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NuSTAR's View of AGN

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Abstract. The launch of the Nuclear Spectroscopic Telescope Array (*NuSTAR*) in June 2012 has opened a new window onto the high-energy universe. The study of active galactic nuclei (AGN) and the supermassive black holes (SMBHs) within them stands to benefit greatly from this observatory. *NuSTAR's* unique combination of focusing X-ray optics, large effective area and low background over the $3-79$ keV energy band allows us to unambiguously probe the nature of complex AGN environs. I will review the planned AGN physics science goals for the mission with a particular focus on joint *XMM/Swift/NuSTAR* and *Suzaku/NuSTAR* observing campaigns to constrain the properties of the SMBHs, inner accretion disks and coronae in six bright, nearby AGN. Obtaining high signal-to-noise spectra across a broad bandpass is crucial for this work, enabling degeneracies between the continuum, reflection and absorption signatures in the spectrum to be broken for the first time. I will show early results from the *Suzaku/NuSTAR* campaign on the bright Seyfert IC 4329A as a preview of the quality of results we can expect from these collaborations.

Key words. Accretion, accretion disks – Galaxies: IC 4329A – Galaxies: active – Galaxies: nuclei – X-rays: galaxies

1. Introduction

High-energy studies of AGN offer the chance to shed light on some of the most powerful physical phenomena in the universe. Since the advent of the unified model (Antonucci 1993; Urry & Padovani 1995), great progress has been made in understanding the structure and energetics of the cores of active galaxies through the high spatial and spectral resolution made possible by orbiting X-ray telescopes such as *Chandra*, *XMM-Newton*, *Suzaku* and *Swift*. Yet with each new discovery unveiled by these instruments, more mysteries seemingly arise. Some of the most pressing unanswered questions in AGN astrophysics are:

- What is the nature and physical origin of the putative "corona?"
- What is the distribution of SMBH spins in the local universe?
- What is the true nature of the soft X-ray excess?
- How are jet triggered and what is their role in the overall energy budget of the AGN?
- What processes create the absorbing structures in AGN?
- What are the true physical properties of obscured AGN, and what is their role in the Cosmic X-ray Background (CXB)?

To answer these questions, the technological strengths of current X-ray observatories must be harnessed and extended over a wider energy range. In particular, a hard X-ray telescope with high effective area above 10 keV, adequate spatial resolution to unambiguously detect AGN, and moderate-to-high spectral resolution would prove invaluable. Such an instrument would enable detection of even Compton-thick AGN, and would provide unprecedented signal-to-noise (S/N) over an energy range well suited to breaking spectral modelling degeneracies, thereby elucidating the physical processes at work in the hearts of the most energetic galaxies in the universe.

The launch of *NuSTAR* (Harrison et al. 2005) in June 2012 addresses these critical scientific requirements. Its two telescope modules each bear four 32×32 CZT detectors, enabling focused images above 10 keV for the first time. This technology offers a ~ 2 orders of magnitude improvement over coded apertures, while the 10 m extendable mast provides a long focal length critical to achieving its ~ 18 arcsec FWHM spatial resolution. The combination of higher effective area than the *XMM*/EPIC-pn above 6 keV and lower background than the *Suzaku*/PIN above 10 keV means that *NusTAR* provides the highest S/N from $3 - 79$ keV of any current X-ray telescope. With spectral resolution ranging from 0.4 keV at 6 keV to 1 keV at 60 keV, *NuSTAR* enables the most sensitive spectral measurements ever achieved of AGN in this energy band. Additionally, its 0.1 msec timing resolution ensures that even the shortest variability timescales for each AGN will be resolved.

2. The NuSTAR AGN physics program

The goals of *NuSTAR*'s research program in AGN physics are designed to overlap with the unanswered questions in AGN science laid out in §1. During the first two years of observations, *NuSTAR* will focus primarily on three topics of great interest to the X-ray astronomy community:

- Determining the properties of the corona;
- Measuring SMBH spins in bright, nearby AGN;
- Characterizing the role of complex absorption vs. reflection in AGN.

Separate *NuSTAR* science programs are dedicated more specifically to examining blazars and obscured AGN, so those two topics will not be further discussed here.

