MODULATION MECHANISM OF TeV, GeV, AND X-RAY EMISSION IN LS5039

M. S. YAMAGUCHI AND F. TAKAHARA
Department of Earth and Space Science, Graduate School of Science, Osaka University, Toyonaka, Osaka 560-0043, Japan
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ABSTRACT

The emission mechanism of the gamma-ray binary LS5039 in TeV, GeV, and X-ray energy bands is investigated. Observed light curves in LS5039 show that TeV and GeV fluxes anticorrelate, whereas TeV and X-ray fluxes correlate. However, such correlated variations have not yet been reasonably explained at this stage. Assuming that relativistic electrons are injected constantly at the location of the compact object as a point source and that they lose energy only by the inverse Compton (IC) process, we calculate gamma-ray spectra and light curves by the Monte Carlo method, including the full electromagnetic cascade process. Moreover, we calculated X-ray spectra and light curves by using the resultant electron distribution. As a result, we are able to qualitatively reproduce spectra and light curves observed by H.E.S.S., Fermi, and Suzaku for the inclination angle $i = 30\degree$ and the index of injected electron distribution $p = 2.5$. We conclude that TeV–GeV anticorrelation is due to anisotropic IC scattering and anisotropic $\gamma\gamma$ absorption, and that TeV–X correlation is due to the dependence of IC cooling time on orbital phases. In addition, the constraint on the inclination angle implies that the compact object in LS5039 is a black hole.

Key words: binaries: close – radiation mechanisms: non-thermal – stars: individual (LS5039) – X-rays: binaries

1. INTRODUCTION

Three gamma-ray binaries have been found so far, which consist of a massive star and a compact object (a neutron star or a black hole). They are LS5039 (Aharonian et al. 2005a), LSI $+61^\circ 303$ (Albert et al. 2006), and PSR B1259-63 (Aharonian et al. 2005b). The compact objects of the first two have not yet been identified, while that of the last one is known to be a young pulsar.

The anisotropic inverse Compton (IC) process and $\gamma\gamma$ absorption are the important electromagnetic processes for high-energy electrons, positrons, and gamma rays occurring in gamma-ray binaries (e.g., Dubus 2006a; Bednarek 2006; Dubus et al. 2008; Khangulyan et al. 2008). Because of the thick radiation field around the OB star, electrons and positrons that are accelerated near the compact object radiate TeV and GeV gamma rays by the IC process. Very high energy gamma rays are absorbed by ultraviolet photons, which come from the OB star and produce $e^\pm$ pairs. Thus, if electrons and positrons lose energy by the IC process, the electromagnetic cascade process develops because the secondary pairs radiate plenty of photons with enough energy to create $e^\pm$ pairs. It is also important to consider anisotropy of the IC process in the binary system. The flux of the IC process, which is affected according to the anisotropic radiation field, depends on the angle between the line of sight and the line joining the center of the OB star and the compact object, so it depends on orbital phases.

Magnetic field affects $e^\pm$ propagation and radiation. If the magnetic field in the system is sufficiently weak, relativistic electrons and positrons proceed straight in a direction of injection, and radiate IC photons in the same direction. However, if it is strong and turbulent, then relativistic electrons and positrons are trapped by such a magnetic field, and can radiate IC photons in any direction. It should be noted that even if synchrotron cooling is negligible compared with IC cooling, electrons and positrons can radiate synchrotron photons. If the magnetic field is sufficiently strong, they lose energy by the synchrotron process.

LS5039 consists of a compact object and a massive star whose spectral type is O6.5 V and whose mass is $M_*=22.9^{+3.4}_{-2.9} M_\odot$, and its binary period is 3.906 days (Casares et al. 2005). In addition, its separation changes from $\sim 2.2 R_\odot$ at periastron to $\sim 4.5 R_\odot$ at apastron, where $R_\odot = 9.3^{+0.7}_{-0.6} R_\odot$ represents the radius of the companion O star (Casares et al. 2005).

For LS5039, spectra and light curves of TeV gamma rays obtained with the H.E.S.S. array of atmospheric Cherenkov telescopes (Aharonian et al. 2006a), and more recently, those of GeV gamma rays obtained with the Fermi Gamma-ray Space Telescope (Abdo et al. 2009) and those of X-rays obtained with Suzaku (Takahashi et al. 2009), have already been reported. These observations show that these fluxes clearly modulate with its binary period, that the GeV gamma-ray flux anticorrelates with TeV gamma-ray flux, and that the X-ray flux correlates with TeV flux.

