The investigation of Particle-Accelerating Colliding-Wind Binaries: a multi-wavelength endeavour

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Outline

Massive stars, binaries, and some of their emission processes

The sub-class of particle accelerators: PACWBs

Non-thermal emission from PACWBs

Concluding remarks
Massive stars, binaries, and some of their emission processes
What stars are we talking about?

**Hertzsprung-Russel diagram**

**Mass:**
Typically larger than $8 - 10 \, M_{\text{sol}}$

**Luminosity:**
Larger than $10^4 \, L_{\text{sol}}$ (most frequently in the range $10^5 - 10^6 \, L_{\text{sol}}$)

**Temperature:**
Larger than 20000 K (up to $\sim 10^5$ K)

**Evolution time-scale:**
A few/several Myr (up to $\sim 10$ Myr)
What stars are we talking about?

A crucial feature of massive stars: the **stellar wind**!

Consequence of the high luminosity
- **strong radiation pressure**
- massive stars lose large amounts of material during their evolution time

Conversion of radiative energy into mechanical energy!
What stars are we talking about?

A crucial feature of massive stars: the **stellar wind!**

Consequence of the high luminosity
→ strong radiation pressure
→ massive stars lose large amounts of material during their evolution time

- Depending on the spectral type/evolutionary stage, typical mass loss rates are in the range $10^{-7} – 10^{-5} \, M_{\odot}/yr$
  
  (mass loss rate of the solar wind $\sim 10^{-14} \, M_{\odot}/yr$)

- Ejected material can reach quite high speeds:
  Terminal velocities typically of the order $1000 – 3000 \, \text{km/s}$

As a result, a huge amount of kinetic power is ejected into the interstellar medium

$$P_{\text{kin}} = \frac{1}{2} \dot{M} V_{\infty}^2 \quad \rightarrow \quad P_{\text{kin}} \approx 3.16 \times 10^{35} \dot{M}_{\text{usual}} V_{\infty,\text{usual}}^2$$  \hspace{1cm} (\text{erg / s})

[ Usual units are $M_{\odot}/yr$ and km/s ]

Important for energy budget considerations!
The physics of massive stars can be viewed/discussed in terms of a succession of energy conversion processes.

\[ P_{\text{kin}} = \frac{1}{2} \dot{M} V_{\infty}^2 \]

Results from a conversion of radiative energy into kinetic power.
Emission processes from individual stellar winds

Thermal radio emission

Stellar winds consist of a plasma, made of ions and electrons, at a typical temperature of a few $10^4$ K.

→ Optically thick thermal bremsstrahlung spectrum

Emission spectrum predicted, and measured, as a power law with a positive spectral index:

$$S_\nu \propto \nu^{0.6}$$
Emission processes from individual stellar winds

Thermal radio emission

Conversion of a small fraction of the kinetic power into thermal radio emission

\[ P_{\text{kin}} = \frac{1}{2} M V^2 \]

\[ L_{\text{radio}} \]
Emission processes from individual stellar winds

The smooth wind is thus able to produce thermal bremsstrahlung in the radio and far-infrared domains. Do we expect significant emission processes to operate at other wavelengths?

Let's turn to one of the most important features of stellar winds: 

\textbf{instabilities} !

Responsible for a fragmentation of the stellar wind, with different parcels of wind material moving at different velocities

\begin{itemize}
  \item fragments moving at different speeds will collide
  \item intrinsic hydrodynamic shocks
  \item significant heating of the post-shock material
\end{itemize}

\rightarrow \textbf{thermal energy available to feed thermal emission processes!}
Emission processes from individual stellar winds

Shock physics:

Rankine-Hugoniot relations for strong shocks

→ post-shock temperature depends on the pre-shock velocity

\[ T_{\text{post-shock}} \approx 13.6 \times V_{\text{usual}}^2 \]

Pre-shock velocity for intrinsic shocks ~ 300 – 600 km/s

→ post-shock temperatures of the order of a few \(10^6\) K

→ stellar winds are expected to be thermal X-ray emitters

Some pioneering works exploring the idea that stellar winds of massive stars could produce thermal X-rays:

Emission processes from individual stellar winds

$L_X - L_{bol}$ relation:

Many observational studies emphasized a likely relation between thermal X-ray luminosity (emerging from the stellar wind) and the bolometric luminosity:

$$\frac{L_X}{L_{bol}} \sim 10^{-7}$$

Results from a competition between X-ray emission and intrinsic free free absorption by the stellar wind material (remember we are talking about soft X-rays, at most at a few keV)


A linear relation between $L_X$ and $L_{bol}$ should exist over a wide range of stellar wind parameters, with some deviations expected for very high / low density stellar winds.
Emission processes from individual stellar winds

Thermal X-ray emission

\[ P_{\text{kin}} = \frac{1}{2} \dot{M} V_\infty^2 \]

Results from a conversion of the kinetic power into thermal X-rays

March 2019

IIST, Trivandrum, India
Emission processes from individual stellar winds

**Thermal X-ray emission**

High resolution X-ray spectra
→ XMM-Newton/RGS spectrum of \( \zeta \) Pup
→ emission line spectrum produced by a hot plasma

Emission processes from individual stellar winds

Thermal X-ray emission

The case of evolved O-type stars:

Denser stellar winds → enhanced intrinsic absorption → reduced \( \frac{L_X}{L_{\text{bol}}} \) ratio

Ex: HD16691 and HD14947 (OIf*)
"presumably single stars"
(De Becker 2013, NewA, 25, 7)

\[
\frac{L_X}{L_{\text{bol}}} \sim 10^{-7.4} - 10^{-7.5}
\]

Low resolution XMM/EPIC spectra, fitted with a 1-T thermal model

March 2019
IIST, Trivandrum, India
When winds collide...

- Systems made of massive stars (O, B, WR...)
- Multiplicity is a crucial feature (binaries, triple and higher multiplicity...)
- A large fraction of massive stars are in binary systems
- Variability on the orbital time-scale is very important
- Strong stellar winds collide and create strong shocks
When winds collide...

A fraction of the wind kinetic power is injected into the colliding-wind region.
Emission processes from colliding winds

Shock physics:

Rankine-Hugoniot relations for strong shocks

→ post-shock temperature depends on the pre-shock velocity

\[ T_{\text{post-shock}} \approx 13.6 \times V_{\infty,\text{usual}}^2 \]

Pre-shock velocity for CW shocks: \( V_\infty \sim 2000 \text{ – } 3000 \text{ km/s} \)

→ post-shock temperature of the order of \text{ a few } 10^7 \text{ K}

→ post-shock plasma expected to be a thermal X-ray emitter
Considering the intrinsic emission from the winds in the system

\[ \frac{L_{X,1}}{L_{bol,1}} \sim 10^{-7} \rightarrow L_{X,1} \sim 10^{-7} L_{bol,1} \]

\[ \frac{L_{X,2}}{L_{bol,2}} \sim 10^{-7} \rightarrow L_{X,2} \sim 10^{-7} L_{bol,2} \]

\[ L_{X,tot} = L_{X,1} + L_{X,2} \sim 10^{-7} (L_{bol,1} + L_{bol,2}) = 10^{-7} L_{bol,tot} \]

\[ \rightarrow \frac{L_{X,tot}}{L_{bol,tot}} \sim 10^{-7} \]
Emission processes from colliding winds

Considering the intrinsic emission from the winds in the system and the contribution from the Colliding-Wind Region (CWR)

\[
L_{\text{X,1}} / L_{\text{bol,1}} \sim 10^{-7} \\
\rightarrow L_{\text{X,1}} \sim 10^{-7} L_{\text{bol,1}}
\]

\[
L_{\text{X,2}} / L_{\text{bol,2}} \sim 10^{-7} \\
\rightarrow L_{\text{X,2}} \sim 10^{-7} L_{\text{bol,2}}
\]

\[
L_{\text{X,tot}} = L_{\text{X,1}} + L_{\text{X,2}} + L_{\text{CWR}} > 10^{-7} (L_{\text{bol,1}} + L_{\text{bol,2}}) = 10^{-7} L_{\text{bol,tot}}
\]

\[
\rightarrow L_{\text{X,tot}} / L_{\text{bol,tot}} > 10^{-7}
\]

A luminosity ratio larger than $10^{-7}$ is often considered as an indication of colliding winds contributing to the overall thermal X-ray emission → indirect indication for binarity!
Emission processes from colliding winds

Thermal X-ray emission

\[ P_{\text{kin,CWR}} = f_{\text{CWR}} P_{\text{kin}} \]

\[ L_{X,\text{CWR}} \]

