Monte-Carlo Simulations of Radio Emitting Secondaries in γ-Ray Binaries

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Abstract

Several binary systems that contain a massive star have been detected in both the radio band and at very high energies. In the dense stellar photon field of these sources, gamma-ray absorption and pair creation are expected to occur, and the radiation from these pairs may contribute significantly to the observed radio emission. We aim at going deeper in the study of the properties, and in particular the morphology, of the pair radio emission in gamma-ray binaries. We apply a Monte-Carlo code that computes the creation location, the spatial trajectory and the energy evolution of the pairs produced in the binary system and its surroundings. The radio emission produced by these pairs, with its spectral, variability and spatial characteristics, is calculated as it would be seen from a certain direction. A generic case is studied first, and then the specific case of LS 5039 is also considered. We find that, confirming previous results, the secondary radio emission should appear as an extended radio structure of a few milliarcseconds size. This radiation would be relatively hard, with fluxes up to \( \sim 10 \) mJy. Modulation is expected depending on the gamma-ray production luminosity, system eccentricity, and wind ionization fraction, and to a lesser extent on the magnetic field structure. In gamma-ray binaries in general, the pairs created due to photon-photon interactions can contribute significantly to the core, and generate an extended structure. In the case of LS 5039, the secondary radio emission is likely to be a significant fraction of the detected core flux, with a marginal extension.

Key words: Gamma-rays: theory – stars: binaries (including multiple): close – Radiation mechanisms: non-thermal

1. Introduction

High-mass binary systems are a well established class of very high-energy (VHE) gamma-ray emitters. Five VHE sources\(^1\) have been associated so far to binaries that contain a massive star: PSR B1259–63 (Aharonian et al. 2005a); LS 5039 (Aharonian et al. 2005a); LS I +61 303 (Albert et al. 2006); Cygnus X-1 (Albert et al. 2007); and HESS J0632+057 (Aharonian et al. 2007; Hinton et al. 2009; Skilton et al. 2009; Falcone et al. 2010; Falcone et al. 2011; Moldón et al. 2011). Among these five, three show clear modulation of the VHE emission associated to the orbital motion: PSR B1259–63 (Aharonian et al. 2005a), LS 5039 (Aharonian et al. 2006), and LS I +61 303 (Albert et al. 2009); thus, the emitter cannot be too far from the star in these sources. The short duration of the VHE flare observed in Cygnus X-1 (Albert et al. 2007) likely implies that this flare is originated not too far from the star, whereas in HESS J0632+057 the situation is less clear (see Skilton et al. 2009; Falcone et al. 2010; Falcone et al. 2011; Moldón et al. 2011). Under the strong ultraviolet photon field of a massive star, gamma-ray absorption can take place (e.g. Ford 1984; Protheroe & Stanev 1987; Moskalenko & Karacala 1994; Bednarek 2000; Boetcher & Dermer 2005; Dubus 2006a; Boetcher 2007; Orellana et al. 2007; Khangulyan et al. 2008; Reynoso et al. 2008; Sierpowska-Bartosik & Torres 2008; Romero et al. 2010), this process leading to the creation of secondary (electron-positron) pairs with energies \( \gtrsim 10 \) GeV and peaking around 30 GeV.

Secondary pairs are created under the stellar photon field and, as shown below, are likely trapped by the stellar wind magnetic field of strength \( B_w \). For small enough values of \( B_w \) and high enough values of the secondary particle energy \( E \), most of the pair energy is emitted, via inverse Compton (IC) scattering of stellar photons, as gammarays with energies above the pair-creation threshold. If the gamma-ray opacity coefficient \( \tau_{\gamma\gamma} \) is \( \gtrsim 1 \), the electromagnetic cascade may significantly affect the distribution of secondary pairs in the system. However, for this to be efficient the initial gamma-ray energy must be well above the pair creation energy threshold, \( \epsilon \gg \epsilon_{th} \sim 1/\epsilon_* \) (i.e. deep in the Klein-Nishina –KN- regime), where \( \epsilon_{th}, \epsilon \) and \( \epsilon_* \) are the threshold, the gamma-ray and the stellar photon en-