Two kinds of models have been suggested so far for explaining $\gamma$-ray spectra and light curves emerging from LS5039. The first kind of model is the microquasar-type model (e.g., Bosch-Ramon & Paredes 2004; Paredes et al. 2006; Bednarek 2006; 2007; Dermer & Böttcher 2006; Khangulyan et al. 2008). Assuming that the compact object in LS5039 is a black hole, several authors computed the propagation of photons from the injection site in the jet, which is located at a certain distance (0 or finite value) from the base of the jet. The other kind of model is the pulsar-type model (e.g., Dubus 2006b; Sierpowska-Bartosik & Torres 2007, 2008a, 2008b; Dubus et al. 2008; Cerutti et al. 2008, 2009). Assuming that the compact object is a neutron star, these authors computed the propagation of photons emerging from relativistic electrons accelerated well near the neutron star, namely, at the termination shock, which is formed by a collision between a pulsar wind and a stellar wind, or near the pulsar magnetosphere. In the papers mentioned above, Bednarek (2006, 2007), Sierpowska-Bartosik & Torres (2007, 2008a, 2008b), and Cerutti et al. (2009) took into account the electromagnetic cascade process.

The TeV flux from LS5039 was investigated in detail by Khangulyan et al. (2008). Assuming that electrons were injected at a certain point along the jet and the counterjet, they calculated the spectra and light curves of the TeV flux taking into account anisotropic IC scattering, $\gamma\gamma$ absorption, the advection of electrons by the jet flow, and synchrotron cooling of electrons. As a result, they reproduced the observed spectra with H.E.S.S. well, but they were not able to reproduce the light curves.
The anticorrelation of GeV and TeV fluxes was explained by Bednarek (2006). Assuming that electrons were injected in the jet and that they cooled only by the IC process, the author performed Monte Carlo simulations for LS5039 and LSI +61° 303 taking into account anisotropic IC scattering and the cascade process. Though he showed that GeV and TeV fluxes anticorrelated, his model did not match the observational data in terms of the ratio of the TeV flux to the GeV one.

The explanation of X-ray spectra and light curves observed by Suzaku has already been tried by Takahashi et al. (2009). They suggested an adiabatic cooling model, so that they could explain X-ray flux modulation qualitatively and reproduce the spectral index observed with Suzaku. When electrons lose energy adiabatically, the resultant power-law index of electron distribution is the same as the injected one, unlike radiative cooling, so that the observed spectral index $\Gamma \sim 1.5$ is consistent with synchrotron emission with electrons that are injected with $p \Gamma = \epsilon_5$ is consistent with synchrotron radiation with electrons that are injected with $p \Gamma = \epsilon_5$.

However, the X-ray emission mechanism, especially its modulation, is not investigated in detail.

We perform Monte Carlo simulations of photon propagation based on a simple geometrical model for LS5039 and aim to understand the physical mechanism in the system by reproducing the observational data of TeV, GeV, and X-ray energy ranges. We assume that electrons and positrons lose energy only by the IC process, so that the cascade processes develop as already discussed in the second paragraph of this section, and we calculate the TeV, GeV gamma-ray, and X-ray spectra emerging to the observer from the system for LS5039. Our model and the calculation method are presented in detail in Section 2 and the numerical results are discussed in Section 3, where the comparison of the results with the observational data is also made. We summarize the emission mechanism in LS5039 in Section 4.

2. MODEL AND METHOD

Our model is shown as a schematic picture in Figure 1. The emission process we consider is shown in the left panel of Figure 1, and by comparing with the observational data, we determine the direction of the observer as shown in the right panel of Figure 1. First of all, electrons and/or positrons are injected isotropically at the location of the compact object. They cool only by the IC process as stated in Section 1 and radiate high-energy photons in various directions in a three-dimensional space when they interact with thermal radiation from the companion star. The high-energy photons also interact with photons from the companion and create $e^\pm$ pairs. We ignore the propagation of these electrons and positrons, so that they radiate IC photons at the places where they are created (and injected). Thus, these electrons and positrons initiate the cascade processes.

We count photons that undergo such a cascade process and escape from the system in any direction. By rotating the direction of the observer, we can obtain spectra from photons escaping in the direction of a certain range of azimuthal angle (the right panel of Figure 1). These are equivalent to spectra from escaped photons during a relevant range of the orbital phase (hereafter we call the spectra “phase-divided spectra”). At the same time, we can obtain the light curves in the GeV–TeV energy range at any inclination angle, when we assume that the emission is stationary during each divided phase. We also calculate spectra of synchrotron radiation by electrons and positrons in the system, assuming a uniform magnetic field and using the electron distribution in steady state derived by the cascade process. Below, we refer to each process (Sections 2.1, 2.2), validity (Section 2.3) and implication (Section 2.4) of the assumptions, and the calculation method (Section 2.5).