The three science goals of the AGN Physics Program are all complicated by the same challenge: determining the true shape of the X-ray continuum. Achieving this objective is a crucial first step toward accurately identifying the properties of the corona, absorption and reflection in a given AGN. Deconvolving these components is virtually impossible with spectra over a limited bandpass, even those with high S/N, due to inherent modelling degeneracies (e.g., Brenneman & Reynolds 2006 vs. Miller, Turner & Reeves 2008). With sensitivity down to 3 keV and up to 79 keV, *NuSTAR* can measure coronal properties with great precision by locating the cutoff energy of the coronal continuum component (typically parameterized by a power-law or Comptonization model). This precision is typically of the order of a few keV out to ~ 150 keV, and worsens to tens of keV beyond this energy as the effective area of the telescope decreases. The *accuracy* of this measured cutoff energy may be suspect without knowledge of the continuum ≤ 1 keV, however, owing to the change in shape of the spectrum due to complex absorption and reflection, as well any additional soft excess component that may be present in many AGN. Similar accuracy issues play a significant role in *NuSTAR's* ability to address, on its own, measurements of black hole spin and separating absorption vs. reflection signatures, even in bright, nearby AGN.

To enable *NuSTAR* to achieve its scientific objectives, we have coordinated simultaneous observations of seven AGN with *XMM, Suzaku*, and/or *Swift*, totaling ~ 1.5 Ms in the current cycle. These observations will yield the highest quality data ever achieved over the $0.2 - 79$ keV range, and will enable us to examine both time-averaged and time-resolved broad band spectra. By isolating the true continuum shape of each AGN, we will be able to accurately and precisely measure the physical properties of their coronae for the first time, converting the high-energy cutoff to an electron temperature and thus breaking the degeneracy between the temperature and optical depth of the plasma. In so doing, we will also be able to charactierize the nature and location of the absorbing structure(s) within the AGN, and to separate the effects of this absorption from the presence of inner disk reflection signatures. If such reflection can be conclusively identified, we can measure the spin of the SMBH at the AGN's core by modelling the effects of frame-dragging on fluorescent spectral lines emitted from matter about to be accreted onto the SMBH (e.g., Reynolds & Nowak 2003; Brenneman & Reynolds 2006; Miller 2007).

The AGN to be observed in our simultaneous campaign are shown in Table 1. While 3C 273 received a long pointing as a calibration target between *Chandra, XMM, Suzaku* and *NuSTAR*, the data will also shed light on the nature of a jetted AGN with prior evidence supporting the presence of inner disk reflection, in the form of a broad Fe Kα line (e.g., Brenneman & Reynolds 2009).

IC 4329A and NGC 4151 are two of the brightest AGN in the X-ray sky (Beckmann et al. 2009), and are being observed with *NusTAR* and *Suzaku* primarily to measure their high-energy cutoffs for the purposes of determining their coronal properties. We have used simulations to estimate that we can constrain the high-energy cutoff with a precision 30% higher with *Suzaku* and *NuSTAR* than we can with *NuSTAR* alone.

MCG–6-30-15, Ark 120 and Swift J2127.4+5654 harbor strong relativistic reflection signatures that have enabled their black hole spins to be measured with great precision (Brenneman & Reynolds 2006; Walton et al. 2013; Miniutti et al. 2009), though their accuracy is still a matter of debate (Patrick et al. 2011). The simultaneous *XMM* and *NuSTAR* observations will provide the highest S/N data over the broadest spectral bandpass ever achieved for these sources, enabling a factor $\sim$ 10 improvement in the precision of these spin constraints and increasing their accuracy by properly modelling the continuum.

Finally, 3C 120 is another example of a radio-loud AGN that harbors a relativistic Fe Kα line (Brenneman & Reynolds 2009), and previous estimates of the inner disk radius in this source suggest that it may possess a SMBH spinning in a direction retrograde to its accretion disk (Cowperthwaite & Reynolds 2012). The addition of simultaneous *Swift*/UVOT data to this observation will enable us to examine multi-wavelength evidence to establish the true inner radius of the disk, and to assess whether it is recessed in conjunction with a major radio outburst from the jet (Marscher et al. 2002; Chatterjee et al. 2009). If it is not recessed, a rare spin measurement for a radio-loud AGN will be possible.

3. Preliminary results: IC 4329A

Though several of the AGN in our campaign have been observed to date, calibration of *NuSTAR* data is ongoing, and our spectral analysis depends critically on precise calibration. As such, we stress that the results quoted in this proceeding are *preliminary* in nature. Here, we showcase some early work on the simultaneous *Suzaku/NuSTAR* observation of IC 4329A (z = 0.0161, Willmer et al. 1991).

Light curves for *Suzaku*/XIS and *NuSTAR* are shown in Fig. 1. Note that there is a $\sim$ 34%, secular decrease in flux over the course of the *Suzaku* observation after an initial $\sim$ 12% increase during the first 50 ks. The *NuSTAR* data follow this behavior.

