Spectral States of Cygnus X-3

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Abstract

Cygnus X-3 is a unique microquasar know to produce relativistic jets and powerful radio flares. A discussion of Cygnus X-3's X-ray/Radio states and their linkage to AGILE gamma-ray detections is given.

Introduction

Cygnus X-3 is an unique X-ray binary (XRB). Its X-ray emission shows a strong 4.8 hour orbital modulation which is typical for a low-mass XRB. But its mass-donating companion is a Wolf-Rayet star (van Kerkwijk et al. 1992) which makes it a high-mass X-ray binary. Also unlike most other XRBs Cygnus X-3 is relatively bright in the radio virtually all of the time (the exceptions being the quenched states). In addition, Cygnus X-3 undergoes giant radio outbursts and there is strong evidence of jet-like structures moving away from Cygnus X-3 at 0.3-0.9c (Mioduszewski et al. 2001). This last characteristic makes Cygnus X-3 a member of a subclass of XRBs called "microquasars" (Mirabel & Rodriguez 1994) which are similar to quasars/AGNs in that they exhibit highly collimated relativistic jets.

Cygnus X-3's X-Ray/Radio States

Cygnus X-3 has been noted to experience low/hard and high/soft states in the soft X-ray (SXR). Hard X-ray (HXR) and radio studies (McCollough et al. 1999, Waltman et al. 1994) have shown there to be at least four X-ray/radio states (quiescence, minor flaring, quenched, and major flares). A more recent study (Szostek, Zdziarski, & McCollough 2008) of the X-ray and radio behavior have shown evidence for six states (quiescent, minor flaring, suppressed, quenched, major flaring, and post-flare). These states appear as a progression of increased activity in the X-ray and radio (see Fig. 1). In all of these states the X-ray spectrum is best represented by a dominant hybrid plasma Comptonization component, a thermal disk component, and several strong emission lines. Also various absorption and reflection components are necessary to understand the system.

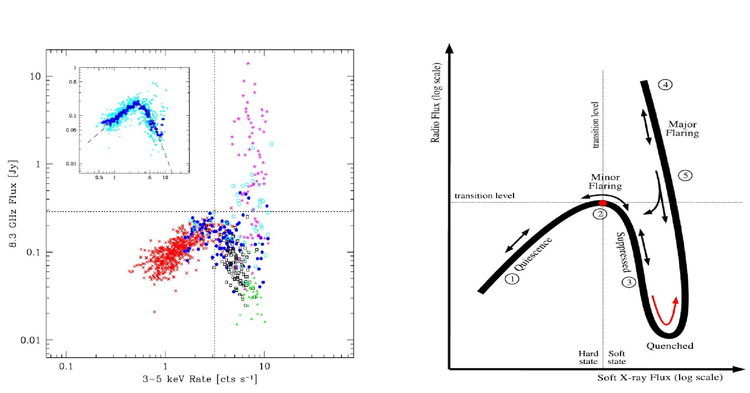

Fig. 1: *left:* The X-ray - radio plot from Szostek, Zdziarski, & McCollough 2008). The transition point is at 3 cts/s (3-5 keV) RXTE/ASM and 0.3 Jy (8.3GHz) GBI. *right:* Diagram of Cygnus X-3's path through the X-ray - radio plot. The post flare state is between the quenched and major flaring regions.

Quiescent State

It is a time of moderate radio brightness (~ 100 mJy), low variability and the HXR flux anti-correlates with the radio (see Fig. 2). Both the radio and X-ray fluxes vary in a correlated manner below the transition level (see Fig. 1).

A recent study (Hjalmarsdotter, et al. 2009) of the low/hard state (quiescent state) of Cygnus X-3 using INTEGRAL found: **(1)** the HXR spectrum has a cutoff at ~ 20 keV (for most black hole XRBs in a state similar to this one the cutoff occurs at ~ 100 keV); **(2)** there is a significant contribution from non-thermal Comptonization, usually this is observed only in soft states; and **(3)** the luminosity of the hard state is significantly higher than other XRBs in this state, implying a model much more radiatively efficient Than the standard ADAF models or a mass of the compact object of greater than 20 solar masses.

Minor Flaring State

The X-ray flux oscillates around its transition value while the radio flux varies up to its transition value (see Fig. 1). Overall variability in both the X-ray and radio increases. While the flux above 10 keV starts to drop the spectrum above 10 keV get progressively harder.

