# Gamma-ray absorption in the binary system LS I +61 303

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**Abstract:** LS I +61 303 is a gamma-ray binary, composed of a compact object of unknow nature and a massive star, which has been detected in the range of very high energy (VHE) gamma-rays. These gamma-rays can interact with the optical photons coming from the star. In each interaction, they are absorbed through pair creation $\gamma\gamma \rightarrow e^- e^+$. This absorption depends strongly on the possible geometries of the system and on the energy of the emitted gamma-ray photon. Therefore, we can study the modulation of the transmission with the orbital phase and with the photon energy. In this work we have made a Fortran code to calculate the transmission of LS I +61 303 system assuming that VHE gamma-rays are produced at the position of the compact object and that we have a point-like massive star. We have done this study for two inclinations, one corresponding to a neutron star compact object and the other to a black hole. We have observed that the maximum absorption occurs slightly before periastron and it is more intense for large inclinations. The energy range with more absorption is between 100 GeV and 10 TeV. We have compared our results with Dubus (2006) and we have observed a significant difference on the absorption for energies above 10 TeV. We have studied the orbital phase of the maximum absorption as a function of the inclination. We have concluded that, if the observed light curve only depended on the transmission, we could know, through this dependence, the nature of the compact object

## I. INTRODUCTION

The technological advances and the development of Cherenkov telescopes, like HESS, MAGIC and VERITAS, have made possible the discovery of the gamma-ray binary systems that emit in the range of very high energies VHE ($>$ 100 GeV). These systems are a particular type of X-ray binaries distinguished by their radiative output with a peak beyond 1 MeV in the spectral energy distribution (Dubus 2013). They are composed of a compact object orbiting around a massive star.

Only five gamma-ray binary systems have been detected: PSR B1259−63, the first binary detected in VHE gamma rays in 2004 by Aharonian et al. (2005a); LS 5039, in 2005 (Aharonian et al. 2005b), HESS J0632+057 (Aharonian et al. 2007); 1FGL J1018.6−5856 (Corbet et al. 2011) and finally LS I +61 303 (Albert et al. 2006), which will be studied in this work. All of them harbor a massive O or Be star, with a mass of 10–20 $M_\odot$, a radius of around 10 $R_\odot$ and a photospheric temperature of 20000–40000 K. The nature of the compact object forming these binary systems, either a black hole or a neutron star, is unknown, except for PSR B1259−63 that contains a radio pulsar and thus a neutron star. Determining the compact object mass could allow us to distinguish between a black hole candidate or a neutron star. The mass function, derived from the radial velocity of the massive star, relates the mass of the star and the compact object to the orbit inclination. A black hole (a compact object with $M > 3M_\odot$), requires a low binary inclination while a neutron star, a high inclination. However, low inclinations are statistically disfavored, assuming the systems that we see have random inclinations. Therefore, the probability that our binary system is formed by a neutron star is higher (Dubus 2013). Casares et al. (2012) summarized the range of possible orbit inclinations $i$ for each gamma-ray binary.

It is important to understand how VHE gamma-rays are produced in these systems. Two different hypotheses are currently discussed for their generation: the *pulsar scenario* and the *microquasar scenario.* In the first hypothesis, the compact object is a neutron star. Due to the high rotation speed of the pulsar and the high magnetic field, a relativistic wind with velocity $\sim c/3$ is produced. This wind is composed of a low density of $e^-$, $e^+$ and presumably protons and ions, and interacts with the stellar wind of the massive star, much denser but slower (1000–2000 km s$^{-1}$). In the region where these winds collide, the pulsar wind particles are accelerated, and the $e^-$ and $e^+$ interact with the stellar photons by the inverse Compton scattering process, obtaining VHE gamma-ray photons. In the second hypothesis, the *microquasar scenario*, the compact object can be a neutron star or a black hole that accretes matter from the stellar wind of the companion. Part of the energy released in the accretion disk is used to generate relativistic jets. These jets accelerate particles that interact with the stellar photons generating gamma-ray photons by inverse Compton scattering (for more details see Dubus 2013 and references therein).

