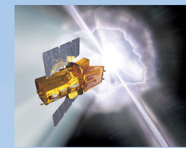
Exploratory X-ray Monitoring of Luminous Radio-Quiet Quasars at High Redshift



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Motivation and Strategy

Were Quasars More X-ray Variable in the Early Universe?

- Powerful quasars, found mostly at high redshift, are ~10^3-10^4 times more luminous than the highly variable local Seyfert galaxies. As a consequence, their emission regions are expected to be physically larger and are thus expected to display slower and milder variations.
- Surprisingly, the past 15 years has seen tentative evidence for quasars of matched luminosity that are *more* X-ray variable as their redshifts increase up to z ≈ 4, even on relatively short timescales (Almaini et al. 2000, MNRAS, 315, 325; Manners et al. 2002, MNRAS, 330, 390; Paolillo et al. 2004, ApJ, 611, 93). This trend suggests evolution of the X-ray variability mechanism, the X-ray emitting region size, or the accretion rate. However, such evolutionary scenarios are perhaps puzzling given that the basic X-ray spectral properties of optically-selected active galactic nuclei (AGNs) have not evolved significantly over cosmic time up to z ≈ 6.
- X-ray monitoring of high-redshift quasars, particularly at $z > 4$, is therefore crucial for resolving this possible discrepancy and for testing evolutionary scenarios of the AGN central engine. While X-ray variability of nearby AGNs has been the subject of intensive study, X-ray variability of high-redshift quasars, has been almost neglected until recently. This project monitors some of the most distant quasars thus probing the earliest stages of AGN formation.

X-ray Monitoring of the Most Distant Quasars

- ***Why X-rays?:*** X-ray variations in AGNs are typically faster and stronger relative to those in, e.g., the optical band. X-ray monitoring is therefore more efficient for studying continuum variations in the most distant quasars.
- ***Goal:*** obtain a *qualitative* assessment of the timescales and amplitudes of X-ray variability in the most distant quasars in order to guide future X-ray missions and provide a benchmark for future X-ray variability studies of distant AGNs. The ultimate goals are to identify the parameters that drive AGN X-ray variability and to test whether X-ray variability has evolved with cosmic time.
- ***Sample:*** a total of seven optically-selected sources, representative of highly luminous type 1 radio-quiet quasars (RQQs). They all display typical blue continua with no broad absorption lines and typical emission line properties, hard X-ray power-law photon indices in the range Γ ~ 1.8 - 2.2, and optical-X-ray spectral slopes (α_{ox}) consistent within 1σ with expectations from their UV luminosities.
- ***Luminosity vs. Redshift:*** the main (*Chandra*) sample of four sources at $z > 4$ is complemented with a comparison (*Swift*) sample of three sources with matched luminosities at lower redshifts in order to distinguish between intrinsic and potential environmental effects on quasar variability by breaking the strong *L-z* dependence inherent in most quasar surveys.

Sample Properties

The *Chandra* Sample

- Redshit: $z > 4$.
- Have > 2 distinct archival epochs (continuous exposures).
- Sufficiently bright for economical *Chandra* observations (too faint for *Swift*).
- Obtain one epoch per source per *Chandra* Cycle.
- Near-simultaneous optical-UV observations provided by ground-based observatories.

Table 1 – Basic Properties of the *Chandra* sample

Quasar	z	M_B	Galactic N_H (10^{20} cm^{-2})	log $L_{2-10\,keV}$ (erg s^{-1})	α_{ox}
Q 0000−263	4.10	−29.3	1.67	45.7	−1.70
BR 0351−1034	4.35	−28.2	4.08	45.4	−1.69
PSS 0926+3055	4.19	−30.1	1.89	45.8	−1.76
PSS 1326+0743	4.17	−29.6	2.01	45.7	−1.76

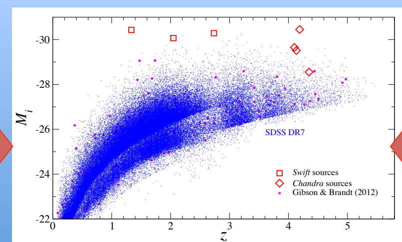

Figure 1 – Absolute *i*-band magnitude vs. redshift for 105,783 SDSS quasars (dots; Schneider et al. 2010, AJ, 139, 2360). The *Chandra* (*Swift*) sources are marked with diamonds (squares). SDSS quasars from the Gibson & Brandt (2012, ApJ, 746, 54) study are marked with circles. One *Chandra* source, PSS 1326+0743, and two *Swift* sources, PG 1247+267 and HS 1700+6416, are also SDSS quasars.