2.1. Injection of Electrons

To begin with, we assume that electrons are injected constantly at the location of the compact object. This assumption may be justified for the specific model, e.g., the pulsar scenario in which electrons are accelerated near the pulsar magnetosphere (Sierpowska-Bartosik & Torres 2007, 2008a, 2008b), because electron energy distribution is independent of the orbital phase in such an injection scenario. On the other hand, the assumption may not be suitable for some models, e.g., the microquasar scenario in which electrons are accelerated at shocks in the jet (Bednarek 2006, 2007; Khangulyan et al. 2008), because electron energy distribution can vary with a change in the separation since the mass transport rate varies with the separation, and thereby the jet power changes. Thus, constant injection is not valid for such models, but we assume constant injection for the sake of simplicity.

In this paper, we discuss only the case where injected electrons have an energy distribution with a single power law, i.e., $N_{e,\text{inj}}(E_e) \propto E_e^{-\beta}$. In addition, the maximum energy and the minimum energy of electrons are assumed as $\gamma_{e,\text{max}} = 10^8$ and $\gamma_{e,\text{min}} = 3 \times 10^3$, respectively.
correspond to that at SUPC and INFC when \( i \) (see Figure 1). In the same manner, and inferior conjunction (INFC), respectively, when correspond to the collision angle at superior conjunction (SUPC) when \( i \) and \( \gamma \) are defined when the angle \( i = 150^\circ \) (solid line), 120° (dashed), 90° (dotted), 60° (double-dotted), and 30° (double-dot-dashed), where \( \alpha \) is the angle between the photon path and the binary axis (Figure 1).

**Figure 2.** Anisotropic IC spectrum. The seed photons for the IC process come from the companion star with a black body spectrum \( (k_B T = 3.3 \mathrm{eV}) \), and injected electrons have a power-law distribution, namely \( p = 2.0 \) (a) and \( p = 2.5 \) (b). The spectra are calculated at \( \alpha = 150^\circ \) (solid line), 120° (dashed), 105° (dotted), 75° (dot-dashed), 60° (double-dotted), and 30° (double-dot-dashed), where \( \alpha \) is the angle between the photon path and the binary axis (Figure 1).

**Figure 3.** Optical depth for high-energy photons in the stellar radiation field at periastron (a) and apastron (b). The origin of the photon path is the location of the compact object, and the calculation is performed for the case that the angle \( \alpha \) is 150° (solid line), 120° (dashed), 90° (dotted), 60° (dot-dotted), and 30° (double-dotted).

### 2.2. IC and \( \gamma \gamma \) Absorption Processes

Figure 2 shows the anisotropic and unabsorbed IC spectra from electrons with steady energy distribution that are injected constantly with power-law distribution, \( p = 2.0 \) and \( p = 2.5 \), in the thermal radiation field from the companion star at \( k_B T = 3.3 \mathrm{eV} \) with finite size. IC fluxes increase and photon indices decrease as the scattering angle \( \alpha \) (Figure 1) becomes larger both for \( p = 2.0 \) and \( p = 2.5 \). It should be noted that the flux at photon energy \( E_\gamma \sim \mathrm{GeV} \) depends strongly on \( \alpha \), while that at \( E_\gamma \sim 1 \mathrm{TeV} \) depends less on \( \alpha \). In addition, Figure 2 shows that flux variation with orbital phase increases as the inclination angle \( i \) increases, because \( \alpha = 150^\circ \) and 30° correspond to the collision angle at superior conjunction (SUPC) and inferior conjunction (INFC), respectively, when \( i = 60^\circ \) (see Figure 1). In the same manner, \( \alpha = 120^\circ \) and 60° correspond to that at SUPC and INFC when \( i = 30^\circ \), and \( \alpha = 105^\circ \) and 75° correspond to that of \( i = 15^\circ \) (see Figure 1). Moreover, the ratio of the GeV flux to the TeV flux is large when \( p = 2.5 \), while it is small when \( p = 2.0 \).

It is inevitable for a high-energy photon to be absorbed in the stellar radiation field. Figure 3 shows the optical depth for \( \gamma \gamma \) absorption. According to this figure, the optical depth increases as the angle \( \alpha \) increases, and the photon energy at the maximum \( \tau \) shifts from \( \sim 1 \mathrm{TeV} \) to \( \sim 100 \mathrm{GeV} \). Furthermore, when \( i \lesssim 30^\circ \) (60° < \( \alpha < 120^\circ \)), \( \tau \) exceeds unity in any orbital phase. Thus, \( \gamma \gamma \) absorption is very efficient in LS5039, so that electromagnetic cascade develops in the case where the synchrotron energy loss of electrons can be ignored.