Suppressed State

The radio flux is below its transition value and the X-ray flux is above its transition value. This state will not result in a radio flare unless the radio flux declines to the quenched state.

Quenched State

It is during this state that radio emission goes very low (10-20 mJy) and the HXR vanishes. This also when the HXR flux switches from an anti-correlation to a correlation with the radio (see Fig. 2). The radio flux is well below the transition level and the X-ray flux is above it. This state is followed by a major radio flare. It is during this state that the highest SXR fluxes are seen.

In Fig. 3 we can see the two types of X-ray spectra that our observed During the quenched state. *Ultra-soft*: This spectrum is a strong thermally dominated with a very weak and hard ($\Gamma \sim 1.7$) power law tail. *Hyper-soft*: A second state recently discovered (Koljonen et al. in prep). This is strong thermally dominated state without the weak Hard power law tail.

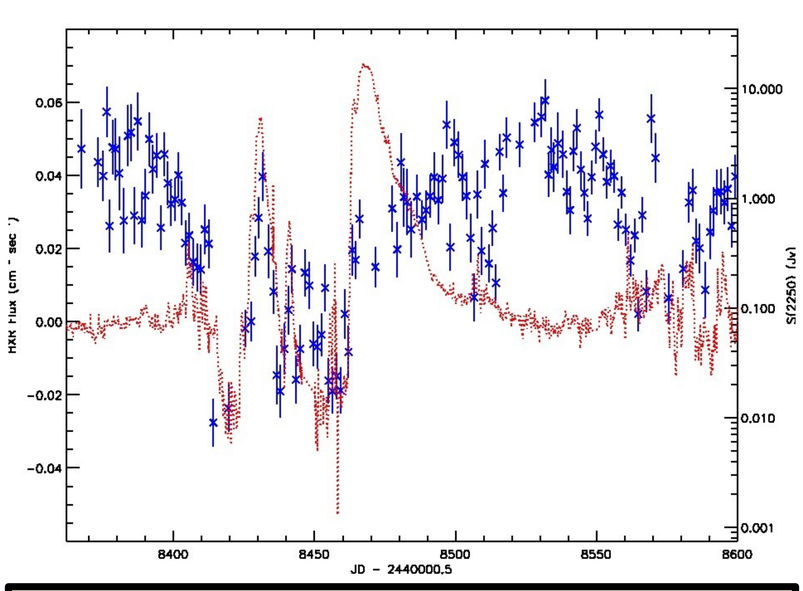

Fig. 2: GBI 2.25 GHz radio data (red) and 20-100 keV CGRO/BATSE data (blue)for Cygnus X-3 in 1991 (McCollough et al. 1999). Note the anti-correlation during the quiescent state and the correlation during the quenched and associated major flare states.

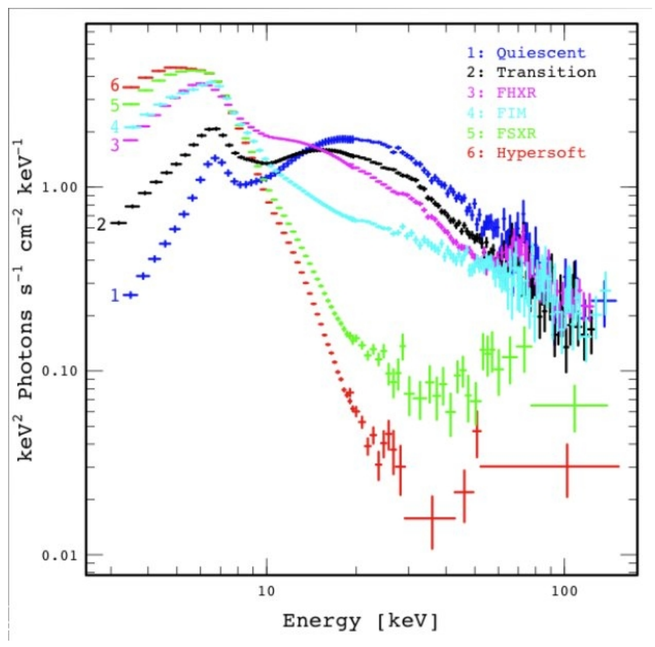

Fig. 3: Various RXTE/PCA/HEXTE spectra for different states. Minor flaring corresponds to state 2. The major flares corresponds to 3-4. States 5-6 corresponds to the quenched state.

