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

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ecap
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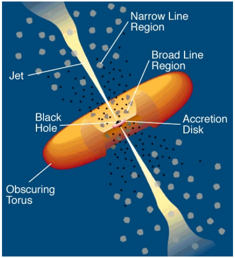
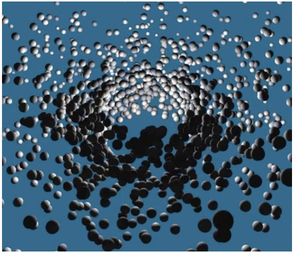
Evidence for Clumpy Tori: Variable **X-ray** Absorption

- We observe variations in X-ray column ($N_{\rm H}$) on timescales from hours to years in **both** optical classes!
- Argues against homogeneous, spatially-extended structures comprising most X-ray absn.
- $\Delta N_{\rm H} \sim 10^{23-24}$ cm^{-2} on timescales $\lesssim 1-3$d observed with *Chandra*, *Suzaku*, or *XMM-Newton* (e.g., NGC 1365, Mkn 766, Risaliti et al. 2005, 2009, 2011)
- ΔCovering Fraction in partial-covering absorbers in type 1s (Risaliti et al. 2011, Puccetti et al. 2007)
- Most clouds/clumpiness so far: commensurate with BLR

Our Goals





(Urry & Padovani 1995, etc.)

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

- Obtain first **X-ray** statistical constraints for CLUMPY torus models via variable X-ray absorption in large samples of Sy Is/IIs.

- *Strategy:* Identify eclipse events in the vast archive of (dozens of) Seyferts monitored with the *Rossi X-ray Timing Explorer*.

Sample Selection; Methodology

Sample:
All X-ray-bright type 1-1.5s and Compton-thin type 1.9-2s with sustained monitoring in *RXTE*'s archive (many sources: 100s–1000s of visits).

37 type I Seyferts, 18 Compton-thin type II Seyferts
We probe $\Delta N_{\rm H}$ on timescales from 0.3 d – 16.0 yr.

Methodology:
1. Examine hardness ratio and photon index light curves for significant, sustained deviations (in excess of typical power-law variations)
2. Perform follow-up time-resolved spectroscopy to confirm absorption, constrain $N_{\rm H}(t)$

Complementary to studies with *Chandra*, *XMM*, *Suzaku*

	RXTE	*Chandra*, *XMM*, *Suzaku*
Potential eclipse durations	$\sim$ 0.3d – 16 yr	$\lesssim 1-2$ d (*C*,*X*: no Earth occultation)
log10($\Delta N_{\rm H}$)	$\sim 22.3-25$ (2–20 keV)	$\sim 21-24$ (0.2–10 keV)
Partial-Covering	Only if $\gtrsim 80-90\%$	Yes.
Ionized Clouds?	Only neutral or near-neutral	Neutral and mod.-ionized

Overview of Results

- Eight "secure" events in five Type I Seyferts

Four "secure" events in three Type IIs

Four weak, "candidate" events in three Type Is

- 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!

($\rightarrow \tau_{\rm V} \sim 20 - 130$; agrees with models & IR SED fits)

- **Inferred Cloud Locations:** $\sim 0.3 - 140 \times 10^4 R_{\rm g}$

– 7/8 objects: Commensurate with outer BLR or inner dusty torus (IR-mapped structures)

– 8th object, NGC 5506: commensurate with inner BLR.

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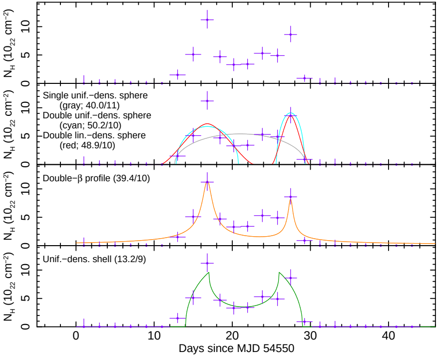
Newest Eclipse Results

