STUDY OF THE SPECTRAL AND temporal CHARACTERISTICS OF X-RAY EMISSION OF THE GAMMA-RAY BINARY LS 5039 WITH SUEZAKU

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ABSTRACT

We report on the results from Suzaku broadband X-ray observations of the galactic binary source LS 5039. The Suzaku data, which have continuous coverage of more than one orbital period, show strong modulation of the X-ray emission at the orbital period of this TeV gamma-ray emitting system. The X-ray emission shows a minimum at orbital phase 0.1, close to the so-called superior conjunction of the compact object, and a maximum at phase 0.7, very close to the inferior conjunction of the compact object. The X-ray spectral data up to 70 keV are described by a hard power-law with a phase-dependent photon index which varies within 1.45–1.61. The amplitude of the flux variation is a factor of 2.5, but is significantly less than that of the factor 8 variation in the TeV flux. Otherwise the two light curves are similar, but not identical. Although periodic X-ray emission has been found from many galactic binary systems, the Suzaku result implies a phenomenon different from the “standard” origin of X-rays related to the emission of the hot accretion plasma formed around the compact companion object. The X-ray radiation of LS 5039 is likely to be linked to very-high-energy electrons which are also responsible for the TeV gamma-ray emission. While the gamma-rays are the result of inverse Compton scattering by electrons on optical stellar photons, X-rays are produced via synchrotron radiation. Yet, while the modulation of the TeV gamma-ray signal can be naturally explained by the photon-photon pair production and anisotropic inverse Compton scattering, the observed modulation of synchrotron X-rays requires an additional process, the most natural one being adiabatic expansion in the radiation production region.

Subject headings: acceleration of particles — X-rays: individual (LS 5039) — X-rays: binaries

1. INTRODUCTION

LS 5039 is a high-mass X-ray binary (Motch et al. 1997) with extended radio emission (Paredes et al. 2000, 2002). This system is formed by a main sequence O type star and a compact object of disputed nature that has been claimed to be both a black hole (e.g., Casares et al. 2005) and a neutron star/pulsar (e.g., Martocchia et al. 2005; Dubus 2006). The compact object is moving around the companion star in a moderately elliptic orbit (eccentricity $e = 0.35$) with an orbital period of $P_{\text{orb}} = 3.9060$ days (Casares et al. 2005).

As summarized in Bosch-Ramon et al. (2007), LS 5039 has been observed several times in the X-ray energy band for limited phases in the orbital period. Flux variations on time scales of days and sometimes on much shorter timescales have been reported. The spectrum was always well represented by a power-law model with a photon index ranging from 1.4 to 1.6 up to 10 keV, with fluxes changing moderately around $I \sim 10^{11}$ erg cm$^{-2}$ s$^{-1}$. Softer spectra and larger fluxes have been also inferred from RXTE observations, although background contamination was probably behind these differences (see Bosch-Ramon et al. 2005). Also, Chandra data taken in 2002 and 2005 showed spectra significantly harder than 1.5 (Bosch-Ramon et al. 2007), but such a hard spectrum was probably an artifact produced by photon pile-up. Recently, Hoffmann et al. (2009) reported the results of INTEGRAL observations in hard X-rays. The source was detected at energies between 25 and 60 keV. The flux was estimated to be $(3.5 \pm 2.3) \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$ (90 % confidence level) around the inferior conjunction (INFC) of the compact object, and a flux upper limit of $1.45 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$ (90 % confidence level) was derived at the superior conjunction of the compact object (SUPC).

LS 5039 has also been detected in very-high-energy (VHE: $E > 0.1$ TeV) gamma-rays (Aharonian et al. 2005a), exhibiting a periodic signal modulated with the orbital period (Aharonian et al. 2006). There are two other binary systems with robust detections in the VHE range: PSR B1259–63 (Aharonian et al. 2005b) and LS I +61 303 (Albert et al. 2006, Acciari et al. 2008). Evidence for TeV emission has been found also in Cygnus X-1 (Albert et al. 2007). PSR B1259–63 is a clear case of a high-mass binary system containing a non-accreting pulsar (Johnston et al. 1992), whereas Cygnus X-1 is a well known accreting black hole system (Bolton 1972). The nature of the compact object in LS 5039 is not yet established, and the origin of the VHE emitting electrons is unclear. They may be related to a pulsar wind or to a black hole with a (sub)relativistic jet. In the standard pulsar-wind scenario, the severe photon-photon absorption makes the explanation of the detection of the VHE radia-
tion problematic, at least at the position corresponding to the orbital phase 0° (see Figs. 16 and 4 from Sierpowska-Bartosik & Torres 2008 and Dubus et al. 2008 and compare with Fig. 5 in Aharonian et al. 2006), in which the emitter is expected to be located between the compact object and the star. However, particles may be accelerated in a relativistic outflow formed at the interaction of the pulsar and the stellar winds (Bogovalov et al. 2008) and radiate far from the compact object, making the pulsar wind scenario a viable option. In the microquasar scenario, the lack of accretion features in the X-ray spectrum may be a problem unless the bulk of the accretion power is released in the form of kinetic energy of the outflow, rather than thermal emission during accretion, as in the case of SS 433 (see e.g., Marshall et al. 2002). At this stage, we cannot give a preference to any of these scenarios, but new data, in particular those obtained with the Suzaku satellite, allow us to make an important step towards the understanding of the nature of the non-thermal processes of acceleration and radiation in this mysterious object.

