X-ray absorption and occultation in LS 5039

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Accepted September 2010

ABSTRACT

Gamma-ray binaries are systems containing a massive star and a compact object that have been detected up to TeV energies. The high energy emission could result from particle acceleration in the region where the stellar wind from the massive star interacts with the relativistic wind from a young pulsar. LS 5039 has the most compact orbit amongst gamma-ray binaries and its X-ray lightcurve shows a stable modulation synchronized with the orbital period. Photoelectric absorption of X-rays in the O star wind and occultation of the X-ray emitting region by the massive star can alter the X-ray lightcurve and spectrum along the orbit. Yet, the X-ray spectrum and lightcurve of LS 5039 do not show intrinsic absorption or X-ray eclipses. We study these effects in the framework of the pulsar wind scenario as a function of the binary inclination angle, the stellar wind mass-loss rate and the size of the X-ray emitter. An extended X-ray emission region $\gtrsim 3R_*$ appears necessary to reconcile the pulsar wind scenario with observations.

Key words: binaries: close – binaries: eclipsing – stars: individual: LS 5039 – stars: mass-loss – gamma-rays: stars – X-rays: binaries

1 INTRODUCTION

Gamma-ray binaries are systems containing a massive star and a compact object that emit most of their power at energies above 100 MeV. They have been detected up to very high energy (VHE) gamma-rays and are thus sites of particle acceleration up to multi-TeV energies. There are three established gamma-ray binaries PSR B1259-63 (Aharonian et al. 2005), LS 5039 (Aharonian et al. 2006; Abdo et al. 2009b) and LS I+61 303 (Albert et al. 2006; Abdo et al. 2009a) and a candidate binary HESS J0632+057 (Aharonian et al. 2007).

The VHE emission in gamma-ray binaries is thought to be due to Compton upscattering of UV photons from the massive star by energetic electrons. Electron acceleration could take place either in a relativistic jet (microquasar scenario, Romero, Christiansen & Orellana 2005; Paredes, Bosch-Ramon & Romero 2006; Dermer & Böttcher 2004) or in the shocked wind of a young pulsar (pulsar wind scenario, Maraschi & Treves 1981; Dubus 2006), where the shock results from the interaction between the pulsar wind and the stellar wind of the companion star. The latter model is known to be operating in case of PSR B1259-63 (Tavani, Arons & Kaspi 1994; Kirk, Ball & Skjæraa 1994). The nature of the compact object and the electron acceleration site are uncertain in the remaining gamma-ray binaries.

Gamma-ray binaries have also been observed in X-rays where their properties differ from those of high-mass X-ray binaries (HMXB). The X-ray spectrum of gamma-ray binaries are power-laws but show no apparent cutoffs up to hundreds of keV. The X-rays are thought to be due to non-thermal synchrotron or inverse Compton emission. Gamma-ray binaries also do not display X-ray outbursts and state transitions as usually seen in accreting binaries.

LS 5039 is the most compact gamma-ray binary, composed of an unknown compact object in a 3.9 day orbit around a O6.5V star (Casares et al. 2005). It has a regular behavior in both gamma-rays and X-rays. The X-ray lightcurve shows an orbital modulation with a remarkable long-term stability (Kishishita et al. 2003; Takahashi et al. 2004; Hoffmann et al. 2004). The modulation is present at low (1–10 keV) and medium (10–40 keV) X-ray energies, with minimum and maximum flux at superior and inferior conjunction respectively. The location of the minima and maxima suggest the modulation is a geometrical effect related to the orientation of the binary with respect to the observer, rather than due to physical changes taking place in the shocked winds region when the compact object travels on its elliptical orbit.

X-ray absorption in the stellar wind and occultation of the X-ray emitting region by the massive star both result in orbital modulations with the correct phases for flux min-
The schematic 2D illustration of the model where the stellar wind and pulsar wind collide. The sizes of the pulsar and star are not to scale.

