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TeV microquasars and very energetic processes in the Galaxy

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The detection at TeV energies of the microquasars LS 5039 and LS I +61 303 has strong implications for galactic compact object astrophysics. Up to now, theoretical models had hinted at the possibility of detecting very high energy photons from microquasars, although the recent observational results are puzzling theoreticians because of the unexpected features of the observed radiation, among them orbital variability as well as quite hard photon indices. In this work, I briefly overview the main elements to consider when studying the spectral and temporal features of the TeV radiation. Moreover, some viable scenarios that might explain such emission are pointed out. We conclude that different factors could dominate in the variability of the emission at very high energies observed from these sources.

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1. Introduction

Microquasars are X-ray emitting binary systems formed by a normal star and a compact object, either a black hole or a neutron star. In these objects, stellar matter is transferred to the compact object and some fraction of it is eventually ejected in the form of two relativistic jets that are launched in opposite directions. These relativistic jets are the characterizing feature of microquasars, namely a sub class of the X-ray binary class, and were observed for the first time in a galactic object at radio frequencies when studying SS 433 ([1], [2]).

During the 90s, microquasars were basically considered to be non thermal radio emitters. It was not expected that microquasars, as a class, could produce particles that were energetic enough to produce gamma-rays. There were for instance some claims of detection of Cygnus X-3 (see, e.g., [3]), the microquasar nature of which was not known at that time, although nowadays these possible detections are not considered as trustful by the very high energy community.

In 2000, Paredes and coworkers ([4]) unveiled the microquasar nature of LS 5039 and proposed this source as the counterpart of one of the unidentified EGRET sources present in the 3rd EGRET catalog ([5]). The detection of relativistic jets in LS I +61 303 ([6, 7]), an already known EGRET source candidate ([8]), made of this source another gamma-ray microquasar candidate. Historically, some previous models had proposed that gamma-rays could be produced in microquasars ([9]), but it was in the early 00s when this possibility was more widely accepted and several models were developed trying to explain or to predict gamma-ray emission from microquasars (e.g. [4], [10], [11], [12], [13]; for a more thorough review on microquasar gamma-ray modeling, see e.g. [14]). Briefly, these models were based on external Compton interaction between jet electrons and star photons of other external radiation fields (e.g. accretion disk/corona emission), self-Compton interaction between jet electrons and their own synchrotron photons, interactions of jet relativistic protons with dense matter targets producing gamma-rays by neutral-pion decay, etc. Although at that time there were just few observational hints of the gamma-ray emitting nature of microquasars, all the mentioned work was very useful since it showed from the theoretical point of view that microquasars could be very attractive targets for the new generation of satellite-borne and ground-based gamma-ray instruments. We remark nevertheless that the main problem during the early stages of microquasar gamma-ray modeling was the lack of data, which left too much room for speculation. Nevertheless, this has been partially solved recently, with the detections by the Cherenkov telescopes HESS and MAGIC of LS 5039 ([15, 16]) and LS I +61 303 ([17]), respectively. The perspective of GLAST and AGILE observing the GeV sky is also very promising.

2. Phenomenology of the TeV microquasars

LS 5039

LS 5039 is a 3.9-days periodical TeV emitter with luminosities in the range $\sim 4\times10^{33}-10^{34}$ erg s^{-1}. The flux peaks around phase 0.8, close to the inferior conjunction of the system, and the minimum of the emission occurs around phase ~ 0.2, there being still a significant amount of radiation. The behavior of the spectrum is that it hardens when flux rises up, and softens when flux decreases in the range $\sim 1.9-3.1$. The differential flux at few 100 GeV appears to be quite constant along the orbit (Fig. 6 in [16]). The found TeV period is consistent with the orbital one