2. OBSERVATION

The temporal and spectral characteristics of the X-ray emission from LS 5039 along the orbit should provide important clues for understanding the acceleration/radiation processes in this source. The fact that all previous X-ray observations of this object have incomplete coverage of the orbital period, or suffered from background contamination, is therefore rather unsatisfactory. This motivated our long, 200 ks observation with the Suzaku X-ray observatory (Mitsuda et al. 2007), which gives us unprecedented coverage of more than one orbital period, continuously from 2007 September 9 to 15 (see Table 1). Suzaku has four sets of X-ray telescopes (Serlemitsos et al. 2007), each with a focal-plane X-ray CCD camera (X-ray Imaging Spectrometer(XIS); Koyama et al. 2007) that are sensitive in the energy range of 0.3–12 keV. Three of the XIS detectors (XIS0, 2 and 3) have front-illuminated (FI) CCDs, whereas XIS1 utilizes a back-illuminated (BI) CCD. The merit of the BI CCD is its improved sensitivity in the soft X-ray energy band below 1 keV. Suzaku contains also a non-imaging collimated Hard X-ray Detector (HXD; Takahashi et al. 2007; Kokubun et al. 2007), which covers the 10–600 keV energy band with Si PIN photodiodes (10–70 keV) and GSO scintillation detectors (40–600 keV). Suzaku has two default pointing positions, the XIS nominal position and the HXD nominal position. In this observation, we used the HXD nominal position, in which the effective area of HXD is maximized, whereas that of the XIS is reduced to on average 88%. Results from XIS2 are not reported here since it has not been in operation since an anomaly in November 2006. In addition, we do not describe in detail the analysis of HXD-GSO data, since the HXD-GSO detected no significant signal from the source.

3. DATA REDUCTION

We used data sets processed using the software of the Suzaku data processing pipeline (version 2.1.6.16). Reduction and analysis of the data were performed following the standard procedure using the HEADAS v6.4 software package, and spectral fitting was performed with XSPEC v.11.3.2.

For the XIS data analysis, we accumulated cleaned events for the XIS0 and XIS2 detectors (XIS1 and XIS3 have front-illuminated (FI) CCDs, whereas XIS1 utilizes a back-illuminated (BI) CCD. The merit of the BI CCD is its improved sensitivity in the soft X-ray energy band below 1 keV. Suzaku contains also a non-imaging collimated Hard X-ray Detector (HXD; Takahashi et al. 2007; Kokubun et al. 2007), which covers the 10–600 keV energy band with Si PIN photodiodes (10–70 keV) and GSO scintillation detectors (40–600 keV). Suzaku has two default pointing positions, the XIS nominal position and the HXD nominal position. In this observation, we used the HXD nominal position, in which the effective area of HXD is maximized, whereas that of the XIS is reduced to on average 88%. Results from XIS2 are not reported here since it has not been in operation since an anomaly in November 2006. In addition, we do not describe in detail the analysis of HXD-GSO data, since the HXD-GSO detected no significant signal from the source.

Another component of the HXD-PIN background is the cosmic X-ray background (CXB). In our analysis, we assumed the CXB spectrum reported by Gruber et al. (1999):

$$I(\nu) = 7.9 \times 10^{-29} \exp \left(-\frac{\nu}{p}\right) \text{ph s}^{-1} \text{keV}^{-1} \text{cm}^{-2} \text{str}^{-1};$$

where $\nu = \text{keV}$ and $p = 41.1$. The CXB spectrum observed with HXD-PIN was simulated by us-
Note.—The exposure time is the net integration time after standard data screening for the XIS and HXD-PIN.