The dense radiation field can absorb the gamma-ray emission through pair production $\gamma\gamma \rightarrow e^- e^+$ (Gould & Schréder 1967). This absorption varies depending on the relative location of the source of gamma-rays, the massive star and the observer. If the gamma-ray emission is isotropic and close to the compact object, the absorption will be periodically modulated in a predictable way (Moskalensko 1995). In this work we have made a study of the absorption variation with energy and with the orbital phase of the gamma-ray binary system

LS I +61 303. In section II, we discuss how the absorption through pair creation occurs and what parametres are involved. In section III, we present the characteristics and the orbital parameters of our system. In section IV, we present our results of the transmission modulation with the orbital phase for a given gamma-ray photon energy, the transmission as a function of the energy for particular orbital phases and the correlation between the orbital phase of maximum absorption and the inclination. Finally, we state our conclusions in section V.

## II. GAMMA RAY ABSORPTION IN A BINARY SYSTEM

The gamma-rays generated by the mechanisms described in section I, can interact with the optical photons coming from the massive star. Each interaction creates an $e^-e^+$ pair. When this happens, gamma-rays are absorbed and we observe a decrease in flux. Here we perform a study of all the parameters that influence in the interaction of the two photons.

The absorption of a gamma-ray of energy $E$ on a star photon of energy $\epsilon$ occurs above an energy threshold given by (Gould & Schréder 1967)

$$\epsilon E \geq \frac{2m_e^2c^4}{(1-\vec{e_\gamma}\vec{e_*})} \tag{1}$$

where $\vec{e_\gamma}$ is a unit vector along the direction of propagation of the gamma-ray and $\vec{e_*}$ is the unit vector along the direction of propagation of the star photon. Absorption can only occur when the stellar photons are at an angle to the gamma-ray and the minimum threshold occurs for head-on collisions (Dubus 2006). In our case, we consider the massive star as a point-like source, and thus $(1-\vec{e_\gamma}\vec{e_*}) = 1+\cos\psi$, where the angle $\psi$ can be seen in Fig.(1). We use a new variable $s$, defined by Gould & Schréder (1967) as

$$s = \frac{\epsilon E}{2m_e^2c^4}(1+\cos\psi). \tag{2}$$

The photons only interact when $s > 1$. Note that the threshold condition for a head-on photon collision ($\psi = 0$) is $\epsilon E = m_e^2c^4$. The total cross section $\sigma_{\gamma\gamma}$ for an interaction $\gamma\gamma$ depends on $s$ by

$$\sigma_{\gamma\gamma} = \frac{1}{2}\pi r_0^2(1-\beta^2)\left[(3-\beta^4)\ln\frac{1+\beta}{1-\beta}\; 2\beta(2-\beta^2)\right] \tag{3}$$

where $r_0 = e^2/mc^2$ is the electron radius and $\beta c$ is the eletron (or positron) velocity in the center-of-mass system. We can relate $\beta$ with $E$, $\epsilon$ and $\psi$ through the variable $s$ by $\beta = \sqrt{1-1/s}$ (Gould & Schréder 1967). For more details on the demonstration see Nikishov & Eksperim (1961).

Here we assume that the massive star radiates like a blackbody with a temperature $T_*$, with radiation density:

$$n_\epsilon = \frac{2\epsilon^2}{h^3c^3}\frac{1}{\exp(\epsilon/kT_*)-1}\ \text{ph cm}^3\ \text{erg}^{-1}\ \text{sr}^{-1}. \tag{4}$$

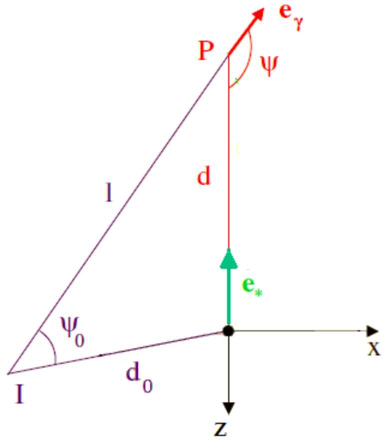

FIG. 1: Geometry for absorption of a gamma-ray at a location P due to pair creation with stellar photons. The gamma-ray is emitted at I and $l$ is the length of the gamma-ray path to P. The $(x, z)$ plane is defined by the star center and the gamma-ray path. Adapted from Dubus (2006).

