MAXI and GLAST studies of Jets in Active Galaxies

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Abstract

The recent launch of GLAST - coinciding with the MAXI workshop - opens a new era for studies of jet-dominated active galaxies, known as blazars. While the emission processes operating in various spectral bands in blazars are reasonably well understood, the knowledge of the details of the structure of the jet, location of the dissipation region with respect to the accreting black hole, and coupling of the jet to the accretion process are known only at a rudimentary level. Blazars are variable, and this provides an opportunity to use the variability in various bands - and in particular, the relationship of respective time series to each other - to explore the relative location of regions responsible for emission in the respective bands. Observationally, this requires well-sampled time series in as many spectral bands as possible. To this end, with its all-sky, sensitive monitoring capability, the recently launched GLAST, and MAXI, to be deployed in 2009, are the most promising instruments bound to provide good sampling in respectively the energetic gamma-ray, and the soft X-ray band. This paper highlights the inferences regarding blazar jets that can be gleaned from such joint observations.

Key words: galaxies: active – X-rays: galaxies – galaxies: quasars

1. Introduction: MAXI and active galaxies

The MAXI All-sky monitor, planned to be deployed on the International Space Station in 2009, will be the pre-eminent facility to monitor the entire sky in the soft X-ray band. The most important extragalactic targets for MAXI will be active galactic nuclei, often strongly variable in the X-ray band. There, the well-sampled time series for many objects - and the resulting Power Density Spectra - are bound to significantly advance our understanding of the central engines of AGN. In particular, those are likely to provide an independent estimate of the masses and mass function of the central black holes, which can be otherwise difficult to obtain via other means, especially for objects at a considerable redshift.

Besides measuring the properties of the time series themselves, the MAXI data will be tremendously useful for cross-correlation of the well-sampled time series against those measured in other bands. One class of AGN where such measurements will be particularly valuable are those active galaxies where the dominant portion of the observed radiation is produced in a relativistic jet pointing close to our line of sight. Such objects are known as blazars, and those are the objects where the

MAXI - GLAST[1] synergy will be most apparent. They generally are characterized by broad-band spectra often extending to the highest observable regimes such as the GeV or even TeV band, coupled with large amplitude, chaotic variability seen in all bands; strong polarization in the radio, optical, and IR; and the presence of strong radio emission arising from extremely compact ($\sim$ milliarcsec) and often physically variable structures imaged with the Very Long Baseline Interferometry (VLBI), often associated with the so-called apparent superluminal expansion. It is in fact the flux measured in the GeV or TeV band that often dominates the overall energetics. Clearly, time-resolved gamma-ray observations, combined with monitoring in other bands, are important for detailed studies of blazars, with the goal of understanding the emission mechanisms, leading in turn to determination of the content of radiating particles, then the structure of the jet (the energy dissipation mechanism) and ultimately its connection to the central engine, presumably powering the blazar phenomenon via accretion onto the supermassive black hole.

[*1] At the time of preparation of this manuscript, GLAST - or Gamma-ray Large Area Telescope - was renamed to be the Fermi Gamma-ray Space Telescope. Since the conference took place prior to renaming, for consistency, this paper will use the name "GLAST" throughout.
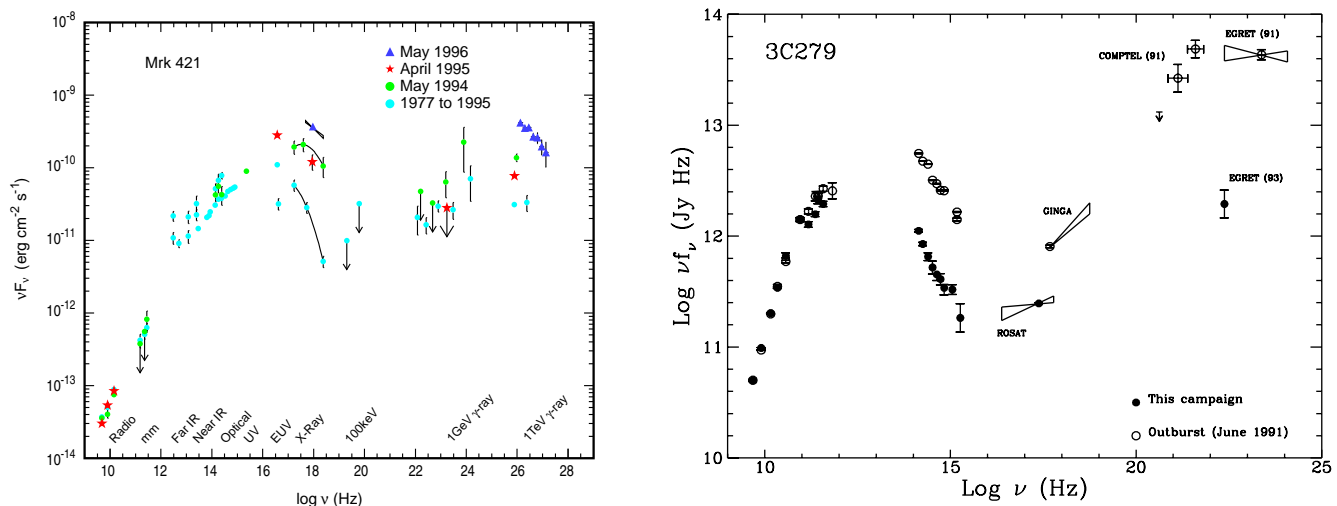
Fig. 1. Examples of broad-band spectra of two blazars. Left panel illustrates the broad band spectrum and variability range in various bands of Mkn 421, the first blazar detected unambiguously in the TeV band (Macomb et al. 1995). Right panel illustrates broad-band spectrum of 3C279, a blazar associated with quasar at $z = 0.524$, detected as a bright gamma-ray source with EGRET (Kniffen et al. 1993). The data are from separate multi-band campaigns, reported in Maraschi et al. (1994) and Wehrle et al. (1998)