Since LS 5039 is located close to the Galactic plane, the contribution from the Galactic ridge X-ray emission (GRXE) must be examined, especially for HXD-PIN spectra. In order to model the shape of the GRXE, data from Suzaku observations of the Galactic ridge region (ObsID: 500009010 and 50009020) were analyzed. The Suzaku spectrum from 3 keV to 50 keV can be well fitted with the Raymond-Smith plasma with a temperature of $kT = 2.2 \pm 0.8$ keV and a power-law function with $\Gamma = 1.92^{+0.28}_{-0.24}$. Although we also tried a power law with exponential cutoff, following the results from the INTEGRAL IBIS (Krivonos et al. 2007), it turned out that the assumption on the spectral shape of the GRXE has negligible effect on the spectral parameters of LS 5039. The normalization of the GRXE spectrum component in the HXD-PIN spectrum of LS 5039 is determined from the XIS spectrum of the LS 5039 observation by excluding an encircled region with a radius of 4.5$''$ centered on the LS 5039 location. The flux of the GRXE is estimated to be 5% of the NXB.

The exposure time is the net integration time after standard data screening for the XIS and HXD-PIN.

4. ANALYSIS AND RESULTS

4.1. Temporal analysis

The light curve obtained from the XIS detector is shown in the top panel of Figure 2. The continuous coverage in X-rays, longer than the orbital period of the LS 5039 system, reveals a smooth variation of a factor 2 in the 1–10 keV count rate. The light curve is drawn over two orbital periods. The orbital phase is calculated with the period of 3.90603 days, and $\phi = 0$ with reference epoch $T_0$ (HJD $- 2400000.5 = 51942.59$) taken from Casares et al. (2005). The light curve from phase $\phi = 1.0$ to 1.5, which was obtained in the last part of the observation, smoothly overlaps with the one obtained at the beginning of the observation ($\phi = 0$–0.5).

In the middle panel of Figure 2 we present the light curve obtained with the HXD-PIN for the energy range 15–40 keV. Although the statistical errors are larger, the modulation behavior is similar to that of the XIS. The amplitude of the modulation is roughly the same between the XIS and HXD-PIN, indicating small changes of spectral shape depending on orbital phase. The spectral parameters obtained for each orbital phase are reported in the following section.

The light curves obtained with Suzaku show that the X-ray flux minimum appears around phase 0.0–0.3 and it reaches maximum around phase 0.5–0.8. In order to quantify the amplitude of the flux variations, we fitted the XIS light curve with a simple sinusoidal function. Due to structures in the light curve, the fit converges with large chi-square ($\chi^2(\phi) = 4.92 (121)$). However, the general trend is well represented by a sinusoidal function:

$$I(\phi) = 0.24 \sin(-0.03) + 0.64 \text{ counts s}^{-1}$$  \hfill (2)

where $I(\phi)$ is the count rate as a function of phase $\phi$. The ratio between the minimum and maximum count rates are 2.21 $^{+0.02}_{-0.01}$ counts s$^{-1}$ for XIS and 2.02 $^{+0.25}_{-0.19}$ counts s$^{-1}$ for HXD-PIN. Structures of the X-ray and hard X-ray light curves are similar to that discovered in the phase diagram of integral fluxes at energies $\gtrsim 1$ TeV obtained on a run-by-run basis from HESS data (2004 to 2005) reported by Aharonian et al. (2006).

In addition to the continuously changing component with respect to the orbital phase, short timescale structures are found around $\phi = 0.8$ and $\phi = 0.7$. The unabsorbed flux changes about a 30% in 0.05 (4.7 hour). A significant dip can be seen around $\phi = 1.55$ in the top panel of Figure 2. In comparison with the data at around $\phi = 0.85$ obtained in the first half of the observation, the flux decreased 50% only.
in this phase. The time duration of this dip corresponds to 0.03. These structures may reflect features of the (possibly changing) environment of the X-ray emitting region, it is therefore of importance to test with further observations if these are persistent features.

4.2. Spectral Analysis

Firstly we study time-resolved (phase-resolved) X-ray spectra. The data are divided into data segments with respect to the assigned phase, and model fitting is performed for XIS spectra for each segment with \(\phi = 0.1\). A single power-law function with photoelectric absorption, provides a good fit for all the segments. In order to study the possible changes of the amount of photoelectric absorption, we here fit the data with \(N_H\) free. The best-fit parameters are presented in Table 2. The derived values of the photon index and absorption column density are consistent with previous observations (Martocchia et al. 2005; Bosch-Ramon et al. 2007). When we fix the \(N_H\) to the value obtained from the time averaged spectrum, resultant photon indices stay same within statistical error.