Results from a conversion of the kinetic power injected in the CWR into thermal X-rays
Emission processes from colliding winds

Thermal X-ray emission

Cyg OB2 #8A: O6lf + O5.5III(f)

\[ \frac{L_X}{L_{bol}} \sim 10^{-5.6} - 10^{-5.5} \]
\[ \rightarrow \text{high X-ray overluminosity} \]


Multi-observatory, phase-folded light curve (P \sim 22 d)

(ephemeris determined on the basis of visible data)

Multiple components model
Emission processes from colliding winds

Thermal X-ray emission

**HD167971:** (O7.5III + O9.5III) + O9.5 I

- Stellar wind of component Aa
- Stellar wind of component Ab
- Stellar wind of component B
- Wind collision region Cwab
- Wind collision region CWAB

How many sources of thermal X-rays in this system?

How should a variability come from?

- Wind collision region CWAB
- Potentially, the eclipse if the AaAb system

\[
P_{AaAb} = 3.32 \text{ d (circular orbit, eclipsing)}
\]

\[
P_{AB} \approx 21 \text{ yr (eccentric orbit)}
\]

*(Leitherer et al. 1987, A&A, 185, 121)*

Emission processes from colliding winds

**Thermal X-ray emission**

Long period, ~21 yr!
Eccentric orbit → significant variation of the separation between 2002 and 2014

CWAB contributes only to a moderate fraction of the overall X-ray spectrum
→ the spectrum is not dominated by the long period wind collision region

However!
Slight – marginal – variation compatible with an eclipse effect between the two observations in 2002

Significant overluminosity:
\[ \frac{L_X}{L_{bol}} \approx 1.3 – 1.8 \times 10^{-6} \]

Thermal X-ray efficiency ratio:
\[ \frac{L_X}{P_{\text{kin}}} \approx 1.2 – 1.6 \times 10^{-3} \]

Emission processes from colliding winds

Thermal X-ray emission

WR140 : WC7pd + O5.5f (III – I)

P ~ 7.9 yr
e ~ 0.9

RXTE X-ray light curve
(2 – 10 keV)

Emission processes from colliding winds

**Thermal X-ray emission**

Eta Car : LBV ?

\[ P \sim 5.5 \text{ yr} \]

Modelling the X-ray spectrum using a hydro + radiative code depending on wind parameters

→ determination of mass loss rates and terminal velocities:

\[ P : 2.5 \times 10^{-4} \, \text{M}_{\odot} / \text{yr} ; 500 - 700 \text{ km/s} \]

\[ S : 10^{-5} \, \text{M}_{\odot} / \text{yr} ; 3000 \text{ km/s} \]

So far, we have learned that..

- individual stellar winds can produce thermal radio emission
- individual stellar winds can produce thermal X-ray emission
- colliding stellar winds can produce additional thermal X-ray emission

Those features are common among Colliding-Wind Binaries (CWB)
The sub-class of particle accelerators: PACWBs
So-called 'standard scenario' for particle acceleration by massive stars → Diffusive Shock Acceleration in the wind collision region in massive binaries

Strong shocks likely to be active in DSA
Particle acceleration in CWBs

So-called 'standard scenario' for particle acceleration by massive stars → Diffusive Shock Acceleration in the wind collision region in massive binaries

\[ \Delta \frac{E}{E} \propto \frac{V}{c} \]

Relative energy gain :

\[ E' = \gamma (E + p_x V) \]

Power law distribution :

\[ N(E) \propto E^{-p} \]

Iterative process with escape probability at every iteration

Strong shocks: \( p \sim 2 \)

(e.g. Longair, 1994, High energy astrophysics – 2\(^{nd}\) Edition)
Particle acceleration in CWBs

$$P_{\text{kin,CWR}} = f_{\text{CWR}} P_{\text{kin}}$$

$$P_{\text{NT}} = f_{\text{NT}} P_{\text{kin,CWR}}$$

Results from a conversion of the kinetic power injected in the CWR into non-thermal particles
Particle acceleration in CWBs

The power injected in non-thermal particles is distributed between electrons and hadrons.

\[ P_{NT} = f_{NT} P_{\text{kin}, CWR} \]

\[ P_e = f_e P_{NT} \quad P_h = f_h P_{NT} \]
Radiative processes involving relativistic electrons:

- **Synchrotron radiation**
  Interaction with the magnetic field

- **Inverse Compton scattering**
  Interaction with the photospheric radiation field

- **Relativistic bremsstrahlung**
  Interaction with nuclei in the stellar wind material
  (most of the time negligible with respect to other processes)
Among the class of CWBs, about 40 systems are known to be particle accelerators:

Catalogue of PACWBs:

- Most PACWBs are identified thanks to synchrotron radiation in the radio domain (relativistic electrons)

- In one case, there is confirmation of non-thermal X-ray and gamma-ray emission (relativistic electrons and protons)

Let's have a look at their non-thermal signatures
Non-thermal emission from PACWBs
Synchrotron emission from PACWBs

The radio spectrum is a combination of thermal (optically thick) emission from the stellar winds, and synchrotron emission produced in the colliding wind region (composite spectrum!). The spectral index can be neither typical of pure NT or T emission.

\[ S_{\nu}^{\text{obs}} = S_{\nu}^{\text{th}} + S_{\nu}^{\text{syn}} e^{-\tau_{\nu}^{\text{ff}}} \]

The diagram illustrates the components of the radio spectrum with the equations for the thermal and synchrotron emissions. The spectral index \( \alpha \) is given by:

\[ \alpha = \frac{\ln \left( \frac{S_{\nu_1}}{S_{\nu_2}} \right)}{\ln \left( \frac{\nu_1}{\nu_2} \right)} \]
Synchrotron emission from PACWBs

Synchrotron emission is the most efficient tracer of particle acceleration in massive binaries! → valuable probe for non-thermal physics in massive binaries

- Spectral index
- Brightness temp.
- Variability

\[ \alpha < 0.6 \ ( \text{for } S_\nu \ \text{prop. to } \nu^\alpha ) \]

\[ \rightarrow \text{deviation w.r.t. pure thermal emission} \]

Component with \( T_B \sim 10^6 - 10^7 \) K

Emission related to the colliding-wind region
- physical conditions are phase dependent
- orientation effect due to free-free absorption


http://www.astro.ulg.ac.be/~debecker/pacwb/
Synchrotron emission from PACWBs

Simulations of radio emission from colliding-wind binaries  

Typical case of a WR + O system

1.6 GHz

22 GHz
Synchrotron emission from PACWBs

• Turn-over processes

**Synchrotron Self-Absorption (SSA)**
- optically thick spectrum with $\alpha = 5/2$
- active if the number density of NT $e$ is high enough

**Razin-Tsytovitch effect**
- suppression of the effect of beaming for NT electrons embedded in a thermal plasma
- strong suppression of synchrotron emission below a cut-off frequency
- may contribute for PACWBs

**Free-free absorption (FFA)**
- absorption of radio photons by thermal electrons very abundant in the wind plasma
- highly dependent on stellar separation, system orientation, wind properties…
- very important for PACWBs, origin of a strong phase-locked variability
Simulations of radio emission from colliding-wind binaries  \( \text{Dougherty et al. 2003, A&A, 409, 217} \)

**Effect of FFA on the spectrum, as a function of the inclination of the system**

- \( i < 0^\circ \): WR wind in front
- \( i > 0^\circ \): O wind in front

→ orientation effects are very important!

At some lower frequencies, the intrinsic synchrotron emission may be high, but severely attenuated by FFA
Synchrotron emission from PACWBs

**Cyg OB2 #8A**: binary system with a period of about 22 d (VLA observations) (Blomme et al. 2010, A&A, 519, A111)

HD167971: triple system with a long period of about 21 yr (VLA observations) (Blomme et al. 2007, A&A, 464, 701)
Synchrotron emission from PACWBs

VLBI observations: imaging of the synchrotron emission region

WR147: a system with an very long orbital period!
(MERLIN observations at 5 GHz)

Cyg OB2 #5: a multiple O-type system including notably a 6.7 yr period!
(VLBA observations at 8.4 GHz)
Synchrotron emission from PACWBs

VLBI observations: imaging of the synchrotron emission region

HD93129A: a system with an orbital period of decades!
(LBA observations at 2.3 GHz)
(Benaglia et al. 2015 A&A, 579, A99)

WR140: a binary system with a period of about 8 yr
(VLBA observations at 8.4 GHz)
High energy NT emission from PACWBs

What about the detection of **high energy NT emission**?