([18]), which implies that the TeV emission is produced or affected by phenomena with associated orbital timescales. Overlapped with the orbital variability, there is a shorter timescale variability (~ 1 h; [20]) that appears clearly overlapped on the emission peak at phase 0.8, looking as a sort of miniflare. This shorter timescale variability may have associated the same spectral trend as that seen in the smoother variable emission. At X rays, the source presents in general a very similar behavior, including short timescale variability also found in different orbital phases ([21]), one of them coinciding with the TeV miniflare and presenting apparently a similar spectral behavior ([22]). The X-ray luminosities are about a factor of two higher than those at TeV. Concerning radio emission, the source presents a 30% variability with a flux of ~ 30 mJy (2.25 GHz) that would be dominated by a non-resolved milliarcsecond core, being the spectrum optically thin ([23, 24, 25]).

LS I +61 303

LS I +61 303 presents variable TeV emission with luminosities in a similar range to those found in LS 5039. The spectral slope is of about 2.6, although the amount of collected data does not allow still to assess whether it changes when the flux varies, but the lightcurve clearly peaks at phase ~ 0.5, roughly similar to the phase of the peaks at radio ([26]), X rays, soft gamma rays ([27], [28]), and high-energy gamma-rays ([29]). However, the exact phases at which the radiation of different energies peaks are not well known since a complete multiwavelength observational campaign has not been performed so far. Moreover, the radio peak/outburst changes periodically its occurrence phase within the range 0.45–0.9 with a four year period ([30], [31]). The X-ray fluxes and spectral indexes are similar and change in a similar fashion as those of LS 5039. The radio fluxes in LS I +61 303 vary by a factor of several and are similar to those of LS 5030 during the quiescent state, being the emission optically thin but during the radio outburst, when it becomes optically thick. Very recently, it has been shown that the extended radio emission is produced at some distance from the binary system, with an appearance of comet-tail which changes the direction to which it points along the orbit (roughly in the opposite direction to that of the companion star), although it is still no clear how these new results fit altogether with previous radio data ([32]). The latter fact, plus the lack of accretion disk features in the X-ray spectrum of the source, have let some authors to propose that the radio extended structures are powered by two colliding winds, one coming from the star and the other generated by a non-accreting pulsar (e.g. [33], [34]), a model that had already proposed in the past to explain the high energy emission from LS I +61 303 (e.g. [35], [36]).

3. Interpretation of the TeV emission from LS 5039 and LS I +61 303

LS 5039

The orbital variability at very high energies shows up a link between the TeV emission and the orbital motion. This link can be via absorption and, if radiation has a leptonic origin, the inverse Compton (IC) emission toward the observer. This is due to variations in the photon-photon and electron-photon interaction angles and in the density of the target field, all of them changing along the orbit. If emission is hadronic via proton proton interaction with the dense stellar wind, the wind density will change as well. Moreover, if accretion disk timescales are shorter than the orbital ones, accretion/ejection changes due to different wind/compact object relative densities along the orbit could leave and imprint in the lightcurve, and changes in the magnetic field, the acceleration efficiency, and perhaps other less relevant factors may also affect the TeV emission. It seems nevertheless that the angular dependence of the IC cross section and some absorption are enough to explain semi-quantitatively the observations, and no significant changes in the injection mechanism or in the intrinsic properties of the emitter are required, but perhaps the magnetic field (for a deeper discussion, see [37]).

The short timescales of the TeV variability found in the source ([20]) constrain the emitter size down to 10^{14} cm. Moreover, the spectrum does not appear significantly affected by absorption. The differential flux at few 100 GeV, if produced inside the binary system, should show large variations due to absorption ([38]), but as noted above it does not appear to change significantly along the orbit. Therefore, TeV photons seem to be produced in a region $\sim 10^{13} - 10^{14}$ cm. In such a region, where the stellar wind density becomes smaller due to the large distance to the star, the most efficient radiation mechanism will be leptonic, namely IC, since a hadronic origin of the radiation would require too high kinetic luminosities in form of relativistic protons (concerning hadronic emission in LS 5039, see, e.g., [39]). The hard observed spectrum points to a low magnetic field in the region, since otherwise synchrotron losses would dominate radiation steepening the particle population and, subsequently, the TeV spectrum. It also implies that, since X-ray fluxes ([21]) are above the TeV fluxes ([16]), both emission components cannot come from the same region if the former is produced by synchrotron process, which appears to be likely.