Major Flaring

It is during this state that the radio emission goes very high (1-20 Jy). The HXR correlates with the radio and rises (see Fig. 2). The SXR is above the transition level, and the radio flux moves up and down by a large factor in a flare. VLBI observations show jets-like features during these flares (Mioduszewski et al 2001). The spectrum shows a thermal spectrum with a pronounced power law tail (see Fig. 3).

Post-Flare

This state represents the return after a major flare to either the minor flaring state or the suppressed one. This state is not strictly a new state since it is dominated (in the radio) by the decaying major radio flare. This state can hide activity occurring in the core of the system.

AGILE Detections

Tavani et al. (accepted by Nature: arXiv:0910.5344) report that during the period mid-2007/mid-2009, the AGILE satellite detected four gamma-ray flares (each lasting 1-2 days). In Table 1 are information about each of these events and their relation ship with the SXR and radio. Fig. 4 shows Cygnus X-3 during the time of the detection of gamma-ray emission.

Table 1 – Major gamma-ray flares of Cygnus X-3

Gamma-ray flaring date	X-ray state	radio state	δT_1 (days)	following radio flare	δT_2 (days) γ-ray/radio	γ-ray flux 10^{-8} ph. cm^{-2} s^{-1} (E > 100 MeV)
(1)	(2)	(3)	(4)	(5)	(6)	(7)
16-17 Apr. 2008 (MJD = 54572-54573)	soft	pre-flare		~ 16 Jy (11 GHz)	~ 0-1	260 +/- 80
2-3 Nov. 2008 (MJD = 54772-54773)	soft	pre-quenched	3-4	~ 1 Jy (15 GHz)	~ 8-9	258 +/- 83
11-12 Dec. 2008 (MJD = 54811-54812)	soft	opt. thick-thin change		~ 3 Jy (11 GHz)	~ 9-10	210 +/- 73
20-21 Jun. 2009 (MJD = 55002-55003)	soft	pre-quenched	~4-5			212 +/- 75

Table 1: The columns are: (a) date; (b) X-ray state; (c) radio state; (d) time from a quenched radio state; (e) radio flare flux; (f) time between gamma-ray event and flare; and (g) gamma-ray flux.

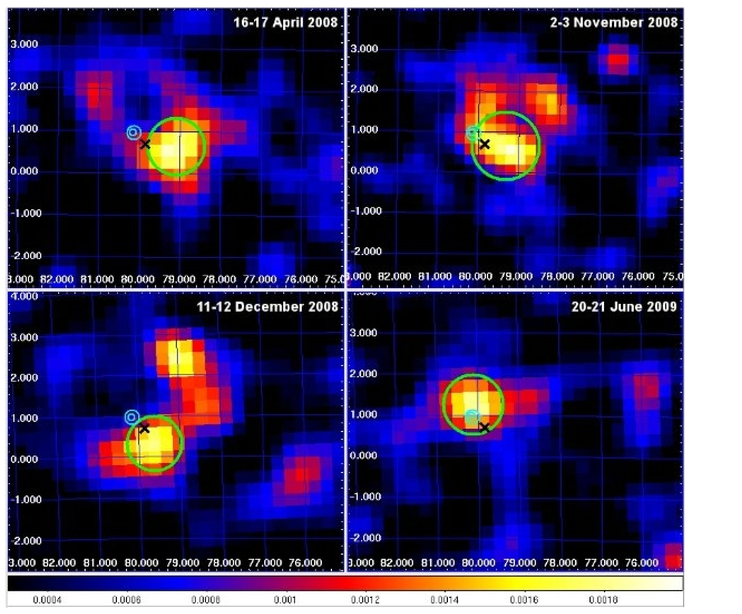

Fig. 4: AGILE detections of Cygnus X-3. The green circle is the AGILE error box. The X is the location of Cygnus X-3. The cyan circles correspond to the location of the nearby source 1AGL J2032+4102.

