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Prospects for Detecting Colliding Winds of Massive Stars with GLAST-LAT

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Abstract. Colliding winds of massive binaries have been proposed as potential sites of non-thermal high-energy photon production. They may account for counterparts of yet unidentified EGRET sources and will presumably be detected with the next generation satellite, pair-conversion telescope, GLAST-LAT, which will be launched in the near future. Here we investigate the properties of high-energy photon production in colliding winds of long-period WR+OB-systems. We found that in the dominating leptonic radiation process, anisotropy and Klein-Nishina effects will likely yield visible spectral and variability signatures in the gamma-ray domain for highly sensitive instruments like GLAST-LAT. In addition to adiabatic and radiative losses we also include particle propagation in our modelling for the first time. The calculations are applied to WR 140 and WR 147. We predict that both systems will be visible for GLAST-LAT, and perhaps also for modern imaging atmospheric Cherenkov telescopes at some orbital phases, but hardly for INTEGRAL above 1 MeV.

The motivation to consider colliding-wind binary (CWB) systems of massive stars as potential γ-ray emitters is mainly supported by two observational facts. Firstly, non-thermal radio emission has been observed from several massive star systems that has been interpreted as synchrotron radiation (Abbott et al. 1986). This directly implies the existence of relativistic particles as well as magnetic fields in the emission region. In some of these binary systems, the origin of this radiation has been deduced from radio images showing an extended, slightly elongated non-thermal feature (e.g. Dougherty et al. 2000) connected with the low wind momentum companion. With relativistic electrons existing in CWBs, inverse Compton (IC) scattering in the intense photospheric radiation field of hot stars and relativistic electron-ion bremsstrahlung interacting with the material in the massive winds cannot be avoided. These are the most favoured leptonic γ-ray production mechanisms in CWBs today. The second hint stems from observations in the γ-ray domain directly. Triggered by the detections of many γ-ray sources by EGRET which are not yet unambiguously identified, indications of a connection to massive-star populations on the basis of positional coincidences, in particular to OB-associations, WR- and Of-stars, CWBs and supernova remnants, has been built up steadily (e.g. Romero et al. 1999).

CWB systems are therefore regarded as candidate γ-ray sources for the upcoming γ-ray mission GLAST and the current generation of imaging atmospheric Cherenkov telescopes as e.g. VERITAS, H.E.S.S., MAGIC, CANGAROO III.

1. Colliding Wind Binary Systems as Gamma-Ray Emitters Today

The idea of CWBs being γ-ray emitters (Montmerle 1979) is as old as the COS-B instrument. Four COS-B sources with a roughly 1° error box have been proposed to be counterparts of CWBs, including WR 140 among others (Pollock 1987). Despite the significantly improved ability of determining the source location and the (more than one order of magnitude) increased flux sensitivity of COS-B's successor, EGRET onboard CGRO, no individual CWB system could be unambiguously identified as a γ-ray emitter so far. Because of the large location error-box in EGRET observations, typically 0.25° for a strong source located at high latitudes (Table 1) and even larger for sources in the galactic plane, many potential counterparts are generally found within the location uncertainty region of the γ-ray source. In addition, the dominant diffuse γ-ray radiation at low galactic latitudes makes the detection of galactic sources like CWBs challenging at γ-energies. Note, however, that there exists intriguing spatial coincidences between some unidentified EGRET sources and CWBs: 3EG J2021+3716, 3EG J2022+4317 and 3EG J2033+4118 with WR 142, WR 140 and Cyg OB2#5, respectively (Kaul & Mitra 1997; Romero et al. 1999; Benaglia et al. 2001).

The enormously improved capabilities of NASA's GLAST-LAT (Table 1), scheduled for launch in February 2007, gives justified hope to finally confirm CWBs as γ-ray emitters. A significantly increased size of the effective area (that includes the total geometric acceptance, conversion probability of γ-rays into pairs and all track reconstruction efficiencies) leads to an improved sensitivity of the instrument. The use of multilayered silicon-strip detectors enables a more precise tracking of the converted pairs produced by the initial γ-rays, significantly improving the source location determination of an object in the sky. The better source location accuracy of GLAST-LAT will easily yield unambiguous identifications of all EGRET sources not yet firmly identified. The anticipated point source sensitivity allows GLAST-LAT to repeat all detections from the Third EGRET Catalog every two to three days.