2 THE GEOMETRIC MODEL

2.1 Shape of the shock

In the pulsar wind scenario, X-rays are emitted by particles accelerated in the shock region where the pulsar wind and the stellar wind of the massive star collide (Fig. 1). The interaction region is bounded by two termination shocks $S_x$ and $S_p$. Downstream (zones 2 and 3), two shocked winds are separated by a tangential contact discontinuity (CD). Upstream (zones 1 and 4), the winds behave as in the case of single star/pulsar. In this example, the stellar wind momentum dominates over the pulsar wind. The stagnation point $R_s$ between the two winds along the line joining the stars is found by equating the ram pressures from the two winds:

$$P_s(R_s) = \frac{Mv(R_s)}{4\pi R_s^2} = \frac{E}{4\pi c(a-R_s)^2} = P_0(a-R_s),$$  

where $a$ is the binary orbital separation, $M$ is the stellar wind mass loss rate and $E$ is the pulsar spindown power. The stellar wind velocity $v$ at the radial distance $r$ from the star’s centre is given by a $\beta$-velocity law (Castor, Abbott & Klein 1974).

$$v(r) = v_\infty \left(1 - \frac{R_s r_0}{r}\right)^\beta,$$  

where $r_0 = 1 - (v_0/v_\infty)^{1/\beta}$ with $v_0$ the initial wind velocity, $v_\infty$ is the wind terminal velocity, $R_s$ is the stellar radius and $\beta \approx 1$ is a parameter describing wind acceleration.

The detailed structure of the shock will depend on the momenta of the winds and on radiative cooling of the gas. Efficient cooling will tend to collapse the termination shocks onto the CD. The shock structure can also be affected by mixing instabilities at the interface and by orbital motion (e.g. Stevens, Blondin & Pollock 1992). There is no general semi-analytic description of the shock structure but a description of the CD can be obtained. The CD is defined as the surface where the perpendicular components of the ram pressures balance each other $p_{\perp} = p_{\perp}$. For each point in space one can then define a dimensionless parameter

$$\eta(r_1) \equiv \frac{E}{Mv(r_1)c} = \frac{R_s^2 \sin^2 \theta_1}{r_1^2 \sin^2 \theta_2},$$  

where $\theta_1$ and $\theta_2$ are angles between the line tangential to the CD at the given point and the direction towards the star or pulsar respectively as illustrated in Fig. 1. $r_1$ and $r_2$ are distances from the star and pulsar respectively. The value of $\eta$ at the stagnation point ($\theta_1 = \theta_2 = \pi/2$) equals

$$\eta_0 = \eta(R_s) = \frac{E}{Mv(R_s)c} = \frac{(a-R_s)^2}{R_s^2} =$$

$$0.05 \left(10^{36} \text{ erg s}^{-1}\right) \left(\frac{10^{-8} \text{ M}_\odot \text{ yr}^{-1}}{M}\right)^{-1} \left[\frac{v(R_s)}{10^8 \text{ cm s}^{-1}}\right]^{-1}. \quad (4)$$

The $\eta_0$ depends on orbital phase via $v(R_s)$ and parametrizes the shape of the shock, which is then obtained by solving the differential equation (Eq. 6 in Antokhin, Owocki & Brown 2004)

$$\frac{dx}{dy} = \frac{1}{y} \left\{ x - \frac{\alpha r_k^2(x, y) \sqrt{\eta} |r_1(x, y)|}{r_1^2(x, y) \sqrt{\eta} |r_1(x, y)| + r_2^2(x, y)} \right\}, \quad (5)$$

with the initial condition $x = R_s$ and $y = 0$. Numerical simulations show that this holds reasonably well in the case of the interaction with a relativistic pulsar wind (Bogovalov et al. 2005). The solution is a 2D profile of the CD $x = f(y)$. The CD is symmetrical with respect to $x$-axis, thus it is best represented in cylindrical coordinates $(\rho, \psi, x)$ as $x = f(\rho)$, where $\rho = \sqrt{y^2 + z^2}$ and $\psi = \arctan(x/y)$.

