First Statistical Tests for Clumpy-Torus Models: Constraints from *RXTE* Monitoring of Seyfert AGN

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Abstract

This presentation is a summary of highlights from Markowitz, Krumpe, & Nikutta (2014) and preliminary results from our follow-up paper, Nikutta, Krumpe, & Markowitz, in prep. We present an analysis of multi-timescale variability in line-of-sight X-ray absorbing gas as a function of optical classification in AGN to derive the first statistical constraints for recent clumpy absorbing torus models. Such models represent the paradigm shift away from the classical assumed "solid donut" morphology and towards a morphology containing numerous discrete clouds or clumps. Such advances come courtesy of sustained long-term X-ray monitoring; we use the vast archive of *Rossi X-ray Timing Explorer* (*RXTE*) multi-timescale monitoring of dozens of type I and Compton-thin type II Seyfert AGN. We search for discrete absorption events due to clouds transiting the line of sight; most of our twelve detected clouds are Compton-thin and are located in the outer BLR or inner dusty torus. We discuss the resulting implications for cloud distributions in the context of Clumpy torus models. We discuss cloud sizes, stability, and radial distribution across a wide range of distances, and explore the exhibited range in density profiles for the highest-quality eclipse events. We discuss possible connections to the mechanisms that form and launch clouds. In addition, all observed clouds are sub-critical with respect to tidal disruption; self-gravity alone cannot contain them. External forces, such as magnetic fields or ambient pressure, are needed to contain them. Otherwise, clouds must be short-lived. Our results apply to both dusty and non-dusty clumpy media, and probe model parameter space complementary to that for short-term eclipses observed with *XMM-Newton*, *Suzaku*, and *Chandra*.

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

1. Introduction

The exact morphology of the circumnuclear gas in active galactic nuclei (AGN) remains unclear, but holds the key to answering how material gets funneled from radii of kpc in the host galaxy down to the accretion disk, and ultimately feeds the supermassive black hole. This unsolved question impacts our understanding of the efficiency of black hole feeding as well as AGN duty cycles.

The community has long been in the process of shifting away from quantifying emission and absorption processes in Seyferts by modeling circumnuclear gas via a simplified homogeneous, Compton-thick " donut "morphology. Instead, a new generation of models describe the torus via distributions of numerous individual clouds (Elitzur 2007; Nenkova et al. 2008), although suggestions that the torus should consist of clouds go as far back as, e.g., Krolik & Begelman (1986); Krolik & Begelman (1988). Often, the clouds are embedded in some outflowing wind from the cold, thin accretion disk which feeds the black hole. Observational support for these models so far has come mainly from fitting IR SEDs in small samples of Seyferts (Ramos Almeida et al. 2011; Alonso-Herrero et al. 2011).

Evidence for clumpy tori also comes from variations in column densities $N_{\rm H}$ of line-of-sight X-ray absorbing columns in both (optically classified) type Is and IIs, with timescales of variability ranging from hours to years (Risaliti, Elvis, & Nicastro 2002). The community has also observed moderately Compton-thick variations in NGC 1365 (Risaliti et al. 2007; Risaliti et al. 2009) and NGC 7582 (Bianchi et al. 2009), as well as rapid changes in covering fractions of partial-covering absorbers (Puccetti et al. 2007; Risaliti et al. 2011; Sanfrutos et al. 2013). When adequate data exist, time-resolved spectroscopy of full eclipse events has yielded constraints on density profiles in the transverse direction for long-duration (3–6 months) eclipses in NGC 3227 (Lamer et al. 2003) and Cen A (Rivers et al. 2011) and for eclipses $\sim$1 d in NGC 1365 (Maiolino et al. 2010) and SWIFT J2127.4+5654 (Sanfrutos et al. 2013). In addition, X-ray obscuration is the only way to probe obscuration inside the dust sublimation radius $R_{\rm d}$, and to test the notion that the dust-free BLR and dusty torus form a common radially extended structure inside and outside $R_{\rm d}$, resepctively (Netzer & Laor 1993; Elitzur 2007; Gaskell et al. 2008).