\(^{1}\) There is also the new GeV gamma-ray binary, 1FGL J1018.6–5856, which may have also been detected at VHE (e.g. Corbet et al. 2011; de Ona Wilhelmi 2010).
energies in \( m_e c^2 \) units. In this regime, say for energies of the secondary pairs \( \gtrsim 1 \text{ TeV} \) and typical stellar temperatures \( \sim (3-4) \times 10^4 \text{ K} \), synchrotron cooling suppresses the cascade under a magnetic field (Khangulyan et al. 2008)

\[
B_w \gtrsim 10 \left( L_*/10^{39} \text{ erg s}^{-1} \right) \left( R/10^{12} \text{ cm} \right)^{-1} \text{ G},
\]

where \( L_* \) and \( R \) are the star luminosity and distance from the star center, respectively. Equation 1 has been derived from Eq. 1 in Khangulyan et al. (2008), which gives the IC cooling timescale in the KN regime with a 10 eV photon field as target. We reproduce the formula here for the sake of clarity:

\[
t_{\text{KN}} \approx 1.7 \times 10^2 (u_*/100 \text{ erg cm}^{-3})^{-1} (E/1 \text{ TeV})^{0.7} \text{ s}, \tag{2}
\]

where \( u_* \) is the stellar radiation energy density, and \( E \) is the electron energy. For \( B_w > \sqrt{8\pi u_*} \), the secondary bolometric luminosity output will be dominated by synchrotron radiation. This implies a magnetic field strength:

\[
B_w \gtrsim 3 \times 10^2 (L_*/10^{39} \text{ erg s}^{-1})^{1/2} (R/10^{12} \text{ cm})^{-1/2} \text{ G}. \tag{3}
\]

All this shows that even for magnetic fields well below equipartition with radiation, synchrotron losses can effectively prevent development of electromagnetic cascades.

Bosch-Ramon et al. (2008a) carried out a detailed semi-analytical study of the spectral properties of the secondary broadband emission for realistic magnetic field values (see also Bosch-Ramon et al. 2008b). In that work, it was shown that the radio, X-ray, and GeV fluxes of secondary emission could be comparable to those observed in gamma-ray binaries, and may even dominate the non-thermal output below \( \epsilon_{\text{th}} \) in some cases. These authors also suggested that the extended radio emission found in LS I +61 303 (Dhawan et al. 2006) may come from secondary pairs. Bosch-Ramon (2009) also proposed this origin for the emission of the marginally resolved radio core of LS 5039 (Ribó et al. 2008).

Although the radio fluxes can be roughly estimated from the semi-analytical study of Bosch-Ramon et al. (2008a), their approach does not allow a proper description of the radio spectrum, lightcurve, and morphology, because synchrotron radio emitting particles have long timescales and are strongly affected by the medium inhomogeneity at spatial scales of \( \sim R \). In that work, the complex 3-dimensional (3D) structure of the secondary trajectories was simplified attaching the secondary pairs to the stellar wind, with the latter being taken as spherically symmetric, with constant velocity, and wind particle and magnetic field energy density \( \propto 1/R^2 \). The magnetic field was considered fully irregular. Finally, the adiabatic cooling of the secondary pairs was not taken into account, which is reasonable at binary spatial scales, but not for the computation of that radio emission produced outside the binary system, affected by wind expansion. Finally, the relevance of free-free absorption was not investigated.

In this work, we present detailed calculations of the evolution of the radio emitting secondary pairs in gamma-ray binaries. The energy and the spatial evolution of the particles in the stellar wind have been computed using a Monte-Carlo code that accounts for ionization/coulombian collision losses, adiabatic, relativistic bremsstrahlung, synchrotron, and IC cooling, as well as diffusion and advection in the wind to follow the trajectories of secondary pairs in the source. The code can also deal with anisotropic diffusion when an ordered magnetic field is dominant, although we do not consider this configuration at this stage. A sketch of the the scenario at the scales of the binary system is shown in Fig. 1. Once the particle energy and spatial distributions have been obtained at a particular orbital phase (accounting for the previous orbital history of the system), the radio emission in a specific direction is calculated, which allows the generation of directional radio maps. The radio maps have been smoothed using a circular Gaussian in order to roughly reproduce what an observer would see using a milliarcsecond (mas) resolution radio interferometer. This is also illustrated in Fig. 1. Spectra and lightcurves, and the impact of free-free absorption, have been discussed. We focus here on a generic case, since our aim is to give a general demonstration of the relevance of secondary radio emission, but we provide also with an instance of the importance of this phenomenon in a real source, applying our calculations to LS 5039. Further and more detailed studies for specific objects of the role of secondary pairs for the radio emission will be presented elsewhere.