NGC 3783

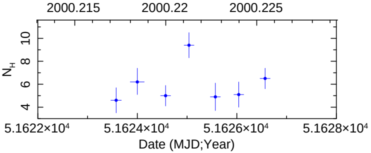


Dur.=$\sim$ 15 $\pm$ 1d

$\Delta N_{\mathrm{H}} = 11 \pm 2$ &

$9 \pm 2 \times 10^{22}$ cm^{-2}

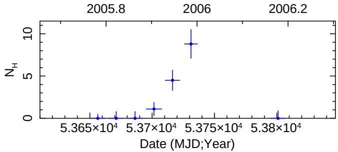
NGC 5506



Dur.=12 ± 7 **hr**

$\Delta N_{\mathrm{H}} = 4 \pm 1 \times 10^{22}$ cm^{-2}

Mkn 509

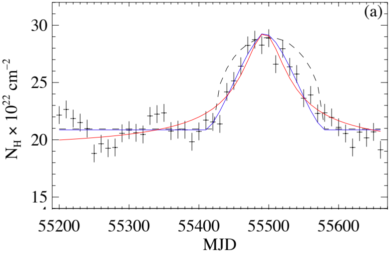


Dur.=$26 - 91$ d

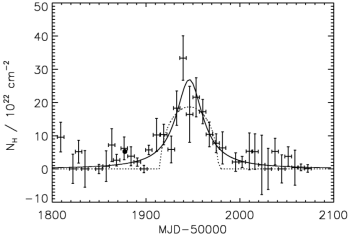
$\Delta N_{\mathrm{H}} = 9 \pm 2 \times 10^{22}$ cm^{-2}

A Range of Profile Shapes

Centaurus A
Rivers, Markowitz & Rothschild (2011, ApJ, 742, L29)
6-month long eclipse, 2010–1
$\Delta N_{\rm H} = 8 \times 10^{22}$ cm^{-2}



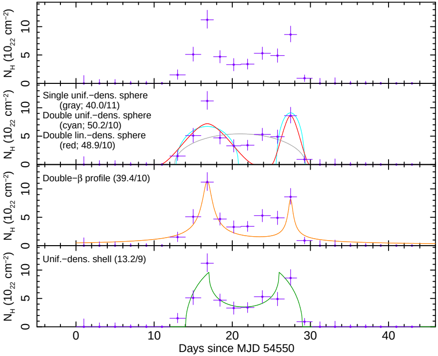
NGC 3227
Lamer et al. (2003)
$\sim$80 day eclipse, 2000–1
$\Delta N_{\rm H} = 26 \times 10^{23}$ cm^{-2}



See also: Sanfrutos et al. (2013), SWIFT J2127.4+5654

A Range of Profile Shapes

NGC 3783



Dur.$=\sim 15 \pm 1$d

$\Delta N_{\rm H} = 11 \pm 2$ &

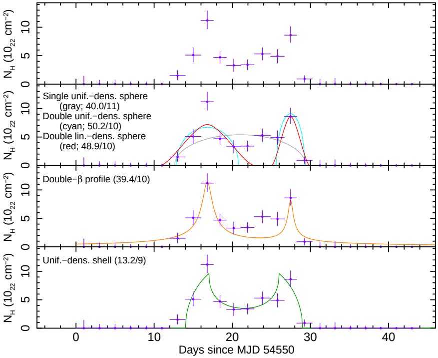
$9 \pm 2 \times 10^{22}$ cm^{-2}

MHD- or IR-driven winds highly relevant? (Fukumura+10, Moscibrodzka+13, etc.)

See also: "Comet" and "anti-comet"-shaped eclipses in NGC 1365:
E. Rivers (Poster F-28)
& Maiolino et al. (2010)

A Range of Profile Shapes

NGC 3783

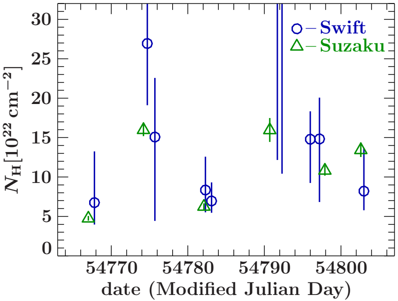


Dur.=$\sim$ 15 $\pm$ 1d

$\Delta N_{\mathrm{H}} = 11 \pm 2$ &

$9 \pm 2 \times 10^{22}$ cm^{-2}

T. Beuchert et al., in prep.: NGC 3227, 2008 Suzaku/Swift campaign



Dur. >26 d

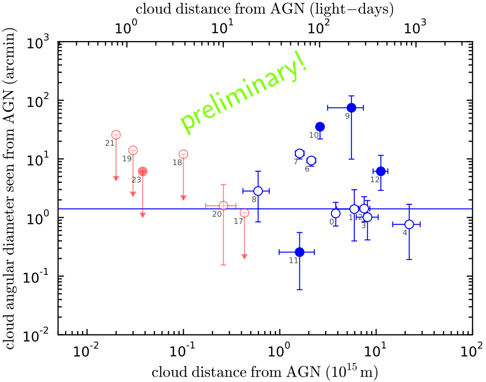
$\Delta N_{\mathrm{H}} \sim 5 - 30 \times 10^{22}$ cm^{-2}