An example 3D representation of the model is shown in Fig. 2. In cases where $\eta_0 < 1$ the stellar wind dominates over the pulsar wind. When $\eta_0 \ll 1$, the opening angle of the CD $\alpha \lesssim 45^\circ$ (where $\alpha$ is an angle between $x$-axis and a line tangential to the CD at a large distance from the stagnation point) and the CD wraps around the pulsar creating a tail-like structure. For $\eta_0 > 1$ the opening angle $\alpha > 90^\circ$ and the CD curves around the massive star. Note that there is a maximum value of $\eta_0$ associated with a minimum realizable distance $R_s^{\text{min}}$ between the star and CD. This is approximately the place where $p_{\perp}(r)$ has its maximum. Stable balance is lost if the pulsar wind moves beyond this point: then the pulsar wind overwhelm the stellar wind and is stopped at the star surface.

The shape of the CD will be correct up to the point where the Coriolis force curves the shock structure. Assuming that the stellar wind is collimating the pulsar wind, this
happens at a distance $\sim v_{\infty} P_{\text{orb}}$, or about 5.4 a.u. (130 $R_\star$) for LS 5039 with the parameters given in [274]. Closer in, the orientation of the surface can also be altered by orbital motion: the skew angle $s$ is given by $\tan s = v_{\text{orb}} / v(a)$ where $v_{\text{orb}}$ is the pulsar orbital velocity.

### 2.2 X-ray emission

In the pulsar wind scenario, the X-ray emission is primarily due to synchrotron emission in the shocked pulsar wind region (zone 3 in Fig. 1) which is tenuous and optically thin to X-rays. The stellar wind region may also be a source of X-rays, either because of the kinetic energy dissipated in the colliding winds (zone 2) or due to small-scale instabilities in the stellar wind (zone 1) [Puls, Vink & Najarro 2008]. In both cases the emission is softer ($kT \approx 0.5$ keV) and weaker ($10^{30} - 10^{33}$ erg s$^{-1}$, e.g. Stevens et al. 1992) than the observed X-ray emission from LS 5039 ($\approx 10^{33}$ erg s$^{-1}$, Takahashi et al. 2009). Detecting X-ray line emission would provide valuable diagnostics of the stellar wind but this emission is most likely swamped by synchrotron emission.

The cooling parameter $\chi \equiv t_{\text{cool}}/t_{\text{dyn}}$ of the O star wind (Stevens et al. 1992) is $\approx 1$ in LS 5039, at the limit of efficient radiative cooling. Isothermal (radiatively efficient) shocks have small widths. The pressure in the shocked pulsar wind will mostly be due to the lowest-energy electrons if the particles have a steep distribution. These electrons have long cooling times and the shock may be more closely approximated as adiabatic rather than isothermal. Complex numerical simulations are required to obtain the detailed structure and emissivity of the shock region. At this stage, we assume that the shocked regions 2 and 3 have a negligible width and that the emissivity is uniform over the 2D shock surface, which should suffice to capture the geometrical effects that we want to investigate.

The 2D shock surface is approximated by the CD surface for $\rho \in (0, \rho_{\text{max}})$ and zero otherwise, with $\rho_{\text{max}}$ the cylindrical radius at which a sphere centered at $(R_s, 0, 0)$ of radius $R_{\text{out}}$ intersects the CD (Fig. 1). The size of the emitting region is conveniently parametrized by $R_{\text{out}}$ in the following. The total flux from the emitting volume is

$$ F(E) = \int_V j_\lambda \, dV = \int_S j_\lambda \, dS, \quad (6) $$

where $j_\lambda$ is the unit volume emissivity, and $\lambda j_\lambda$ is the constant surface emissivity. The unit surface element of CD equals

$$ dS = \sqrt{1 + \left(\frac{\partial f}{\partial \rho}\right)^2} \, \rho \, d\rho \, d\psi. \quad (7) $$