2. Monte-Carlo simulations of secondary pairs in gamma-ray binaries

For an appropriate study of the secondary radio emission, detailed calculations of the energy and spatial evolution of the secondary pairs are required, accounting for the star radiation field and the properties of the stellar wind. Given the difficulties of treating the magnetic field structure and adiabatic cooling in the wind in a semi-analytical approach, we have performed Monte-Carlo simulations in which secondary pairs are injected, move (diffuse and are advected), and cool down in a 3D space. The 3D nature of the problem comes from the combination of the advection in the wind plus the orbital motion (a significant regular \( B_w \)-field structure would also require a 3D treatment). The problem treated by the Monte-Carlo method is similar to that described by the diffusion advection equation (e.g. Jones 1990; Blandford & Eichler 1987). The radiation timescales \( (t = |E|/\dot{E}) \), where \( \dot{E} \) is the electron energy loss rate) adapted to the environments of gamma-ray binaries are:

\[
t_{\text{sync}} \approx 40 (B/100 \text{ G})^{-2} (E/1 \text{ GeV})^{-1} \text{ s}, \tag{4}
\]

\[
t_{\text{IC Th}} \approx 50 (u_*/300 \text{ erg cm}^{-3})^{-1} (E/1 \text{ GeV})^{-1} \text{ s}, \tag{5}
\]

\[
t_{\text{thr}} \approx 5 \times 10^5 (n_w/10^{10} \text{ cm}^{-3})^{-1} \text{ s}, \tag{6}
\]

for synchrotron, IC (Thomson) and relativistic Bremsstrahlung, respectively (see Bosch-Ramon & Khangulyan 2009 for the IC cooling rate accounting also for the KN regime used in the calculations), with \( n_w \) being the wind density (see below), \( u_* \) the energy density of the target photon field, and \( B \) the ambient magnetic field. For the adiabatic and ionization cooling timescales,
respectively, where $v_\infty$ is the wind velocity at infinity, and $R_*$ the stellar radius.

2.1. Injection of secondary pairs in the binary system

We have calculated the injected spatial and energy distribution of secondary pairs for a given primary gamma-ray spectrum and a stellar black-body photon field. This is done tracking the path of a photon produced in the emitter location and moving with a certain direction in the binary system. The location in which a given gamma ray is absorbed is obtained using the (anisotropic) gamma-ray absorption differential probability due to photon-photon interactions (point-like treatment of the star; see below):

$$\frac{dw}{dl} = (1 - \cos\theta) \int d\epsilon_\gamma \sigma_{\gamma\gamma} \left( \epsilon_\gamma (1 - \cos\theta) \right) n_\star (\epsilon_\gamma, R),$$

where $l$, $\theta$, $n_\star$ and $\sigma_{\gamma\gamma}$ are the length of the path covered by the gamma ray, the gamma-ray/stellar photon interaction angle, the stellar photon specific density, and the pair-creation cross section (Gould & Schr"eder 1967), respectively. This quantity is integrated along the photon path $\int_0^l dw$ to obtain the probability of interaction up to a certain location. In this work, the absorption probability is computed along the photon trajectory with small steps, and the Monte-Carlo algorithm is applied to define the interaction point.

The injection rate of secondary pairs depends strongly on the spectrum and angular distribution of the primary gamma rays. To mimic the effect of the anisotropic IC scattering in the angular distribution of primary gamma rays, a gamma-ray direction probability at injection $\propto (1 - \cos\theta)$ has been introduced, where $\theta_\star$ is the angle between the gamma-ray path and the direction from the star to the gamma-ray emitter, i.e. gamma rays have a higher probability to be emitted towards than away from the star. This angular dependence would roughly correspond to an average one between the Thomson and KN IC regimes (see Fig. 6 in Khangulyan et al. 2008).

In Fig. 2, we show the distribution of injected secondary pairs in a gamma-ray binary for three different energies. We have focused here on a generic case, in which we have adopted a circular binary system ($e = 0$) of one week period, formed by a massive, primary star of mass $M_*$ and compact object of mass $M_X$, such that $M_* + M_X = 22 M_\odot$. This yields an orbital separation distance of $R_{\text{orb}} = 3 \times 10^{12}$ cm. The inclination of the system has been fixed to $i = 45^\circ$, and the phase 0.0/0.5 has been taken at the superior/inferior conjunction of the compact object (supc/infc). The main star parameters have been fixed to $L_* = 6 \times 10^{38}$ erg s$^{-1}$, $R_* = 10^{12}$ cm and $T_* = 3 \times 10^4$ K, where $T_*$ is the star temperature. The gamma-ray emitter has been assumed to be point-like, at the compact object location, with $R_\text{e} = R_{\text{orb}}$, although the actual location and size of the VHE emitter in gamma-ray binaries has not been defined yet, being possible to have an extended production region not only in the jet but also in the colliding wind scenario (see, e.g., Bogovalov et al. 2008). No eccentricity and a fixed $i$-value have been taken for the sake of simplicity, since our aim is to illustrate the main characteristics of the secondary radio emitter.