SEE POSTER # F-05

Clouds spanning BLR & Dusty Torus:

Nikutta, Krumpe, Markowitz, in prep.:

Cloud's angular diameter as seen from central source:

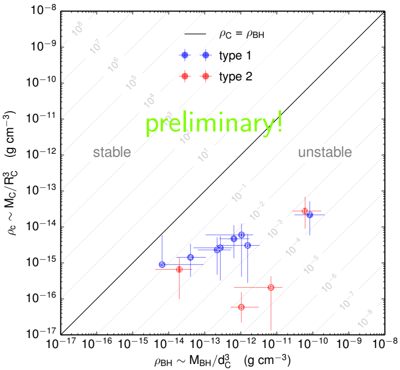


Increase in diameter with $r_{\rm cl}$ consistent with disk $\rightarrow$ cloud formation theory (e.g., X. Chen et al. 2014)

Are clouds confined?

Nikutta, Krumpe, Markowitz, in prep.:

Clouds are typically unstable against tidal shearing...



... suggesting external confinement: ambient intercloud medium? magnetic fields? (e.g., Elitzur + Shlosman 2006)

Summary

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

⊙We triple the number of eclipse events observed with RXTE: 12 secure events in 8 Seyferts; durations span $\lesssim$ 1d to $\gtrsim$ 1 yr.

⊙ No Compton-thick eclipses; $N_{\rm H,X}$ $(4 - 26 \times 10^{22}\ {\rm cm}^{-2})$ 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;
commensurate with inner BLR in one source.

⊙ Probabilities to observe sources in eclipse $\rightarrow$ constraints for type Is/IIs in $\{$ $N_{\rm eq}$, σ, i $\}$ parameter space

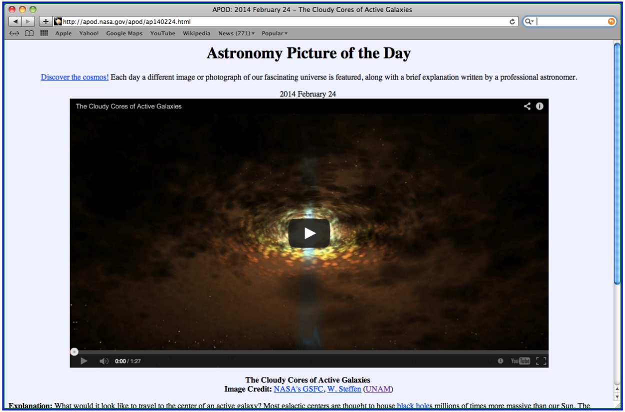
Summary, cont'd:

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

- ⊙ Typical cloud size: ~0.2 lt-dy.
- ⊙ We're seeing a wide range of time-resolved $N_{\mathrm{H}}(t)$ profiles: Irregular profiles – clouds being ripped in two? filamentary/turbulent winds?
- ⊙ Clouds likely confined by external pressure (Nikutta et al., in prep.)

Press Release, Febr. 2014:

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


APOD: 2014 February 24 – The Cloudy Cores of Active Galaxies

http://apod.nasa.gov/apod/ap140224.html

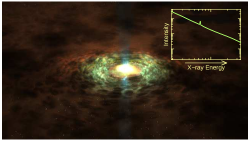
Astronomy Picture of the Day

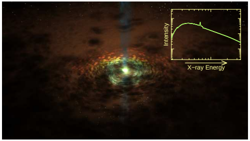
Discover the cosmos! Each day a different image or photograph of our fascinating universe is featured, along with a brief explanation written by a professional astronomer.

