



# Gamma rays from colliding winds in massive binaries

## Status and prospects

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### Abstract

Binary systems formed by early-type stars with strong winds are known to display variable non-thermal radio emission, thermal X-rays, and, at least in one case (Eta Carina),  $\gamma$  rays. Some of these systems are quite eccentric and the conditions for efficient particle acceleration and  $\gamma$ -ray production might manifest only occasionally. In this paper, I briefly review the physics of colliding wind binaries with emphasis on the observational signatures of non-thermal particle acceleration. I discuss, in particular, the case of the system HD 93129A which is made up of an O2 If\* star (the primary) and an O3.5 V star (the secondary). The primary is among the earliest, hottest, most massive, luminous, and windy O stars in the Galaxy. The periastron passage during 2018 will offer an outstanding observational window that will be exploited by an international multi-wavelength campaign.

**Keywords** Emission-line stars (Of · Be · Luminous Blue Variables · Wolf–Rayet · etc.) ·  $\gamma$ -Ray sources · Mass loss and stellar winds · Radiation mechanisms

**Mathematics Subject Classification** 97.30.Eh · 98.70.Rz · 97.10.Me · 95.30.Gv

## 1 Introduction

Early-type massive stars are very luminous and generate strong winds with mass loss rates up to  $\sim 10^{-5} M_{\odot} \text{ year}^{-1}$ . At the end of their lives, the most massive stars can lose mass at even higher rates. The escape velocity of these winds reaches several times  $1000 \text{ km s}^{-1}$ .

If these stars form binary systems, something that is quite common since they are born in groups inside giant molecular clouds, the winds will collide. The result of such collision is the formation of a system of shocks, which will heat up

the plasma of the winds. When the shocks are adiabatic, diffusive non-thermal particle acceleration can occur (Eichler and Usov 1993). The resulting population of relativistic particles will cool locally mainly through synchrotron radiation and inverse Compton (IC) up-scattering of stellar photons. As a consequence, colliding wind binaries (CWBs) may become non-thermal radio and even  $\gamma$ -ray sources (Benaglia and Romero 2003). The power law index of the spectral distribution of particles can vary widely from  $-1$  to values even steeper than  $-2$  depending on the system geometry and escape conditions (e.g. Bykov 2014).

De Becker and Rauq (2013) have identified 43 binary or multiple systems with non-thermal emission in the Galaxy (see also De Becker et al. 2017). Current interferometric radio observations of some of these systems allow to map the evolution of the non-thermal region along the orbit yielding the possibility to get insights into the mechanism of particle acceleration in changing physical conditions. Thus, CWBs are a kind of natural laboratories for the investigation of cosmic ray production.

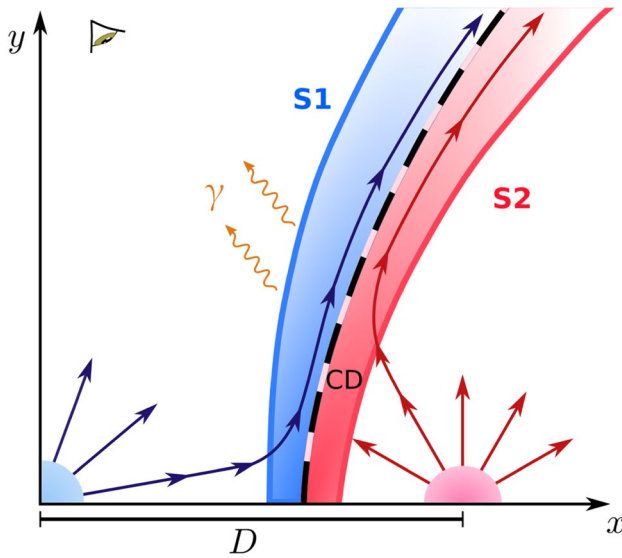
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**Fig. 1** Sketch of the system of shocks formed in a CWB. There are two shocks (S1 and S2) that move in opposite directions from the contact discontinuity (CD). From del Palacio et al. (2016)

## 2 Particle acceleration in the colliding winds of early-type binaries

In an early-type binary, the winds from the primary and the secondary stars flow nearly radially and collide at a point located at a distance  $r_i$  from the  $i$ -star, given by

$$r_1 = \frac{1}{1 + \eta^{1/2}} D, \quad r_2 = \frac{\eta^{1/2}}{1 + \eta^{1/2}} D. \quad (1)$$

Here, the subscript “1” stands for the primary star, and “2” for the secondary,  $D$  is the binary separation, and the parameter  $\eta$  is defined in terms of the wind terminal velocities  $v_\infty$  and the stellar mass loss rates  $\dot{M}$ :

$$\eta = \frac{\dot{M}_2 v_{\infty,2}}{\dot{M}_1 v_{\infty,1}}. \quad (2)$$

A system of two shocks is formed in the collision: one moves in the wind of the primary (S1) and the other in the wind of the secondary (S2). Matter flows away along the shocked region that surrounds the contact discontinuity (CD); see Fig. 1.