The photon index (\(\Gamma\)) values are plotted as a function of orbital phase in the top panel of Figure 3. The spectral shape varied such that the spectrum is steep around SUPC (\(\phi \sim 1.6\)) and becomes hard (\(\phi \sim 1.5\)) around apastron. The modulation behavior of \(\Gamma\) is somewhat different from that observed using HESS in the VHE range. The amplitude of the variation is \(0.1\), which is much smaller than the change of 0.6 in the VHE region (Aharonian et al. 2006). The 1–10 keV flux changes from \(5 \times 10^{12} \text{erg cm}^{-2} \text{s}^{-1}\) (\(\phi = 0.1\)) to \(1.5 \times 10^{12} \text{erg cm}^{-2} \text{s}^{-1}\) (\(\phi = 0.6\)).

In all the data segments, the source is significantly detected with the HXD-PIN, indicating that hard X-ray emission extends at least up to 70 keV. Note also that although the XIS and HXD-PIN spectra do not overlap, they seem to be smoothly connected in the gap between 10 and 15 keV.

To study the shape of the spectrum above 10 keV, the XIS spectra and the PIN spectrum in the range 15–70 keV after subtraction of background (NXB + CXB + GRXE) are jointly fitted (Figure 4 Top). The time-averaged spectra are well represented by an absorbed power-law model with \(\Gamma = 1.51 \pm 0.02\) with reduced \(\chi^2 = 0.99\) (235 degrees of freedom). We find no cutoff structure in the energy range of the HXD-PIN. The spectra within the phase intervals \([0.616 < \phi < 0.816]\) and \([0.58 < \phi < 0.958]\), which correspond to the INFC and SUPC, respectively, are also shown in Figure 4. The best-fit parameters are presented in Table 3.

Althought earlier observations by RXTE suggested the presence of an iron emission line at 6.7 keV (Ribo et al. 1999), later observations by Chandra and XMM could not find evidence of it (e.g. Bosch-Ramon et al. 2005). A careful study of new and longer RXTE observations, using slew data to account for background emission, revealed that the earlierly reported 6.7 keV emission line is likely a background feature.
favor's a non-thermal origin of the X-rays. This conclusion is supported by the general similarities between the properties of the observed X-rays and TeV gamma-rays. Namely, both radiation components require a rather hard energy distribution of parent electrons with a power-law index of 2. This directly follows from the photon index of the synchrotron radiation $\Gamma$, and agrees quite well with the currently most favored interpretation of the TeV gamma-rays, in which they would be produced by IC scattering off the anisotropic photon field of the massive companion star.

Assuming that the TeV gamma-ray production region is located at a distance from the companion star of $d = 2 \times 10^7$ cm (i.e. the binary system size), and taking into account that gamma-rays are produced in the deep Klein-Nishina (KN) regime with significantly suppressed cross-section, for the well known luminosity of the optical star $L' = 7 \times 10^8$ erg s$^{-1}$, one can estimate quite robustly the strength of the magnetic field in the emission region. The numerical calculations show that the field should be around a few Gauss (see e.g. Fig. 5). For such a magnetic field strength, the energy intervals of electrons responsible for the two emission components overlap substantially, as shown in Figure 5. Therefore, we are most likely dealing with the same population of parent electrons, which should be located at large distances from the compact object, in the system periphery, to prevent the severe absorption of the TeV radiation and the subsequent intense emission from the pair-created secondaries (Khangulyan et al. 2008a; Bosch-Ramon et al. 2008a).

It should be noted that the observed X-ray emission is very difficult to explain as synchrotron emission produced by sec-

### Table 2

| Orbital Phase Intervals | Photon index | $N_H$ (wabs) $10^{21}$ cm$^{-2}$ | Flux [1-10 keV] $10^{-12}$ erg cm$^{-2}$ s$^{-1}$ | $\chi^2$ ( ) |
|-------------------------|--------------|----------------------------------|---------------------------------|-------------|
| INFC (0.45 $< \phi < 0.9$) | 1.48 0.02 | 7.82 0.18 | 10.78 0.05 0.97 (111) |
| SUPC (0.45, 0.9 $< \phi$) | 1.55 0.02 | 7.77 0.20 | 6.72 0.04 0.94 (111) |
| All Phases (time averaged) | 1.51 0.01 | 7.71 0.2 | 8.07 0.03 0.81 (118) |
| 0.0-0.1 | 1.57 0.04 | 6.86 0.44 | 5.62 0.03 0.99 (111) |
| 0.1-0.2 | 1.61 0.04 | 7.67 0.46 | 5.18 0.03 1.04 (111) |
| 0.2-0.3 | 1.51 0.03 | 7.23 0.37 | 5.67 0.02 1.13 (107) |
| 0.3-0.4 | 1.49 0.03 | 7.42 0.43 | 7.34 0.03 1.01 (111) |
| 0.4-0.5 | 1.45 0.02 | 7.63 0.26 | 9.73 0.01 0.96 (111) |
| 0.5-0.6 | 1.46 0.03 | 7.82 0.45 | 9.95 0.02 1.15 (105) |
| 0.6-0.7 | 1.46 0.03 | 7.82 0.37 | 12.05 0.02 0.77 (118) |
| 0.7-0.8 | 1.51 0.02 | 7.61 0.33 | 11.27 0.02 1.10 (108) |
| 0.8-0.9 | 1.52 0.04 | 7.63 0.47 | 10.29 0.03 0.87 (111) |
| 0.9-1.0 | 1.59 0.03 | 8.35 0.41 | 7.84 0.02 1.06 (111) |

