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New evidence for extreme particle acceleration in microquasars

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Abstract. Microquasars are binary systems consisting of a neutron star or stellar-mass black hole accreting gas from a companion star and producing relativistic jets. Here we report the AGILE detections of γ-ray emission from the microquasars Cyg X-1 and Cyg-3 between 100 MeV and 3 GeV. A significant transient gamma-ray emission was detected on 2009, October 16, during a spectral "hard state" of Cyg X-1. This shows that extreme particle acceleration can occasionally occur in microquasars also in the hard state, for which a spectral cutoff above 1 MeV is predicted by theoretical models. No persistent emission was found for Cyg X-1 integrating all our data accumulated in the period between 2007 July and 2009 October, during which the source was in the hard state, confirming the overall spectral cutoff above 1 MeV. Several flaring episodes were instead detected for Cyg X-3 following a repetitive pattern. The γ-ray emission detected by AGILE always occured while the source was in the "soft state", and always preceding a major radio flare. These γ-ray intense flares thus turn out to occur during the preparation and energy charging before the plasmoid energization and ejection.

Key words. Gamma rays: stars – X-rays: binaries

1. Introduction

Microquasars are X-ray binary systems composed of an accreting compact object (a Black Hole or a Neutron Star) of few solar masses and a donor star. The accretion occurs through a disk above which we find a "hot corona" composed by hybrid thermal/non-thermal plasma; the system exhibits collimated jets of relativistic particles ejected along its polar axes. Microquasars show a typical X-ray spectra with 2 main states: the hard state, caracterized by a strong emission in the hard X-ray band and a cutoff around MeV energies, and a soft state, with strong emission at low energies due to black body emission from the disk and a power law tail extending beyond MeV energies. This peculiar spectrum can be explained in a scenario of a hybrid population of thermal (Maxwellian) and non-thermal electrons in the plasma of the hot corona (Coppi 1999). Following this model, the soft state X-ray spectrum is dominated by thermal Black

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Body emission from disk at low energies (few keV), and by Comptonization processes on soft photons from disk by non-thermal electrons in the corona, producing the power law tail at high energy; the hard X-ray state is totally dominated by Comptonization processes on soft photons by a quasi-thermal population of electrons in the hot corona.

The AGILE mission, operational since April 2007 (Tavani et al. 2009), is characterized by a very compact and innovative instrument consisting of two co-aligned imaging detectors operating in the energy ranges 30 MeV – 30 GeV (GRID, Barbiellini et al. 2002) and 18 – 60 keV (Super-AGILE, Feroci et al. 2007), as well as by an anticoincidence system (Perotti et al. 2006) and a calorimeter (Labanti et al. 2006). AGILE's performance is characterized by very large fields of view (2.5 and 1 sr for the gamma-ray and hard X-ray bands, respectively), optimal angular resolution (PSF=3° at 100 MeV and PSF=1.5° at 400 MeV) and good sensitivity especially in the energy range 100 MeV – 1 GeV.

Extensive monitoring of Galactic microquasars is one of the crucial goal of the AGILE mission. Two of the most important microquasars of our Galaxy are hosted in the Cygnus region: Cyg X-1 and Cyg X-3. From April, 2007 and October, 2009 AGILE operated in a fixed-pointing mode, during which the Cygnus region was repeatedly observed for a total of $\sim$ 315 days. Since November 2009 AGILE is operating in "spinning mode", and the Cygnus region is daily monitored.

2. Cyg X-1

Cyg X-1 is a binary system composed of a compact object, a Black Hole with a mass of $20 \pm 5 M_{\odot}$ (Ziółkowski 2005), and a O9.7 Iab supergiant star, with orbital period of 5.6 days. This system, located at the distance of 2 kpc, is among the brightest X-ray binaries and has been extensively monitored from radio to X-ray energy bands. Cyg X-1 spends most of its time in the hard state, characterized by a relatively low flux of soft X-ray photons (1 – 10 keV), a clear peak of the photon energy spectrum in the hard X-ray band (around 100 keV), and an energy cutoff around 1 MeV (e.g. McConnell et al. 2002; Del Monte et al. 2010). Occasionally the system moves to a soft X-ray state, characterized by a large flux in soft X-ray and a tail extending beyond 1 MeV. Determining the highest photon energies from Cyg X-1 is of crucial theoretical importance: a detection of photon emission well above a few MeV from Cyg X-1 would provide a clear signature of efficient non-thermal acceleration processes occurring in the system, that would need to be accounted for in Cyg X-1 models and Black Holes accretion disk modelling. On 2006, September 24, a very high energy emission (E>300 GeV) from Cyg X-1 was detected by the MAGIC Cherenkov telescope for about 1 hour, while the source was in a hard state. The episode happened $\sim$ 1 day before an hard X-ray maximum detected n the energy band 20-80 keV by INTEGRAL (Türler et al. 2006) and *Swift*/BAT (15-50 keV)

