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Gamma rays from colliding winds of massive stars

Abstract. Colliding winds of massive binaries have long been considered as potential sites of non-thermal high-energy photon production. This is motivated by the detection of non-thermal spectra in the radio band, as well as by correlation studies of yet unidentified EGRET $\gamma$-ray sources with source populations appearing in star formation regions.

This work re-considers the basic radiative processes and its properties that lead to high energy photon production in long-period massive star systems. We show that Klein-Nishina effects as well as the anisotropic nature of the inverse Compton scattering, the dominating leptonic emission process, likely yield spectral and variability signatures in the $\gamma$-ray domain at or above the sensitivity of current or upcoming gamma ray instruments like GLAST-LAT. In addition to all relevant radiative losses, we include propagation (such as convection in the stellar wind) as well as photon absorption effects, which a priori can not be neglected.

The calculations are applied to WR 140 and WR 147, and predictions for their detectability in the $\gamma$-ray regime are provided. Physically similar specimen of their kind like WR 146, WR 137, WR 138, WR 112 and WR 125 may be regarded as candidate sources at GeV energies for near-future $\gamma$-ray experiments.

Finally, we discuss several aspects relevant for eventually identifying this source class as a $\gamma$-ray emitting population. Thereby we utilize our findings on the expected radiative behavior of typical colliding wind binaries in the $\gamma$-ray regime as well as its expected spatial distribution on the $\gamma$-ray sky.

Keywords Stars: early-type · Stars: binaries · Stars: winds, outflows · Gamma rays: theory · Radiation mechanisms: non-thermal

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1 Introduction

By far the most convincing evidence for particle acceleration to relativistic energies mediated by the supersonic (terminal velocity $v_\infty \sim 1000$-5000 km/s) winds of massive ($M \sim 10^{-6.49} \ldots 10^{-5} \, \text{M}_\odot/\text{yr}$), hot ($T \sim 30000 \ldots 50000 \text{K}$) stars comes from the observation of non-thermal radio emission (e.g. [1]). This has been interpreted by synchrotron emission on the basis of the measured spectra (much steeper than the canonical value $\alpha_r \sim +0.6$, $F_\nu \propto \nu^{-\alpha_r}$) and high brightness temperatures of $\sim 10^6 \ldots 10^7 \text{K}$, far exceeding $\sim 10^4 \text{K}$ expected from free-free emission from a steady-state isothermal radially symmetric wind [2]. Those particles have been suggested to be accelerated either in shocks caused by the instability of radiatively driven winds [3], in the shocked wind collision region of multiple systems or in the termination shock [4]. Triggered by these observations it has been quickly realized that $\gamma$-ray emission should be expected as well, either through leptonic processes (inverse Compton scattering (IC) of the copious stellar UV photons (e.g. [5]), relativistic bremsstrahlung (e.g. [6]) or hadronic interactions of co-accelerated ions with the dense wind material (e.g.[7,8]). This has established a plausible physical setting for massive star systems being putative $\gamma$-ray emitters. Indeed, positional coincidences of Wolf-Rayet (WR) stars with the population of so far unidentified EGRET sources have been found for 13 WR-binary systems [9,10,11]. Recently, the presence of non-thermal radio emission has been linked to the binarity status of the stellar systems [12], which supports the picture of particles being predominantly accelerated at the forward and reverse shocks from the colliding supersonic winds from massive stars.
In this work we consider long-period binary systems as the most prospective $\gamma$-ray emitters detectable by the near-future experiment GLAST-LAT, and extend previous theoretical work by including propagation, and anisotropy and Klein-Nishina (KN) effects of the inverse Compton (IC) scattering process.

Since the IC process has been shown to likely dominate the $\gamma$-ray production (e.g. [19,22]), this process is prone to determine the spectral appearance of WR-binaries at high energies. Here Klein-Nishina as well as anisotropy effects, neglected in past modeling of these systems, may provide valuable features that can be instrumental in identifying this source population at $\gamma$-ray energies. Further spectral imprints are expected from particle propagation within the extended colliding wind region. A simplified geometry of the system proofs sufficient to highlight these effects.