Typically for clumpy-torus models such as the Clumpy models by Nenkova et al. (2008), the cloud distribution is preferentailly concentrated towards the equatorial plane, and is described by a Gaussian angular distribution σ, mean number of clouds along an equatorial ray N_0, and a given radial power-law distribution out to some maximum radius, with each cloud being identical and having the same optical depth.

A statistical survey of the environments around supermassive black holes has been needed to properly constrain parameter space in the Clumpy models. These parameters so far have been constrained only from IR SED fitting, as mentioned above. In our 2014 paper, Markowitz, Krumpe, & Nikutta (2014; hereafter MKN14), we present the first such *X-ray-absorption*-based survey, the longest AGN X-ray monitoring study to date. Our survey quantifies line-of-sight X-ray absorption by clouds that transit the line of sight to the central engine. We assessed the relevance of Clumpy torus models as a function of optical classification by exploring absorption over a wide range of length scales (both inside and outside the dust sublimation zone).

2. Methodology

We consider archival data collected with *RXTE*'s Proportional Counter Array (PCA). *RXTE* was the first X-ray mission to operate using sustained monitoring campaigns, with regularly spaced visits, usually 12 ks each, over durations of weeks to years.

RXTE visited 153 AGN over its lifetime. We only consider sources with mean 2–10 keV flux $\gtrsim 8 \times 10^{-12}$ erg cm^{-2} s^{-1}, and visited at least four times during the mission. We do not consider blazars. Due to the PCA's energy resolution, we cannot accurately quantify changes in $N_{\rm H}$ when a steady full-covering Compton-thick absorber is present, other than verifying that none of the seven Compton-thick sources monitored by *RXTE* transitioned to/from being Compton-thin. The final target list consists of 37 type I and 18 Compton-thin type II AGN. Here, we classify "type I" to include Sy 1.0, 1.2, and 1.5; we classify "type II" to include Sy 1.9 and 2 (we had no type 1.8s in our sample). 11/18 type IIs in our sample show evidence for "hidden" BLRs, manifested via scattered/polarized optical emission or via IR Paschen lines, and we adhere to the assumption that BLRs do exist in all our objects, and that optical classifications are due to increasing levels of obscuration in the optical band, independent of assumptions about system orientation.

We examined 7–10/2–4 keV hardness ratio ($HR1$) light curves; assuming full-covering absorption, $HR1$ peaks at column densities roughly $1 - 3 \times 10^{23}$ cm^{-2} while giving us sensitivity down to $\sim$ a few 10^{22} cm^{-2}. A simple power-law fit to the 2–10 keV band, not accounting for absorption, can also indicate excess absorption: measurements of the "apparent" photon index suddenly falling to values lower than $\sim 1.5 - 1.6$, the typically flattest coronal power-laws measured in unabsorbed Seyferts, are likely due to absorption events. We distinguish between "secure" vs "candidate" eclipse events: the former group are those confirmed via binned time-resolved spectral fitting to have a temporary increase in $N_{\rm H}$. Additional analysis details and eclipse identification criteria are presented in MKN14.

As a caveat, we are only able to detect an absorption event and rule out spectral pivoting if the cloud's covering fraction is greater than $\sim 80 - 90\%$, and if its ionization parameter ξ [erg cm s^{-1}] is less than $\log \xi \sim 1 - 2$. Our findings are thus complementary to those derived using the archival databases of other X-ray missions: *XMM-Newton*, *Chandra*, and *Suzaku* can probe clouds with lower column densities, partial covering, and/or high-ionization absorption, and eclipse events with durations $\lesssim$1–3 d (Turner et al. 2008; Risaliti et al. 2011). However, unlike *RXTE*, these missions generally do not perform sustained monitoring campaigns and are not able to detect absorption events longer than $\sim$ a few days. In addition, *RXTE*-PCA's coverage above 10 keV affords increased sensitivity to higher absorbing columns.

3. Summary of main results

We find twelve "secure" X-ray absorption events (confirmed with spectral fitting) across eight Seyferts: NGC 3783, NGC 3227, MR 2251–178, Mkn 79, Mkn 509, Cen A, Mkn 348, and NGC 5506. Four of these eclipse events were reported previously (Lamer et al. 2003; Rivers et al. 2011; Rothschild et al. 2011; Smith et al. 2001; Akylas et al. 2002). We also report an additional four "candidate" events in three Seyferts (NGC 3783, NGC 3516, and Fairall 9).