Diffusive shock acceleration operates in both shocks if they are adiabatic, so some particles depart from the Maxwell–Boltzmann distribution and acquire a power law spectrum with index  $\sim -2$ . The cutoff of this population will depend on the competing rates of acceleration and losses (see De Becker 2007 for a detailed discussion).

In the steady state, the particle distribution can be obtained from the transport equation:

$$\frac{\partial}{\partial E} \left[ \frac{dE}{dt} \Big|_{\text{loss}} N(E) \right] + \frac{N(E)}{t_{\text{esc}}} = Q(E), \quad (3)$$

where  $t_{\text{esc}}$  is the convection timescale,  $Q(E)$  is the source term, and  $\frac{dE}{dt} \Big|_{\text{loss}}$  includes all kind of losses. In several situations of astrophysical interest, magnetic field amplification can occur (e.g. Schure et al. 2012). This can significantly modify the maximum energies that can be achieved and the shape of the spectrum.

## 3 Non-thermal radiation

Relativistic electrons cool in the colliding wind region through synchrotron, Bremsstrahlung, and IC radiation. Protons suffer  $pp$  collisions, but they are convected away before cooling. They can reach multi-TeV energies and are later injected into the interstellar medium. As for the electrons, the ratio of magnetic to photon energy densities in the shocked region will determine which mechanism, synchrotron or IC, is more efficient:

$$\frac{L_{\text{synchr}}}{L_{\text{IC}}} = \frac{U_B}{U_{\text{ph}}}. \quad (4)$$

Since the photon density is contributed by the bolometric luminosity of the stars, we get the following expression for the IC power (De Becker 2007):

$$L_{\text{IC}} = \frac{2}{c} \frac{L_{\text{synchr}}}{B^2} \left( \frac{L_1}{r_1^2} + \frac{L_2}{r_2^2} \right), \quad (5)$$

where  $B$  is the magnetic field in the colliding wind region and  $L_i$  is the bolometric luminosity of the  $i$ -star. Conditions vary along the orbit in any eccentric system, so the importance of each contribution will change with the relative position of the stars. The radiation will be affected by different absorption processes that depend on the particle and photon densities, so the appearance of a particular system to distant detectors will change from one case to another (e.g. del Palacio et al. 2016).

Radiative models of different degrees of complexity have been developed by Benaglia and Romero (2003), Pittard and Dougherty (2006), Reimer et al. (2006), and Reitberger et al. (2014), among others. The reader is referred to these works for additional details.

## 4 Current observational status

Most of particle-accelerating CWBs have been detected in radio using interferometric techniques. A classical example is the well-known system WR140 (Dougherty et al. 2005). In X-rays, the detection of non-thermal radiation is hampered by the high temperatures reached by the shocked plasma. This makes the thermal radiation overwhelm any non-thermal contribution (mainly due to IC) below energies of  $\sim 10$  keV. So far, only two systems have been shown to have non-thermal X-rays: Eta Carinae and WR 140.

In  $\gamma$ -rays, the situation is similar: only Eta Carina has been clearly detected by *AGILE* satellite (later confirmed by *Fermi*; see Tavani et al. (2009)). Recently, the association of the Wolf–Rayet binary W11 with a *Fermi* source has been suggested by Pshirkov (2016) and debated by Benaglia (2016).

