Galactic black holes in the hard state, a multi-wavelength view of accretion and ejection

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Abstract.
The canonical hard state is associated with emission from all three fundamental accretion components: the accretion disk, the hot accretion disk corona and the jet. On top of these, the hard state also hosts very rich temporal variability properties (low frequency QPOs in the PDS, time lags, long time scale evolution). Our group has been working on the major questions of the hard state both observationally (with multi-wavelength campaigns using RXTE, SWIFT, SUZAKU, SPITZER, VLA, ATCA, SMARTS) and theoretically (through jet models that can fit entire SEDs). Through spectral and temporal analysis we seek to determine the geometry of accretion components, and relate the geometry to the formation and emission from a jet. In this presentation I will review the recent contributions of our group to the field, including the SWIFT results on the disk geometry at low accretion rates, the jet model fits to the hard state SEDs (including SPITZER data) of GRO J 1655-40, and the final results on the evolution of spectral (including X-ray, radio and infrared) and temporal properties of selected black holes in the hard states. I will also talk about impact of ASTROSAT to the science objectives of our group.

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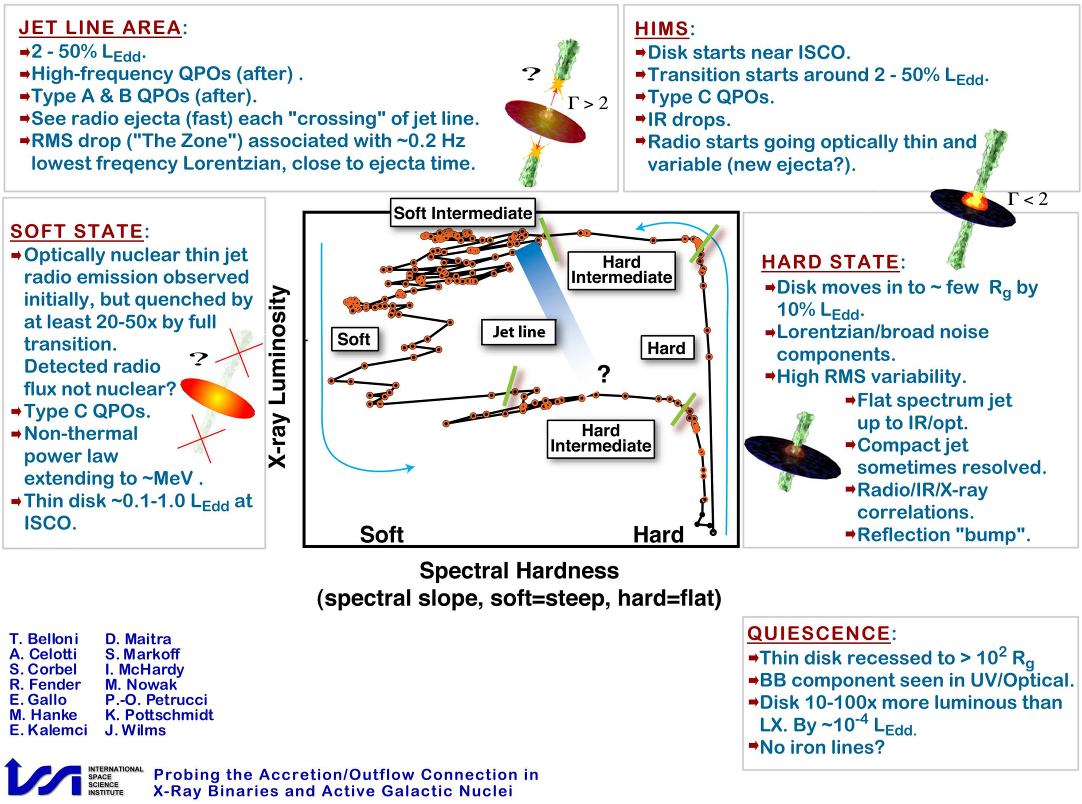
INTRODUCTION

With the launch of RXTE [1], there has been a tremendous increase in our understanding of spectral and temporal properties of Galactic black hole transients (GBHTs). The main reason for this is the quick pointing capability of the satellite making daily monitoring of these sources possible. This, merged with the daily near simultaneous observations in other wavelengths, especially radio and infrared, resulted in a general evolutionary picture of the spectral and temporal properties of these sources based on their fluxes and and hardness properties. This picture is summarized in Fig. 1.