LS I +61 303

The TeV emission produced in LS I +61 303, peaking at phases far from periastron passage, when angular effects are unlikely to be significant and photon-photon absorption is not important, is likely to be related with an increase in the relativistic particle injection[1]. In the leptonic scenario, another possible physical reason could be a decrease of the magnetic field, letting more energy to be released via the IC channel. However, this explanation appears hard to reconcile with the raising radio/X-ray fluxes at similar phases. In the hadronic scenario, an increase in the injection of relativistic protons seems to be the more suitable explanation. As in the previous case, a leptonic mechanism will likely be more efficient than a hadronic one, although the dense circumstellar wind surrounding the source renders the latter still a viable TeV emitting process ([41]). X-ray fluxes are slightly above TeV fluxes. In the leptonic scenario, the moderately hard TeV spectrum would point as in LS 5039 to two different regions for the X-rays and the TeV photons. In the hadronic scenario, an additional primary leptonic population is required to explain the higher X-ray fluxes. We note that, whatever the real nature of the compact object, LS I +61 303, any model to explain TeV emission should be able to predict the large relativistic particle energy budget, required to explain the high X-ray/GeV/TeV fluxes in phases around ~ 0.5, several times larger than in other orbital phases.

4. Applying a toy model to the TeV microquasars

We have applied a one zone model to the emitting region taking into account synchrotron and IC emission. The injection luminosity choice is somewhat arbitrary for the case of LS 5039, chosen to be reasonable and not to differ much from observations, since we do not intend to fit data

[1] We note that cascades could produce a similar effect ([40]), although the required conditions, very slow diffusion of the generated pairs, could not take place.

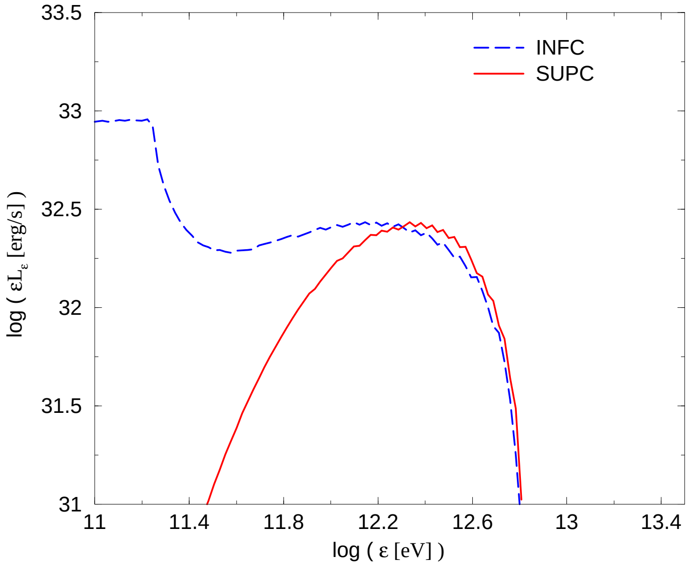

Figure 1: Computed IC spectral energy distribution of LS 5039 above 100 GeV of the radiation produced at 0.4 orbital radius above the compact object for SUPC and INFC. To compute the shown curves, photon-photon absorption has been taken into account. Photon-photon absorption prevents that detectable amounts of radiation will reach the observer (for the SUPC, radiation is extremely reduced). The injection luminosities are 10^{35} erg s^{-1}.

but only giving an indicative value. For LS I +61 303, the injection has been fixed to reproduce roughly the lightcurve observed by MAGIC. Convection is taken into account for the emitting particles, taking a mildly relativistic velocity (as it would be the case for an emitting outflow). The maximum particle acceleration efficiency is kept below the electrodynamical limit (qBc) but suitable to reach the energies of the observed photons. Doppler effects are not considered in this toy model, although we point out that LS 5039 and LS I +61 303 jets are considered to be mild relativistic ([4, 42], [6, 7]). The magnetic field strength has been set relatively low to obtain hard TeV spectra, as the observed ones.