**Inverse Compton scattering is expected to be active in CWBs**

→ **what about soft X-ray observations (below 10 keV)?**

Soft X-ray spectra are dominated by the thermal emission from the colliding winds (and from individual winds)

→ **soft X-rays not adequate** (no detection of any IC scattering component in XMM spectra so far)

→ **strong requirement to explore hard X-rays**

(De Becker 2007, A&ARv, 14, 171)
Inverse Compton scattering

Considering the high radiative energy density, IC scattering is the most efficient cooling process for relativistic electrons in a CWR.

Energy loss rate:

$$-\left(\frac{dE}{dt}\right)_{IC} = \frac{4}{3} \sigma_T c U_{rad} \gamma^2 \beta^2$$

Typical energy of scattered photons:

$$<\nu> = \frac{4}{3} \gamma^2 \nu_o$$

For a population of relativistic electrons:

$$\left(\frac{dE}{dV dt d\nu}\right)_{IC} \propto \nu^{-\frac{p-1}{2}}$$

(Blumenthal & Gould 1970, Rev. Mod. Phys., 42, 237)

Comparison to synchrotron radiation:

Energy loss rate:

$$-\left(\frac{dE}{dt}\right)_{synch} = \frac{4}{3} \sigma_T c U_{mag} \gamma^2 \beta^2$$

Synchrotron/IC luminosity ratio:

$$\frac{L_{synch}}{L_{IC}} = \frac{-\left(\frac{dE}{dt}\right)_{synch}}{-\left(\frac{dE}{dt}\right)_{IC}} = \frac{U_{mag}}{U_{rad}}$$

$$U_{mag} << U_{rad} \rightarrow IC \text{ dominates}$$

High energy NT emission from PACWBs
High energy NT emission from PACWBS

Energy injected in relativistic electrons is mainly radiated through IC scattering, because the energy density in the radiation field is larger than that of the local magnetic field.
High energy NT emission from PACWBs

What about emission processes involving relativistic protons?

**Neutral pion decay from proton-proton collisions**

\[ p + p \rightarrow \pi^0 + X \]
\[ \pi^0 \rightarrow \gamma + \gamma \]

→ a fraction of relativistic protons can interact with thermal material, and finally produce \( \gamma \)-rays

→ in principle, CWB could be \( \gamma \)-ray emitters up to energies limited by the energy spectrum of relativistic protons

However, the interaction gamma-rays with the intense ambient radiation field yields \( \gamma + \gamma' \rightarrow e^+ + e^- \) (pair creation)

→ the radiation field produced by massive stars is quite opaque to \( \gamma \)-rays, and a significant attenuation is expected

Energy injected into relativistic protons (and potentially heavier nuclei) is expected to be partly radiated through hadronic processes, and the residual energy contributes to the population of Galactic cosmic-rays.

High energy NT emission from PACWBs
Inverse Compton scattering in hard X-rays:

- Several PACWB in the Cygnus region → no detection with INTEGRAL (De Becker et al. 2007, A&A, 472, 905)


- WR140 potentially detected with Suzaku, but might be a contamination by a background Seyfert galaxy (Sugawara et al. 2015, PASP, 67, 121)

Eta Car: extreme CWB with a $P \sim 5.5$ yr
High energy NT emission from PACWBs

Detection in $\gamma$-rays:


- 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)
High energy NT emission from PACWBs

Can we make some predictions about the expected emission of PACWBs in the high energy domain (where detections so far are rare)?

→ yes, we can!

The long period system HD93129A:
Spectral energy distributions for different situations/orbital phases, confronted to sensitivity curves for various observatories
→ significant variability
→ chances of detection depend on the assumed parameters, and on the orbital phase
→ strong evidence that elusive high energy detections may become more probable if systems are probed at adequate epochs

High importance of models to help to prepare observations!

Concluding remarks
Concluding remarks

- Colliding-wind massive binaries (CWBs) display a rich and diversified physics

- Many physical processes are at work in various spectral domains, hence the interest of multi-wavelength investigations

- These systems can be particle accelerators, hence the PACWB status

- PACWB are efficient non-thermal emitters in the radio domain, and are very good candidates for high energy non-thermal emission

- These systems offer the opportunity to study the same non-thermal physics as supernova remnants, but in a different part of the parameter space and a different geometry

- A better understanding of their physics, considering their full Galactic population, is relevant in the context of the study of the sources of Galactic cosmic-rays
Thank you!