Our group is mainly interested in the hard state which is associated with emission from all three fundamental accretion components: the accretion disk, the hot accretion disk corona and the jet. We work on the characterization of the spectral and temporal parameters of the GBHTs in the hard state to understand state transitions and conditions for jet formation. We investigate whether jets affect X-ray spectral properties through the analysis of the high energy cut-offs with RXTE and INTEGRAL. We also study the



JET LINE AREA:

- 2 - 50% L_{Edd}.
- High-frequency QPOs (after) .
- Type A & B QPOs (after).
- See radio ejecta (fast) each "crossing" of jet line.
- RMS drop ("The Zone") associated with ~0.2 Hz lowest freqency Lorentzian, close to ejecta time.

HIMS:

- Disk starts near ISCO.
- Transition starts around 2 - 50% L_{Edd}.
- Type C QPOs.
- IR drops.
- Radio starts going optically thin and variable (new ejecta?).

SOFT STATE:

- Optically nuclear thin jet radio emission observed initially, but quenched by at least 20-50x by full transition. Detected radio flux not nuclear?
- Type C QPOs.
- Non-thermal power law extending to ~MeV .
- Thin disk ~0.1-1.0 L_{Edd} at ISCO.

HARD STATE:

- Disk moves in to ~ few R_g by 10% L_{Edd}.
- Lorentzian/broad noise components.
- High RMS variability.
  - Flat spectrum jet up to IR/opt.
  - Compact jet sometimes resolved.
  - Radio/IR/X-ray correlations.
  - Reflection "bump".

QUIESCENCE:

- Thin disk recessed to > 10^2 R_g
- BB component seen in UV/Optical.
- Disk 10-100x more luminous than LX. By ~10^{-4} L_{Edd}.
- No iron lines?

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Probing the Accretion/Outflow Connection in X-Ray Binaries and Active Galactic Nuclei

FIGURE 1. General description of spectral states on a hardness - intensity diagram [2]. The figure shown in the hardness-intensity diagram of GX 339-4 in the 2002-2003 outburst. The other sources show a similar behavior. This complete picture has emerged during an International Space Science Institute meeting in Bern. (http://www.issibern.ch/teams/proaccretion/Documents.html)

contribution of jets to the overall multiwavelength spectra (spectral energy distribution, SED). Here, we will summarize our results from each of these subjects outlined above.

CHARACTERIZATION OF GALACTIC BLACK HOLE TRANSIENTS DURING OUTBURST DECAYS

Daily monitoring observations provide us very important opportunities to understand physical processes close to the black hole as the accretion rate changes during an outburst. The outburst decays are especially important, as it is guaranteed that state transitions will be observed. Moreover, jets will re-appear as shown in Fig. 1. If this re-appearing is a "turn-on", the outburst decays are very important in understanding how jets are formed.