Note.—Fitting Suzaku XIS0 +XIS3 spectrum of LS5039 by a power-law with photoelectric absorption in 0.6–10 keV. Photon index $\Gamma$, absorbing column density $N_H$, and the 1–10 keV flux $F_{1-10}$ (corrected for absorption) are shown with 68.3 % (1 $\sigma$) error. The orbital phase $\phi$ is calculated from the ephemeris of Casares et al. (2005).

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| All Phases (time averaged) | 1.51 0.02 | 7.7 0.2 | 0.95 (175 d.o.f.) |
| INFC (0.616 $< \phi < 0.816$) | 1.49 0.04 | 7.9 0.4 | 0.87 (111) |
| SUPC (0.358 $< \phi < 0.958$) | 1.55 0.05 | 6.9 0.5 | 1.06 (111) |

Note.—Power-law fitting to the XIS/HXD-PIN spectrum. The errors of spectral parameters are at the 90% confidence level.

(The Bosch-Ramon et al. 2008a). The Suzaku data confirm this result. In an attempt to find the possible signature of iron emission lines from LS 5039, we analyzed the phase-averaged spectrum. The upper limits on iron line structures are determined by fitting a Gaussian at various energies and line widths at which Fe emission might be expected. The power-law continuum model parameters are fixed with the best fit values and a Gaussian component is added to the power-law function. The central energy of the Gaussian line is swept from 6.0 keV to 7.1 keV in steps of 0.1 keV. Line widths are changed from 0.01 keV to 0.09 keV in steps of 0.01 keV, together with lines with larger widths of 0.15 and 0.20 keV. An equivalent width is determined at each grid point. The resulting upper-limit on the equivalent width is 40 eV with 90% confidence level.

5. DISCUSSION

The X-ray emission observed with Suzaku is characterized by (1) a hard power law with $\Gamma > 1.5$ extending from soft X-rays to 70 keV, (2) clear orbital modulation in flux and photon index, (3) a moderate X-ray luminosity of $L_X = 10^{38} (\frac{d}{10^7})^2$ erg s$^{-1}$, (4) a small and constant absorbing column density, and (5) a lack of detectable emission lines.

Although variable X-ray emission has been found from more than two hundred galactic binary systems, the Suzaku data hardly can be explained within the “standard accretion” scenario where X-rays are produced by a hot thermal (comptonized) accretion plasma around the compact object. The lack of X-ray emission lines (at the level of sensitivity of Suzaku) as well as the hard $E^{-1.5}$ type energy spectrum of the X-ray continuum, extending from soft X-rays up to 70 keV, favors a non-thermal origin of the X-rays. This conclusion is supported by the general similarities between the properties of the observed X-rays and TeV gamma-rays. Namely, both radiation components require a rather hard energy distribution of parent electrons with a power-law index of 2. This directly follows from the photon index of the synchrotron radiation $\Gamma$, and agrees quite well with the currently most favored interpretation of the TeV gamma-rays, in which they would be produced by IC scattering off the anisotropic photon field of the massive companion star.

Assuming that the TeV gamma-ray production region is located at a distance from the companion star of $d = 2 \times 10^7$ cm (i.e. the binary system size), and taking into account that gamma-rays are produced in the deep Klein-Nishina (KN) regime with significantly suppressed cross-section, for the well known luminosity of the optical star $L' = 7 \times 10^8$ erg s$^{-1}$, one can estimate quite robustly the strength of the magnetic field in the emission region. The numerical calculations show that the field should be around a few Gauss (see e.g. Fig. 5). For such a magnetic field strength, the energy intervals of electrons responsible for the two emission components overlap substantially, as shown in Figure 5. Therefore, we are most likely dealing with the same population of parent electrons, which should be located at large distances from the compact object, in the system periphery, to prevent the severe absorption of the TeV radiation and the subsequent intense emission from the pair-created secondaries (Khangulyan et al. 2008a; Bosch-Ramon et al. 2008a).