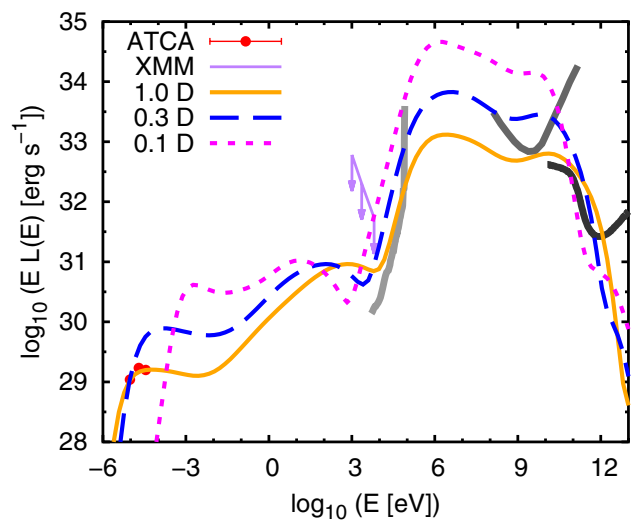
## 5 Eta Carinae

Eta Carinae is a heavily obscured and peculiar source. The system includes a luminous blue variable—LBV—star of 90 solar masses and a luminosity of about  $5 \times 10^6 L_{\odot}$ . The secondary is a WR star of  $\sim 30$  solar masses. The mass loss rate of the primary is huge, reaching perhaps up to  $10^{-3} M_{\odot} \text{ year}^{-1}$ . Terminal wind velocities of the primary and secondary winds are estimated to be  $\sim 500$  and  $3000 \text{ km s}^{-1}$ , respectively. For a general overview, see Reitberger et al. (2012).

The conditions in the shocks change along the orbit, inducing variability in particle acceleration,  $\gamma$ -ray production, and absorption. There is a clear variability with the orbital phase. Different behaviour is observed at low (0.3–10 GeV) and high ( $> 10$  GeV)  $\gamma$ -ray energies. Short-term variability occurs at periastron. The flux of the high-energy component varies by a factor 34, but is different during the two periastron passages observed so far. The multi-wavelength behaviour suggests that the low-energy component is produced by IC scattering, whereas the high-energy one might be the result of  $pp$ -interactions. The maximum energies for protons could reach  $\sim 10^{15}$  eV (Balbo and Walter 2017).

## 6 HD 93129A

The most promising binary system for future  $\gamma$ -ray detection is perhaps HD 93129A. This is the most massive binary known in the Galaxy, with a total mass of  $200 \pm 45 M_{\odot}$ , even more than Eta Carinae. The system is located at 2.3 kpc; the primary is an O2 If\* star and the secondary is likely an O3.5 V star. The wind collision region of HD 93129A was



**Fig. 2** Broadband SEDs for the epoch of radio observations (1.0D), and two additional epochs: 2016 (0.3D), and roughly the periastron passage (0.1D). For the epoch of radio observations, we show the ATCA data and upper limits in the X-ray flux derived from Benaglia et al. (2006). We show instrument sensitivity curves for 1-Ms NuSTAR (grey), 4-year Fermi (dark grey), and 50-h CTA (black). From del Palacio et al. (2016)

recently resolved for the first time using very large baseline interferometry by Benaglia et al. (2015). These data at radio frequencies allow to characterize the injection spectrum of relativistic particles, so some detailed models have been produced (del Palacio et al. 2016). A key ingredient is the magnetic field strength. Multifrequency observations including radio, optical, X-ray (*XMM-Newton* and *NuSTAR*), and  $\gamma$ -ray observatories (*Swift* and *AGILE*) are programmed to cover the periastron passage towards the end of 2018. The observations will allow to investigate the physical properties of the acceleration region and to detect the expected high-energy emission. In Fig. 2, we show the spectral energy distribution (SED) estimated for a low value of the magnetic field and a hard injection spectrum (see del Palacio et al. 2016 for details). The actual SED will allow to solve the inverse problem and to determine constraints on the physical parameters.

## 7 Conclusions

Colliding wind binaries are, in many cases, non-thermal radio sources. This clearly indicates that particles (at least electrons) are accelerated in them up to relativistic energies. Since this acceleration occurs in a region that has an important photon energy density provided by the luminous stars, IC interactions are unavoidable. However, the high magnetic field can quench the high-energy emission if synchrotron radiation becomes the main cooling channel. In addition, the non-thermal radiation can be suppressed by

the high densities of thermal gas and the absorbing photon fields. The conditions for particle acceleration vary along the orbit, with optimal windows for observations occurring at different times for different wavelengths.

So far,  $\gamma$  rays have been detected for sure only from Eta Carinae, an extremely massive colliding wind system that includes a rare luminous blue variable star and a Wolf–Rayet companion. Two different components in the high-energy radiation are distinguished, suggesting that more than a single mechanism operates in the system.

HD 93129A is another very massive colliding wind binary with a long period ( $\sim 100$  years). It is a confirmed non-thermal radio source and an excellent candidate for GeV  $\gamma$ -ray emission. The forthcoming periastron passage in late 2018 will offer a unique opportunity to study this remarkable system and determine the physical conditions in the acceleration zone. There is an ongoing international campaign that includes *Chandra*, *NuSTAR*, *XMM-Newton*, and *Swift*. Data from *AGILE* would be essential to complement this combined effort.<sup>1</sup>

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<sup>1</sup> *Fermi*, being an instrument for surveys, is perhaps not the best option for tracking this event.