size of the system.

(De Becker, Benaglia, Romero,& Peri 2017, A&A, in press)

If one considers magnetic amplification, the surface level is lower by 1 or several orders of magnitude !

(Falceta-Gonçalves & Abraham 2012, MNRAS, 423, 1562)

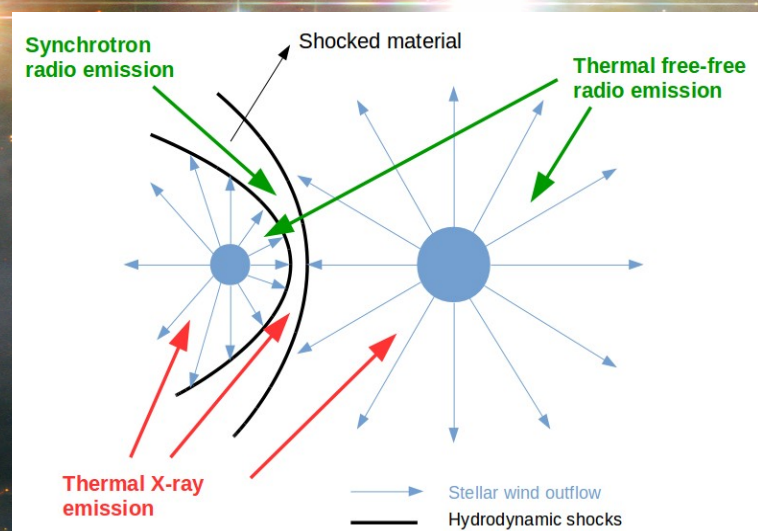
→ we do not have to care about the magnetic field strenght in our candidate selection

The fraction of PACWBs among CWBs

If one has to focus on a list of targets to identify new PACWBs, how should we select candidates ?

<u>4. Should we focus on objects with a strong thermal X-ray spectrum ?</u>

A strong thermal X-ray spectrum fro the wind-wind interaction region is often considered
As an indication of high kinetic power injection in the wind collision
→ plenty of kinetic power should be available for other processes as well
→ strong thermal X-ray emitters could be significant non-thermal emitters (?)



The fraction of PACWBs among CWBs

If one has to focus on a list of targets to identify new PACWBs, how should we select candidates ?

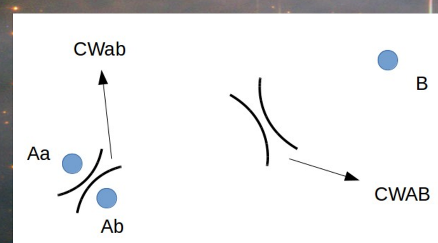
4. Should we focus on objects with a strong thermal X-ray spectrum ?

Not necessarily !

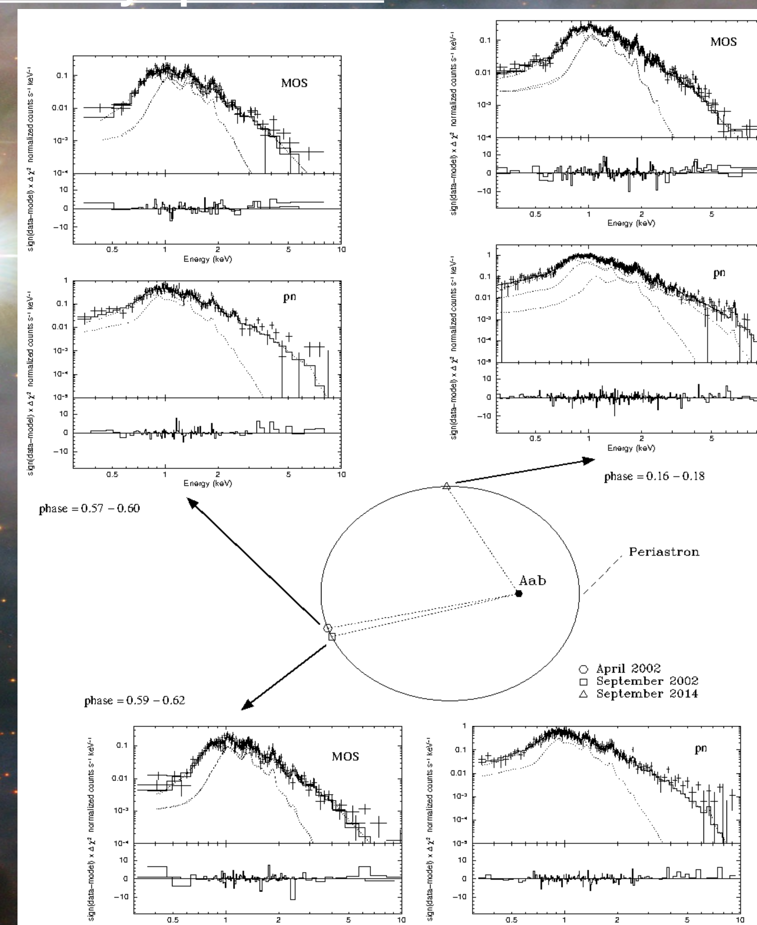
For instance, the case of the triple system HD167971 :