The "secure" events span durations from less than one day (for NGC 5506) to 1.5 years (for Mkn 348). The clouds are modeled to have column densities spanning $4 - 26 \times 10^{22}$ cm^{-2}; we did not detect any full-covering Compton-thick clouds. Assuming a Galactic gas/dust ratio, these X-ray columns imply dust with V-band extinction $A_V = 22-144$ mag., and V-band optical depths τ_V of 20–132. These values are consistent with optical depths typically used in CLUMPY modeling (Nenkova et al. 2008) and derived by fits to IR SEDs by Alonso-Herrero et al. (2011) and Ramos Almeida et al. (2011).

To estimate the distance to a given cloud from the supermassive black hole $r_{\rm cl}$, we use the measured eclipse duration and column density, combined with constraints on the cloud ionization level. Specifically, we follow §4 of Lamer et al. (2003) and assume that clouds are in Keplerian orbits and that each cloud has a uniform density. Cloud diameter $D_{\rm cl} = N_{\rm H}/n_{\rm H} = v_{\rm cl}t_{\rm D}$, where $t_{\rm D}$ is the measured eclipse time and $v_{\rm cl}$ is the transverse velocity, equal to $\sqrt{GM_{\rm BH}/r_{\rm cl}}$. Using the definition of ionization parameter ξ, one obtains (see Eqn. 3 of Lamer et al. 200 3): $r_{\rm cl} = 4\times10^{16}M_7^{1/5}L_{42}^{2/5}t_{\rm D}^{2/5}N_{\rm H,22}^{-2/5}\xi^{-2/5}$ cm, where $M_7 = M_{\rm BH}/10^6M_\odot$, $L_{42} = L_{\rm ion}/(10^{42}$ erg s$^{-1})$, $N_{\rm H,22} = N_{\rm H}/(10^{22}$ cm$^{-2})$, and $t_{\rm D}$ is in units of days.

Our constraints on the ionization parameters for our clouds are poor. Given the column densities of our clouds and the energy resolution of the PCA, we can safely rule out values of log(ξ) above ~ 2. We therefore calculate distances assuming log(ξ) $= -1$, 0, or +1. Uncertainty on $r_{\rm cl}$ is thus dominated by uncertainty on ξ.

We obtain best-estimate values of $r_{\rm cl}$ that are typically tens to hundreds of light-days from the central engine, and lie in the range $1-50\times10^4R_{\rm g}$ ($0.3-140\times10^4R_{\rm g}$ accounting for uncertainties).

The clouds in 7/8 objects (all except NGC 5506) are consistent with the dust sublimation zone considering uncertainties on $r_{\rm cl}$, i.e., in the outer BLR and/or inner dusty torus. However, this "clustering" may be in part associated with our observational bias to select eclipses with events of ~tens of days, as per our selection function. In Cen A, the clouds are inferred to be consistent with residing entirely in the dusty zone. In contrast, NGC 5506 has the lowest value of $r_{\rm cl}/R_{\rm d}$; this cloud is likely the least dusty of the secure events in our sample, and is likely commensurate with that source's BLR.

The average cloud diameter was $\sim$ 5 light-hours (roughly the Sun–Neptune distance). In addition, the inferred diameters and locations for these (full-covering) clouds imply upper limits to the size of the X-ray continuum-emitting region. These limits are as low as $2R_{\rm g}$ for NGC 5506 and $45-65R_{\rm g}$ for NGC 3783, Mkn 79, and Mkn 509. The average cloud mass was $10^{-5.2}$ $M_\odot$, and the average number density was $10^{8.5}$ cm^{-3}.

4. Resolving clouds' density profiles

When adequate time-resolved data are present, we can obtain information on a given cloud's density profile in the transverse direction, and recent results are beginning to reveal a diversity in cloud profile shapes.

