OUTFLOWS OF VERY IONIZED GAS IN THE CENTERS OF SEYFERT GALAXIES:
KINEMATICS AND PHYSICAL CONDITIONS

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ABSTRACT

Mid-resolution spectra are used to deduce the size and kinematics of the coronal region in a sample of Seyfert galaxies by means of observations of the [Fe xi], [Fe x], [Fe vii], [Si vi], and [Si vi] lines. These coronal lines (CLs) extend from the unresolved nucleus up to a few tens to a few hundreds of parsecs. The region of the highest ionized ions studied, [Fe xi] and [Fe x], is the least spatially extended and concentrates at the center; intermediate-ionization lines extend from the nucleus up to a few tens to a few hundred parsecs; lower [O iii]–like ions are known to extend to the kpc range. All together indicate a stratification in the ionized gas, usually interpreted in terms of nuclear photoionization as the driving ionization mechanism. However, CL profiles show various peculiarities: they are broader by a factor of 2 than lower ionization lines, the broadening being in terms of asymmetric blue wings, and their centroid position at the nucleus is blueshifted by a few hundred km s\(^{-1}\). Moreover, in NGC 1386 and NGC 1068, a double-peaked [Fe vii] line is detected in the nuclear and extended coronal region, this being the first report of this type of profile in CLs in active galactic nuclei. If interpreted as outflow signatures, the total broadening of the lines at zero-intensity levels implies gas velocities up to 2000 km s\(^{-1}\). Although the stratification of ions across the coronal region means that photoionization is the main power mechanism, the high velocities deduced from the profiles, the relatively large spatial extension of the emission, and the results from photoionization models indicate that an additional mechanism is at work. We suggest that shocks generated by the outflow could provide the additional required power for line formation.

Subject headings: galaxies: individual (Circinus, MCG –6-30-15, NGC 1068, NGC 1386, NGC 3227, NGC 3783) — galaxies: Seyfert — infrared: galaxies — line: formation

1. INTRODUCTION

Coronal lines (CLs) are collisionally excited forbidden transitions within low-lying levels of highly ionized species (ionization potential >100 eV). They can be produced by either a hard UV continuum (Ferguson et al. 1997), a hot collisionally ionized plasma (Viegas-Aldrovandi & Contini 1989), or most plausibly, a mix of both processes (Contini et al. 1998a). Because of their high ionization potential (IP), these lines are particularly suitable for finding information on the otherwise difficult to access observationally, extreme-UV to soft X-ray region of the ionizing spectrum (Prieto & Viegas 2000). Due to the high energies involved in their production, CLs are genuine tracers of the active galactic nucleus (AGN) power mechanism. Pure starbursts, when boosted by massive OB stars in their Wolf-Rayet phase, may show He ii lines but not lines of higher IP ions (\(\chi > 54\) eV).

Observationally, CLs are present with comparable strength in AGN spectra regardless of their class (Penston et al. 1984; Erkens et al. 1997; Prieto & Viegas 2000; Rodríguez-Ardila et al. 2002; Reunanen et al. 2003). The peak position is usually blueshifted relative to the systemic velocity of the host galaxy (\(\Delta V \approx 500–800\) km s\(^{-1}\)), and broader than low-ionization lines (Penston et al. 1984; De Robertis & Osterbrock 1986; Erkens et al. 1997; Rodríguez-Ardila et al. 2002). That has led to the idea that CLs are associated with outflows, formed in a intermediate region between the classical narrow-line and broad-line regions (NLRs and BLRs, respectively). The BLR has sizes of less than a few hundred light-days (Peterson et al. 2004) and thus remains unresolved; the coronal region, because of its lower velocity dispersion, should be placed further out but still relatively close to the BLR, considering the high ionization level of the gas. Accordingly, the coronal region has also remained spatially unresolved.

The physical nature of the coronal line region (CLR) has called the attention of many authors, starting with the pioneering work by Penston et al. (1984), who discovered the systematic blue-shifting and broadening of this high-ionization gas. Erkens et al. (1997) found that the CL occurs predominantly in objects with a soft X-ray excess and suggested a possible relationship between the CLR and the absorption edges associated with warm absorbers present in nearly 50% of AGNs. Porquet et al. (1999) showed that the CL may, in fact, be formed by the warm absorber. If that is the case, the CLR should be dense (\(n \sim 10^6\) cm\(^{-3}\)) and located at a comparable distance to the BLR. On the other hand, Ferguson et al. (1997) photoionization calculations show that the CLR can form in gas with densities of \(10^2–10^5\) cm\(^{-3}\) and extends up to several hundred parsecs, thus coinciding with the size of the extended NLR. However, they claim that except for the lower
ionization CLs ([Ne vi], [Si vii], [Ca viii], and [Fe vii]) that can form efficiently in gas that is roughly ~10 pc and beyond, the rest of the CLs form optimally in gas that is less than 10 pc from the ionization source.

CLs are present all across the electromagnetic spectrum. The highest ionization species are located in the X-ray region. In the optical, the most prominent ones are from iron. Dust extinction and the fact that reliable detection of these lines requires medium to high spectral resolution and a large signal-to-noise ratio (S/N) has made measurements of these lines difficult. The near- and mid-infrared regions, less affected by extinction, are very rich in CLs from different species and ionization levels. Indeed, they are often the dominant lines in the near-IR spectra of Seyfert galaxies (Reunanen et al. 2003).

The current availability of adaptive optics in 8 m telescopes enabled Prieto et al. (2005) to determine the size and morphology of the CLR for the first time. It is found to extend from the nucleus up to 30–200 pc radii at most, and be aligned preferentially with the direction of the lower ionization cones seen in Seyfert galaxies. As expected, the CLR is primarily produced very close to the active nucleus but is nevertheless resolved over several tens of parsecs. This, together with its preferential alignment with the ionization cone, suggests the possibility that the nuclear radiation is intrinsically collimated or that some additional in situ excitation mechanism is needed to explain CL gas at those observed distances from the ionizing source. This paper attempts to address those issues by studying the physical conditions of the coronal gas.

2. OBSERVATIONS

In order to maximize the spatial resolution in physical scales, the sample of objects chosen for this work is composed of six of the nearest and brightest Seyfert galaxies: Circinus (Seyfert 2), NGC 1068 (Seyfert 2), NGC 1386 (Seyfert 2), NGC 3783 (Seyfert 1), MCG –6–30–15 (Seyfert 1), and NGC 3227 (Seyfert 1.5). Table 1 lists the characteristics of these galaxies. The spatial scale (pc arcsec^{-1}) was derived assuming $H_0 = 75$ km s^{-1} Mpc^{-1}. These objects were observed at medium-resolution spectroscopy, $R = 2600$ (~120 km s^{-1}) in the optical, $R = 3000$ (~100 km s^{-1}) in the near-IR, with a slit width of 1", the slit being always oriented north-south. The slit was nearly aligned to the position angle (P.A.) of the [O iii] emission for most sources, listed in column (5) of Table 1. The differences in P.A. of the extended ionized gas and that of the slit is, for the majority of sources, not larger than 15°, except for MCG –6–30–15, where the difference is 65° and the opening angle is small, about 30° maximum. In Circinus, the slit is aligned with the edge of the ionization cone: the P.A. of the cone is ~44° NW, but the opening angle of the cone is ~90°.

The spectroscopic configurations, telescopes, and instrumentation employed for the optical and near-IR observations, as well as data reduction and extraction procedures, were as follows. A log of the observations is in Table 2.

The optical iron CLs [Fe vii], [Fe x], and [Fe xi] were observed in service mode (program 68.B-0627[A]) with the imaging spectrograph EMMI (ESO Multi-Mode Instrument) at the ESO NTT (New Technology Telescope). Two grating positions were needed: one centered at $\lambda = 6230$ Å, in order to include the [Fe vii] and [Fe x] lines and the low-ionization line [O i] 6300, used for comparative purposes. The plate scale of this setup is 0.35 pixel^{-1}. The second position was centered at $\lambda = 7950$ Å to observe the [Fe xi] 7890 line (plate scale 0.27 pixel^{-1}).