### 2.3. Cooling Timescale and Effect of the Stellar Wind

The emission from the system LS5039 can be considered a stationary one if a divided phase has a range of a tenth of one orbital period. This is meaningful when electrons whose energy range is \( 3 \times 10^3 < \gamma_e < 10^8 \) cool completely on a much shorter timescale than that of the phase range. The ratio of IC cooling time for electrons in the Thomson regime \( t_{\mathrm{IC, T}} \) to a tenth of an orbital period \( T_{\mathrm{orb}}/10 \sim 3.4 \times 10^4 \) s is

\[
\frac{t_{\mathrm{IC, T}}}{T_{\mathrm{orb}}/10} \sim 4 \times 10^{-4} \left( \frac{\gamma_e}{3 \times 10^3} \right)^{-1} \left( \frac{a}{a_{\mathrm{per}}^\mathrm{T}} \right)^2.
\]

On the other hand, high-energy electrons cool in the Klein–Nishina regime so that

\[
\frac{t_{\mathrm{IC, KN}}}{T_{\mathrm{orb}}/10} \sim 10^{-2} \left( \frac{\gamma_e}{10^8} \right)^{0.7} \left( \frac{a}{a_{\mathrm{per}}^\mathrm{KN}} \right)^2,
\]

where \( t_{\mathrm{IC, KN}} \sim 22 (a/a_{\mathrm{per}}^\mathrm{KN})^2 (E_e/1 \mathrm{TeV})^{0.7} \) s is the cooling time of electrons in the Klein–Nishina regime (Aharonian et al. 2006b). Thus, the electrons with \( 3 \times 10^3 < \gamma_e < 10^8 \) lose energy sufficiently fast in the divided phase, and therefore it is a good approximation that the emission from the system is stationary.

It is necessary that advection of electrons by stellar wind be ignored in order to validate our assumption of negligible propagation of electrons. The ratio of the advection length
during IC energy loss to the scale length of the system is

\[ \frac{v_w t_{IC,KN}}{L_{sys}} \sim 10^{-1} \left( \frac{v_w}{3 \times 10^8 \text{cms}^{-1}} \right) \left( \frac{\gamma_e}{10^8} \right)^{0.7} \left( \frac{a}{a_{peri}} \right)^2 \times \left( \frac{L_{sys}}{0.1 \text{AU}} \right)^{-1}. \]

(3)

where \( v_w \) is the wind velocity of a massive star and an electron with \( \gamma_e = 10^8 \) is assumed, for it cools more rapidly than an electron with \( \gamma_e = 3 \times 10^7 \) (Equations (1) and (2)). Thus, the assumption of trapped electrons is a good approximation of electrons with \( 3 \times 10^7 < \gamma_e < 10^8 \).

### 2.4. Constraint on the Magnetic Field

The magnetic field is limited by the assumptions about cooling and propagation of electrons and positrons. The former gives an upper bound because if the magnetic field is larger than a certain value, synchrotron loss is a dominant process, and the latter gives a lower bound because if it is smaller than a certain value, the gyro radius of an electron with the highest energy is comparable to the scale length of the system. In order for the assumption that electrons lose energy only by the IC process to remain valid, cooling times of IC (\( t_{IC} \)) and the synchrotron (\( t_{sy} \)) process must satisfy the condition

\[ t_{sy} > t_{IC}. \]

(4)

It is sufficient to give this condition at electron energy \( \sim 30 \text{ TeV} \), which corresponds to the energy of electrons radiating the photons with the highest energy observed, and electrons with such high energy lose energy in the Klein–Nishina regime. Thus, Equation (4) is reduced to

\[ B \lesssim 0.2 \left( \frac{E_e}{30 \text{ TeV}} \right)^{-0.85} \left( \frac{a}{a_{peri}} \right)^{-1} \text{G}, \]

(5)

at periastron, where \( E_e \) is the electron energy, \( a \) is the separation, and \( a_{peri} \) is \( a \) at periastron. At the same time, \( B \lesssim 0.1 \text{ G} \) at apastron, for \( a_{apa} \sim 2a_{peri} \).

In order for the propagation of electrons to be ignored, the gyro radius of electrons must be smaller than the scale of the system, i.e., \( E_e/eB \lesssim L_{sys} \sim 0.1 \text{ AU} \). This leads to

\[ B \gtrsim 0.1 \left( \frac{\gamma_e}{10^8} \right) \text{G}. \]

(6)

Therefore, under the condition of a uniform magnetic field, Equations (5) and (6) give \( B \sim 0.1 \text{ G} \).