2. Gamma-ray Large Area Telescope and MAXI as the key tools for studies of blazars

GLAST's main instrument, the Large Area Telescope, or LAT, relies on the conversion of gamma-rays into electron-positron pairs; tracking of those pairs allows the determination of the direction of the incident gamma-ray. Such a design results in a wide solid angle of the sky, ~ 2 steradians, simultaneously available to the detector. During the normal operation, GLAST points away from the Earth, and slight rocking of the axis of the spacecraft allows monitoring of the entire sky on time scales shorter than a day-long or even shorter, since the whole sky is surveyed in ~ 3 hours. GLAST's bandpass covers ~ 20 MeV to ~ 300 GeV, featuring a peak effective area (at ~ 1 GeV) of $\sim 10,000$ cm^2. The point spread function of the instrument (corresponding to 68% containment) is about 0.5° at 1 GeV, and the energy resolution is about 10% (the details of the instrument are given in Atwood et al. 2008). Those parameters are significantly better than the LAT's predecessor, the EGRET instrument onboard of the Compton Gamma-ray Observatory, allowing studies for many more blazars at shorter time scales than previously possible.

3. Diversity of blazar emission processes in the X-ray band

Why is then the X-ray band important for understanding of blazars? Bulk of the emission arises in the Doppler-boosted relativistic jet; in a sub-class of blazars showing quasar-like properties, a (generally) small fraction of the optical and UV light is also detected to be emitted nearly isotropically, in the accretion disk, and often reprocessed in the broad emission line region. The Lorentz factors of the jets $\Gamma_{\rm jet}$ are measured via superluminal expansion, and are roughly ~ 10 (Jorstad et al. 2001). The broad-band spectra (plotted in the log $(E \times F(E))$ vs. $\log(E)$ form) of two representative objects studied extensively, 3C279, and Mkn 421, are shown in Figure 1. Very broadly, the emission consists of two peaks, one with a maximum between the far IR and soft X-ray band, and another in the gamma-ray band. Since the low energy peak often shows considerable polarization (measured so far in the radio, IR and optical bands), it is generally agreed upon that the dominant emission mechanism responsible for radiation in the low-energy peak is the synchrotron process of ultra-relativistic electrons accelerated in magnetic field. Most modeling suggests that the Lorentz factors of electrons $\gamma_{\rm el}$ radiating near the peak are around $10^3 - 10^4$ for the (generally higher luminosity) blazars associated with quasars (such as 3C279 in Fig. 1), and $10^5 - 10^6$ for line-devoid, generally lower luminosity objects (such as Mkn 421 in Fig. 1), which are often sources of TeV gamma-ray emission. The high energy peak, on the other hand, is generally attributed to Compton scattering by the same population of electrons that produce the low energy peak, with target photons being the ambient, external, diffuse (quasi-isotropic) radiation field in the former class, and the synchrotron radiation internal to the jet in the latter class. Probably the most compelling reason for the difference between the two classes is the mass accretion rate (in Eddington units). In the latter class, the accretion corresponding to a low $L/L_{\rm Edd}$ forms a "hot" flow, where the density of the accreting material is never sufficiently high to allow

efficient cooling and formation of a "standard, " "cold" - and thus luminous accretion disk, and therefore the energy is advected to the black hole with the falling matter. In the former class, $L/L_{\rm Edd}$ might be higher, allowing for a "cold" (roughly $10,000 - 30,000$ Kelvin), luminous disk to form - and thus we detect the quasi-isotropic signatures of accretion such as the emission lines, and sometimes even the "blue bump."

