GLAST TESTING OF A PULSAR MODEL MATCHING H.E.S.S. OBSERVATIONS OF LS 5039

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ABSTRACT

LS 5039 is one of a handful of X-ray binaries that have been recently detected at high-energy γ-rays, in this case, by the High Energy Stereoscopic System (H.E.S.S.). The nature of this system is unknown: both a black hole and a pulsar have been invoked as possible compact object companions. Here we work with a model of the high-energy phenomenology of the system in which it is assumed that the companion object is a pulsar rotating around an O6.5 V star in a ~3.9 day orbit. The model assumes two different sets of power-law spectral parameters of the interacting primary leptons corresponding to the two orbital phase intervals defined by H.E.S.S. as having different γ-ray spectra and very high energy (VHE) cutoffs. We show that the H.E.S.S. phenomenology is completely explained by this model. We present predictions for photons with lower energies (for $E > 1$ GeV), subject to test in the forthcoming months with the GLAST satellite. We find that GLAST will be able to judge on this model within 1 year.

Subject headings: gamma rays: observations — gamma rays: theory — X-rays: binaries — X-rays: individual (LS 5039)

Online material: color figures

1. INTRODUCTION

The Gamma-ray Large Area Space Telescope (GLAST) is the next generation γ-ray observatory due for launch in 2008 May. Its primary instrument is the Large Area Telescope (LAT), which will measure γ-ray flux and spectra from 100 MeV to ~100 GeV. LAT is the successor of the EGRET experiment that flew on board the Compton Gamma Ray Observatory. LAT will have better angular resolution, greater effective area, wider field of view, and broader energy coverage than EGRET. Developing predictions for the GLAST energy domain on which to test models of LS 5039 is then timely and worth exploring.

In a previous work (Sierpowska-Bartosik & Torres 2007, to which we refer the reader for references), under the assumption that LS 5039 is composed of a pulsar rotating around an O6.5 V star in a ~3.9 day orbit, we presented the results of a theoretical modeling of the high-energy phenomenology observed by H.E.S.S.3 The main difference between the previous model and the current one is that the former assumed a constant spectrum describing the interacting particles along the orbit, whereas now it is allowed to vary. The previous model (including a detailed account of the system geometry, Klein-Nishina inverse Compton [IC] scattering, γ-γ absorption, and cascading) was able to describe reasonably well the rich details found in the system, both flux- and spectrum-wise. However, almost the complete spectral energy distribution at superior conjunction, as well as other features of the observed orbital variation of the H.E.S.S. energy spectra, remained to be consistently explained. With models that do not entirely match the observed data at the highest energies, the study of lower energy predictions lacks testing power (strictly speaking, these models are already ruled out by H.E.S.S. observations). Here, we analyze and motivate the description of the VHE data, allowing for a variable spectrum of interacting primary leptons along the orbit, and indicate that the new model can nicely explain the H.E.S.S. observations. We then present predictions for the flux and spectrum as a function of phase for photons with lower energies, where H.E.S.S. is not sensitive but GLAST is. LS 5039 is near the Galactic center and has two other γ-ray sources nearby, as well as a significant Galactic diffuse background: it is not an easy target for GLAST (see Dubois 2006). In order to study orbital variability, the need to integrate long time intervals and make harder energy cuts to bring the signal above background was reported.

2. THE PULSAR MODEL WITH ORBITAL VARIABILITY IN THE INTERACTING PRIMARY SPECTRUM

The main features of the model are described by Sierpowska-Bartosik & Torres (2007). For LS 5039’s parameters the star wind dominates over the putative pulsar’s, and a shock wraps around the latter. We assume then that the volume of the system is shock-separated as a result of the collision between the pulsar and the massive star winds. Between the pulsar and the shock, inside the pulsar wind zone (PWZ), relativistic leptons are assumed to be frozen in the magnetized pulsar wind which propagates radially from the pulsar. In this PWZ, we compute Klein-Nishina IC cascades against thermal radiation from the massive star. Secondary γ-rays move into the massive star wind region and whereas some escape the binary system, others get absorbed due to the γ-γ process. These cascades are followed by means of a Monte Carlo procedure. We have computed geometric dependences on the opacities to these processes. For close binaries, the radiation field of hot massive stars (type O, Be, or WR, having typical surface temperatures in the range $T_{\text{s}} \sim 10^4$–$10^6$ K and linear dimension $R_{\odot} \sim 10 R_{\odot}$) dominates along the whole orbit over other possible fields (e.g., the magnetic field or the thermal field of the neutron star). This thermal radiation field is anisotropic for $e^+e^-$ injected close to the pulsar (the radiation source is misplaced with respect to the electron injection place).

