Metal abundances and excitation of extranuclear clouds in the Circinus galaxy *

A new method for deriving abundances of AGN narrow line clouds

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Abstract. Spectra of extranuclear clouds within the ionization cone of Circinus galaxy are presented and modelled assuming photoionization by the Seyfert 2 nucleus but no preconceived assumption concerning the spectral shape of the ionizing AGN radiation or the gas density distribution.

The most important result is that, regardless of the assumed AGN spectral shape or density distribution, the metal abundances are remarkably well (±0.2 dex) constrained by the data. Oxygen and neon are found to be a factor of 5 below solar, while nitrogen is solar (cf. Table 3). The large N/O overabundance is in agreement with the chemical enrichment expected from the old (circum)nuclear starburst. Similar studies of extranuclear clouds in other objects could therefore provide a powerful tool to determine metallicities and trace past starburst activity in AGNs.

Other implications such as the role of shock excitation, which is effectively excluded, and the intrinsic shape of the AGN ionizing continuum, which is poorly constrained by the data, are also discussed.

Key words: Galaxies: abundances; Galaxies: active; Galaxies: starburst; Galaxies: individual: Circinus

1. Introduction

The Circinus galaxy (A1409-65) is a nearby (≃4 Mpc) gas rich spiral lying close to the galactic plane in a region of relatively low (A_V ≃1.5 mag) interstellar extinction (Freeman et al. 1977). Several observed characteristics indicate that this galaxy hosts the nearest Seyfert 2 nucleus known. These include optical images showing a spectacular [OIII] cone (Marconi et al. 1994 hereafter M94); optical/IR spectra rich in prominent and narrow coronal lines (Oliva et al. 1994, hereafter O94; Moorwood et al. 1996, hereafter M96); X-ray spectra displaying a very prominent Fe-K fluorescent line (Matt et al. 1996) and optical spectropolarimetric data which reveal relatively broad Hα emission in polarized light (Oliva et al. 1998). Complementary to these is observational evidence that this galaxy has recently experienced a powerful nuclear starburst which is now traced by the near IR emission of red supergiants (Oliva et al. 1995, Maiolino et al. 1998) and which may have propagated outwards igniting the bright ring of O stars and HII regions visible in the Hα image (M94). Such a starburst could have been triggered by gas moving toward the nuclear region and eventually falling onto the accretion disk around the black hole powering the AGN.

A debated issue is whether nuclear starbursts are common features of AGNs and if they are more common in type 2 than in type 1 Seyferts, as suggested by e.g. 10μm observations (Maiolino et al. 1995) and studies of the stellar mass to light ratios (O94). Since starbursts are predicted and observed to deeply modify the chemical abundances of the host galaxy (e.g. Matteucci & Padovani 1993), such an effect should also be evident in this and other Seyferts. However, to the best of our knowledge, no reliable measurement of metallicity for the narrow line region clouds of Seyfert 2's exists in the literature. In particular, although has been since long known that the large [NII]/Hα ratio typical of Seyferts cannot be easily explained using simple models with normal nitrogen abundances (e.g. Osterbrock 1989, Komossa & Schulz 1997), the question of whether its absolute (N/H) or relative (e.g. N/O) abundance is truly different than solar is still open. Finding a reliable method to derive metallicities and, therefore, to trace and put constraints on past starburst activity is the main aim of this paper.

We chose the Circinus galaxy as a benchmark because its emission line spectrum is characterized by remarkably narrow (≃150 km/s) emission lines which are particularly easy to measure and which indicate relatively low dynamical activity. This last aspect may be used to put tight constrains on the possible contribution of shock excitation which may complicate the modelling of the observed spectrum and the determination of metallicities.

