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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 $n_e \sim 10^3$ cm$^{-3}$ and a relatively high ionization parameter of $\log U \sim 1$. 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 ($n_e \sim 10^7-10^{10}$ cm$^{-3}$), their profiles tend to have full width at half-maxima (FWHM) intermediate between those of the broad and narrow emission lines (FWHM $\sim 500$–$1500$ km s$^{-1}$; e.g. Penston et al. 1984; Appenzeller & Oestricher 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 $\sim 80$–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 ($T_e \sim 10^4$–$10^5$ 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; Rodriguez-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 \( \text{O} \ VII \) and \( \text{O} \ VIII \) 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 \( \sim 20 \) AGN, he found firm evidence that both the \( \text{[Fe} \ VII] \lambda 6087 \) and \( \text{[Fe} \ X] \lambda 6375 \) 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 \( \text{[Fe} \ X] \) 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 \( H_0 = 70 \text{\ km\ s}^{-1}\ \text{Mpc}^{-1} \), \( \Omega_M = 0.3 \), 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 SpEx 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 \( \sim 400 \text{\ km\ s}^{-1} \). 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 mm\(^{-2}\) 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 \( \sim 330 \text{\ km\ s}^{-1} \). 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 \( \text{[Fe VII]} \lambda 3759 \) relative to that at wavelengths \( \gtrsim 5000 \) 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, \( \text{[S} \ VIII] \lambda 9911, \text{[S} \ IX] \lambda 1.252 \mu \text{m}, \text{[Si} \ VII] \lambda 1.965 \mu \text{m} \) and \( \text{[Si} \ X] \lambda 1.430 \mu \text{m} \) (see Table 1). Two of these emission lines are blended, namely, \( \text{[S} \ IX] \) with \( \text{[Fe} \ II] \lambda 1.257 \mu \text{m} \) and \( \text{[Si} \ VII] \) with \( \text{H} \beta \lambda 1.957 \mu \text{m} \). In these cases, we have assumed a Gaussian profile in the deblending procedure. In the optical, we have measured four iron emission lines, namely, \( \text{[Fe} \ VII] \lambda 3759, \text{[Fe} \ VII] \lambda 3795, \text{[Fe} \ VII] \lambda 5721 \) and \( \text{[Fe} \ VII] \lambda 6087 \) (see Table 2). We have considered also \( \text{[Fe} \ X] \lambda 6375 \), but this line is extremely weak in NGC 4151 and makes up only \( \sim 15 \) per cent of the total blend with \( \text{[O} \ I] \lambda 6364 \) (Pelat, Alloin & Bica 1987). We do not observe significant variability in the flux of the entire blend, which constrains the \( \text{[Fe} \ X] \) variability to be 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 \( \text{[S} \ III] \lambda 9531 \) and \( \text{[O} \ III] \lambda 5007 \) 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 \( \gtrsim 50–100 \)) and, therefore, the main sources of measurement errors are of a subjective
nature, namely, the placement of the local continuum and related to this the setting of the extension of the emission line. These are problematic in most cases since the lines in question sit on top of broad emission lines, namely, [S ii] λ6531 in the blue wing of Paα, [S viii] in the blue wing of Paβ, [S iv] in the blue wing of Brγ, [O i] λ6300 in the red wing of Hβ and [Fe x] in the blue wing of Hγ. Therefore, in order to estimate meaningful uncertainties for the measured line fluxes we have considered in addition to the statistical errors due to the data quality also profile comparisons. These were done in velocity space between the scaling lines [S ii] λ6531 and [O i] λ6300 and the coronal lines and helped us judge the influence of the continuum placement on the recovery of the true line profile. The total estimated 1σ uncertainties for all measured line fluxes are listed in Tables 1 and 2. They are ~1–2 per cent for the strongest lines and ~3–15 per cent for the weakest ones.

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] λ6509 and [O i] λ4959. Their observed ratios, which should be close to the theoretical values of [S ii] λ6531/[S ii] λ6509 = 2.58 and [O i] λ5007/[O i] 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.

In addition to the emission lines, we have measured in the near-IR spectra the continuum fluxes at the rest-frame wavelengths of ~1 and ~2.1 μm (see Table 3). As we have shown in Landt et al. (2011), the former is dominated by the accretion disc flux, which is believed to be the main source of ionizing radiation in AGN and so the driver of the observed variability, whereas the latter is emitted from the hot dust component of the obscuring torus, which, if its location indeed coincides with that of the coronal line region, should have a variability response similar to it. Furthermore, we have derived the hot dust temperature from blackbody fits to the near-IR spectral continuum as described in Landt et al. (2011) and list it also in Table 3. In Section 4, we will compare these values to the optical coronal line ratios [Fe v] λ6087/[Fe v] λ7379 and [Fe v] λ5159/[Fe v] λ6087, which are suitable indicators of the gas temperature and density (Nussbaumer, Storey & Storey 1982; Keenan & Norrington 1987), respectively (listed in Table 3).
2.2 X-ray spectroscopy

Between 2000 December and 2011 June, the time period that overlapped 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 software1 (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 $2 \times 10^{21}$ m$^{-2}$. Three of the campaigns have multiple observations, with two of them (2000 December and 2003 May) extending over a period of 2–3 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 (Detmers 2009) and in order to improve the S/N ratio, we have stacked the individual RGS spectra into one spectrum per campaign. We have treated the 2006 May 16 and November 29 observations separately, since the time span between them is about half a year. The longest and shortest observations are for the 2000 December and 2011 May campaigns with total exposure times of 131 and 32 ks, respectively.