LS 5039

In Fig. 1, 2 and 3 we show the difference between the spectra produced in two phases of the orbit for which the angular dependence of the IC cross section has the most significant effects: during the inferior and the superior conjunction (INFC and SUPC, phases 0.059 and 0.72 respective, [18]). The emitter location has been taken to be at 0.4, 4 and 40 orbital radius above the compact object (Fig. 1, 2 and 3 respectively), and the emitting region size has been taken to be $\sim 1/3$ of the former distance. We note, as discussed above, the significance of the angular effects. The effects of photon-photon absorption are dominant only within the binary system. Cascading effects have not been take into account (see, e.g., [39]).

LS I +61 303

The TeV spectra for two phases, periastron and phase 0.5, and the lightcurve at very high energies are shown in Fig. 4 and 5, respectively. We note that absorption could be relevant to suppress emission during periastron passage (we note that cascading effects are not considered

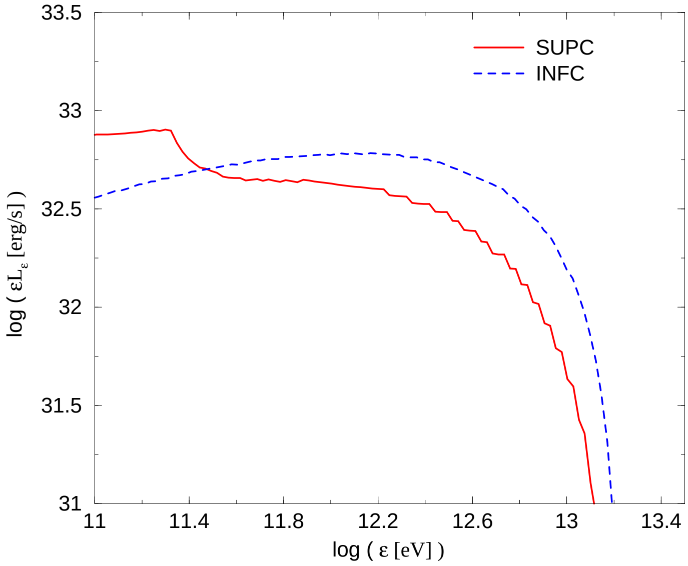

Figure 2: Computed IC spectral energy distribution of LS 5039 above 100 GeV of the radiation produced at 4 orbital radius above the compact object. Here it is easy to notice the impact of the angular dependence of the IC cross section on the spectral shape. To compute the shown curves, photon-photon absorption has been taken into account. The impact of absorption is still visible but minor. The injection luminosities are 10^{35} erg s^{-1} and 10^{36} erg s^{-1} for the SUPC and the INFC, respectively.

