LS 5039 is the only X-ray binary persistently detected at TeV energies by the Cherenkov HESS telescope. It is moreover a γ-ray emitter in the GeV and possibly MeV energy ranges. To understand important aspects of jet physics, like the magnetic field content or particle acceleration, and emission processes, such as synchrotron and inverse Compton (IC), a complete modeling of the multiwavelength data is necessary. LS 5039 has been detected along almost all the electromagnetic spectrum thanks to several radio, infrared, optical and soft X-ray detections. However, hard X-ray detections above 20 keV have been so far elusive and/or doubtful, partly due to source confusion for the poor spatial resolution of hard X-ray instruments. We report here on deep (∼300 ks) serendipitous INTEGRAL hard X-ray observations of LS 5039, coupled with simultaneous VLA radio observations. We obtain a 20–40 keV flux of 1.1 ± 0.3 mCrab (5.9 (±1.6) × 10^{-12} \text{ erg cm}^{-2}\text{s}^{-1}), a 40–100 keV upper limit of 1.5 mCrab (9.5 \times 10^{-12} \text{ erg cm}^{-2}\text{s}^{-1}), and typical radio flux densities of ∼25 mJy at 5 GHz. These hard X-ray fluxes are significantly lower than previous estimates obtained with BATSE in the same energy range but, in the lower interval, agree with extrapolation of previous RXTE measurements. The INTEGRAL observations also hint to a break in the spectral behavior at hard X-rays. A more sensitive characterization of the hard X-ray spectrum of LS 5039 from 20 to 100 keV could therefore constrain key aspects of the jet physics, like the relativistic particle spectrum and the magnetic field strength. Future multiwavelength observations would allow to establish whether such hard X-ray synchrotron emission is produced by the same population of relativistic electrons as those presumably producing TeV emission through IC.

Keywords X-ray binaries · Microquasars · X-rays · Gamma-rays

1 Introduction

Microquasars are radio-emitting X-ray binary sources, comprising a compact object (black hole or neutron star) and a companion star, which produce jets through the accretion-ejection mechanism and generate radiation along the electromagnetic spectrum (e.g.führer). For several aspects, they are scaled-down versions of Active Galactic Nuclei (AGN) or quasars, from which their name comes. While less numerous than AGNs, microquasars allow for a more detailed study of some of the AGN important properties thanks to both their closer locations and their faster variability.
As X-ray binaries, microquasars generally produce electromagnetic radiation mainly through accretion and emit most of their luminosity in the soft (0.1–20 keV) and hard (>20-keV–1 MeV) X-ray domains. γ-ray (E > 1 MeV) emission from microquasars is rarely observed. On the other hand, a class of AGNs, blazars, are strong γ-ray emitters, presenting little accretion disk radiation. The γ radiation produced in blazars is thought in general to come from IC scattering of synchrotron photons by the high-energy particles of the jet, or Synchrotron Self Compton (SSC). This emission, linked to the jet, is therefore particularly important because it gives information on the poorly known ejection process and on the jet composition and magnetic field. However, the study of the γ radiation is hampered by the limited knowledge available on the seed photon field that is boosted by the high energy particles. Microquasars suffer to some extent also the same problem. Moreover, the origin of hard X-ray emission in some microquasars, like LS 5039, is still under debate since accretion disk traces are not present and the jet could be the dominant component, like in blazars. Nevertheless, there is no need at present of large Lorentz factors to explain the γ-ray variability in microquasars, unlike the case of their extragalactic relatives.

LS 5039 is a microquasar with slightly variable and extended radio emission [23]. It is a binary system with a ~3.9 days orbital period composed by an O6.5 V-type donor star and (likely) a black hole as the compact object [4]. LS 5039 is the only microquasar detected at TeV energies by the HESS telescope up to now [5,6] and it is also a γ-ray emitter in the GeV range [27] and possibly in the MeV range [8,9]. The properties of the emission of LS 5039 are quite unlike the ones of more common microquasars like for instance GRS 1915+105 where the thermal emission from the disk dominates the total luminosity. Therefore, LS 5039 is a laboratory in which new aspects of the accretion-ejection mechanism and radiative processes can be studied. The origin of the emission has been proposed to be due either to an accretion-powered relativistic jet (e.g. [10,11,12]) or to the interaction between the relativistic wind of a young non-accreting pulsar and the stellar wind of the donor star [13] (and references therein), although the detection of a collimated jet from ~1 to 100 milliarcsecond scales renders the second scenario unlikely.