Data were reduced using IRAF standard procedures, that is, bias subtraction and division by a flat-field frame. Wavelength and flux calibration were carried out by means of HeNeAr lamp frames and observations of spectroscopic standards taken during the night, respectively. A log of observations is presented in Table 2. One-dimensional (1D) frames were extracted from the two-dimensional (2D) images by summing up rows along the spatial direction. The optimal number of rows to be summed varied from source to source and depended on the achieved spatial resolution.
For the near-IR CLs, the observations were also carried out in service mode (program 68.B-0627[B]) with the imager-spectrograph ISAAC mounted on the Very Large Telescope (VLT) Antu 8.2 m telescope. Two different grating positions were used. For the spectral region covering [Si vi] \( \lambda \)19630, the grating was centered at \( \lambda = 19800 \) Å. This setup allows the simultaneous observation of that line and H2 \( \lambda \)19570. The second grating position, centered at 24400 Å, was to observe [Si vi] \( \lambda \)24830 and the Q(0) H2 lines. The detector was a 1024 \( \times \)1024 array with a spatial scale of 0.013 arcsec. The intrinsic spatial resolution of the optical and near-IR spectra was 3 km s\(^{-1}\) for the optical spectra centered at 6230 Å, 1.3 km s\(^{-1}\) for the ones centered at 7950 Å, and 4.6 km s\(^{-1}\) for the near-IR data.

### 3. RESULTS

#### 3.1. Spatial Extraction of the Coronal Line Spectra

Two-dimensional spectra of each galaxy were averaged in the spatial direction into separate extraction windows. The spatial size of these windows was selected to optimize both S/N and spatial resolution. The sizes of the extraction window are given in Table 2, column (7), and in general correspond to the achieved spatial resolution (seeing) of the data. In galaxies with strong continua, to mitigate nuclear scatter light in the off-nuclear spectra, the nuclear extraction window was enlarged by factors between 20% and 100%.

Aperture windows were extracted consecutively north and south of the nuclear one. Because of the differences in plate scale between the blue and red detectors in the optical and the near-IR array, besides the effect of seeing variations, the extraction window is different from line to line even within the same object.

Figures 1--6 show the extracted spectra along the spatial direction for all the objects in the sample. Usually, one or two extractions ahead of the last one showing extended coronal emission are plotted. Each spectrum is identified by its distance (in parsecs) from the nucleus, measured from the center of the extraction window to the nuclear peak position. The value following the \( \pm \) sign is the radius of the extraction window. The dotted lines mark the position, relative to the systemic velocity of the galaxy, of [Fe ii] \( \lambda \)6087 and [Fe x] \( \lambda \)6374 (blue spectra) and [Fe ii] \( \lambda \)7889 (red spectra). [Fe ii] \( \lambda \)5721 is also present in all objects. This line is weaker than [Fe ii] \( \lambda \)6087 and therefore is not shown in any of the figures.

Information about near-IR CLs [Si vi] \( \lambda \)19630 and [Si vii] \( \lambda \)24830 is available for three objects in the sample: Circinus, NGC 1068, and NGC 3727. No ESO ISAAC observations of the remaining galaxies could be scheduled within ESO Paranal service mode observations. Spectra for these three sources are shown in

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**Table 2**

| Galaxy (1) | Date of Observation (2) | Telescope (3) | Instrument (4) | Seeing (arcsec) (5) | Air mass (6) | \( D^* \) (arcsec) (7) | \( \lambda_0 \) (Å) (8) | Exposure Time (s) (9) |
|-----------|------------------------|--------------|----------------|---------------------|-------------|----------------------|-----------------|------------------|
| NGC 1068 | 2001 Nov 24 VLT ISAAC 0.60 1.15 0.6 24400 10 | VLT ISAAC | 0.60 1.15 0.6 24400 10 | | | | | |
| Circinus | 2002 Feb 28 NTT EMMI 0.91 1.25 1.1 7890 4 | NTT EMMI | 0.91 1.25 1.1 7890 4 | | | | | |
| NGC 3227 | 2002 Feb 28 NTT EMMI 0.92 1.53 0.9 19800 10 | NTT EMMI | 0.92 1.53 0.9 19800 10 | | | | | |
| NGC 1386 | 2002 Nov 27 NTT EMMI 1.20 1.01 1.4 6230 4 | NTT EMMI | 1.20 1.01 1.4 6230 4 | | | | | |
| NGC 3783 | 2002 Oct 2 VLT ISAAC 0.56 1.48 0.6 24400 10 | VLT ISAAC | 0.56 1.48 0.6 24400 10 | | | | | |
| MCG –6-30-15 | 2002 Feb 28 NTT EMMI 1.05 1.08 2.1 6230 4 | NTT EMMI | 1.05 1.08 2.1 6230 4 | | | | | |

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\( a \) \( D \) is the diameter of the extraction window used to define the nuclear spectrum and those of adjacent regions. Spectra shown in Figs. 1--9 are extracted according to this value.

\( b \) Aperture size for the nuclear spectrum. Spectra for the extended regions were extracted using a window size of 1.4 and 1.1 for the blue and red regions, respectively.
Figures 7, 8, and 9, respectively. The spatial resolution $\sim 0.6$ FWHM is superior to that achieved in the optical; the spectral resolution is comparable, 100 km s$^{-1}$.

Table 3 lists the size (radius, in parsecs) of the coronal region derived from [Fe vii] $\lambda 6087$, [Fe x] $\lambda 6374$, and [Fe xi] $\lambda 7889$, respectively. For comparison, the table also lists the radius of the emitting region measured from [O i] $\lambda 6300$ and [S iii] $\lambda 6312$. The size derived from the latter is uncertain because the line is intrinsically weak outside the nuclear region. The last column in the table gives the NLR radius based on [O iii] $\lambda 5007$ line emission data taken from the literature.

Tables 4 and 5 list the FWHM (in km s$^{-1}$, already corrected for instrumental resolution) of the CLs, as well as that of [O i] $\lambda 6300$, included for comparative purposes. Also, the shift of the centroid position of each line component relative to the systemic velocity is given. Centroids and FWHMs were estimated after a multi-Gaussian fit to the lines. In most cases, a two-Gaussian fit, accounting for a narrow and a broad component, was necessary to improve the reduced $\chi^2$. In cases of low S/N, only a single-component fit was used. The tables provide the resulting parameters from a two-Gaussian fit when that was possible. In [Fe x] $\lambda 6374$, the fitting procedure accounts for the presence of [O i] $\lambda 6363$, whose width and flux were fixed according with the values derived for [O i] $\lambda 6300$. Typical errors in the Gaussian centroid position was $\sim 20$ km s$^{-1}$.

3.2. Specifics to Each Object

3.2.1. Circinus

This is the nearest AGN in the sample, allowing us to map the gas emission with a spatial resolution of $\sim 27$ pc in the blue and $\sim 20$ pc in the red. In the optical spectra (Fig. 1), [Fe vii] $\lambda 6087$, [Fe x] $\lambda 6374$, and [Fe xi] $\lambda 7889$ are prominent and broader than [O i] $\lambda 6300$. All the iron line regions extend several tens of parsecs, including [Fe xi], which extends within the central 20 pc radius (Table 3). In contrast, [O i] $\lambda 6300$ extends up to 200 pc in radius (Fig. 1 shows only the central 53 pc region).

The Fe CLs are stronger in the north direction, coinciding with the location of the ionization cone. South of the nucleus, the line spectrum is much weaker due to a combination of extinction by the large dust lanes that cover the southeast region, and the presence of a circumnuclear star-forming region. This is supported by the weakness of [O i] $\lambda 6300$, which is almost reduced to noise at 100 pc south from the center, and the line ratios [N ii]/H$\alpha$ and [S ii]/H$\alpha$, almost a factor of 2 smaller than those at the same distance to the north.
The Si CLs [Si vi] and [Si vii] extend to similar distances, but the extension is seen equally north and south of the nucleus; [Si vii] extends farther north, up to 35 pc (Fig. 7). The inferred size of [Si vii] region confirms VLT subarcsecond imaging results in this line (Prieto et al. 2005). Indeed, the [Si vii] image reveals a two-sided ionization cone, the northwest side being located about 30 pc within the much larger, one-side-only cone seen in [O iii] λ5007 or Hα.