Based on the lack of significant variability in this source on any time scale in the observation, it is safe to make physical inferences about the system by modelling the time-averaged data in order to maximize S/N. An examination of the time-averaged spectrum fit with a simple power-law model modified by Galactic photoabsorption (Fig. 2) shows three prominent residual features: (1) a $\sim$ 60% drop in the data-to-model ratio below 2 keV, owing to the presence of complex absorption; (2) a relatively narrow Fe Kα emission line at 6.4 keV, likely originating from neutral gas in the outer accretion disk or torus; (3) a Compton hump above 10 keV, also originating from reflection. This simple fit yields χ^2/ν = 160 and is clearly not an adequate representation of the spectrum. Applying an ionized absorber, a distant, neutral reflection component and a high-energy cutoff to the power-law improves the fit

Table 1. Targets in the *NuSTAR* AGN Physics Program to be observed simultaneously with *XMM, Suzaku* and/or *Swift*.

AGN	NuSTAR (ks)	XMM (ks)	Suzaku (ks)	Swift (ks)
3C 273	300	39	40	20
Ark 120	90	150		
MCG–6-30-15	180	300		
3C 120	180	300		300
Swift J2127.4+5654	180	300		
NGC 4151	150		150	
IC 4329A	120		120	

to $\chi^2/\nu = 1.07$ and reproduces the spectrum very well.

The XSPEC preliminary best-fit parameters of this fit are listed in Table 2, and the best-fit model components are shown in Fig. 2. Note that we do not yet include error bars on the model parameters, owing to the ongoing calibration effort for *NuSTAR*. We stress also that these parameter values are subject to change once the final calibration is achieved. We do note, however, that the cross-calibration between all of the instruments is presently $\leq 10\%$.

The spectrum is best represented by a fairly flat power-law continuum ($\Gamma \sim 1.73$) with a high-energy cutoff of $E_{\rm cut} \sim 151$ keV. Reflection from cold, distant material (via `pexmon`, Nandra et al. 2007) is evident with a reflection fraction of $R \sim 0.23$ and an iron abundance of Fe/solar ~ 2.0. Both components are affected by Galactic photoabsorption ($N_{\rm H} = 4.61 \times 10^{20}\,{\rm cm}^{-2}$) as well as an ionized absorber, which totally covers the source and has a modest column density of $N_{\rm H} \sim 6.1 \times 10^{21}\,{\rm cm}^{-2}$ and an ionization of $\log\xi \sim 0.74$. This absorber is represented by an XSTAR-generated, multiplicative table model. There is somewhat marginal statistical evidence (i.e., improvement in the overall goodness-of-fit of $\Delta\chi^2/\Delta\nu = 20/3$) for relativistic, inner disk reflection in this AGN, in the form of a broadened Gaussian line at $E \sim 6.5$ keV with a breadth of $\sigma \sim 384$ eV and a strength of $EW \sim 41$ eV. The narrow Fe Kα and Kβ emission lines arising from the distant, neutral reflector have equivalent widths of $EW \sim 40$ eV and $EW \sim 13$ eV, respectively, when parameterized with unresolved Gaussian components. Attempting to fit this marginal broad iron feature with a relativistic line model (e.g., `kerrdisk` Brenneman & Reynolds 2006) yields no improvement in fit, and the parameters are unconstrained. Additionally, there is an emission line included in the fit at $E = 0.78$ keV, likely O VII, with a breadth of $\sigma \sim 20$ eV and a strength of $EW \sim 33$ eV.

4. Conclusions

With its unique combination of high effective area, low background, focusing optics and broad spectral bandpass, *NuSTAR* is providing the highest S/N spectra of AGN above 10 keV that has ever been achieved. When used simultaneously with X-ray telescopes at lower energies with high spectral resolution, such as *XMM, Suzaku* and *Swift*, unprecedented advances in our understanding of AGN physics are possible.

We have reported on an ongoing campaign to observe seven AGN simultaneously with some or all of these four telescopes. The primary science goals of this campaign are threefold: (1) to achieve a better understanding of the nature of the corona, breaking the degeneracy between its temperature and optical depth, (2) to achieve the most precise, accurate spin constraints to date for a small sample of AGN, and (3) to robustly deconvolve the continuum, reflection and absorption signatures in these galaxies.

Table 2. Preliminary best-fitting model parameters for the simultaneous *Suzaku/NuSTAR* observation of IC 4329A. Errors are not quoted on the individual parameters because the calibration for *NuSTAR* is not yet finalized.

