PROCEEDINGS OF SCIENCE

AGN variability at hard X-rays

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The global variability properties of AGN at the highest energy X-rays have been poorly studied up to now. *Swift*/BAT offers the unique opportunity to observe a large number of AGN on different time scales in the hard X-ray band above 15 keV. We present here a sample of 110 bright AGN from the 58-month BAT survey, whose variability characteristics were studied as a function of some basic AGN properties, such as the AGN class, luminosity and black hole mass. This represents the largest sample to date for which such a study has been carried out. The blazars in the sample show larger variability than the radio quiet objects, while the radio galaxies exhibit intermediate properties between blazars and Seyfert galaxies. Within the Seyfert class, Seyfert 1.5–2 show only slightly larger variability than Seyfert 1, and the three Narrow Line Seyfert 1 of the sample are on average less variable than their broad line equivalent. We do not find any significant correlation between the amplitude of the variations and hard X-ray luminosity or black hole mass, while harder sources are found to be more variable than objects with steeper hard X-ray spectra. Comparing our results on Seyfert galaxies with observations at energies below 10 keV, we find significant differences, some likely resulting from the different time scales probed in these energy bands, and other (e.g. the lack of anti-correlation between variability and black hole mass) possibly suggesting a different physical origin of the variability below and above 10 keV.

An INTEGRAL view of the high-energy sky (the first 10 years) - 9th INTEGRAL Workshop and celebration of the 10th anniversary of the launch
15-19 October 2012
Bibliotheque Nationale de France, Paris, France

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[*] Speaker.

PoS(INTEGRAL 2012)065

1. Introduction

While the X-ray studies below 10 keV have provided in the last 20 years a large number of results to help establish the empirical properties of variability in AGN (e.g., power spectral density studies, the scaling of variability with BH mass and accretion rate, the correlation with variations at other wavelengths [1]), our knowledge of hard X-ray variability in the domain above 20 keV is mostly based on studies of the spectral variations of single objects or small samples (e.g., with *BeppoSAX* [2], *INTEGRAL* [3, 4], *Suzaku* [5]), and only a few bright AGN could be monitored on time scales of months to years (with *CGRO*/BATSE [6] and *Fermi*/GBM [7]). Within the last 10 years, thanks to the *INTEGRAL* and *Swift* all-sky surveys, increasingly large samples of hard X-ray AGN are available [8, 9, 10], and in particular the BAT instrument on board *Swift* provides the possibility of monitoring a large AGN sample on time scales of years.

A study of the hard X-ray variability of a sample of 44 AGN based on the first 9 months of BAT observations [11] suggested that absorbed AGN (i.e., with intrinsic hydrogen column density $N_\mathrm{H} > 10^{22}\,\mathrm{cm}^{-2}$) appear to be more variable than unabsorbed ones and that more luminous AGN are also more variable at hard X-rays. Other studies, extended to 5 years of data, have been presented on limited AGN samples [12, 13, 14].

Here we present our analysis of a sample of 110 AGN, based on the BAT 58-month survey catalog[1] for which light curves spanning 66 months of BAT observations are publicly provided by the BAT team. The goal of our study is to characterize the AGN variability in the 14–195 keV band and to compare it with the timing properties at softer X-rays, in the hope to gain insight into the mechanisms underlying AGN variability.

2. Sample selection and description

We selected all the sources identified as AGN in the BAT 58-month catalog, excluding the dozen for which a contamination due to source confusion is possibly present. The initial sample is therefore composed by 613 AGN, whose light curves have been rebinned to 30 days and filtered in order to exclude data based on limited exposure time or with large error bars [15]. As a first characterization of the sample, we applied a χ^2 test to each light curve defining it as variable when a null hypothesis probability of $P_{\chi^2_\mathrm{red}} \leq 5\%$ was found for a fit to a constant intensity source. Following this criterion, 36% of the AGN in the sample show variability.