- triple system : periods of about 3 days and 21 years
- the brightest O-type synchrotron radio emitter, with the NT radio emission coming from the 'long-period wind collision' (CWAB on the figure)

The X-ray spectrum is not dominated by CWAB, but by Cwab with additional contributions from the 3 individual stellar winds



→ potential candidates should not be restricted to strong thermal X-ray emitters



(De Becker 2015, MNRAS, 451, 1070)

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Multiwavelength observations

Concluding remarks

Multiwavelength observations

1. As we are dealing with binary – or higher multiplicity – systems, multiplicity investigations are strongly needed. In addition, the determination of the spectral classification of the stars is also important.

Spectroscopic investigations and high angular resolution imaging techniques (e.g. Sana et al. 2011, De Becker et al.2012, Sana et al. 2013, Le Bouquin et al. 2017)

Output :

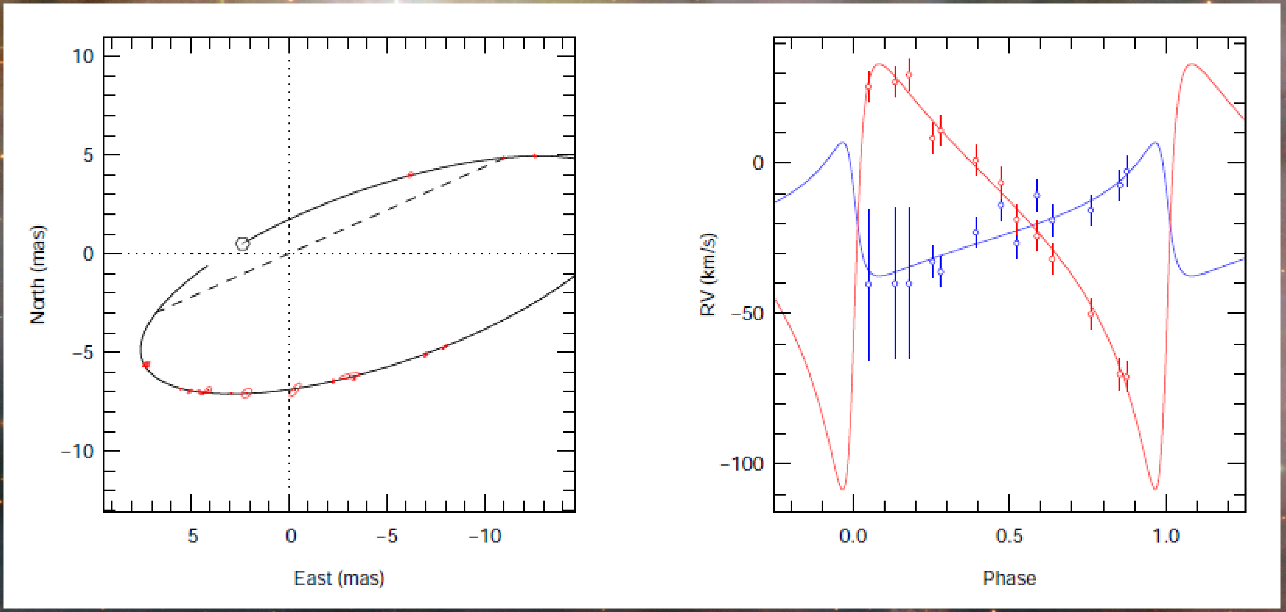
- orbital parameters → time evolution of the system
- spectral classification → stellar parameters