In the following we consider the sketch of a colliding wind region (CWR) that has been presented by e.g. Eichler & Usov (1993) [19] with the stagnation point defined by balancing the wind momenta with the assumption of spherical homogenous winds. Since in general $\dot{M}_{WR} > \dot{M}_{OB}$ and $v_{\infty,WR} \approx v_{\infty,OB}$ the shock distance to the OB-star, $x_{OB}$, is much smaller than to the WR-star. We shall neglect here the interaction of the stellar radiation fields on the wind structure ([23,24]): This effect is inherent to short-period binaries, and may influence the wind speed, thereby weakening the ram balance, shock strength and temperature. Thus our theoretical considerations here shall be restricted to long-period binaries. The stellar winds are permeated by magnetic fields originating from the surface of the massive star. Estimates for surface magnetic field strengths range from below $B_s = 100$ G (e.g. [25]) up to $\sim 10^4$ G in WR-stars [26]. In the following we fix this value to a reasonable 100 G, unless stated otherwise, and use the well-developed magnetic rotator theory (e.g. [27]) to estimate the field strength $B_G$ (in Gauss) at the CWR. Typically $> mG$ or higher field strengths are expected, assumed to be constant throughout the emission region, at the CWR in long-period binaries. The shocked high-speed winds are creating a region of hot gas that is separated by a contact discontinuity, and a forward and reverse shock follows. The gas flow velocity in this region away from the stagnation point will be some fraction of the wind velocity which we keep constant at $V$ for simplicity. A simplification of the geometry from a bow-shaped to a cylinder-shaped collision region (with radius $r$ perpendicular to the line-of-centres of the two stars, and given thickness) allows us to solve the relevant continuity equations analytically (see [28]). Here we consider diffusive shock acceleration (with acceleration rate $a$) out of a pool of thermal particles, and take into account (continuous) radiative losses (synchrotron, IC, bremsstrahlung and Coulomb losses), (energy-independent) diffusion by introducing an escape time $T_0$ and convection with speed $V$ (set to $V = 1/2v_{\infty,OB}$ if not noted otherwise). The maximum particle energy is thereby determined self-consistently.

At a distance $> r_0$ from the stagnation point convection along the post-shock flow will dominate over diffusion. At $r_0$ diffusion balances convection. Correspondingly, the emission region is divided into a region where acceleration/diffusion dominates, the "acceleration zone",...
and the outer region where convection dominates, the "convection zone". The steady-state diffusion-loss equation can be solved analytically provided suitable approximations for the KN cross section are applied (see [28]). Fig. 1 shows an example of all loss time scales for typical parameters of WR-binaries. The transition region, between the Thomson and extreme KN range of the IC cross section, appears relevant for typical long-period WR-systems. A rigorous treatment of the Compton losses must therefore include KN effects.

We find electron spectra with smooth roll-overs that cut-off at higher energies as compared to electron spectra that remain in the Thomson approximation throughout the whole particle energy range. In the convection region the particles loose energy radiatively as well as through expansion losses while in the post-shock flow. This leads to a dilution of the particle density as well as a deficit of high energy particles. The corresponding volume-integrated photon spectra soften (see Fig. 2), as a deficit of high energy particles. The corresponding volume-integrated (i.e. acceleration plus convection zone) IC spectrum is also shown (upper dashed line). All other parameters are the same as in Fig. 1.

Details are described in [28].