This paper presents new optical and infrared spectroscopic data and is structured as follows. Observations and data reduction are described in Sect. 2 and the results are analyzed in
Table 1. Observed and dereddened line fluxes

|       | Nucleus | KnC |
|-------|---------|-----|
|       | ($4.6^\prime\times2^\prime$) | ($4.1^\prime\times2^\prime$) |
|       | $A_V=4.5$ | $A_V=1.9$ |
|       | F (1) | I (2) | F (1) | I (2) | $A_V/A_V$ (3) |
| [OII] $\lambda$3727 | 77 | 270 | 78 | 133 | 1.49 |
| [NeIII] $\lambda$3869 | 45 | 136 | 41 | 66 | 1.45 |
| [SII] $\lambda$4073 | 47 | 7 | 5 | 3 | 1.40 |
| H$\beta$ $\lambda$4102 | 17 | 24 | 24 | 24 | 1.40 |
| H$\gamma$ $\lambda$4340 | 35 | 46 | 46 | 46 | 1.34 |
| [OIII] $\lambda$4363 | 16 | 21 | 21 | 21 | 1.34 |
| HeII $\lambda$4686 | 32 | 41 | 54 | 60 | 1.24 |
| [ArIV] $\lambda$4711 | 9 | 10 | 10 | 10 | 1.23 |
| [ArIV] $\lambda$4740 | 9 | 10 | 10 | 10 | 1.22 |
| H$\beta$ $\lambda$4861 | 100 | 100 | 100 | 100 | 1.18 |
| [OIII] $\lambda$4959 | 365 | 320 | 317 | 300 | 1.15 |
| [OIII] $\lambda$5007 | 1245 | 1025 | 1048 | 965 | 1.14 |
| [HeII] $\lambda$5146 | <8 | <7 | <7 | <7 | 1.09 |
| [N] $\lambda$5199 | 28 | 18 | 9 | 7 | 1.08 |
| [FeII] $\lambda$5530 | <17 <10 | <7 <5 | 1.05 |
| HeII $\lambda$5411 | 5.9 | 4.4 | 1.02 |
| [FeII] $\lambda$5721 | 23 | 9 | 8.9 | 6.0 | 0.95 |
| [NII] $\lambda$5755 | 4.7 | 0.95 |
| HeI $\lambda$5876 | 35: | 12: | 15 | 9.7 | 0.92 |
| [FeII] $\lambda$6087 | 36 | 11 | 16 | 9.7 | 0.89 |
| [OIII] $\lambda$6300 | 165 | 42 | 46 | 26 | 0.85 |
| [SIII] $\lambda$6312 | 20: | 5: | 11 | 6 | 0.85 |
| [OIII] $\lambda$6364 | 56 | 14 | 16 | 8.6 | 0.84 |
| [FeX] $\lambda$6374 | 55 | 14 | <4 <2 | 0.84 |
| [ArV] $\lambda$6435 | 5.4 | 2.9 | 0.83 |
| [NII] $\lambda$6548 | 535 | 116 | 154 | 81 | 0.81 |
| H$\alpha$ $\lambda$6563 | 1390 | 298 | 565 | 295 | 0.81 |
| [NII] $\lambda$6583 | 1620 | 343 | 457 | 237 | 0.81 |
| HeI $\lambda$6678 | 5.2 | 2.6 | 0.80 |
| [SII] $\lambda$6716 | 490 | 96 | 128 | 64 | 0.79 |
| [SII] $\lambda$6731 | 496 | 96 | 113 | 57 | 0.79 |
| [ArV] $\lambda$7006 | 10: | 2: | 14 | 6.4 | 0.75 |
| [ArIII] $\lambda$7136 | 148 | 22 | 61 | 27 | 0.73 |
| [CaII] $\lambda$7291 | <20 <3 | <4 <2 | 0.70 |
| [OII] $\lambda$7319 | 45 | 6 | 12 | 5.2 | 0.70 |
| [OII] $\lambda$7330 | 40 | 5 | 10 | 4.5 | 0.70 |
| [ArIII] $\lambda$7751 | 38 | 4 | 12 | 4.8 | 0.64 |
| [FeII] $\lambda$7892 | 112 | 11 | <9 <3 | 0.62 |
| [FeII] $\lambda$8617 | <40 <3 | <13 <4 | 0.52 |
| [SIII] $\lambda$9069 | 980 | 53 | 220 | 65 | 0.48 |
| [SIII] $\lambda$9531 | 2900 | 134 | 570 | 155 | 0.44 |
| [Cl] $\lambda$9850 | 70 | 2.9 | <33 <9 | 0.42 |
| [SIV] $\lambda$9913 | 100 | 4.1 | 0.41 |
| Ps7 $\lambda$10049 | 90: | 4: | 0.40 |
| [FeII] $\lambda$16435 | 470 | 7.1 | 30: | 5: | 0.17 |
| [SiIV] $\lambda$19629 | 640 | 8 | <90 <15 | 0.12 |
| H$\gamma$ $\lambda$21213 | 400 | 4.7 | 50: | 8: | 0.11 |
| Br$\gamma$ $\lambda$2165 | 230 | 2.7 | 18: | 3: | 0.11 |
| H$\beta$ flux$^a$ | 10 | 1350 | 5 | 36 |