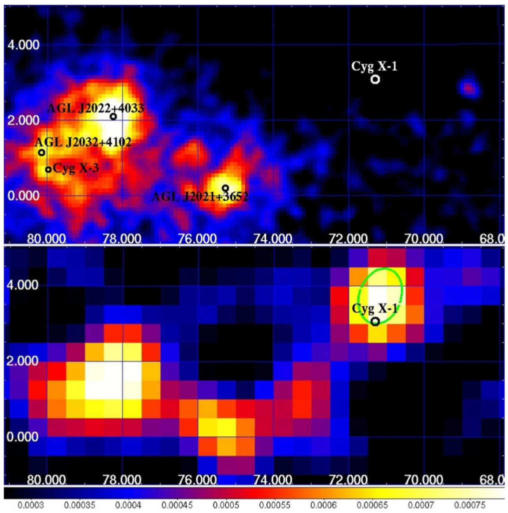

Fig. 1. AGILE-GRID *gamma*-ray intensity maps above 100 MeV of the Cygnus region in Galactic coordinates, with a 3-bin Gaussian smoothing. Upper panel: 2 years integrated map (pixel size: 0.1°); white circle: optical position of Cygnus X-1; black circles: persistent γ-ray sources in the Cygnus region. Lower panel: 1 day map of the γ-ray flaring episode (MJD 55119.97 - 55120.96) (pixel size: 0.5°); black circle: otpical position of Cygnus X-1; green contour: AGILE-GRID 2σ Confidence Level. Plot from Sabatini et al. (2010).

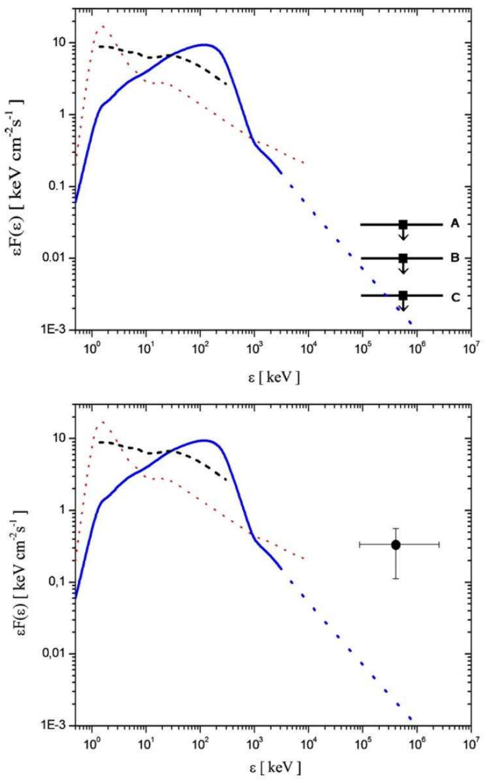

Fig. 2. Cygnus X-1 spectral energy distribution in typical states (Zdziarski et al. 2002): hard in blue solid line, soft in red dotted line, intermediate in black dashed line. The blue dashed line extrapolated from the hard X-ray state is a purely graphical extension of the trend suggested by the historical data. Upper panel: AGILE 2σ upper limits above 100 MeV for integration times of: 2 weeks (A), 4 weeks (B) and $\simeq$ 315 days (C). Bottom panel: the AGILE-GRID broadband spectrum (100 MeV – 3 GeV) for the flaring episode is reported. Plot from Sabatini et al. (2010).

