A ROTATING HOLLOW CONE ANISOTROPY OF TeV EMISSION FROM BINARY SYSTEMS

A. Neronov
INTEGRAL Science Data Center, 16 chemin d’Ecogia, CH-1290 Versoix, Switzerland; andrii.neronov@obs.unige.ch

AND

M. Chernyakova
Dublin Institute for Advanced Studies, 31 Fitzwilliam Place, Dublin 2, Ireland; masha@cp.dias.ie

ABSTRACT

We show that TeV γ-ray emission produced via interactions of high-energy particles with the anisotropic radiation field of a massive star in binary systems should have a characteristic rotating hollow cone anisotropy pattern. The hollow cone, whose axis is directed away from the massive star, rotates with a period equal to the orbital period of the system. We note that the two-maxima pattern of the TeV energy band light curve of the γ-ray-loud binary LS 5039 can be interpreted in terms of this rotating hollow cone model. Adopting such an interpretation, we are able to constrain the geometry of the system—either the inclination angle of the binary orbit, or the elevation of the γ-ray emission region above the orbital plane.

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1. INTRODUCTION

Gamma-ray-loud binary systems are a newly identified class of sources in which either accretion onto the compact object (a neutron star or a black hole) or interaction of an outflow from the compact object with the wind and radiation from a massive companion star leads to the production of very high energy (VHE) γ-ray emission. Three such systems, PSR B1259–63, LS 5039, and LSI +61 303, have been firmly detected as persistent or regularly variable TeV γ-ray emitters (Aharonian et al. 2005, 2006; Albert et al. 2006). The VHE γ-ray emission from the γ-ray-loud binaries is variable on the orbital period (or shorter) timescale. This implies that the emission region is located close to the binary system, in a highly inhomogeneous and anisotropic particle and photon background produced by massive companion star.

In what follows we show that if the γ-ray emission from such a region is produced in interactions of isotropically distributed VHE particles with photons from the massive star, it should have a characteristic “rotating hollow cone” anisotropy; i.e., most of the photons are emitted at a certain angle with respect to a symmetry axis directed radially away from the massive star. Orbital motion of the emission region around the massive star leads to the rotation of the emission cone. Rotation of the hollow cone on the orbital timescale leads to the appearance of 0, 1, or 2 maxima in the orbit-folded light curve in the VHE band, occurring at the phases when the line of sight is inclined at an angle with respect to the cone axis, i.e., at the moments of passage of the of the cone through the line of sight (similarly to the hollow cone models of period-folded light curves of pulsars; see, e.g., Lyne & Graham-Smith 2005).

The orbital modulation of the γ-ray flux, related to the passage of the hollow cone through the line of sight, could be most clearly detected if there were no additional sources of the modulation, related, e.g., to the ellipticity of the binary orbit, or to the absence of spherical symmetry of the wind/radiation from the companion star. Among the three γ-ray-loud binary systems mentioned above, the system LS 5039 is characterized by the lowest ellipticity of the orbit. In this system the compact object orbits a O6.5 V star which emits isotropic stellar wind (contrary to the other two systems in which the massive star is of the Be type). The influence of the anisotropy of the photon field of the massive star on the properties of the γ-ray emission in binaries in general, and in LS 5039 in particular, was first studied by Khangulyan et al. (2005, 2007). In what follows we calculate the angular brightness profile of the hollow cone in LS 5039, and find that the observation of the two maxima of the orbit-folded light curve constrains the inclination of the binary orbit to be $i > 40^\circ$, if the emission is produced in the vicinity of the compact object. This result can be stated also in an opposite way: if the inclination of the binary orbit is $i < 40^\circ$, the two-maxima structure of the orbit-folded light curve can be explained only if the VHE γ-ray emission region is displaced from the position of the compact object. This can be the case if the emission is produced in a jet. In this latter case, we show that the existence of the two maxima of the light curve constrains the elevation of the emission point above the orbital plane.

2. ANISOTROPY OF VHE γ-RAY EMISSION IN A CENTRAL PHOTON FIELD

Consider the γ-ray emission produced by interactions of VHE particles $X$ (e.g., protons or electrons) with the soft photon field in the vicinity of a massive star. Assume for simplicity that the size of the emission region is much less than the distance from the region to the center of the star and that the VHE particles in the region have isotropic velocity distribution. In spite of the isotropy of the VHE particle distribution, the γ-ray emission will be anisotropic. The anisotropy arises because of the Doppler effect which leads to the decrease (increase) of the rate of interaction of the VHE particles moving with (moving opposite to) the soft photon field of the massive star.