### 2.3 Absorption and occultation

The uniform emission of X-rays is affected in two, orbital phase-dependent, ways. First, X-rays can undergo photoelectric absorption as they cross the dense stellar wind. The wind density at the distance $r$ from the stellar center is

$$ n(r) = \frac{\dot{M}}{4 \pi \mu m_H r^2 v(r)}, \quad (8) $$

where $m_H$ is hydrogen mass while $\mu = 1.3$ is the mean molecular weight. Second, at some phases and for some inclinations, parts of the emitting surface of the CD are occulted by the massive star and are thus invisible to the observer (black regions in Fig. 2).

In order to estimate the impact of absorption and occultation on the observed flux, a random sample of $N$ points is uniformly distributed on the surface of CD out to $R_{\text{out}}$ (see Fig. 2 and Appendix A). Each point corresponds to a $N$-th part of the emitting surface and has a flux equal $1/N$ (the total flux is normalized to unity). The observed flux at given energy $E$, inclination angle $i$ and orbital phase $\phi$ is

$$ F(E, i, \phi) = \frac{1}{N} \sum_{j=1}^{N} \exp[-\sigma(E) N_{\text{HI}}(i, \phi)] \zeta(i, \phi), \quad (9) $$

where $N_{\text{HI}}$ is the stellar wind’s hydrogen column density obtained from integration of $n(r)$ along the line of sight from point $j$. $\sigma$ is the photoelectric cross section of the plasma which is a function of photon energy $E$. If the plasma is ionized, $\sigma$ also depends on plasma ionization parameter which varies along the line of sight. $\zeta$ is the occultation function which value is 0 whenever a line of sight crosses the interior of the massive star and 1 otherwise.

In calculations of $N_{\text{HI}}$ the parts of the line of sight that cross the pulsar side of the CD (zones 3 and 4 in Fig. 1) are considered to be empty since neither unshocked nor shocked pulsar wind have sufficient densities to absorb X-rays. For simplicity, we also assume that zone 1+2 are described by Eq. 2 all the way from the stellar surface out to the CD i.e. we ignore the density enhancement in the shocked stellar wind (zone 2). Again (922.2), detailed numerical simulations would be required to model this appropriately. An estimate can be derived using the thin shell colliding wind model of Canto, Raga & Wilkin (1996). The surface density of the shock is $\approx 3M \sqrt{\eta}/(16\pi a v)$ in the orbital plane, where it is maximum. This corresponds to a column density across the shock $N_{\text{H}}$ shock $\approx 7 \times 10^{19} \dot{M} 10^{-3} M_\odot/yr r_{19}^{1/2} a_{0.1}^{-1} v_{2000}^{-1} \text{ km/s}^{-2}$, compared to

![Figure 2. 3D illustration of LS 5039 in the framework of the pulsar wind scenario. The plot is in units of orbital separation and the massive star is plotted to scale. The dark sphere is the massive star, the light grey (green) points represent the CD surface, the dark grey (red) points are the points that emit X-rays, whereas black points are in the shadow of the massive star. The arrow represents the direction to the observer at inclination 60° and the phase of superior conjunction.](image-url)
the wind column density \( N_H \approx 2 \times 10^{21} \text{cm}^{-2} \) from \( R_* \) to infinity (for the same wind parameters). \( N_{\text{H,shock}} \) is also about 30 times less than the inferred wind column density at superior conjunction (see §2.4). We conclude that taking into account the density enhancement in the shocked region is unlikely to change our results significantly.

