Astro 2020 Science White Paper: Probing the Physical Properties of the Corona in Accreting Black Holes

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Abstract: The corona is a key component of most luminous accreting black holes, carrying 5 – 30 % of the power and in non-jetted Active Galactic Nuclei (AGN), creating all the X-ray emission above $\simeq 1 - 2\,$keV. Its emission illuminates the inner accretion disc, creating the atomic line-rich reflection spectrum used to diagnose and map the accretion flow and measure black hole spin. The corona is likely powered magnetically by the strong differential rotation of the accretion disc and it may be intimately related to relativistic jets. Recent work shows that many black hole coronae may be dominated by electron-positron pairs produced by photon-photon collisions in the compact coronal environment. Despite the corona being an integral component of AGN and black hole binary systems, much is still unknown about the nature of the corona, such as its geometry, location, and the physical mechanisms powering the emission. In this white paper we explore our current understanding of coronal properties, such as its temperature, obtained from measurements with existing hard X-ray telescopes such as *NuSTAR*, and discuss important questions to be addressed in the coming decade surrounding the nature of the corona. Hard X-ray observations will continue to dispel the mystery of coronae and open up this part of the quasar engine to full understanding.

1 Introduction to Coronae

The corona is an important component of most luminous accreting black holes, creating the variable, hard ($> 2\,\text{keV}$) X-ray emission that is commonly observed in Active Galactic Nuclei (AGN). The corona is named after the Solar corona but its luminosity in AGN is more than 10^{15} times greater, despite its physical extent being similar in black holes systems of $10^6 - 10^7 M_\odot$. Its properties scale with mass above and below that range. It is generally considered that the corona is composed of a hot cloud of plasma located close to the accretion disc (Haardt & Maraschi, 1993). Compton upscattering of UV/optical photons from the accretion disc by electrons in the corona produces the intrinsic X-ray continuum (Rybicki & Lightman, 1979).

The coronal X-ray emission illuminates the accretion disc, which gives rise to the reflection spectrum containing atomic lines, most notably of iron, which are used to diagnose and map the accretion flow. Doppler shifts and gravitational redshift enable the inner edge of the disc to be located and, assuming that it is the Innermost Stable Circular Orbit (ISCO), mean that the spin of the black hole can be measured (Reynolds, 2014). Reverberation mapping studies and the observed rapid X-ray variability from many AGN indicate that the corona is physically small, of the order 3-10 gravitational radii ($\mathrm{r}_g = GM/c^2$) in radius and height above the black hole (e.g., Emmanoulopoulos et al., 2014; Uttley et al., 2014). Observations of microlensing in quasars also indicate compact X-ray emitting regions (Chartas et al., 2016).

2 Compactness and the $\Theta - l$ Plane

The corona is not only physically small, but also compact in the radiative sense, meaning that the ratio of luminosity to radius, L/R, is large. The compactness is usually described by the dimensionless parameter $l = \frac{L}{R}\frac{\sigma_T}{m_e c^3}$, where σ_T is the Thompson scattering cross section and m_e the electron mass (Guilbert et al., 1983). The density of high energy photons can be high enough that photon-photon collisions can lead to electron-positron pair production. Increased energy fed to the corona then has the effect of producing more particles to share the energy, limiting any rise in coronal temperature and preventing pair production from quickly becoming a runaway process and exceed annihilation. It thereby acts as an l-dependent thermostat (Svensson, 1984; Zdziarski, 1985; Stern et al., 1995). The coronal temperature can also be characterised by the dimensionless parameter

$\Theta = k_B T/m_e c^2$, where k_B is the Boltzmann constant. In determining coronal temperatures from X-ray spectra, it is usually assumed that $k_B T = E_{cut}/2$, where E_{cut} is the high-energy cutoff in the spectrum (Petrucci et al., 2001).

Within the corona, two-body collisions are the simplest heating and thermalization mechanism. It is commonly assumed that the corona is magnetically powered (Merloni & Fabian, 2001) by the strong differential rotation of the accretion disc. Radiation pressure may cause a pair wind if there are open field lines from the corona. Twisted field lines extending along the black hole spin axis may accelerate a jet of pairs from the corona. The pair thermostat behaviour defines a line in the $\Theta - l$ plane to the right of which a static physical corona cannot exist. The precise location of the pair line depends on the geometry of the corona and nature of the soft photon field. Figure 1 illustrates the location of some pair lines for different geometries, such as a slab and hemispherical corona, along with particle coupling lines.

Observations of AGN X-ray spectra show that most AGN do indeed lie to the left of the $\Theta - l$ line (Fabian et al., 2015). More recently, a significant number of AGN exhibit coronal temperatures that are much lower than expected for a fully thermal pair plasma (e.g., Tortosa et al., 2017a; Kara et al., 2017; Xu et al., 2017). One possible means of producing a low temperature corona is by considering the corona to be hybridized, composed of a mixture of thermal and non-thermal particles (e.g., Zdziarski et al., 1993; Ghisellini et al., 1993; Fabian et al., 2017). Only a small fraction of non-thermal electrons with energies above 1 MeV would be needed to result in runaway pair production. The cooled pairs share the energy, resulting in a reduction of the coronal temperature (Fabian et al., 2017).