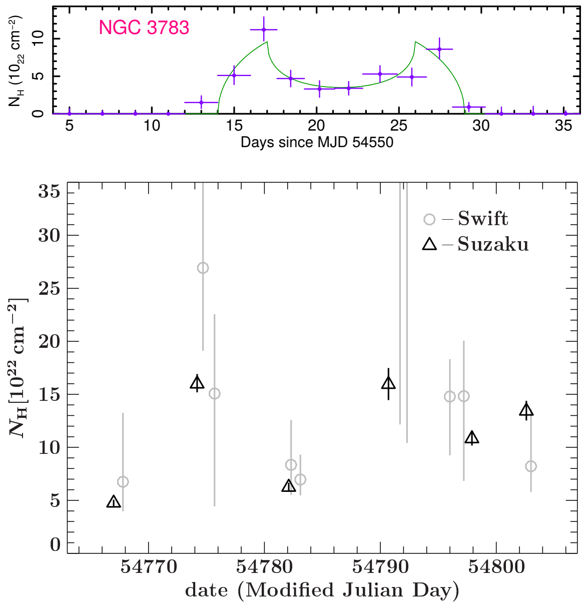

Fig. 1. The community is starting to amass a variety in behavior in clouds' column density profiles as traced by $N_{\rm H}(t)$, when adequate sampling and signal-to-noise allow. *(Top panel)* — From MKN14: an 18-day long eclipse event in NGC 3783 as traced by *RXTE*, revealing two column density peaks. *(Bottom panel)* — From Beuchert et al. (2015): a five-week *Suzaku*/*Swift* campaign on NGC 3227 in 2008 caught the source obsured by an ionized cloud with an irregular density profile.

For example, the 2010–11 eclipse in Cen A observed by Rivers et al. (2011) had a $N_{\rm H}$ profile that was symmetric in time and centrally-peaked; Rivers et al. (2011) found that a centrally-peaked number density fit better than a uniform number-density sphere. Lamer et al. (2003) and Sanfrutos et al. (2013) also observed symmetric $N_{\rm H}$ profiles in the 2000–1 eclipse of NGC 3227 and an eclipse in SWIFT J2127.4+5654, respectively.

However, many other eclipse profiles reveal embedded overdense/underdense regions: a double-peaked $N_{\rm H}$ profile in NGC 3783 observed by MKN14, a highly variable profile in a NGC 3227 event during a five-week *Suzaku*/*Swift* campaign measured by Beuchert et al. (2015) (see Fig. 1), and "comet" and "anti-comet" shapes observed in NGC 1365 by Maiolino et al. (2010) and Rivers et al. (2015).

These profiles may be clues as to how clouds are formed and sculpted, e.g., the torus may be a dynamically active place, with eclipsing clouds possibly being due to MHD winds launched upwards from the disk (Fukumura et al. 2010; Czerny & Hryniewicz 2011) and/or compressed by poloidal magnetic fields (Emmering et al. 1992).

5. On non-variable absorption in type IIs

We find evidence in eight type II Seyferts for a baseline level of X-ray absorption that is constant in time over timescales from 0.6 to 8.4 years; the observed hardness ratios place limits on $\Delta N_{\rm H} \sim 0.6 - 9 \times 10^{22}$ cm^{-2} (see Fig. 2). In the context of clumpy-torus models explaining all the observed absorption, one would require that a large number of very low-column density ($\ll 10^{22}$ cm^{-2}) clouds along the line of sight, with the total number of clouds along thre line of sight remaining roughly constant within each object. Alternately, the constant level of absorption can be explained by absorbing structures associated with the host galaxy, e.g., dust lanes (Gould et al. 2012). Another possibility is a medium of non-clumpy, highly homogeneous gas close to the black hole, such as a homogeneous intercloud medium.

However, in Cen A, MKN14 detected an 80-day "anti-eclipse": the baseline level of absorption temporarily dipped by $\sim$ 14% then recovered. This event suggests that material close to the black hole is not highly homogeneous, and that we witnessed a transit across the line of sight by a relatively underdense region.

6. Instantaneous probabilities to witness an eclipse

We derived the probability to catch a type I/II source undergoing an eclipse event that has any duration between 0.2 d and 16 yr, taking into account the highly inhomogeneous sampling in our X-ray observations. That is, we estimated the probability to instantaneously observe a source undergoing an eclipse event due only to a cloud passage through the line of sight, and independent of long-term constant absorption, e.g., associated with gas in the host galaxy.