The interaction rate of particles $X$ with momenta $p$ with soft photons with momenta $p_\gamma$ is given by (Landau & Lifshitz 1980)

$$R = \int n_\gamma n_\gamma \sigma \frac{P_X \cdot p_\gamma}{E_X \epsilon_\gamma} dE_X d\epsilon_\gamma d\Omega,$$

(1)
where $\sigma$ is the interaction cross section, $n_p(P_j)$ is the particle distribution, $n_s(p_r)$ is the soft photon distribution, and $P_r \cdot p$ is the scalar product of the 4-momenta of the interacting particles,

$$P_r \cdot p = E_r \epsilon_r (1 - \cos \zeta)$$

($\zeta$ is the angle between the particle velocities), which contains the Doppler factor $1 - \beta \cos \zeta$ (we assume that the particle velocity is $\beta = 1$).

If the soft photon field in the emission region were isotropic, integration of the interaction rate of equation (1) over the soft photon angular distribution would average out of the angular integration of the interaction rate of equation (1) over the soft velocity is $\gamma$.

where is the cross section of production of $E_{\gamma}$ particles, easily performed and the resulting expression for the rate of production of $E_{\gamma}$ rays facilitates the escape of $E_{\gamma}$ rays moving in the direction away from the star. On the other hand, the reduction of the interaction rate has twofold consequences. On one hand, it leads to the reduction of the power of the $E_{\gamma}$-ray emission by the particles moving in the direction away from the star. On the other hand, the reduction of the interaction rate of the soft photons with the emitted VHE $E_{\gamma}$-rays facilitates the escape of $E_{\gamma}$-rays moving in the direction away from the star. A competition between the decrease of the interaction rate, $R_{\text{prod}}(\zeta)$, and the increase of the $E_{\gamma}$-ray “survival probability” (i.e., of $\exp[-\tau_{\text{abs}}(\zeta)]$, where $\tau_{\text{abs}}(\zeta)$ is the optical depth with respect to the pair production) leads to the appearance of a maximum of the $E_{\gamma}$-ray flux

$$F_r(\zeta) \sim R_{\text{prod}}(\zeta) \exp[-\tau_{\text{abs}}(\zeta)]$$

at an angle $0 < \zeta < \pi$, i.e., to the appearance of a hollow cone anisotropy pattern.

At large distances from the massive star one can approximate the angular distribution of the soft photons by that of a point source. Under this simplifying assumption, one finds that the integration over the angular distribution of the UV photons is easily performed and the resulting expression for the rate of production of $E_{\gamma}$-rays takes the form

$$R_{\text{prod}}(\zeta) \approx n_x n_s \sigma_{\text{prod}} (1 - \cos \zeta),$$

where $\sigma_{\text{prod}}$ is the cross section of production of $E_{\gamma}$-rays in interaction of the particles $X$ with the soft photon field.

An estimate of the optical depth for the $E_{\gamma}$-rays escaping from the production region can be obtained by multiplying the absorption rate per $E_{\gamma}$-ray on the size of the absorbing region. The absorption rate is given by expression (1) in which the particle $X$ is a $E_{\gamma}$-ray and the cross section $\sigma$ is the pair production cross section, $\sigma_{\text{abs}}$. Estimating the size of the absorption region to be of the order of the distance $D$ of the emission point from the massive star, one finds

$$\tau_{\text{abs}} = R_{\text{abs}} D n_e \sim n_s \sigma_{\text{abs}} D (1 - \cos \zeta).$$

Substituting equations (4) and (5) into equation (3) one finds

$$F_r(\zeta) \sim \sigma_{\text{prod}} (1 - \cos \zeta) \exp[-n_s D \sigma_{\text{abs}} (1 - \cos \zeta)].$$

Two effects affect the anisotropy pattern of the $E_{\gamma}$-ray emission. First, the explicit dependence of $F_r$ on $\cos \zeta$ is introduced in equation (6) by the Doppler effect. An additional implicit dependence on $\zeta$ is introduced through the energy dependence of the interaction cross sections $\sigma_{\text{prod}}$, $\sigma_{\text{abs}}$. Indeed, in general $\sigma = \sigma(E_{\text{CM}})$, where the $E_{\text{CM}}$ is the center-of-mass energy, which, in the case $E_{\text{CM}} \gg m_e$, depends on $\zeta$ as $E_{\text{CM}} \sim (1 - \cos \zeta)^{1/2}$.