4 Application to archetypal systems

4.1 WR 140

The archetypical WR-binary system WR 140 (WC 7pd + O4-5 V), located in the Cygnus constellation at a distance of \( \sim 1.85 \) kpc, is one of the most detailed studied specimen of its kind. Its long (\( \sim 8 \) years) period and extreme eccentricity (\( e \approx 0.88 \)) makes it a diverse system
to study its non-thermal behavior in the radio band. For
the first time, Dougherty et al. (2005) resolved the
bow-shaped arcs of the emission region at 8 epochs of 8.4
GHz VLBA observations. We used the synchrotron spec-
tra and system parameters as published in [30] to predict
its non-thermal high energy emission at various phases.
With these values the CWR is located at a distance $x_{OB}$
of 0.32 times the stellar separation. For a surface mag-
netic field of 100 G roughly equipartition values for its
field strength at the CWR location follow. With a rela-
tivistic particle injection energy of $\sim 10^{-2\ldots-3}\%$ of
the kinetic wind energy, the synchrotron fluxes at the con-
sidered phases (0.2, 0.67, 0.8, 0.95) could be reproduced.
From radio observational grounds, relativistic electrons
at least up to $\sim$10-100 MeV do exist. This limits the dif-
fusion coefficient $\kappa$ to sufficiently low values which will
allow the acceleration rate to overcome the Coulomb loss
rate at low energies. A further constraint of the diffusion
coefficient is provided by the spectral shape of the non-
thermal radio component, if the shock compression ratio
and convection velocity are known. On the other side, $\kappa$
is limited by Bohm diffusion. For $\kappa = 2 \cdot 10^{-9}\text{cm}^2\text{s}^{-1}$ up
to $\sim 10^8\text{MeV}$-electrons are expected at least at apastron,
where radiative losses are sufficiently small not to affect
the cutoff particle energy (see Fig. 5). The self-consistent
determination of the maximum particle energy allows
sound predictions at the highest energies. Note that KN
effects will alter the emitting electron spectrum above
$\sim 10^4\text{MeV}$, as indicated in Fig. 5. This is in contrast to
phases close to periastron. The intense stellar radiation
field there limits the electron spectrum to $\sim 100\text{MeV}$
(see Fig. 5). As a consequence, the corresponding photon
spectrum from IC scattering cuts off already in the soft
$\gamma$-ray band (see Fig. 4), and hadronically produced pho-
tons may dominate at (sub-)GeV energies, albeit with a
possibly undetectable flux level even for the more sensi-
tive near-future experiments. EGRET observations, that
were carried out rather around periastron, therefore did
not lead to detections. Mainly as a result of including
also hadronic ion-ion interactions into the calculations
for $\pi^0$ production, the corresponding $\pi^0$-decay $\gamma$-ray flux
in Pittard & Dougherty [31] extends to higher energies
than considered here. The association of WR 140 to the
unidentified EGRET source 3EG J2022+4317 appears to
be vague: With WR 140 being located $\sim 0.67^\circ$ away from
the nominal position of 3EG J2022+4317, and barely consistent with the 99% source location uncertainty con-
tour a conclusive identification seems farfetched. It is
due to the extreme eccentricity of this system, leading
to significant changes in the stellar radiation field den-
sity at the shock location, that causes a blurring of the
phase-locked flux variations expected otherwise from the
anisotropy of the dominating IC scattering process. In-
deed, orbital flux variations in this system are reduced
to a factor $\sim 2 - 3$ (see Fig. 4). In general, relativistic
bremsstrahlung radiation lies always below the IC emis-
sion level in these systems. When compared to the ex-
pected IC flux, $\pi^0$-decay $\gamma$-ray production is small, even
if the total wind energy is transformed into relativis-
tic protons/ions. This makes WR-binary systems rather
unpromising putative neutrino and cosmic ray sources
within our model.

Fig. 4 implies that WR 140 may be detectable with
GeV-instruments like GLAST-LAT even at individually
selected phases if the electrons reach sufficient high ener-
gies, while INTEGRAL requires Msec exposures for any
detection above 1 MeV. The expected extent of the pho-
ton spectrum to $\sim 10 - 100$ GeV at phases where the
binary separation is large, may even allow low-energy
threshold Imaging Atmospheric Cherenkov Telescopes
(IACTs) to gain important information on the cutoff
of WR 140’s spectrum. This may allow to further con-
strain the diffusion coefficient. Note that photon absorp-
tion due to $\gamma\gamma$ pair production can not a priori be ne-
glected in colliding wind systems. E.g. for WR 140 the
optical depth $\tau_{\gamma\gamma}(r=r_0,E \approx 100\text{GeV}) \approx 1$ at phase
0.67, $\tau_{\gamma\gamma}(r=r_0,E \approx 100\text{GeV}) \approx 3$ at phase 0.95.

4.2 WR 147

Due to its proximity WR 147 (WN8h + B0.5V) is one of
the few binary systems where high resolution radio
observations lead to resolving this system into its com-
ponents (Williams et al. 1997). The observed radio mor-
phology supports a binary separation of $\sim 417$ AU for a
source distance of 650 pc. We used the system parame-
ters as published in Setia Gunawan et al. (2001) [32] to-
gether with the observed synchrotron spectrum to model
its expected spectral behaviour at high energies. Since
WR 147’s inclination $i$ nor eccentricity $e$ are known, we
assumed for our modeling $e = 0$ and $i = 90^\circ$. The ob-
served synchrotron spectrum could be reproduced within
its observational uncertainties if $\sim 0.15\%$ of the OB-wind
kinetic energy is transformed into relativistic electrons,
and assuming a surface magnetic field of 30 G (translating into 25 mG fields at the CWR). Due to its huge binary separation the emitting particle spectra are not limited by IC losses but rather by the size of the acceleration region. Fig. 5 presents the expected orbital IC flux variations due to the anisotropic nature of the IC process for the above described parameter set. Here the maximum flux and photon cutoff energy, expected when the WR-star is behind the OB-star along the sight line, are more than one order of magnitude higher than their minimum values. Absorption of $>50$ GeV photons turns out negligible for this system, provided its eccentricity is small.