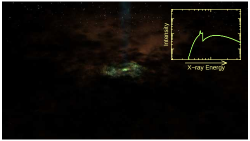
2014 February 24

The Cloudy Cores of Active Galaxies
Image Credit: NASA's GSFC, W. Steffen (UNAM)

Explanation: What would it look like to travel to the center of an active galaxy? Most galactic centers are thought to house black holes millions of times more massive than our Sun. The







Begin Backup Slides

Inferred Radial Distances from SMBH

$$\xi = \frac{L_{\rm ion}}{n_{\rm H} r_{\rm cl}^2} \qquad v_{\rm cl} = \sqrt{\frac{r_{\rm cl}}{G M_{\rm BH}}} = \frac{D_{\rm cl}}{t} = \frac{(N_{\rm H}/n_{\rm H})}{t}$$

$$r_{\rm cl} = 4 \times 10^{16}\text{cm } M_{\rm BH,7}{}^{1/5} L_{\rm ion,42}{}^{2/5} t_{\rm days}{}^{2/5} N_{\rm H,22}{}^{-2/5} \xi^{-2/5}$$

Event	$r_{\rm cl}$ (lt-days)	$r_{\rm cl}$ ($10^4 R_{\rm g}$)
NGC 3783/2008.3	147 ± 10	8.6 ± 0.7
Mkn 79/2003.5	229 ± 81	7.5 ± 2.7
Mkn 79/2003.6	290^{+42}_{-35}	$9.6^{+1.4}_{-1.1}$
Mkn 79/2009.9	314^{+91}_{-74}	$10.4^{+3.0}_{-2.5}$
Mkn 509/2005.9	851 ± 230	0.5 ± 3.0
MR 2251–178/1996	460–5700	4–49
NGC 3227/2000–1	82 ± 8	19 ± 2
NGC 3227/2002.8	23 ± 7	5.3 ± 1.6
Cen A/2003–4	214^{+70}_{-93}	$6.2^{+2.0}_{-2.6}$
Cen A/2010–1	101 ± 7	2.9 ± 0.2
NGC 5506/2000.2	62 ± 25	1.2 ± 0.5
Mkn 348/1996–7	432 ± 76	50 ± 9

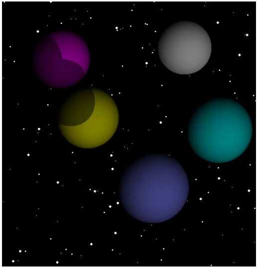
$r_{\rm cl}$ spans
$\sim 0.3 - 140 \times 10^4 R_{\rm g}$

Physical properties of individual clouds

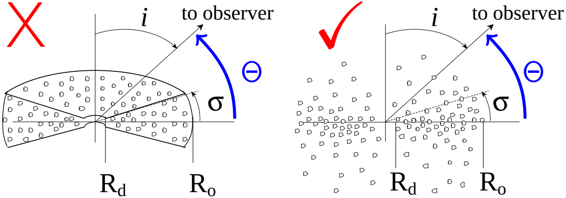
Inferred diameters: $(v_{\rm cl}t)$: span 0.02 – 4 lt.-dys

Inferred number densities $(\frac{N_{\rm H}}{D_{\rm cl}})$:
span $\sim 10^7 - 10^9$ cm^{-3}

Inferred masses: $10^{26} - 10^{31}$ gm



Comparison to CLUMPY models



(Nenkova et al. 2008)

Presence of eclipses in type Is: sharp-edged tori disfavored!

$N_{\rm LOS}(\Theta) = N_0 \exp(-(\frac{\sigma}{\Theta})^2)$

σ = torus angular width

N_0 = avg. no. of clouds along an equatorial ray

Probability of witnessing an eclipse

(Due to clouds only, not constant host galaxy absn.)

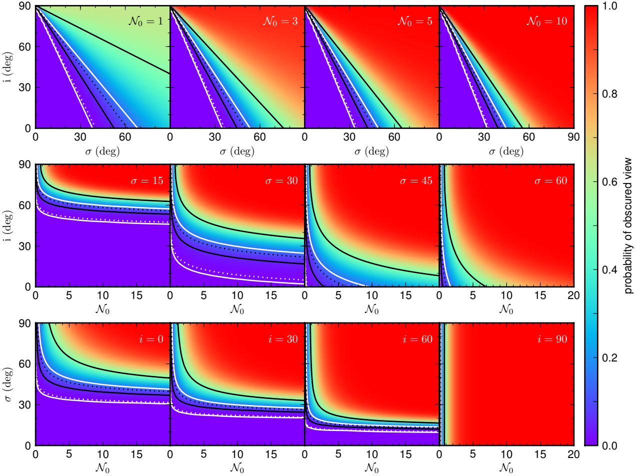
Must take into account the highly-heterogeneous sampling patterns (observing biases)