### 2.4 Parameters for LS 5039

We adopt the following binary parameters for LS 5039: \( v_{\infty} = 2.4 \times 10^6 \text{ cm s}^{-1} \), \( R_* = 9.3R_\odot \), \( M_* = 23M_\odot \) and \( T_* = 3.9 \times 10^4 \text{ K} \). For the wind of the massive star, we adopt \( \beta = 1 \) and \( v_0 = 2 \times 10^6 \text{ cm s}^{-1} \) (Eq. 2). The value of \( M \) in LS 5039 is not well constrained and varies from \( \sim 3 \times 10^{-8} \) to \( 7.5 \times 10^{-7} \text{ M}_\odot \text{ yr}^{-1} \) favoured in the most recent literature (Kuulkrijtik \& Puls 2000; McSwain \& Gies 2002; McSwain et al. 2004; Casares et al. 2004; Szalai, Kiss \& Sarty 2010). These mass loss rates are derived from H\(_\alpha\) line fitting, a diagnostic which is known to be affected by wind clumping (Puls et al. 2008). The true \( M \) could be a factor 2–3 lower than the \( M \) estimated from H\(_\alpha\). The large range of \( \eta \) that we explore covers this uncertainty.

The binary inclination angle is \( i \gtrsim 40^\circ \) if the binary contains a neutron star. The orbit eccentricity is \( e = 0.33 \), while the angle of the line of nodes is \( \omega = 236^\circ \) (Arakona et al. 2002). For these orbital parameters the periastron, apastron, pulsar superior and inferior conjunction correspond to orbital phases \( \phi = 0, 0.5, 0.645 \) and 0.67 respectively. The respective binary separations are \( 1.4 \times 10^{12}, 2.82 \times 10^{12}, 1.46 \times 10^{12}, \) and \( 2.59 \times 10^{12} \text{ cm} \). The skew angle is \( s = 23^\circ \) at periastron and \( 8^\circ \) in apastron. This has a negligible impact on the conclusions and is not taken into account.

A strict lower limit on the value of \( E \) in LS 5039 is \( \sim 10^{35} \text{ erg s}^{-1} \) which implies 100% radiative efficiency to gamma rays (at a distance of 2-3 kpc). At the other end of the scale, the pulsar wind will impact the star surface if the scale, the pulsar wind will impact the star surface of the scale, the pulsar wind will impact the star surface of the scale, the pulsar wind will impact the star surface. Such a situation is thought to occur in the black widow pulsars where the wind from the low-mass neutron star does not collapse implies a maximum \( M_{\text{max}} \) which implies 100% radiative efficiency to gamma rays. For example, for a point X-ray source located at the pulsar position, at the phase of superior conjunction, and at inclination angle \( i = 40^\circ \), the upper limit on the stellar wind mass loss rate is \( M_{\text{max}} = 7.3 \times 10^{-8} \text{ M}_\odot \text{ yr}^{-1} \). For a point source located at the stagnation point, the \( M_{\text{max}} \) is lower, since the line of sight probes regions of the stellar wind with higher density. For an X-ray emitting point source located at \( R_* \) and for which \( \eta \eta_{\text{max}} \), then \( M_{\text{max}} = 2.3 \times 10^{-8} \text{ M}_\odot \text{ yr}^{-1} \).

These values of \( M_{\text{max}} \) are at the lower end of the \( M \) scale for the Galactic O stars, \( (\sim 10^{-8} - 10^{-6} \text{ M}_\odot \text{ yr}^{-1}) \). For a point X-ray source located at the pulsar position, at the phase of superior conjunction, and at inclination angle \( i = 40^\circ \), the upper limit on the stellar wind mass loss rate is \( M_{\text{max}} = 7.3 \times 10^{-8} \text{ M}_\odot \text{ yr}^{-1} \). For a point source located at the stagnation point, the \( M_{\text{max}} \) is lower, since the line of sight probes regions of the stellar wind with higher density. For an X-ray emitting point source located at \( R_* \) and for which \( \eta \eta_{\text{max}} \), then \( M_{\text{max}} = 2.3 \times 10^{-8} \text{ M}_\odot \text{ yr}^{-1} \).

