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

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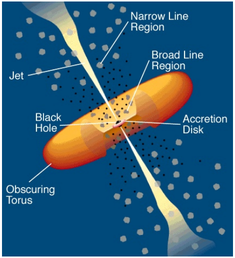
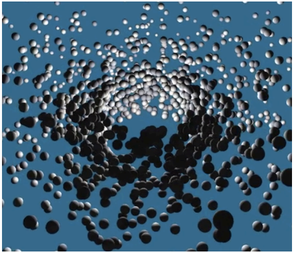
Objective: Morphology of Accreting/Outflowing Gas in AGN





(Urry & Padovani 1995, etc.)

(Nenkova et al. 2008; Elitzur et al. 2006)

- Continuous structures? Discrete clumps/clouds? Both?
- Trace geometry/densities of structures that transit the line of sight and temporarily absorb the centrally-emitted X-rays.
- Refine CLUMPY model parameters for cloud distributions

X-ray eclipse events in the RXTE archive

Survey of X-ray eclipse events in the RXTE archive using large samples of Type I & Compton-thin Type IIs, and probing $\Delta N_{\rm H}$ on timescales from days to years

Markowitz, Krumpe, & Nikutta 2014, MNRAS 439 1403:
Identify eclipse events due to transiting clouds
→ locations
→ properties of individual clouds
→ eclipse probabilities

Nikutta, Krumpe, & Markowitz, in prep.:
⟶ cloud sizes; cloud stability;
⟶ Bayesian methods to constrain Clumpy-model parameters

Evidence for Clumpy Tori

- IR SED fitting at high spatial resolution for a couple dozen Seyferts (Ramos Almeida et al. 2011)
- Silicate features (9.7μm & 18μm) span a range of emission AND absorption within each type
- X-ray: Variations in $N_{\rm H}$ on timescales from hours to years in **both** optical classes!

$\Delta N_{\rm H} \sim 10^{23-24}$ cm^{-2} on timescales $\lesssim 1-3$d observed with *Chandra*, *Suzaku*, or *XMM-Newton*; commensurate with **BLR** (e.g., NGC 1365, Mkn 766, Risaliti et al. 2005, 2009, 2011)

MKN14 Methodology

Rossi X-ray Timing Explorer (Dec. 1995 – Jan. 2012)

Proportional Counter Array (PCA), 2–60 keV

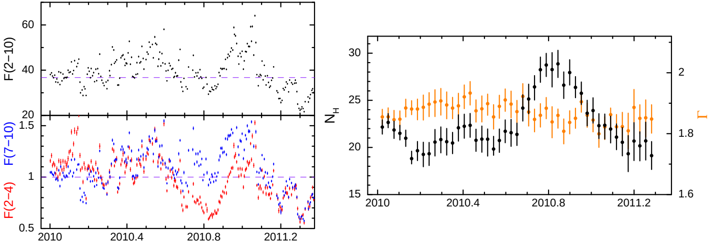
Sustained flux & spectral monitoring campaigns!

X-ray flux & spectral variability on timescales from hours to a decade

MKN14 Methodology

- 55 Seyferts monitored by RXTE, $\Delta T = 0.3$ d – 10 yr
- 37 Type I, 18 Type II
- Examine hardness ratio and photon index light curves
- Follow-up time-resolved spectroscopy to constrain $N_{\rm H}(t)$

Example event: Clumpy Absorber in Cen A



Rivers, Markowitz, & Rothschild, 2011, ApJ, 742, L29

RXTE monitoring: 6-month long eclipse, 2010–1

$\Delta N_{\mathrm{H}} = 8 \times 10^{22}$ cm^{-2}

Overview of Markowitz et al., 2014, MNRAS, 439, 1403

• Twelve spectroscopically-confirmed transit events by lowly-ionized clouds in eight Seyferts (eight events are new)

• Durations span $\sim$ 12 hr to $\sim$ 550 d

• $\Delta N_{\rm H}$ spans $4 - 26 \times 10^{22}$ cm^{-2}
(No Compton-thick eclipse events)

• Typical cloud size ~0.2 lt-dy, located in outer BLR/inner dusty torus, $10^{4-5} R_{\rm g}$ from BH (complementary to short-term BLR events by Risaliti et al.)