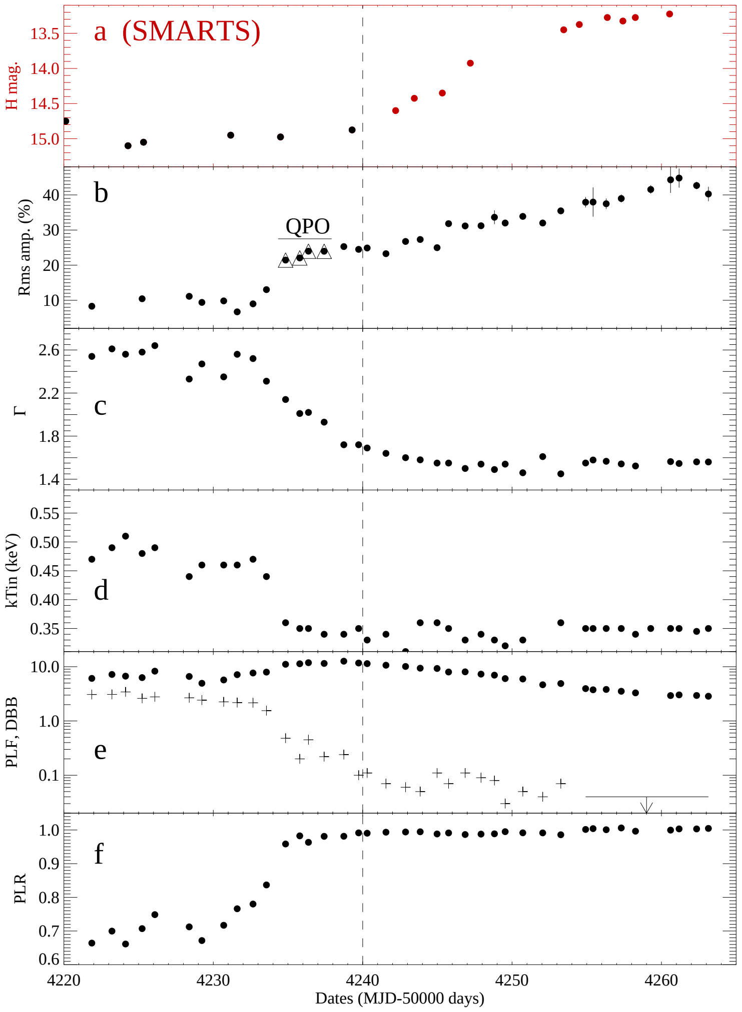

FIGURE 2. Evolution of spectral and temporal parameters of GX 339-4 in the 2007 outburst decay. (a) SMARTS H band magnitude, (b) rms amplitude of variability, the observations in triangles also show QPOs, (c) spectral index, (d) inner disk temperature, (e) circles are power-law flux and crosses are disk blackbody flux in 3-25 keV band in units of 10^{-10} ergs cm^{-2} s^{-1}, (f) the ratio of the power-law flux to the overall flux in 3-25 keV band (PLR).

State transitions during the outburst decay

GBHTs show transitions from softer states to harder states as they decay in an outburst. There are usually two distinct transitions, the first one is from a soft state to an intermediate state. The main characteristics of this transition is a fast rise in the rms amplitude of variability in the Fourier spectrum accompanied by an increase in the power law flux [3, 4]. A second, slower transition usually occur afterwards as the spectral index slowly decreases [5]. An example is shown in Fig. 2.

For this case the first fast transition and the slower transition started around the same time, at MJD 52434. The increase in the rms amplitude is accompanied by a decrease in the power-law index, in the inner disk temperature and flux, an increase in the power-