We define $l$ as the lenght of the gamma-ray path from its emission at a distance $d_0$ and at an angle $\psi_0$ with respect to the star (point I in Fig.(1)) until the interaction with the stellar photon (point P in Fig.(1)), and we define $d$ as the distance between the star and the point P. The lenght $l$ is related to $\psi$ by

$$\psi = \tan^{-1}\left(\frac{d_0\ \sin\psi_0}{d_0\ \cos\psi_0 - l}\right)\ \text{for}\ l < d_0\ \cos\psi_0$$
$$\psi = \pi + \tan^{-1}\left(\frac{d_0\ \sin\psi_0}{d_0\ \cos\psi_0 - l}\right)\ \text{for}\ l > d_0\ \cos\psi_0. \tag{5}$$

In addition, $d$ is related to $l$ by $d^2 = d_0^2 + l^2 - 2d_0 l\cos\psi_0$.

Finally we can calculate $\psi_0$ with the relationship $\cos\psi_0 = \sin(V+\omega)\sin i$, where $V$ is the true anomaly, $\omega$ is the periastron angle and $i$ is the inclination of the orbit of the compact object around the massive star.

Now, we can define the differential absorption opacity seen by a gamma ray of energy $E$ at position P and travelling in the direction $\vec{e_\gamma}$ due to photons of energy $\epsilon$ emitted from the star along $\vec{e_*}$, assuming that the star is point-like (Dubus 2006) using

$$d\tau_{\gamma\gamma} = \pi\left(\frac{R_*}{d}\right)^2\sigma_{\gamma\gamma}n_\epsilon(1+\cos\psi)dl d\epsilon. \tag{6}$$

We can calculate the total opacity to infinity for a gamma-ray of given energy $E$ with the double integral

$$\tau_{\gamma\gamma} = \int_0^\infty dl\int_{\epsilon_{min}}^\infty \frac{d\tau_{\gamma\gamma}}{d\epsilon dl}d\epsilon \tag{7}$$

where $\epsilon_{min} = 2m_e^2c^4/E(1+\cos\psi)$ is the threshold energy. To be able to solve the integral we have made a change of variables. We have rewritten the energy integral as a definite integral on $\beta$ within the interval [0,1] and the intgral on $l$ into a definite integral on $\psi$ between $[\psi_0, \pi]$.

We have written a Fortran code that solves the two integrals using the composite trapezoidal rule. With this program we can study the gamma-ray transmission in a binary system. The inputs of the program are the eccentricity and the semimajor axis of the orbit of the compact object around the star, the argument and the phase of the periastron, the radius and the temperature of the massive star and the gamma-ray energy or the orbital phase that we want to study. The output is the gamma-ray transmission as a function of the orbital phase for different energies and inclinations or the gamma-ray transmission as a function of the energy for different orbital phases and inclinations. This program also draws the orbit of the compact object around the massive star for each inclination.

## III. THE BINARY SYSTEM LS I +61 303

LS I +61 303 is a gamma-ray binary with a Be main sequence star, with a circumstellar disk, and a compact object orbiting around it (Albert et al. 2006). It is located at a distance of 2 kpc and the massive star has a $T_* = 22500$ K and $R_* = 10\ R_\odot$. The orbital period from radio observations is $P_{\rm orb} = 26.496$ days (Gregory 2002). The orbital parameters obtained from optical spectroscopy are: eccentricity $e = 0.72 \pm 0.15$, argument of the periastron $\omega = 21.0 \pm 12.7°$ and phase of the periastron $\Phi_{\rm peri} = 0.23 \pm 0.02$. The superior conjunction is at $\Phi_{\rm sup.conj} = 0.16$ and the inferior conjuction at $\Phi_{\rm inf.conj} = 0.26$ (Casares et al. 2005). The phase of periastron is different from 0 because the reference time has traditionally been set by using the first radio observation.

At VHE, LS I +61 303 has been clearly detected several times with both MAGIC (Albert et al. 2006) and VERITAS (Acciari et al. 2008). The source displays VHE gamma-ray periodicity, with minima taking place near periastron and maxima occuring on average at phase 0.6–0.7, although the source has also shown a second peak at phase 0.84 in one of the cycles (Anderhub et al. 2009). The periodic modulation has also been observed at optical and infrared wavelenghts, X-ray, radio and HE (high energy between 0.1 and 100 GeV) (Paredes-Fortuny et al. 2015). Anderhub et al. (2009) show the VHE gamma-ray and X-ray light curves for LS I +61 303 and present a correlation of X-ray/VHE emission based on simultaneus data. In Fig.(2) we show the orbit of the binary system LS I +61 303 that we have drawn with the Fortran code.