Multiwavelength observations

1. As we are dealing with binary – or higher multiplicity – systems, multiplicity investigations are strongly needed. In addition, the determination of the spectral classification of the stars is also important.

The triple system HD150136, with its 3D orbit derived from a combination of spectroscopic and astrometric measurements

Periods of 2.7 d and ~8 yr. ; e ~ 0.7.



(Le Bouquin et al. 2017, A&A, in press)

Multiwavelength observations

2. Identification of additional members of the catalogue through dedicated radio observations.

Select targets for radio observations :
- no need to investigate strongly magnetic objects
- no need to focus on the systems with huge wind kinetic power (though, late-type main-sequence objects are less favorable)
- no need to investigate objects with very strong wind collisions
- no need to restrict to a narrow range of orbital periods

→ At this stage, no specific parameter/ingredient seems to be required to discriminate between PA and non-PA
(De Becker, Benaglia, Romero & Peri, 2017, in press)

→ Plenty of system deserve to be considered

Multiwavelength observations

2. Identification of additional members of the catalogue through dedicated radio observations.

Apply adequate observation strategies

- **Variability** → repeated observations, ideally at well-selected orbital phases
- **Spectral characterization** → measurements, at least, at 2 frequencies
- **Longer wavelengths** → where synchrotron emission should dominate the spectrum (e.g. 20 to 100 cm with GMRT)
- If feasible, **VLBI imaging** → resolve spatially the NT and the T components of the system

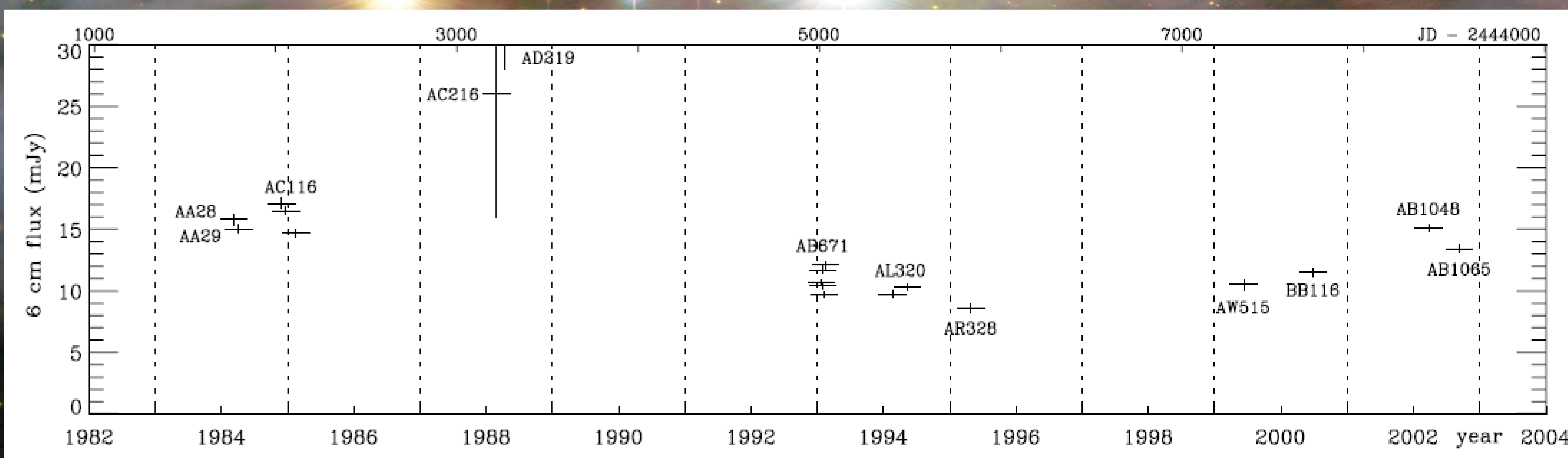
→ upgrade the catalogue and improve our estimate of the frequency of PACWBs among CWBs