Component	Parameter (units)	Value
absorber	$N_{\rm H}$ ($\rm cm^{-2}$)	6.10×10^{21}
	$\log \xi$ ($\rm erg\,cm\,s^{-1}$)	0.74
power-law	Γ	1.73
	$E_{\rm cut}$ (keV)	151
	K ($\rm ph\,cm^{-2}\,s^{-1}$)	2.84×10^{-2}
pexmon	$R\,(\Omega/2\pi)$	0.23
	Fe/solar	2.0
zgauss	rest E (keV)	0.78
	σ (keV)	0.02
	EW (eV)	33
zgauss	rest E (keV)	6.50
	σ (keV)	0.38
	EW (eV)	41
fit	χ^2/ν	4714/4406 (1.07)

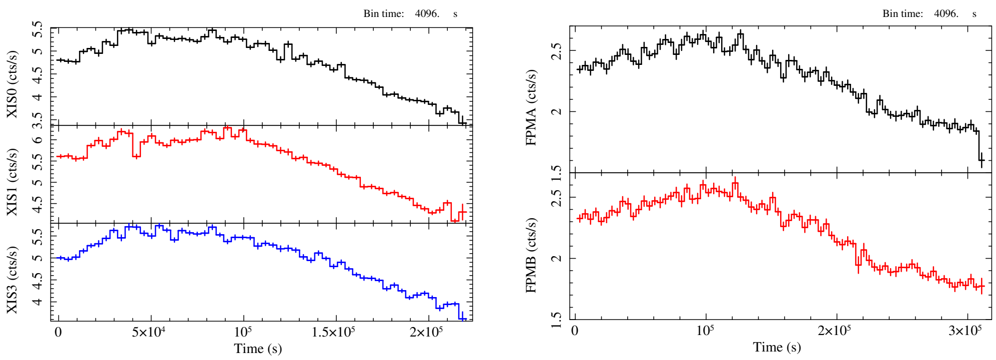

Fig. 1. Light curves for the *Suzaku*/XIS (0.2-12 keV, left) and *NuSTAR* (3-79 keV, right) observations of IC 4329A.

To date, we have completed observations on four of our targets. Though the calibration of *NuSTAR* is ongoing, we report on our preliminary analysis of the spectral and timing properties of IC 4329A here. This AGN displays little spectral variability during the course of its 120 ks *Suzaku/NuSTAR* observation, and an examination of the time-averaged spectrum reveals that the principal spectral components are a continuum power-law with a high-energy cutoff, modest reflection from distant, neutral material, and a relatively small amount of ionized absorption. Evidence to support the presence of inner disk reflection is marginal, at best, which will prohibit us from measuring the spin of the supermassive black hole in this AGN. However, the combined spectrum is of sufficiently high quality that we expect to derive the most accurate, precise measurement ever obtained for the high-energy cutoff of the power-law in IC 4329A.

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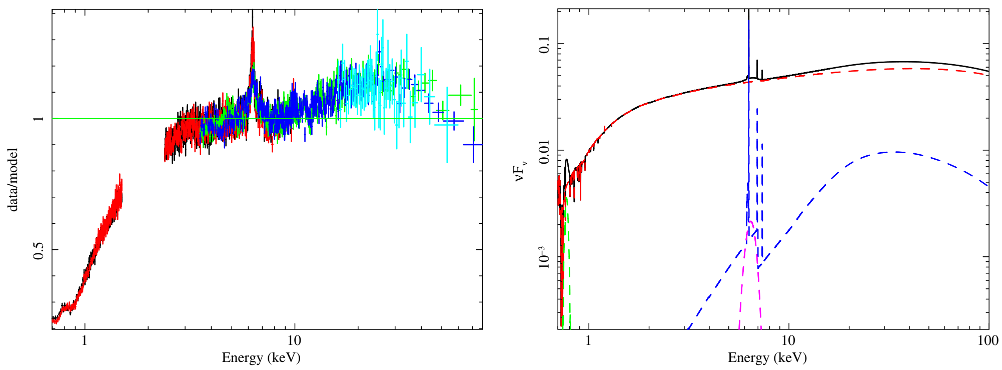

Fig. 2. *Left:* Ratio of the simultaneous *Suzaku*/*NuSTAR* time-averaged spectrum of IC 4329A to a power-law. The power-law is fit over the 3 – 5 keV and 7 – 79 keV bands to highlight the residual, non-continuum components of the spectrum, i.e., the ionized absorber and reflection features. Black and red data points depict the *Suzaku*/XIS-FI and XIS-BI spectra, respectively. Green and dark blue data points show the *NuSTAR*/FPMA and FPMB spectra, respectively. Light blue data points show the *Suzaku*/PIN data. The horizontal green line represents a data-to-model ratio of unity. *Right:* The preliminary best-fit model components for the simultaneous *Suzaku*/*NuSTAR* spectrum of IC 4329A. The summed model is shown by the black solid line, while the individual model components are shown as dashed lines: absorbed power-law in red, distant reflection in blue (including the narrow fluorescent lines of Fe Kα and Kβ, as well as a Compton shoulder) and the marginal presence of a broadened Fe Kα line in magenta. The O VII emission line is shown in green.

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