The *Swift* Sample

- Luminosities comparable to the *Chandra* sample, but lower redshifts ($1.33 < z < 2.74$).
- Largest number of distinct archival epochs (3 - 12).
- Sufficiently bright for economical *Swift* observations.
- Obtain ~3 epochs per source per *Swift* Cycle.
- Simultaneous optical-UV observations provided by *Swift/UVOT*.

Table 2 – Basic Properties of the *Swift* sample

Quasar	z	M_B	Galactic N_H (10^{20} cm^{-2})	log $L_{2-10\,keV}$ (erg s^{-1})	α_{ox}
PG 1247+267	2.04	−29.5	0.90	45.9	−1.69
PG 1634+706	1.33	−30.1	4.48	45.9	−1.69
HS 1700+6416	2.74	−29.9	2.66	45.6	−1.83

Light Curves, Variability Amplitudes, and Structure Functions

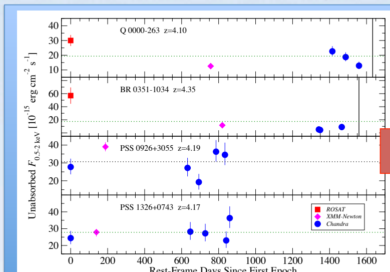

Figure 2 – Light curves of the *Chandra* sources as of June 2014. Galactic-absorption corrected flux in the 0.5-2 keV band is plotted as a function of rest-frame days relative to the first X-ray epoch for each source. Squares, diamonds, and circles mark *ROSAT*, *XMM-Newton*, and *Chandra* observations, respectively. Vertical lines mark the remaining scheduled Cycle 15 epochs. The dotted line in each panel indicates the mean flux.

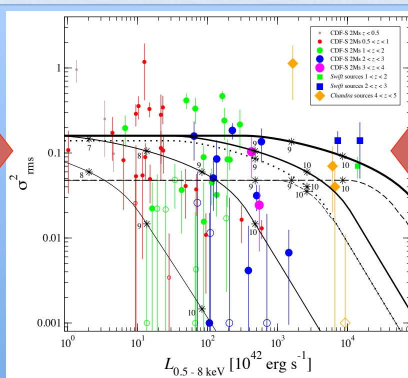

Figure 4 – Excess variance (σ^2_{rms}; see below) vs. luminosity in the observed-frame 0.5-8 keV band. Circles represent X-ray-selected AGNs from the 2 Ms exposure of the *Chandra* Deep Field-South survey. Squares and diamonds represent the *Swift* and *Chandra* sources, respectively. Symbol sizes increase with increasing source redshift, and open symbols indicate non-variable sources; brown, red, green, blue, magenta, and orange symbols mark sources at $z < 0.5$, $0.5 < z < 1$, $1 < z < 2$, $2 < z < 3$, $3 < z < 4$, $4 < z < 5$, respectively. Sources with negative σ^2_{rms} values have been assigned a fixed excess variance of $\sigma^2_{rms} = 0.001$. Error bars on σ^2_{rms} represent "formal" errors due only to flux measurement errors and not those due to red-noise intrinsic scatter. Simulations of σ^2_{rms} as a function of X-ray luminosity, using the Papadakis et al. (2008, A&A, 487, 475) model, are represented by: (1) continuous lines using $T_{max,\,rest}$ = 8 yr, $T_{min,\,rest}$ = 1 day, and L/L_{Edd} = 0.001, 0.01, 0.1, 0.5, where line thickness increases with increasing L/L_{Edd}, (2) dashed lines using $T_{max,\,rest}$ = 3 yr, $T_{min,\,rest}$ = 100 days, and L/L_{Edd} = 0.1, 0.5, where line thickness increases with increasing L/L_{Edd}, and (3) a dotted line using $T_{max,\,rest}$ = 3 yr, $T_{min,\,rest}$ = 1 day, and L/L_{Edd} = 0.1. Stars with annotated values along each curve indicate log M_{BH} values (in units of $M_\odot$) derived from the corresponding X-ray luminosity and the assumed L/L_{Edd}.

