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Gamma-ray monitoring of Cygnus X-1 with the AGILE satellite

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Abstract. AGILE carried out extensive observations of the Cygnus region in the period 2007 July - 2011 May, providing detailed gamma-ray monitoring of Cygnus X-1 in both its typical spectral states (hard and soft). A flux upper limit of 3×10^{-8} ph cm^{-2} s^{-1} for the gamma-ray emission in the 0.1-3 GeV energy range during the hard state was established; however a 1-day or shorter time variable gamma-ray emission can be produced during this spectral state, having important theoretical implications for the current Comptonization models for Cyg X-1 or other microquasars. During the period 2010 June - 2011 May the source was in the soft spectral state and AGILE monitoring provides the first gamma-ray upper limit for this state. A possible other gamma-ray flaring event was also detected during the hard-to-soft transistion.

1. Introduction

Cyg X-1 is a binary system discovered by Bowyer et al. (1965) containing a O9.7 Iab supergiant star orbiting (5.6 days of period) around a compact star with a mass function of $f = 0.24 \pm 0.01\,M_{\odot}$ and a mass upper limit of $M_X > 7\,M_{\odot}$. Cyg X-1 is then considered to be the prototypical black hole (BH) binary system in our Galaxy (e.g., Tanaka & Lewin 1995), and attracted considerable attention since its initial mass range determinations. Theoretically, accretion processes onto a BH system are extensively studied using Cyg X-1 as a typical example. In particular, disk hydrodynamics and radiative and pair-creation properties of Cyg X-1 have been modeled with particular emphasis on the X-ray range and the highest detectable energies (e.g., Zdziarski 1988; Gierlinski et al. 1999; Bednarek & Giovannelli 2007; Zdziarski, Malzac & Bednarek 2009).

The system spends most of its time in the so called ”hard state” characterized by a relatively low flux of soft X-ray photons (1-10 keV), a clear peak of the power spectrum in the hard X-ray band (around 100 keV), and an energy cutoff around 1 MeV (e.g., McConnell et al. 2000, Del Monte et al., 2009). Occasionally, Cyg X-1 changes state shifting its energy power spectrum to a ”soft state” characterized by a large flux in soft X-rays, a lower hard X-ray flux, and a tail extending to energies up to 1 MeV and beyond (McConnel et al, 2002).
Cyg X-1 is also detected in ”intermediate hard states”, which usually show a less intense hard X-ray emission and a shift of the spectral hump towards energies less than 100 keV (Malzac et al., 2006).
Extensive theoretical modelling of Cyg X-1 high-energy spectral states have been car-

Send offprint requests to: S. Sabatini ried out using Comptonization models (e.g., Titarchuk 1994; Poutanen & Svensson 1996; Coppi 1999). These models (based on synchrotron and inverse Compton emission by electrons (and pairs) energized in a hot corona with large Thomson depth surrounding the inner part of the accretion disk) usually predict a spectral cutoff near 1 MeV. Since the detection of a non-thermal power law spectral component extending up to ~ 1MeV energies during the "soft" and "intermediate" states, the issue of determining the variability and highest photon energies from Cyg X-1 has been of crucial theoretical importance.

Before the AGILE extensive monitoring of Cyg X-1 , only temporally sparse information has been available in the energy range above a few MeV. The gamma-ray instruments on board of CGRO observed the Cygnus region several times (typically with 2÷4 weeks long integrations) during the period 1991-1997. In particular, the EGRET instrument provided an overall upper limit to the flux of $10 \times 10^{-8}\,\mathrm{ph\,cm^{-2}\,s^{-1}}$ above 100 MeV for the "hard" spectral state only. EGRET observations did not cover at all the "soft" state.
The only observation of CGRO during a soft state of Cyg X-1 was carried out in May, 1997, following an X-ray alert provided by RXTE (Cui et al., 1997). OSSE and COMPTEL observed Cyg X-1 from June 14 to June 25, 1997 and this led for the first time to the detection of a high energy power-law up to about 7 MeV (McConnell et al., 2002). This indication of a power-law component extending to MeV and beyond was also supported in recent years by several INTEGRAL observations of Cyg X-1 (Cadolle Bel et al., 2006).