We searched for a persitent emission from Cyg X-1 integrating all the AGILE data (E>100 MeV) between 2007 July and 2009 October. The AGILE-GRID dataset extends for $\sim$ 300 days, during which the system was in its typical hard X-ray state (Del Monte et al. 2010). No statistically significant gamma ray source is detected at a position consistent with that of Cyg X-1 (Fig. 1, upper panel). The 2-sigma upper limit for the gamma-ray flux in the energy range 100 MeV – 3 GeV is equal to 3×10^{-8} ph cm^{-2} s^{-1}. The lack of long-term γ-ray emission from the source confirms the spectral cut-off at MeV energies, in overall agreements with Comptonization models on Cygnus X-1 emission (Fig. 2, upper panel). We also searched for a transient gamma-ray emission from Cyg X-1 on a timescale of 1 day in all the available AGILE data from 2007 June to 2009 July. Only one gamma-ray flaring episode was definitely detected from a position consistent with Cyg X-1. Integrating the AGILE data (E>100 MeV) between 2009 October, 15 (UTC 23:13:36) and 2009 October, 16 (UTC 23:02:24) we found a detection at galactic coordinates (l, b) = (71.2, 3.8) ± 0.7 (stat) ± 0.1 (syst) with a significance of 5.3 σ and a flux F= (232 ± 66) × 10^{-8} ph cm^{-2} s^{-1} (Fig. 1, bottom panel). The γ-ray episode happened during a hard state just before the system was detected to subsequently evolve into one of the relatively rare dips in the Swift/BAT hard X-ray light curve. Our detection of October 16, 2009 is the first reported 1-day gamma-ray flare in the energy range 100 MeV – 3 GeV from the system during a hard state. This rapid transient episode shows that extreme particle acceleration processes - responsible for γ-ray emission - may occur also during a hard state, characterized by a strong hard X-ray emission from a hot quasi-thermalized corona, for which a cut-off at MeV energies was predicted. The γ-ray flux detected during the flaring episode is well above the prediction of the standard Comptonization models (Fig. 2, bottom panel).

3. Cyg X-3

Cyg X-3 is microquasar composed by a Wolf-Rayet star orbiting around a compact object of still unknown nature with an orbital period of 4.8 hours. Cyg X-3 is a very variable system, and it shows very strong radio flares reaching up to 10-20 Jy. Radio observations at milliarcsec scales shows emission from relativistic jets with an inclination to the line-of-sight of $\leq$ 14°. Cyg X-3 shows a peculiar X-ray spectra, with 5 main X-ray spectral states (Hjalmarsdotter et al. 2009) and exhibits a strong correlation between radio and soft X-

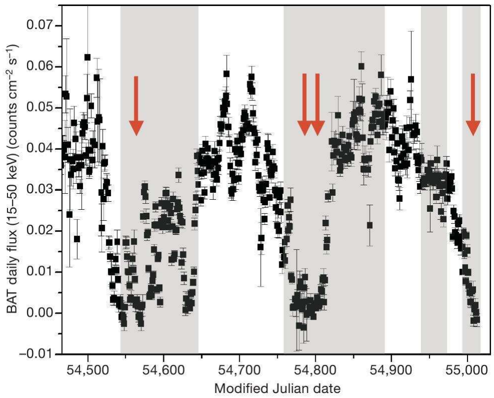

Fig. 3. Hard X-ray (15-50 keV) daily light curve of Cygnus X-3 as monitored by Swift/BAT between January 1, 2008 and June 25, 2009. Gray regions represent AGILE pointing at the Cygnus region. The red arrows mark the dates of major γ-ray flares of Cyg X-3 as detected by the AGILE instrument above 100MeV. Plot from Tavani et al. (2009).