For type Is, it is 0.006 (error range: 0.003–0.166); for type IIs, 0.110 (0.039–0.571). Our uncertainties are conservative, as they take into account our selection function, candidate eclipse events in addition to the secure ones, uncertainties in the observed durations, and uncertainties in the contributions of individual objects 's sampling patterns to our total sensitivity function; we used a Monte Carlo "bootstrap" method to estimate uncertainties.

Although subject to low number statistics, our observations hint at differences in the distributions of observed eclipse event durations and probabilities for type I and II objects. In addition, assuming that all type Is or IIs have a common cloud distribution morphology, then these instantaneous probability values can be compared to CLUMPY theoretical predictions that assume certain cloud distribution parameters (CLUMPY parameters inclination angle, angular distibution of clouds, and number of clouds along an equatorial ray) to provide constraints on these parameters.

However, as a caveat, these probabilities were derived with a sample that had some biases due to highly inhomogeneous X-ray sampling, and due to type Is' being sampled $\sim 4 - 5$ times more often than type IIs. We were also limited in sensitivity to changes in column density no lower than $\sim 10^{22}$ cm^{-2}. In addition, we were not highly sensitive to absorption by highly-ionized or partial covering gas; our PCA spectra were sensitive to ionization levels up to $\log \xi \sim 1 - 2$. When one considers the full range of possible cloud properties, the resulting probabilities will almost certainly be higher.

7. Preliminary results from Nikutta et al., in prep: additional constraints on cloud properties

We also present a brief overview of results from our forthcoming paper in which we derive additional constraints on cloud properties.

The "long-term event" clouds in MKN14 inferred to reside in the outer BLR/inner dusty torus and the "short-term event" clouds reported by Risaliti et al. (2007), Risaliti et al. (2009), Maiolino et al. (2010), Sanfrutos et al. (2013), and Turner et al. (2008) and inferred to reside in the BLR are all roughly consistent with a common angular size as seen from the central source, $\sim$ 1.4 arcmin. That is, cloud physical diameters are consistent with increasing linearly with linear distance from the central black hole. This fact may provide a hint at cloud formation mechanisms: if clouds are formed from the disk, for example, various cloud fragmentation mechanisms e.g., Amaro-Seoane & Chen (2014), may be applicable.

This small average angular size also suggests that in order for clumpy-torus models to explain the total observed median line of sight absorption in type I/II Seyferts (Ramos Almeida et al. 2011), a total of 4×10^7 (type Is) or 8×10^7 (type IIs) clouds may exist across the BLR + dusty torus (assuming no cloud overlap). These values assume that clouds only account for all absorption; the presence of an intercloud medium or absorption due to host galaxy dust lanes along the line of sight would of course yield lower cloud numbers.

We also infer that the 12 secure clouds events from MKN14 do not possess sufficient self-gravitational resistance to tidal shearing. A cloud in orbit will be able to withstand gravitational torque only if its density is greater than the "ambient" local density of the black hole mass spread out evenly over the sphere of the cloud's orbit. We use the estimates of cloud number density from MKN14, and find that clouds are underdense by factors of 10–1000 to resist tidal shearing. The ambient pressure from an inter-cloud medium could suffice to confine clouds (Netzer 2013). Alternatively, an ambient magnetic field can confine clouds, as suggested by Rees (1987) for BLR clouds (although the argument also applies to torus clouds); we estimate that the minimum required magnetic field strength is only a few milli-Gauss.

8. Future prospects

While the *RXTE* sample represents the best current opportunity to explore long-term eclipses and clouds in the outer BLR/dusty torus, we were limited to exploring neutral or near-neutral, full-covering or near-full-covering (covering fraction $\gtrsim 90\%$) clouds.