We assume that the injected power in relativistic leptons, which initiates the cascading processes, is a fraction of the...
spin-down luminosity, $L_{\text{sd}}$. We particularize on the simplest case in which leptons are described, after being reprocessed by losses whose dominance can be a function of orbital phase, by a power-law in energy that may be constant (as in Sierpowska-Bartosik & Torres 2007) or vary along the orbit. Here, we focus on the case in which two different power laws are assumed for the interacting lepton population, corresponding to the two orbital intervals proposed by H.E.S.S. around inferior (0.45 < $\phi$ ≤ 0.90) and superior (0 ≤ $\phi$ ≤ 0.45 and $\phi$ > 0.90) conjunction (INFC and SUPC). Table 1 shows the model parameters chosen. In both cases we assume nominal values of $L_{\text{sd}} = 10^{37}$ erg s$^{-1}$ and $E_{\text{max}} = 50$ TeV. Note that $L_{\text{sd}}$ and the fraction of it that is converted into relativistic leptons ($\beta$) are obviously related. The position of the shock (which defines the size of the PWZ for which we compute the cascades) is defined by the parameter $\eta = L_{\text{sd}} / \langle MV_{\gamma} \rangle$, where the wind velocity, $V_{\gamma}$, depends on the radial distance from the massive star, and $M$ is the star mass-loss rate. Then, $MV_{\gamma}$ and $L_{\text{sd}}$ are also connected. Different sets of parameters (e.g., a smaller $L_{\text{sd}}$ with a higher $\beta$) give similar results. This is the consequence of a mild dependence with $\eta$ of the distance from the pulsar to the shock. In the models presented here, only a small fraction (≈1%) of the pulsar’s $L_{\text{sd}}$ ends up in relativistic leptons. This is consistent with ions carrying much of the wind luminosity.

Once the pulsar injects relativistic leptons (which could itself be subject to orbital variability), or alternatively, a close-to-the-pulsar shock accelerates a primary population assumed to be isotropic in the pulsar rest frame (e.g., Kirk et al. 1999), the interacting lepton population arises from the equilibrium between injection and the losses operating in the system along the orbital evolution. In this sense, SUPC and INFC of LS 5039 may indeed represent qualitatively different physical scenarios, as noted already by Aharonian et al. (2006). Let us consider first the maximum energy to which leptons are accelerated in the case where latter proceeds in a shock. The high temperature of the star and the hard spectrum of the VHE radiation measured imply (unless a very hard injection proceeds) that IC must happen in the Klein-Nishina regime. For dominant IC cooling, shock acceleration and cooling timescale equality imply that $E_{\text{max}} \propto (Bw)^{3/2}$, where $B$ is the magnetic field and $w$ is the target photon energy density (e.g., Kargylyan et al. 2008). Since $w \propto d^{-2}$, with $d$ the binary separation, and $B$ is a decreasing function of $d$, e.g., $B \propto d^{-\alpha}$, $E_{\text{max}}$ increases by a factor ≈10 from periastron (in the SUPC broad-orbital range) to apastron (in the INFC broad-orbital range), leading to a spectral hardening around INFC. At the highest energies, synchrotron losses (whose timescale is $\propto E^{-3}$) are expected to dominate and steepen the spectrum. The changeover energy from IC to synchrotron domination of the radiative losses depends on $B$ and $d$; if $B$ is not exactly $\propto 1/d$, it may also introduce a spectral hardening at apastron. Finally, adiabatic losses happening with the typical scales of the system associated with the flow patterns—i.e., the standoff distance of the pulsar wind shock (which scales with, and is less than, the distance between the stars) divided by the postshock speed ($c/\beta$)—generates a timescale that is independent of energy and, for LS 5039, close to or even smaller than the Klein-Nishina cooling times. In general, if leptons enter the production region with a rate described by a power law with index $\alpha_{\gamma}$, in the case of dominant radiative losses either by synchrotron or Thomson IC, the slope of the interacting population is steepened to $\alpha_{\gamma} + 1$. In the case of dominance by Klein-Nishina IC, the decrease in the cross section is such that the distribution index is slightly modified or even hardened at most by <0.5 in index, with hardening decreasing with the ratio $U_{\gamma}/U_{\beta}$ (Moderski et al. 2005). In the case of adiabatic dominance, the slope of the interacting population remains the same. Given that the losses’ dominance along LS 5039’s orbit can be a function of phase, and in addition that also the opacity to pair production is phase dependent, it seems natural to assume that in approximating the distribution of the interacting lepton population with a power law, it has a different index along the two broad-phase intervals whose qualitative observed features differ the most. In this context, the distinction between electron spectra at INFC and SUPC should be understood as an average of a smoother phase dependence of the electron primary spectrum, which could in turn be tested with future quality of data if more complex modeling is available.