The anisotropy pattern resulting from the Doppler effect can be found if one ignores the energy dependence of $\sigma_{\text{prod}}$, $\sigma_{\text{abs}}$. This is done in Figure 1 (the constant $\tau_0 = n_s D \sigma_{\text{abs}}$ is taken to be $\tau_0 = 3$). From this figure one can see that most of the $E_{\gamma}$-ray flux is emitted along a thick hollow cone with opening angle $\zeta_0$ and thickness comparable to the opening angle, $\Delta \zeta \sim \zeta_0/2$. The energy dependence of the interaction cross sections leads to the energy-dependent angular brightness profile of the thick hollow cone. The cone becomes wider at higher energies, where the absorption is less efficient (see Fig. 5 below). The nonzero brightness at $\zeta = 0$ is due to the finite radius of the star.

3. GEOMETRICAL MODEL OF VARIABILITY OF $E_{\gamma}$-RAY EMISSION

If the location of the emission region is determined by the position of the compact object (e.g., the $E_{\gamma}$-ray emission is produced in the vicinity of the compact object, or in the jet emitted by the compact object), the orientation of the hollow cone changes when the compact object moves around the star, as shown in Figure 2 [where the emission region is supposed to be situated at an elevation $h$ above the compact object, so that the hollow cone axis is inclined at an angle $\chi = \arctan(h/D)$, where $D$ is the binary separation distance].

Changes of the orientation of the hollow cone with respect to the line of sight should lead to the orbital modulation of the
observed γ-ray flux. Depending on the relation between the inclination angle \(i\) of the binary orbit plane and the opening angle of the hollow cone, \(\zeta_0\), two characteristic patterns of the orbital modulation are possible. If the inclination of the orbit is \(i > \pi/2 - \zeta_0 - \chi\), the direction of the line of sight passes through the “wall” of the cone 2 times per orbit. This should lead to the appearance of two maxima in the orbit-folded light curve. If the binary orbit is circular, the maxima of the light curve occur when the true anomaly of the orbit (angular orbital phase \(0 < \Phi < 2 \pi\) from the periastron) takes the values

\[
\Phi_{1,2} = \Phi_{\text{inf}} \pm \Delta \Phi,
\]

where \(\Phi_{\text{inf}}\) is the anomaly of the inferior conjunction and

\[
\Delta \Phi = \arccos \left[ 1 - \sin (i + \chi) - \cos \zeta_0 \right] (\cos \chi \sin i). \tag{8}
\]

If the binary orbit is elliptical, an additional orbital modulation of the γ-ray flux can occur because of the variation of the distance of the emission region from the massive star (which leads to the modulation of the γ-ray production/absorption rates) with the orbital phase. As the inclination of the orbit decreases to \(i \leq \pi/2 - \zeta_0 - \chi\), the two maxima at \(\Phi_1\) and \(\Phi_2\) merge at the phase \(\Phi_{\text{inf}}\).

Since the opening angle of the hollow cone \(\zeta_0\) depends on the γ-ray energy, the condition \(i > \pi/2 - \zeta_0(E_r) - \chi\) can be satisfied only in a certain interval of energies, so that a merger of the two maxima \(\Phi_{1,2} = \Phi_{\text{inf}} \pm \Delta \Phi(E_r)\) at the phase of inferior conjunction can be observable at a particular energy \(E_0\) at which \(\zeta_0(E_0) = \pi/2 - i - \chi\).

4. THE CASE OF LS 5039

LS 5039 is one of the several X-ray binaries detected as sources of the VHE γ-ray emission (Aharonian et al. 2006). In this binary system the compact object rotates with the period \(P = 3.9078 \pm 0.0015\) days around a massive O6.5 V star. The orbit is eccentric (\(e = 0.35\)). The inclination of the orbit is \(20^\circ < i < 60^\circ\) (Casares et al. 2005). The orbit-folded light curve of the source at the energies \(E \geq 1\) TeV (Aharonian et al. 2006) has two maxima at the orbital phases \(\phi_1 = 0.55, \phi_2 = 0.85\). The two maxima are apparently not symmetric: the first maximum around \(\phi_1\) spans a broader range of the orbital phase, while the second maximum is more sharp. The second maximum happens closer to the phase of the inferior conjunction, \(\Phi_{\text{inf}} \approx 0.716\), than the first one.