Table 1. Anticipated GLAST-LAT capabilities[a] in comparison to EGRET

	EGRET	GLAST-LAT
Energy range	20 MeV-100 GeV	20 MeV-300 GeV
Energy resolution	$\sim 10\%$	$\sim 9\%$, 0.1-100 GeV (1σ, on-axis)
Effective area	1500 cm^2	10^4cm^2 at 10 GeV
Angular resolution	5.8° (100 MeV)	3.4°($>$ 100 MeV), 0.086°($>$ 10 GeV)
Field-of-view	0.5 sr	2.4 sr
Point src sensitivity (5σ, >100 MeV)	$\sim 5\times10^{-8}$cm^{-2}s^{-1}	3×10^{-9}cm^{-2}s^{-1}
Src location determ.	15′	0.4′(1σ rad, 10^{-7}cm^{-2}s^{-1} $>$ 100MeV 1-yr sky survey, high b)
Split 10^{-7}cm^{-2}s^{-1} srcs	75′	6′

[a]GLAST Science Brochure

Several efforts have been devoted to predict γ-ray emission from CWBs (Rauw 2004, for a review) based on either leptonic (mostly IC) and/or hadronic (π^0-decay γ-rays; e.g. Torres et al. 2004) processes. The calculated mean γ-ray luminosities lie in the range 10^{32-35}erg/s. Regarding the expected capabilities of more powerful γ-ray instruments, theoretical simulations of CWB systems are highly desirable. Since the IC process has been shown to likely dominate the γ-ray production (e.g. Eichler & Usov 1993; Mücke & Pohl 2002), this process deserves special care. For a mono-directional beam of photons interacting with electrons, the scattered power per volume element is monotonically increasing from small to large scattering angles (s.a.) reaching its maximum at s.a. 180° (Brunetti 2000). This anisotropic behaviour applies to IC γ-ray production in the collision region of binary systems with pronounced unequal wind momenta, where the seed photons reach the interaction region from a prefered direction. As shown below, this leads to orbital IC flux variations (see also Mücke & Pohl 2002), depending on the inclination of the system, that should be detectable in the future. If electrons in a UV radiation field are accelerated to energies $\gtrsim 10^3$ MeV, Klein-Nishina (KN) effects start to set in, that substantially alter the spectral shape at high energies (Reimer et al. 2004). In addition, radio observations reveal an extended, non-uniform region of synchrotron emission (Dougherty et al. 2000). Propagation calculations take this into account.

In the following, we briefly discuss these points. For our considerations we shall use the sketch of a colliding wind region that has been presented by Eichler & Usov (1993) with the stagnation point defined by balancing the wind momenta and under the assumption of spherical winds. The shocked high-speed winds are creating a region of hot gas that is separated by a contact discontinuity. The gas flow in this region away from the stagnation point will be some fraction of the wind velocity which we keep constant at V here. 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) allows us to solve the relevant simplified diffusion-loss equations analytically. We consider first-order Fermi acceleration (with acceleration rate a) out of a pool of thermal particles with energy E_0, and take into account radiative losses (synchrotron, IC, bremsstrahlung and Coulomb losses), (energy-independent) diffusion by introducing an escape time T_0 and convection/advection with speed V (which we call "convection" in the following). At a distance $>r_0$ from the stagnation point, convection dominates over diffusion with r_0 determined by balancing the diffusion and convection loss time. Correspondingly, we divide the emission region into a region where acceleration/diffusion dominates, the "acceleration zone", and the outer region where convection dominates, the "convection zone". The relevant continuity equations for the steady-state particle spectra simplify to:

$$\frac{\partial}{\partial E}(\dot{E}\,N(E)) + \frac{N(E)}{T_0} = Q_0\,\delta(E-E_0) \qquad (1)$$