Variability in Cyg X-1 above 100 keV was observed on several different time scales, from months to seconds (e.g. Brocksopp et al.1999, Pottschmidt et al.2003, Ling et al.1997) and giant outburst episodes have been detected in the 15-300 keV by the Interplanetary Network (Golenetskii et al., 2003) during both spectral states. A remarkable, although isolated, TeV flaring event of very high-energy emission above ~300 GeV from Cyg X-1 was reported by the MAGIC Cherenkov telescope during a set of observations in 2006 (Albert et al., 2007). The reported VHE emission (for a pre-trial significance above 4σ) was detected on September 24, 2006 for about 2 hours (corresponding to an orbital phase of 0.9) during a relatively bright hard X-ray emission phase. This detection of transient and very rapid TeV emission from Cyg X-1 indicates that extreme particle acceleration processes may occur also during a hard spectral state, paving the way to detect non-Comptonized components also in states previously believed to be characterized by a cutoff above a few MeV.

In this proceeding we report the results of the AGILE search for short timescale gamma-ray emission from Cyg X-1 in the energy range 100 MeV - 3 GeV during the period 2007 July - 2011 May. Our data provide the first long timescale monitoring for this important BH system at the gamma-ray energies.
The AGILE mission has been operating since 2007 April and equipped with two co-aligned imaging detectors operating in the energy ranges 30 MeV - 30 GeV (GRID) and 18-60 keV (SAGILE) respectively (Tavani et al., 2009). The GRID performance is characterized by large fields of view (2.5 and 1 sr for the gamma-ray and hard X-ray bands, respectively) and optimal angular resolution (PSF=3 deg at 100 MeV and PSF=1.5 deg at 400 MeV). See Pittori et al (these proceedings) for updates about the main results of the mission.

2. Gamma-ray monitoring during the hard spectral state

Cyg X- spends 90% of its time in the hard spectral state. AGILE collected extensive observations in the period July 2007 to June 2010 during which the system was in the hard state.

2.1. *Search for persistent gamma-ray emission*

Multi-source likelihood analysis was used to search for persistent emission from Cyg X-1 position in the integrated sky map of the Cygnus region above 100 MeV for the period 2007 July - 2009 October (Fig 1, upper panel). No statistically significant gamma ray source is detected at a position consistent with that of Cygnus X-1. The 2-σ upper limit for the gamma-ray flux in the energy range 100 MeV - 3 GeV is equal to $3 \times 10^{-8}\,\mathrm{ph\,cm^{-2}\,s^{-1}}$. Data integrations of 2÷4 weeks exposure from single observation blocks give typical 2-σ upper limits in the range $(10-30)\times 10^{-8}\,\mathrm{ph\,cm^{-2}\,s^{-1}}$.

2.2. Search for transient gamma-ray emission

Motivated by the X-ray variability of Cyg X-1 and by the particular sequence of flaring gamma-ray emission from Cygnus X-3 (Tavani et al., 2009), we carried out a systematic search for short (day-) timescale variability of the Cyg X-1 gamma-ray emission. We used two independent and automatic statistical methods for a blind search of candidate gamma-ray transients in the region surrounding Cyg X-1 : a multi-source likelihood analysis and a method based on the false discovery rate (for more details see Sabatini et al., 2010).

All of the available AGILE data in the archive from 2007 June to 2009 mid-October were searched for variability on timescales of 1-day with both the Likelihood and FDR methods. Here we consider only candidates with at least 5σ pre-trial significance. Only one gamma-ray flaring episode was definitely detected in our thorough search by both independent methods. The bottom panel of Fig 1 shows the AGILE gamma-ray intensity map above 100 MeV for this episode. The emission peaked during the time interval 2009-10-15 (UTC 23:13:36) to 2009-10-16 (UTC 23:02:24). The AGILE-GRID multi-source likelihood analysis finds a 5.3σ (pre-trial) detection at the position (l,b)=71.2, 3.8 ± 0.7 (stat) ± 0.1 (syst) consistent with the position of Cyg X-1, for a gamma-ray flux of $F_\gamma = (232 \pm 66) \times 10^{-8}\,\mathrm{ph\,cm^{-2}\,s^{-1}}$ in the energy range 100 MeV - 3 GeV.

The flaring episode occurred during a hard spectral state (MJD= 55120) . The orbital phase of Cyg X-1 was in the range 0.38-0.56. The system was detected to subsequently evolve into one of the relatively rare dips of the hard X-ray light curve.