Replotting the orbit-folded TeV γ-ray light curve as a function of the true anomaly, \(\Phi\) (to produce Fig. 3, we have calculated the true anomalies of each data point of the top panel of Fig. 5 of Aharonian et al. [2006] and rebinned the data into bins of the width \(d\Phi = 15^\circ\), rather than as a function of \(\phi\), a symmetry in the positions of the two maxima can be found.

Namely, the light curve can be satisfactorily fitted with a phenomenological model which is a sum of a constant (weakly modulated emission which can be produced, e.g., at larger distances) and two Gaussians, whose centers are equally spaced from the phase of the inferior conjunction, \(\Phi_{\text{inf}} = 224^\circ\) (see Fig. 3). The positions of the centers of the Gaussians, found by the fit, are \(\Phi_{1,2} = \Phi_{\text{inf}} \pm 35^\circ\), while the widths of the Gaussians are nearly equal, \(\delta \Phi_{1,2} \approx 22.5^\circ\) (if the phase of the inferior conjunction is left free, while fitting, the fit finds the phase \(\Phi_{\text{inf}} \approx 226.5^\circ\), consistent with the value \(\Phi_{\text{inf}} \approx 224.2^\circ \pm 3.3^\circ\) found by Casares et al. [2005]). The Gaussian centered at the phase \(\Phi_1\) is found to have \(\approx 1.5\) times higher normalization than the Gaussian centered at \(\Phi_2\).

The observed symmetry of the positions of the maxima of the orbit-folded light curve can be interpreted, in a straightforward way, in terms of the rotating hollow cone model, discussed in the previous sections. In particular the phase shift of equation (7) is \(\Delta \Phi = 35^\circ\). From equation (8) (which can be used, for a low-eccentricity orbit, as a first approximation) one can find the relation between \(i\) and \(\zeta_0\), shown in Figure 4. Taking into account the constraint on the inclination angle, \(20^\circ < i < 60^\circ\) (Casares et al. 2005), we find that the opening angle of the hollow cone anisotropy pattern is constrained to \(40^\circ < \zeta_0 < 75^\circ\), if the emission is assumed to come from the vicinity of the compact object (\(\chi = 0^\circ\) in Fig. 2).

5. A CONSTRAINT ON THE GEOMETRY OF LS 5039

The opening angle of the hollow cone, \(\zeta_0(E_r)\), can be found once the emission process leading to the γ-ray production and the location of the emission region are known. Comparing the theoretically predicted value of \(\zeta_0(E_r)\) to the one implied by the data one can, in principle, constrain the geometry of the system. In particular, assuming that the location of the emission region is known, one can constrain the inclination of the binary orbit with respect to the line of sight. Otherwise, if the inclination of the orbit would be known, one would be able to constrain the location of the emission region, in particular, its distance from the star and/or elevation above the orbital plane.

Different locations of the VHE γ-ray emission region are assumed in different models of activity of LS 5039. In the model of “compact pulsar wind nebula” (see, e.g., Dubus et al. 2007), the emission region is assumed to surround the compact object (\(h = 0\) in the notations of Fig. 2). In a “micro-quasar” model the TeV emission is assumed to be produced in a jet, so that the emission region is displaced from the position...
of the compact object (it is situated above or below the orbital plane, \( h \neq 0 \); see, e.g., Khangulyan et al. 2007). In both types of models the VHE \( \gamma \)-rays are produced via the inverse Compton scattering of the soft photons by the VHE electrons.

To find the rate of production of \( \gamma \)-rays via the inverse Compton scattering, one has to numerically integrate equation (1), with \( \sigma_{\text{prod}} \) being the Klein-Nishina cross section, over the angular and energy distributions of soft photons at a distance \( D \) from the massive star. The result of such integration is shown by the dotted curves in Figure 5 for electron energies, \( E_e = 1 \) and 10 TeV for the case when the emission region is situated at the distance of the periastron of the binary orbit.