We then quantified the amplitude of the variations for each light curve using the numerical approach proposed by Almaini et al. [16]. The method is based on a maximum-likelihood estimate of the σ_Q parameter defined by those authors, which represents the variability of the time series, optimized for cases with non uniform uncertainties, and which corresponds to the excess variance for constant measurement uncertainties. The σ_Q parameter is normalized by the average value of the time series and multiplied by 100 to obtain the variability estimator $S_\mathrm{V} = \sigma_\mathrm{Q}/\langle F \rangle \times 100\%$. Hence, S_V represents an estimate of the intrinsic variability amplitude of a time series, corrected by the measurement uncertainties, and in percentage units.

The final AGN sample is then selected based on 2 criteria: a) S_V can be computed for the given light curve (i.e., the measured intrinsic variability is larger than the measurement uncertainties);

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[1] http://swift.gsfc.nasa.gov/docs/swift/results/bs58mon/

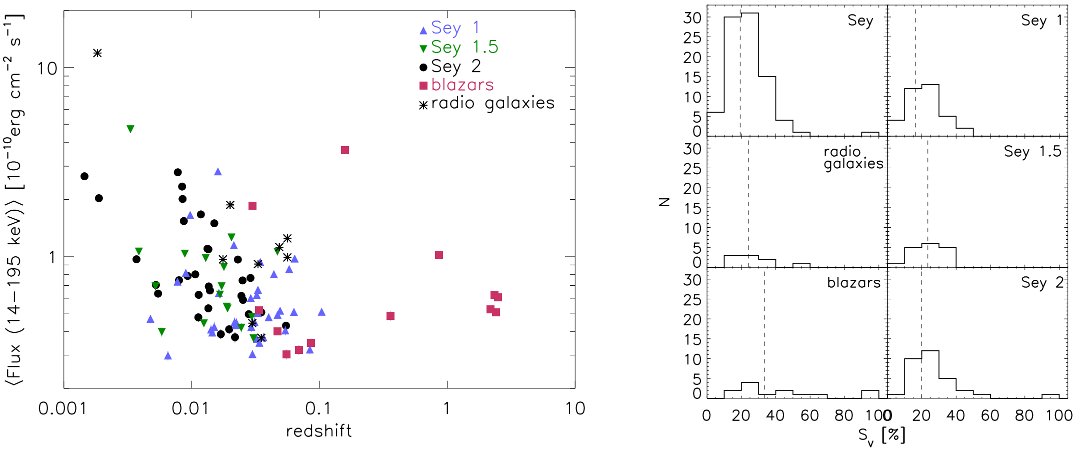

Figure 1: *Left*: Distribution in the 14–195 keV flux and redshift space of the 110 AGN in our sample, separated into the different AGN classes. *Right*: Histograms of the variability amplitude estimator $S_{\rm V}$ for the different AGN classes. The vertical dashed lines indicate the average value of $S_{\rm V}$ for each AGN class.

b) the average value of the signal-to-noise ratio of the points in the light curve is larger than 2. Subsequent analyses were then carried out on the resulting sample of 110 AGN, out of which 88 are Seyfert galaxies (36 type 1, 17 of intermediate type, 32 type 2, and 3 Narrow Line Seyfert 1), 9 radio galaxies and 13 blazars. The objects in the sample have 14–195 keV fluxes between $F = 3\times10^{-11}$ and $1.1\times10^{-9}\,{\rm erg\,cm^{-2}\,s^{-1}}$, and the radio quiet AGN are a local population with an average redshift of $\langle z\rangle = 0.023$ (Fig.1, left panel).

3. Amplitude of the variations

The $S_{\rm V}$ values computed for the 110 AGN in our BAT sample are presented in Fig. 1 (right panel) for the different AGN classes, together with their weighted average value per class. The uncertainties on the $S_{\rm V}$ parameter were computed using a bootstrap method, building a frequency distribution from which the 5th and 95th percentiles are taken as an estimate of the 90% confidence intervals [17].