For each object class:
Num. Events ($t_{\rm D}$) / Num. "campaigns" ($t_{\rm D}$) $\rightarrow$ Prob. ($t_{\rm D}$);
Integrate Prob. ($t_{\rm D}$) from 0.2 to 5848 days:

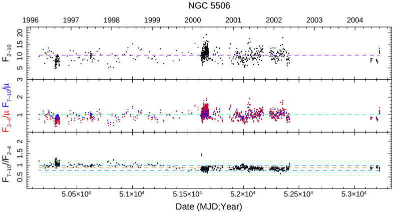
$\overline{P_{\rm ecl}}$ (type Is) = 0.007 (range: 0.004–0.161)
$\overline{P_{\rm ecl}}$ (type IIs) = 0.110 (0.052–0.520)
(conservative errors: we consider candidate + secure events, uncertainties on observed $t_{\rm D}$, sampling biases)

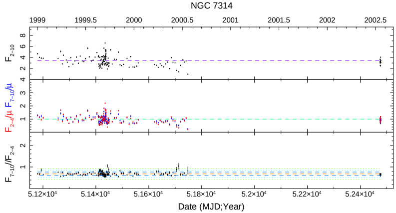
Probability of witnessing an eclipse

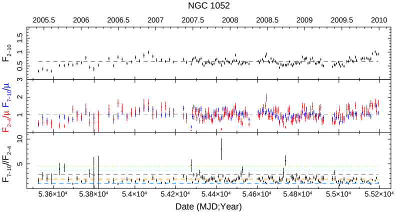
Compare derived values of $\overline{P_{\rm ecl}}$ to predictions as a function of $\{N_{\rm eq}, \sigma, i\}$:

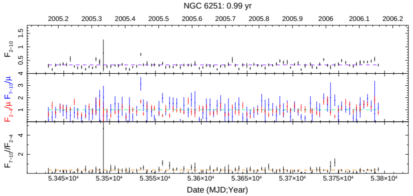


Type IIs with *non-variable* obscuration: CLUMPY irrelevant?





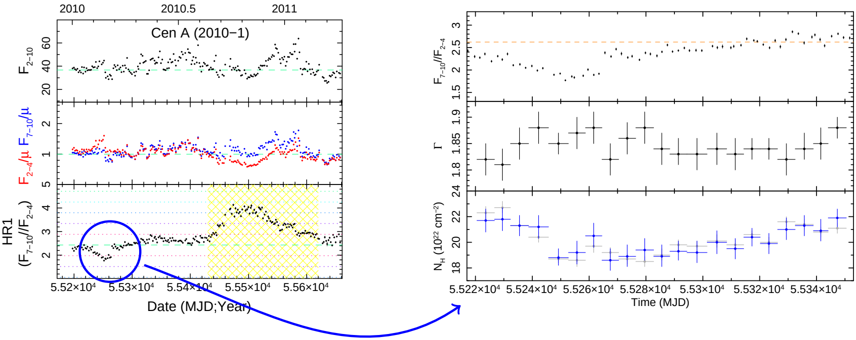




Likely large-scale gas assoc. with host galaxy (>>10s of pc).

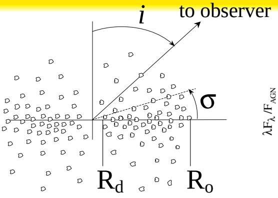
Or: If close to BH, must be highly homogenous ($\Delta N_{\rm H} \lesssim 10^{22.5}$ cm^{-2})

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

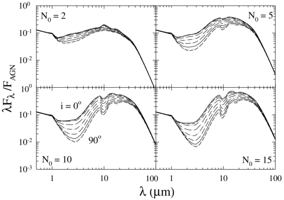


$N_{\mathrm{H,baseline}}$ originates in not-completely-homogeneous medium close to the BH?

Supporting CLUMPY models via IR SED fitting



(Nenkova et al. 2008)



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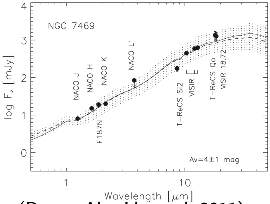

(Ramos-Almeida et al. 2011)

BAYES-CLUMPY: Bayesian fitting of IR SEDs with free parms for $\tau_{\rm V}$, inclination i, cloud distribution (incl. N_0, σ).

Ramos-Almeida et al. (2011): SED fits for 21 nearby Seyferts (need high spatial resolution)