### Table 1

| Parameter Adopted value |
|--------------------------|
| Constant lepton spectrum along the orbit: |
| Fraction of $L_{\text{sd}}$ in leptons, $\beta$ | $10^{-2}$ |
| Slope of the power-law, $\Gamma_{\gamma}$ | $-2.0$ |
| Variable lepton spectrum along the orbit: |
| Fraction of $L_{\text{sd}}$ in leptons at INFC interval, $\beta$ | $8.0 \times 10^{-3}$ |
| Slope of the power-law at INFC interval, $\Gamma_{\gamma}$ | $-1.9$ |
| Fraction of $L_{\text{sd}}$ in leptons at SUPC interval, $\beta$ | $2.4 \times 10^{-2}$ |
| Slope of the power-law at SUPC interval, $\Gamma_{\gamma}$ | $-2.4$ |

3. MATCHING OF H.E.S.S. RESULTS AND PREDICTIONS FOR GLAST

Figure 1 shows the results of our model, both flux- and spectrum-wise, compared with corresponding H.E.S.S. data (obtained from Aharonian et al. 2006). The spectra for LS 5039 are presented in two broad orbital phase intervals around INFC and SUPC. Each of the experimental data points represents a typical time span of 28 minutes. The corresponding phases for apastron, periastron, INFC, and SUPC are marked. Two periods are shown. To ease the comparison with our earlier result using a constant spectrum of interacting particles along the orbit (Sierpowska-Bartosik & Torres 2007) we include it (with a finer gridding) also in these plots.

H.E.S.S. has also provided the evolution of the normalization and slope of a power-law fit to the 0.2–5 TeV data in 0.1 phase binning along the orbit (Aharonian et al. 2006). The use of a power-law fit was limited by low statistics in such shorter suborbital intervals: i.e., higher order functional fittings such as a power law with exponential cutoff were reported to provide a no better fit and were not justified. To directly compare with these results, we have applied the same approach to treat the model predictions; i.e., we fit a power law in the same energy range and phase binning. This comparison is shown in Figure 2. We find a rather good agreement between model predictions and data.

Figure 1 also shows the spectral energy distribution predictions extended for energies above 1 GeV. The steeper the primary spectrum, the higher the flux produced at lower energies, which is particularly notable for the SUPC broad phase interval (see thick and thin curves of Fig. 1, which show the minimum flux that is needed for a source to be detected by GLAST after 1 month and 1 year of operation in all-sky survey, for an $E^{-2}$ source). At these flux levels, a 20% uncertainty in the determination of the flux, a resulting significance of about 8 $\sigma$, and

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4 See http://www-glast.slac.stanford.edu/software/IS/glast_lat_performance.htm.
a spectral index determined to about 6% would be achieved. Even if these sensitivities maybe slightly worse for a low-latitude source, if this model is correct, GLAST should be able to quantify the orbital variability after a few months of integration. The fact that the system periodicity is $\sim3.9$ days allows for a fast buildup of integration time at each of the portions of the orbit. A month integration around SUPC will be obtained after $\sim2$ months of all-sky survey, putting this model to the test soon after GLAST launch.\(^5\) Our model also predicts a clear anticorrelation between the expected output at TeV and GeV energies, which can be seen comparing the light curves shown in Figures 1 and 3.

\(^5\) LS 5039 is positionally coincident with 3EG J1824−1514 (Hartman et al. 1999; Paredes et al. 2000), whose average $\gamma$-ray flux above 100 MeV is $\sim3.5 \times 10^{-7}$ photons cm$^{-2}$ s$^{-1}$. Our model predictions are consistent with this observation too.
lower the energy range, the more anticorrelated the signal, which is a consequence of the phase dependence of the cascading and absorption processes. A hardness ratio defined within the GLAST energy domain does not vary as much as it does when constructed combining the fluxes at low and high γ-ray energies (a factor of 3 vs. an order of magnitude), but it may be useful as a first check before integration time is achieved for determining the spectrum. This is shown in Figure 4.

4. CONCLUDING REMARKS

A detailed modeling of LS 5039, under the assumption that it contains a pulsar, is able to fully describe the challenging H.E.S.S.-observed phenomenology found in the system. Observed light curves, spectra (Fig. 1), and short-timescale spectral variability (Fig. 2) are matched with a variable spectrum of primary particles along the orbit, where two phase intervals are considered. It is interesting to see that the influence of the orbital inclination angle is minor along all energy intervals within our theoretical model. Predictions of the model at lower γ-ray energy domains are ready for testing with GLAST. We find that GLAST will be able to judge on this model within 1 year. Features both at the light curve and spectral level can be recognized. Additional tests will come at higher energy yet beyond the current reach, e.g., behavior of the spectra at shorter phase intervals to be compared with data from the next generation of ground-based instruments: H.E.S.S. II and the planned Cerenkov Telescope Array (CTA).

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