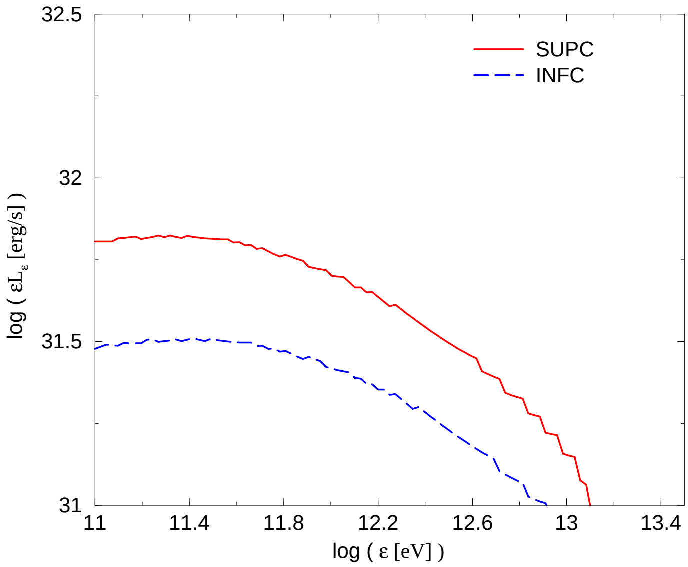

Figure 3: Computed IC spectral energy distribution of LS 5039 above 100 GeV of the radiation produced at 40 orbital radius above the compact object for SUPC and INFC. The signifi cantly lower level of emission is due to the dilution of the stellar radiation fi eld with distance, which at the present location of the emitter renders quite long IC timescales that are longer than the convection ones. The injection luminosities are 10^{35} erg s^{-1}.

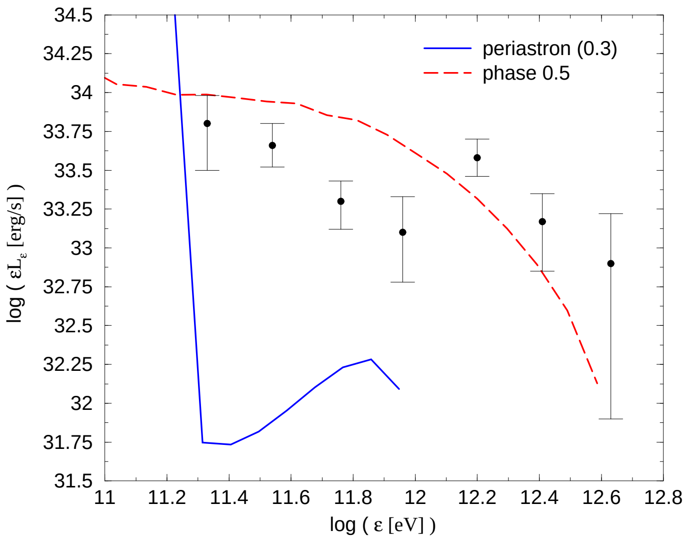

Figure 4: Computed IC spectral energy distribution of LS I +61 303 above 100 GeV for two orbital phases, the periastron passage and phase 0.5 (see also [44]). The injection luminosities are $\sim 10^{36}$ erg s^{-1}.

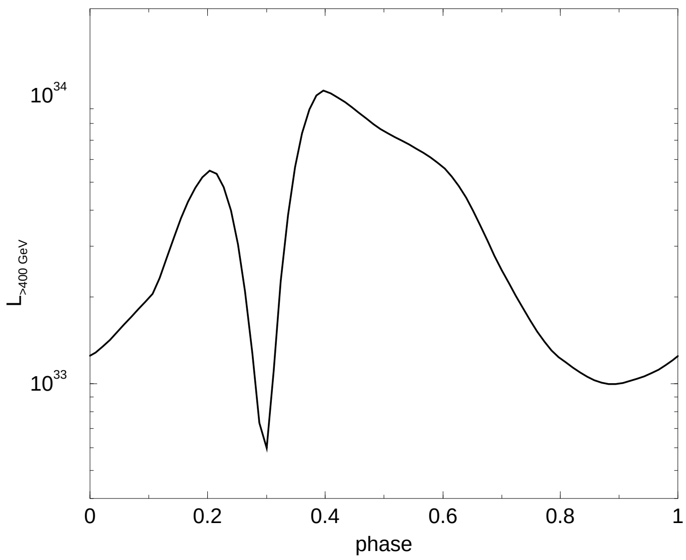

Figure 5: Computed IC lightcurve of the radiation produced above 100 GeV in LS I +61 303.

here), as seems to be the case. In any case, to explain the maximum of the emission, it is required a higher injection rate of relativistic particles in the emitting region. Here, the location and size of the emitter have taken both to be $1/3$ of the orbital radius. The ephemeris used here are those presented by Grundstrom and coworkers ([43])[2].