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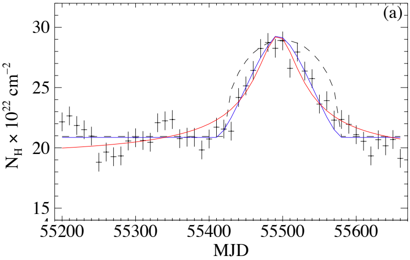
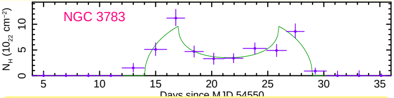
Resolving Clouds' Density Profiles: A range in profile shapes

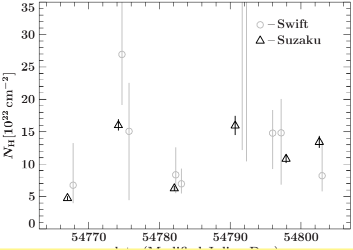


Cen A (E. Rivers+2011)

See also: Lamer+2003, Sanfrutos+2013



NGC 3783 (Markowitz+2014)



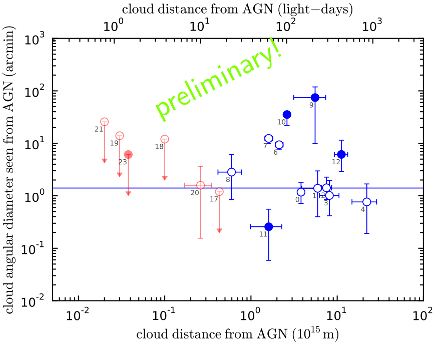
NGC 3227 (Beuchert+2015)

See also: "comet" & "anti-comet" shaped profiles in NGC 1365 (E. Rivers+2015, Maiolino+2010)

MHD- or IR-driven dusty winds relevant?

Cloud angular diameter as seen from central source

Nikutta, Krumpe, & Markowitz, "A Sky Full of Beads," in prep.:

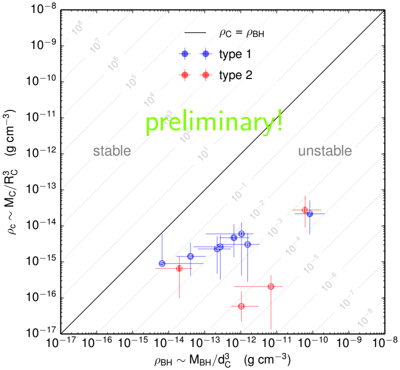


• Physical cloud size increases linearly with distance?
Disk fragmentation processes (Amaro-Seoane & Chen 2014)?

• $\sim 4 \times 10^7 / 8 \times 10^7$ **clouds (BLR + TOR)** needed for median covering factors for Is/IIs

Clouds externally confined to prevent tidal shearing:

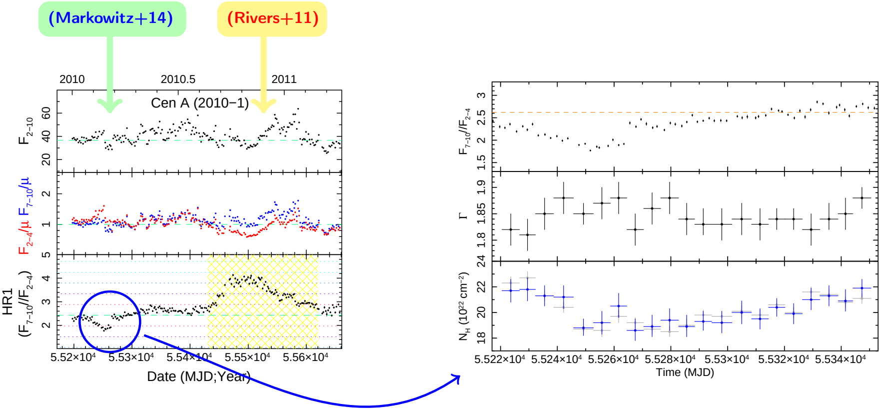
Nikutta, Krumpe, & Markowitz, in prep.:



- Clouds underdense by 10^{1-3} to resist tidal disruption via self-gravity
- Suggests external confinement: ambient intercloud medium?

Magnetic fields? (e.g., Elitzur & Shlosman 2006) $B \sim$ **mG** sufficient

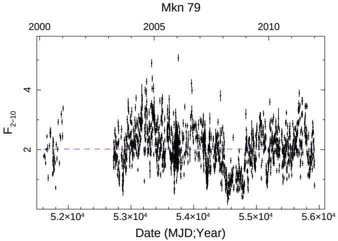
Cen A: Small variation in "baseline" N_{H} (indep. of clumps)

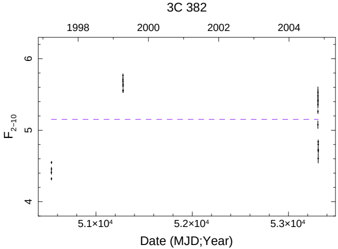


$\sim$ 80-d transit by an underdense region.

$N_{\mathrm{H,baseline}}$ originates in not-completely-homogeneous medium close to the BH?