In the X-rays, NGC 4151 is classified as an obscured Seyfert 1 galaxy, i.e. the soft X-ray emission is heavily obscured by an absorber. However, this absorption is not as deep as that observed for Seyfert 2 galaxies and a very weak continuum is present. This absorber is different from the warm absorber detected in the ultraviolet (UV) and X-ray spectra of $\sim$50 per cent of Seyfert 1 galaxies (Crenshaw, Kraemer & George 2003). It has a much larger column density, outflow velocity and velocity broadening, is variable

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 II] 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 II] λ9531/[S II] λ9069 ratio in the latter spectrum (∼13.3 per cent). The flux of the Hα broad line...
that the higher the ionization potential, the higher the flux increase, namely, a factor of ∼5 in the first two and a half years, decreased by a factor of ∼4 in the next three years, and then increased again by a factor of ∼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 Paβ 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 ∼2 for the Ne ix f line, ∼45 per cent for the O VII f line and no significant variability for the N vi 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 ∼31 per cent) and the N vi f line (by ∼30 per cent).

In the entire time period sampled by the data, no significant variability is observed for the recombinant line O viii r, whereas the intercombination line O viii i showed strong variability between 2000 December and 2006 May, with a flux decrease by ∼62 per cent followed by a flux increase by ∼82 per cent. No significant variability is observed for the O viii 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 viii α line showed also significant variability between 2000 December and 2006 May, but contrary to the O viii i line, its flux increased first (by ∼37 per cent) and then decreased (by ∼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 viii f line; a significant flux decrease is observed for the N vii α line only between 2003 May and 2006 November (by ∼34 per cent) and for the C vi α line only between 2006 May and 2006 November (by ∼28 per cent).
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:

$$\tau_{\text{var}} = \tau_\text{h} + \tau_\text{rec}. \tag{1}$$

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 $\approx$8–10 pc at the source. Their contour maps of the [Si vi] and [S iv] 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 $\approx$5–7 pc at the source. Their contour maps of the [Si 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 $\approx$50–80 pc.

The source NGC 4151 was observed with the Space Telescope Imaging Spectrograph (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 $\approx$7 pc at the source. Nelson et al. (2000) presented measurements of the $\lambda$3759, $\lambda$5721 and $\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 [Fe vii] $\lambda$3759 emission was spatially unresolved, but the [Fe vii] $\lambda$5721 and [Fe vii] $\lambda$6087 emission lines showed extents of up to $\approx$70–100 pc from the nucleus. Along the other position angle (P.A. 221$^\circ$), all three [Fe vii] emission lines were spatially resolved, however, with much lesser extents of $\approx$20–50 pc from the nucleus. In all cases, the [Fe 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 Spectrograph (ACIS) on-board the Chandra X-ray observatory. By applying subpixel event 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 O vii, i and r, O viii and Ne ix, f and r show an extremely bright nucleus surrounded by extended emission in the inner region of $\approx$130 pc, and for the O vii and O viii emission lines also very low level emission ($\approx$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 $\approx$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 [Fe vii] $\lambda$3759, [Fe vii] $\lambda$5159 and [Fe vii] $\lambda$6087 and the three lines from the helium-like ion of oxygen O vii f, O vii i and O viii r, 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 [Fe vii] lines (see Fig. 5) and a ionization parameter versus density grid for the O vii 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 [Fe vii] $\lambda$6087/$\lambda$3759 and [Fe 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 O vii (f+i)/r (the so-called G ratio) and O viii f (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).
assumed the cases of either photoionization or collisional ionization equilibrium.

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 \( n_e \sim 10^3 \text{ cm}^{-3} \) 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 \( n_e \sim 10^2 \text{ cm}^{-3} \) and \( n_e \lesssim 10^5 \text{ cm}^{-3} \), 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 \([\text{Fe VII}], n_{\text{crit}} \sim 3 \times 10^7 \text{ cm}^{-3}\).

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 \( T_e = 10^{4.25} \text{ K} \) and a number density of \( n_e = 10^3 \text{ cm}^{-3} \).
this effect for a gas of number density $n_e = 10^3 \text{ cm}^{-3}$ in dependence of the ionization parameter. At an ionization parameter of $\log U \sim 1$ the expected increase in the [Fe vii] $\lambda 5159/\lambda 6087$ ratio is a factor of $\sim 1.5$, whereas the increase in the [Fe viii] $\lambda 6087/\lambda 3759$ ratio is only $\sim 10$ per cent.

From Fig. 5, we estimate a temperature of $T \sim 10^{4.25} \text{ K} \sim 18 \times 10^{3}$ K for the Fe$^{2+}$ gas. At this temperature, the recombination time is

$$\tau_{\text{rec}} \approx \frac{1}{n_e \cdot 1.70 \times 10^{-10} \text{s}},$$

(2)

which for a gas number density of $n_e = 10^3 \text{ cm}^{-3}$ 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 $L_{2-10\text{ keV}} \sim 10^{33} \text{ erg s}^{-1}$ resulting from our fits for the highest flux epoch as a proxy for the ionizing luminosity producing O 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 $r_{\text{th}} \sim 730$ 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 $r_{\text{th}}$ 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 NERL. 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 $n_e \sim 10^{10} \text{ cm}^{-3}$. This scaling gives at the observed lag time for the hot dust (of $\sim 50$ d) a density of $n_e \sim 10^9 \text{ cm}^{-3}$, 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 $n_e \sim 10^9 \text{ cm}^{-3}$, 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 NERL. 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 vii] $\lambda 6087/[\text{Fe viii}] \lambda 3759$ (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 Hα broad line relative to that of the Paβ 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
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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