Oliva et al. (1994, 1999) report for Circinus CLs widths comparable to those of lower ionization lines, FWHM ~100 km s⁻¹. As illustrated by Figures 1 and 7, all the CLs show an asymmetric profile with a sharp cutoff at the red side and an extended wing to the blue side—less obvious, e.g., in [O i] λ6300. The FWHM of both low- and high-ionization lines are rather similar, ~100 km s⁻¹; yet, at one-third of the line maximum all CLs have developed a prominent blue asymmetric wing, and at 10% of the maximum, this wing extends to ~400 km s⁻¹ at the nucleus. At this same position to the red, the highest velocity measured is 200 km s⁻¹ (the nuclear profile in velocity space is shown in Fig. 11). The same characteristics apply to the Si line profiles.

The line profiles in the nuclear region are complex: low- and high-ionization lines show a broad component, but [O i] 1.963 μm, [Al ix] 2.040 μm, and [Ca viii] 2.32 μm lines, all showing the same kinematics characteristics, namely, a blue-shifted wing reaching 500 km s⁻¹ at the base of the line but only 200 km s⁻¹ on the red side (cf. their Fig. 8).

As a reference, H₂ molecular lines—seen in large numbers in the ISAAC spectra—are detected up to 150 pc from the center (only the central 51 pc region is shown in the figures). H₂ emission is the strongest at the nucleus, and then fades progressively outward. At about 20 pc south from the nucleus, H₂ is slightly enhanced due to the presence of a star-forming ring.

3.2.2. NGC 1386

This object is a factor 2 farther than Circinus. The coronal emission was mapped with a spatial scale of ~70 pc FWHM (Table 2). Figure 2 shows weak extended coronal emission up to 50 pc radius in [Fe x] and [Fe xi], and up ~100 pc radius in [Fe vii] (see also Table 3). The extended emission is slightly stronger north of the nucleus than to the south. In contrast, [O i] and [S iii] tend to be stronger toward the south. [O iii] λ5007 shows high collimated emission, composed of several blobs distributed in the north-south direction (Schmitt et al. 2003). The brightest [O iii] blob is about 1″ north, coinciding with extended [Fe vii] at the same location in the spectra.

The line profiles in the nuclear region are complex: low- and high-ionization lines show a broad component, but [O i]
shows in addition a prominent narrow component, FWHM $\approx 100$ km s$^{-1}$, whereas [Ar III] and the Fe CLs show a broader profile: $300$ km s$^{-1} < $ FWHM $\approx 800$ km s$^{-1}$. [Fe VII] $\lambda 6087$, having the highest S/N, shows a double-peaked profile, with the red peak stronger than the blue one. This double peak is seen up to $80$ pc north and south of the nucleus. A double-peaked profile is also seen in [Fe VII] $\lambda 5721$, which is detected in the spectra but is not shown because it is weaker than [Fe VII] $\lambda 6087$. As reported below, NGC 1068 presents a similar double-peaked profile in [Fe VII]. The S/N limits the discussion about the [Fe X] and [Fe XI] profiles, for which only a single Gaussian could be fitted to the data. No near-IR CL observations are available for this object.

3.2.3. NGC 1068

NGC 1068 is at nearly the same distance as NGC 1386 and NGC 3727. The spatial scale achieved in this case is $\sim 100$ pc in the blue spectra and $\sim 80$ pc in the red one. A rapid inspection of the optical spectra (Fig. 3) reveals its complexity, dominated by extreme broadening in all low- and high-ionization lines. Even at our midspectral resolution, it is difficult to characterize the line profiles and their spatial extension due to blending. For example, the FWHM of [Fe VII] is $\sim 1700$ km s$^{-1}$, whereas that of [O I] is $\sim 1000$ km s$^{-1}$. NGC 1068 thus shows the largest gas velocities in the sample. Hence, most of the coronal emission discussion is limited to [Fe VII] $\lambda 6087$ and [Si VII] $2.48 \mu m$, since these are the best isolated lines.

[Fe VII] $\lambda 6087$ is the most extended CL, up to $210$ pc north of the nucleus, but [Si VII]—next in IP—is by far the strongest line, a factor 3 stronger, although covering half that spatial size. All other CLs decrease in strength and size of the emitting region with increasing IP, [Fe XI] being the weakest, a factor 30 lower in flux than [Si VII], and the smallest region, with less than a 40 pc radius (Tables 4 and 5). The characterization of the [Fe X] $\lambda 6374$ region is difficult because this line is strongly blended with [O I] $\lambda 6300$. A multiple-Gaussian fitting, fixing parameters for [O I] $\lambda 6363$ as determined from a fit to the [O I] $\lambda 6300$ line, leads to a conservative upper limit of $100$ pc radius for the [Fe X] $\lambda 6374$ region.

Both [Si VII] $\lambda 19630$ and [Si VII] $\lambda 24830$ extend north and south of the nucleus up to a $100$ pc radius (Fig. 8), half the [Fe VII] region.
but comparable to that of [Fe vii] (Table 3). The particular spatial morphology of [Si vii] emission region has been revealed at subarcsecond scales by VLT adaptive optics images (Prieto et al. 2005). [Si vi] shows a central three-blob structure within the inner 7 pc radius, surrounded by diffuse emission up to 70 pc radius. The present spectroscopy just confirms the Si coronal size derived from imaging. The reported size for the [Si vii] $\lambda 19630$ region, derived from NICMOS imaging (Thompson et al. 2001) is much larger: $\sim 300$ pc to the south and 200 pc to the north. However, we believe that the image from Thompson et al. is largely contaminated by the satellite line H$_2$ $\lambda 19570$. This is easily seen in Figure 8, in which both lines appear heavily blended. Moreover, Figure 8 shows that at distances larger than $\sim 135$ pc, only H$_2$ is detected.

For comparison, [O i] $\lambda 6300$ is detected up to 525 pc north and south from the center (Fig. 3 shows a smaller region). All lines are stronger toward the north side of the nucleus, which coincides with the preferential direction of the [O iii] line emission and the radio jet.

Undoubtedly the most reliable information about the kinematics of the coronal gas can be derived first from [Fe vii] $\lambda 6087$, which is the best isolated line, and second, from [Si vii] $\lambda 2.48 \mu m$, also isolated but falling just at the edge of the ISAAC detector, hampering the detection of the most redshifted gas.

At the unresolved nucleus, [Fe vi] $\lambda 6087$ shows a prominent double-peaked profile (FWHM $\sim 1700$ km s$^{-1}$) on top of a much broader component with FWZI $> 4000$ km s$^{-1}$. The spatially resolved [Fe vii] also shows a double-peaked component both north and south of the nucleus (Fig. 3). At first glance, it could be said that the double peak may result from the combination of a large integration window size and a strong velocity gradient. In order to confirm that this peculiar profile structure is real, we have extracted spectra row by row along the spatial direction in the 2D frame of NGC 1068. At the redshift of this galaxy (see Table 1), each pixel corresponds to a projected distance of about 26 pc. The left panel of Figure 10 shows the resulting spectra mapped up to 250 pc north and 180 pc south of the peak light profile distribution. The fact that the double-peaked profile in [Fe vii] is detected at scales below the one covered by the integrated spectra of Figure 3 strongly supports the presence of double-peaked CLs in NGC 1068. Moreover, it can be seen that the relative distance between the blue and red peaks increases outwards to the north, from $\sim 700$ km s$^{-1}$ at the nucleus to $\sim 1400$ km s$^{-1}$ at 180 pc.
Note, however, that the shift of the red peak changes little relative to the line centroid. It moves from \( \sim 500 \text{ km s}^{-1} \) in the nucleus to \( \sim 600 \text{ km s}^{-1} \) at 180 pc. In contrast, the blue peak shifts from \( \sim 200 \text{ to } \sim 800 \text{ km s}^{-1} \) within the same distance interval. Further to the north, the centroid position of each of the two peaks remains stable, with the red peak being significantly weaker than the blue one. South of the nucleus, the shape of the coronal profile changes significantly if compared to the northern one: the blue peak becomes broader and its centroid position gets closer to the red one. At \( \sim 100 \text{ pc} \) south from the center, the blue and red peaks have FWHMs of \( \sim 1600 \text{ and } \sim 300 \text{ km s}^{-1} \), respectively, but the former starts fading gradually. In fact, at 180 pc, only a narrow red peak is visible.

