MAXI and AGN X-ray Variability

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Abstract

The X-ray emission from AGN comes from very close to the central black hole and observations of the way in which that emission varies provide the best diagnostic of the origin of the variations, the structure of the emission region and how it scales with mass and accretion rate. Spectral variations also enable us to study the structure of the gas surrounding the central X-ray source and, by comparing X-ray variations with those seen in other wavebands, eg optical, we can deduce the origin of those other-band variations. In this paper I will briefly highlight some recent relevant observations, mainly from the Rossi X-ray Timing Explorer (RXTE), which are relevant to the above topics and will indicate the areas in which future observations with MAXI will improve our understanding.

Key words: AGN - X-ray variability - MAXI

1. The important questions in AGN X-ray Variability

Ever since the realisation that Active Galactic Nuclei (AGN) were powered by accretion onto supermassive black holes, astronomers have wondered how the emission from those black holes might compare with, or differ from, the emission from the much smaller black holes in Galactic black hole X-ray binary systems (GBHs). GBHs occur in a number of spectral-timing states, particularly the low-flux, hard-spectrum 'hard' state and the high-flux, soft-spectrum 'soft' state. Before we can compare GBHs with AGN, we therefore need to be sure that we are comparing the same thing and so the first question which I will discuss below (Section 2) is whether AGN are found in the same 'states' as GBHs. As one might reasonably assume that variability timescales might scale with the size of the system, ie with black hole mass, the search for characteristic timescales which might occur in both GBHs and AGN has been a major aim (eg M^{c}Hardy 1988,1989). In Section 3 I will therefore review current progress in GBH/AGN timescale comparisons.

Once we have achieved a reasonable measurement and classification of X-ray variability, we are then in a position to try and build physical models to explain the variability. In Section 4 I will review our current understanding of such models. Most of the X-ray observations of AGN have been of relatively radio quiet Seyfert galaxies, whose X-ray emission is not relativistically beamed. However AGN whose emission comes predominantly from a relativistic beam oriented close to the line of sight, ie blazars, are bright X-ray sources which will also be detectable by MAXI. Are the variability patterns of blazars the same as those of non-beamed AGN or does relativistic beaming shorten the observed characteristic timescales? In Section 5 I will review how blazar X-ray variability is related to that of Seyferts and GBHs. In Section 6 I will review our present improved understanding of the relationship between X-ray and optical variability in AGN and in Section 7 I will discuss how observations of X-ray spectral changes can tell us about the gas surrounding the AGN.

2. AGN X-ray States

The PSDs of the GBH Cyg X-1 in both its high/soft and low/hard states are shown in Fig 1. In the soft state the low frequency PSD is described by a powerlaw of slope -1 (ie $P(\nu) \propto \nu^{-\alpha}$ where $\alpha \sim 1$) which steepens above a bend frequency, ν_B (or timescale T_B) to a steeper slope of $\alpha > 2$. In the hard state there is a second bend at low frequencies below which the PSD flattens to $\alpha = 0$. If the S/N is high enough, hard state PSDs can also usually be described as the sum of a number of Lorentzian shaped components, giving a somewhat bumpy appearance, as can be seen in the hard state PSD of Cyg X-1 in Fig 1.

The energy spectra of AGN are more comparable to those of GBHs in the hard than the soft state, which initially led observers to presume that AGN would also be in the hard state. In order to determine AGN PSDs over a sufficiently large frequency range that their state may be determined it is, however, necessary to monitor them for many years. Although attempts were made to

