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Soft X-ray lags and the correlation with black hole mass in radio quiet AGN

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Abstract. The study of time lags between X-ray energy bands in active galactic nuclei (AGN) represents a powerful tool to unveil the physical origin of the different spectral components observed in time-averaged spectra, and to understand the geometry of the inner regions. We present results of a systematic analysis of time lags between X-ray energy bands in a large sample of unabsorbed, radio quiet active galactic nuclei (AGN), observed by XMM-Newton. The analysis of X-ray lags is performed in the Fourier-frequency domain, between energy bands where the soft excess and the primary power law dominate the emission. The 15 (out of 32 analysed sources) detected soft X-ray lags (i.e. variations in the soft band are delayed with respect to variations in the hard band) show a highly significant correlation with the black hole mass, supporting the idea that the lags originate in the innermost regions of AGN.

Key words. Galaxies: active – Galaxies: nuclei – X-rays: galaxies

1. Introduction

The geometry and conditions of matter around supermassive black holes (BHs) in active galactic nuclei (AGN) are still largely debated. The extreme variability events commonly observed in AGN X-ray light curves have proved to be very powerful in improving our understanding of the structure of matter in the strong gravity regime close to the BH. In this contribution we will focus on the analysis of reverberation time delays in the X-ray band (e.g. Fabian et al 2009, Zoghbi et al 2010), which allow to probe very small scales, down to few gravitational radii, r_g.

The mass-scaling relations linking AGN and galactic BHs (e.g. Merloni et al 2003, McHardy et al 2006, Körding et al 2007) suggest that the same physical mechanism is at work in accreting sources spanning a wide range of masses. Standard accretion disc models predict that the characteristic time-scales of these accreting systems depend linearly on the BH mass (e.g. Shakura & Sunyaev 1973, Treves et al 1988). In De Marco et al (2011) we speculate that similar mass-scaling properties might explain the observed difference among soft X-ray lags (i.e. variations in the soft energy band lagging variations in the hard energy band) in two AGN of different mass (i.e. 1H0707-495 and PG1211+143). Here, we present results of a systematic analysis of soft X-ray lags in a large sample of nearby AGN (De Marco et al 2013), with the aim of testing the existence of a correlation of the soft X-ray

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lag's characteristic time-scales (i.e. frequency and amplitude) with BH mass.

2. Selection of the sample and analysis

We analysed a sample of well-exposed, X-ray unobscured ($N_H < 2 \times 10^{22}\mathrm{cm}^{-2}$), radio quiet AGN observed by *XMM-Newton* in targeted observations as of June 2010. The sample is extracted from the *CAIXAvar* sample (Ponti et al 2012) and includes only sources having at least one observation with a longer than 40 ks exposure, published black hole mass, M_{BH}, and significant variability in their X-ray light curves. The latter selection has been carried out by including all the sources with 2-10 keV excess variance (as computed by Ponti et al 2012) different from zero at $\gtrsim 2\sigma$ confidence level. The final sample includes a total of 32 sources.

We made use of all the available XMM-*Newton* observations (ecluding only those highly corrupted by background flares). We analysed only data from the EPIC-pn camera (because of its high effective area and S/N over the 0.3-10 keV energy band). Data reduction was performed using XMM Science Analysis System (SAS v. 10.0), starting from the Observation Data Files (ODF) and following standard procedures.

We computed time lag vs frequency spectra between light curves extracted in the soft and hard X-ray energy bands. The soft and hard energy bands were selected so as to single out energies dominated by the soft excess and the primary power law. The time-lag frequency spectra were computed following the techniques described in Nowak et al (1999).

3. Results

We set as the detection threshold for a soft X-ray lag, the 2σ confidence level ($\sim$ 95 per cent), producing 15 out of 32 sources showing a soft lag with significance well above this limit (11 soft lags having significance > 99 per cent, and the remaining 4 above the 97 per cent confidence level). Our results are perfectly consistent with those already reported in the literature for eight of the sources of our sample (Ark 564, Arévalo et al 2006; 1H0707-495, Zoghbi et al 2010; Mrk 1040, Tripathi et al 2011; Mrk 766, MCG-6-30-15, Emmanoulopoulos et al 2011; RE J1034+396, Zoghbi & Fabian 2011; NGC 3516, Turner et al 2011; PG 1211+143, De Marco et al 2011). Moreover, we report a total of 7 newly detected soft lags (i.e. NGC 4395, NGC 4051, NGC 7469, Mrk 335, NGC 6860, NGC 5548, Mrk 841). The observed values of lag amplitudes and frequencies span about two decades (i.e. $\tau \sim 10 - 600$ s and $\nu \sim 0.07 - 4 \times 10^{-3}$ Hz). These new detections significantly increase the number of soft/negative lags observed in nearby AGN.

3.1. Correlation of soft X-ray lags with BH mass

In Fig. 1 we show the lag frequency and amplitude vs BH mass (ν_{lag} vs M_{BH} and τ vs M_{BH}) trends on a logarithmic scale. BH mass (and related uncertainty) estimates have been taken from the literature (a detailed compilation of references is reported in De Marco et al 2013), preferably choosing estimates obtained from reverberation mapping and stellar velocity dispersion techniques. In the 5 out of 15 cases for which this kind of measurements were not available, we used estimates obtained from the empirical relation between the optical luminosity at 5100Å and the broad line region size (e.g. Bentz et al 2009). The unknown mass uncertainties have been replaced with the estimated dispersion of the adopted relation for mass determination (i.e. 0.5 dex in the case of single epoch methods, and 0.4 dex for the others).

The Spearman's rank correlation coefficient, ρ, for the two data sets have been computed, yielding $\rho \sim -0.79$ and $\rho \sim 0.90$ respectively for ν_{lag} and τ, corresponding to a correlation with significance $\gtrsim 4\sigma$.