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### 3 X-RAY ABSORPTION IN LS 5039

Observations show no signatures of X-ray absorption by the stellar wind in LS 5039. The XMM-Neutron and Suzaku spectra of LS 5039 are absorbed by an equivalent hydrogen column density consistent with the Galactic value. The upper limit on the intrinsic column density at the phase of superior conjunction (where the line of sight column density related to the stellar wind is highest) is as low as \( N_{\text{H}}^\text{max} = 2.6 \times 10^{21} \text{ cm}^{-2} \) (Bosch-Ramon et al. 2006; Takahashi et al. 2009).

The photoelectric absorption depends on four parameters, \( M, i, R_{\text{out}} \), and \( \eta_0 \). This can be used to estimate the maximum allowed \( M_{\text{max}} \) for which the line of sight column density does not exceed \( N_{\text{H}}^\text{max} \). For example, for a point X-ray source located at the pulsar position, at the phase of superior conjunction, and at inclination angle \( i = 40^\circ \), the upper limit on the stellar wind mass loss rate is \( M_{\text{max}} = 7.3 \times 10^{-8} \text{ M}_\odot \text{ yr}^{-1} \). For a point source located at the stagnation point, the \( M_{\text{max}} \) is lower, since the line of sight probes regions of the stellar wind with higher density. For an X-ray emitting point source located at \( R_* \) and for which \( \eta_0 = \eta_{\text{max}} \), then \( M_{\text{max}} = 2.3 \times 10^{-8} \text{ M}_\odot \text{ yr}^{-1} \).

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The X-ray absorption column density is

\[
F(E) = \exp[-\sigma(E)N_{\text{H}}],
\]

where the intrinsic flux equals 1. In our case however, where
an extended X-ray source is absorbed by a stellar wind, the line of sight column density of each X-ray emitting surface element is different and the observed flux is given by Eq. 9. In general, the observed spectra of a source covered by an uniform absorber and of a source covered by stellar wind are different ($\lesssim 5 \text{ keV}$). We assume that the spectral fitting is not able to distinguish between different types of absorbers if the fluxes at 1 keV are equal i.e.

$$\frac{1}{N} \sum_{j=1}^{N} \exp[-\sigma(1\text{keV})N_{Hj}(i, \phi)] = \exp[-\sigma(1\text{keV})N_{H\text{max}}]. \quad (11)$$

where $\sigma(1\text{keV}) = 2.4 \times 10^{-22} \text{ cm}^2$. This is justified, because at energies $\gtrsim 2 \text{ keV}$, the photoelectric cross-section decreases quickly and the difference between the two absorbed spectra is relatively small. Furthermore, the spectrum is most sensitive to absorption at energies $\lesssim 2 \text{ keV}$, but below 1 keV the sensitivity of the instruments starts to drop and the data errors increase which may also make it difficult to distinguish between different models.

In order to obtain the lower limit on the size of the X-ray emitting region at 1 keV, we explore the parameter space $(M, \eta, R_{\text{out}}, i)$ to find solutions that satisfy Eq. 11 at superior conjunction. In this calculation we reject points which are occulted by the star (adjusting $N$ accordingly) to test only the effect of absorption.

The estimated minimum size of the 1 keV X-ray source is shown in Fig. 3. The size of the emitting region must be larger to compensate for the denser gas when the mass loss rate is increased. For $\eta_0 \approx \eta_{\text{max}}$ and at large emitter size, the results are not sensitive to inclination changes. The highly collimated pulsar wind shock ($\eta_0 \ll 1$) needs to have a large emitting surface to explain the observations.

Figure 3. The minimum size of the X-ray 1 keV emission region at superior conjunction. The dots mark the results of calculations, the lines are linear fits to the points. The dashed lines correspond to $\eta_0 = 0.004$ at superior conjunction, the solid lines correspond to maximum value of $\eta_0 = \eta_{\text{max}} = 0.6$ at periastron. The grey (red) and black correspond to $i = 40^\circ$ and $i = 60^\circ$ respectively.