The right panel of Figure 10 shows equivalent line profiles for [O \text{i}] \( \lambda 6300 \), emphasizing the different kinematics followed by neutral gas. Unfortunately, [O \text{i}] \( \lambda 6300 \) is polluted by [S \text{iii}] \( \lambda 6312 \), which is separated from the former in velocity space by \( \sim 570 \text{ km s}^{-1} \) at rest, which makes its interpretation uncertain. Nevertheless, two main differences arise: first, no evidence of a double-peaked structure is seen at the nucleus. Second, the centroid position of the line coincides with the systemic velocity of the galaxy and its shift along the spatial direction is consistent with rotation around the nucleus. The only similarity seen between the two profiles is the presence of a narrow red peak that appears at \( \sim 50 \text{ pc} \) to the south and \( \sim 130 \text{ pc} \) to the north. The peak to the north is probably a second narrow [O \text{i}] component, judging from a similar component seen in [O \text{i}] \( \lambda 6363 \) (see Fig. 3); the component to the south is presumably due to [S \text{iii}].

For comparison, \textit{Hubble Space Telescope} Space Telescope Imaging Spectrograph (\textit{HST STIS}) spectroscopy shows complex [O \text{iii}] \( \lambda 5007 \) and H\( \beta \) line profiles (Cecil et al. 2002) with multiple, broad peak components and persistent line blueshifting, indicating velocities larger than 2000 km s\(^{-1}\) at the faintest levels. These complex profiles have their origin in a multitude of knots, many unresolved (size \(< 4 \text{ pc} \)), and filamentary structure seen across the extended NLR of the galaxy (cf. \textit{HST FOC} [O \text{iii}] \( \lambda 5007 \) images of NGC 1068). The spatial resolution of the present spectra is poorer, very likely averaging over many of the
clouds seen in the FOC (Faint Object Camera) image, including mostly those along the jet. However, in velocity space, the $\text{[Fe\ vii]}$ line traces the same complex profile and gas velocities (Fig. 10). Thus, the $\text{[O\ iii]}$ and $\text{[Fe\ vii]}$ clouds should be the same.

Summarizing, the high-ionization gas, as mapped by $\text{[Fe\ vii]}$, shows clear imprints of an outflowing wind, with the approaching and the receding components visible at different spatial locations and their speed increasing outward. In contrast, the neutral gas, as mapped by $\text{[O\ i]}$, seems to have a more relaxed kinematics.

Moving up in IP, the line profiles become narrower (Figs. 3 and 8). Gas velocities traced by $\text{[Fe\ xi]}$ (although the profile is badly affected by telluric absorptions a broad Gaussian fit is feasible) and the silicon lines are in the range $300\ \text{km\ s}^{-1} < \text{FWHM} < 1000\ \text{km\ s}^{-1}$. The nondetection of higher velocity components is a limitation of the spatial resolution and S/N: higher velocity components are dumped in the continuum noise. The Si lines follow a similar kinematics to that shown by $\text{[Fe\ vii]}$: the peak position of the silicon lines are blueshifted to the north and redshifted to the south. However, the profiles do not show the prominent double peak seen in $\text{[Fe\ vii]}$, which is probably because the ISAAC spectra have higher spatial resolution, hence the possibility of spatially separating the blue- and redshifted components. Still, at certain locations they do show hints of multiple velocity components (e.g., $\text{[Si\ vi]}$ at 45 pc south, $\text{[Si\ vii]}$ at 135 pc north; Fig. 8). Overall, the Si and $\text{[Fe\ vii]}$ line profiles show a broader profile north of the nucleus than south of it (Fig. 8); since the radio jet is seen to the north, the broadening might be associated with the passage of the jet through the gas clouds.

Previously, Marconi et al. (1996) reported FWHM $\sim 1000\ \text{km\ s}^{-1}$ for both optical and near-IR CLs, which is lower than that measured in intermediate-ionization lines, e.g., $\text{[O\ iii]}\lambda\lambda5007$ (FWHM $\sim 1500\ \text{km\ s}^{-1}$), in apparent contradiction to the present results. They also reported on systematic line blueshifts that increase with the IP, reaching $\sim 300\ \text{km\ s}^{-1}$, but such a trend is not obvious from the present data.

### 3.2.4. NGC 3227

This is a Seyfert 1.5 at the same distance as NGC 1068. The spatial resolution achieved was $\sim 60\ \text{pc}$ in the blue and $\sim 40\ \text{pc}$ in the red. However, to avoid contamination of scattered light from
the BLR—traced by Hα—in the off-nuclear spectra, a larger extraction window, with a diameter of 100 pc in the blue and 80 pc in the red was considered.

NGC 3227 shows the weakest CL region in the sample, and it is unresolved at the spatial resolution achieved. Figure 4 exhibits weak [Fe vii], and perhaps [Fe x], the latter being strongly blended with [O i] λ6363. [Fe xi] λ7889 is not detected. The coronal region is restricted to the nuclear window, i.e., within the inner 50 pc radius from the center. [O i] λ6300 extends along the full length of the slit, i.e., a ~300 pc radius both north and south (only the inner 130 pc radius is shown in Fig. 4).

[Si vi] λ19630 extends up to 45 pc north of the nucleus, consistent with the [Fe vii] size. [Si vii] λ24830 is not detected, consistent with the nondetection of [Fe xi]. The absence of these high-ionization lines indicates that a much softer ionizing continuum illuminates the NLR, lacking photons with energies ≥200 eV, than in the other galaxies of the sample.

For assessing the kinematics, [Fe vii] is the best isolated and highest S/N line. It is nevertheless affected by telluric residuals on its red side. A Gaussian fit to the line indicates a FWHM ≈ 900 km s⁻¹, almost a factor 2 larger than that of [O i] λ6300 (Table 4), and a centroid blueshifting of −125 km s⁻¹.

3.2.5. NGC 3783 and MCG-6-30-15

These two galaxies are more distant, and the only type 1 Seyfert galaxies of the sample. The spatial resolution achieved was about 100 pc for MCG-6-30-15, and ~200 pc for NGC 3783. The actual spatial bin used in these cases is 20%–50% larger than the spatial resolution (Table 2), in order to prevent off-nuclear spectra getting contaminated by nuclear light. The nuclear windows are set by summing up all the spectra containing broad Hα emission. No near-IR spectra are available for these objects.

NGC 3783 (Fig. 5) presents the largest CLR, with a more than 400 pc radius in the [Fe vii] λ6087 line; this is also confirmed by [Fe vii] λ5721 line, present in all our spectra but not shown for the sake of simplicity. [Fe x] and [Fe xi] are also extended but to about half radius (Table 3). [O iii] 5007 Å, however, is distributed in a halo around the nucleus, extending up to a radius of 140–175 pc (HST image in Schmitt et al. 2003). This is about a factor 2 smaller than the [Fe vii] region. We suspect that an oversubtraction of the continuum image is removing [O iii] emission from the outer regions of the halo. We note that, e.g., [Ar iii] (Fig. 5), is already very prominent 210 pc from the nucleus.
TABLE 3
SIZE OF THE CORONAL AND LOWER IONIZATION LINE REGIONS IN SEYFERT GALAXIES

| Object                  | [Fe vi] (IP = 100 eV) | [Fe x] (IP = 240 eV) | [Fe xi] (IP = 260 eV) | [Si vi] (IP = 170 eV) | [Si viii] (IP = 205 eV) | [O i] (IP = 0.0 eV) | [S iii] (IP = 24 eV) | [O iii] (IP = 35.1 eV) |
|-------------------------|------------------------|----------------------|-----------------------|-----------------------|------------------------|---------------------|---------------------|----------------------|
| Circinus                | 53 N–27 S              | 27 N-S               | 21 N-S                | 17 N-S                | 35 N–17 S              | 200                 | 27                  | >500                 |
| NGC 1386                | 108 N–49 S             | 49 N-S               | 53 N–38 S             | NA                    | NA                     | 235                 | 157                 | 165                  |
| NGC 1068                | 210 N–105 S            | <~100                | <~40                  | 90 N–135 S            | 135 N-S                | 525                 | 210                 | 375                  |
| NGC 3222                | ~78                    | ~78                  | 45 N                  | NA                    | ...                    | 106                 | 518d                |
| NGC 3783                | 437 N–302 S            | 235 N–302 S          | 120 N                 | NA                    | NA                     | 540 N–270 S         | <135                | 175                  |
| MCG –6-30-15            | <~90                   | <~90                 | <50                   | NA                    | NA                     | ~300                | ~300                | 295                  |
| NGC 3081                | ...                   | ...                  | ...                   | 120 N                 | ...                    | ...                 | ...                 | ...                  |
| ESO 428-G014            | ...                   | ...                  | ...                   | 120 NW–160 SE         | ...                    | ...                 | ...                 | ...                  |