To infer the functional dependence of ν_{lag} and τ from M_{BH} we adopted the least squares linear regression approach described in Bianchi et al (2009). The results of the fits (overplotted as continuous and dotted lines in Fig. 1) are $\mathrm{Log}\,\nu_{\mathrm{lag}} = -3.50[\pm 0.07] - 0.47[\pm 0.09]\,\mathrm{Log}(M_7)$ and $\mathrm{Log} \mid \tau \mid = 1.98[\pm 0.08] + 0.59[\pm 0.11]\,\mathrm{Log}(M_7)$, where $M_7 = M_{\mathrm{BH}}/10^7 M_\odot$. The estimated scatter

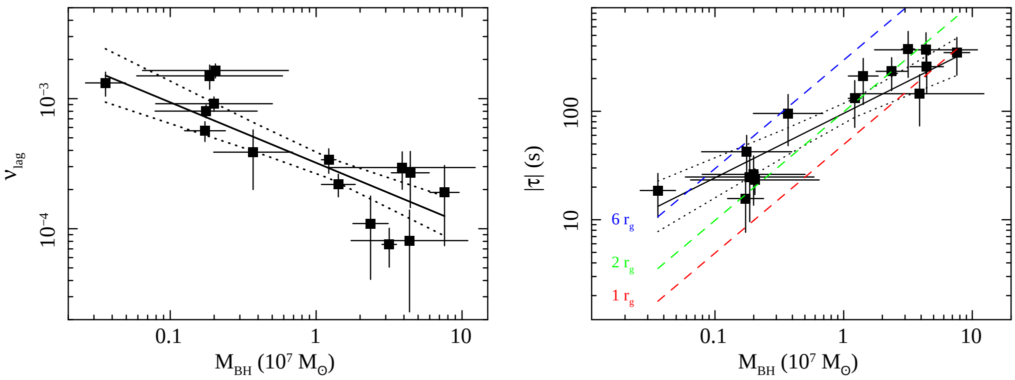

Fig. 1. Negative lag frequency (*left panel*) and absolute amplitude (*right panel*) plotted as a function of BH mass. The overplotted continuous and dotted lines represent the best fit linear models and the combined 1-σ error on the slope and normalization. The dashed lines in the right panel represent the light crossing time at $1r_g$, $2r_g$, and $6r_g$ as a function of mass.

around the best fit model is $\sigma_s \sim 0.19$ and 0.23, respectively for the τ–M_{BH} and ν_{lag}–M_{BH} relations.

Finally, we checked whether the absence of a soft lag in the remaining 17 sources may be real or due to poor statistics. To this aim we included in the correlation plots also the marginal soft lag detections, i.e. 10 with significance between 1-2σ, and 7 with significance $< 1\sigma$. The resulting τ–M_{BH} correlation is shown in Fig.2, where the $> 1\sigma$ detections are plotted with error bars, while the $< 1\sigma$ are marked as 90 per cent upper limits. The agreement with the overall correlation is clear, with the significance increasing to $> 5\sigma$ confidence level.

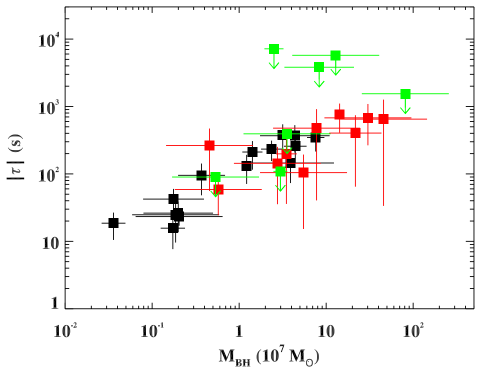

Fig. 2. The 10 marginal soft lags with significance between 1-2σ (red data points) and the 7 with significance $< 1\sigma$ (green upper limits) overplotted to the 15 detections at $> 2\sigma$ (black data points).

4. Discussion

We presented results from a systematic analysis of X-ray lag vs frequency spectra in radio quiet AGN. A total number of 15 out of 32 sources show a significant soft X-ray lag in their light curves, thus significantly increasing the number of soft X-ray lag detections in nearby AGN. The main result is the discovery of a highly significant ($\gtrsim 4\sigma$) correlation between the time-scales (frequency and amplitude) of the detected soft/negative lag and the BH mass. Moreover, none of the remaining 17 sources is, with the available data, significantly outside the observed correlation. Thus all the 32 analysed sources are consistent with showing the same lag properties, and a mass-scaling of soft X-ray lag cannot be excluded in any of them. These results are in agreement with predictions of disc-reverberation models, since the scale of the system, and the corresponding light crossing time ($t_c = r_g/c$, where $r_g = GM/c^2$ is the gravitational radius) depend linearly on the mass of the central object. Despite the inferred best fit slopes for the lag-BH mass relations are statistically different from a linear trend, it is worth noting that the data are affected by several biases (e.g. red noise leakage, length of the observation, see De Marco et al 2013 for details) that have the effect of flattening the intrinsic slope.

5. Conclusions

The overplotted light crossing time at $1r_{\rm g}$, $2r_{\rm g}$, and $6r_{\rm g}$ trends as a function of BH mass in Fig. 1 highlight that the observed soft lags all lay within this range of quite small distances. However, it is worth noting that a more precise inference of the distance mapped by the lag requires a complex treatment and modeling (e.g. Wilkins & Fabian 2013). Even if a thorough understanding of all the soft X-ray lag properties in AGN is yet to be gained, these results all support the idea that these kind of studies are fundametal for probing the physics and geometry of the innermost regions of AGN.

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