Hot Coronae in local AGN: present status and future perspectives

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Coronal parameters in local Seyfert galaxies

One of the main open problem for AGN is the nature of the primary X-ray emission.

It is due to Comptonization of soft photons, but the geometry, optical depth and temperature of the emitting corona are largely unknown.

Most popular models imply $E_{\text{cut}} = 2 - 3 \times kT_e$ (Petrucci+00,+01), so measuring $E_{\text{cut}}$ helps constraining Comptonization models.
Before the launch of NuSTAR, we only had a handful of results based on non-focusing, and therefore strongly background-dominated, satellites (BeppoSAX-PDS, Suzaku HXD-PIN, INTEGRAL, Swift-BAT).

Perola+02

De Rosa+12; Molina+13
<table>
<thead>
<tr>
<th>Source</th>
<th>Ref.</th>
<th>$\Gamma$</th>
<th>$E_\gamma$</th>
<th>log(Mass/M$_\odot$)</th>
<th>Ref.</th>
<th>$L_{2-10keV}$</th>
<th>$F_{2-10keV}$</th>
<th>$kT_e$</th>
<th>$\tau$</th>
<th>geom.</th>
<th>model</th>
</tr>
</thead>
<tbody>
<tr>
<td>NGC 5506</td>
<td>1</td>
<td>1.91 ± 0.03</td>
<td>720$^{+130}_{-190}$</td>
<td>8.0 ± 0.2</td>
<td>(A)</td>
<td>0.006</td>
<td>0.053</td>
<td>6.2</td>
<td>440$^{+230}_{-250}$</td>
<td>0.02$^{+0.2}_{-0.01}$</td>
<td>slab</td>
</tr>
<tr>
<td>MCG 5-23-16</td>
<td>2</td>
<td>1.85 ± 0.01</td>
<td>170 ± 5</td>
<td>7.7 ± 0.2</td>
<td>(B)</td>
<td>0.058</td>
<td>0.18</td>
<td>10.4</td>
<td>25 ± 2</td>
<td>3.5 ± 0.02</td>
<td>sphere</td>
</tr>
<tr>
<td>SWIFT J2127.4</td>
<td>3-4</td>
<td>2.08 ± 0.01</td>
<td>180$^{+75}_{-40}$</td>
<td>7.2 ± 0.2</td>
<td>(J)</td>
<td>0.136</td>
<td>0.14</td>
<td>2.9</td>
<td>70$^{+40}_{-30}$</td>
<td>0.5$^{+0.3}_{-0.2}$</td>
<td>slab</td>
</tr>
<tr>
<td>IC4329A</td>
<td>5-6</td>
<td>1.73 ± 0.01</td>
<td>185 ± 15</td>
<td>6.99 ± 0.3</td>
<td>(H)</td>
<td>1.291</td>
<td>0.56</td>
<td>12.0</td>
<td>37 ± 7</td>
<td>1.3 ± 0.1</td>
<td>slab</td>
</tr>
<tr>
<td>3C390.3</td>
<td>7</td>
<td>1.70 ± 0.01</td>
<td>120 ± 20</td>
<td>8.4 ± 0.4</td>
<td>(H)</td>
<td>0.241</td>
<td>1.81</td>
<td>4.03</td>
<td>33 ± 6</td>
<td>3.4 ± 0.5</td>
<td>sphere</td>
</tr>
<tr>
<td>3C382</td>
<td>8</td>
<td>1.68 ± 0.03</td>
<td>215$^{+150}_{-60}$</td>
<td>9.2 ± 0.5</td>
<td>(D)</td>
<td>0.048</td>
<td>2.34</td>
<td>2.9</td>
<td>330 ± 30</td>
<td>0.2 ± 0.02</td>
<td>slab</td>
</tr>
<tr>
<td>GRS 1734-292</td>
<td>9</td>
<td>1.65 ± 0.05</td>
<td>53 ± 10</td>
<td>8.5 ± 0.1</td>
<td>(L)</td>
<td>0.038</td>
<td>0.056</td>
<td>2.9</td>
<td>12 ± 1</td>
<td>2.9 ± 0.2</td>
<td>slab</td>
</tr>
<tr>
<td>NGC 6814</td>
<td>10</td>
<td>1.71 ± 0.04</td>
<td>135$^{+70}_{-35}$</td>
<td>7.0 ± 0.1</td>
<td>(C)</td>
<td>0.003</td>
<td>0.021</td>
<td>0.2</td>
<td>45$^{+100}_{-20}$</td>
<td>2.5$^{+0.5}_{-0.4}$</td>
<td>sphere</td>
</tr>
<tr>
<td>MCG +8-11-11</td>
<td>10</td>
<td>1.77 ± 0.04</td>
<td>175$^{+10}_{-50}$</td>
<td>7.2 ± 0.2</td>
<td>(E)</td>
<td>0.754</td>
<td>0.51</td>
<td>5.6</td>
<td>60$^{+140}_{-30}$</td>
<td>1.9$^{+0.4}_{-0.3}$</td>
<td>sphere</td>
</tr>
<tr>
<td>Ark 564</td>
<td>11</td>
<td>2.27 ± 0.08</td>
<td>42 ± 3</td>
<td>6.8 ± 0.5</td>
<td>(H)</td>
<td>1.313</td>
<td>0.39</td>
<td>-</td>
<td>15 ± 2</td>
<td>2.7$^{+0.2}_{-0.3}$</td>
<td>sphere</td>
</tr>
<tr>
<td>PG 1247+267</td>
<td>12-13</td>
<td>2.35 ± 0.09</td>
<td>90$^{+120}_{-35}$</td>
<td>8.9 ± 0.2</td>
<td>(M)</td>
<td>0.024</td>
<td>0.79</td>
<td>0.05</td>
<td>46$^{+60}_{-20}$</td>
<td>1.4$^{+0.3}_{-0.2}$</td>
<td>sphere</td>
</tr>
<tr>
<td>Ark 120</td>
<td>14-15</td>
<td>1.87 ± 0.02</td>
<td>180$^{+80}_{-40}$</td>
<td>8.2 ± 0.1</td>
<td>(H)</td>
<td>0.085</td>
<td>0.92</td>
<td>2.3</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>NGC 7213</td>
<td>16</td>
<td>1.84 ± 0.03</td>
<td>&gt; 140</td>
<td>8.0 ± 0.2</td>
<td>(G)</td>
<td>0.001</td>
<td>0.012</td>
<td>1.3</td>
<td>230$^{+70}_{-250}$</td>
<td>0.2 ± 0.1</td>
<td>sphere</td>
</tr>
<tr>
<td>MCG 6-30-15</td>
<td>17-18</td>
<td>2.06 ± 0.01</td>
<td>&gt; 110</td>
<td>6.4 ± 0.1</td>
<td>(E)</td>
<td>0.238</td>
<td>0.056</td>
<td>5.5</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>NGC 2110</td>
<td>19</td>
<td>1.65 ± 0.03</td>
<td>&gt; 210</td>
<td>8.3 ± 0.2</td>
<td>(K)</td>
<td>0.035</td>
<td>0.35</td>
<td>12.5</td>
<td>190 ± 130</td>
<td>0.2 ± 0.1</td>
<td>slab</td>
</tr>
<tr>
<td>Mrk 335</td>
<td>21-22</td>
<td>2.14 ± 0.03</td>
<td>&gt; 174</td>
<td>7.2 ± 0.1</td>
<td>(H)</td>
<td>0.284</td>
<td>0.18</td>
<td>1.9</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Fairall 9</td>
<td>20</td>
<td>1.95 ± 0.02</td>
<td>&gt; 242</td>
<td>8.1 ± 0.7</td>
<td>(H)</td>
<td>0.054</td>
<td>0.60</td>
<td>2.9</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Mrk 766</td>
<td>17-23-24</td>
<td>2.22 ± 0.03</td>
<td>&gt; 441</td>
<td>6.3 ± 0.1</td>
<td>(I)</td>
<td>1.254</td>
<td>0.046</td>
<td>1.4</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>PG 1211+143</td>
<td>26</td>
<td>2.51 ± 0.2</td>
<td>&gt; 124</td>
<td>8.2 ± 0.2</td>
<td>(H)</td>
<td>0.047</td>
<td>0.35</td>
<td>1.0</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

So far, about twenty sources have been observed and their primary continua investigated.
Coronal parameters in local Seyfert galaxies

Fabian+15

(Middei+; Tortosa+, in prep.)
Coronal parameters (Swift J2127.4+5654)

Marinucci+14,+16
Coronal parameters (Swift J2127.4+5654)

Using compTT (Titarchuk+94) with two different geometries we get:

**SLAB**
- $kT_e = 70 \pm 35$ keV
- $\tau = 0.35^{+0.35}_{-0.20}$

**SPHERE**
- $kT_e = 50 \pm 25$ keV
- $\tau = 1.3^{+1.0}_{-0.7}$

Statistically equivalent
The $\tau$-$kT_e$ diagram (in a slab geometry)

1. How can we translate the commonly derived photon indices and high-energy cutoff values into optical depths and electronic temperatures?
2. Is there a more populated region in the $\tau$-$kT$ parameter space?
A MC code for Comptonization in Astrophysics (MoCA)

Assumptions and advantages:
1. Shakura-Sunyaev neutral accretion disc
2. Extended coronae
3. Single photon approach
4. Polarization signal

\[ T(R) = \left[ \frac{3GMm}{8\pi R^3 \sigma_{SB}} \left( 1 - \sqrt{\frac{R_{in}}{R}} \right) \right]^{\frac{1}{4}} \]

\[ d\tau = n_e \sigma_{kn} \, dx \]

Tamborra+, submitted
MoCA in action

We simulate a coronal configuration and fit it with a cutoff powerlaw, retrieving the corresponding values of $E_c$ and $\Gamma$

$M_{bh}=10^7 \ M_{\odot}$ ; $\dot{m}=1$, $kT_e=100 \ \text{keV}$; $\tau=1$
MoCA in action

We simulate a coronal configuration and fit it with a cutoff powerlaw, retrieving the corresponding values of $E_c$ and $\Gamma$

$M_{bh}=10^7 M_{\odot}; \dot{m}=1, kT_e=100 \text{ keV}; \tau=1$
The $\tau$-$kT_e$ diagram in AGN

The region of the observed parameters ranges between $kT=50-100$ keV and $\tau=0.5-2.25$.
The region of the observed parameters ranges between $kT=50-100$ keV and $\tau=0.5-2.25$.
We can define the most populated region in both slab and spherical geometries but we cannot discriminate between the two.
A fresh pair of eyes: X-ray polarimetry

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polarisation sensitivity</td>
<td>$1.8%$ MDP for $2 \times 10^{-10} \text{ erg/s cm}^2$ (10 mCrab) in 300 ks (CBE)</td>
</tr>
<tr>
<td>Spurious polarization</td>
<td>$&lt;0.3%$</td>
</tr>
<tr>
<td>Number of Telescopes</td>
<td>3</td>
</tr>
<tr>
<td>Angular resolution</td>
<td>28'' (CBE)</td>
</tr>
<tr>
<td>Field of View</td>
<td>12.9x12.9 arcmin$^2$</td>
</tr>
<tr>
<td>Focal Length</td>
<td>4 meters</td>
</tr>
<tr>
<td>Total Shell length</td>
<td>600 mm</td>
</tr>
<tr>
<td>Range Shell Diameter</td>
<td>24 shells, 272-162 mm</td>
</tr>
<tr>
<td>Range of thickness</td>
<td>0.16-0.26 mm</td>
</tr>
<tr>
<td>Effective area at 3 keV</td>
<td>854 cm$^2$ (three telescopes)</td>
</tr>
<tr>
<td>Spectral resolution had to do with</td>
<td>$16%$ @ 5.9 keV (point source)</td>
</tr>
<tr>
<td>Timing</td>
<td>Resolution $&lt;8,\mu s$</td>
</tr>
<tr>
<td></td>
<td>Accuracy 150 $\mu s$</td>
</tr>
<tr>
<td>Operational phase</td>
<td>2 yr</td>
</tr>
<tr>
<td>Energy range</td>
<td>2-8 keV</td>
</tr>
<tr>
<td>Background (req)</td>
<td>$5 \times 10^{-3} \text{ c/s/cm}^2/\text{keV/det}$</td>
</tr>
<tr>
<td>Sky coverage, Orbit</td>
<td>50 %, 540 (0°)</td>
</tr>
</tbody>
</table>

**IXPE**
(Imaging X-ray Polarimetry Explorer)

Selected by NASA (SMEX) for a launch in early 2021

**P.I.: Martin Weisskopf (MSFC)**

It will re-open the X-ray polarimetry window!
Since I is proportional to the intensity of the polarized component and Q is related to the angle of polarization their ratio contains information about the polarized signal after each scattering.
A fresh pair of eyes: X-ray polarimetry

We focus on the brightest Seyfert 1 and 2 objects of the sample (NGC 2110 and IC 4329A):
We focus on the brightest Seyfert 1 and 2 objects of the sample (NGC 2110 and IC 4329A) and retrieve observing times to obtain an MDP=2%: this should suffice in distinguishing between the two models.

<table>
<thead>
<tr>
<th>Source</th>
<th>$\Gamma$</th>
<th>$E_c$ [keV]</th>
<th>$F_{2-8\text{keV}}$ (erg cm$^{-2}$ s$^{-1}$)</th>
<th>Exposure time (ks)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NGC 2110</td>
<td>$1.65 \pm 0.03$</td>
<td>$&gt; 210$</td>
<td>$1.04 \times 10^{-10}$</td>
<td>450</td>
</tr>
<tr>
<td>IC 4329A</td>
<td>$1.73 \pm 0.01$</td>
<td>$184 \pm 14$</td>
<td>$1.00 \times 10^{-10}$</td>
<td>450</td>
</tr>
</tbody>
</table>

Type 1

Type 2
Simulations with MoCA have showed that the observed cutoff energies and photon indices occupy a well-defined region in the $\tau$-kT diagram.

X-ray polarimetry will be the next tool to reveal the geometry of the coronae in AGN.

We are currently working on running more simulations and trying different geometries.

Stay tuned...