It should be noted that the observed X-ray emission is very difficult to explain as synchrotron emission produced by sec-
Fig. 5.— The radiative cooling times as a function of electron energy. The blue line corresponds to IC losses at the distance \( d = 2 \times 10^{17} \) cm from the optical star (the star luminosity and temperature were assumed to be \( L = 7 \times 10^{38} \) erg/s and \( T = 38 \times 10^{3} \) K, respectively). The red line corresponds to the synchrotron losses for B-field \( B = 3 \) G. The filled regions reproduce the electron energy intervals relevant to the HESS (yellow), Fermi (light blue) and Suzaku (green) energy domains. Formally, two radiation channels, synchrotron radiation of very high energy electrons (light green) and IC scattering of low energy electrons in the Thompson regime (dark green) can produce X-ray photons in the Suzaku energy domain.

ondary (pair-produced) electron and positrons. Since the pair production cross-section has strong energy dependence with a distinct maximum, for the target photons of typical energy of \( 10 \) eV, the major fraction of the absorbed energy will be released in the form of \( 100 \) GeV electrons. Thus secondary pair synchrotron emission must show a spectral break in the Suzaku energy band unless one assumes unrealistically high magnetic fields, \( B \approx 1 \) kG, in the surroundings of the gamma-ray emission region (Khangulyan et al. 2008a; Bosch-Ramon et al. 2008a).

Figure 5 shows the synchrotron and IC cooling times of electrons, as a function of electron energy, calculated for the stellar photon density at \( d = 2 \times 10^{17} \) cm and for a magnetic field \( B = 3 \) G. It can be seen that synchrotron losses dominate over IC losses at \( E_{\gamma} \approx 1 \) TeV. Note that the TeV gamma-ray production takes place in the deep KN regime. This implies that the cooling time, \( t_{\text{cool}} = \frac{E_{\gamma}}{P_{\gamma}} \), of electrons generating GeV gamma-rays via IC scattering (Thomson regime) is shorter than the cooling time of TeV electrons responsible for producing very high-energy gamma-rays (KN). The same applies for synchrotron cooling time of multi-TeV electrons that produce low-energy (MeV) gamma-rays by synchrotron radiation. One should therefore expect significantly higher MeV (synchrotron) and GeV (IC) fluxes than at keV and TeV energies, provided that the acceleration spectrum of electrons extends from low energies to very high energies. However, in the case of existence of low-energy and very-high-energy cutoffs in the acceleration spectrum, the gamma-ray fluxes \( > 10 \) MeV and at GeV energies would be significantly suppressed.

To better understand the energy ranges of the electrons responsible for X-ray and gamma-ray production, we show in Figure 5 the energy zones of electrons relevant to the Suzaku, Fermi, and HESS radiation domains. Note that the reconstruction of the average energy of electrons responsible for the IC gamma-rays depends only on the well known temperature of the companion star \( T = 38 \times 10^{3} \) K. The light green zone in Figure 5 marked as “Suzaku synchrotron”, corresponds to electrons responsible for the synchrotron photons produced in the energy interval \( 1 \text{ keV} \sim 40 \text{ keV} \). For a reasonable range of magnetic field values, the energy interval of electrons relevant for Suzaku data overlap on one hand with the HESS energy interval, and can overlap with the Fermi one. This should allow us, in the case of detection of MeV/GeV gamma-rays by Fermi, to considerably reduce the parameter space, in particular, to better localize the X- and gamma-ray production regions from electromagnetic cascade constraints, and derive the broadband energy spectrum of electrons and the strength of the magnetic field, both as a function of the orbital phase.

Formally, when X-rays and TeV gamma-rays are produced by the same population of very-high-energy electrons, one should expect a general correlation between the light curves obtained by Suzaku and HESS. In this regard, the similarity between the Suzaku and HESS light curves seems to be natural. However, such an interpretation is not straightforward in the sense that two major mechanisms that might cause modulation of the TeV gamma-ray signal are related to interactions of electrons and gamma-rays with the photons of the companion star, i.e. anisotropic IC scattering and photon-photon pair production (Khangulyan et al. 2008a; Dubus et al. 2008), and thus cannot contribute to the X-ray modulation. The X-ray modulation requires periodic changes of the strength of the ambient magnetic field or the number of relativistic electrons. Note, however, that the change of magnetic field would not have a strong impact as long as the radiation proceeds in the saturation regime and synchrotron losses dominate in the relevant energy interval. One would also expect modulation of the synchrotron X-ray flux if the energy losses of electrons are dominated by IC scattering, although in such a case we should observe significantly lower X-ray fluxes.