[2]The results obtained with the new ephemeris and those presented in [45], using [46] ephemeris, do not differ signifi cantly.

5. Conclusions and further comments

We conclude that the two TeV microquasars are efficient particle accelerators with likely leptonic very high energy emission. Besides the fact that both present very similar spectral energy distributions from radio to TeV energies, it is worth noting that the variability they present, likely being in both cases of orbital origin, is due to different effects. In LS 5039, the main factor of variability could be the changing geometry of the IC interaction along the orbit, being absorption effects probably non negligible either and variable as well (see also [37]). In LS I +61 303, the origin of the variability could be due to injection changes, the origin of which are unclear although it has been pointed out historically that these injection variations could be produced by wind inhomogeneities ([47], [41], [45]). Finally, absorption can well be the reason why the source was only detected for phases > 0.3 ([17]).

The mysterious character of these sources make their study very complicated and the comprehension of a global picture a very hard task.

In LS I +61 303 it seems clear that variability at different wavelengths is linked, but it is not so evident what is the physical relationship between the origin of the radiation at different energy bands. If the radio emitter is indeed located outside the binary system, and radio outburst emission is optically thick, there are two possible explanations. Either the region is wide, i.e. comet-tail like, and then the required amount of energy in the electron relativistic population and magnetic field is very high, or the region very is compact, implying therefore that it forms part of a really collimated structure, i.e. a jet. In the first case, it is necessary still to explain how such large amount of energy can be carried out of the system and deposited in form of relativistic electrons at the mentioned distance from a putative colliding wind shock structure located inside the binary system. In the second case, a real jet could really carry energy outside the binary system, although it is still required to understand why the core of the radio emission along most of the orbit is not in the inner regions of the jet. The present data cannot still constrain properly the X-ray and the TeV emitters, but it is unlikely that they will be originated too far away (lack of efficiency for the radiative processes), nor too close (lack of efficiency for stellar IC due to the source compactness and an associated likely high magnetic field). Further data taken at X rays and TeV, and if possible in coincidence with high resolution radio observations, could allow to better understand the enigmatic behavior of the source.

In LS 5039, the information concerning the TeV radiation properties allows to infer some of the emitter properties. Nevertheless, as described above, the radio component does not follow apparently the X-ray and TeV behavior. It seems that all the emission is generated within several AU, but still it seems to be produced in different regions depending on the energy we look at. Therefore, to explain the multiwavelength non thermal spectrum of the source, it will be required to apply physically consistent inhomogeneous models. Unfortunately, the physics of the source is not well known, but multiwavelength simultaneous observations are the best way to endorse modeling and could constrain important parameters of phenomenological models.

6. Regarding other jet TeV emitters: active galactic nuclei and gamma-ray bursts

The physical nature and size scales of the compact object (i.e. supermassive blackholes instead of stellar mass compact objects, in the case of active galactic nuclei), or the associated timescales ("extremely" short for gamma-ray bursts and "extremely" long for active galactic nuclei, compared with those in microquasars) quickly show that the emitter region is to be different in active galactic nuclei, gamma-ray bursts and microquasars. Nevertheless, a key point is the requirement of large Doppler factors in the extragalactic TeV emitters harboring compact objects and jets, a characteristic that is apparently not shared, as mentioned above, by TeV microquasars. Moreover, the location of the emitter in microquasars does not appear to be in the so-called blazar zone, in the jet inner part, nor in the internal nor external shock zone in gamma-ray bursts, in an outer jet region (i.e. in a microquasar, it would be well outside and far from the binary system). The microquasar TeV emitting region is in the jet middle scales, close to -though probably outside- the binary system. Although it is unclear yet what are the conditions concerning the magnetic field, particle acceleration, or radiative processes, in the jets of these discussed three types of sources, it seems clear that direct comparison cannot be made between them when considering their very high energy radiation. There should be nevertheless a common background, and it is probably the presence of (mildly/strongly) relativistic outflows.

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