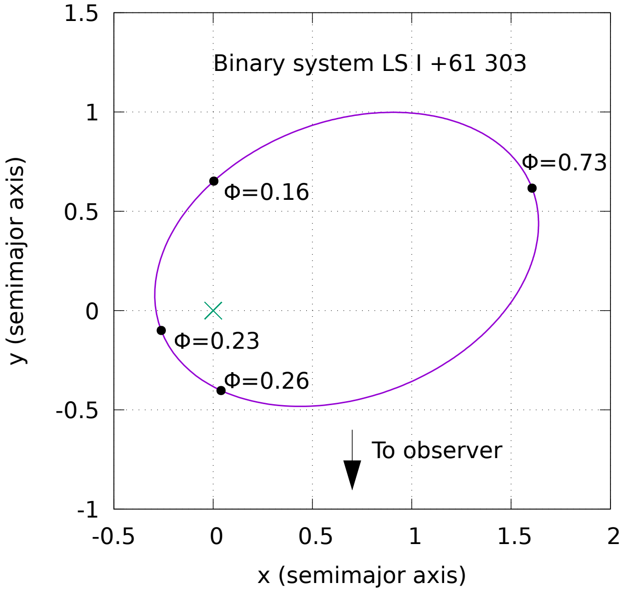

FIG. 2: Orbit of the compact object (solid line) around the massive star (cross) in the binary system LS I +61 303. This representation corresponds to an inclination of $i = 0°$. The orbital phases corresponding to periastron, apastron and superior and inferior conjunctions have been indicated.

## IV. RESULTS AND DISCUSSION

We used the program described in section II to obtain different results for the system LS I +61 303 by modifying some input values. We have done 3 different studies. First, we have obtained the gamma-ray transmission as a function of the orbital phase for different gamma-ray energies and inclinations. Second, we have made an analysis of the absorption as a function of the energy at different orbital phases. Finally, we have studied how the phase of maximum of absorption varies as a function of the inclination.

### A. Transmission with orbital phase

In Fig.(3) we show the modulation of the gamma-ray transmission ($e^{-\tau}$) with orbital phase for three different photon energies for the binary system LS I +61 303. We have done this for two different inclinations, low (20°) and high (60°), to check how absorption varies depending on this parameter. The maximum absorption occurs slightly before the periastron ($\Phi = 0.23$). In these orbital phases, the compact object is close to the massive star and *behind* it (see Fig.(2)). This is why the photon absorption is much greater. For high inclinations, the absorption peak is more intense because, with respect to the observer, the compact object is closer to the star than for low inclinations. In the apastron we also have absorption, but less intense than before periastron. For example, for an energy of 1 TeV and an inclination of 20°, the absorption in the apastron is around 15% of the emitted flux, while at phase 0.21 it is around 60%. The amplitude of the absorption variation is greater at high inclinations. The $i = 60°$ case presents a maximum transmission just after the minimum and for energies of 1 TeV we observe a transmission peak.