4 OCCULTATION IN LS 5039

The occultation of the X-ray emitting region by the massive star does not depend on energy, thus its only signature in the spectrum is a periodic reduction in flux. The amplitude and duration of occultation depend on three main parameters $i$, $\eta_0$ and $R_{\text{out}}$. We find that the duration of the occultation is longest for binaries with circular orbits and where at all phases $\eta_0 > 1$ (when the CD curves around the massive star). The occultation duration can last up to 40% of the orbital period. The latter is because curved portions of the CD are partly occulted by the star even at phases away from the superior conjunction. The amplitude of occultation is highest if the inclination is high and the size of the emitting region is small compared to the size of the star. However, this situation is unlikely to occur in LS 5039 since $\eta_0 \lesssim 0.6$ (see 2.4).

When $\eta_0$ is below unity, occultation influences the shape of the X-ray lightcurve only around superior conjunction. Lightcurves calculated for the most preferable conditions to observe occultation in LS 5039 (high $\eta_0$, high $i$ and small $R_{\text{out}}$) are shown in Fig. 4. The dip in the lightcurve caused by occultation is narrow and covers only $\Delta \phi \sim 0.2$ in phase around superior conjunction. The depth of the minimum strongly depends on $R_{\text{out}}$. Note also that for large $R_{\text{out}}$ two minima appear, separated by a local maximum. This effect is related to the size of the shadow cast by the star onto the CD surface, which is larger when the line of sight is tangential to the surface of CD. These two local minima are too narrow ($\Delta \phi \sim 0.025$) to be resolved in the *Suzaku* lightcurve. A similar lightcurve study for $\eta_0 \ll 1$ shows even deeper and narrower minimum than in case of $\eta_0 \sim \eta_{\text{max}}$ (Fig. 4).

The X-ray modulation cannot be explained by occultation alone but this does not preclude an observable effect in
the form of a sharp drop in flux around superior conjunction.
In order to place an upper limit on this effect, we normalize
the Suzuki lightcurve to 1 and fit it with a sine function in
order to remove the orbital modulation. The standard de-
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Figure 5. The areas above each curve correspond to permitted
values of $i$ and $R_{\text{out}}$ for which effect of occultation at superior con-
duction does not exceed the $3\sigma_d$ limit. Each curve corresponds
to different value of $\eta_0$, solid 0.6, dashed 0.08, dotted 0.02, 
dotted-dashed 0.004 measured at periastron.

the observed upper limit on the intrinsic column density and
on the depth of the occultation dip. Limiting the effects of
absorption and occultation requires the X-ray source to be
extended. The minimum size of the X-ray emitting region,
which depends on the stellar mass loss rate, shape of CD and
inclination, varies between $3-15 R_\star$. An emitter size
$>4R_\star$ with $\eta_0 \gtrsim 0.02$ would be compatible with a $90^\circ$ binary
inclination. The limit based on the lack of X-ray eclipses and
assuming a point source at the compact object location is
$60^\circ$ (Casares et al. 2003). A large X-ray source also loosens
the constraints on the stellar mass loss rate derived from
the observed lack of intrinsic absorption. For example, for
$\eta_0 \sim 0.004$, an emission region $\sim 3R_\star$ at inclination $\sim 50^\circ$,
allows a mass-loss rate of $1.5 \times 10^{-7} M_\odot$ yr$^{-1}$ compared to
$4.7 \times 10^{-8} M_\odot$ yr$^{-1}$ for a point source located at the pulsar
position. A more precise determination of the stellar wind
mass loss rate would greatly help narrow down the possibil-

5 CONCLUSIONS

Using a 3D model of a gamma-ray binary in the framework
of the pulsar wind scenario, we tested the influence of X-ray
absorption and occultation on the lightcurve and spectrum
of LS 5039. We find that occultation cannot be respon-
sible for the smooth X-ray orbital modulation in LS 5039,
since this would require $\eta_0 > 1$. This appear unlikely be-
because there is no sign in the UV lines (McSwain et al. 2004)
that the O star wind is quenched on the hemisphere facing