### 2.5. Method of Calculation

We calculate phase-divided spectra and light curves emerging from the system by IC and \( \gamma \gamma \) absorption as well as the resultant energy distribution of electrons. We performed a numerical calculation of IC scattering and the subsequent cascade under the condition of fixed separation by the Monte Carlo method based on the stationary emission discussed above, and thereby determined the energy and the direction of the escaped photons.

In the Monte Carlo procedure, physical quantities are determined by weighted random numbers in each process. First of all, the energy and the direction of an injected electron are determined by random numbers. Second, the energy and the direction of a target photon in the IC process in the observer frame are determined by random numbers, which in turn determine the energy of the incident photon in the electron rest frame. The energy and the direction of the scattered photon in the electron rest frame are determined by physical quantities before the scattering and by one random number with the distribution of a differential cross section. These physical quantities after the scattering determine the energy of the scattered photon in the observer frame. We assume that the direction of this outgoing photon equals that of the injected electron because injected electrons have extremely relativistic energy in our model. The location of annihilation of the photon, the energy and the direction of a partner photon in the photon–pair annihilation process, and the direction of the \( e^\pm \) pair in the center of the \( e^\pm \) mass frame are also determined with random numbers. The energy and the direction of the \( e^\pm \) pair in the center of the \( e^\pm \) mass frame determine their energy in the observer frame and they cause IC scattering again. We can calculate the radiation transfer taking into account the cascade process by iterating such a procedure.

Synchrotron spectra are calculated by assuming a uniform magnetic field and using the resultant energy distribution of electrons and positrons. We can obtain their energy distribution by weighting the energy distribution resulting from the Monte Carlo method by their cooling time. Therefore, assuming the value of the magnetic field we can derive the synchrotron spectra. Thus, we can calculate the spectra and the light curves of a circular-orbit approximation in keV, GeV, and TeV energy ranges, taking as parameters, the separation \( a \) (the radius of the circular orbit), the inclination angle \( i \), and the power-law index \( p \) of the injected electrons.

### 3. RESULTS

#### 3.1. Inverse Compton Spectra and Light Curves

The results of the Monte Carlo calculation are shown in Figure 4, where we assume that the binary orbit is a circular one. The phase-divided spectra by the IC cascade process are shown in the left panels of Figure 4, and the light curves of fluxes in the TeV and GeV bands are shown in the right panels of Figure 4. The spectra and light curves shown in Figures 4(a) and (e) are calculated for \( p = 2.0, i = 30^\circ, a = a_{peri} \) and that in Figures 4(b) and (f), Figures 4(c) and (g), and Figures 4(d) and (h) are calculated by changing the separation to \( a = a_{apa} \), the inclination angle to \( i = 60^\circ \), and the power-law index of distribution of injected electrons to \( p = 2.5 \), respectively.

First, we discuss the results shown in Figures 4(a) and (e). There are some remarkable points in the spectra of GeV and TeV in the case of \( p = 2.0, i = 30^\circ, a = a_{peri} \) (Figure 4(a)). In the TeV energy range, the photon indices are smaller than 2 at all divided phases since the optical depth decreases monotonically with the photon energy (Figure 3) and since the spectrum without \( \gamma \gamma \) absorption has a flat feature in the TeV energy range (Figure 2(a)). The photon energy at which the flux in the TeV range becomes minimum is different from that at which the optical depth becomes maximum (e.g., the solid line in Figure 4(a) and the dashed line in Figure 3(a)), though we naively expect that these two kinds of energy are equal. The gap is due to the cascade process, which moves the photon energy to a lower energy band, so that the photon energy of the minimum flux shifts to higher energy. On the other hand, in the GeV energy band IC photons are not subject to the \( \gamma \gamma \) absorption in the stellar radiation field (Figure 3(a)), but the photon indices of all phases slightly increase compared with the IC spectra without
absorption (Figure 2) because of the cascade process. Another noticeable fact is that the flux at energy $\gtrsim 10$ GeV decreases in each orbital phase, since the optical depth rapidly increases at $\sim 100$ GeV. As for light curves under the same condition (Figure 4(e)), the GeV flux varies inversely with the TeV flux because of the anisotropic IC radiation in GeV and because of the efficient absorption in TeV, as can be expected from the spectra. In addition, the amplitude of flux variation in the GeV range is approximately a factor of 3, while that in TeV greatly exceeds this by 1 order of magnitude, consistent with Bednarek (2006).