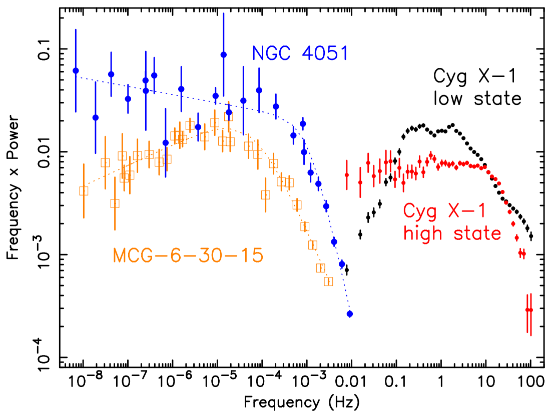

Fig. 1. PSDs of NGC4051 (filled circles) and MCG-6-30-15 (open squares), unfolded from the distortions introduced by the irregular sampling, compared with the PSDs of the GBH Cyg X-1 in both the high/soft and low/hard states. The low frequency part of the PSDs of both NGC4051 and MCG-6-30-15 are determined from observations by *RXTE* and the high frequency parts come from observations by XMM-Newton.

determine the long timescale variability of AGN using archival data from a variety of satellites (eg M^{c}Hardy 1988; Papadakis and M^{c}Hardy 1995), and PSD bends were detected, it was not until *RXTE* was launched in 1995 that it was possible to measure PSD shapes with sufficient accuracy to determine AGN states. A number of long timescale AGN monitoring programmes have been carried out with *RXTE* and in Fig 1 I show the PSDs resulting from two of the longest running monitoring campaigns (M^{c}Hardy et al 2004 and 2005). Although the PSDs of NGC4051 and MCG-6-30-15 both extend almost 4 decades below the high frequency bend, and the low frequency bend in Cyg X-1 lies only about 1.5 to 2 decades below the high frequency bend, in neither case is a second bend seen. It is therefore almost certain that both AGN are in the soft state.

We note that the bend MCG-6-30-15 is at a longer timescale than that in NGC4051. As the black hole mass is larger in MCG-6-30-15, these observations are consistent with scaling of bend timescale with black hole mass (discussed in more detail in Section 3). In some other AGN of larger black hole mass there is not sufficient coverage of the PSD below the bend to determine with any confidence whether the AGN is in a soft or hard state. However in only one case, Akn564, is there any detection of a second bend at low frequencies and all other cases are consistent with a soft-state interpretation.

2.1. Akn564: A very high state AGN?

In Fig 2, lower panel, I show the PSD of the very high accretion rate narrow line Seyfert 1 galaxy (NLS1), Akn564 (M^{c}Hardy et al 2007). We can see that the PSD can be described well by the sum of two Lorentzian shaped components. Although this shape describes the PSD of GBHs in the hard state, it actually also describes the PSDs in most cases apart from in the soft state. Thus when the energy spectrum is very soft and the flux is very high (the very high state, or VHS, when the accretion rate is very high), the PSDs of GBHs have a similar form, the only difference being that the peak Lorentzian frequencies are at higher frequencies in the VHS. As Akn564 has an accretion rate which is at approximately at the Eddington limit, we interpret its PSD as being that of a VHS object.

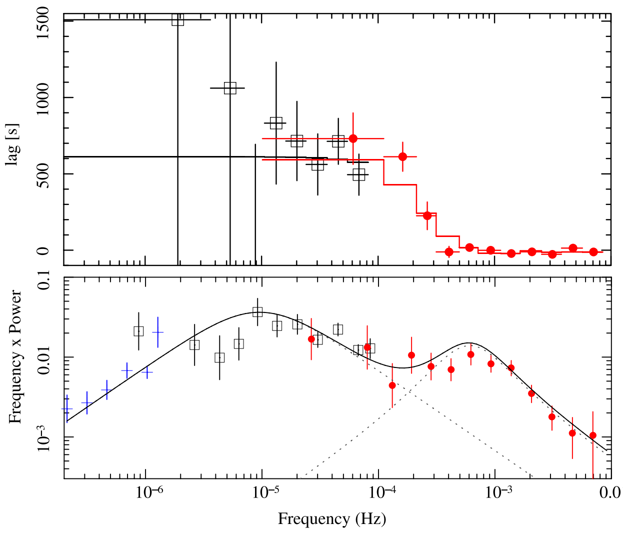

Fig. 2. Top panel: Lag between the hard (2-10 keV) and soft (0.5-2 keV) X-ray bands as a function of Fourier frequency, for Akn564. A positive lag means that the hard band lags the soft. Bottom panel: PSD of Akn564 showing a fit to the two-Lorentzian model (M^{c}Hardy et al 2007). Note how the cross-over frequency between the two Lorentzians corresponds to the frequency at which the lags rapidly change.