In the context of the accretion-powered model, the high energy emission is due to IC scattering in the jet of a seed photon field. The seed photons could be photons produced by synchrotron processes, which generate also the radio emission at lower energies, or by the optical-UV photons of the donor star (see Fig.1). The hard X-ray spectrum and the flux ratio between hard X-rays and GeV-TeV emission differ depending on the dominant energy losses, either synchrotron, Thomson IC or Klein-Nishina IC. Therefore, from the hard X-ray spectral shape and comparing the hard X-rays to the GeV-TeV flux, the magnetic field and even the dominant seed photon field (e.g. stellar or synchrotron), can be inferred. A complete modeling of the emission of LS 5039 is crucial for our understanding of the properties of the X-ray and the γ-ray emitting region(s), as well as of the jet itself. Therefore, hard X-ray emission is to be studied because it can shed light on the highest energy part of the electron spectrum. In the following we will present previous X-ray observations of LS 5039 and report serendipitous INTEGRAL hard X-ray observations at the position of the source. This is presented altogether with simultaneous VLA observations at 5 GHz, being also discussed in the general context of the source.

2 Previous soft and hard X-ray Observations

In soft X-rays (<20 keV) LS 5039 has been detected several times (see [10] and references therein). It is a weak source, \( L_X \sim 10^{34} \text{erg s}^{-1} \), with a power-law spectrum with photon index \( \Gamma \approx 1.5 \). Its flux is variable (factor ~2) with temporal scales similar to the orbital period [10]. The variability seems to be associated to the eccentric orbit of the system, \( e \approx 0.35 \). The likely origin of the emission is synchrotron radiation but a thermal origin from comptonization of a thermal plasma cannot at present be excluded. In this last case X-ray and γ-ray emission would hardly appear correlated.

However, the results of hard X-ray observations of LS 5039 have been so far unclear, partly due to source confusion for the poor spatial resolution of hard X-ray instruments. A BATSE detection in the 20–100 keV range was reported in the Earth Occultation catalog [14], with an average flux level of about 3.3 mCrab (3.4 ± 0.8 mCrab at 20–40 keV and 3.0 ± 0.7 mCrab at 40–70 keV)\(^1\). This is 2 to 3 times stronger than the extrapolation of previously reported RXTE/PCA soft X-rays flux measurements [10]. Moreover no detection has been reported in the second ISGRI source catalog, with 5σ upper limits of ~1 mCrab in the range 20–40 keV and ~1.5 mCrab at 40–100 keV, for an exposure time of 780 ks [15].

3 Observations

We report here on the results of serendipitous INTEGRAL observations with contemporaneous radio monitoring of LS 5039. The hard X-ray observation lasted 300 ks (i.e. ~1 orbital period) and was performed in the standard 5×5 dithering pattern. The target of the observation was the bright low mass X-ray binary GX 17+2 at a 2.6 degree angular distance from LS 5039. The source was thus in the Fully Coded Field of View of the IBIS/ISGRI hard X-ray camera [16] and therefore observed at full sensitivity in the 20–200 keV energy band. On the other hand, due to its smaller Field Of View, the JEM-X soft X-ray (3–35 keV) instrument had only about 50% sensitivity at the position of LS 5039. We remark that the 1 arcmin angular resolution of the IBIS/ISGRI camera allows to separate LS 5039 from nearby objects and that the 3σ detection sensitivity for a 300 ks ISGRI observation is

\[^1\] 1 mCrab = 5.4 \times 10^{-12} \text{ erg cm}^{-2} \text{s}^{-1} (20–40 \text{ keV}); 6.3 \times 10^{-12} \text{ erg cm}^{-2} \text{s}^{-1} (40–100 \text{ keV}); 3.95 \times 10^{-12} \text{ erg cm}^{-2} \text{s}^{-1} (40–70 \text{ keV)}
Fig. 1 Spectral energy distribution of LS 5039 from radio to TeV energies, a model adapted from [12] is superimposed in which the most important spectral components are shown. The references for the black and white data points can also be found in [12]. We remark that the MeV detection obtained with COMPTEL is very probably overestimated due to source confusion. Our VLA detection is represented by a violet square, while our INTEGRAL results are represented by red filled circles (see zoom in the inset).