(1) Observed line flux, relative to H$\beta=100$
(2) Dereddened flux (H$\beta=100$), a colon denotes uncertain values.
(3) Blank entries are undetected lines with non-significant upper limits
(4) From Savage & Mathis (1979) and Mathis (1990)
$^a$ Units of $10^{-15}$ erg cm$^{-2}$ s$^{-1}$ Å$^{-1}$

Fig. 1. Slit positions overlaid on grey-scale line images. The positions of the various knots are marked.

Fig. 2. Spectrum of the nucleus, i.e. the central region at PA=318° (cf. Figs. 1, 4). Fluxes are in units of $10^{-16}$ erg cm$^{-2}$ s$^{-1}$ Å$^{-1}$.

2. Observations and Data Reduction

Long slit optical spectra were collected at the ESO NTT telescope in March 1995 using a dichroic beam splitter feeding both blue (1024$^2$ Tek-CCD with 0.37"/pix) and red (2048$^2$ Tek-CCD with 0.27"/pix) arms of EMMI. Simultaneous blue (3700–5000 with $\simeq$1.7 Å/pix) and red (5000–10000 with $\simeq$1.2 Å/pix) spectra were obtained through a 2" slit centered on the optical nucleus at two position angles (cf. Fig. 1). The first was at PA=318°, roughly aligned with the [OIII] cone axis and including the brightest [OII] emitting knots, while the second was at PA=243° and along the low excitation rim visible in the [SII] and “true colour” images shown in Fig. 5 and Fig. 10 of Sect. 3. In Sect. 4 we constrain the excitation conditions of the gas and model the observed spectra in terms of photoionization from the AGN. The derived chemical abundances are discussed in Sect. 5 and in Sect. 6 we draw our conclusions.
utes over the 3700–5000, 5000–7300 and 7700–10080˚A wavelength ranges, respectively. The spectra at PA=243 µm, particularly strong in the nuclear spectrum where the equivalent variations are summarized in Table 1. Dilution by a stellar continuum is particularly useful for the modelling described in Sect. 4.8.

The quasi-complete spectra of the nucleus and of knot C are strongly useful for the modelling described in Sect. 4.8.

3. Results

3.1. Line fluxes and ratios

The quasi-complete spectra of the nucleus and of knot C are shown in Figs 3, 4, respectively, and the derived line fluxes are summarized in Table 3. Dilution by a stellar continuum is particularly strong in the nuclear spectrum where the equivalent width of [OIII]5007 is only 50 Å (cf. Table 2) and a factor of \( \sim 10 \) lower than found in typical Seyfert 2’s. The stellar contribution is normally estimated and subtracted using either off-nuclear spectra extracted from the same 2D long slit frames, or a suitable combination of spectra of non-active galaxies used as templates (e.g. Ho 1996, Ho et al. 1997). However, neither of the methods proved particularly useful because line emission contaminates the stellar emission all along the slit, and we could not find any template which accurately reproduces the prominent stellar absorption features typical of quite young stellar populations. The fluxes of weak lines (<5% of the continuum) in the nucleus are therefore uncertain and, in a few cases, quite different than those reported in O94, the largest discrepancy being for [Ni] which is a factor of 2 fainter here.

The spectrum of knot C has a much more favourable line/continuum ratio and shows many faint lines which are particularly useful for the modelling described in Sect. 4.8.