Multiwavelength observations

2. Identification of additional members of the catalogue through dedicated radio observations.

The triple system HD167971, with a radio modulation on a time-scale of about 21 years → most probably the orbital period

- *(Blomme et al. 2007, A&A,464, 701)*



Multiwavelength observations

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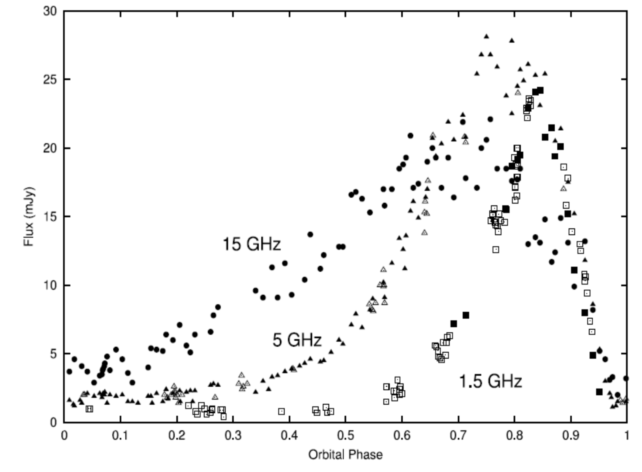
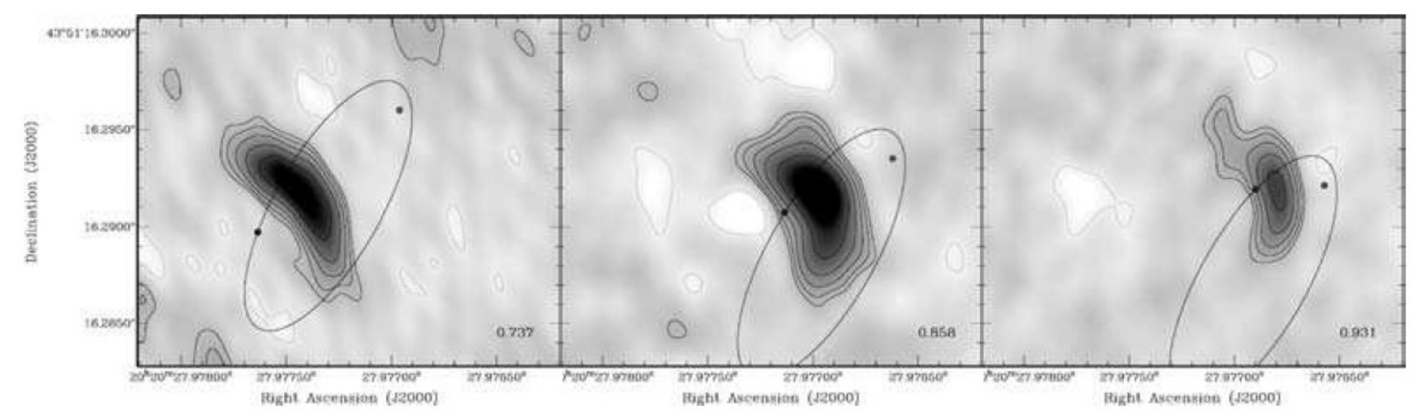
The emblematic WR system WR140 (P ~8 yr ; e ~0.9)
(Dougherty et al. 2005, ApJ, 623, 447, Dougherty et al 2007, ASP Conf. Series, 367, 271)