Notes.—Size is radius in parsecs measured from the nucleus. References are provided for those values taken from the literature. N-S means the same distance to the north and south; NA = not available. [O iii] 5007 sizes are measured from imaging data. [Si vii] images exist only for the four objects quoted in the table; two of them are not included in this spectroscopy study. The other two, Circinus and NGC 1068, show comparable size to that reported here from spectroscopy.

a This value is 1 order of magnitude smaller than the one determined by Oliva et al. (1999) using [S iii] 9531. The large discrepancy between the two sizes is likely due to the slit orientation, which in our case is along the edge of the ionization cone (P.A. = –7°), while in Oliva et al. (1999) is along its axis (P.A. = –44°). Clearly, the [S iii] 9531 emission is highly anisotropic and it seems to follow that of [O iii] 5007 (see Fig. 1 of Oliva et al. 1999).

b Veilleux & Bland-Hawthorn (1997).
c Schmitt et al. (2003).
d Mundell et al. (1995).
e Prieto et al. (2005).

The iron CLs are broader than [O i] by about a factor of 2. At the nucleus, they show a broad blueshifted wing with FWHM ~ 1000 km s\(^{-1}\). At all spatial locations, the coronal peak position is systematically shifted to the blue by more than 100 km s\(^{-1}\) (Table 4). [O i] 6300 shows a clear double-peaked profile, but [Fe vii] does not: coronal gas is clearly more turbulent than neutral gas, and a double peak in [Fe vii] may be masked by the large width of the line.

In MCG –6-30-15 (Fig. 6), the Fe CL emission is unresolved, and thus restricted to the inner 100 pc radius in [Fe vii] and [Fe x] and less than 50 pc radius in [Fe xi]. In contrast, [O i] 6300 and [S iii] 6312 extend up to 300 pc north and south from the center (this emission is not easily seen in Fig. 6, but cuts were chosen so as not to overcrowd the figure). These low-ionization lines are also narrow, FWHM ~ 100 km s\(^{-1}\), and symmetric, whereas the Fe CLs show the typical blue wing, with FWHM ~ 1500 km s\(^{-1}\) (Table 4). Both the narrow and the broader component of the Fe lines show a systematic blueshifting; that of the narrow component increases with IP, up to −140 km s\(^{-1}\) in [Fe xi]; the shift of the broad component is more uniform with IP, but larger, in the range of ~300 km s\(^{-1}\).

4. THE SIZE OF THE CORONAL LINE REGION

Table 3 provides a compilation of the sizes of the CLRs derived in this work. The table also includes coronal sizes derived from the high spatial resolution [Si vii] 2.48 \(\mu\)m imaging of Prieto et al. (2005). The smallest “resolved” coronal region is found in Circinus, with a radius of ~20 pc; the largest is found in NGC 3783, with radius of 400 pc. Overall, the coronal region size averages in the 100 pc range. At each individual object, the CLR size decreases with increasing IP, i.e., the harder the photons, the closer to the nucleus the highly ionized ions are created.

Lower ionization lines extend to much larger radii in Seyfert galaxies, from several hundred parsecs to kiloparsecs. Table 3 also includes the sizes of [O i] 6300 and [S iii] 6312 line regions extracted from the present data, and that of [O iii] 5007 taken from the literature. The CLR is at least a factor 2–3 smaller than that of [O iii] or [O i]. The most extreme case is Circinus, with a coronal region a factor 10 smaller than that of [O iii].

These differences in sizes indicate a very stratified NLR, namely, lines with IP larger than 100 eV are restricted to the inner 100 pc radius, whereas medium-ionization gas, i.e., IP < 54 eV, extends to a region at least twice that value. Lines with IP < 30 eV extend over a region comparable to or larger than that of the medium-ionization lines. Photoionization produces this type of stratification, and thus it should be the principal source of gas excitation in these galaxies.

Besides stratification, the ionized gas in Seyfert galaxies is known to be collimated in large nuclear bicones, seen in H\(\alpha\) or [O iii]. We know from previous work based on long-slit spectroscopy carried out in directions both along and perpendicular to the ionization cone (Reunanen et al. 2003), and from direct imaging in the [Si vii] 2.48 \(\mu\)m line (Prieto et al. 2005), that the coronal emission tends to extend preferentially along or within the ionization cone traced by medium-ionization gas. Indeed, the latter work shows that the coronal gas is more collimated than the medium-ionization gas.

5. KINEMATICS OF THE CORONAL GAS

CLs are, in general, identified with a broad and blueshifted profile. Assuming that the emission comes from an unresolved nuclear region, the systematic blueshifting has been interpreted as an outflowing wind, provided that nuclear obscuring material prevents us from seeing the receding flow (e.g., Penston et al. 1984; Evans 1988; Erkens et al. 1997; Rodríguez-Ardila et al. 2002).

The current spectroscopic data conforms to this prototype coronal profile, albeit with some added complexity. This can be seen in Figure 11, in which the “nuclear” profiles of the best defined CLs for the objects in the sample are compared. For reference purposes, the profile of a lower ionization line is also included in the figure. In all objects a velocity shift was applied to the centroid positions to bring them all to \(V = 0 \) km s\(^{-1}\). Figure 11 shows that all CLs are asymmetric and broader than the reference low-ionization line. In most cases, the profiles display a prominent blue asymmetry. At 20% of peak intensity, the blue wing extends up to 1200 km s\(^{-1}\), while the red one goes only up to 600 km s\(^{-1}\). The less extreme case is Circinus: at 20% of maximum, the blue and red wings extend only to 250 and 100 km s\(^{-1}\), respectively. The most extreme one is NGC 1068, with blue and red wings extending in velocities up to 2000 km s\(^{-1}\); the FWZI is larger than 4000 km s\(^{-1}\). NGC 1068 and NGC 1386 are the only two objects displaying a double-peaked coronal profile,
easily seen in [Fe vii] in both the nuclear and extended regions. To our knowledge, no previous detection of this type of CL profile has been reported for any other Seyfert galaxy.

The points below summarize the main kinematic results:

1. In cases of high S/N and nonblending, CL profiles could be fit with a two-Gaussian component: a narrow one with FWHM comparable to, or slightly larger than, that of the lower ionization lines, and a broad, usually blueshifted, component with FWHM ranging from 700 (e.g., Circinus) to 1500 km s\(^{-1}\) (e.g., MCG −6-30-15 and NGC 3783) and centroid shifts in the range 100–600 km s\(^{-1}\). The centroid position of the narrow component remains in general at the systemic velocity, as is the case for the neutral gas lines, [O i] in the optical and H\(_2\) in the near-IR.

2. Blueshifting of the coronal emission is also seen in the spatially resolved emission, and at both sides of the nuclear region along the slit position (e.g., Circinus, NGC 1068 and NGC 3783). If the emission is a rather collimated wind, blueshifting at both sides of the nucleus would require the axis of the wind to be rather close to the plane of the sky in type 2 objects, or close to the line of sight in type 1. As the counterpart receding gas is usually not seen, this requires the presence of obscuring material at the base of the wind.

3. One would expect an increase of the CL width with IP, as the higher the IP, the closer to the ionization source the line is formed. Gas velocities should then approach those of the BLR.

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3. One would expect an increase of the CL width with IP, as the higher the IP, the closer to the ionization source the line is formed. Gas velocities should then approach those of the BLR. No such trend is generally seen in the data. As Figure 11 illustrates, the Seyfert 1 galaxies MCG −6-30-15 and NGC 3783 show an increase in line width with IP, whereas in the type 2 sources of the sample the opposite is found. However, this could be an obscuration effect in type 2 objects, which will affect mostly the higher ionization lines because they are formed closer to the center.