A more natural reason for the modulation of the synchrotron fluxes would come from dominantly adiabatic losses. The adiabatic cooling of electrons in binary systems can be realized through complex (magneto)hydrodynamical processes, e.g. due to interactions between a black hole jet or a pulsar wind with the dense stellar wind of a massive companion star (see e.g. Bogovalov et al. 2008, Perucho & Bosch-Ramon 2008). The orbital motion could naturally produce the modulation of adiabatic cooling of electrons around the orbit (see e.g. Khangulyan et al. 2008b). Note that because of the relatively small variation of the X-ray flux over the orbit, a factor of only two, the requirements for this scenario are quite modest. We note that dominant adiabatic losses have been invoked by Khangulyan et al. (2007) to explain the variations of the X-ray and TeV gamma-ray fluxes from the binary pulsar PSR B1259–63.

The detected power-law spectrum of X-rays with photon index \( = 1.5 \) implies that the established energy spectrum of electrons is also a power-law with index \( \gamma = 2 \). This agrees well with the hypothesis of dominance of adiabatic losses, because the adiabatic losses do not change the initial spectrum of electrons. Thus the required power-law index \( \gamma = 2 \) implies a reasonable acceleration spectrum \( Q(E) / E_2 \). Otherwise, in an environment dominated by synchrotron losses, the acceleration spectrum should be very hard, with a power-law index \( \gamma = 1 \), or should have an unrealistically large low-energy cutoff at \( E \approx 1 \) TeV to explain the observed X-ray spectra.

Obviously, adiabatic losses modulate the IC gamma-ray
flux in a similar manner. However, unlike X-rays, the TeV gamma-rays suffer significant distortion due to photon-photon absorption (see e.g. Böttcher 2007) and anisotropic IC scattering with its strong hardening of the gamma-ray spectrum (Khangulyan & Aharonian 2005). All this leads to additional orbital modulation of the gamma-ray signal, and it is likely that these two additional processes are responsible for the strong change of gamma-ray flux, much more pronounced than that seen in X-rays (see Fig. 2). The Suzaku data presented in this paper implies a key additional assumption, namely that the accelerated electrons must loose their energy adiabatically before they cool radiatively.

In order to demonstrate that the suggested scenario can satisfactorily explain the combined Suzaku X-ray and HESS gamma-ray data, we performed calculations of the broad-band spectral energy distributions (SEDs) of the synchrotron and IC emission, assuming a simple model in which the same population of electrons is responsible for both X-rays and TeV gamma-rays. We also assumed that the emission region has homogeneous physical conditions. This is a reasonable assumption given that we deal with very short cooling timescales (\(100\) s), thus electrons cannot travel significant distances while emitting.

In the regime dominated by adiabatic energy losses, the synchrotron X-ray flux is proportional to \(t_{\text{ad}}\). The X-ray modulation seen by Suzaku is then described by the modulation of the adiabatic loss rate. In Fig. 3 we show \(t_{\text{ad}}\) that is inferred from the X-ray data. The required adiabatic cooling timescales are \(1\) s. Any consistent calculation of the adiabatic cooling requires the solution of the corresponding hydrodynamical problem, and one needs to know in detail the nature of the source. At the present stage, we consider the simple example of adiabatic cooling in a relativistically expanding source. In such a case, the adiabatic loss rate can be written as: \(t_{\text{ad}}(i) = t_{\text{ad}}/r_{\text{sh}} = 3R_1\) s, where \(R_1 = (10^{11}\) cm) is the characteristic size of the source. The required variation of the adiabatic cooling is thus reduced to the modulation of the size of the radiation region \((R_1 = 0.3\)–1). The size in turn depends on the external pressure exerted by, e.g., the stellar wind from the massive star. The expected weaker external pressure around apastron implicitly assumed in our model would be broadly consistent with the radial dependence of the wind pressure.

In Fig 7 we show the SEDs averaged over the INFC (\(0 < \theta < 0.9\)) and SUPC (\(0 < \theta < 0.9\)) phase intervals. The corresponding gamma-ray data have been previously reported by HESS (Aharonian et al. 2006). Since both the absolute flux and the energy spectrum of TeV gamma-rays vary rapidly with phase, in order to compare the theoretical predictions with observations, we should use smaller phase bins, ideally speaking with the time intervals \(t = 100\) s corresponding to the characteristic cooling timescales of electrons. Because of the lack of the relevant gamma-ray data available to us, we here use the X-ray and gamma-ray data integrated over \(0.45\). While this compromise does not allow us to perform quantitative studies, it can be used to make a qualitative comparison of the model calculations with observational data.