Blazars show a larger average variability ($\langle S_{\rm V}\rangle_{\rm bla} = 33\pm2\%$) and a wider range of $S_{\rm V}$ than Seyfert galaxies ($\langle S_{\rm V}\rangle_{\rm Sey} = 19.3\pm0.5\,\%$), as expected if the hard X-ray emission of blazars is dominated by jet radiation, as opposed to radio quiet objects for which the hard X-rays are assumed to be produced by thermal Comptonization in a hot corona [18]. Based on a Kolmogorov-Smirnov test, there is a probability $P_{\rm KS} \geq 98\%$ that the blazars and the Seyfert samples are not drawn from the same distribution. On the other hand, the radio galaxies have a rather intermediate behaviour ($\langle S_{\rm V}\rangle_{\rm RG} = 24.0\pm1.4\,\%$), in agreement with their hard X-ray spectrum being often due to the superposition of a Seyfert-like and a blazar-like emission component [19, 20]. The Seyfert 1.5 and 2 objects ($\langle S_{\rm V}\rangle_{\rm Sey1.5+2} = 20.8\pm0.6\,\%$) have a slightly higher variability than the Seyfert 1 ($\langle S_{\rm V}\rangle_{\rm Sey1} = 16.5\pm0.9\,\%$), a not significant difference when tested with a KS-test ($P_{\rm KS} \sim 94\%$).

4. Correlation results

We searched the literature for the masses of the central black holes $M_{\rm BH}$ in the 110 AGN

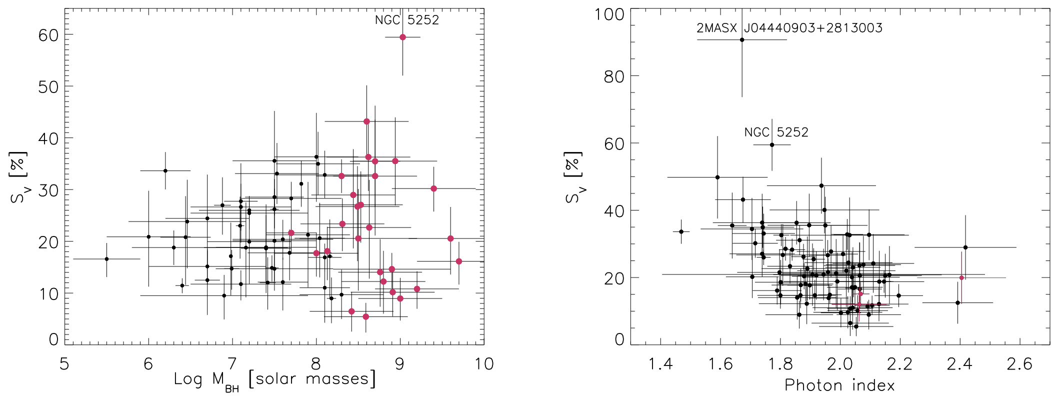

Figure 2: *Left*: S_V versus central black hole mass for the Seyfert sample (circles). The objects that are expected to have a PSD time break at time scales larger than 30 days are highlighted in red. *Right*: S_V versus the 14–195 keV photon index for the Seyfert sample (NLS1 in red). An anti-correlation is detected at $P_{\rm corr} > 99.9\%$ confidence level.

in the sample. An estimate of the black hole mass was found for 91 objects, obtained with several different methods (e.g., reverberation mapping, water maser stellar kinematics, stellar velocity dispersion), hence affected by very different measurement uncertainties.

At softer X-rays (< 20 keV), a well established anti-correlation is observed between the variability and the black hole mass [21, 22], as well as between variability and luminosity [23, 24]. When testing our data set for the presence of such relations, we did not find any significant anti-correlation of S_V with black hole mass (Fig. 2, left panel) or with luminosity. This different behaviour between the hard and soft X-ray results might be, at least in part, explained by the time scales probed by our work. In fact, our variability analysis is sensitive to time scales of months to years, while most of the variability studies below 20 keV sample shorter time scales of days to weeks. Indeed, when the soft X-ray analyses cover longer time scales, the anti-correlations between luminosity or black hole mass and variability become less significant [25]. They show a progressively shallower slope until the point where they disappear for year time scales. This could explain why the early BAT variability studies found an anti-correlation between S_V and luminosity [11, 12].