As is apparent from Figure 1, the minimum between the two peaks is located in the X-ray band. In the former sub-class (as in 3C279), the optical / UV spectrum, being generally quite steep (soft), is presumably the "tail" of the synchrotron component, while the X-ray emission - generally showing relatively hard spectra, with energy indices $\alpha_{\rm X} < 1$ - suggests an association with the onset of the Compton component. There, at least in the context of the models considered above, the X-ray emission is due to the *low energy end* of the electron energy distribution. Since the observed X-ray spectra are not measured to be harder than $\alpha_{\rm X} < 0$ - this suggests that the X-ray band probes the "most populous" part of the electron population, where the electron number density is the greatest. With this, in the blazars associated with quasars, the *X-ray spectral measurements are crucial in determining the total content of the radiating particles in the jet.* As an aside, in principle, such a measurement could be performed in the low-frequency radio regime, since the low-frequency radio and X-ray bands both mirror the low energy electron population. There, however, the synchrotron self-absorption makes the lowest energy portion of the jet inaccessible, and since the inner jet is thus optically thick, the radio observations can penetrate only down to a "photosphere" and thus probe considerably more extended spatial region.

The situation in the latter class of blazars - such as Mkn 421 - is the opposite. There, the low-energy (synchrotron) component peaks in the optical/UV or even the soft X-ray regime; the X-ray spectra are generally much softer (with $\alpha_{\rm X} \sim 1$ or softer) than in blazars associated with quasars and represent the high energy portions/tails of the synchrotron spectral component. Here, the X-ray band probes the highest energy "tail" of the electron distribution. Detailed studies in this band are indispensable in determining the extent of the energy distribution of the most energetic radiating electrons, which in turn is needed to provide the strongest constraints on the particle acceleration mechanisms.

4. Two facets of time variability

High energy emission from essentially all active galaxies is variable, which provides a difficulty but also an opportunity. On one hand, a reliable measurement of the broad-band spectrum must be obtained simultaneously, but on the other hand, the time variability in any

single band - but also, a relationship of such variability amongst various bands - provides an opportunity to explore causal relationships between the respective emission processes and/or emission regions. With this, there are clearly two separate aspects - and associated challenges - of time variability studies of any astronomical sources. One is the sensitive measurement of properties of the time series in any single band, while the other is cross-band correlations.

4.1. Intra-band variability

The "standard" approach for the former aspect is to measure the Power Density Spectrum, which is essentially a Fourier transform of the time series. Another is the Structure Function; both were covered in detail in presentations at the Workshop, including those by McHardy, Hayashida, and past presentations by Kataoka, Edelson, Markowitz and others: in reference to blazars, see, in particular, a review by Kataoka (2008). Over a narrow range, PDSs or SFs of such time series are generally well-described by a power law, but the index of the power law changes with the variability frequency, at some "break" frequency $f_{\rm break}$. In accreting black holes - where the emission is presumably mainly due to nearly-isotropic radiation from the accretion disk - this break frequency has been demonstrated to correlate well with the mass of the accreting object (see, e.g., the relevant figure in McHardy, these proceedings, an extension of earlier work by Hayashida et al. 1998). Remarkably, this relation seems to hold down to masses of stellar size black holes.

Studies of jet-dominated blazars are quite sparse, with the first robust report for a sample of X-ray bright BL Lac objects by Kataoka et al. (2001), suggesting a break on day-long time scales, but with no clear correlation with the black hole mass (which, in turn, is difficult to determine in blazars). So far, reports for a clear PDS break are limited to one object, 3C273 possessing at least some blazar-like characteristics, but also showing substantial contribution from the emission from the accretion disk (McHardy, these proceedings; see also I. McHardy's presentation at the Blazar Variability Workshop in Paris, April 2008). There, the break frequency seems to follow that expected from the BH mass. Clearly, more detailed studies of blazars are needed, to determine their PDSs, compare those to the results for non-jet AGN, and determine whether there is any clear correlation with the black hole mass. Such studies are challenging, since they require well-sampled monitoring over a long span of time, corresponding to many years. MAXI is ideally positioned for this task.