3 Current Modeling and Measurements

Current spectral modeling of the Comptonization spectrum can be divided into two categories: phenomenological modeling with a cut-off power law and the description with physical models. These physical models vary in their assumptions for the spectral shape of seed photons, geometry of the Comptonizing region and amount of radiation physics included. Popular Comptonization models such as `compTT` (Titarchuk, 1994), which allows the user to choose different simple geometries, have been used extensively. More recent, physically more self-consistent calculations such as `eqpair` (Coppi, 1999), `BELM` (Belmont et al., 2008), and `MoCa` (Tamborra et al., 2018), include a variety of geometries, hybrid coronae, and polarization. All these models describe the current data equally well in most cases.

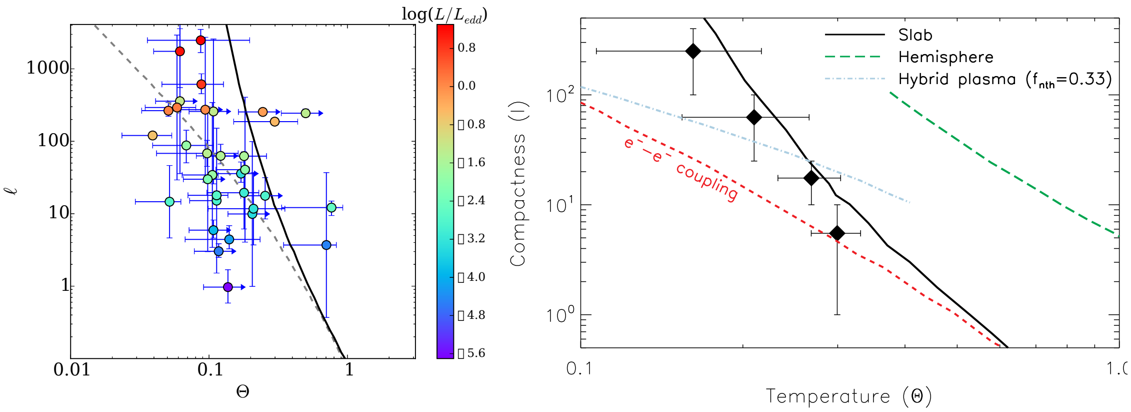

Figure 1: *Left panel:* Compactness–temperature diagram for sources with a cutoff energy inferred by *NuSTAR* observations, color-coded based on their Eddington ratio (updated from Ricci et al., 2018). The continuous line represents the pair line for a slab corona. *Right panel:* Same as the left-handed plot, with median values of the compactness and temperature for the unobscured AGN from the *Swift*/BAT sample (Ricci et al., 2018). The red dashed curves show the boundary to the region dominated by electron–electron coupling, while the dashed green and continuous black curves represent the runaway pair production limits for a a hemisphere and a slab corona, respectively. The runaway pair production limit obtained considering a hybrid plasma with 33 % of non-thermal electrons is shown by the cyan dot–dot–dashed curve.

The high sensitivity of *NuSTAR* above 10 keV has transformed studies of the X-ray Comptonization spectrum of AGN, allowing measurements of the high-energy cut-off from single epoch observations in relatively large samples of nearby AGN for the first time. Previous studies were only focused on the brightest nearby AGN (e.g., Nicastro et al., 2000; Lubiński et al., 2016). This has resulted in numerous studies exploring the Comptonization spectrum of single objects in great detail (e.g., Ballantyne et al., 2014; Matt et al., 2014; Baloković et al., 2015; Tortosa et al., 2017b). Some of these studies have been able to not only constrain the coronal temperature by detecting and measuring the high-energy roll-over of the spectrum and but also its variability (Ballantyne et al., 2014; Zoghbi et al., 2017; Ursini et al., 2018). Although these variations of the cut-off energy are established, it is unclear how they can be understood in the context of the pair coronae model. Do magnetic instabilities cause the coronal heating to be variable or are geometrical changes behind the observed temperature changes?