Table 1 INTEGRAL/ISGRI observation log and results.

| Obs. Date (MJD) | 20–40 keV flux (mCrab) | 40–100 keV flux (mCrab) |
|-----------------|------------------------|------------------------|
| 53665.08–53669.36 | 1.1 ± 0.3 | < 1.5 |

Table 2 VLA observation log and results. Each measurement corresponds to a 5 minute snapshot observation.

| Obs. Date (MJD) | 4.86 GHz flux density (mJy) |
|-----------------|-----------------------------|
| 53667.07         | 25.1 ± 0.2                  |
| 53667.86         | 25.1 ± 0.1                  |
| 53668.96         | 24.4 ± 0.3                  |

∼1 mCrab. At the same time we obtained contemporaneous radio snapshots at 4.86 GHz with the NRAO2 VLA in order to monitor the source behavior. The observation logs are shown in Tables 1 and 2 respectively.

2 The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

4 Results

We analyzed the INTEGRAL observations using the standard analysis pipeline [17] and we produced images in the 20–40 and 40–100 keV bands for the whole observation. No clear detection of LS 5039 was found, in contrast with the expected ∼10σ detection for a ∼3 mCrab source according to [14]. After a careful subtraction of all the bright sources in the field of view, we were able to find at the position of LS 5039 a ∼4σ excess in the 20–40 keV energy band. If this excess is real, then the implied flux is ∼1.1 ± 0.3 mCrab. No excess is detected in the 40–100 keV band with a 3σ upper limit of 1.5 mCrab. We note that these values are in agreement with the upper limits derived from the absence of the source in the most recent ISGRI source catalog [15]. Unfortunately, the weakness of the detection hampers the possibility of searching for an orbital modulation at hard X-ray energies.

In soft X-rays, the off-axis position of the source in JEM-X and the presence of the noise induced by GX 17+2 prevented the source detection. This result is compatible with an extrapolation of the possible detection in the 20–40 keV
band. Our results are also broadly consistent with those presented by [10] at soft X-ray energies.

The snapshot observations we obtained with the VLA showed the source at a moderate level of activity with an average flux of about 25 mJy, in agreement with historic values of 23–26 mJy at 5 GHz [13].

The observation results are quoted in Tables 1 and 2 and are plotted in Fig. 1 (see the inset to evaluate the hard X-rays results).

5 Discussion and conclusions

Our results indicate that LS 5039 is a weak hard X-ray emitter, detected at \( \approx 1 \) mCrab in the 20–40 keV energy range and with a flux below 1.5 mCrab in the 40–100 keV interval. These results are in agreement with extrapolation of RXTE/PCA data and with previous upper limits from the ISGRI source catalog. However, they are \( \approx 3 \) times lower than previously reported BATSE values. The INTEGRAL measurements can be considered as an average along an orbital cycle. Therefore, the mentioned discrepancy cannot be due to orbital variability. Alternatively, it could be due to long-term variations in the hard X-ray flux of LS 5039, as observed in soft X-rays and in the equivalent width of the H\( \alpha \) line and thought to be caused by long-term variations of the wind of the primary [19].

On the other hand, the radio flux density measurements indicate that the source was not experiencing a particular low level of activity. Nevertheless, we recall that radio emission variations are small and that no long-term variability has yet been detected at radio wavelengths, suggesting that the radio and X-ray emission are not correlated.

Although these results may allow to refine the jet models proposed by [12], see Fig. 1, the modeling of the radiation in the whole spectral range is not straightforward. Actually, the relatively hard observed TeV spectrum [6] and the X-ray fluxes slightly higher than those observed at TeV energies do not fit in the one-zone leptonic scenario (the particle spectrum at the energies of interest would be dominated by synchrotron losses instead of by IC Klein Nishina ones, rendering the TeV spectrum much softer than observed). Therefore, the soft X-rays and the TeV photons are probably coming from different regions. In fact, the detection between 20–40 keV and the upper limit in the range 40–100 keV presented here hint to a change in the spectral behavior of the source. This suggests that hard X-rays could be due to synchrotron emission that is produced by the same relativistic electrons that produce TeV radiation through IC.

A longer pointed INTEGRAL or Suzaku observation is needed to detect any eventual orbital hard X-ray variability, and to detect the source in the 40–100 keV energy range. Only simultaneous soft/hard X-ray and TeV observations would permit to obtain enough spectral and temporal information to fully characterize the relativistic electron spectrum, the seed photon field and the magnetic field strength, and to establish whether the X-ray and the TeV emission have indeed their origin in the same population of electrons.

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