The AGILE dataset extends for ~300 days, during which the system was in its typical

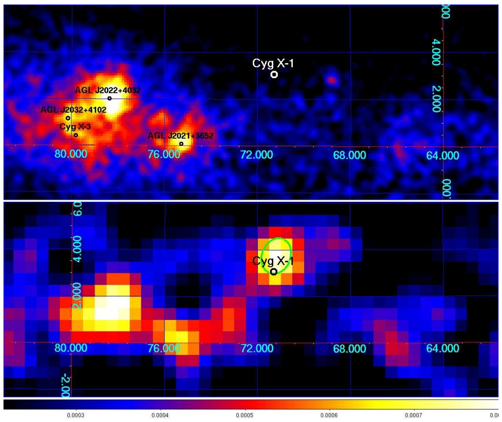

Fig. 1. AGILE gamma-ray intensity maps above 100 MeV of the Cygnus Region in Galactic coordinates displayed with a 3-bin Gaussian smoothing . *Upper panel:* AGILE 2-years integrated map. Pixel size is 0.1°. We overlayed the nominal position of Cyg X-1 with a white circle and show the other sources from AGILE catalogue. The color bar scale is in units of photons $\mathrm{cm^{-2}\,s^{-1}\,pixel^{-1}}$. *Lower panel:* AGILE 1-day map of the flaring episode of Cyg X-1 (2009-10-15 UTC 23:13:36 to 2009-10-16 UTC 23:02:24). Pixel size is 0.5°. The black circle is the optical position of Cyg X-1 and the green contour is the AGILE 2σ confidence level.

hard X-ray state (Del Monte et al., 2009). The lack of relatively strong gamma-ray emission on a timescale of weeks together with the deep upper limit obtained by integrating all AGILE-GRID data clearly confirms the existence of a spectral cutoff between 1 and 100 MeV in the typical hard state (Fig 2, upper panel). This gamma-ray average spectral behaviour of Cyg X-1 in the hard state during week-month timescales is in overall agreement with Comptonization models (e.g., Titarchuk 1994; Poutanen & Svensson 1996; Coppi 1999). However, our detection of of October 16, 2009 is the first detection of a relatively intense 1-day gamma-ray flare in the energy range 100 MeV -3 GeV from the system during a hard state. This shows that physical processes can occasionally be more complex than predicted by current models (see Fig 2, lower panel). Efficient particle acceleration occurs also in states characterized by the presence of a hot corona that should be in

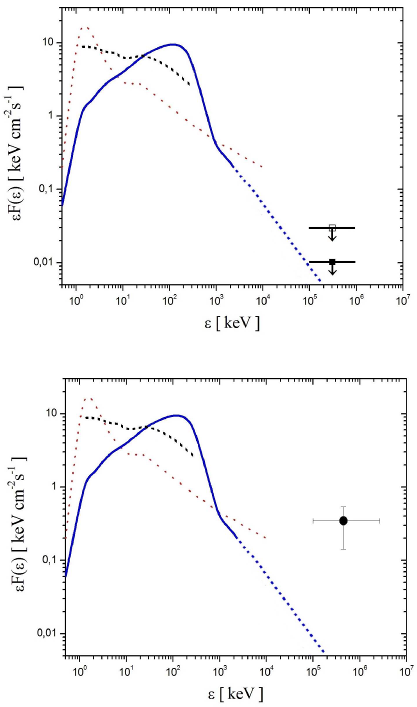

Fig. 2. Cyg X-1 spectral energy distribution in typical states (“hard” in solid line, “soft” in dotted line, “intermediate” in dased line; Gierlinski et al. 1999, Zdziarski et al. 2002). *Upper panel*: AGILE 2σ upper limits above 100 MeV for a typical integration time of 2 and 4 weeks. *Lower panel*: AGILE data above 100 MeV for the flaring episode. The dashed line extrapolated from the hard X-ray state is a purely graphical extension of the trend suggested by the historical data.

pair-Comptonized equilibrium (e.g., Zdziarski 1988; Zdziarski et al. 2009). The gamma-ray emission can have leptonic or hadronic origin (e.g., Perucho & Bosch-Ramon 2008), depending on the model as well as on the assumptions on the acceleration site (close or far from the inner disk and/or jet). Lack of simultaneous TeV data prevents a more complete spectral analysis of the gamma-ray flaring event.