An extended X-ray source in gamma-ray binary can be
expected in the pulsar wind scenario. High-energy electrons
will be accelerated and randomized all along the termina-
tion shock of the pulsar wind. The shock distance from the
pulsar is smaller towards the stellar companion than away
from the O star, the efficiency of particle acceleration may
also change at different locations. Calculations also show
that the synchrotron emission from the electrons peaks in
the 1–10 keV range only after significant cooling (Dubus
2006; Dubus, Cerutti & Henri 2008). For a typical magnetic
field of $0.1-1$ G, the injected electrons radiate primarily syn-
chrotron above $0.1$ MeV while they upscatter stellar photons
to energies above a GeV. The electrons are advected away in
the shocked flow with an initial speed $c/3$. The bulk of the
1–10 keV radiation is emitted at a distance $\approx 3R_\star$ from the
star in Fig. 4 of Dubus (2008). More detailed modeling is re-
quired to obtain the exact evolution of the shock conditions
with distance and quantify precisely the extent of the X-ray
emission region. Such modeling would also yield the precise
contribution to the X-ray emission and absorption from the
shocked stellar wind region, which we have neglected here

The application to other known gamma-ray binaries is
not straightforward since these contain a Be star with a
dense equatorial outflow in addition to the tenuous stellar
wind. The geometry of the interaction region with the pulsar
wind changes between the polar wind and disk wind and can
have a complicated shape at the transition that has yet to
be investigated. However, the wider orbits of LS I+61°303
and PSR B1259-63, the estimated inclination of $36^\circ$ in PSR
B1259-63, will limit the impact of absorption and occulta-
tion on the lightcurve.
ACKNOWLEDGMENTS

This work was supported by the European Community via contract ERC-StG-200911 and in part by the Polish MNiSW grant NN203065933.

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6 APPENDIX A - RANDOM GENERATION OF UNIFORMLY DISTRIBUTED POINTS ON THE 3D SURFACE.

Here we explain how to generate a random sample of points uniformly distributed on a 3D surface $S$, symmetrical with respect to $x$-axis, described by a function $f(\rho)$ where $\rho = \sqrt{y^2 + z^2}$. We adopt an accept-reject algorithm commonly used for generating random samples drawn from an arbitrary distribution.

First, we generate $N$ random points distributed uniformly on the $yz$-plane. The points are denoted in polar coordinates as $(\rho_1, \psi_1), (\rho_2, \psi_2), ..., (\rho_N, \psi_N)$ where $\rho_i \in (0, \rho_{\text{max}})$ and $\psi_i \in (0, 2\pi)$.

Second, we assign to each point a random number $w_i \in (0, 1)$, where $w_1, w_2, ..., w_N$ are drawn from an uniform distribution. The $w_i$ are weights, used to accept and reject points on the basis of a density function

$$P(\rho_i) \sim \frac{dS}{M \rho_i \Delta \rho \Delta \psi} =$$

$$= \frac{1}{M} \sqrt{1 + \left(\frac{f(\rho_i + \Delta \rho) - f(\rho_i)}{\Delta \rho}\right)^2}, \quad (13)$$

where $\Delta \rho \to 0$, $P(\rho_i) \in (0, 1)$, $dS$ is a unit 3D surface element given by Eq. 7, and

$$M = \sqrt{1 + \left(\frac{f(\rho_{\text{max}} + \Delta \rho) - f(\rho_{\text{max}})}{\Delta \rho}\right)^2}. \quad (14)$$

Finally, from our sample of points uniformly distributed on the 3D surface, we choose only points for which $w_i < P(\rho_i)$. In the paper, $f$ is the solution to Eq. 5 while $\rho_{\text{max}}$ is determined by $R_{\text{out}}$ and has to be found numerically. An example sample of points is plotted in Fig. 2.