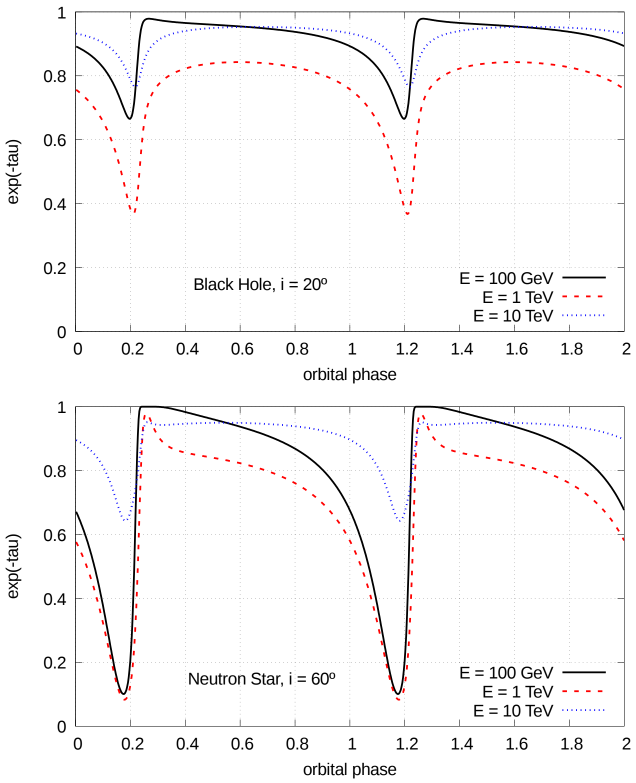

FIG. 3: Gamma-ray transmission as a function of orbital phase for three different photon energies in LS I +61 303. The top panel corresponds to a black hole of 4 $M_\odot$ ($i = 20°$) and the bottom panel to a neutron star of 1.4 $M_\odot$ ($i = 60°$). In both cases, the maximum absorption occurs slightly before the periastron ($\Phi = 0.23$).

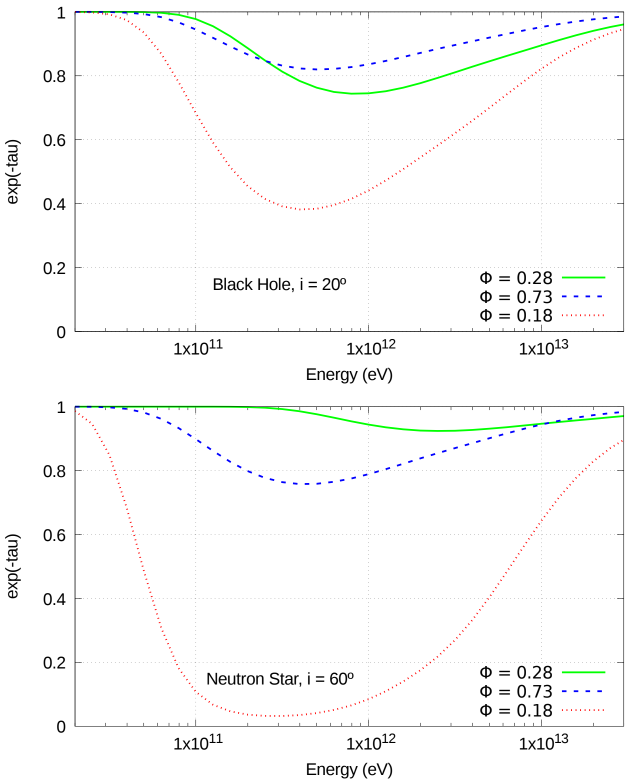

FIG. 4: Gamma-ray transmission as a function of the energy at three different orbital phases in LS I +61 303. The top panel corresponds to a black hole of 4 $M_\odot$ ($i = 20°$) and the bottom panel to a neutron star of 1.4 $M_\odot$ ($i = 60°$). In both cases, the maximum absorption occurs in the energy range of 100 GeV–10 TeV.

Dubus (2006) conducted the same study but considering an extended star with the corresponding radius. If we compare their results with ours, we observe, in the case of neutron star and $E = 10$ TeV, more absorption in Dubus than in ours for the phases slightly before periastron.

### B. Transmission with the energy

We show in Fig.(4) the gamma-ray transmission as a function of the energy at three different orbital phases: $\Phi = 0.28$ (slightly after inferior conjuction), $\Phi = 0.73$ (apastron) and $\Phi = 0.18$ (slightly before periastron). The maximum absorption occurs before periastron in the 100 GeV–10 TeV energy range. In the neutron star case ($i = 60°$) we have more absorption than in the black hole one ($i = 20°$) for the orbital phases 0.18 and 0.73. However, for $\Phi = 0.28$, we have more absorption in the black hole case than in the neutron star one. This is because for an inclination of $i = 60°$ the compact object passes *behind* and *in front of* the massive star respect to the observer, but for an inclination of $i = 20°$ we see the orbit nearly from above and, therefore, the differences on the absorption between these orbital phases are less relevant.

The energy range where there is more absorption is given by the $\gamma\gamma$ interaction cross section and by the black-body radiation density of the star (see Eq. (3) and Eq. (4)). In our case, the massive star has a temperature $T_* = 22500$ K. Therefore, the energy range where the $\gamma\gamma$ interaction is more efficient is 100 GeV–10 TeV.