4.2. Inter-band variability

The inter-band variability studies are equally difficult, again, because of the severe effect of sampling on the
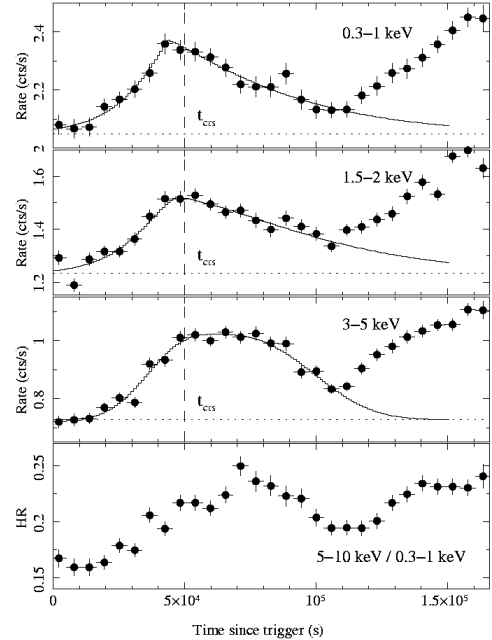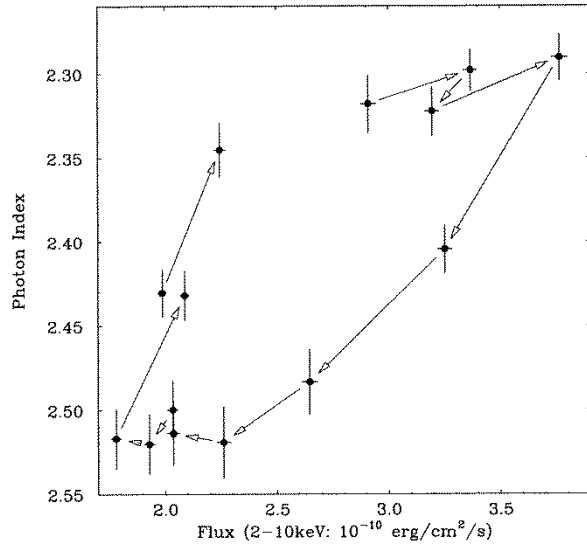
Fig. 2. Results of time-resolved X-ray spectroscopy of blazars. Left panel shows the evolution of the spectrum of blazar Mkn 421 observed in 1994 with the ASCA satellite, with the X-ray spectrum becoming harder when the source increased in intensity; the total length of the observation was about 1 day (from Takahashi et al. 1996). Right panel shows the Suzaku observation of another TeV-emitting blazar, 1ES1218+304. There, the spectral variability had an opposite sense: the source become brighter in soft X-rays, while the hard X-ray flare peaked $\sim$ 20 ks later (from Sato et al. 2008).

robustness of determination of any lags or leads. With this, since many instruments provide data for a single source at a time, planning, scheduling, and coordination of various facilities is quite complex and challenging. Nonetheless, there are some recent successes resulting from well-planned campaigns: one notable example using a large suite of telescopes ranging from radio to X-ray bands, and including optical polarimetry, is the variability study of BL Lacertae (Marscher et al. 2008). There, the data indicate that there are multiple dissipation regions in the jet, and at least some of the X-ray flux arises at a distance $\sim$ thousands of R_S from the black hole. This observational result has many implications on the structure and the content of the jet, and similar observations need to be conducted using other objects.

Another important observational result concerns monitoring the TeV-emitting blazars, such as Mkn 421 mentined in Sec. 3. There, at least in the context of widely accepted leptonic models, the X-ray band and the TeV band both should reflect the high-energy end of the radiating electron population, so variability patterns should be correlated. While this is generally the case, the amplitudes of flares detected in the respective X-ray and TeV bands do not necessarily follow the trend expected in the simplest scenarios (for a recent discussion, see, e.g., Fossati et al. 2008). Clearly, more detailed understanding of those objects will require good temporal coverage in the X-ray band.

Meeting those goals requires overcoming rather severe observational challenges. The determination of the PDSs and inter-band correlations alike is difficult because of strong detrimental effect of the sampling pattern on the resulting PDS and cross-correlation function, as discussed in the last Section below. Data are sparse, because most X-ray facilities observe one object at a time (or, at most one field with a bright blazar at a time). With this, MAXI, monitoring all sky simultaneously, provides much better sampled X-ray data for a number of objects. Still, it is important to note that MAXI is sufficiently sensitive only for a limited number of blazars, since blazars often can be relatively faint in the X-ray band (see above). Still, given the need for good sampling, a temporal coverage of MAXI is indispensable.