If we Fourier analyse lightcurves into components of different frequencies, we can measure the lag spectrum, ie the lag between different energy bands as a function of Fourier frequency. In the upper panel of Fig 2 we plot the lag spectrum between the hard (2-10 keV) and soft (0.5-2 keV) energy bands for Akn564 from a combination of *ASCA* and *XMM-Newton* observations. We note that the lags are relatively constant (and large) at low frequencies and also constant (but very short) at high frequencies, with a rapid change in lag at about the frequency where we change from one Lorentzian component to another in the PSD (bottom panel). Similar behaviour is seen in GBHs. We interpret the combined lag and PSD spectra as showing that there are two separate regions where the variations are mainly generated. Although *XMM-Newton* can measure lags on timescales shorter than a day, it is hard to measure lags on months or years timescales as the energy range of *RXTE* does not extend below 2 keV. With its extended energy range, MAXI can potentially give us the very valuable long timescale lags.

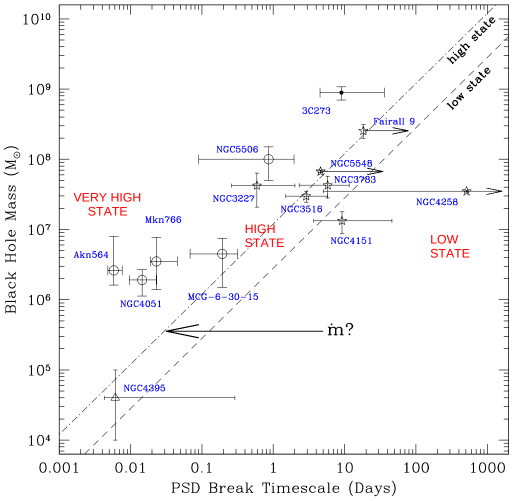

Fig. 3. PSD bend timescales as a function of black hole mass (M^{c}Hardy et al 2004 and 2005). The lines marked 'high state' and 'low state' are just linear extrapolations from typical bend timescales of Cyg X-1 in the high-soft and low-hard states.

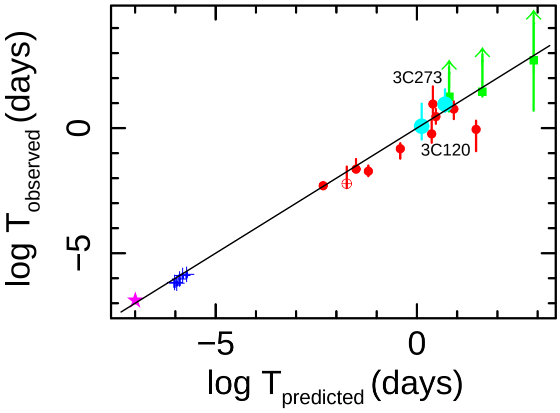

Fig. 4. Log of the observed vs. the predicted PSD bend timescales (in units of days). The star is GRS1915+105 and the crosses are Cyg X-1. The red circles are the AGN which were included in the fit and the three green squares, whose upper bend timescales are unbounded, are AGN which were not included in the fit. We also plot the blazar 3C273 (M^{c}Hardy et al, in preparation, and Section 5 here) and the radio galaxy 3C120.

3. Scaling of Characteristic AGN and Binary Timescales

Scaling of PSD timescales between AGN and GBHs has been carried out in two main areas: scaling of the timescale of the high frequency bend, and scaling of the amplitude of the high frequency part of the PSD at frequencies above the bend. M^{c}Hardy (1988) defined the Normalised Variability Amplitude (NVA) which is the square root of the power in the PSD (in rms units) at a fixed frequency (10^{-4}Hz which is above the Poisson noise level and also above the bend frequency). As black hole mass measurements were very rare at that time, NVA could only be scaled with luminosity as a proxy and it was found to decrease as luminosity increased. Green et al (1993) found a similar result. A refined analysis by Hayashida et al (1998), now with more black hole masses available, found an inverse scaling of high frequency AGN PSD amplitude with black hole mass. Recently Gierlinski et al (2008) have demonstrated a similar correlation in hard state GBHs with possible similarity for AGN. In none of these analyses is any dependence on accretion rate indicated although, in these AGN samples, the range of accretion rates available was not large. Gierlinksi et al suggest that the high frequency part of the PSD in hard state GBHs is limited by the innermost stable orbit, which should depend only on mass. Further work is necessary to determine how the mainly soft-state AGN fit into this pattern. Scaling of the bend timescale, T_B, is more relevant to MAXI as measurement of T_B requires long timescale monitoring, hence we will concentrate on it here. MAXI does not have sufficient sensitivity to define PSD slopes on short timescales ($\sim$day) above the bend.

Early archival observations (M^{c}Hardy 1988; Papadakis and M^{c}Hardy 1995) indicated a probable scaling of black hole mass with T_B but it was not until monitoring began with *RXTE* in 1996 that the long timescale lightcurves necessary to measure T_B became available (eg Edelson and Nandra 1999; Uttley et al 2002; Markowitz et al 2003). A rough scaling of T_B with mass was noted but there was a great deal of scatter. In Fig 3 I show an updated version of the plot originally shown in M^{c}Hardy et al 2004 and 2005. It was noticed that, for a given black hole mass, the highly accreting NLS1s had shorter bend timescales than AGN with lower accretion rates, indicating that T_B scaled approximately inversely with accretion rate. A proper 3D analysis of T_B as a function of black hole mass and accretion rate (in Eddington units), covering both AGN and soft-state GBHs showed that $T_B \propto M/\dot{m}_E$ (M^{c}Hardy et al 2006). A comparison of the observed bend timescales with those predicted by this relationship is shown in Fig 4. We can see that the relationship applies over 10 decades of timescale. Subsequent work by Koerding et al (2007) shows that, with a slight offset, the hard state GBHs and neutron stars also follow the same mass/accretion rate scaling. Thus as far as we can tell, almost all accreting objects behave in the same way.

We have simulated MAXI lightcurves (Fig 5) of typical AGN (5 mCrab) of 3 year duration (with thanks for assistance from Jan Kataoka). If the input PSD model has a slope of -1 at low frequencies and -2 at high frequencies, and a bend at a timescale of 10 days, MAXI has difficulty finding the bend. A single powerlaw PSD of slope -1.3 fits (Fig 6) the simulated PSD as well as one with a bend. However if we force the slope below

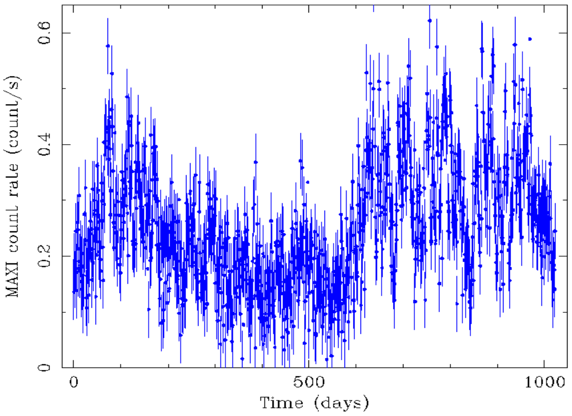

Fig. 5. Simulated MAXI lightcurve for a 5 mCrab source with a PSD of low frequency slope -1, high frequency slope -2 and bend timescale 10 days.

the bend to be -1, which applies in almost all AGN, then MAXI is able to find the bend timescale quite accurately. Also, if we can add in high frequency data from SUZAKU or *XMM-Newton* as we typically do with *RXTE* data, then with MAXI data we can find the bend timescale quite well. However we stress that, to be really useful, the observations must continue for at least 5 years, and probably 10.

4. Origin of the Variations

We have previously found that the rms variability scales linearly with flux in both GBHs (Uttley and M^{c}Hardy 2001) and AGN (eg see Fig 7). Thus variations on short timescales (which determine the rms variability) must be responding to variations on long timescales (which determine the average flux level). A model which produces just this type of variability was proposed by Lyubarskii (1997). He proposed that accretion rate variations are produced in the outer parts of the accretion disc and propagate inwards where they modulate the intrinsic variations being produced by more inner radii. As higher frequency variations will tend to be damped by viscosity, and as the characteristic damping timescale will tend to decrease as we move in towards hotter parts of the accretion disc, the net affect is that the outermost parts of the disc are responsible mostly for the low frequency variations and the inner parts for the higher frequencies. The fact that the variations from the outer parts modulate the variations from the inner parts automatically produces the rms-flux relationship.

Note that the Lyubarskii model produces accretion rate variations, but these variations are not the same as X-ray variations. This basic model has therefore been incorporated into a more general emission model by Churazov et al (2001) and Kotov et al (2001) which has subsequently been quantified by Arevalo and Uttley (2006).

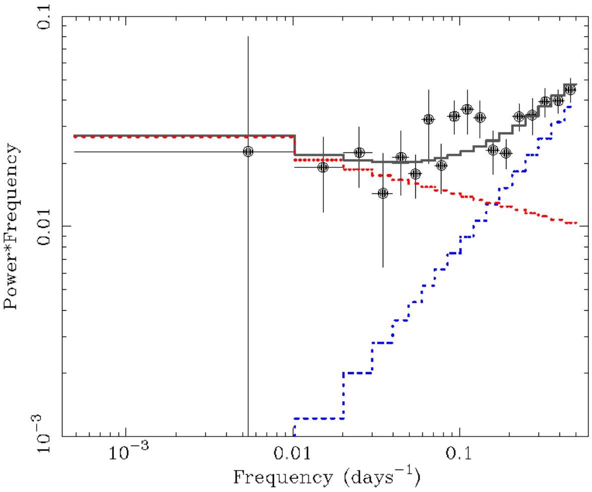

Fig. 6. PSD derived from the lightcurve shown in Fig 5. The best fit single powerlaw, including the Poissonian noise, is shown as a continuous solid line. The dot-dash line shows the PSD with noise removed and the dotted line shows the Poisson noise.

In this model the variations propagate inwards and eventually modulate the X-ray emission region. Thus the source of variations and the source of X-ray emission are separated. If the X-ray emission region has a radial temperature, or energy, gradient, with higher energy photons being emitted, preferentially, at smaller radii, then we can explain many of the spectral-timing observations of AGN, such as the lag spectra (eg M^{c}Hardy et al 2007). The lags then represent the time it takes for the variations to propagate from the centroid of the low energy emission to the centroid of the higher energy emission. If the low frequency variations are all produced at larger radii than any of the X-ray emission region then all Fourier frequencies will produce the same lag. But if some of the higher frequency variations are produced within the X-ray emission region, then the location of the effective centroid of the low energy emission region, as seen by the high frequency variation, will move inwards, thus reducing the lag.

5. X-ray Variability of Blazars

The X-ray emission from blazars is almost certainly inverse Compton emission from a relativistic jet oriented towards the observer (eg M^{c}Hardy et al 2007b). Thus the emission mechanism is probably different to that in Seyfert galaxies where thermal Compton scattering from an un-beamed emission region is probably responsible. One might therefore naively expect that any blazar timescales would be subject to relativistic time dilation and hence observed timescales would be shorter than the intrinsic source timescales. We have monitored the X-ray emission from a number of blazars and have begun to derive bend timescales. In Figs 3 and 4 we plot the blazar

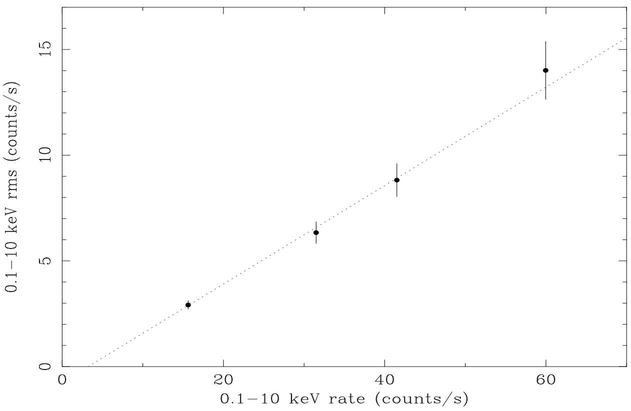

Fig. 7. Rms-flux relationship for the Seyfert galaxy NGC4051 (M^{c}Hardy et al 2004).