Cygnus X-3's State During AGILE Detections

Fig. 5 shows the Cygnus X-3 Swift/BAT light curve with the times of the gamma-ray detections. They all occur during times of low HXR flux periods (quenched emission). In Fig. 6 is a plot of where the events fall on a X-ray- radio plot. It is apparent that these events all occur around the quenched region of the diagram. Also for three of the four events there is a major radio flare (1 Jy or larger) within ~1-10 days of the event (see Table 1).

It is important to note that the quenched state is a "rare" state for Cygnus X-3:

(a) *Radio:* GBI radio data (at 2.25 and 8.3 GHz) show that Cygnus X-3 has fluxes below 15 mJy only 1.4% and 1.2% of the time, respectively. Ryle/AMI observations (15 GHz) show that Cygnus X-3 is found below 10 mJy only 2.9% of the time.

(b) *HXR:* The Swift/BAT (15-50 keV) daily averages has a HXR flux of <0.001 cts cm^{-2} s^{-1} or below detection levels only 6.8% and 3.3% percent of the time, respectively.

(c) *SXR:* The RXTE/ASM (2-12 keV) single dwell measurements show that Cygnus X-3 reaches its highest values during the quenched state. Individual measurement of > 35 cts/s (467 mCrab) and > 40 cts/s (533 mCrab) occur 2.7% and 0.9% of the time, respectively.

The combined probabilities of the simultaneous SXR and HXR fluxes for the four gamma-ray events show a range of 0.003 - 0.03 for the days for which gamma-ray emission was detected. This leads to a joint probability of occurrence estimate for all four events to be ~ 2x10^{-5}. A description of these calculations are given in Tavani et al. (see arXiv:0910.5344).

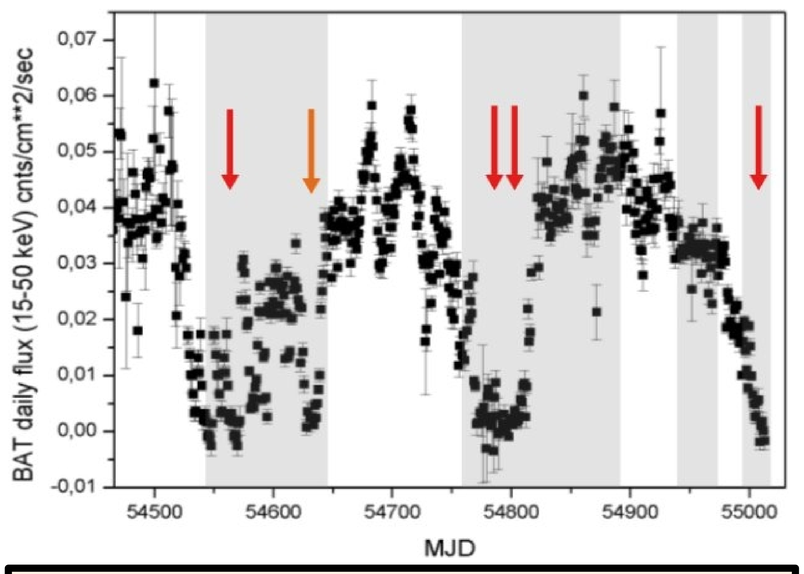

Fig. 5: Swift/BAT light curve during the period mid-2007/mid-2009. The red arrows represents the time of the AGILE detections. The orange arrow is a low-intensity gamma-ray flare also observed.

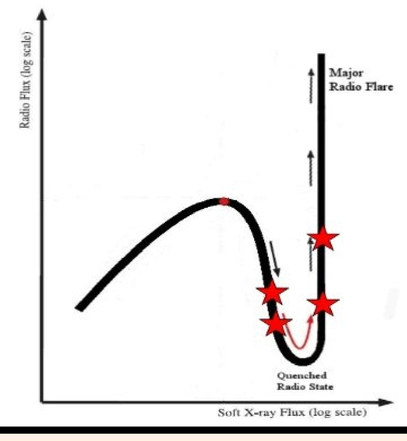

Fig. 6: Location of the AGILE detections in the X-ray - radio plot of Cygnus X-3.

Summary

The detection of transient gamma-ray emission above 100 MeV from Cygnus X-3 provides direct evidence that extreme particle acceleration and non-thermalized emission can occur in microquasars with a repetitive pattern. The observations show a clear correlation between gamma-ray emission and special transitional spectral states of Cygnus X-3.