4.3. Recent intra-band spectral variability studies of blazars: Suzaku observation of 1ES 1218+304

The cross-band variability studies show great promise as a tool to study the details of structure of blazar jets emitting over a broad range of spectral bands as above. But even studies of spectrally-resolved variability in a single band (such as, e.g., wide-band X-ray observations) can be very fruitful. Among the most important results regarding the nature of the radiating particle distribution in blazars was the Asca observation of the X-ray spectral variability in the TeV-emitting blazar Mkn 421, with the broad-band spectrum shown in Fig. 1. There, the
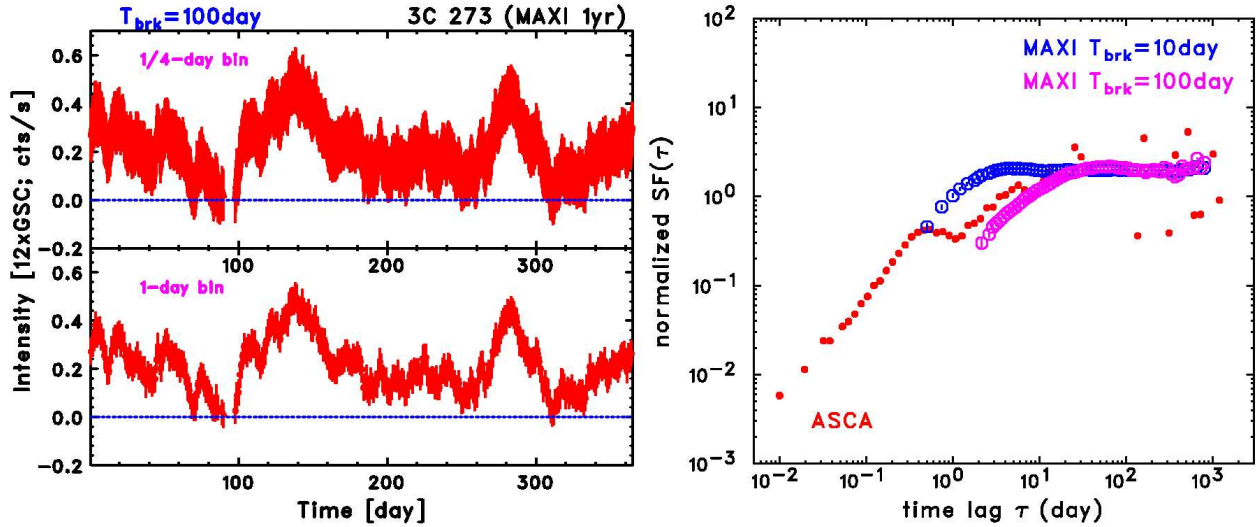
Fig. 3. Right panel: Simulated X-ray light curve of 3C273 as observed with MAXI. Data are binned at 1/4 day (upper plot) and 1 day (lower plot) intervals. Right panel: Structure Function for the blazar Mkn 421 calculated from the simulated light curves obtained with MAXI; the assumed mean flux is 10 milliCrab. For comparison, the plot also includes SF derived from combining the Asca and RXTE ASM data. (Figure from Kataoka 2008)

X-ray spectrum corresponds to the most energetic tail of the electron distribution, and the Asca data revealed that the X-ray spectrum became harder as the object became brighter, with hardening of the spectrum occurring more rapidly than the increase of brightness. More importantly, in the decay phase, the spectrum became softer more rapidly than the flux decrease (Takahashi et al. 1996; see Fig. 2, left panel). At least regarding the flux decay phase, this is precisely the kind of spectral variability expected in the synchrotron or Compton process, where the energy loss is energy dependent. The knowledge of the characteristic synchrotron cooling time $\tau_{\rm cool}(E)$ - going as $\tau_{\rm cool} \propto E^{-1/2}$ (derived from the cooling time scale for electrons $\tau_{\rm cool}(\gamma_{\rm el}) \propto \gamma_{\rm el}^{-1}$) - allowed an independent constraint on the Lorentz factors of the radiating electrons $\gamma_{\rm el}$, and, in fact, yielded values of $\gamma_{\rm el}$ similar to those inferred from broad-band spectral fitting.