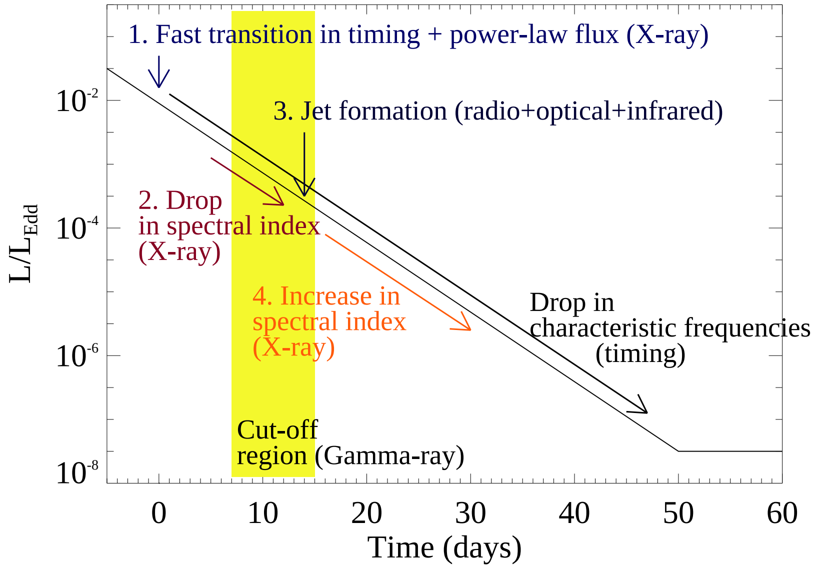

FIGURE 3. The general picture that summarizes the evolution of GBHTs during outburst decay. From [5].

law flux and the power-law ratio (PLR). We note that for many other sources there is a lag between the first fast transition and the slower transition. The slower transition is observed as the hardening of the spectrum from MJD 52434 to MJD 52450. When the spectral index was around 1.7, an increase in the infrared flux is observed. This is associated with the synchrotron emission from the jet [6].

After investigating the behavior for several sources, our group came up with a general picture for the multiwavelength evolution of GBHTs during outburst decays [5]. Fig. 3 summarizes the overall trends. One important outcome of this work is determining the conditions for jet formation in GBHTs. For all the sources we have analyzed, the jets are observed only if the spectral index is less than 1.7, and the disk flux is less than 1% of the overall flux in the 3-25 keV band. We also note the distinction between appearing of the jet, and sustaining the jet. These are the conditions for the jet to appear in the hard state, but during outburst rise, jets have been observed at steeper indices and stronger disk fluxes [4].

Where is the inner edge of the accretion disk?

Many hard state models assume a geometry for which an accretion disk recedes away from the black hole as the spectrum hardens [7, 8]. In fact, there have been circumstantial evidence for the recession, such as decreasing characteristic frequencies, decreasing disk temperature and flux, decreased reflection fraction. Yet some of these observational facts can also be understood without the need of a recessed disk. In fact, there have been

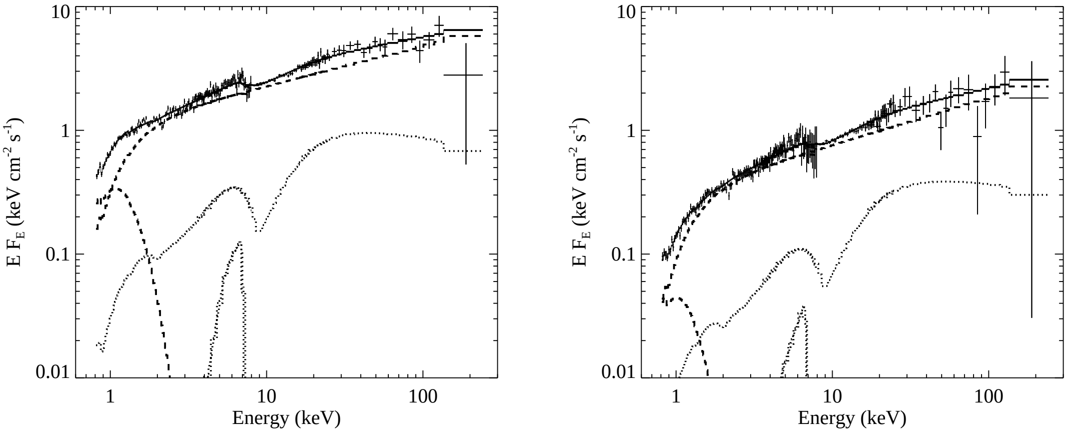

FIGURE 4. RXTE - SWIFT joint fit to GX 339-4 data in the hard state. The left panel and right panel are for 2% and 0.8% L_{edd} respectively. The fit model includes absorption, disk blackbody, reflection and iron line emission modelled by the Laor model.

reports claiming that the inner disk stays at the marginally stable orbit even deep in the hard state [9, 10].