For $p = 2.0$, $i = 30^\circ$, $a = a_{\text{apa}}$ (Figures 4(b) and (f)), the spectra and the light curves in the energy range of 0.1–10 GeV are almost the same as in the case of $a = a_{\text{peri}}$. When the compact object is located far from the companion star, the stellar radiation field at the compact object becomes thinner, so that IC cooling time of electrons becomes longer because of the less reaction rate of IC scattering. Thus, if the injection rate of electrons is constant, the electron number density at the same energy becomes larger. On the other hand, the GeV flux is proportional to the number density of electrons because in the 0.1–10 GeV energy range, photons are not absorbed in the
One notices that the amplitudes of flux (dashed line in Figure 4(e)) become larger than the case of absorbed photons changes with the separation. Nevertheless, which changes with the separation because the amount of energy moving to lower energy band by the cascade process, the amplitude of flux variation in the GeV band can change with the amount of energy of absorbed photons changes with the separation. Nevertheless, the amplitude of the GeV flux in the case $a = a_{\text{peri}}$ (solid line) and $a = a_{\text{apa}}$ (dashed). This implies less impact of cascade process as stated above. This means that the amplitude of flux variation in the GeV band can change with the amount of energy moving to lower energy band by the cascade process, which changes with the separation because the amount of energy moving to lower energy band is as large as that at periastron in spite of the thinner field. However, the GeV flux is actually subject to the radiation field. Therefore, the flux, which is equivalent to the product of the power by IC process per electron and the electron number, is as large as that at periastron in the case of absorbed photons changes with the separation. Nevertheless, the amplitude of the GeV flux in the case $a = a_{\text{apa}}$ (dashed line in Figure 4(f)) is almost the same as in the case $a = a_{\text{peri}}$ (dashed line in Figure 4(e)). This implies less impact of cascade on variation of the GeV flux. Thus, flux variation in that energy range is determined almost exclusively by the anisotropic IC radiation. In contrast, the TeV flux becomes larger than the case of $a = a_{\text{peri}}$, because the optical depth becomes smaller than unity in that phase. Another important feature is the power-law index of electron distribution and synchrotron spectrum. When $p = 2.0$, the index of electron distribution at $\gamma_e \sim 10^6$, an electron that radiates photons with keV energy, is $\sim 1.5$ because of the Klein–Nishina effect and the contribution of secondary electrons, so that the photon index at keV is $\sim 1.3$. On the other hand, in the case of $p = 2.5$ the relevant spectrum is almost flat, and accordingly the photon index is $\sim 1.5$.

**3.2. Synchrotron Spectra**

The electron distributions and the synchrotron spectra are shown in Figure 5. The electron number density of the case $a = a_{\text{apa}}$ (dashed line in Figures 5(a) and (b)) is three or four times larger than that of the case $a = a_{\text{peri}}$ (solid line in Figures 5(a) and (b)) at any energy range, because the IC cooling time is inversely proportional to the energy density of the stellar radiation field (note that we consider the case where the injection rate is constant). As a result, the flux by synchrotron radiation in the case $a = a_{\text{apa}}$ is about four times larger (Figures 5(c) and (d)).

Another important feature is the power-law index of electron distribution and synchrotron spectrum. When $p = 2.0$, the index of the electron distribution at $\gamma_e \sim 10^6$, an electron that radiates photons with keV energy, is $\sim 1.5$ because of the Klein–Nishina effect and the contribution of secondary electrons, so that the photon index at keV is $\sim 1.3$. On the other hand, in the case of $p = 2.5$ the relevant spectrum is almost flat, and accordingly the photon index is $\sim 1.5$.

**3.3. Comparison with Observations**

Taking into account the eccentricity of the binary system, we have also calculated spectra averaged around SUPC and INFC (Figure 6), and light curves (Figure 7) to compare with
Figure 6. Comparison of numerical results with the observational data obtained with Suzaku (XIS; Takahashi et al. 2009), Fermi (Abdo et al. 2009), and H.E.S.S. (Aharonian et al. 2006a). The spectra averaged in the phases around SUPC (numerical: solid line; observed: filled circle) and around INFC (numerical: dashed; observed: open circle) are shown, where the orbital phase is divided into 0–0.45, 0.9–1.0 (around SUPC), and 0.45–0.9 (around INFC). The condition of the numerical calculation is $p = 2.5, i = 30^\circ$, $B = 0.1$ G (thick line). We also show synchrotron spectra in the case of $B = 3$ G (thin line) as a guide, assuming the power-law distribution of electrons shown in Figure 5(b).