The more-readily available high quality hard X-ray data has also allowed the study of larger samples of sources. Most notable is the *Swift*-BAT sample, comprised of all those AGN detected by the all-sky 14–195 keV BAT survey (e.g., Baumgartner et al., 2013; Oh et al., 2018). Analysis of the spectra obtained with

BAT over the course of the *Neil Gehrels Swift* mission has shown that a high-energy cutoff is ubiquitous in the X-ray spectra of AGN, and that the median cutoff energy of local unobscured AGN is $E_{\rm C} = 210 \pm 36\,{\rm keV}$ (Ricci et al., 2017). These studies have also found correlations of cut-off energy with other physical parameters of the accreting black hole. In particular, the cut-off energy has been shown to be connected to the Eddington ratio, $\lambda_{\rm Edd}$ (Ricci et al., 2018): AGN with $\lambda_{\rm Edd} > 0.1$ are found to show a lower median cut-off energy ($E_{\rm C} = 160 \pm 41\,{\rm keV}$) than those with $\lambda_{\rm Edd} \leq 0.1$ ($E_{\rm C} = 370 \pm 51\,{\rm keV}$). This result is in good agreement with the idea that coronae which are radiatively compact are also cooler, since they are rarely found in the region in the temperature-compactness parameter space dominated by runaway pair production. Studies aimed at better understanding the relationship between coronal properties and the physical characteristics of accreting supermassive black holes exploiting *NuSTAR* (Kamraj et al., 2018; Tortosa et al., 2018) are currently ongoing.

4 Future Goals

Detailed studies of black hole coronae have only just begun. There is considerable scope to determine the geometry, i.e. the size, shape and location, of the corona in individual sources using relativistic reflection and reverberation of the coronal emission. Low frequency lag signals are likely due to small spectral changes in the coronal emission. The thermal/non-thermal nature of the coronal plasma can be found from observation of any non-thermal tail to the emission and the pair content from detection of the 511 keV annihilation line (Lubiński et al., 2010; Siegert et al., 2016). The likely hybrid nature of the corona raises the question of the fraction of non-thermal particles present. In order to investigate the presence of features such as hard non-thermal tails in X-ray spectra and robustly test hybrid plasma models, next-generation hard X-ray observatories with high sensitivity at energies beyond 100 keV will be essential.

Coronae are typically unobservable outside of the X-ray band. However, if probed at sufficiently high resolution ($<$ 1”) and high frequency ($> 30\,{\rm GHz}$), radio emission in radio-quiet (RQ) AGN may be traced to the X-ray-emitting corona (Inoue & Doi, 2014). Beyond the tentative scaling between luminosities, $L_{\rm X}/L_{\rm R} \approx 10^4 - 10^5$ (Smith et al. 2016, Behar et al. 2018), sensitive high-resolution and high-frequency observations of nearby RQ AGN with ALMA, VLA, and VLBA are expected to reveal spectral shapes of the radio emission from hybrid coronae (e.g., Inoue & Doi 2018, Panessa et al. 2019).

Some relativistic jet models invoke the corona as the base of a jet (Merloni & Fabian, 2002). Future studies that tie together measurements of the coronal temperature from hard X-ray spectroscopy with constraints on coronal size and location from reverberation measurements in the soft X-ray band (e.g., Wilkins et al. 2015) and properties of relativistic jets in the radio band (e.g., King et al. 2017) will pave the way to understanding the physical relationship between AGN coronae and jets. High-throughput observatories with broadband X-ray coverage such as *STROBE-X* (Ray et al., 2019) or *HEX-P* (Madsen et al., 2018), would enable both of these key X-ray measurements for large samples of nearby AGN.

As X-ray polarimetry becomes available in the early 2020-ies with IXPE (Weisskopf, 2018), studies of polarimetric properties of coronae in both X-ray and radio promise to reveal the geometry of the hot plasma, and possibly properties of the magnetic field that permeates it. AGN coronae may be powered by magnetic reconnection (Di Matteo, 1998), which would imply that heating is intermittent, and emission is variable. In the case of stellar mass black hole systems, rapidly variable near IR emission can be correlated with X-ray variability (e.g., Gandhi et al., 2010, 2016). Future multi-wavelength monitoring could reveal the variability of coronal emission in relation to variability of other AGN components, like the accretion disk, to which it is inextricably connected (e.g., Mehdipour et al. 2016). With sufficient understanding of the disc-corona system and its non-linear scaling with luminosity, optical (rest-frame UV) data readily available from large-area surveys (e.g., LSST), and X-ray observations of unobscured quasars at cosmological distances may soon start to provide competitive constraints on cosmological parameters (Lusso & Risaliti, 2017).

In summary, while the corona is a fundamental component of luminous black hole systems, responsible for powering the X-ray emission in AGN, much is still unknown about its nature, and even origin. Current observations of AGN with hard X-ray satellites such as *NuSTAR* have allowed significant progress to be made in the field, through measurements of the high energy cutoff and in-depth studies of the Comptonization spectra of AGN for the first time. However, coronal measurements made using *NuSTAR* are based on subtle downturns in continuum spectra near ~ 50 keV, which are used to infer cutoff energies of ~ 100 keV or higher. Future observations with next-generation hard X-ray telescopes such as *HEX-P*, combined with multi-wavelength monitoring will be of critical importance for deepening our understanding of the corona and answering the questions briefly discussed in this white paper within the coming decade.

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