4. The kinematics of NGC 1068 deserves special attention. The best coronal-emission kinematics is traced by [Fe vii]. The line profile both north and south of the nucleus shows a double-peaked component, visible up to ∼250 and ∼180 pc, respectively, each tracing blueshifted and redshifted gas. This type of

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### TABLE 4

**FWHMs, Shifts, and Fluxes for Optical Lines**

| Aperture | [Fe vii] FWHM | [Fe vii] ΔV | [Fe vii] Flux | [O i] FWHM | [O i] ΔV | [O i] Flux | [Fe x] FWHM | [Fe x] ΔV | [Fe x] Flux | [Fe xi] FWHM | [Fe xi] ΔV | [Fe xi] Flux |
|----------|--------------|------------|--------------|-----------|----------|-----------|-------------|-----------|-------------|-------------|----------|-------------|
|          | (1)          | (2)        | (3)          | (4)       | (5)      | (6)       | (7)          | (8)       | (9)         | (10)        | (11)     | (12)        |
| **Circinus** |              |            |              |           |          |           |             |           |             |             |          |             |
| Nucleus | 120 | −15 | 1.14 ± 0.10 | 105 | 0.0 | 6.23 ± 0.10 | 140 | 32 | 2.30 ± 0.12 | 105 | −11 | 3.82 ± 0.14 |
| 400 | −250 | 1.11 ± 0.45 | 110 | −58 | 1.86 ± 0.11 | 135 | 20 | 0.55 ± 0.12 | 160 | −70 | 0.50 ± 0.14 |
| 27 pc N | 290 | −84 | 0.77 ± 0.15 | 130 | −76 | 0.85 ± 0.06 | 105 | 24 | 2.37 ± 0.10 | 120 | 60 | 1.07 ± 0.10 |
| 53 pc N | 160 | 20 | 0.49 ± 0.10 | 110 | −35 | 1.20 ± 0.19 | 580 | −100 | 2.41 ± 0.80 | 250 | −120 | 1.57 ± 0.50 |
| 27 pc S | 740 | 81 | 6.88 ± 1.08 | 575 | 87 | 1.87 ± 0.50 | 320 | −45 | 0.69 ± 0.11 |           |          |             |
|          | 1410 | −180 | 3.08 ± 1.20 | 650 | −55 | 31.1 ± 6.6 | 1800 | 220 | 11.7 ± 6.5 | 705 | −115 | 8.0 ± 0.8   |
| 78 pc S | 700 | 173 | 1.03 ± 0.08 | 720 | −75 | 7.8 ± 0.5 |           |          |             |           |          |             |
| **NGC 1386** |              |            |              |           |          |           |             |           |             |             |          |             |
| Nucleus | 1670 | −39 | 142.0 ± 17.3 | 900 | 0.0 | 173.9 ± 9.0 | 1595 | −150 | 47.8 ± 17.0 | 760 | −165 | 16.4 ± 1.3  |
| 105 pc N | 1450 | −250 | 81.0 ± 11.5 | 1020 | −50 | 177.1 ± 8.4 | 1380 | −175 | 28.5 ± 11.3 | 680 | −165 | 4.1 ± 1.4   |
| 210 pc N | 990 | −695 | 14.3 ± 2.3 | 1280 | −30 | 44.2 ± 3.2 |           |          |             |           |          |             |
| 105 pc S | 1890 | 85 | 29.4 ± 6.5 | 650 | −55 | 31.1 ± 6.6 | 1800 | 220 | 11.7 ± 6.5 | 705 | −115 | 8.0 ± 0.8   |
| 210 pc S | 370 | 595 | 1.6 ± 0.2 | 720 | −75 | 7.8 ± 0.5 |           |          |             |           |          |             |
| **NGC 1068** |              |            |              |           |          |           |             |           |             |             |          |             |
| Nucleus | 965 | −125 | 4.09 ± 0.56 | 520 | −35 | 20.04 ± 0.9 |           |          |             |           |          |             |
| **NGC 3227** |              |            |              |           |          |           |             |           |             |             |          |             |
| Nucleus | 160 | −30 | 0.97 ± 0.13 | 105 | −12 | 1.66 ± 0.15 |           |          |             |           |          |             |
| 670 | −277 | 1.21 ± 0.30 |           |          |             | 2090 | −340 | 4.33 ± 1.00 | 1530 | −330 | 4.70 ± 1.40 |
| **MCG −6-30-15** |              |            |              |           |          |           |             |           |             |             |          |             |
| Nucleus | 540 | −120 | 22.15 ± 0.63 | 255 | −37 | 16.87 ± 0.43 | 625 | −170 | 10.60 ± 1.00 | 310 | −75 | 2.88 ± 0.70 |
| 1380 | −600 | 7.80 ± 1.57 |           |          |             | 1320 | −635 | 7.85 ± 2.02 | 1080 | −320 | 7.69 ± 2.37 |
| 270 pc N |          |          |              |           |          |           |             |           |             |             |          |             |
| 270 pc S |          |          |              |           |          |           |             |           |             |             |          |             |

**Notes.** —FWHM and shifts from the centroid position (both in km s\(^{-1}\)), and fluxes (in units of 10\(^{-13}\) ergs cm\(^{-2}\) s\(^{-1}\)) for the optical coronal and [O i] 6300 lines measured in the nuclear and adjacent regions in the galaxy sample. Two entries for an aperture give the result of a two-Gaussian fit to the line. Typical error in the Gaussian centroid is 20 km s\(^{-1}\), but increases greatly (50%–100%) for low S/N lines.
profile has not ever been reported in the literature for a Seyfert galaxy. One could think of several geometries to account for this complex kinematics, e.g., gas moving in circular orbits in a thick toroid with the rotation axis close to the north-south direction, leading to a double-peaked spectrum at both sides of the nucleus. Alternatively, radial motions within a cone with its axis closely oriented to the plane of the sky could lead to a double-peaked spectrum at both sides of the nucleus. The density gradient within the photoionized structure and is responsible for the systematic blueshift observed for CLs.

6. IS PHOTOIONIZATION DRIVING THE CORONAL LINE EMISSION?

CLs are collisionally excited and can be produced by a gaseous region photoionized by a hard UV continuum (Ferguson et al. 1997), a hot ionized plasma (Viegas-Aldrovandi & Contini 1989), or a mix of both (Contini et al. 1998a). Radiation from the central source alone cannot explain, however, the systematic blueshifting of the lines. An alternative approach still invoking photoionization was suggested by Binette (1998), who proposed that radiation pressure from the central engine generates a strong density gradient within the photoionized structure and is responsible for accelerating the matter-bounded gas (the zone of high excitation), explaining the systematic blueshift observed for CLs.

Moreover, the following constraints are set by the observations regarding the nature of the coronal regions. The size of the emitting clouds are expected to be less than 2 pc in Circinus and less than 7 pc in NGC 1068 on the basis of the spatial resolution achieved in the [Si vi] images by Prieto et al. (2005). Cloud velocities, if reflecting any NLR velocity field of accelerating gas, should reach up to 1000 km s\(^{-1}\).

In order to investigate the most plausible scenario for the production of the CLs, taking into account the above constraints, we first tested the possibility that the coronal region, which extends up to several tens of parsecs from the central engine, can be produced by pure photoionization. To this purpose, models with the AANGABA code (Gruenwald & Viegas 1992) were run. The ionizing spectrum suggested by Oliva et al. for Circinus (1999; see their Fig. 7) was adopted; solar values (Grevesse & Anders 1989) were assumed for the gas chemical abundances.

Two values for the luminosity of the ionizing radiation were adopted: \(L_{\text{ion}} = 10^{43.5}\) and \(10^{44.5}\) ergs s\(^{-1}\), as used, e.g., by Ferguson et al. (1997) and Oliva et al. (1999) in their respective photoionization models. The number of ionizing photons, \(Q_{\text{H}}\), contained by those two spectral energy distributions are \(2.5 \times 10^{53}\) and \(5.0 \times 10^{53}\).