Figure 7. Light curves of numerical results (solid line) and the observational data (circle with error bar); those of the (a) H.E.S.S. energy band, 0.2–5 TeV (Aharonian et al. 2006a), (b) Fermi, 0.1–10 GeV (Abdo et al. 2009), and (c) Suzaku, 1–10 keV (Takahashi et al. 2009) are shown. The numerical result is normalized so that the maximum value matches the observed one. $\phi = 0$ and $\phi = 0.5$ represent a periastron phase and an apastron phase, respectively. SUPC and INFC phases are shown in each panel.

the observational data. In calculating the spectra and the light curves, we divided the orbital phase into 10 equal parts, and assigned the separation in each part the average value of both ends. Thus, this calculation is made for five different separations. The parameters are selected from the previous section so that the ratio of TeV flux to GeV one and flux variation in the GeV range approximately match the observational data. The spectra of $p = 2.5$ better fit the observational data in terms of the TeV-to-GeV flux ratio than $p = 2.0$, and those of $i = 30^\circ$ fit better in terms of flux variation at the photon energy $\sim 1$ GeV than $i = 60^\circ$.

It is seen that the observed spectra can be reproduced reasonably well. That is, it matches the observation that the flux in the INFC phase is larger than that in SUPC for X-ray and TeV energy ranges, and conversely the INFC flux is smaller in the GeV range. Moreover, serendipitously the photon index in the X-ray range is reproduced. However, the spectra have several issues that do not reproduce the observations in detail. First of all, the model underpredicts the flux at the Suzaku energy range by 2 orders of magnitude for $B = 0.1$ G, which is the most critical. Second, it overpredicts the flux in 1–10 GeV and shows a break at higher energy than the Fermi data. Finally, for the spectra around INFC the model overpredicts the flux in 0.2–1 TeV while it matches the observation in the energy band $\gtrsim 1$ TeV, and for the spectra around SUPC the model overpredicts the flux more than 1 TeV while it matches in 0.2–1 TeV. The issue of the keV range may be solved by increasing the magnetic field up to 3 G (see thin curves in Figure 6(b)), which is consistent with the result in Takahashi et al. (2009). However, if so, the synchrotron cooling becomes the dominant process for electrons with $\gamma_e \gtrsim 2 \times 10^6$, which radiates IC photons with $E_{\gamma} \gtrsim 1$ TeV and synchrotron photons with $E_{\gamma} \gtrsim 10^2$ keV, so that fluxes at energy $E_{\gamma} \gtrsim 1$ TeV decrease and synchrotron spectra have a break at $E_{\gamma} \sim 10^2$ keV.

This modification to the synchrotron spectra would resolve the issue that the numerical data of $B = 3$ G overpredict the observational data in the energy range of 0.1–1 GeV. At the same time, these facts mean that the flux of 0.1–10 GeV and 1–10 keV energy ranges would not be subject to synchrotron cooling, even if we set $B = 3$ G, because it is the electrons with energy $E_e \gtrsim 1$ TeV that are affected by synchrotron cooling, and because the electrons that radiate synchrotron photons with energy 1–10 keV have energy $E_e \lesssim 1$ TeV. Moreover, electrons that radiate 0.1–10 GeV photons by the IC process have energy $E_e \lesssim 100$ GeV. On the other hand, when $B = 3$ G it is hard for electrons to be accelerated up to several tens of TeV (e.g., Khangulyan et al. 2008; Takahashi et al. 2009). The overprediction of the flux in the 1–10 GeV range may be relevant to higher energy photons than the stellar radiation field. If stellar photons with energies of 10–100 eV exist, photons with energies of 1–100 GeV are subject to $\gamma\gamma$ absorption, so that the discrepancy of the spectra in that energy band may be resolved.

Light curves also approximately match the observational data; that is, TeV–GeV anticorrelation and TeV–X correlation are reproduced (Figure 7). The flux for $E_{\gamma} < 10$ GeV is determined only by the angle $\alpha$ (Section 3.1), so that the GeV flux correlates with $\alpha$. On the other hand, anisotropic IC spectra more than 100 GeV also correlate with $\alpha$, but the effect that it gives on cascade spectra is minor. Instead, $\gamma\gamma$...
absorption is effective in that energy range (Figure 3), so that the TeV flux anticorrelates with $\alpha$. Thus, GeV and TeV fluxes anticorrelate. Moreover, the synchrotron flux correlates with the binary separation (Section 3.2), and the binary separation in LS5039 is short around SUPC and long around INFC. Therefore, TeV and X-ray fluxes appear to correlate.