The theoretical calculations of the SEDs are in a reasonable agreement with the observed spectra, though they do not perfectly match the gamma-ray fluxes. One can improve the fits by introducing slight phase-dependent changes in the spectra of accelerated electrons, but it is beyond the scope of this paper given the caveat mentioned above. We should also note that the calculations of low energy gamma-rays (in the Fermi domain) are performed assuming that the injection spectrum of electrons continues down to 10 GeV. If this is not the case, the gamma-ray fluxes in the Fermi energy domain may be significantly suppressed. On the other hand, the detection of gamma-rays by Fermi would allow us to recover the spectrum of electrons in a very broad energy interval, and thus distinguish between different acceleration models. Another important feature in this scenario is that a hard synchrotron spectrum extending up to a few MeV is required by the robust detection of 10 TeV gamma-rays from the system. A future detection of the emission at MeV energies may bring important information on the presence of highest energy particles in the system.

The reproduction, at least qualitatively, of the observed spectral and temporal features of the nonthermal radiation with the simple toy model supports the production of X-ray and TeV gamma-rays by the same population of parent particles and allows us to derive several principal conclusions. The electron energy distribution should be a power-law with an almost constant index of \(\gamma = 2 \chi - 1 < 2\) to explain the X-ray spectra. Note that in an isotropic photon gas when the Compton scattering takes place in the deep KN regime such an electron distribution results in a quite steep TeV spectrum with photon index \(\gamma + 1 < 3\). This does not agree with HESS observations. However, the anisotropic IC provides a remarkable hardening of the gamma-ray spectrum (Khangulyan & Aharonian 2005), in particular, 2 would...
be expected for the INFC, and it has indeed been observed using HESS (Aharonian et al. 2006). We also note that, to explain the VHE spectrum at SUPC, we have to assume that the emission region is located at a distance \( 2 \times 10^6 \) cm from the compact object, in the direction perpendicular to the orbital plane. In the standard pulsar scenario, the production region cannot be located far away from the compact object, and even invoking electromagnetic cascading (see e.g. Fig. 16 in Torres & Sierpowska-Bartosik 2008), one cannot reproduce the reported fluxes around orbital phase 0.0 (Khangulyan et al. 2008a; Bosch-Ramon et al. 2008a).

We have found that the magnetic field strength cannot deviate much from a few G. We can also derive a constraint on the size of the emission region, imposing a maximum expansion speed of \( c \) (the speed of light), and the Hillas criterion (Hillas 1984), in which the minimum size of a source capable of accelerating particles to a given energy \( E_a \) is \( R = R_L \) (where \( R_L = E_a c/300B_G \) cm), the Larmor radius. This estimate yields a size of \( 10^{10} - 10^{11} \) cm, which agrees quite well with the estimate based on the required timescale of adiabatic cooling. Note that the requirement of fast adiabatic losses imposes a strong constraint on the acceleration rate of electrons. Indeed, the acceleration timescale can be expressed as: \( t_{\text{acc}} = R/c < 1 \) s, where 1 parametrizes the acceleration efficiency. In extreme accelerators with the maximum possible rate allowed by classical electrodynamics \( c = 1 \). The HESS spectrum provides evidence of electron acceleration well above 10 TeV. Therefore, \( t_{\text{acc}} < t_{\text{ad}} \) 1 s is required at \( E_e \) = 10 TeV, which translates into \( < 3 \) for \( B \geq 3 \) G. Thus we arrive at the conclusion that an extremely efficient acceleration with \( < 3 \) should operate in a compact region of \( R < 10^3 \) cm.

Finally, we would like to emphasize that in the scenario described here different radiation energy intervals are characterized by fundamentally different light curves. While the synchrotron X-ray modulation is caused by adiabatic losses, the light curve in gamma-rays depends critically, in addition, on effects related to interactions with the optical photons of the companion star. Two of these effects, photon-photon pair production and anisotropic Compton scattering are equally important for the formation of the light curve of TeV gamma-rays. On the other hand, only the effect of anisotropic Compton scattering has an impact on the formation of the light curve of GeV gamma-rays. The difference of light curves in the X-ray and GeV and TeV gamma-ray intervals in this scenario is shown in Figure 6.

6. SUMMARY

The Suzaku X-ray satellite has observed LS 5039 for the first time with imaging capabilities over one and a half orbits. The Suzaku data show strong modulation of the X-ray emission at the orbital period of the system and the X-ray spectral data are described by a hard power-law up to 70 keV. We found the close correlation of the X-ray and TeV gamma-ray light curves, which can be interpreted as evidence of production of these two radiation components by the same electron population via synchrotron radiation and IC scattering, respectively. Whereas there are at least two reasons for the formation of a periodic TeV gamma-ray light curve, both related to the interaction with photons from the companion star (photon-photon absorption of VHE gamma-rays and IC scattering in an anisotropic photon field), the modulated X-ray signal requires an additional effect. A simple and natural rea-
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