2.1.1. Treatment of the star

In these calculations, we have adopted a point-like approximation for the star (e.g. Dubus 2006a; see also Sect. 4.2.1 in Bosch-Ramon & Khangulyan 2009). This approximation fails close to the stellar surface, at a dis-


Fig. 2. Projection in the orbital plane of the spatial distribution of the secondary pairs injected at three different energies: $E = 10$ GeV (left panel), 300 GeV (central panel) and 10 TeV (right panel). This has been computed using Monte-Carlo simulations. The gamma-ray emitter is located at $(x, y) = (0, 3 \times 10^4)$ cm, and the star at $(x, y) = (0, 0)$ cm. Most of the secondary pairs are produced towards the star, with a plateau in their concentration up to the distance at which $\tau_{\gamma\gamma} \sim 1$. This distance changes with energy and has a minimum around few 100 GeV for most of the interaction angles, corresponding to a peak in the pair absorption.

2.2. Energy and spatial evolution of secondary pairs

2.2.1. Transport of secondary pairs

A secondary pair is injected where the gamma ray was absorbed, and the subsequent locations are computed accounting for the local direction and strength of the wind magnetic field, which is assumed to have an ordered and magnetic field, which is assumed to have an ordered and
Fig. 3. Maps of the injection rate per volume unit for injected pairs of 100 GeV, dominant in radio. This has been computed semi-analytically. Two cases are presented: a generic case (top) with the parameter values of Table 1, and a case with the properties of LS 5039 around periastron (bottom; see Table 2). The calculation accounting for the star finite size is shown at the left, and the point-like approximation at the right. Units are the logarithm of the rate density normalized to the peak value. The star is located to the left in both maps.

Fig. 5. Primary gamma-ray emission between 20 GeV and 2 TeV in the direction to the observer, for four different orbital phases: 0.0 (solid line), 0.25/0.75 (long-dashed line), and 0.5 (dotted line). The thin lines show the unabsorbed spectra, and the thick ones show the same but accounting for photon-photon absorption.

a disordered component. We consider the stellar rotation axis to be perpendicular to the orbital plane.

The ordered wind magnetic field can be described as

$$B_w(r, \phi) = B_r \hat{e}_r + B_\phi \hat{e}_\phi,$$

where

$$B_r \approx B_* (R_*/R)^2,$$

$$B_\phi \approx B_* (v_{w,\phi}/v_{w,\infty})(R_*/R),$$

and $B_*$ and $v_{w,\phi}$ are the magnetic field at the star surface and the initial azimuthal wind velocity, respectively. For the calculations, $B_*$ is fixed to a value of 200 G (see Bosch-Ramon et al. 2008b and references therein), high enough to suppress the electromagnetic cascade. We neglect here the region within the Alfvén radius from the star, typically confined to a region $R_A < 2 R_*$, since almost all secondary pairs are created farther from the star. The wind velocity can be expressed as

$$v_{w,r}(r, \phi) = v_{w,\infty} \hat{e}_r + v_{w,\phi} \hat{e}_\phi,$$

and the azimuthal one:
The processes in play: ionization, adiabatic, relativistic bremsstrahlung, synchrotron, and IC cooling. Thus, at each time step \( j \), a certain amount of energy \( \Delta E^j = \hat{E} dt^j \) is restored to the particle energy at \( j - 1 \), where \( dt^j \) is such that \( \Delta E^j \ll E^{j-1} \), and \( \hat{E} \) includes the cooling mechanisms specified above. We note that the energy losses depend not only on the particle energy, but also on the particle position in the system.

In the region close to the star (\( R \sim \text{few} R_* \)), IC cooling dominates for basically all the particle energies, although at this distance there are none or very few radio emitting particles. Farther out, adiabatic cooling in the wind becomes faster. The energy distribution of radio secondaries almost does not depend on the original gamma-ray spectrum, since radio emitting secondary pairs are mostly produced around \( \epsilon_{\text{th}} \) and then cool down. Dominant IC cooling yields an electron energy distribution below the pair creation threshold \( \propto E^{-2} \), whereas adiabatic cooling renders \( \propto E^{-1} \).