3.2. Spatial distribution of emission lines

The spatial variation of the most important lines is visualized in Figs. 5, 6, which show contour plots of the continuum subtracted long slit spectra and selected spectral sections of the various knots respectively. The fluxes are summarized in Table 3 together with the extinctions which were derived from hydrogen recombination lines assuming standard case-B ratios (Hummer & Storey 1987). A remarkable result is the large variations of the typical line diagnostic ratios [OIII]/Hβ, [OI]/Hα, [NII]/Hα and [SII]/Hα which are plotted in Fig. 4 and range from values typical of high excitation Seyferts (nucleus, knots A, B, C, D), to low excitation LINERs (knots H, I) and normal HII regions (knots E, L). Another interesting result is the steep extinction gradient between the regions outside (knots C, D, H, I) and those close to the galactic disk (nucleus and knots A, E, L). However, a comparison between the Brγ map (Moorwood & Oliva 1994), the Hα images (M94) and the observed Brα flux from the whole galaxy (M96), do not show evidence of more obscured (\( A_V \sim 10-30 \)) ionized regions such as those observed in NGC4945 and other starburst galaxies (e.g. Moorwood & Oliva 1988). Nevertheless, these data cannot exclude the presence of deeply embedded ionized gas which is obscured even at 4.5µm (i.e. \( A_V > 50 \) mag).

Particularly interesting is the variation of the line ratios between the adjacent knots C and D. The ratio [FeII]/Hβ is a factor of 2 larger in knot D than in C, but this most probably reflects variations of the iron gas phase abundance (see also Sect. 4.3). Much more puzzling is the spatial variation of the low excitation lines [OI], [SII], [NII] which drop by a factor 1.8, while the high excitation lines HeII, [OIII], [NeIII], [ArII] together with the [SII] density sensitive ratio and [OIII]/[OII] vary by much smaller amounts (cf. Table 2). This cannot therefore be explained by variations of the ionization parameters, which should first of all affect the [OIII]/[OII] ratio. A possible explanation for this is discussed in Sect. 4.8.

\[ \text{Fig. 3. Spectrum of Knot C, i.e. a region 15.5}^{\prime}\text{ from the nucleus at PA=318}^{\circ} \text{(cf. Figs. 1, 4). Flux units are as in Fig. 2.} \]
Dereddened fluxes relative to H\(\beta\) Binette et al. (1996, hereafter B96). However, it should be kept in mind that \(T_e(\text{OIII}) > T_e(\text{NII})\) does not necessarily indicate the presence of density bounded clouds.

Table 2. Fluxes of significant lines in the various knots\(^1\)

| Nucleus | KnA 4.6”x2” | KnB 4.1”x2” | KnC 4.1”x2” | KnD 4.1”x2” | KnE 5.4”x2” | KnF 5.7”x2” | KnG 4.1”x2” | KnH 6.5”x2” | KnJ 8.4”x2” | KnL 4.3”x2” |
|---------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|
| \[\text{OIII}\] \(\lambda\lambda 3727\) | 270 | 740 | 312 | 133 | 112 | \(< 200\) | 650 | 400 | 410 | 380 | 290: |
| HeII \(\lambda 4686\) | 41 | 40: | 30: | 60 | 53 | \(< 25\) | | | | | |
| \[\text{OIII}\] \(\lambda 5007\) | 1025 | 900 | 690 | 965 | 815 | 20: | 400 | 230 | 260 | 250 |
| [FeVI] \(\lambda 6087\) | 11 | \(< 11\) | \(< 6\) | 9.7 | 19 | \(< 15\) | \(< 10\) | | | |
| [O] \(\lambda 6300\) | 42 | 51 | 24 | 26 | 13: | 5 | 62 | 31 | 100 | 95 | 13 |
| [NI] \(\lambda 6583\) | 343 | 407 | 223 | 237 | 133 | 128 | 425 | 265 | 585 | 586 | 159 |
| [SII] \(\lambda 6716\) | 96 | 130 | 75 | 64 | 37 | 45 | 162 | 105 | 285 | 342 | 59 |
| [SII] \(\lambda 6731\) | 96 | 105 | 60 | 57 | 32 | 35 | 124 | 83 | 210 | 238 | 51 |
| [ArIII] \(\lambda 7136\) | 22 | 14: | 11 | 27 | 22 | \(< 10\) | 10: | \(< 15\) | \(< 10\) | | |
| [SIII] \(\lambda 9531\) | 134 | 68 | 61 | 155 | 139 | 29 | | | | | |
| \(\text{H}α\) flux\(^c\) | 4000 | 590 | 430 | 110 | 32 | 820 | 330 | 260 | 9 | 9 | 1500 |
| \(W_λ(\text{H}α)\)\(^d\) | 23 | 10 | 37 | 72 | 30 | 59 | 8 | 21 | 5 | 5 | 24 |
| \(W_λ(\text{OII})\)\(^d\) | 50 | 20 | 60 | 300 | 100 | \(< 3\) | 8 | 12 | 7 | 7 | |