To effectively explore larger regions of [$N_{\rm H}$, covering fraction, ξ, Δt] parameter space in the future, our idealized "X-ray monitoring wish list" for obtaining additional constraints from X-ray eclipses thus includes: •Sustained monitoring with evenly-spaced sampling, down to timescales of hours, with consistent source-to-source coverage to mitigate observing biases as a function of time. •Soft X-ray coverage to access lower column densities and lower values of $\Delta N_{\rm H}$ compared to PCA, and to access constraints on cloud ionization parameter. •Access to lower 2–10 keV fluxes and a larger number of type IIs, as they are expected to harbor a higher number of line of sight clouds if orientation is the dominant factor in type I/II unification. In the context of clouds being produced in a disk wind, however, BLR/torus cloud production may be hampered towards low luminosities (Elitzur & Ho 2009), and cloud numbers as a function of luminosity across the BLR and dusty torus must be tested. We also need to test whether "baseline" levels of absorption are truly constant, indicating either host galaxy absorption or a highly-homogeneous intercloud medium, or variable, suggesting transiting over- or under-dense regions close to the AGN. •We must span a wider range of luminosities than in MKN14 to test if covering factor evolves with luminosity, as implied by multiple high-redshift studies (Ueda et al. 2014). •At least CCD-quality spectral monitoring to fully deconvolve variations in $N_{\rm H}$ and Γ, and confirm partial-covering events. •Ideally, if optical/UV monitoring is in place simultaneous to X-ray monitoring, such monitoring can tell us whether the cloud is dusty.

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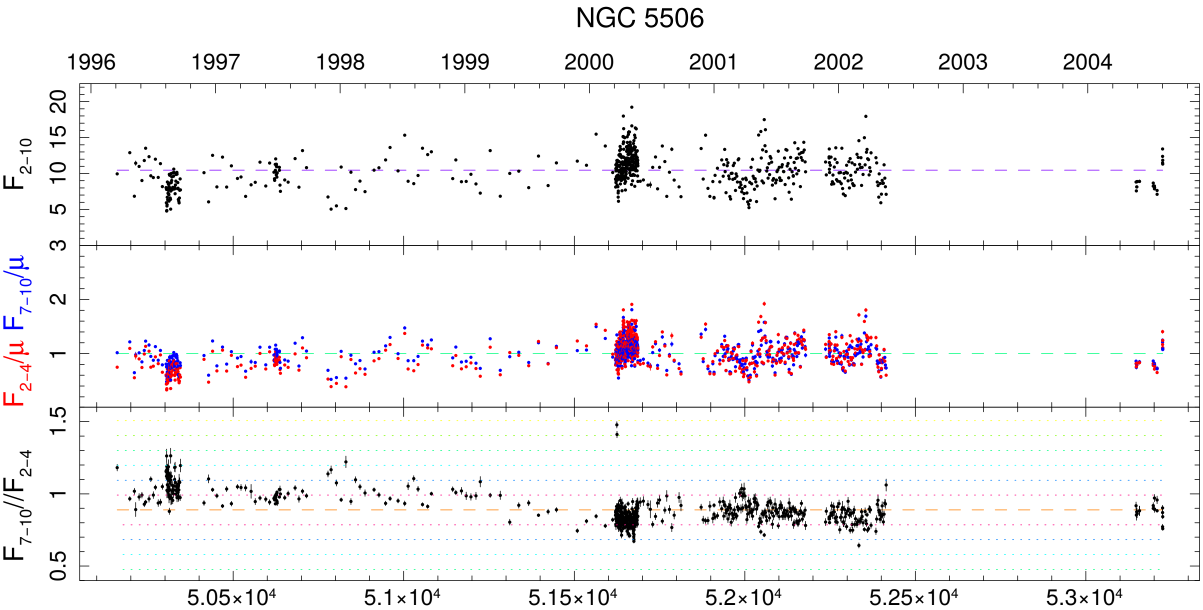

Fig. 2. From MKN14: *RXTE*-PCA light curve of the Sy 1.9 NGC 5506, showing light curves for the 2–10, 2–4, 7–10 keV bands, and the 7–10/2–4 keV hardness ratio. The hardness ratio is consistent with a baseline level of absorption that is constant down to $\Delta N_{\rm H} \sim 1 \times 10^{22}$ cm^{-2} for a duration of eight years; the exception is the short-term cloud transit in 2000. (The mild shift in average harness ratio in 1999 is instrumental, and not intrinsic to the source.)