### Table 5

| Aperture (1) | FWHM (2) | \(\Delta V\) (3) | Flux (4) | FWHM (5) | \(\Delta V\) (6) | Flux (7) |
|-------------|----------|-----------------|---------|----------|-----------------|---------|
| Circinus    |          |                 |         |          |                 |         |
| Nucleus     | 125      | -37             | 37.6 ± 1.7 | 100      | 18              | 53.0 ± 0.4 |
| 17 pc N     | 290      | -210            | 21.5 ± 3.5 | 270      | -100            | 49.3 ± 1.1 |
| 17 pc S     | 145      | -60             | 6.8 ± 2.0  | 100      | 20              | 1.9 ± 0.2  |
|             | 245      | -275            | 0.4 ± 0.2  | 180      | -90             | 1.7 ± 0.2  |
|             | 140      | -45             | 12.2 ± 2.7 | 100      | 28              | 2.8 ± 0.2  |
|             | ...      | ...             | ...       | 170      | -85             | 4.40 ± 0.6 |
| NGC 1068    |          |                 |         |          |                 |         |
| Nucleus     | 950      | -185            | 421 ± 90  | 330      | 0.0             | 117.3 ± 13.8 |
| 45 pc N     | 175      | -130            | 48.2 ± 5.7 | 350      | 38              | 123.9 ± 3.5 |
| 90 pc N     | 710      | -180            | 259.5 ± 13 | 710      | -270            | 89.8 ± 6.9  |
| 135 pc N    | 650      | -105            | 57.1 ± 2.6 | 390      | 35              | 31.7 ± 1.4  |
| 135 pc S    | 790      | 47              | 9.4 ± 3.1  | 960      | -580            | 27.3 ± 3.4  |
| 45 pc S     | 1090     | -38             | 164 ± 36  | ...      | ...             | 26.0 ± 2.4  |
| 90 pc S     | 380      | 375             | 25.5 ± 3.0 | 290      | -60             | 34.3 ± 3.0  |
| 135 pc S    | 330      | 412             | 11.6 ± 1.3 | 360      | 610             | 14.8 ± 0.60 |
| NGC 3227    |          |                 |         |          |                 |         |
| Nucleus     | 660      | -40             | 25.0 ± 4.0 | ...      | ...             | ...      |

Notes.—FWHM and shifts from the centroid position (both in km s\(^{-1}\)), and fluxes (in units of \(10^{-15}\) ergs cm\(^{-2}\) s\(^{-1}\)) for the near-IR coronal lines measured in the nuclear and adjacent regions of the galaxy sample (two entries for an aperture correspond to the results from a two-Gaussian fit to the line).
and $2.5 \times 10^{44}$ photons s$^{-1}$, respectively. A grid of models was built with the density in the range $10^{-2}$ to $10^6$ cm$^{-3}$, and the ionization parameter $U = \Phi_H/nc$ from $10^{-2}$ to 1, where $\Phi_H$ is the flux of ionizing photons reaching the coronal region, defined as $\Phi_H = Q_H/4\pi D^2$, $D$ being the distance from the emitting cloud to the central source, assuming the covering factor unity. For each $\Phi_H$—or equivalently $L_{\text{ion}}$—there is a relation between $U$, $n$, and $D$ (see, for example, Ferguson et al. 1997). This means that for a given AGN, i.e., a given $L_{\text{ion}}$, $U$ is not a free parameter anymore if we know $D$ from the spatially resolved observations. The $U$, $n$, and $D$ relation is given in Figure 12. Since CLs require high ionization parameters (Ferguson et al. 1997), the distance from the nucleus to the CL emitting cloud is limited, as we see below.

With the above parameters in mind, the distribution of the fraction of iron and silicon ions producing the observed CLs versus the size of the emitting cloud was computed. The results are shown in Figures 13 and 14, respectively, for $n_e = 10^4$ cm$^{-3}$ and $U = 10^{-2}$, $10^{-1}$, and 1. Ion fractions for models with $U = 10^{-2}$ (Fig. 13c) and the two values of $L_{\text{ion}}$ coincide, and Fe$^{+10}$ is not present in these clouds. A density of $n_e = 10^4$ cm$^{-3}$ is taken at face value following the estimate derived for Circinus from [Ne v] 14.3 $\mu$m/24.3 $\mu$m (Moorwood et al. 1996). Moving to higher densities will press more for higher ionization parameters,
but in that case, following Figure 12, it will be difficult to explain the spatial extension of the coronal region.

It can be seen from Figures 12 and 13 that only the single-cloud models with \( U \geq 0.1 \) show \( \text{Fe}^{+6}, \text{Fe}^{+9}, \) and \( \text{Fe}^{+10} \). Clouds with lower values of \( U \) tend to be dominated by \( \text{Fe}^{+6} \) and less ionized species. The distributions of \( \text{Si}^{+5} \) and \( \text{Si}^{+6} \) are similar to that of \( \text{Fe}^{+6} \). The figures also show that the geometrical width of the clouds emitting the CLs is less than 1 pc for \( U = 0.1 \) and less than 5 pc for \( U = 1 \), if \( n_e = 10^4 \text{ cm}^{-3} \).

Notice that the lower the density, the wider the coronal region size. Considering \( U \leq 0.1 \) and an average coronal region size of 150 pc, it appears that a density of \( n_e = 10^4 \text{ cm}^{-3} \) is too large to account for the observed dimensions (Fig. 12). We thus conclude that densities down to at least \( n_e = 10^3 \text{ cm}^{-3} \) are required. Lower densities will lead to even larger regions, but that will penalize line detection, as the emission is proportional to \( n_e^2 \). Larger distances could be reached if the filling factor were low.

Yet, very high spatial resolution images in [Si vii] 2.48 \( \mu \text{m} \) of Seyfert galaxies (Prieto et al. 2005) show that the coronal emission is not yet resolved in blobs/knots at spatial scales of 10–15 pc, but shows instead diffuse morphology. With such low surface brightness it would be difficult to detect any emission if the filling factor were low.

Thus, assuming that lines from different IP ions, e.g., [Fe vii], [Fe x], and [Fe xi], are all produced in the same cloud, a cloud density of \( n_e = 10^3 \text{ cm}^{-3} \), and a \( U \) value between 0.1 and 1, according to Figure 12 the maximum size of the CLR is \( \leq 100 \text{ pc} \) for the brighter source (\( L_{\text{ion}} = 10^{44.5} \text{ ergs s}^{-1} \)), and \( \leq 30 \text{ pc} \) for the dimmer one if it is powered entirely by photoionization.

Diagnostic diagrams based on flux ratios between the three optical iron lines provide a good test for the photoionization models, and are shown in Figure 15. Because of the relationship between \( U, n, \) and \( D \), the loci of the results from all the models are represented by the same curve (dashed line). On this curve, the dots correspond to different values of \( U (\log U = -2, -1.5, -1, \) and 0) for \( n_e = 3 \times 10^3 \text{ cm}^{-3} \) and \( L_{\text{ion}} = 10^{44.5} \text{ ergs s}^{-1} \). Shock-dominated models are represented by the solid line. For the latter, the shock velocity varies from 300 to 900 km s\(^{-1}\), increasing from left to right. Most data points fall in the shock-dominated region. Symbols correspond to different galaxies: filled circles, Circinus; filled triangles, NGC 1386; filled squares, NGC 1068; open triangles, MCG – 6-30-15; stars, NGC 3783.

**Fig. 13.** Ionic abundance for the Fe ions vs. the geometrical depth of the cloud \( \Delta R \), for \( L_{\text{ion}} = 10^{43.5} \text{ ergs s}^{-1} \) (thin lines) and \( L_{\text{ion}} = 10^{44.5} \text{ ergs s}^{-1} \) (thick lines); \( \text{Fe}^{+10} \) (solid lines), \( \text{Fe}^{+9} \) (dash-dotted lines), and \( \text{Fe}^{+6} \) (dashed lines). (a–c) Results for models with \( U = 1, 0.1, \) and 0.01, respectively, and density \( n_e = 10^4 \text{ cm}^{-3} \). In (c), the results corresponding to the two values of \( L_{\text{ion}} \) coincide, and \( \text{Fe}^{+10} \) is not present in these clouds.

**Fig. 14.** Ionic abundance of the Si ions vs. the geometrical depth of the cloud \( \Delta R \), for \( L_{\text{ion}} = 10^{43.5} \text{ ergs s}^{-1} \) (thin lines) and \( L_{\text{ion}} = 10^{44.5} \text{ ergs s}^{-1} \) (thick lines); solid lines \( \text{Si}^{+5} \), dashed lines \( \text{Si}^{+6} \). (a–c) Results for models with \( U = 1, 0.1, \) and 0.01, respectively, and density, \( n_e = 10^4 \text{ cm}^{-3} \). In (c), the results corresponding to the two values of \( L_{\text{ion}} \) coincide.

**Fig. 15.** Observed Fe CL ratios for the nuclear and extended region measured in the AGN sample compared with predictions from pure photoionization models (dashed line). Dots correspond to different values of \( U [-2, -1.5, -1, \) and 0] for \( n_e = 3 \times 10^3 \text{ cm}^{-3} \) and \( L_{\text{ion}} = 10^{44.5} \text{ ergs s}^{-1} \). Shock-dominated models are represented by the solid line. For the latter, the shock velocity varies from 300 to 900 km s\(^{-1}\), increasing from left to right. Most data points fall in the shock-dominated region. Symbols correspond to different galaxies: filled circles, Circinus; filled triangles, NGC 1386; filled squares, NGC 1068; open triangles, MCG – 6-30-15; stars, NGC 3783.
and 0) for \( n_e = 3 \times 10^5 \, \text{cm}^{-3} \) and \( L_{\text{ion}} = 10^{44.3} \, \text{ergs s}^{-1} \). Note that a density of \( 3 \times 10^5 \, \text{cm}^{-3} \) was chosen because it is located between the two limiting cases, i.e., \( 10^2 \) and \( 10^4 \, \text{cm}^{-3} \). Data plotted in this figure are extracted from Table 4. The line ratios show an ample disagreement with these standard photoionization models.

The only way for single-cloud photoionization models to reproduce the iron line ratios is to find a way to shift the photoionization results up to and on the left on both panels of Figure 15. This could be achieved with an increase of the [Fe \( x \)] line with respect to the [Fe \( vii \)] line, and the latter relative to [Fe \( x \)]; or the opposite: a decrease of the [Fe \( x \)] line with respect to [Fe \( vii \)] and [Fe \( xi \)]. Our results were obtained using effective collision strengths calculated using the distorted wave method (Krueger & Czyzak 1970; Nussbaumer & Storey 1982). More recently, atomic data for those lines have been available in the literature, mainly due to the so-called Iron Project (Hummer et al. 1993). These calculations are carried out using the \( R \)-matrix method and account for resonances. These resonances tend to increase the excitation cross sections, and the net effect is an increase of the collision strengths, mainly at lower temperatures (Aggarwal & Keenan 2003; Berrington et al. 2000; Pelan & Berrington 2001). A close look into the new data shows that indeed the new collision strengths are higher than the values used in this paper, as expected. Compared to the previous values used in our calculations, the increase is more significant for Fe \( x \) than for the lines of the other two ions, Fe \( xi \) being the second one most affected. Thus, the [Fe \( xi \)]/[Fe \( vii \)] ratio should increase if calculated with new atomic data, as well as [Fe \( xi \)]/[Fe \( vii \)], although by a smaller factor. On the other hand, [Fe \( xi \)]/[Fe \( x \)] should decrease. In brief, the overall tendency is to shift the photoionization results presented in Figure 15 (dashed line) to the right, leading to a larger disagreement with the observational data.

We then consider the additional effect of shock excitation coupled with photoionization to explain the coronal emission. As a constraint, we assumed that the observed velocity width (at FWHM) measures the actual shock velocity that passes through the gas, which should then be in the range \( 300–900 \, \text{km s}^{-1} \). The resulting composite models are also shown in Figure 15 (solid line). They were generated using the code SUMA, which accounts for the coupled effect of shock and photoionization (Viegas & Contini 1997). In these composite models \( L_{\text{ion}} \) has the same values as those used in the pure photoionization models.

If the coronal region clouds are shock dominated, there is no upper limit for the distance of the coronal emission to the nucleus as there is for the pure photoionization case. In order to limit the average cloud density to \( 10^5 \, \text{cm}^{-3} \), models with shock velocities higher than \( 500 \, \text{km s}^{-1} \) would have been needed. The resulting composite models are also shown in Figure 15 (solid line). These models were generated using the code SUMA, which accounts for the coupled effect of shock and photoionization (Viegas & Contini 1997). In these composite models \( L_{\text{ion}} \) has the same values as those used in the pure photoionization models.

The models presented provided a first insight into the physical processes powering the CLR. Self-consistent models for a given object would require a more comprehensive analysis of the whole emission-line spectrum, which is out of the main focus of this paper. As already discussed for some AGNs (Contini et al. 1998a, 1998b, 2003), we expect that photoionization, as well as shock, must contribute to the physical conditions of the different types of emitting clouds present in the NLR. The results shown in Figure 15 support this scenario.

7. CONCLUDING REMARKS

1. CLs are expected to be presented in all types of AGNs. This work surveyed at unprecedented spectral and spatial resolution five CLs covering a large range both in IP, between 100 and 260 eV, and wavelength (optical and near-IR regions) in six Seyfert galaxies: three type 2, two type 1, and one type 1.5. We found that they are all present in the galaxies, with the exception of NGC 3727, where only ions from the lowest IPs are detected.

2. The coronal region is spatially resolved over scales that range from a few tens of parsecs up to a few hundreds of parsecs from the center. The size of the emitting region varies with the IP: the higher the IP the more compact the region becomes. This stratification indicates that nuclear photoionization is the principal excitation mechanism.

3. CL profiles are characterized by two components: a narrow one, whose centroid and FWHM values are within the range found for lower ionization lines, and a broader one, whose centroid is systematically shifted to the blue by a few hundreds of \( \text{km s}^{-1} \) and has a FWHM at least a factor 2 larger than that of the lower ionization lines. The gas velocities implied by this component vary from object to object, and are in the range from 500 up to 2000 \( \text{km s}^{-1} \). This blueshifting is interpreted as an outflowing wind. However, a nuclear wind should have an approaching and a receding component. As the blueshifted component is the one often seen, the redshifted one has to be obscured by dust at the base of the wind.

4. We are, however, able to see the receding component of the wind in two objects: NGC 1068 and NGC 1386. This interpretation comes from the detection of a spatially resolved double peak in the [Fe \( vii \)] line, each peak tracing, respectively, blueshifted and redshifted gas at each spatial location. A spatially resolved double peak could be produced by gas moving in circular orbits in a thick toroid with the rotation axis close to the north-south direction, or by radial motions along a collimated cone, with the axis closely oriented to the plane of the sky. The observational evidence supports this latter scenario.

5. For a luminosity of the ionizing radiation source in the range \( 10^{43.5} \text{–} 10^{44.5} \, \text{ergs s}^{-1} \), single-cloud photoionization models indicate that to produce detectable coronal emission over a wide range of IPs, the ionization parameter must be larger than 0.1 and the density should be larger than \( 10^7 \, \text{cm}^{-3} \). Under these conditions, such simple single-cloud models can account for coronal emission of up to 100 pc from the nucleus if the ionizing radiation luminosity is higher than \( 10^{44} \, \text{ergs s}^{-1} \). For lower luminosities the size of the coronal regions can at most reach 50 pc, which is smaller than the results obtained for some of the galaxies of our sample. In addition, these models fail to explain the observed Fe line ratios. Furthermore, even multicloud photoionization models, mimicking the stratification of the NLR, can hardly reproduce the observations, leading us to conclude that another energy source must be present.

6. In support of the above result, diagnostic diagrams using the Fe lines show that single-cloud photoionization models largely...
depart from the trend shown by the data. However, if the contribution of additional shock excitation is included, with shock velocities between 300 and 900 km s\(^{-1}\) in agreement with observations, the combined photoionization-plus-shock effect is able to account for the observed ratios.

7. It is interesting to remark that the systematic presence of H\(_2\) lines in the nuclear region of AGNs implies very large variations in the physical conditions of the gas, capable of sustaining highly ionized species along with molecules that easily dissociate with the radiation of the central engine. The molecular H\(_2\) emission clearly relates to a different type of cloud from that traced by the ionized gas, on the basis of both its kinematic — low rotation, narrow line widths — and spatial distribution, which usually extends over several hundred parsecs to kiloparsecs from the nucleus, and preferentially in directions perpendicular to the ionization cone (Reunanen et al. 2002, 2003; Rodríguez-Ardila et al. 2004, 2005).

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