In the Monte-Carlo simulation we have considered an equal number of primary gamma-rays (\( 10^4 \)) and \( 2 \times 10^4 \) for the generic and LS 5039 cases, respectively) per logarithmic energy bin with the angular distribution described in Sect. 2.1. The injection process has been implemented during the relevant time interval, starting early enough before the time \( t \), to account for all the relevant secondary pairs (say, at \( t < t_{\text{min}} \), \( t \)). The orbital motion of the primary gamma-ray source has been accounted in the calculations of the injection rate. The Monte-Carlo code calculates the secondary pair energy and space distribution at the time \( t \) keeping record of the time of creation \( t^s \) and the initial pair energy. To compute the final radiative output of the secondary pairs one has to account for the adopted gamma-ray injection spectrum (\( \Gamma = 2.5 \)) and the corresponding normalization, i.e. one needs to know how many particles correspond in reality to one particle of the simulation.

Table. Binary system properties

| Parameter [units] | Symbol | Value |
|-------------------|--------|-------|
| Stellar radius [cm] | \( R_* \) | \( 10^{12} \) |
| Orbit separation distance [cm] | \( R_{\text{orb}} \) | \( 3 \times 10^{12} \) |
| Emitter-to-star distance [cm] | \( R_e \) | \( 3 \times 10^{12} \) |
| Stellar temperature [K] | \( T_\star \) | \( 3 \times 10^4 \) |
| total system mass [\( M_\odot \)] | \( M_\star + M_X \) | 22 |
| Star surface magnetic field [G] | \( B_\star \) | 200 |
| Mass-loss rate [\( M_\odot \text{ yr}^{-1} \)] | \( \dot{M} \) | \( 10^{-6} \) |
| Wind speed at infinity [cm s\(^{-1} \)] | \( v_\infty \) | \( 2.5 \times 10^8 \) |
| Distance [kpc] | \( d \) | 2 |
| Superior conjunction | \( \text{supc} \) | 0.0 |
| Inferior conjunction | \( \text{infc} \) | 0.5 |
| Inclination angle [°] | \( i \) | 45 |
| Irregular magnetic field fraction | \( \eta \) | 1 |
| 1 TeV specific flux [TeV\(^{-1} \text{ s}^{-1} \)] | \( n_{\text{TeV}} \) | \( 3 \times 10^{-11} \) |
| Gamma-ray photon index | \( \Gamma \) | 2.5 |
An analytical code has been used to compute the total amount of secondary pairs generated per energy bin for the primary gamma-ray distribution $dN_{\gamma}/d\gamma$. This value, divided by the number of secondary particles per energy bin injected in the simulation, gives the weight of an electron/positron from the evolved distribution of particles. This weight depends on the secondary particle energy, and may vary with the orbital phase, i.e. with injection time $t_\ast$.

Pairs created at different epochs $t_\ast$ can contribute to the radio emission at the same frequency at the final time $t$, since pairs may have different initial energies and spatial trajectories and therefore cooling times differ as well.

In Figs. 6 and 7, we show the (evolved) secondary location distribution and density map, respectively, projected in the observer plane for four different phases, 0.0, 0.25, 0.5, and 0.75.

2.3. Secondary pair radiation

From the energy and the spatial distribution of particles at a specific orbital phase, we have computed the synchrotron emission convolving the particle energy distribution with the one-particle power function. Computing the fluxes from 2D small regions or bins in the observer plane (image pixels), i.e. integrating in depth, permits to extract radio morphologies. The radio emission has been calculated in the optically thin approximation of synchrotron radiation, valid at frequencies above few GHz for the relevant spatial scales. For a 10 mJy source with the self-absorption turnover at $\sim$ 1 GHz, the radio emitter size would be constrained to $\approx 5 \times 10^{13} (B/1 \text{ G})^{1/4} \text{ cm}$ (Bosch-Ramon 2009) (where $B$ would be the radio emitter characteristic magnetic field), or $\sim 1$ mas at few kpc.