3. Gamma-ray monitoring during the soft spectral state

On the 28th of June 2010 Cygnus X-1 entered in a transitional state, passing from the hard to the soft state. The soft X-ray brightnening of the source starting around 10th of June 2010 was announced by the MAXIGSC ATel 2711 and the subsequent X-ray increased emission was reported by RXTE/ASM (ATel 2714), confirming the transition of the source to the soft spectral state. The rapid fall in hard X-rays around June 29 - July 01 2010 was also reported by Fermi GBM (ATel 2734). A multi-wavelength campaign followed the transition episode, providing a welth of data from the gamma-rays to the radio (AGILE, FERMI-GBM, MAXI-GCS, RXTE AMS, SWIFT, AMI, MERLIN, e-VLBI WSRT). All observations showed the source to be in a intermediate-soft state (Belloni et al,1996). The source finally reached the soft state in the 11th of July 2010 (ATel 2734) and remained in this state for about 11 months.

3.1. Search for persistent gamma-ray emission

Fig 3 shows a deep AGILE gamma-ray integration of the Cygnus region above 100 MeV during the whole 'soft state' period, i.e. 2010 June - 2011 May (MJD: 55378-55647). No gamma-ray persistent emission from Cygnus X-1 was detected during the soft state of the source: a multisource likelihood analysis of the region provides a 2σ upper limit for the energy range 100 MeV - 5 GeV of 20×10^{-8} ph cm^{-2} s^{-1}.

Fig 4 shows the typical soft spectral state (dashed line) and AGILE upper limit above 100 MeV: this is the first long-term observation at the gamma-ray energies for the system and shows that a sharp cut-off is needed at energies above about 100 MeV to match the data.

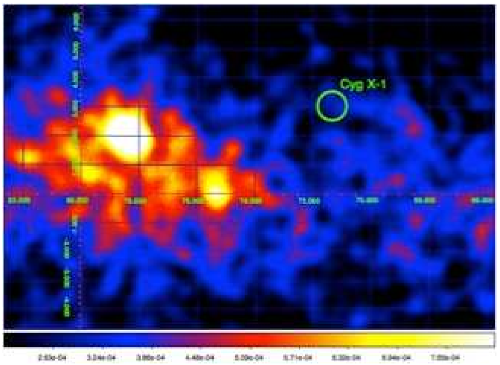

Fig. 3. AGILE gamma-ray intensity map above 100 MeV of the Cygnus Region in Galactic coordinates displayed with a three-bin Gaussian smoothing. Pixel size is 0.1° and the nominal position of Cygnus x-1 is overlayed in green. The color bar scale is in units of photons $cm^{-2}s^{-1}$

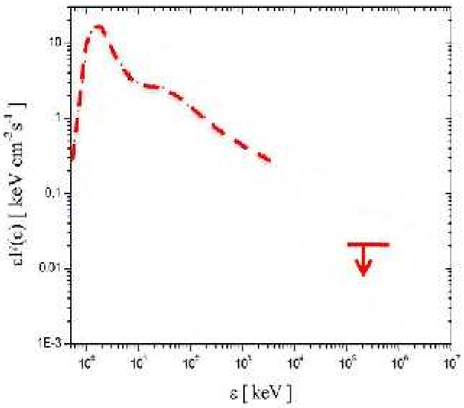

Fig. 4. Cyg X-1 spectral energy distribution in the typical soft state (Gierlinski et al. 1999, Zdziarski et al. 2002). AGILE 2-σ upper limit above 100 MeV for a deep integration during the soft spectral state (MJD 55378-55647) is shown. is shown.

3.2. Search for transient gamma-ray emission

As reported in previous section, episodic gamma-ray transient events can occur in this system on the day (or shorter) time scale. Here we show possible evidence for transient emission during the 2010 hard-to-soft transition of the source: a maximum likelihood analysis of the AGILE data yelds a flux excess above 100 MeV of 145±78 $\times 10^{-8}$ ph cm^{-2} $s^{-1}$with a 3σ pre-trial statistical significance integrating from 2010-06-30 10:00 UT to 2010-07-02 10:00 UT. As the statistics of the candidate detection is low we will not further discuss this event, although simultaneous multi-wavelength data could strengthen the result.

4. Conclusion

We have showed a long-term monitoring of Cyg X-1 at the gamma-ray energies above 100 MeV by the AGILE mission. Deep upper limits for both the hard and the soft spectral states are shown, giving important constraints to the predictions of current models. A 1-day gamma-ray transient episode during the hard state is reported, showing that efficient particle acceleration can occur also in states characterized by the presence of a hot corona.

5. Discussion

VALENTI BOSCH-RAMON: What is the post-trial significance of the flaring event in the hard state?

SABINA SABATINI: The post-trial significance is 4σ, according to $\chi^2_3/2$ distribution and multiple testing correction.

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