This is an interesting problem also for jet formation. We know that jets exist deep in the hard state, and there are models which require a disk to launch jets [11]. There are also other models that only require a geometrically thick corona [12, 13].

We have analyzed the SWIFT and the RXTE data of GX 339-4 at 2% and 0.8% of the Eddington Luminosity (L_{edd}) to investigate the position of the inner edge of the accretion disk quite deep in the hard state. The details of the analysis have been discussed in detail in [14], here we only summarize the results (see Fig. 4). At 2% L_{edd} the jet has just appeared, and the fit with the relativistically broadened iron line model [15] resulted in a disk inner radius of $3.6 \pm^{1.4}_{1.0}$ R_g where R_g is the gravitational radius. At 0.8% L_{edd}, the addition of the iron line did not improve the fit, however a limit on the inner disk radius of 10 R_g could still be obtained through the reflection component.

These results imply that even in the hard state the inner disk does not recess much. We must note that to obtain the disk inner radius, we assumed that the broadening is due to gravitation of the black hole, but there is also an alternative explanation [16]. Even though this work shows that presence of a disk close to the black hole does not prevent jet from forming, it does not mean that disks are required to form a jet, since jets are observed in quiescence [17] even though the disk at those luminosities are at around 1000 R_g [18].

High energy cutoffs, still an open question

Another interesting result that came out of the evolutionary studies of GBHTs during outburst decay is the disappearance of the high energy cut-off. When we analyze PCA+HEXTE data from RXTE, we add a cut-off to our fit model (absorption + disk

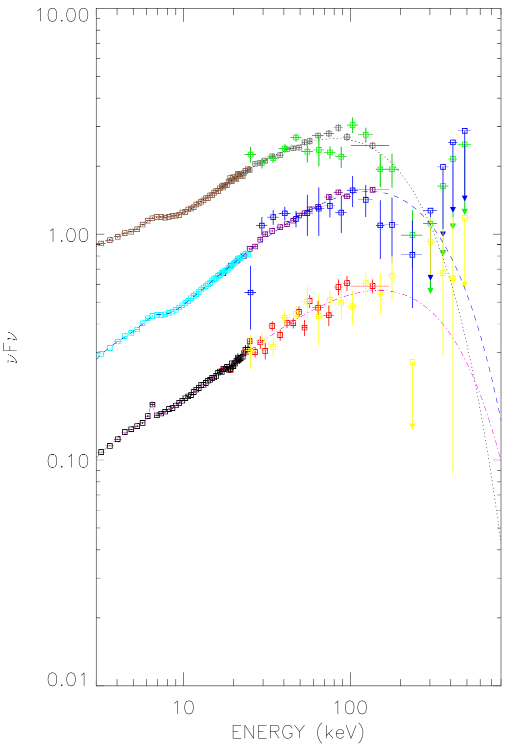

FIGURE 5. Right: fits to PCA, ISGRI, SPI, HEXTE, BAT data of GRO J 1655−40 in 2005. From [21].

blackbody + power-law + smeared edge) and check if it improves the fit significantly. In the hard-intermediate state we often need to add an exponential cut-off to the spectra. However, at most a couple of days after the jet turns on, the fit does not require a cut-off in the PCA-HEXTE band (see Fig. 3).

The presence of an exponential cut-off is often interpreted as thermal Comptonization, and lack of a cut-off may be a sign of non-thermal Comptonization [19]. Disappearing cut-offs might be a direct sign of jet influence through injecting non-thermal electrons into the system [5]. The monitoring observations are often short, 1 - 2 ks, and the number of long observations with RXTE deep in the hard state is limited. On the other hand, some of these sources are in the field of view of the INTEGRAL observatory, and longer exposures allow similar work on high energy spectra.