Typical radio fluxes of about 20 mJy are obtained at 5 GHz for the parameter values adopted here. Note that, fixing $\Gamma$, the secondary radio flux is $\propto N_{TV}/d^2$. The spectral shape of the specific flux is almost flat, $F_\nu \propto$ constant, since adiabatic losses dominate the secondary pair evolution. Part of the radio emission originates nevertheless in regions in which IC cooling dominates, which softens the spectrum. Free-free absorption, of coefficient $\tau_{ff}$, could be relevant. Adopting a simple prescription for $\tau_{ff}$ which does not depend on the orbital phase in a circular orbit (see Eq. 1 in Bosch-Ramon 2009, adapted from Rybicki & Lightman 1979), we find that for ionization fractions $X_{\text{ion}} \gtrsim 0.1$, the radio fluxes should be already significantly affected. Another effect of the free-free absorption is a strong spectral hardening, although for $X_{\text{ion}} \rightarrow 1$ a combination of the energy and the spatial distribution of secondaries yields again a flat spectrum. All this is shown in Fig. 8. Regarding the magnetic field geometry, fixing $\eta = 1$ implies that the synchrotron power does not depend on the magnetic field orientation and therefore the orbital phase. For $\eta > 1$, changes in the $B_\phi$-line of sight angle could introduce moderate orbital flux variability. For a dominantly toroidal magnetic field, synchrotron flux variations would be of the order of $\sin^2(\pi/2)/\sin^2(i)$ (2 for $i = 45^\circ$), with two dips and two enhancements along the orbit when the $B_\phi$-line of sight angle reached $i$ and $\pi/2$, respectively.

The radiation image can be computed as it would be seen by the observer projecting the 3D emitter in the observer plane and dividing them in 2D bins. From that, synchrotron maps could be produced convolving the fluxes in these bins with a circular Gaussian of full width half maximum (FWHM) of 1 mas. The result will be similar to an image obtained by a radio interferometer with angular resolution of 1 mas. In Figs. 9, 10 and 11, we show three sets of 5 GHz radio images at four different phases: 0.0 (supc), 0.1 (long-dashed line) and 1 (dotted line), respectively.

We have focused in this work on the synchrotron radio emission. We note nevertheless that for the parameter values adopted here, the synchrotron X-ray and IC GeV fluxes would be both about $10^{-11}$ erg s$^{-1}$ cm$^{-2}$. A more detailed study of the higher energy secondary radiation will be presented elsewhere.

3. Application to LS 5039

We have applied our Monte-Carlo code and radiation model presented above to LS 5039. LS 5039 is a high-mass X-ray binary, detected in VHE gamma rays (Aharonian et al. 2005b; Aharonian et al. 2006), which has been observed in radio with different VLBI instruments for more than a decade (Martí et al. 1998; Paredes et al. 2000; Paredes et al. 2002; Ribó et al. 2008). The work by Ribó et al. 2008 presents VLBA observations at 5 GHz in which the radio core appears as marginally resolved, with two small dipolar elongated extensions that show a moderate change in the position angle. The core and extension fluxes are 18–20 mJy and 6–4 mJy, respectively, having the whole structure an angular size of several mas. The radio struc-
Fig. 6. Computed spatial distribution of the secondary pairs, projected in the observer plane ($i = 45^\circ$), for four different phases: 0.0 (top, left), 0.25 (top, right), 0.5 (bottom, left), and 0.75 (bottom, right). About $10^5$ particles have been injected (black spots), among which about $10^4$ particles have GHz synchrotron emitting energies (light blue spots).

Fig. 7. Density map of the radio secondary populations shown in Fig. 6. Intensity units are arbitrary.
Fig. 9. Computed image of the 5 GHz radio emission, in the direction to the observer, in units of mJy per beam.

Fig. 10. Gaussian convolved image of the 5 GHz radio emission shown in Fig. 9.
Fig. 11. Residuals of the images presented in Fig. 10 after subtracting a point-like (Gaussian) source with the same flux.

features found in the source have been associated either to a jet (Paredes et al. 2000) or a shocked pulsar wind (Dubus 2006b). The binary system consists of an O6.5 main sequence star and a compact object of unclear nature (neutron star or black hole; see Casares et al. 2005). The system semi-major axis is $a = 2.2 \times 10^{12}$ cm, with eccentricity $e = 0.34$ and orbital period $P = 3.9$ days. The phase 0.0 corresponds to the periastron passage, and phases 0.05 and 0.67 to supc and infc of the compact object, respectively. The inclination angle of the orbit is not known and could be in a range between $i \approx 15^\circ - 75^\circ$. The stellar mass-loss rate has been taken to be $\sim 3 \times 10^{-7} M_\odot/yr$. The ephemeris, orbital parameters, system-observer geometry, star and stellar wind properties, and inclination angle constraints have been taken from Casares et al. 2005 and Aragona et al. 2009 (see also Sarty et al. 2010). Following the approach for the generic case, $i$ has been fixed to $45^\circ$ (though our results should not change qualitatively for $i$ values $45 \pm 15^\circ$). The values of $B_*$ and $\eta$ have been taken also as in the generic case, 200 G and 1, respectively. The parameters adopted for LS 5039 are presented in Table 2.