Multiwavelength observations

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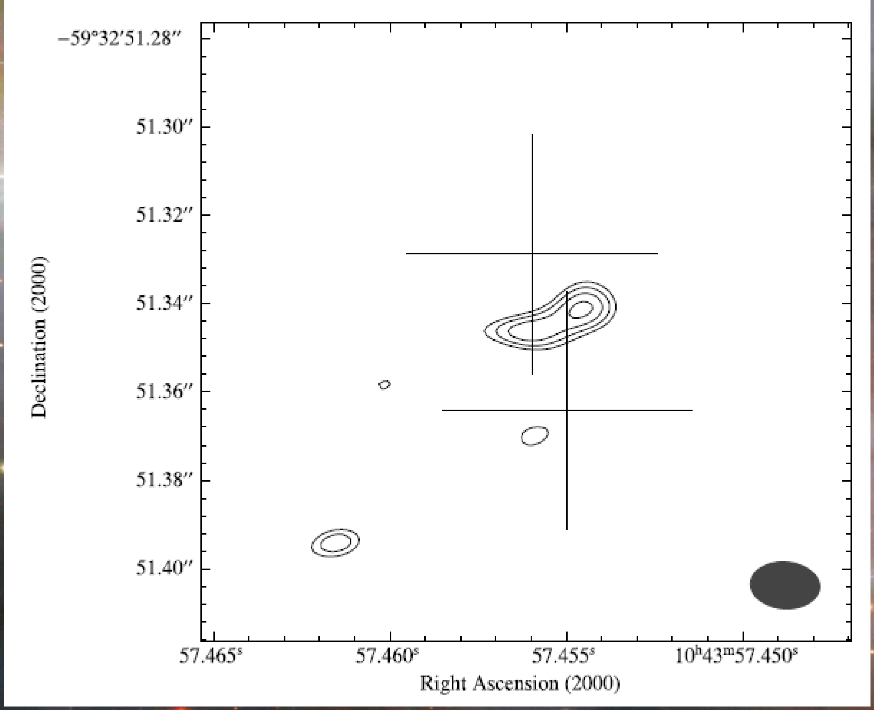
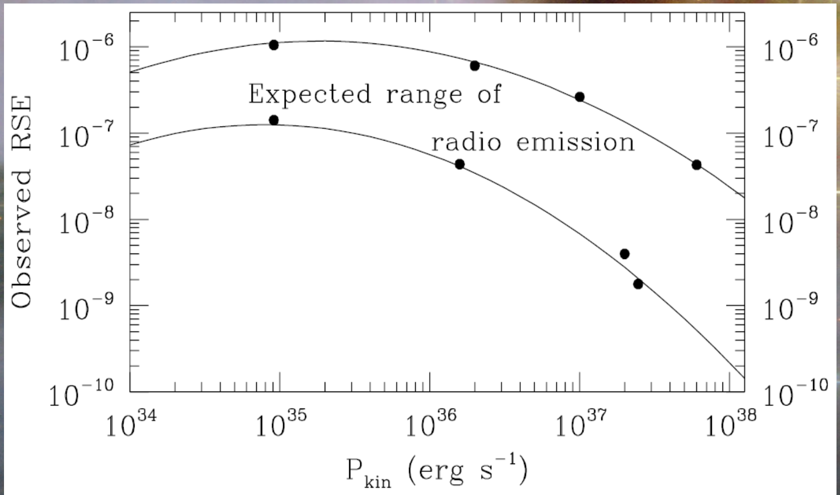
HD93129A, a very long period O-type system with imaged colliding-wind region using the Long Baseline Array at 2.3 GHz.

(Benaglia et al. 2015, A&A,479, A98)



Multiwavelength observations

2. Identification of additional members of the catalogue through dedicated radio observations.



Reasonable ranges of flux densities could be estimated on the basis of the present census of radio observations of PACWBs

(De Becker, Benaglia, Romero & Peri, 2017, in press)

→ helpful to prepare new observations

For a given stellar category, the kinetic power can be estimated
→ « truncated banana plot » gives a range of Radio synchrotron efficiency (L_{synch}/P_{kin})
→ assuming a spectral shape, one estimates a range of flux densities at a given frequency

Multiwavelength observations

3. Identification of additional members of the catalogue through dedicated hard-X-ray observations.

Soft X-rays dominated by thermal emission
→ strong need to explore hard X-rays (i.e. above 10 keV) to search for an inverse Compton scattering spectrum (power law)