On the other hand, one would expect a dependence of variability on the black hole mass, for a sub-sample of objects, if the power spectral density (PSD) function of AGN in the hard X-rays followed the same law as that measured in the soft X-rays. In fact, AGN PSD below 20 keV have been estimated for a number of bright Seyfert galaxies suggesting a possible common shape of the X-ray PSD [26]. The PSD of these objects has a power law shape with a plateau at time scales $> T_{\rm break}$. McHardy et al. have suggested that all black holes could follow the same law relating the value of $T_{\rm break}$ to that of the black hole mass and accretion rate (represented by the bolometric luminosity). Speculatively one could assume that this law is valid also for AGN hard X-ray emission, and estimate $T_{\rm break}$ using the measured black hole masses and an estimate of the bolometric luminosities. For the sub-sample of AGN that would have $T_{\rm break} > 30$ days, the PSD would still be increasing in the time frequency range probed by our BAT study, and therefore a dependence of the variability on the black hole mass would be expected. However, even for these objects (in red in the left panel of Fig. 2) there is no anti-correlation between variability and black hole mass. This discrepancy could be explained either by the uncertainties on the measured black hole mass, estimated bolometric luminosities and $T_{\rm break}$ law, which could be too large to allow a sufficiently accurate estimate of $T_{\rm break}$, or if the same law is not valid at both soft and hard X-rays, pointing to an intrinsic difference at the origin of the variations in these two bands (as for example observed in 3C 273 [27]), or if a further change in the PSD shape occurs on large time scales (as observed in Akn 564 [28] and in Galactic black holes), further complicating the expected $S_{\rm V}$ vs $M_{\rm BH}$ relation.

A significant anti-correlation is detected in our sample between variability and the hard X-ray spectral slope (Γ), which is provided in the BAT catalog as a result of a simple power law fit of the 8-bin spectra. Applying a Spearman rank correlation test, we found a correlation coefficient of $R = -0.48$ corresponding to a probability of $P_{\rm corr} > 99.99\%$ (Fig. 2, right panel). The anti-correlation is still significant at a $P_{\rm corr} > 99.99\%$ level ($R = -0.53$) when excluding the objects with the hardest spectra ($\Gamma \leq 1.7$) and those with the largest intrinsic absorption ($N_{\rm H} > 10^{23}\,{\rm cm}^{-2}$). This anti-correlation appears to be opposite to the trend observed at soft X-rays, where AGN with softer spectra are more variable [22]. This is for example the case for Narrow Line Seyfert 1 galaxies at soft X-rays, which are known to present softer spectra and higher variability compared to their broad line equivalent. Yet, even though the 3 NLS1 in our sample indeed have $\Gamma > 2$, they show relatively small variability, $\langle S_{\rm V}\rangle_{\rm NLS1} = 15 \pm 3\,\%$ (red circles in the right panel of Fig. 2). On the other hand, the $S_{\rm V}$ vs Γ trend observed in our sample resembles that of Galactic black holes, which show larger variability during their hard state (i.e., when the hard power law component dominates over the accretion disc one), and present a decrease of variability with the softening of the spectrum in their hard-intermediate state [29].

5. Conclusions

We presented here the preliminary results obtained from the study of the hard X-ray variability properties of a sample of 110 AGN drawn from the *Swift*/BAT 58-month survey. This represents the largest hard X-ray AGN sample for which such study has been carried out up to date.

The average variability of the different AGN classes is consistent with the unified model of AGN, in particular with blazars hard X-ray emission being dominated by the jet component, radio galaxies presenting a superposition of Seyfert-like and blazar-like properties, and Seyfert 1 and Seyfert 2 not showing significant differences in their timing behaviour. When comparing our results to those obtained in the softer X-ray band, significant differences are found, which can be in part accounted for by the longer time scales probed by our analysis compared to those in the band below 10–20 keV. Yet, an intrinsic difference of the processes responsible for the soft and hard X-ray emission in AGN cannot be excluded.

A more comprehensive analysis, including the study of variability on different hard X-ray bands and different time scales, will be soon presented [15].

Acknowledgments

SS and FM acknowledge the Centre National d'Etudes Spatiales (CNES) for financial support. This work has been supported by the LabEx UnivEarthS[2] project “Impact of black holes on their environment”. We thank the anonymous referee for the constructive comments that helped to improve this paper.

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