Therefore start with scanning the WR-binary population for physically similar systems. A (not complete) list encompasses WR 146, WR 137, WR 112 and WR 125, with WR 112 being the most distant ($\sim 4$ kpc) of them.

### Perspectives for the gamma-ray band

The identification of a specific colliding wind system or the population thereof as $\gamma$-ray emitters requires first: a convincing positional association, and second: its physical relation with the detected $\gamma$-ray source.

The most up-to-date catalog of WR-stars in the Milky Way lists more than 220 sources with a detected binary frequency of $\sim 40 - 50\%$ in the solar neighborhood [33]. Its spatial distribution reflects the spiral arm structure of our Galaxy with a slight asymmetry with respect to the galactic plane (33 and references therein). 64 WR-(systems) are found in the solar neighbourhood ($< 2$ kpc), more than 25 have been detected in the immediate vicinity ($< 30$ pc) of the galactic center. The total number of WR-(systems) in the Galaxy has been estimated to up to $\sim 8000$ [44], total OB-star number counts in our Galaxy may reach values as high as 60000 [35]. This is orders of magnitude larger than the number of all, presumably galactic, but still unidentified $\gamma$-ray sources detected to date.

Intriguing positional coincidences of massive star populations, among them colliding wind systems, with unidentified EGRET sources have been found in the past (e.g.
however no individual binary system could unambiguously be identified as a high energy $\gamma$-ray emitter so far. This is most likely a statistical issue. EGRET’s large location error box, typically $\sim 0.25^\circ$ for a strong point source at high latitudes, and even larger for sources in the galactic plane, allows to find many plausible counterparts within the positional uncertainty of the $\gamma$-ray source. Furthermore, the strong diffuse $\gamma$-ray background at low galactic latitudes makes the detection of any non-periodic galactic source close to the instrument sensitivity even more challenging. The capabilities of EGRET’s successor, GLAST-LAT \footnote{\url{http://www-glast.slac.stanford.edu/software/IS/glast_lat_performance.htm}}, will improve here. Its expected ability of both detecting weak signals \cite{v} and at the same time locating an object in the $\gamma$-ray sky within $\sim 0.5^\circ - 5^\circ$, solves the confusion problem at least among the galactic bright EGRET sources.

How will a typical CWS appear at $\gamma$-ray energies? What are its observable characteristics that may discriminate it from the wealth of other plausible $\gamma$-ray source classes?

To begin with, the available energy kinetic wind energy $L_w = M v_w^2/2$ provides a firm upper limit on the photon production rate from each process, and thus on the expected flux level. Inserting typical mass loss and wind parameters one finds the kinetic energy of massive star winds to be of order $1\%$ of the bolometric radiative energy output, or typically $\sim 10^{38}$ erg/s. Taking into account the efficiency of the particle acceleration process, much smaller values will rather be the rule.

Furthermore, colliding wind regions will appear not extended, but point-like on the $\gamma$-ray sky for both present and near future satellite and ground based instruments.

Our study implies that detectable phase-locked orbital variations in the $\gamma$-ray band occur, however, they may possibly be blurred by the geometry of the system (in particular due to eccentricity and inclination). Flux variations at high energies may additionally be expected from modulations of the geometry and size of the emitting region, modulations of the stellar target photon field density, inhomogeneities and/or shocks in the wind outflow, etc. The time scale of these variations is determined by the respective physical cause.

Spectral hints on the expected low-energy IC component of CWBs may be deduced from their visible synchrotron spectrum. Spectral indices at GHz frequencies in the range $\alpha_\nu = 0.3 \ldots 1.3$ has been detected so far from the current limited sample of non-thermal emitters among the WR-binary systems. This may hint towards photon spectra with photon index $\alpha_{\text{ph}} < 2.5$ far below the cutoff energy. At GeV-energies KN, anisotropy and propagation effects may have an impact on the spectral shape.

With these characteristics at hand, a population study may be instrumental to finally unveil the class of massive star binary systems as high energy emitters.

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