$$\vec{\nabla}(\vec{V}\;N(E,r)) + \frac{\partial}{\partial E}[(\dot{E} - \frac{E}{3}\vec{\nabla}\vec{V})\;N(E,r)] = 0 \qquad (2)$$

for the acceleration and convection zone, respectively. We found analytical solutions that incorporate KN effects by introducing suitable approximations for the KN loss rate for energies $E_s > 10^{-1.5}\mathrm{MeV}/\epsilon_T$ where $\epsilon_T \approx 10$ eV is the characteristic energy of the photospheric seed photon field. Note that E_s is lower than the energy where the classical KN regime starts, $E_{\mathrm{KN}} = m_e^2c^4/\epsilon_T$, in order to include also KN effects already in the transition region between the Thomson and KN regime. We find electron spectra with smooth roll-overs above E_s

that cut off at higher energies as compared to electron spectra that remain in the Thomson approximation throughout the whole particle energy range. Int the convection region, the particles lose energy radiatively as well as through expansion losses while flowing along the convection region. This leads not only to a dilution of the particle density but also to a deficit of high energy particles, which may leave a signature (see Fig. 1 left, at ~ 100 MeV) in the corresponding volume-integrated photon spectra, depending on the relative size of the convection region with respect to the acceleration region. The emitted IC flux per volume element depends on the s.a. which itself is a function of the orbital parameters and the geometry of the emission region. In the anisotropic case, orbital variations of the IC luminosity are therefore expected for such systems (see Fig. 1). A detailed description of the solutions along with some applications will be published in Reimer et al. (2004).

2. Application to WR 140 and WR 147

The foremost examples of non-thermal radio emitting CWB systems are WR 140 and WR 147. Fig. 1 shows our predictions for their γ-ray emission using parameters as described in the figure caption. Obviously, both sources are detectable with GLAST-LAT at all orbital phases if the electrons reach sufficiently high energies. INTEGRAL's SPI seems to encounter increasing difficulties to detect such systems at energies above 1 MeV. Relativistic bremsstrahlung radiation lies always below the IC emission level. π^0-decay γ-ray production can be neglected, even for cosmic ray enhancement factors of 1000 and more, when compared to the expected IC flux. Orbital flux variations due to the anisotropy of the Compton scattering process by more than an order of magnitude are expected for large inclination systems (see WR 147) which may, however, become blurred with flux variations due to changes in the seed photon density for strongly excentric systems (e.g. WR 140).

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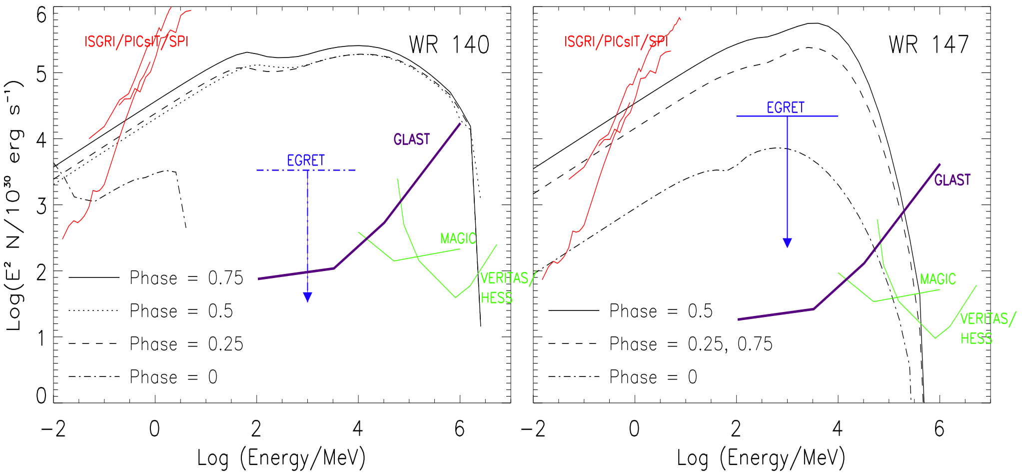

