Variable absorption and blurred reflection in NGC 4151 mapped with *XMM-Newton*, *Suzaku* and *NuSTAR*

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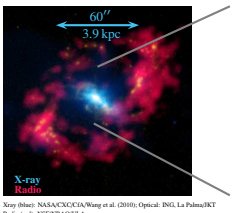
Abstract

We present preliminary results on time resolved spectroscopy of the Seyfert 1.5 galaxy NGC 4151. We extend on recent work by Keck et al., who find evidence for relativistically blurred, disk-reflected emission in a 150 ks *Suzaku*/*NuSTAR* observation from 2012. Besides using `relxill` in their best-fit model, they can also model two components in a "lamp-post" geometry of different height but require an additional layer of a weak partial covering absorber. We perform additional testing by using the latest lamp-post version of `relxill`, which incorporates a fully self-consistent angle-resolved treatment of ionized reflection, and also take into account the soft X-rays below 2.5 keV. We can confirm their results and find strong evidence for a co-existence of blurred reflection with two neutral absorbers, one partial coverer ($\sim 40\%$) and one fully covering the same. Due to strong degeneracies that usually arise between partial covering and inner disk reflection, disentangling both effects has been subject of debate for NGC 4151 ever since sufficient X-ray data have been available. Based on this model, we perform a time-resolved spectroscopy of all *Suzaku*, *NuSTAR* and *XMM-Newton* observations from mid 2011 until the end of 2012. We can report significant absorption variability on time-scales from parts of a day to one year and indications of changes of the inner disk reflection. The soft X-rays show a tentative positive correlation with the hard X-rays favoring a mixture of emission from both the nucleus and large-scale NLR gas. The most prominent soft emission lines are consistent with high resolution spectroscopic studies of both nuclear and extended emission as resolved with Chandra gratings.

Introduction to NGC 4151

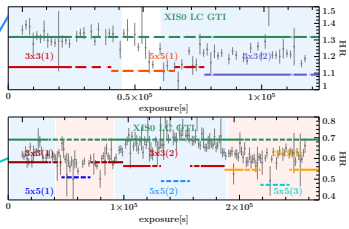
- **Closest, brightest** Seyfert 1 galaxy ($D \sim 13$ Mpc; Mundell & Shone 1999)
- Jet-cloud/Host-interaction, **soft X-rays from extended, bi-conical ENLR**, mainly photo-ionized gas (e.g. Wang et al., 2010, 2011c)
- **Non-relativistic radio jet** (Ulvestad et al., 2005)
- Highly ionized **wind outflow** detected in the X-rays (Tombesi et al., 2011)
- Nucleus: **variability of absorption and/or covering fraction** (Schurch & Warwick, 2002; Warwick et al., 1995; Puccetti et al., 2007; Yaqoob et al., 1993)
- Unblurred, neutral Compton reflection (Schurch & Warwick, 2002)
- **Blurred, relativistic reflection?** ✓ Zdziarski et al. (2002), Nandra et al. (2007); ✗ Schurch et al. (2003), Patrick et al. (2012)
- Fe Kα reverberation (Zoghbi et al., 2012): corona few r_g above disk
- Indication of **lamp-post geometry**: Keck et al. (2015)

X-ray observations



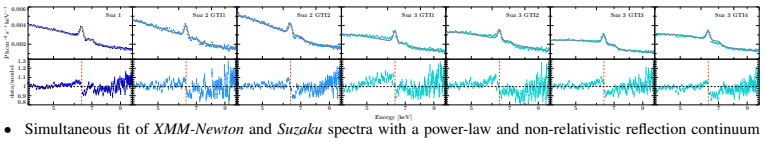
Xray (blue): NASA/CXC/CfA/Wang et al. (2010); Optical: ING, La Palma/IKT
Radio (red): NSF/NRAO/VLA

XMM 1	2011-06-12
XMM 2	2011-11-25
XMM 3	2011-12-09
XMM 4	2012-05-13
XMM 5	2012-06-10
XMM 6	2012-11-14
XMM 7	2012-12-10
Suz 1	2011-11-17
Suz 2	2011-12-18
Suz 3 / NuSTAR	2012-11-11



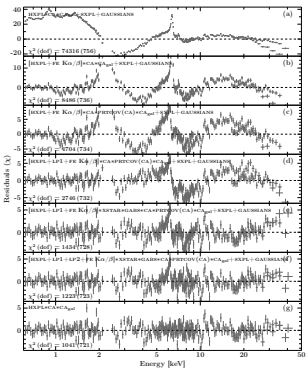
- X-ray spectra extracted from a radius of $40'' - 90''$ depending on the instrument
- *XMM-Newton*: XMM 1–XMM 7 with ~3–10 ks each; *Suzaku*: Suz 1 and Suz 2 with ~50 ks, Suz 3 with ~ 150 ks; *NuSTAR* simultaneous to Suz 3
- $6 - 10/2 - 5$ keV–**hardness ratio variability** during Suz 1 and Suz 3 (*right*) → Bayesian block analysis: observation-resolved spectroscopy

Initial fits using non-relativistic reflection `xillver`



- Simultaneous fit of *XMM-Newton* and *Suzaku* spectra with a power-law and non-relativistic reflection continuum using `xillver`, partially covered by near-neutral gas (`zxipcf`, covering > 90%) being fully covered by a Galactic column (`tbnew`)
- Decent fit to continuum, residuals show signs for broad wing of Fe line and highly ionized absorption.

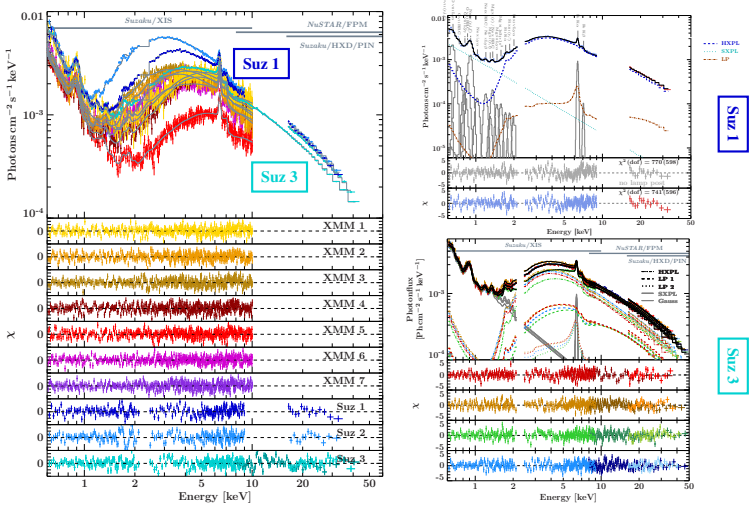
Development of baseline model for Suz 3



Choose Suz 3 for a development of a baseline model because of its long exposure (150 ks) and simultaneity to *NuSTAR*.

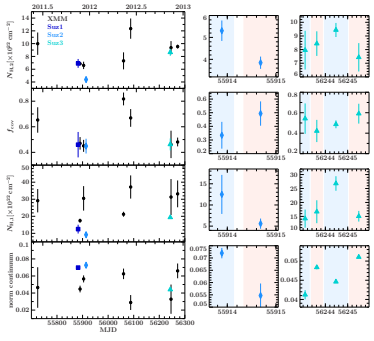
Left: **(a,b)** Comptonized continuum (**HXPL**) absorbed by neutral gas (**CA**, `tbnew`) + soft X-ray continuum (**SXPL**) including a blend of Gaussians after Ogle et al. (2000) – both continua are modeled with `nthcomp`; **(c)** + **narrow Fe Kα/β** lines; **(d)** + **partial covering CA**; **(e)** fit of broad red wing with `relxilllpCp`, a relativistical "lamp-post" reflection code including `nthcomp` (released soon): **LP 1**, height $\sim 3.1\, r_{\rm evt}$; **(f)** + `XSTAR` **warm absorber** ($\log \xi \sim 2.8$) and abs. line at 8 keV; **(g)** best-fit using an additional lamp-post component, **LP 2**, height $\sim 17\, r_{\rm evt}$.

Time-resolved spectroscopy



Left: Model fit of **Suz 3–derived model** to all *XMM-Newton* and *Suzaku* (+*NuSTAR*) data. The spectra of Suz 2 and Suz 3 are average spectra. There are clear signs for **absorption and flux variability**; **free parameters** (shown in bottom right box of the poster) are: columns $N_{\rm H,1}$, $N_{\rm H,2}$ of partially and fully covering absorbers, covering fraction $f_{\rm cvr}$ and HXPL / SXPL / lamp-post continuum **flux normalizations**.
Top right: absorbed model components (HXPL, SXPL, one lamp-post component, narrow Fe Kα line) and the spectrum of Suz 1 with a fit of the derived baseline model. Gray residuals demonstrate the need for only a single lamp-post component of the height $\gtrsim 12\, r_{\rm s}$ (same for Suz 2). The centroid energies of the narrow Gaussians are fixed according to Ogle et al. (2000) and Wang et al. (2011c).
Bottom right: four time-resolved single *Suzaku*/*NuSTAR* spectra of Suz 3 with absorbed and variable model components for the HXPL, SXPL and the two required lamp-post components: LP 1, LP 2.

Absorption variability and parameter evolution



Time evolution of the free parameters $N_{\rm H,1}$, $N_{\rm H,2}$, $f_{\rm cvr}$ (resp. $N_{\rm H,1}$) and primary continuum normalization. The time-resolved parameter evolution within Suz 2 and Suz 3 is shown in the color-shaded plots (see HR-plots on top for the definition of the time-intervals).
Significant variability of absorbers both in $N_{\rm H}$ and $f_{\rm cvr}$ detected **down to parts of a day** → BLR dynamics? A detailed analysis of results will follow.

Results:

- Strong evidence for absorption variability down to time-scales of parts of a day.
- Set of three absorbers detected (1,2: variable): (1) partial covering, neutral ($\sim 40\%$, $N_{\rm H,1} \sim 10 - 40 \times 10^{22}$ cm^{-2}), (2) full coverering, neutral ($N_{\rm H,2} \sim 4 - 14 \times 10^{22}$ cm^{-2}), (3) highly ionized warm absorber ($\log \xi \sim 2.8$, $N_{\rm H} \sim 1.1 \times 10^{22}$ cm^{-2})
- Good constraints on the partial coverer in combination with two primary lamp-post sources of minimal ($1.1\, r_{\rm evt}$) and intermediate ($17\, r_{\rm evt}$) height as modeled with `relxill`.
- Indications for variability of the inner disk reflection component, i.e., the lowest primary source in a lamp-post geometry.

Acknowledgments & References

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This research has made use of the ISIS (Houck & Denicola, 2000) scripts provided by the Dr. Karl Remeis observatory, Bamberg, Germany at http://www.sternwarte.uni-erlangen.de/isis/. Figures were created using the `slxfig` module (credit: J.E. Davis).