Given the uncertainties in the source properties, and the known complexities of the orbit and VHE flux/photon-index lightcurve, we do not aim in this section at carrying a thorough analysis of the different possibilities, what is left for future work. Otherwise, we intend to give two possible instances of the source behavior, and for that we focus on two phases, 0.2, slightly after supc, and 0.8, slightly after infc. The distribution of the gamma rays injected in the system has been chosen such that the source should show absorbed fluxes and photon indices similar to the observed ones (Aharonian et al. 2006) in the direction to the observer. For this, we have deabsorbed the observed VHE spectra (see, e.g., Boetcher 2007) assuming a point-like emitter in a certain location, as explained below, emitting in the energy range from 20 GeV up to 2 TeV. Since the observed lightcurve shows a relatively smooth behavior around phases 0.45–0.9 and 0.9–0.45 (Aharonian et al. 2006), for simplicity we have adopted typical specific fluxes and photon indices to compute the radio emission: $\nu n_{\text{TeV}} = 10^{-12}$ TeV$^{-1}$ s$^{-1}$ cm$^{-2}$ and $\Gamma = 2.5$ (phase 0.2), and $3 \times 10^{-12}$ TeV$^{-1}$ s$^{-1}$ cm$^{-2}$ and $\Gamma = 2$ (phase 0.8). Since the location of the emitter is not well constrained (Khangulyan et al. 2008; Bosch-Ramon et al. 2008b), two different heights have been chosen that optimize the radio fluxes without entering in strong conflict with the X-ray fluxes. At phase 0.2, we have located the emitter at a height of $10^{12}$ cm, and at $2 \times 10^{12}$ cm at phase 0.8, perpendicularly to the orbital plane, in the observer side of that plane. There is no additional emitter assumed at a location symmetric with respect to the orbital plane, although if gamma-rays were produced in a symmetric bipolar jet, this component should be also included in the calculations. However, given the expected higher wind free-free opacity for this component, its contribution is expected
to be smaller than the one considered here. We have computed the secondary injection and evolution starting a phase interval of 0.5 earlier than the phases in which the radiation is evaluated, i.e. $0.7 \rightarrow 0.2$ and $0.3 \rightarrow 0.8$. However, most of the radio emission, including the outermost region of the emitter, comes from secondary pairs injected within a phase interval of 0.2 earlier, due to adiabatic cooling.

The resulting images of the raw radio emission, of the source convolved with a Gaussian, and the residuals after extracting a point-like source are presented in Fig. 12. The figure shows that the radiation, with a typical emitter size of $\sim 1$ mas, would be difficult to resolve, although the bigger size of the system around infc may lead to a marginal extension. The obtained total fluxes at 5 GHz are about 6 and 10 mJy at phases 0.2 and 0.8, respectively. The complex flux evolution along the orbit of the primary (deabsorbed) gamma-ray spectra yield different spectra from those of the generic case, obtaining $F_\nu \propto \nu^{-0.5}$ (0.2) and $\propto \nu^{-1.0}$ (0.8). This is due to secondary pairs injected at different phases, with different absorbed luminosities, produce the radiation at different frequencies at the same orbital phase. The computed luminosities in the range 1–10 keV are of about $10^{34}$ erg s$^{-1}$, similar to those observed in this energy range (e.g. Bosch-Ramon et al. 2007; Takahashi et al. 2009). These X-ray fluxes already constrain the fluxes of the radio emission to several mJy at most. These results are nevertheless sensitive to the radial profile of $B_\nu$, which is not well known, thus we do not treat here the high-energy output of the secondary emission. The impact of free-free absorption in the wind has not been considered either, but this process could reduce significantly the secondary radio emission mainly for phases around supc under high ionization fractions.