Looking closely at light curves, one finds that those in the H.E.S.S. band do not match the observation especially around SUPC (Figure 7(a)), while those in the Fermi band are well reproduced (Figure 7(b)); those of X-ray appear to match the observational data in terms of variation, but there is a phase difference of $\Delta \phi \sim 0.15$ (Figure 7(c)). This is somewhat puzzling and this problem is related to the variation amplitude between SUPC and INFC at the Suzaku energy band.

### 3.4. Mass Range of the Compact Object

Using the results of flux variation in the GeV range, we can put a limitation on the mass of the compact object.

To begin with, the amplitude of flux variation is determined by the inclination angle. The GeV flux, which is not subject to $\gamma\gamma$ absorption, is decided exclusively by the angle $\alpha$ under the condition of constant injection, because it is independent of the separation (Section 3.1). Moreover, the inclination angle determines the amplitude (Section 2). Therefore, by determining the inclination angle, we can find the decisive value of the amplitude. In the case of LS5039, the inclination angle is $i = 15^\circ - 30^\circ$, since the observational data show that the amplitude is a factor of 3–6 (Figures 2 and 7).

The limitation of the inclination angle is equivalent to the limitation of the mass of the compact object. Determining the value of the mass function by observations, we can obtain the relation between the inclination angle, the mass of the companion star, and the mass of the compact object. Thus, given the mass range of the companion star, we can decide the range of the compact object by determining the range of the inclination angle. We obtain that the mass of the compact object is $3 - 7 M_\odot$ for $i = 15^\circ - 30^\circ$ and $m_* = 22.9^{+3.4}_{-2.9} M_\odot$ (Casares et al. 2005). This means that the compact object is a black hole under the assumption of constant injection.

If we do not assume constant injection, the observational data might be reproduced even for $i > 30^\circ$, which would allow the lower limit on the mass of the compact object to be under 3 $M_\odot$. However, this requires the assumption that the injection rate is smaller around the SUPC phase, which is near the periastron, and that it is larger around the INFC phase, which is near the apastron, which is contrary to naive expectation.

### 4. SUMMARY

We calculate X-ray, GeV, and TeV spectra and light curves from LS5039 with the same band as observed by H.E.S.S., Fermi, and Suzaku, respectively, under three kinds of assumptions. First, electrons are injected constantly and isotropically at the location of the compact object. Second, these electrons lose energy only by IC cooling against stellar photons. Therefore, an electromagnetic cascade develops as long as electrons have energy larger than $\sim 30$ GeV, because they radiate IC photons, which also produce $e^\pm$ pairs. Finally, these electrons and positrons radiate at the position of injection or production. The last two assumptions set limits on the uniform magnetic field in the system, around $B \sim 0.1$ G.

By performing Monte Carlo simulations, we have shown that the observed spectra and light curves can be reproduced qualitatively. The numerical calculations with these assumptions yield two important results. One is that variation of the GeV flux synchronized with the orbital period depends almost only on the change in $\alpha$ (Figure 1). It is hardly influenced by the change in the separation; that is, the change in thickness of the radiation field and the variation in the degree of cascade. Thus, we can determine the range of the inclination angle from the variation of the GeV flux since the change in $\alpha$ is determined by the inclination angle. The range of the inclination angle in turn determines the mass of the compact object as $3 - 7 M_\odot$, which implies that the compact object in LS5039 is a black hole. The other is that the X-ray flux varies with binary separation, because the number density of electrons and positrons varies with the thickness of the thermal photon field by the IC cooling process.

From these results and the fact that the TeV flux varies with $\alpha$ by the variation of the optical depth, we can derive TeV–GeV anticorrelation and TeV–X correlation, namely, the TeV flux anticorrelates with $\alpha$ but the GeV flux correlates with it, so that TeV and GeV fluxes anticorrelate. In addition, the X-ray flux correlates with the separation, so that TeV and X-ray fluxes appear to correlate because of the orbital geometry of LS5039.

However, this model has several problems in terms of comparison with the observational data. First of all, the X-ray flux is drastically underpredicted for $B = 0.1$ G, though the photon index is reproduced well. Second, the flux in the 1–10 GeV range is overpredicted; in other words, the cutoff energy is overpredicted. Third, the photon index around SUPC at photon energy $> 1$ TeV is smaller than 2, while that of the observational data is larger than 2. Finally, X-ray flux modulation shows an advance by $\Delta \phi \sim 0.15$, compared to the observation data. These problems are deferred to future research.

The most important assumption which must be modified is the cooling process. X-ray flux and TeV flux at SUPC and INFC would be modified by taking into account synchrotron cooling, though efficient acceleration must be assumed as stated in Section 3.3.

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