To find the optical depth \( \tau_{\text{abs}}(\xi) \) for the \( \gamma \)-rays emitted at different angles \( \xi \) (see eq. [3]), one first calculates the \( \gamma \)-ray absorption rate, given by equation (1) with the cross section \( \sigma_{\text{abs}} \) being the pair production cross section, at each point of the \( \gamma \)-ray trajectory. This is done similarly to the calculation of the inverse Compton scattering rate, via an integration over the soft photon angular distribution. Next, one has to integrate the absorption rate along the \( \gamma \)-ray trajectory, from the emission point to infinity. The result of such numerical integration is shown by the dashed curves in Figure 5 for \( \gamma \)-ray energies \( E_\gamma = 1 \) and 10 TeV, assuming that emission is produced at the distance of the periastron of the binary orbit.

Substituting the numerically found \( R_{\text{prod}}(\xi, E_\gamma) \) and \( \tau_{\text{abs}}(\xi, E_\gamma) \) into equation (3) one can find the angular brightness profile of the hollow cone for different orbital phases and different photon energies. The angular brightness profile, calculated for the periastron (apastron) of the binary orbit, is shown by the thick, solid, black (gray) curve in Figure 5. We assume that the energies of \( \gamma \)-rays are approximately equal to the energies of the primary electrons, which is true in the Klein-Nishina regime of the inverse Compton scattering.

The first maximum of the TeV band light curve of LS 5039 takes place at the orbital phase \( \Phi = 224^\circ - 35^\circ = 193^\circ \), close to the apastron of the orbit. From Figure 5 one can see that at this phase the opening angle of the cone changes in the range \( 30^\circ < \xi_0(E_\gamma) < 60^\circ \) when the \( \gamma \)-ray energy changes from 1 to 10 TeV. Comparing this numerically calculated range of values (shaded region in Fig. 4) to the one implied by the observational data, one can find from Figure 4 that if the VHE \( \gamma \)-ray emission is produced close to the compact object (i.e., at \( \chi = 0^\circ \)) the inclination angle of the binary orbit should be \( \beta > 40^\circ \).

The constraint on \( \chi \), \( \beta \) can be reformulated in a different way: if the inclination angle of the orbit is small, e.g., \( i \sim 25^\circ \) (see Casares et al. 2005), the \( \gamma \)-ray emission is not produced close to the compact object. Instead, from Figure 4 one can find that in this case the elevation \( \chi \) of the emission region above the orbital plane should be \( \chi \sim 15^\circ \). If the emission region is located in a jetlike outflow orthogonal to the orbital plane, the emission region should be situated at the height \( \xi = D \tan \chi > 0.3D \) above the orbital plane, where \( D \) is the binary separation distance (see Fig. 2 for notation).

6. SUMMARY

We have shown that VHE \( \gamma \)-ray emission from \( \gamma \)-ray-loud binaries is expected to have a rotating hollow cone anisotropy pattern, determined by the Doppler effect in the anisotropic radiation field of a massive star (Fig. 1). This anisotropy leads to the appearance of a double-peak structure of the orbit-folded light curve, with the two peaks situated at equal distance \( \Delta \Phi \) (eq. [8]) from the phase of the inferior conjunction. We have demonstrated that such a symmetric double-peak structure is observed in the particular case of LS 5039. In this case, a measurement of the phase shift \( \Delta \Phi \) enables us to find a relation between the opening angle of the hollow cone, \( \xi_0 \), and the inclination of the binary orbit, \( i \) (see Fig. 4). Comparing the value of \( \xi_0 \) inferred from the data, to the one found from numerical calculation of the angular brightness profile of the cone (Fig. 5), we were able to constrain the inclination of the binary orbit and/or the elevation of the VHE \( \gamma \)-ray emission region above the orbital plane in this particular source.

In the particular case of LS 5039, the rotating hollow cone model discussed above can be tested if the statistics of the signal from the source become high enough to allow a splitting of the source light curve at the energies \( E > 1 \) TeV into two energy bins (e.g., 1 TeV \(< E < 10 \) TeV and \( E > 10 \) TeV). In this case the predicted shifts of the two maxima of the light curve toward each other (or even a merger of them) at the higher energies should be observable. If observed, such an effect would be clear evidence in favor of the proposed model.

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