The excess variance is defined as $\sigma^2_{rms} = \frac{1}{N_{obs}\langle f\rangle^2}\sum_{i=1}^{N_{obs}}\left[\left(f_i-\langle f\rangle\right)^2-\sigma_i^2\right]$, and its error is defined as $s_D/\left(\langle f\rangle^2\sqrt{N_{obs}}\right)$, where $s_D^2=\frac{1}{N_{obs}-1}\sum_{i=1}^{N_{obs}}\left\{\left[\left(f_i-\langle f\rangle\right)^2-\sigma_i^2\right]-\sigma^2_{rms}\langle f\rangle^2\right\}^2$, f_i and σ_i are the flux and its error in the ith observation, respectively, N_{obs} is the number of observations, and $\langle f\rangle$ is the mean flux of the light curve (Turner et al., 1999, ApJ, 524, 667).

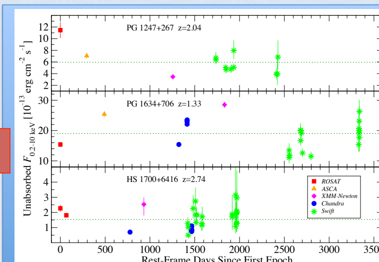

Figure 3 – Light curves of the *Swift* sources. Galactic-absorption corrected flux in the observed frame 0.2-10 keV band is plotted as a function of rest-frame days relative to the first X-ray epoch for each source. Squares, triangles, diamonds, circles, and stars indicate *ROSAT*, *ASCA*, *XMM-Newton*, *Chandra*, and *Swift* observations, respectively. A much earlier *Einstein* observation of PG 1634+706 with an unabsorbed flux of $F_{0.2\text{-}10\,keV}$ = (16.0±3.2) × 10^{-13} erg cm^{-2} s^{-1} is not shown in the middle panel, for clarity. The dotted line in each panel indicates the mean flux.

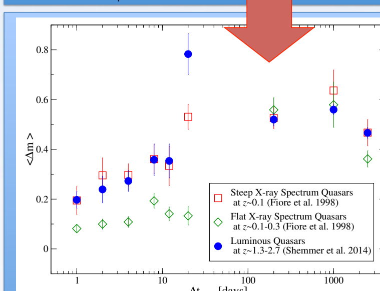

Figure 5 – Ensemble structure function (SF; see below) of the *Swift* sources (circles) compared to the ensemble SFs of the steep- and flat-X-ray-spectrum quasars at low redshift, marked by squares and diamonds, respectively, adapted from Fiore et al. (1998, ApJ, 503, 607). Average magnitude difference in each time bin is plotted as a function of rest-frame time interval. The temporal behavior of the *Swift* sources is remarkably similar to that of steep-X-ray-spectrum quasars, perhaps due to the fact that both groups have similarly high accretion rates.

The structure function is defined as $\Delta m_{ji} = \left|2.5\log\left[f(t_j)/f(t_i)\right]\right|$, where $f(t_j)$ and $f(t_i)$ are the fluxes of a source at epochs t_j and t_i, respectively, such that $t_j > t_i$, and every t_i is measured in rest-frame days since the first epoch, i.e., $t_1 = 0$ (Fiore et al. 1998, ApJ, 503, 607).

Summary and Ongoing Work

- RQQs exhibit an excess in X-ray variability, above the well-known amplitude-luminosity anticorrelation, almost independent of L or z, at $L > 10^{44}$ erg s^{-1} in the 0.5-8 keV band. This excess may be primarily due to higher L/L_{Edd} values at higher L and z.
- There is no direct evidence of evolution in the X-ray variability of RQQs up to z ~ 4.2, but a firmer conclusion will require continued monitoring, especially of the *Chandra* sources.
- Sources from both samples vary more on longer timescales than on shorter timescales, in agreement with AGN behavior at lower L or z, and some exhibit significant variability on timescales as short as ~ 1 day in the rest frame.
- Luminous RQQs display significant variations in α_{ox} values which are dominated by the X-ray variations. This confirms earlier reports that the dispersion in the luminosity-corrected α_{ox} distribution of type 1 RQQs may be dominated by variability.
- Except for HS 1700+6416, no significant X-ray spectral variations are detected in any of the sources, even for corresponding flux variations of up to a factor of ~ 4.
- Continued monitoring will enable better characterization of the X-ray variability properties, especially for the *Chandra* sources for which structure functions (see Fig. 5) could be constructed in order to quantify their variability timescales.

The initial results of this project appear in Shemmer et al. (2014, ApJ, 783, 116). *Left*: link to paper. *Right*: link to poster.