### 4. Discussion

This work shows that the radio emission detected from compact gamma-ray binaries that contain a massive star could have a non-negligible component coming from the secondary pairs created in the vicinity of the gamma-ray emitter. Actually, the following simple estimate of the radio flux already indicates this. Assuming that secondary pairs cool mainly through adiabatic cooling in the region in which they produce radio emission, which is the case for a wide range of parameter values, and a wind velocity of $2 \times 10^6$ cm s$^{-1}$, the expected fluxes can be derived from the formula:

$$F_{5\, \text{GHz}} \sim \left(\frac{1}{4\pi d^2}\right) \times \left(\frac{E_{\text{radio}}}{E_0}\right) \left(\frac{t_{\text{ad}}}{t_{\text{sync}}}ight) \tau_{100} \times \left(\frac{L_{\text{VHE}}}{10^{35} \text{erg s}^{-1}}\right) \left(\frac{B_{\text{eq}}}{10 \text{G}}\right) \times \left(\frac{L_\nu}{10^{38} \text{erg s}^{-1}}\right) \left(\frac{R_\nu}{3 \times 10^{12} \text{cm}}\right)^{-1} \left(\frac{d}{2 \text{kpc}}\right)^{-2} \text{mJy},$$

where $E_{\text{radio}}$ is the energy of the radio emitting particles, $\tau_{100}$ the angle averaged opacity at gamma-ray energies around 100 GeV, $t_{\text{sync}}$ the synchrotron cooling timescale, $E_0 \sim 30$ GeV the secondary typical injection energy, $L_{\text{VHE}}$ the VHE luminosity, $B_{\text{eq}} = B_{\phi}(R_c)$, and $d$ the distance to the source. In Eq. (18), the product $(L_\nu/10^{38} \text{erg s}^{-1})(R_\nu/3 \times 10^{12} \text{cm})^{-1}$ should be substituted by $\sim 2$ for $\tau_{100} \geq 1$ (and $\tau_{100}$ fixed to 1). In sources with parameters such that $F_{5\, \text{GHz}} \geq 1$ mJy, secondary radio emission should not be neglected. The most crucial point here is whether magnetic fields of the order of 10 G can be found at few $R_c$ from the star.

As shown in this work, secondary radio emission from gamma-ray binaries would not be only relevant in flux, but they could also present resolvable extensions. In general, the spectra can be flat or softer depending on $u_\ast$ (adiabatic vs IC cooling dominance), and the absorbed gamma-ray luminosity and the radio emitter conditions, in particular $v_\nu$ and $B_\nu$, along the orbit. In the particular case of LS 5039, we find that a dominant fraction of the marginally extended core of LS 5039 (Ribó et al. 2008) could be of secondary origin, with a changing relatively soft spectrum. Since the computed additional extension appears marginal, the observed elongated emission at 5 GHz beyond the core in LS 5039 would be likely related to an intrinsic primary radio emitter.

Regarding morphology, we find that a spiral-like shape would be expected, although typically the small angular size of the radio source presently prevents detailed imaging. Such a spiral-like shape was also predicted in Bosch-Ramon et al. (2008a), although the treatment there was simpler than in the present work. It is worthy noting that the wind conditions could differ from those adopted here, and then the shape, and even the radio emitter extension, may change. More collimated radio structures, or a magnetic field increase downstream the wind leading to more extended radio emission, cannot be discarded.

It is remarkable that the spatial distribution of the radio emitting secondary pairs is strongly determined by their injection, which depends on the stellar photon field and the gamma-ray emitter location, and by the stellar wind inhomogeneities and anisotropies, but not by $B_\nu$. Only a very regular $B_\nu$, with very large $\eta$-values, could modify significantly the distribution of the radio emitting secondary pairs, since then these particles would move at $c$ along
Fig. 12. Computed raw (top), Gaussian convolved (middle), and residual images (bottom) of the emission at 5 GHz from LS 5039 in the direction to the observer for the phases 0.2 (right) and 0.8 (left).
the dominantly toroidal $B_w$, i.e. leaving the system with a speed $c B_w/B_{\phi}$, between $v_w$ and $c$. For reasonable $B_w$ and $\eta$-values, particles are trapped in the wind, and their energy distribution is determined by IC and adiabatic cooling. The magnetic field strength is then relevant only for the synchrotron fluxes (recall $F \propto B_w$), and its level of (ir)regularity, $\eta$, for variability. Polarization would also be affected by $\eta$, and polarization observations may probe the $B_w$ geometry. However, the high density of cold free electrons in the stellar wind could induce strong Faraday rotation. A proper study of the impact of this on the final polarization degree and angle requires a devoted investigation.

System eccentricity, a significant regular magnetic field component, and free-free absorption would be sources of radio variability and should be considered when studying specific cases. Changes in the gamma-ray luminosity would also lead to a smooth modulation of the secondary radio emission. To finish with, it seems likely that in gamma-ray binaries, the radio emission from inner regions can be, if not dominated, significantly contaminated by secondary radiation. Secondary pairs should not be neglected when understanding the broadband non-thermal emission in compact gamma-ray sources, nor the physical connection of the radiation produced in different bands.

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