Recently, the high energy spectra of GRO J1655−40 were analyzed by two groups. Caballero García et al. [20] used JEM-X, ISGRI and SPI on INTEGRAL and found that no cut-off was necessary to fit the spectrum in the hard state, whereas Joinet et al. [21] used PCA and HEXTE on RXTE, ISGRI, SPI on INTEGRAL, and BAT on SWIFT (see Fig. 5) and found that a cut-off is required in the spectrum. This may show that some cross-calibration problems still exist between instruments, and the results depend tightly on how the analysis has been performed.

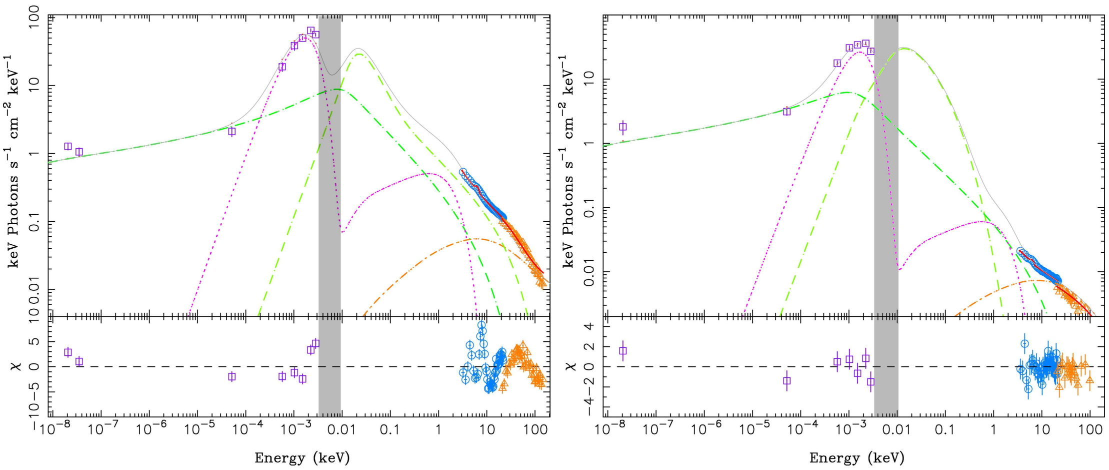

FIGURE 6. SED fits to GRO J1655−40 data in the hard intermediate state (left) and the hard state (right) [24]. The gray regions show the ASTROSAT UVIT band.

BROAD BAND MODELING OF BLACK HOLE TRANSIENTS WITH JETS

Significant progress has been achieved during the last few years in terms of incorporating emission from the jet to the fits of multi-wavelength SEDs [22, 23]. These models can fit an entire SED, from radio to hard X-rays with χ^2 values comparable to that of X-ray only data. This fitting was applied to the SEDs of GRO J1655−40 in hard and intermediate states (see Fig. 6). For the details of the model and the fitting procedure, see Migliari et al. [24].

The reduced χ^2 for the hard state is 0.9, providing a good fit. We note that the inner disk radius is a fit parameter, and for the hard state it is found to be between 2 and 5 R_g. For the hard intermediate state the fit is not acceptable (reduced χ^2 of 8.5) and an additional coronal component is required along with the jet model.

SUMMARY AND THE FUTURE WITH ASTROSAT

In this work we summarized our group's efforts to understand the physical processes around GBHTs in the hard state, from phenomenological characterization to physical models. We have found different types of state transitions during the outburst decay, established conditions for jet formation, and discussed the position of the inner disk radius and the presence or lack there of non-thermal emission from these systems deep in the hard state.

Most of these studies heavily relied on RXTE which may be in its final year. On the other hand, there are still unanswered questions in the field which requires daily monitoring of GBHTs with multi-wavelength coverage. ASTROSAT [25] will be very useful for the type of studies described here; it will provide simultaneous multiwavelength coverage in the near and far UV, optical, and X-ray for jet formation and evolution studies. More importantly, the UVIT telescope on ASTROSAT could provide information on an unexplored part of the SED for sources that are not affected significantly from absorption (see Fig. 6).

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