Figure 1. **Left:** IC-spectra of WR 140 at a distance of 1.32 kpc with an orbital period of 2900 days, an inclination angle $i = 60°$, an eccentricity of 0.84 and $\omega = 32°$, the argument of periastron for the following CWB parameters: bolometric O-star luminosity $L_{\rm bol} = 10^{5.8} L_{\odot}$, with effective temperature $T_{\rm eff} = 43000$ K, $\eta = 0.057$, the wind momentum ratio, electron spectral index p=2, convection velocity of 900-1000 km/s. An injected electron energy of ~1% of the WR-wind kinetic energy, a total emission volume of $\sim 0.1 {\rm AU}^3$ and an O-star surface magnetic field of 100 G, which leads to field strengths of 0.1-1.5 G in the wind collision zone (in agreement with estimates for the equipartition magnetic field: Benaglia & Romero 2003; Dougherty et al. 2003), explains the flux level of the cm radio data. The diffusion coefficient $\kappa_{\rm a}$ determines the acceleration rate. $\kappa_{\rm a}$ must be low enough to allow for relativistic electron energies sufficient to explain the observed synchrotron radiation, and that gains are able to overcome Coulomb losses. The highest possible rate corresponds to the Bohm diffusion coefficient. Here we used an acceleration rate that allows one to produce >100 MeV photons via the IC process at least at orbital phases close to apastron: $\kappa_{\rm a} = 2 \cdot 10^{19} {\rm cm}^2 {\rm s}^{-1}$ leading to $r_0 \approx 2 \cdot 10^{11}$cm. Smaller diffusion coefficients are also possible which would also allow the production of MeV-photons close to periastron. Note that photon absorption through $\gamma\gamma$-pair production suppresses the γ-ray luminosity at ≥100 GeV significantly at periastron to a few 10% at apastron (not shown in the figure). The EGRET upper limit is taken from Mücke & Pohl (2002). INTEGRAL, GLAST-LAT and IACT sensitivities are from http://www.rssd.esa.int/Integral/AO2/, http://www-glast.slac.stanford.edu/software/IS/glast_lat_performance.htm, and Weekes et al. (2002), respectively. **Right:** IC-spectra of WR 147 at a distance of 650 pc for the following CWB parameters: bolometric O-star luminosity $L_{\rm bol} = 10^{4.7} L_{\odot}$, with effective temperature $T_{\rm eff} = 28500$ K, $\eta = 0.013$, the wind momentum ratio, electron spectral index p=2, convection velocity of 266 km/s. The observed radio flux level can be reproduced for a B-star surface magnetic field of 30 G (translating into a 6 mG field strength in the wind collision region, close to its equipartition value Benaglia & Romero 2003) if ~ 0.1% of the WR-wind kinetic energy is injected into the emission region of a total estimated volume of $\sim 2.6 \cdot 10^5 {\rm AU}^3$. Again the diffusion coefficient is chosen such to overcome Coulomb losses and allow the production of >100 MeV through the IC process. With $\kappa_{\rm a} = 10^{22} {\rm cm}^2/{\rm s}$ convection is dominant only in a small part of the total emission region, and the acceleration site covers a size of $r_0 = 4 \cdot 10^{14}$cm. Neither eccentricity nor the inclination of the system are known so far. We use $i = 90°$ and $e = 0$ for this application and define phase zero for the WR-star in front of the B-star. The EGRET upper limit is taken from Benaglia & Romero (2003).

Discussion

Gloria Koenigsberger: I was just wondering, how is it that this convection region is established?

Anita Reimer: You have actually both effects in general, diffusion and convection. But convection can only be important if the convection velocity is large enough. At lower r, which is the distance from the stagnation point, the convection velocity is very low and diffusion is more important, so you can neglect convection and at larger r, convection becomes important.

Gloria Koenigsberger: You are talking about a wind region, correct?

Anita Reimer: Yes, I am talking about the gas flow that is between the two contact discontinuities in the collision region.

Anita Reimer