If we compare our results with Dubus (2006), we can observe little diferences in the high energy range (above 10 TeV) for the orbital phase $\Phi = 0.18$. In our case, we have a 90% of the total flux while Dubus has 77% for an energy of 12 TeV. This difference is the consequence of considering a point-like star. If the star has a radius $R_*$ then we must consider the solid angle of the star surface element emitting photons along $\vec{e_*}$: $d\Omega = \sin\theta d\phi d\theta$. This new parameter changes Eq. (1) and increases the range of energies in which interactions occur because the energy threshold decreases.

### C. Orbital phase of maximum absorption with inclination

We have shown that the maximum absorption occurs at an orbital phase slightly before the periastron. How-

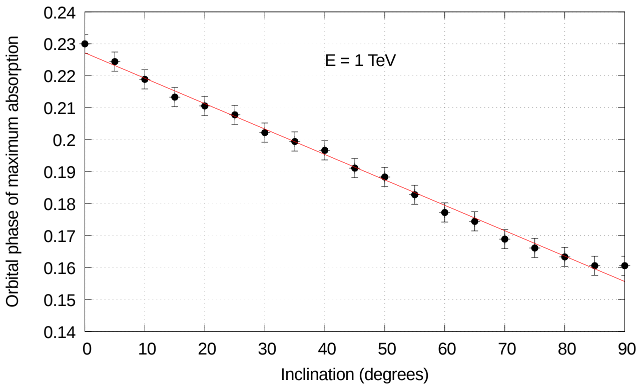

FIG. 5: Orbital phase of maximum absorption as a function of the inclination for an energy of 1 TeV. The data can be fitted by a linear regression (red line). The error associated with the determination of the orbital phase of maximum absorption is represented with error bars. The orbital phase of maximum absorption varies between the superior conjuction ($\Phi = 0.16$ for $i = 90°$) and the periastron ($\Phi = 0.23$ for $i = 0°$).

ever, this orbital phase varies as a function of orbit inclination (see Fig.(3)). This dependence is shown in Fig.(5). The range of variation lies between periastron ($\Phi = 0.23$), when we see the orbit from above ($i = 0°$), and the superior conjunction ($\Phi = 0.16$), when we see the orbit edge-on ($i = 90°$). If the observed light curve only depended on the transmission, we could know, through the orbital phase of the maximum absorption, the system inclination. Therefore, we could obtain an approximate value for the mass of the compact object (see section I). This could allow us to unveil the nature of the compact object, either a black hole or a neutron star.

### D. Final considerations

We have performed the study of the gamma-ray transmission in LS I +61 303 taking into account some approximations. First of all, we have considered a point-like massive star. Second, we have not considered any extended circumstellar disk for the Be star. Therefore, we only have a stellar photon source and one radiation density distribution. Third, we have assumed that the $e^-e^+$ pairs generated through $\gamma\gamma$ interactions do not have enough energy to interact again by inverse Compton scattering. This could be the case if the magnetic field is high and the energy is lost through synchrotron radiation. Finally, we have considered that the gamma-ray emission is isotropic and close to the compact object.

In addition, the shape of any observed VHE gamma-ray light curve (e.g., the one from Anderhub et al. 2009) would differ from the shape of our transmission curves because, in our study, we have not considered the variable injection of particles along the orbit or the fact that invers Compton scattering is anisotropic.

## V. CONCLUSIONS

Gamma-ray binary systems generate VHE gamma-ray photons that interact with stellar photons through $e^-e^+$ pair creation. We have studied the transmission of gamma-rays as a function of the orbital phase for different energies and inclinations, and the transmission as a function of the energy for different orbital phases and inclinations, for the LS I +61 303 binary system. We have written a Fortran code to calculate the opacity, solving the two integrals by the composite trapezoidal rule. We have observed that the maximum absorption occurs slightly before periastron and it is more intense for high inclinations. In this orbital phase the compact object is closer to the star and *behind* it. The most efficient energy range for the $\gamma\gamma$ interaction is between 100 GeV and 10 TeV. When we compare our results with Dubus (2006), the relevant difference appears above 10 TeV. We have made a point-like star aproximation and this increases the energy threshold ($\epsilon_{min}$). Therefore, the range of energies where the interaction occurs is smaller and there is less absorption. We have observed that the orbital phase of maximum absorption varies with the orbit inclination. Therefore, if the light curve only depended on transmission, this could be a method to determine the compact object mass and its nature.

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