Of course the implicit assumption in the analysis above is that the acceleration process is very rapid, significantly more rapid than the electron energy loss time scale even at the highest observable energy (note that the acceleration time scales for more energetic electrons are longer, with the dependence of the acceleration time scale on the photon energy going as $\tau_{\rm acc}(E) \propto E^{1/2}$, derived from $\tau_{\rm acc}(\gamma_{\rm el}) \propto \gamma_{\rm el}$). This, in turn, might depend on a particular blazar, or even on a particular event. In fact, an opposite behavior to that described above for Mkn 421 was detected recently with Suzaku in another TeV-emitting blazar 1ES1218+304, via observations reported

by Sato et al. (2008). There, the ~ 2 day long observation revealed a well-resolved X-ray flare with a rise time of ~ 50 ks. The spectrally resolved Suzaku light curve (see Fig. 2, right panel) indicated that the hard X-ray (5 - 10 keV) flux in the flare clearly lagged that in the soft X-rays (0.3 - 1 keV) by about 20 ks. This was associated with the profile of the flare, which became more symmetric at higher energies. This lag can now be interpreted as an energy-dependent signature of the electron *acceleration* process. Those two features of the energy-resolved time series now suggest that the acceleration and cooling time scales in this object are roughly comparable for electrons radiating at ~ 2 keV - and this puts further constraints on the electron acceleration process, and in particular, on the level of turbulence in magnetic field (see Sato et al. 2008).

5. Future facilities to study blazars in the X-ray band

The launch of GLAST is taking place when several X-ray sensitive observatories are operational and delivering high quality data, but also with several additional ones under construction. Most notably, the Chandra satellite, featuring the bandpass of $\sim 0.5 - 10$ keV, is providing probably the most sensitive measurements on many sources. Important discovery with Chandra - mainly owing to the superb quality, sub-arc sec imaging - was the detection and mapping of the kpc size X-ray emitting jets in a number of blazars, including those that are bright gamma-ray emitters detected with EGRET. XMM-Newton observatory has capabilities in many ways

similar to Chandra's, with somewhat worse point spread function of its three mirrors, but with substantially better effective area, allowing sensitive measurements of flux variability of active galaxies on even shorter time scales than Chandra. Just as is the case for Chandra, XMM-Newton is also in a deep (several day-long) orbit, allowing uninterrupted data streams and unambiguous variability studies on time scales of a $\sim$ day down to the Poisson limit, generally corresponding to a few hundred seconds. Suzaku has possibly the best effective area for its low-energy (XIS) detectors, and also features an additional, hard X-ray detector - extending the bandpass (for most AGN) to at least 50 keV; however, the low-Earth orbit and Sun angle constraints place some limitations on the sampling pattern and the resulting measurements of the intra- and cross-band variability properties. Swift satellite features nearly all-sky pointing capability, and is bound to be an important tool for rapidly responding to, and following exceptional flares of blazars. In the near future, NuSTAR, sensitive in the hard X-ray ($\sim 10 - 80$ keV) band, slated to be launched in 2011 or 2012, will be monitoring the hard X-ray flux for at least a few blazars for $\sim$ weeks, but both Swift and NuSTAR, with their low-Earth orbits, will be subjects to periodic source occultations. All those facilities, however, can observe only *one target at a time*. With the Rossi X-ray Time Explorer - with its All-Sky Monitor - nearing the end of its operational life, a working all-sky monitor is essential, and that capability will be provided by MAXI. This will be important for GLAST, but equally, or even more so, for the current and future TeV-sensitive Cerenkov telescopes. MAXI will provide a trigger and monitoring capability for observations of the TeV-emitting blazars regardless whether they are or are not subjects on ongoing multi-band campaigns.

What are MAXI's capabilities to measure variability of blazars? Bright objects such as 3C273 ($\simeq 5$ milliCrab) and Mkn 421 ($\simeq 10$ milliCrab) can be detected with more than 5 σ level every day, allowing for the first time non-bias monitoring of the sources from daily to more than yearly time scales. Figure 3 (left panel) shows the simulated long-term (1 year) light curve for 3C273, assuming a PSD slope of 2.0 with a break time of $1/f_{\rm break} \simeq 100$ day. The resultant structure function (calculated as in Kataoka 2008) is illustrated in the right panel of Figure 3: it clearly reveals variability nature of blazars on long time scales, significantly longer than the characteristic break. Detailed measurements of such features in the PDS and SF are bound to probe whether the variability properties are mainly governed by the changes in the accretion flow, or by the properties of the energy dissipation process and attendant instabilities in the relativistic jet.

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