Probability of witnessing an eclipse





Highly heterogeneous time-sampling:

Sampling styles varied wildly from object to object

Some timescales were better sampling than others for each object

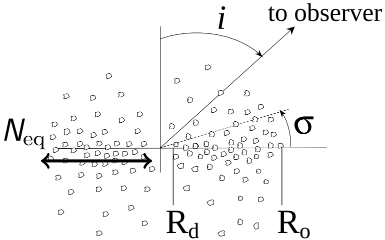
Monte Carlo "bootstrap" method to estimate uncertainties

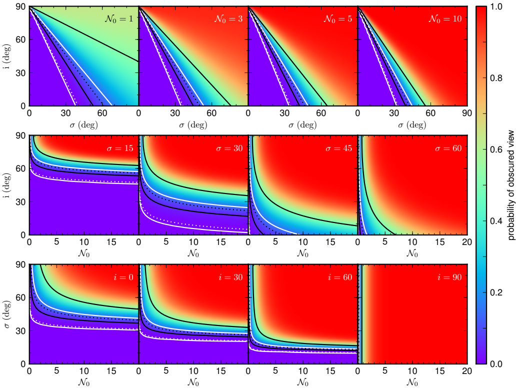
$\longrightarrow \overline{P_{\rm ecl}}$ (type Is) $= 0.007$ (0.004–0.161)

$\longrightarrow \overline{P_{\rm ecl}}$ (type IIs) $= 0.110$ (0.052–0.520)

Probability of witnessing an eclipse

Compare $\overline{P_{\rm ecl}}$ to predictions as a function of CLUMPY cloud distribution parameters $\{N_{\rm eq}, \sigma, i\}$:





Idealized "Wish list" for improvements/advancements:

Sustained monitoring with EVEN sampling, down to timescales of HOURS, with consistent source-to-source coverage (removes observing biases as a function of time)

SOFT X-RAY COVERAGE: access lower $\Delta N_{\rm H}$ than PCA.

Access lower 2–10 keV fluxes, to access more Type IIs!

SPECTRAL monitoring to deconvolve $\Delta N_{\rm H}$ and $\Delta\Gamma$, confirm partial-covering events.

Span a wide range of luminosities

Simultaneous optical monitoring: is a given eclipsing cloud dusty?

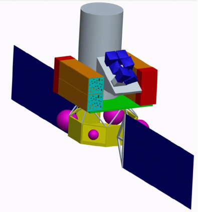
Future Studies with eROSITA

extended ROentgen Survey with an Imaging Telescope Array (DLR/Roskosmos)

Primary instrument on *Spectrum X-Γ*
(Launch: 2017 from Baikonur)

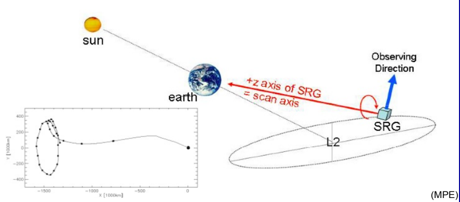
First X-ray survey of entire sky
since RASS (but 30× more sensitive!)

Monitor entire sky over 0.2–10 keV
with CCD resolution (detectors based on *XMM-Newton* EPIC pn)

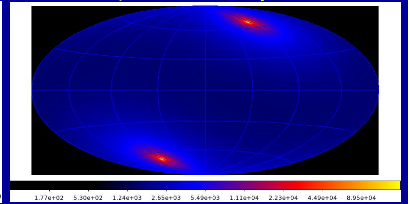


(Image credits: MPE)

Future: eROSITA



Exposure after 4 years:



(from C.Schmid)

- Largest survey of Fe Kα profiles and line-of-sight absorbers to date
- Long-term monitoring: variability in absorbers and Fe Kα components, as a function of luminosity & object type

Summary

Multi-timescale (days–years), sustained, X-ray spectral monitoring of 55 Seyferts with RXTE → First systematic X-ray constraints on a new generation of *clumpy*-absorber models.

- We triple the number of eclipse events observed with RXTE: 12 events in 8 Seyferts; durations span $\lesssim$ 1d to $\gtrsim$ 1 yr.
- No Compton-thick eclipses; $N_{\rm H,X}$ $(4 - 26 \times 10^{22}$ cm$^{-2})$ agrees with $\tau_{\rm V}$ values used in CLUMPY.
- X-ray absorbing clouds commensurate with inner edge of dusty torus or outer BLR in 7/8 sources
- Typical cloud size: $\sim$0.2 lt-dy.

Summary, cont'd:

- Some events have well-resolved $N_{\mathrm{H}}(t)$ profiles
- Irregular profiles: MHD winds, etc.?
- Probabilities to observe sources in eclipse $\rightarrow$ constraints for type Is/IIs in $\{ N_{\mathrm{eq}}, \sigma, i \}$ parameter space
- Nikutta et al., in prep: Constraints cloud angular diameter; clouds likely exernally confined to prevent shearing
- Pathfinder investigations for eROSITA (launch $\gtrsim$2017; 0.2–10 keV)

Press Release, Febr. 2014, APOD 2/24/2014:

Video Animation by Wolfgang Steffen, UNAM, Ensenada, Mexico: