Variability of the Coronal Line Region in NGC 4151

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Variability of the coronal line region in NGC 4151

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ABSTRACT
We present the first extensive study of the coronal line variability in an active galaxy. Our data set for the nearby source NGC 4151 consists of six epochs of quasi-simultaneous optical and near-infrared spectroscopy spanning a period of about 8 yr and five epochs of X-ray spectroscopy overlapping in time with it. None of the coronal lines showed the variability behaviour observed for the broad emission lines and hot dust emission. In general, the coronal lines varied only weakly, if at all. Using the optical [FeVII] and X-ray O VII emission lines we estimate that the coronal line gas has a relatively low density of $n_e \approx 10^3$ cm$^{-3}$ and a relatively high ionization parameter of $\log U \approx 1$. The resultant distance of the coronal line gas from the ionizing source is about two light years, which puts this region well beyond the hot inner face of the obscuring dusty torus. The high ionization parameter implies that the coronal line region is an independent entity rather than part of a continuous gas distribution connecting the broad and narrow emission line regions. We present tentative evidence for the X-ray heated wind scenario of Pier & Voit. We find that the increased ionizing radiation that heats the dusty torus also increases the cooling efficiency of the coronal line gas, most likely due to a stronger adiabatic expansion.

Key words: quasars: emission lines – quasars: individual: NGC 4151 – galaxies: Seyfert – infrared: galaxies – X-rays: galaxies.

1 INTRODUCTION
In addition to the broad and narrow emission lines, the spectra of active galactic nuclei (AGN) display high ionization emission lines, the so-called coronal lines, which require energies $\gtrsim 100$ eV to be excited. The coronal line region is believed to lie at distances from the central ionizing source intermediate between those of the broad (BELR) and narrow emission line region (NELR) and to possibly coincide with the hot inner face of the circumnuclear, obscuring dusty torus (as first suggested by Pier & Voit 1995). Support for this assumption comes from the fact that the coronal lines have higher critical densities for collisional deexcitation than the low ionization narrow emission lines ($n_e \approx 10^7$–$10^{10}$ cm$^{-3}$), their profiles tend to have full width at half-maxima (FWHM) intermediate between those of the broad and narrow emission lines (FWHM $\approx 500$–$1500$ km s$^{-1}$; e.g. Penston et al. 1984; Appenzeller & Oestreich 1988; Erkens, Appenzeller & Wagner 1997; Rodríguez-Ardila et al. 2002, 2011) and the emission from this region is often extended but much less so than that from the low ionization NELR (on scales of $\approx 80$–$150$ pc; e.g. Prieto, Marco & Gallimore 2005; Müller-Sánchez et al. 2006, 2011; Mazzalay et al. 2013). Coronal lines are observed with similar frequency in both types of AGN (Osterbrock 1977; Koski 1978), but type 1 AGN have stronger coronal line emission relative to their low ionization narrow lines than type 2 AGN (Murayama & Taniguchi 1998). Therefore, it is likely that the coronal line region has two components, one compact and one spatially extended, with only the latter remaining unobscured by the dusty torus in type 2 AGN.

The high ionization potentials of the coronal lines can be produced either in a hot, collisionally ionized plasma, as is the case for the solar corona from which these lines have their name, or in a gas photoionized by the hard continuum of the AGN. In the first case, the electron temperatures would be of the order of $T_e \approx 10^6$ K and in the second case much lower ($T_e \approx 10^3$–$10^5$ K). Currently,
photoionization is favoured, since for most AGN the observed flux ratios between different coronal lines can be reproduced within a factor of $\sim 2$–3 by these models (Oliva et al. 1994; Ferguson, Korista & Ferland 1997), whereas the temperature of the hot plasma would need to be fine-tuned within a very narrow range (Oliva et al. 1994). In any case, the coronal line region is most likely dust free, since strong emission from refractory elements such as iron, silicium and calcium are observed, which would be severely reduced in a dusty environment.

The coronal lines are often blueshifted relative to the low-ionization narrow lines (e.g. Penston et al. 1984; Erkens et al. 1997; Rodríguez-Ardila et al. 2002), which indicates that the coronal line gas is in outflow. However, as Mullaney et al. (2009) concluded for the source Ark 564, the potential coronal line emitting clouds must have undergone acceleration to the observed velocities prior to these lines being produced, i.e. they have reached their terminal velocity against the opposing drag and gravitational forces. Then, given also the similar estimated physical conditions and location, it has been proposed that the partly ionized gas that produces the O VII and O VIII absorption lines and edges seen in the soft X-ray spectra of many AGN, i.e. the so-called ‘warm absorber’, produces also the coronal lines in its (colder) outer regions (Netzer 1993; Erkens et al. 1997; Porquet et al. 1999). In this wind model for the coronal line region, a considerable contribution from shock ionization is expected.

The most stringent constraints on the properties of the coronal line emitting region could come from variability studies, in particular if the variability of several coronal lines can be compared with each other and with that of other AGN components such as the BELR and the X-ray continuum. However, mainly due to the weakness of these emission lines and also lack of data, very few studies of this kind have been attempted so far. Veilleux (1988) did the only systematic study of the coronal line variability. In his sample of 20 AGN, he found firm evidence that both the [Fe VII] $\lambda$6087 and [Fe X] $\lambda$6375 emission lines varied (during a period of a few years) for only one source (NGC 5548) and tentative evidence for another seven sources (including NGC 4151). Then, within a general optical variability campaign on the source Mrk 110 lasting for half a year, Kollatschny et al. (2001) reported strong [Fe x] variations. More recently, follow-up optical spectroscopy of a handful of objects with unusually prominent coronal lines selected from the Sloan Digital Sky Survey (SDSS) showed that in half of them the coronal lines strongly faded (by factors of $\sim 2$–10), making these sources candidates for stellar tidal disruption events (Komossa et al. 2009; Yang et al. 2013).

In this paper, we present the first extensive study of the coronal line variability in an AGN. Our data set for the nearby, well-known source NGC 4151 ($z = 0.0033$) is unprecedented in that it includes six epochs of quasi-simultaneous optical and near-IR spectroscopy spanning a period of $\sim 8$ yr and five epochs of X-ray spectroscopy overlapping in time with it. Furthermore, the observations in each wavelength were performed with the same telescope and set-up. This paper is organized as follows. In Section 2, we present the data and measurements. In Section 3, we discuss the observed variability behaviour of the near-IR, optical and X-ray coronal lines, for which we seek an interpretation in the context of the location of and excitation mechanism for the coronal line emission region in Section 4. Finally, in Section 5, we summarize our main results and present our conclusions. Throughout this paper, we have assumed cosmological parameters $H_0 = 70\,\text{km}\,\text{s}^{-1}\,\text{Mpc}^{-1}$, $\Omega_M = 0.3$, and $\Omega_\Lambda = 0.7$.

## 2 THE DATA AND MEASUREMENTS

### 2.1 Near-IR and optical spectroscopy

We have six epochs of quasi-simultaneous (within 3–14 d) near-IR and optical spectroscopy for NGC 4151 (see Tables 1 and 2). The near-IR spectroscopy was obtained with the SpX spectrograph (Rayner et al. 2003) at the NASA Infrared Telescope Facility (IRTF), a 3 m telescope on Mauna Kea, Hawai‘i, in the short cross-dispersed mode (SXD, 0.8–2.4 $\mu$m). All data except those from 2010 were obtained through a slit of $0.8 \times 15$ arcsec giving an average spectral resolution of FWHM $\sim 400\,\text{km}\,\text{s}^{-1}$. A narrower slit of $0.3 \times 15$ arcsec was used for the 2010 epoch. The four epochs spanning the years 2004–2007 are our own data and were presented in Landt et al. (2008, 2011). The near-IR spectra from 2002 and 2010 were discussed by Riffel, Rodríguez-Ardila & Pastoriza (2006) and Schnülle et al. (2013), respectively. The optical spectra were obtained with the FAST spectrograph (Fabricant et al. 1998) at the Tillinghast 1.5 m telescope on Mt. Hopkins, Arizona, using the 300 1 $\text{mm}^{-1}$ grating and a 3 arcsec long-slit. This set-up resulted in a wavelength coverage of $\sim 3720$–7515 Å and an average spectral resolution of FWHM $\sim 330\,\text{km}\,\text{s}^{-1}$. The slit was rotated to the parallactic angle only for the 2006 January epoch, however, except for the 2004 data, all spectra were observed at a very low airmass (sec $z \sim 1.05$). The May 2004 spectrum was observed at an airmass of sec $z \sim 1.3$ and so the flux loss due to atmospheric differential refraction is expected to be $\sim 20$ per cent at the observed wavelength of [Fe VII] $\lambda$3759 relative to that at wavelengths $\geq 5000\,\text{Å}$ (Filippenko 1982). The 2006 January data were discussed in Landt et al. (2008), whereas all other optical spectra were retrieved from the FAST archive.

We have measured the fluxes of the strongest near-IR and optical coronal lines by integrating the observed profiles over the local continuum, i.e. we have not assumed a specific line shape. In the near-IR, we have measured two sulphur lines and two silicon lines, namely, [S VIII] $\lambda$9911, [S IX] 1.252 $\mu$m, [Si VII] 1.965 $\mu$m and [Si X] 1.430 $\mu$m (see Table 1). Two of these emission lines are blended, namely, [S IX] with [Fe II] 1.257 $\mu$m, and [Si VI] with H2 1.957 $\mu$m. In these cases, we have assumed a Gaussian profile in the deblending procedure. In the optical, we have measured four iron emission lines, namely, [Fe VII] $\lambda$3759, [Fe VII] $\lambda$5159, [Fe VIII] $\lambda$5721 and [Fe VIII] $\lambda$6087 (see Table 2). We have considered also [Fe X] $\lambda$6375, but this line is extremely weak in NGC 4151 and makes up only $\sim 15$ per cent of the total blend with [O I] $\lambda$6364 (Pelat, Alloin & Bica 1987). We do not observe significant variability in the flux of the entire blend, which constrains the [Fe x] variability to below a factor of $\sim 2$.

Since both the near-IR and optical spectra were obtained in non-photometric sky conditions, we study in the following the temporal changes of the coronal lines in relative rather than absolute flux. In particular, we scale the coronal line emission to that of a strong, forbidden low ionization emission line that is unblended and observed in the same spectrum. The emission region that produces the low ionization narrow lines is believed to be located at large enough distances from the central ionizing source for its flux to remain constant on time-scales of decades. We have scaled the near-IR and optical coronal lines to the [S III] $\lambda$9531 and [O III] $\lambda$5007 emission lines, respectively.

The error estimates on the line fluxes are crucial for assessing the significance of the coronal line variability. The data are of relatively high signal-to-noise ratio (continuum S/N $\geq 50$–100) and, therefore, the main sources of measurement errors are of a subjective
Table 1. Near-IR emission line fluxes and ratios.

<table>
<thead>
<tr>
<th>Observation date</th>
<th>[S ii] λ9531 (erg s$^{-1}$ cm$^{-2}$)</th>
<th>[S ii] λ10069 (erg s$^{-1}$ cm$^{-2}$)</th>
<th>[S ii]/[S iii]</th>
<th>[S iv] λ13106 (erg s$^{-1}$ cm$^{-2}$)</th>
<th>[S iv]/[Si iii] λ1806 (erg s$^{-1}$ cm$^{-2}$)</th>
<th>[S iv]/[S iii] λ1252 µm (erg s$^{-1}$ cm$^{-2}$)</th>
<th>[S iv]/[Si iii]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2002 Apr 30</td>
<td>(7.61 ± 0.09)e−13</td>
<td>(2.66 ± 0.02)e−13</td>
<td>2.86 ± 0.04</td>
<td>(2.49 ± 0.21)e−14</td>
<td>30.6 ± 3.6</td>
<td>(2.44 ± 0.12)e−14</td>
<td>31.2 ± 1.6</td>
</tr>
<tr>
<td>2004 May 23</td>
<td>(1.06 ± 0.02)e−12</td>
<td>(3.89 ± 0.08)e−13</td>
<td>2.73 ± 0.08</td>
<td>(5.35 ± 0.60)e−14</td>
<td>19.8 ± 2.3</td>
<td>(2.64 ± 0.28)e−14</td>
<td>40.2 ± 4.3</td>
</tr>
<tr>
<td>2006 Jan 8</td>
<td>(1.17 ± 0.01)e−12</td>
<td>(4.40 ± 0.06)e−13</td>
<td>2.66 ± 0.04</td>
<td>(3.81 ± 0.26)e−14</td>
<td>30.7 ± 2.1</td>
<td>(3.41 ± 0.14)e−14</td>
<td>34.3 ± 1.4</td>
</tr>
<tr>
<td>2006 Jun 12</td>
<td>(9.97 ± 0.10)e−13</td>
<td>(3.85 ± 0.07)e−13</td>
<td>2.59 ± 0.05</td>
<td>(3.38 ± 0.19)e−14</td>
<td>29.5 ± 1.7</td>
<td>(3.54 ± 0.12)e−14</td>
<td>28.2 ± 1.0</td>
</tr>
<tr>
<td>2007 Jan 24</td>
<td>(8.17 ± 0.14)e−13</td>
<td>(2.79 ± 0.06)e−13</td>
<td>2.93 ± 0.08</td>
<td>(3.09 ± 0.38)e−14</td>
<td>26.4 ± 3.3</td>
<td>(3.01 ± 0.29)e−14</td>
<td>27.1 ± 2.6</td>
</tr>
<tr>
<td>2010 Feb 27</td>
<td>(8.89 ± 0.15)e−13</td>
<td>(2.98 ± 0.06)e−13</td>
<td>2.98 ± 0.08</td>
<td>(4.00 ± 0.36)e−14</td>
<td>22.2 ± 2.0</td>
<td>(3.31 ± 0.19)e−14</td>
<td>26.9 ± 1.6</td>
</tr>
</tbody>
</table>

Table 2. Optical emission line fluxes and ratios.

<table>
<thead>
<tr>
<th>Observation date</th>
<th>[O iii] λ5007 (erg s$^{-1}$ cm$^{-2}$)</th>
<th>[O iii] λ4959 (erg s$^{-1}$ cm$^{-2}$)</th>
<th>[O iv] λ14500 (erg s$^{-1}$ cm$^{-2}$)</th>
<th>[Fe vii] λ3759 (erg s$^{-1}$ cm$^{-2}$)</th>
<th>[O ii] λ7320 (erg s$^{-1}$ cm$^{-2}$)</th>
<th>[Fe vii] λ5159 (erg s$^{-1}$ cm$^{-2}$)</th>
<th>[O ii] λ3727 (erg s$^{-1}$ cm$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2002 Apr 11</td>
<td>(8.52 ± 0.03)e−12</td>
<td>(2.96 ± 0.03)e−12</td>
<td>2.88 ± 0.03</td>
<td>(7.87 ± 1.38)e−14</td>
<td>108.3 ± 19.0</td>
<td>(4.23 ± 0.57)e−14</td>
<td>201.4 ± 27.0</td>
</tr>
<tr>
<td>2004 May 28</td>
<td>(1.18 ± 0.01)e−11</td>
<td>(4.60 ± 0.04)e−12</td>
<td>2.57 ± 0.02</td>
<td>(1.85 ± 0.25)e−13</td>
<td>63.8 ± 8.7</td>
<td>(6.60 ± 0.73)e−14</td>
<td>178.8 ± 19.7</td>
</tr>
<tr>
<td>2006 Jan 5</td>
<td>(1.17 ± 0.01)e−11</td>
<td>(3.92 ± 0.02)e−12</td>
<td>2.99 ± 0.02</td>
<td>(9.66 ± 0.58)e−14</td>
<td>121.1 ± 7.3</td>
<td>(5.36 ± 0.21)e−14</td>
<td>218.3 ± 8.7</td>
</tr>
<tr>
<td>2006 May 29</td>
<td>(9.80 ± 0.04)e−12</td>
<td>(3.86 ± 0.03)e−12</td>
<td>2.54 ± 0.02</td>
<td>(9.25 ± 1.36)e−14</td>
<td>106.0 ± 15.6</td>
<td>(5.34 ± 0.60)e−14</td>
<td>183.5 ± 20.7</td>
</tr>
<tr>
<td>2007 Feb 9</td>
<td>(1.46 ± 0.01)e−11</td>
<td>(5.09 ± 0.04)e−12</td>
<td>2.87 ± 0.03</td>
<td>(7.45 ± 1.20)e−14</td>
<td>196.0 ± 31.6</td>
<td>(5.32 ± 0.40)e−14</td>
<td>274.4 ± 20.9</td>
</tr>
<tr>
<td>2010 Feb 18</td>
<td>(9.79 ± 0.03)e−12</td>
<td>(3.14 ± 0.02)e−12</td>
<td>3.12 ± 0.03</td>
<td>(6.82 ± 1.15)e−14</td>
<td>143.6 ± 24.3</td>
<td>(3.46 ± 0.29)e−14</td>
<td>283.0 ± 24.1</td>
</tr>
</tbody>
</table>

In order to further constrain the significance of the observed coronal line variability, we have considered the two extreme cases of where no variability and the highest variability are expected. For both scaling lines we observe also the other emission line that is emitted from the same upper level, namely, [S ii] λ9531 and [O ii] λ10069 and [O ii] λ4959. Their observed ratios, which should be close to the theoretical values of [S ii] λ9531/[S iii] λ9531 = 2.58 and [O ii] λ5007/[O iii] λ4959 = 2.92 (Kramida et al. 2013), are not expected to vary and so their observed variability sets a lower threshold for the significance of the coronal line variability. Then, we have measured the fluxes of the two prominent broad emission lines Paβ (in the near-IR) and Hα (in the optical). Since the BELR is expected to be the most variable of any AGN emission line region, the observed variability of these broad lines gives an estimate of the maximum value that can be reached within the current data set. These results are also listed in Tables 1 and 2.
on much shorter time-scales and only partially covers the X-ray continuum source. In order to differentiate this absorber from the warm absorber, we follow Kaastra et al. (2014) and will call it ‘the obscurer’. Since the soft and hard X-ray continua as well as the properties of the obscurer, such as its column density, covering factor and potentially also the ionization, are known to vary on day time-scales or less, we have not combined the EPIC pn spectra, but fitted them separately.

The presence of the obscurer in NGC 4151 allows us to study in detail the X-ray emission lines, which would otherwise be swamped by the high continuum flux. However, the obscurer also complicates the analysis, in particular the continuum fitting, since the absorption is so deep that the individual absorption lines blend and create a pseudo-continuum. Decomposing the total absorption into obscurer and warm absorber and characterizing each individually is not possible without prior knowledge of the ionization structure of the warm absorber. This, however, is not known for NGC 4151 since it has never been observed in an unobscured state. However, for the Seyfert 1 galaxy NGC 5548 we have high-quality X-ray spectra in both the unobscured (Steenbrugge et al. 2003, 2005; Detmers 2003 May) extending over a period of 2–3 d and another one (2011 May) extending over a period of 2–3 d and another one (2011 May).

### 2.2 X-ray spectroscopy

Between 2000 December and 2011 June, the time period that overlaps with our optical and near-IR observations, there were five observational campaigns with XMM–Newton on NGC 4151 (see Table 4). We have reduced these archival data sets using the standard tasks in the XMM–Newton SAS software (version 13.5.). All the X-ray spectral analysis was done using the SPEX software\(^1\) (Kaastra, Mewe & Nieuwenhuijzen 1996). We have assumed solar abundances as given by Lodders & Palme (2009) and corrected all spectra for a Galactic column density of \(2 \times 10^{20} \text{ cm}^{-2}\). Three of the campaigns have multiple observations, with two of them (2000 December and 2003 May) extending over a period of 2–3 d and another one (2011 May) spanning a period of a month. Since the X-ray emission lines are not expected to vary on days to weeks time-scales, we have not combined the EPIC pn data.

### Table 4. XMM–Newton archival observations.

<table>
<thead>
<tr>
<th>No.</th>
<th>Observation date and time</th>
<th>Exp. (ks)</th>
<th>Obs ID</th>
<th>Campaign</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>2000:12:22 04:02:18</td>
<td>5</td>
<td>0112380601</td>
<td>2000 Dec</td>
</tr>
<tr>
<td>3</td>
<td>2003:05:25 08:37:56</td>
<td>19</td>
<td>0143500101</td>
<td>2003 May</td>
</tr>
<tr>
<td>6</td>
<td>2004:05:26 16:40:42</td>
<td>40</td>
<td>0402660101</td>
<td>2006 May</td>
</tr>
</tbody>
</table>

*Note. *\(^\ast\) no EPIC data.

\(^1\)http://www.sron.nl/spex
the hard X-rays, and added a modified blackbody in the soft X-ray regime. The fit also includes, but the parameters are frozen, the best-fitting model for the emission lines, both narrow and broad, and the radiative recombination continua as determined from the RGS spectra. The Fe Kα and Kβ lines, which can only be studied with the EPIC instruments, were fitted as Gaussians. Both lines are unresolved. We fit the spectra in the 0.3–10 keV energy range and used the option of optimal binning available in SPEX. This gives an acceptable fit to the EPIC-pn spectra. However, due to the heavy absorption, there is a certain degeneracy between the normalization and temperature of the modified blackbody, the hydrogen column density, ionization parameter and for the obscurer also the covering factor, of the absorption components and the normalization of the emission lines and radiative recombination continua (frozen in the EPIC pn fit). In Table 5, we list the fluxes and 1σ errors for the eight strongest X-ray coronal lines, mainly from oxygen but also from nitrogen, carbon and neon, and the unabsorbed 2–10 keV continuum fluxes. The errors on the line fluxes are ∼3–10 per cent for the strongest lines and ∼10–20 per cent for the weakest lines. The errors for the 2011 May observing campaign are much larger on all measurements (∼20–60 per cent).

3 THE VARIABILITY BEHAVIOUR

3.1 The near-IR and optical coronal lines

In the ∼8 yr period sampled by the near-IR and optical spectroscopy, the ionizing flux of the accretion disc, which is assumed to be the main driver for the variability of the broad line, coronal line and hot dust emission regions, decreased by a factor of ∼2 in the first five years and increased by a factor of ∼4 in the following three years (see Fig. 1). We note that the flux increase of ∼9 per cent observed between the 2004 May and 2006 January epochs is consistent with zero once the deviations from the theoretical value of the [S III] λ9531/[S III] λ9069 ratios measured in these spectra are taken into account (∼5.5 and ∼2.9 per cent, respectively). The Paβ broad line region and hot dust emission responded to the accretion disc variability in a similar way (see Figs 2 and 1, respectively); their flux decreased in the first two years by ∼70 and ∼50 per cent, respectively, and then continuously increased for the next six years by a factor of ∼3 and ∼4, respectively. We note that the flux decrease of ∼20 per cent observed for the hot dust emission between the 2006 June and 2007 January epochs is similar to the deviation from the theoretical value measured for the [S III] λ9531/[S III] λ9069 ratio in the latter spectrum (∼13.3 per cent). The flux of the Hα broad line

<table>
<thead>
<tr>
<th>Observation epoch</th>
<th>O i α λ5577 keV (ph s⁻¹ cm⁻²)</th>
<th>O i λ5698 keV (ph s⁻¹ cm⁻²)</th>
<th>O i λ5768 keV (ph s⁻¹ cm⁻²)</th>
<th>Ne X i λ8099 keV (ph s⁻¹ cm⁻²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000 Dec</td>
<td>(5.05 ± 0.17) x 10⁻⁴</td>
<td>(0.70 ± 0.09) x 10⁻⁴</td>
<td>(1.51 ± 0.10) x 10⁻⁴</td>
<td>(0.59 ± 0.04) x 10⁻⁴</td>
</tr>
<tr>
<td>2003 May</td>
<td>(5.10 ± 0.21) x 10⁻⁴</td>
<td>(0.43 ± 0.09) x 10⁻⁴</td>
<td>(1.36 ± 0.13) x 10⁻⁴</td>
<td>(0.56 ± 0.04) x 10⁻⁴</td>
</tr>
<tr>
<td>2006 May</td>
<td>(4.70 ± 0.21) x 10⁻⁴</td>
<td>(0.78 ± 0.11) x 10⁻⁴</td>
<td>(1.55 ± 0.13) x 10⁻⁴</td>
<td>(0.45 ± 0.08) x 10⁻⁴</td>
</tr>
<tr>
<td>2006 Nov</td>
<td>(3.89 ± 0.24) x 10⁻⁴</td>
<td>(0.55 ± 0.31) x 10⁻⁴</td>
<td>(1.49 ± 0.34) x 10⁻⁴</td>
<td>(0.49 ± 0.07) x 10⁻⁴</td>
</tr>
<tr>
<td>2011 May</td>
<td>(5.63 ± 0.95) x 10⁻⁴</td>
<td>(0.98 ± 0.58) x 10⁻⁴</td>
<td>(1.80 ± 0.62) x 10⁻⁴</td>
<td>(0.87 ± 0.16) x 10⁻⁴</td>
</tr>
</tbody>
</table>

Table 5. X-ray emission line and continuum fluxes.
region also decreased in the first two years (by $\sim 35$ per cent) and increased in the next two years (by $\sim 20$ per cent), but then it decreased for a short period (between 2006 June and 2007 January) before it increased strongly for the last three years (by a factor of $\sim 2$; see Fig. 3). The intermittent flux decrease might be caused by a reddening event, which we discuss further in Section 4.

The variability response of the near-IR coronal lines in the 4 yr period between 2006 January and 2010 February is similar to that of the Pa$\beta$ broad line region and hot dust emission, with a trend that the higher the ionization potential, the higher the flux increase, namely, $\sim 69$ per cent for the [Si VII] line, $\sim 28$ per cent for the [S VIII] line, and no significant variability for the [Si II] line (see Fig. 2). In the first two years sampled by the data significant variability is observed only for the [S VIII] line; a flux increase by $\sim 54$ per cent. Then, for all but the [S IX] line, a flux decrease (instead of the increase seen for the broad line region and hot dust emission) is observed between 2004 May and 2006 January, namely, $\sim 52$ per cent for the [Si VII] line, $\sim 55$ per cent for the [S VIII] line, and $\sim 28$ per cent for the [Si VI] line.

Between 2002 April and 2006 January, we detect significant variability for only one optical coronal line, namely, [Fe VII] $\lambda 3759$, which behaves similar to the [S VIII] line (see Fig. 3); a flux increase (by $\sim 70$ per cent) followed by a flux decrease (by $\sim 90$ per cent). The flux decrease observed for the H$\alpha$ broad line region between 2006 June and 2007 January is clearly evident for the [Fe VII] $\lambda 3759$, [Fe VII] $\lambda 5159$ and [Fe VII] $\lambda 5721$ lines; their fluxes changed by $\sim 85$, $\sim 50$ and $\sim 25$ per cent, respectively. If we consider the period of 2006 January–2007 January instead, we observe a similar behaviour also for the [Fe VII] $\lambda 6087$ line; its flux decreased by $\sim 18$ per cent. In the following three years, the [Fe VII] $\lambda 6087$ line flux increased by $\sim 20$ per cent, as observed for the broad line region and hot dust emission, whereas none of the other optical coronal lines varied significantly.

### 3.2 The X-ray coronal lines

In the $\sim 10.5$ yr period sampled by the X-ray spectroscopy the unabsorbed 2–10 keV continuum flux, which is assumed to be produced by the central ionizing source and so to be linked to the accretion disc flux, increased by a factor of $\sim 5$ in the first two and a half years, decreased by a factor of $\sim 4$ in the next three years, and then increased again by a factor of $\sim 2$ in the next five years.

The variability response of the three forbidden X-ray coronal lines in the period between 2006 November and 2011 May is similar to that of the near-IR coronal lines and that of the Pa$\beta$ broad line region and hot dust emission, and again with a trend that the higher the ionization potential, the higher the flux increase, namely, a factor of $\sim 2$ for the Ne IX f line, $\sim 45$ per cent for the O VII f line and no significant variability for the N VII f line (see Fig. 4). Then, whereas the flux stayed roughly constant in the first two and half years sampled by the data, similar to the near-IR coronal lines, a flux decrease (instead of the increase seen for the broad line region and hot dust emission) is observed in the period between 2003 May and 2006 May for the O VII f line (by $\sim 31$ per cent) and the N VII f line (by $\sim 30$ per cent).

In the entire time period sampled by the data, no significant variability is observed for the recombination line O VII r, whereas the intercombination line O VII i showed strong variability between 2000 December and 2006 May, with a flux decrease by $\sim 62$ per cent followed by a flux increase by $\sim 82$ per cent. No significant variability is observed for the O VII i line after 2006 May, which could be due to the relatively large errors on the line flux for the following two observing epochs. The O VII r line showed also significant variability between 2000 December and 2006 May, but contrary to the O VII i line, its flux increased first (by $\sim 37$ per cent) and then decreased (by $\sim 27$ per cent). Also for this line there is no significant variability after 2006 May. The variability response of the two permitted X-ray coronal lines with the highest ionization potentials is similar to that of the O VII f line; a significant flux decrease is observed for the N VII f line only between 2003 May and 2006 November (by $\sim 34$ per cent) and for the C VII f line only between 2006 May and 2006 November (by $\sim 28$ per cent).

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**Figure 3.** Same as Fig. 2 for the optical coronal lines. For comparison, we show also the [O III] $\lambda 4959$ narrow line and H$\alpha$ broad line, which are expected not to vary and to vary maximally, respectively.

**Figure 4.** The variability of the X-ray coronal lines in the period 2000 December–2006 May. The flux values were normalized to the value of the May 2006 epoch. We plot 1$\sigma$ error bars. The ionization potentials of the coronal lines are given at the top right.
4 THE ORIGIN OF THE CORONAL LINE EMISSION REGION

The current understanding is that the coronal line region in AGN is dust-free, photoionized and located beyond the BELR at distances from the central ionizing source similar to those of the hot inner face of the obscuring dusty torus. In this scenario, we expect to observe the coronal line flux to vary similarly to that of the broad lines and hot dust emission but on time-scales longer and shorter than the former and latter, respectively. With our data set we can test the first premise, although its sparse time sampling does not allow us to measure any variability time-scales.

The variability behaviour observed for the broad lines and hot dust emission in the period covered by our data is both similar and simple; a flux decrease of \(\sim 40\)–\(70\) per cent in the first two years followed by a strong flux increase by a factor of \(\sim 2\)–\(4\) in the following six years. This variability behaviour is not observed for any of the coronal lines. In general, the coronal lines varied weakly if at all, with the largest flux change observed to be only \(\sim 50\)–\(90\) per cent in a period of about 2 yr. Specifically, in the first four years sampled by the data, the coronal lines either did not vary significantly or showed the opposite behaviour to that of the broad lines and hot dust emission. In the last four years sampled by the data, only the coronal lines with the highest ionization potentials showed a variability behaviour similar to that of the broad lines and hot dust emission, but with a much reduced amplitude (a lower flux change per year by a factor of \(\sim 2\)–\(4\)), whereas the flux of the coronal lines with relatively low ionization potentials remained unchanged.

The characteristic variability response time is a sum of the light travel time, which depends mainly on the location of the emission region, and the recombination time, which depends strongly on the gas number density:

\[
\tau_{\text{var}} = \tau_L + \tau_{\text{rec}}. \tag{1}
\]

Therefore, the low variability amplitude observed for the coronal line gas in NGC 4151 indicates either that it is located well beyond the broad line region and dusty torus or that it has a relatively low density or both. In the following, we use published results from high-spatial-resolution imaging campaigns at near-IR, optical and X-ray frequencies and apply plasma diagnostics to our own data in order to constrain both the location and gas number density of the coronal line emission region.

4.1 Published high-spatial-resolution observations

NGC 4151 has a well-measured hydrogen broad line region lag time of about a week (Zu, Kochanek & Peterson 2011) and a hot dust lag time varying between \(\sim 30\)–\(70\) d (Koshida et al. 2014). One possible explanation for the fact that the coronal line region reacted much weaker to changes in the ionizing flux than both the broad line and hot dust emission regions is that it is located much further out than them.

High-spatial-resolution observations of NGC 4151 in the near-IR were presented by several authors. Storchi-Bergmann et al. (2009) used the Gemini Near-IR Integral Field Spectrograph (NIFS) on 2006 December to image the source in the 0.94–2.42 \(\mu\)m wavelength range with a spatial resolution of 0.12–0.16 arcsec, which corresponds to \(\sim 8\)–\(10\) pc at the source. Their contour maps of the \([\text{Si} \text{ vi}]\) and \([\text{Si} \text{ vii}]\) coronal lines show a compact, spatially unresolved region. Müller-Sánchez et al. (2011) and Iserlohe et al. (2013) used the Keck OH Suppressing InfraRed Imaging Spectrograph (OSIRIS) on 2006 March and 2005 February/May, respectively, to image the source in the 1.96–2.38 \(\mu\)m wavelength range with a spatial resolution of 0.08–0.11 arcsec, which corresponds to \(\sim 5\)–\(7\) pc at the source. Their contour maps of the \([\text{Si} \text{ vi}]\) coronal line show a bright nucleus containing \(\sim 70\) per cent of the total emission, which is surrounded by low-level extended emission up to \(\sim 50\)–\(80\) pc.

The source NGC 4151 was observed with the Space Telescope Imaging Spectrometer (STIS) on-board the HST on several occasions. These observations span a large optical wavelength range and have a spatial resolution of 0.1 arcsec, corresponding to \(\sim 7\) pc at the source. Nelson et al. (2000) presented measurements of the \([\text{Fe} \text{ vii}] \lambda 3759, \lambda 5721\) and \([\text{Fe} \text{ vii}] \lambda 6087\) coronal line fluxes along the slit at two different position angles for observations taken between 1998 January and June. Along one of the position angles (P.A. 70\(^\circ\)), the \([\text{Fe} \text{ vii}] \lambda 3759\) emission was spatially unresolved, but the \([\text{Fe} \text{ vii}] \lambda 5721\) and \([\text{Fe} \text{ vii}] \lambda 6087\) emission lines showed extents of up to \(\sim 70\)–\(100\) pc from the nucleus. Along the other position angle (P.A. 221\(^\circ\)), all three \([\text{Fe} \text{ vii}]\) emission lines were spatially resolved, however, with much lesser extents of \(\sim 20\)–\(50\) pc from the nucleus. In all cases, the \([\text{Fe} \text{ vii}]\) emission was dominated by the nuclear flux.

Wang et al. (2011a,b) analysed the deep exposure of NGC 4151 taken in 2008 March with the Advanced CCD Imaging Spectrometer (ACIS) on-board the Chandra X-ray observatory. By applying subpixel region repositioning and binning techniques they were able to improve the effective spatial resolution of the ACIS images to better than 0.4 arcsec, which corresponds to \(\approx 25\) pc at the source. Their emission line maps of \([\text{O} \text{ vii}]\), \([\text{O} \text{ viii}]\), \([\text{Ne} \text{ ix}]\) and \([\text{Ne} \text{ ix}]\) show a bright nucleus surrounded by extended emission in the inner region of \(\approx 130\) pc, and for the \([\text{O} \text{ vii}]\) and \([\text{O} \text{ viii}]\) emission lines also very low level emission (\(\sim 10\) per cent of the total flux) up to \(\approx 2\) kpc.

In summary, high-spatial-resolution observations of NGC 4151 show that whereas its coronal line emission region is extended in some chemical species, the total flux that our variability study is most sensitive to is dominated by the unresolved nuclear region. This region can currently be constrained by direct imaging only to \(\lesssim 5\) pc (or \(\lesssim 15\) light years), which is much larger than the measured distance of the hot dust emission of \(\sim 2\) light months.

4.2 Plasma diagnostics

For the optical and X-ray coronal line gas, we can estimate the density using the three iron lines \([\text{Fe} \text{ vii}] \lambda 3759, \lambda 5159\) and \([\text{Fe} \text{ vii}] \lambda 6087\) and the three lines from the helium-like ion of oxygen \([\text{O} \text{ vii}]\), \([\text{O} \text{ viii}]\) and \([\text{O} \text{ viii}]\) respectively. Using the plasma simulation code CLOUDY (last described by Ferland et al. 1998), we have generated a temperature versus density grid for the collisionally excited \([\text{Fe} \text{ vii}]\) lines (see Fig. 5) and a ionization parameter versus density grid for the \([\text{O} \text{ viii}]\) lines (see Fig. 6). The iron collision strengths were taken from Witthoeft & Badnell (2008). For the photoionization simulations, we have approximated the incident radiation field with the mean AGN spectral energy distribution derived by Mathews & Ferland (1987). As discussed by previous studies, the line ratios \([\text{Fe} \text{ vii}] \lambda 6087/\lambda 3759\) and \([\text{Fe} \text{ vii}] \lambda 5159/\lambda 6087\) are suitable indicators of temperature and density, respectively (Nussbaumer et al. 1982; Keenan & Norrington 1987), whereas the X-ray line ratios \([\text{O} \text{ viii}] (f+i)/r\) (the so-called G ratio) and \([\text{O} \text{ viii}] f/i\) (the so-called R ratio) trace the ionization parameter, which is directly related to the kinetic gas temperature, and density, respectively, for a given column density (Porquet & Dubau 2000; Porter & Ferland 2007). We
assumed the cases of either photoionization or collisional ionization equilibrium.

**Figure 5.** The observed optical coronal line ratios [Fe VII] $\lambda$6087/$\lambda$3759 versus [Fe VII] $\lambda$5159/$\lambda$6087, overlaid with curves of constant temperature ($log T = 4, 4.1, 4.2, \ldots, 5$ K) and constant number density ($log n_e = 3, 3.2, 3.4, \ldots, 7$ cm$^{-3}$) for the case of photoionization equilibrium. The case of collisional ionization equilibrium is shown in green. We plot 1$\sigma$ error bars.

**Figure 6.** The observed X-ray coronal line ratios O VII $f+i$/$f$ (G ratio) versus O VII $f$/$f$ (R ratio), overlaid with curves of constant ionization parameter ($log U = -1, -0.5, 0, \ldots, 2$) for two constant number densities ($n_e = 10^3$ cm$^{-3}$ and $n_e = 10^5$ cm$^{-3}$) and a fixed column density of $N_H = 10^{21}$ cm$^{-2}$, assuming photoionization equilibrium. The case of collisional ionization equilibrium is shown in green. We plot 1$\sigma$ error bars.

The measurements for NGC 4151 in both Figs 5 and 6 give two main consistent results; the coronal line gas is photoionized rather than collisionally ionized and its density appears to be relatively low. In the case of the optical coronal line gas, if we assume that the gas density did not change with time, four of the observing epochs constrain it to $n_e \sim 10^3$ cm$^{-3}$ within $\sim 1\sigma$, whereas the two observing epochs 2006 January and June reach this value within $\sim 2\sigma$. If we assume the gas density changed between observing epochs, at the $2\sigma$ level it varied between $n_e \sim 10^2$ cm$^{-3}$ and $n_e \lesssim 10^3$ cm$^{-3}$, since at the low-density limit the grid contours fall on top of each other. The highest density value is about two orders of magnitude lower than the critical density of [Fe VII] $n_{\text{crit}} \sim 3 \times 10^7$ cm$^{-3}$. We get a similar result for the X-ray coronal line gas; assuming the gas density did not change with time, two observing epochs (2006 November and 2011 May) constrain it to $n_e \sim 10^4$ cm$^{-3}$ within $\sim 1\sigma$, whereas three observing epochs reach this value within $\sim 3\sigma$. If we assume the density changed between observing epochs, at the $2\sigma$ level it varied between $n_e \sim 10^{12}$ cm$^{-3}$ (i.e. close to the critical density) and $n_e \lesssim 10^3$ cm$^{-3}$, since at the low-density limit the grid contours fall on top of each other.

It is worth noting that all measured O VII ratios and most of the [Fe VII] ratios are to the right of the theoretical grids. In the case of O VII, there are no known uncertainties in the atomic data and adding a contribution from collisionally ionized plasma would not increase the R ratios, which are observed to be much higher than predicted by theory. Similarly high R ratios are also found in other AGN, e.g. $R = 5.50$ for Mrk 3 (Pounds & Page 2005) and $R = 7.73$ for NGC 1068 (Kraemer et al. 2015). However, in the case of [Fe VII], it is possible that some contribution from fluorescence is present given the relatively low gas density in combination with the large ionization parameter we estimate below. The large number of permitted Fe VII lines in the far-UV can be pumped by the continuum, which, when radiatively decaying, will add to the lower levels responsible for the [Fe VII] lines studied here. Fig. 7 shows the importance of continuum pumping on the optical coronal line ratios [Fe VII] $\lambda$6087/$\lambda$3759 (red solid line) and [Fe VII] $\lambda$5159/$\lambda$6087 (black solid line) in dependence of the ionization parameter. The gas is assumed to have a temperature of $T_e = 10^{4.25}$ K and a number density of $n_e = 10^2$ cm$^{-3}$.
this effect for a gas of number density \( n_\text{e} = 10^3 \text{ cm}^{-3} \) in dependence of the ionization parameter. At a ionization parameter of \( \log U \sim 1 \) the expected increase in the \([Fe \text{ vii}] \lambda 5159/\lambda 6087\) ratio is a factor of \( \sim 1.5 \), whereas the increase in the \([Fe \text{ viii}] \lambda 6087/\lambda 3759\) ratio is only \( \sim 10 \) per cent.

From Fig. 5, we estimate a temperature of \( T \sim 10^{4.25} \text{ K} \sim 18000 \text{ K} \) for the \( Fe^{16+} \) gas. At this temperature, the recombination time is

\[
\tau_{\text{rec}} \approx \frac{1}{n_\text{e} \cdot 1.70 \times 10^{-10} \text{s}},
\]

which for a gas number density of \( n_\text{e} = 10^3 \text{ cm}^{-3} \) results in \( \tau_{\text{rec}} \approx 5.9 \times 10^8 \text{ s} \approx 2.2 \) months. We note that we have used the total recombination coefficient, i.e. the sum of the radiative and dielectronic recombination coefficients, which was calculated based on the atomic data presented by Gu et al. (2006). This value differs from that listed in Osterbrock & Ferland (2006) by about an order of magnitude, since the latter represented only the radiative recombination coefficient. From Fig. 6, we constrain the ionization parameter for all X-ray observing epochs at the 1σ level to \( \log U \sim 1 \). Then, using the unabsorbed X-ray luminosity of \( L_{2-10 \text{ keV}} \sim 10^{43} \text{ erg s}^{-1} \) resulting from our fits for the highest flux epoch as a proxy for the ionizing luminosity producing \( O \text{ vii} \) and the best-fitting X-ray spectral slope of this epoch of \( \Gamma \sim 1.43 \) to estimate the mean ionizing photon energy, the calculated distance of the coronal line region from the central ionizing source for the above gas density is \( \tau_{\text{th}} \sim 730 \) light days \( \sim 2.0 \) light years. This value, which is far below the resolution provided by current direct imaging results (see Section 4.1), puts this region well beyond the hot inner face of the obscuring dusty torus. Together our estimates of \( \tau_{\text{rec}} \) and \( \tau_{\text{th}} \) give a characteristic variability response time of \( \tau_{\text{var}} \approx 2.2 \) yr, which is consistent with our main observational result that the coronal line gas emission in NGC 4151 has varied in an observing period of \( \sim 8-11 \) yr, but only weakly so relative to the variability observed for the broad lines and hot dust emission.

But how can we explain our other observational result that during half the time period covered by the data the variable coronal lines showed the opposite trend to the flux changes observed for the broad lines and hot dust emission, i.e. their emission decreased instead of increased? In order to answer this question, we first need to understand how the coronal line region in NGC 4151 relates to the BELR, the dusty torus and the low ionization NELR. For this purpose, we have plotted in Fig. 8 the run of gas number density with radius for a relationship \( n \propto r^{-2} \), which keeps the ionization parameter constant. We have scaled this relationship to the observed lag time for the hydrogen BELR (of about a week) and the typical density for this emission region of \( n_\text{e} \sim 10^{10} \text{ cm}^{-3} \). This scaling gives at the observed lag time for the hot dust (of \( \sim 50 \) d) a density of \( n_\text{e} \sim 10^5 \text{ cm}^{-3} \), which is consistent with what is currently assumed for the dusty torus material. From the relationship in Fig. 8, we see that, at the density estimated for the coronal line region of \( n_\text{e} \sim 10^7 \text{ cm}^{-3} \), a ionization parameter typical of the BELR is reached at distances from the ionizing source of \( \sim 55 \) light years, which is in the range observed for the spatially resolved low-ionization NELR. However, the coronal line region in NGC 4151 appears to require a much higher ionization parameter than the hydrogen BELR for its lines to form, which, at a given radius, can only be achieved by a considerable drop in density. Therefore, it seems that the coronal line region is not part of a continuous gas distribution but rather an independent entity.

One possibility proposed by Pier & Voit (1995) is that the coronal line region is a layer on the inner part of the dusty torus that becomes an efficient coronal line emitter only when evaporated in an X-ray heated wind. If this scenario applies to NGC 4151, the wind will have undergone adiabatic expansion from its launch location at the inner face of the torus until the gas density and distance from the ionizing source are optimal to give the required high ionization parameter. In the process, the coronal line gas will cool. In Fig. 9, we present tentative evidence for this scenario. In the bottom panel, we compare the temperature of the coronal line gas as measured by the line ratio \([Fe \text{ vii}] \lambda 6087/[Fe \text{ viii}] \lambda 3759\) (the higher its value, the lower the gas temperature; see Fig. 5) with that of the hot dust. We find that the two temperatures behave in opposite ways; the temperature of the coronal line gas is high when the hot dust temperature is low and vice versa. Only the data from 2007 January is an exception to this trend and might indicate a reddening event, which could also explain the decreased flux of the \( H_\alpha \) broad line relative to that of the \( Pa\beta \) broad line for this epoch (see Section 3.1). In the top panel of Fig. 9, we show the continuum flux at rest-frame wavelength of \( \sim 1 \mu \text{m} \), which samples the accretion disc luminosity, versus the hot dust temperature. A clear correlation is apparent, which indicates that the change in temperature for the hot dust is due to direct heating by the central ionizing source. Therefore, the increased AGN radiation that heats the dusty torus appears to increase the cooling efficiency of the coronal line gas. In the scenario of Pier & Voit (1995), the dusty clouds will be evaporated in an X-ray heated wind more efficiently for higher AGN luminosities, which will lead to an increase in mass outflow rate but also to a stronger adiabatic expansion and so cooling.

5 SUMMARY AND CONCLUSIONS

We have presented the first extensive study of the coronal line variability in an AGN. Our data set for the nearby, well-known source NGC 4151 is unprecedented in that it includes six epochs of quasi-simultaneous optical and near-IR spectroscopy spanning a

Figure 8. The density run with radius calculated for the relationship \( n \propto r^{-2} \) (black solid line) and scaled to the observed lag time and expected gas number density for the hydrogen broad line region in NGC 4151 (black dashed lines). The red dashed lines show the observed lag time and expected gas number density for the hot dust. The estimated density and distance of the coronal line region are indicated by the blue dashed lines.
period of \( \sim 8 \) yr and five epochs of X-ray spectroscopy overlapping in time with it. Our main results are as follows.

(i) The variability behaviour observed for the broad emission lines and hot dust emission was not mirrored in any of the coronal lines. The coronal lines varied only weakly, if at all. Specifically, in the first four years sampled by the data, the coronal lines either did not vary significantly or showed the opposite behaviour to that of the broad lines and hot dust emission, whereas after that only the coronal lines with the highest ionization potentials showed a variability behaviour similar to that of the broad lines and hot dust emission, but with a much reduced amplitude (a lower flux change per year by a factor of \( \sim 2–4 \)).

(ii) We have applied plasma diagnostics to the optical [Fe \( \text{VII} \)] and X-ray O \( \text{VII} \) emission lines in order to constrain the gas number density, temperature and ionization parameter of the coronal line region. We find that this gas has a relatively low density of \( n_e \approx 10^6 \text{ cm}^{-3} \) and requires a relatively high ionization parameter of \( \log U \approx 1 \).

(iii) We estimate the distance of the coronal line region in NGC 4151 from the central ionizing source for the above gas density to be \( \tau_\text{var} \sim 2.0 \) light years. This value, which is well below the spatial resolution provided by current direct imaging results, puts this region well beyond the hot inner face of the obscuring dusty torus (of \( \sim 2 \) light months). Together with the recombination time this results in a characteristic variability time-scale of \( \tau_{\text{var}} \approx 2.2 \) yr, which is consistent with our main observational result that the coronal line gas emission has varied in an observing period of \( \sim 8–11 \) yr, but only weakly so relative to the variability observed for the broad emission lines and hot dust emission.

(iv) Since the coronal line region requires a much higher ionization parameter than the BELR, it cannot be part of a continuous gas distribution but is rather an independent entity. One possibility is that this region is a layer on the inner part of the dusty torus that becomes an efficient coronal line emitter only when evaporated in an X-ray heated wind (Pier & Voit 1995). We present tentative evidence for this scenario in the form of a temperature anticorrelation between the coronal line gas and hot dust, which indicates that the increased AGN radiation that heats the dusty torus appears to increase the cooling efficiency of the coronal line gas, most likely due to a stronger adiabatic expansion.

In a future paper, we plan to present a similar study of the coronal line variability for the well-known AGN NGC 5548.

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