Non-thermal high energy emission processes constitute a complementary indicator of PA
→ good sensitivity (e.g. INTEGRAL lack the required sensitivity)
→ good angular resolution (~ a few arcmin, or better)
→ spectral analysis capability (spectral index determination)

→ this provides a complementary and independent approach to identify additional PACWBs

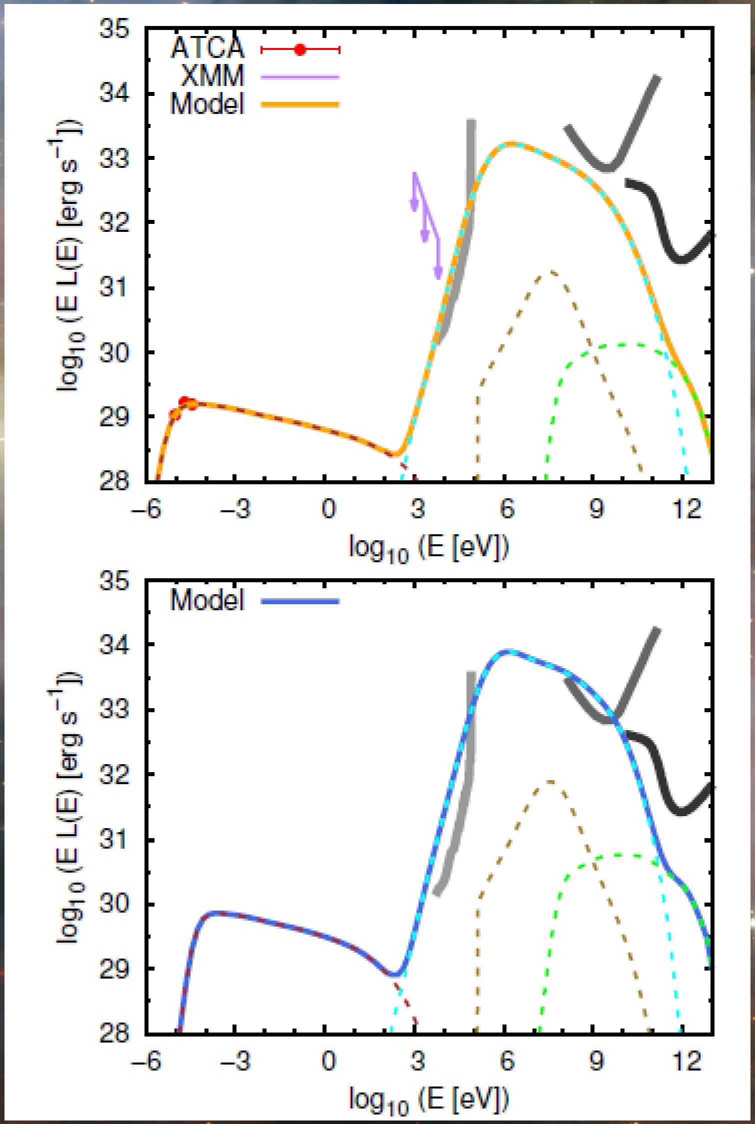
Multiwavelength observations

4. Improving our understanding of the non-thermal physics of these objects

Recent modelling allows to refine our understanding of the physics of these objects (e.g. HD93129A)

→ predicting capability

→ identification of necessary measurements to go one step further



(del Palacio et al. 2016, A&A, 591, A139)

Concluding remarks

I. Particle acceleration in CWBs is not a scarce phenomenon

The study of PACWBs is now switching to a new regime. From a few individual studies of massive binaries, one can now consider the study of a real class of objects.

II. The role of MW observations is highly important

I.a. Optical (and IR) observations :

- determination of the orbital parameters
- determination of the nature of the companion(s)

→ starting point for defining observation strategies

II.b. Radio observations to identify synchrotron radio emitters, and **hard X-ray** (and gamma-ray) **investigations** needed as well

→ identification of additional members in the catalogue

III. The determinaiton of the fraction of PACWBs among CWBs is a critical question


Thank you !