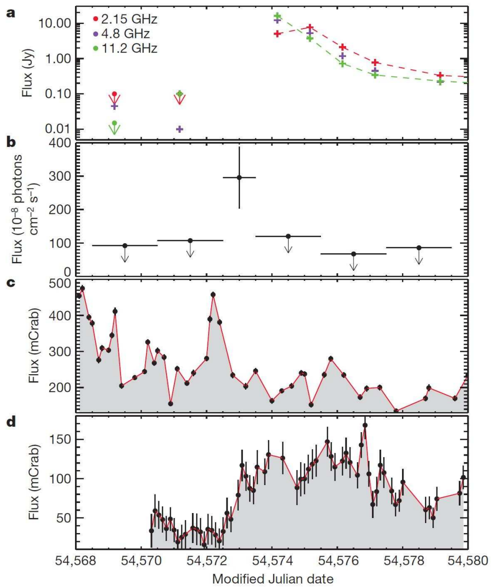

Fig. 4. Multi-frequency light curve of Cygnus X-3 during the period 13-27 April 2008. a: the major radio flare detected by the RATAN-600 radio observatory; on April 18, 2008 a $\sim$ 16 Jy major are was detected at 11 GHz. b: AGILE-GRID γ-ray light curve: a major γ-ray flare (photon flux of $(260 \pm 80) \times 10^{-8}$ photons cm^{-2} s^{-1}) was detected 1 day before the radio flare. c: soft X-ray (1.3-12.1 keV) light curve (6h averaged values) from RXTE/ASM. d: hard X-ray (20-60 keV) light curve from Super-AGILE (average from 14 observations per day). Plot from Tavani et al. (2009).

ray emission (Szostek et al. 2008). Agile detected, for the first time at energy above 100 MeV, several γ-ray flares from a source positionally consistent with Cyg X-3. Remarkably, all the γ-ray flaring episodes are associated with special radio and X-ray/hard X-ray spectral states. Indeed, the γ-ray flares occur in coincidence with low hard X-ray fluxes or during transitions from low hard X-ray fluxes to high (Fig. 3) and are followed by a major radio flare. This repetitive pattern is shown in Fig. 4 where the AGILE γ-ray data (E>100 MeV) for the period 13-27 April 2008 are showed together with the radio (RATAN-600), soft X-ray (ASM) and hard X-ray (Super-AGILE) data. The γ-ray flares tend to occur in the "gully" of the hysteresis curve (Fig. 5) which corresponds to states of very low radio flux density and strong soft X-ray flux that are preludes to major radio flares. Cygnus X-3 spends only a few percent of its time in this rare states.

Extensive analysis of Cyg X-3 data show that every local minimum of the hard X-ray light curve is associated with γ-ray emission, and that all the γ-ray flaring detections happened while the source was entering in the quenched state, or moving towards a major radio flare (see G.Piano PhD Thesis, in preparation). Our detection of Cyg X-3 above 100 MeV is a direct evidence that extreme particle acceleration and non-thermalized emission can occur in microquasars with a repetitive pattern. These accelerated particles can produce photon emission at energies thousands of times larger than the maximum energy so far detected ($E \sim 300$ keV). Comptonization models (thermal and non-thermal) that reproduce the spectral states up to 300 keV must take into account the new data above 100 MeV.

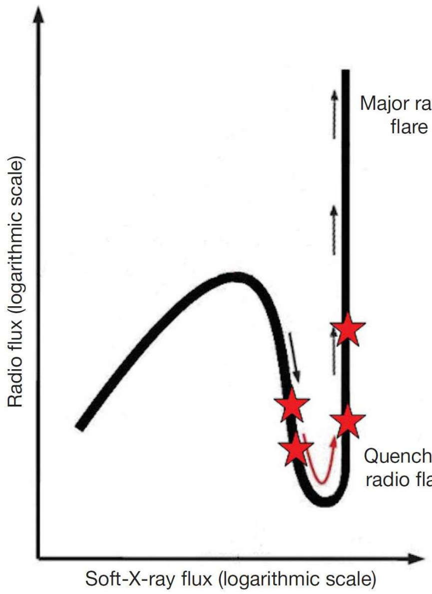

Fig. 5. Schematic representation of the radio and X-ray spectral states of Cyg X-3, (adapted from Szostek et al. 2008). The red stars mark the approximate positions of the major γ-ray flares detected by AGILE. Plot from Tavani et al. (2009).

4. Conclusions

The AGILE-GRID γ-ray detections of Cygnus X-1 and Cygnus X-3 represent the first solid identifications of microquasars above 100 MeV.

The γ-ray emission from the jet of Cyg X-1 during a simultaneous strong hard X-ray emission from the corona suggests a link between the two emitting regions. For Cyg X-3, the simultaneous strong soft X-ray emission from the disk and γ-ray emission from the jet suggests a scenario in which the corona dissolves and the accretion power from the disk charges directly the jet, that emits in γ-rays via Inverse Compton interaction with the soft photons from the disk.

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