3C273 and note that it fits very well with the moderate accretion rate (ie probably soft state) non-beamed Seyfert galaxies, without the need to invoke time dilation. We therefore conclude that the source of the variations (ie not the source of the X-rays) lies outside the jet and simply modulates the jet emission in some non-linear way. If we tap on the jet from outside (ie in the 'laboratory', or observers frame, ignoring the small redshift correction for 3C273) then any observer in the laboratory frame will see modulations at the same tapping frequency. Only if the source of the variations is within the jet will the observed frequency be affected by the relativistic motion of the emitting region.

We have also calculated the rms-flux relation for 3C273 and 3C279. Both blazars display a linear relationship exactly the same as for Seyfert galaxies. This observation provides additional support to the suggestion that the origin of the variations is just the same as in Seyfert galaxies and GBHs, ie accretion rate variations propogating in thro the disc and corona and eventually modulating the jet.

6. Relationship between X-ray and Optical Variability

The origin of optical variations in Seyfert galaxies has, for many years, been at best a mystery and, at worst, a complete muddle. It has often been suggested that optical variability arises from reprocessing of X-ray variation but most early X-ray/optical studies found either weak (Peterson et al 2000) or non-existent (Done et al 1990) X-ray/optical correlations. Only in the case of NGC5548 (Uttley et al 2003) was a strong X-ray/optical correlation found. We therefore began a programme of optical monitoring observations with the Liverpool robotic telescope on La Palma (LT), and with the SMARTS telescopes in Chile (eg Arevalo et al 2008) to parallel our *RXTE* X-ray monitoring, supplemented published observations (eg Sergeev et al 2005) and data from other robotic telescopes (eg MAGNUM - in collaborations with Minezaki and colleagues).

A pattern is now slowly emerging. On short timescales (weeks), we see quite a strong correlation with close to zero lag but on longer timescales (months/years) we often see variations in the optical which have no parallel in the X-rays. An example is shown in Fig 8 from Breedt et al (2008). The short-timescale correlation is almost certainly due to reprocessing of X-ray emission by the accretion disc. Given the likely light-travel time to the reprocessing region, a lag close to zero days is expected and is entirely consistent with the observations. The additional variability seen in the optical band is not yet well constrained by observations but there are two main possibilities - geometry changes or accretion rate changes. The geometry of the X-ray source could be changing slowly, eg the X-ray emitting corona could be expanding or contracting, altering the solid angle subtended at the X-ray source by the reprocessing region. Alternatively, accretion rate changes in the disc could either move radially the reprocessing region, again altering its solid angle at the X-ray source, or accretion rate changes could alter the intrinsic thermal emission from the disc. At present (Breedt et al 2008) all of these possibilities are consistent with the observations. We would expect the long timescale variations in intrinsic emission from the disc to be more important in high accretion rate sources where the disc is more luminous. There are hints that that might be the case but further observations are required for confirmation.

As can be seen from Fig 8, in order to study X-ray/optical variability it is not necessary to monitor on a hourly timescale. Observations every few days are quite sufficient to follow the optical variations. Thus MAXI is very well suited to this programme. However again I note that a two-year period of observations would not be enough to detect any pattern above the random fluctuations which are also seen in the optical and X-ray lightcurves. It is necessary to observe for typically 5, or more, years.

7. X-ray Spectral Variability and Absorption

Monitoring of X-ray spectra can enable us to study the absorbing gas surrounding the AGN. In Fig 9 we see both the X-ray flux and the X-ray photon index of NGC3227 over a 4 year period (from Lamer et al 2003). The photon index was derived assuming a constant Galactic absorbing column. We note that at about MJD-50000 of 1900 there is an extreme apparent hardening of the spectrum with little change of X-ray flux. As the spectrum becomes almost unphysically hard (photon index of zero), a more likely explanation is that it is the absorbing column that is changing. If we fix the photon index and allow the column to change, then we find that the col-

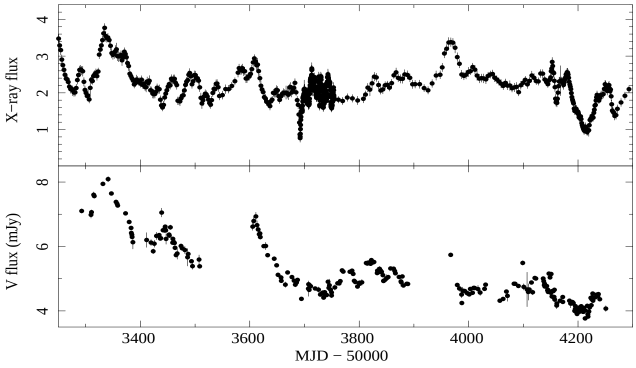

Fig. 8. Top panel: 2-10 keV X-ray flux from *RXTE* for Mkn79. Bottom panel: V-band flux from the Liverpool robotic telescope, MAGNUM and the Crimean observatory (Breedt et al 2008).

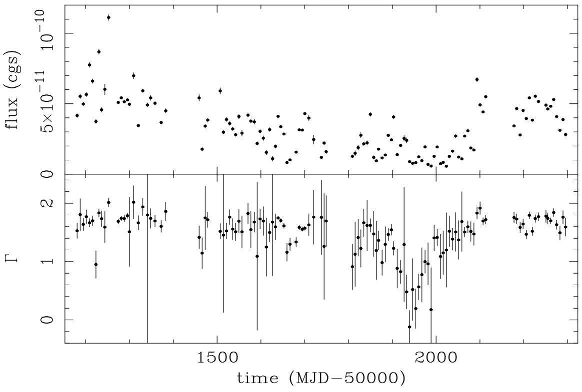

Fig. 9. 2-10 keV X-ray flux (top panel) and X-ray photon index (bottom panel) from *RXTE* for NGC3227, assuming a constant absorbing column (Lamer et al 2003).

umn varies from a very low value up to $\sim 10^{23}$ cm^{-2}, and back again over a period of 100 days, which we interpret as an absorbing cloud passing over the source. As there was also an XMM-Newton observation at the same time which enabled us to determine the ionisation parameter of the absorbing gas and hence determine the distance of the gas cloud from the central X-ray source. We found that it lay at a distance of about 14 light days, at about the inner edge of the broad line region.

With the extended soft spectral range of MAXI compared to *RXTE* it will be possible to detect other large, long timescale, spectral events in many AGN, and to measure the frequency of such events, thereby providing a broad overview of the large scale structure of the gas surrounding the central X-ray source in AGN.

8. Conclusions

Over the last two decades, and particularly since the launch of *RXTE* in 1995, observations of the X-ray variability of AGN have improved our understanding of the inner workings of AGN much more than all of the measurements of single, or few-epoch, multi-band spectral energy distributions have ever done, no matter how many bands they covered. We now know, at least to first order, how emission regions scale with black hole mass and accretion rate over a huge dynamic range. We have a reasonable model for the way in which the variations are produced. We are beginning to understand how optical variations in AGN are produced and we are able to study the gas surrounding the AGN, and its movement, by monitoring its affect on the X-ray spectrum. With MAXI we are going to be able to improve our understanding of most of the above topics, particularly those which require long-timescale observations, ie scaling of PSD bend timescales, relationship between variations in other bands such as the optical and spectral variations caused by movement of surrounding gas across the source. However to be really useful it is important that MAXI continues for a good deal longer than the nominal 2 year lifetime. Most previous advances have required lightcurves of 5 years or more and so I strongly urge that MAXI remains in operation for at least 5 years, and preferably 10.

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