\(^1\) Dereddened fluxes relative to H\(\beta\)=100, extinctions are computed imposing H\(\alpha\)=290 and the adopted visual extinctions are given at the top of each column. Blank entries are undetected lines with non-significant upper limits.

\(^\alpha\) H\(\beta\) is weak and the derived extinction is therefore uncertain.

\(^\beta\) Possibly overestimated due to contamination by foreground gas with lower extinction.

\(^\gamma\) Dereddened flux, units of 10\(^{-15}\) erg cm\(^{-2}\) s\(^{-1}\).

\(^\delta\) Equivalent widths in Å of nebular emission lines.

### 3.3. Diagnostic line ratios

Temperature and density sensitive line ratios are summarized in Table 3. Note that only a few values are available on the nucleus because of the strong stellar continuum which prevents the measurement of faint lines.

#### 3.3.1. Electron temperature

The relatively large \(T_e(\text{OIII})\) yields lower \(T_e(\text{SII})\) and much cooler [NI], [SII] temperatures. Typical of gas photoionized by a “typical AGN”, i.e. a spectrum characterized by a power law continuum with a super-imposed UV bump peaked at \(\approx 50–100\) eV (e.g. Mathews & Ferland [1987]). As \(T_e(\text{OIII})\) mainly depends on the average energy of \(h\nu < 54\) eV ionizing photons, “bumpy” spectra, which are quite flat between 13 and 54 eV, yield hot [OIII]. The lower ionization species, such as [NI] and [SII], mostly form in the partially ionized region, heated by soft X-rays, whose temperature cannot exceed \(10^4\) K due to the powerful cooling by collisionally excited Ly\(\alpha\) and 2–photon emission. The contrast between the OIII and SII temperatures can be further increased if sub–solar metallicities are adopted, because [OIII] is a major coolant while [NI] only plays a secondary role in the cooling of the partially ionized region.

An alternative explanation for the OIII, NII etc. temperature differences is to assume that part of the line emission arises from density bounded clouds. In this case there is no need to adopt a “bumpy” AGN spectrum and detailed models, assuming a pure power law ionizing continuum, were developed by Binette et al. (1996, hereafter B96). However, it should be kept in mind that \(T_e(\text{OIII}) > T_e(\text{NII})\) does not necessarily indicate the presence of density bounded clouds.

#### 3.3.2. Electron density

There is a clear trend between \(n_e\) and excitation of the species used to determine the density.

The [SII] red doublet yields densities lower than [OII] which is compatible with a single-density cloud for the following reason. If the flux of soft X-rays (200–500 eV) is strong enough, then [SII] lines are mostly produced in the X-ray heated region where the average hydrogen ionization fraction is quite low (\(\lesssim 0.1\)). The lines of [OII] on the contrary can only be produced in the transition region, where the ionization degree is close to unity, because of the very rapid O–H charge exchange reactions. Hence \(n_e(\text{SII}) < n_e(\text{OII})\) most probably indicates the presence of a strong soft-X flux, as one indeed expects to be the case for an AGN spectrum. This is also confirmed by the detailed modelling described below.

The higher densities in the fully ionized region are new results because the blue [ArIV] doublet is usually too weak in AGN spectra and the FIR [NeV] lines are only accessible with the ISO-SWS spectrometer [MS98]. The [ArIV] density of knot C is equal, within the errors, to that derived by [OII] thus indicating that no large variations of densities are present in this cloud.

### 4. Photoionization models

Several photoionization models for the Circinus galaxy have been discussed in the literature. These used line intensities and ratios measured from the central regions of the galaxy and were
Table 3. Temperature and density sensitive line ratios.

| Ratio                  | Value  | Diagnostic |
|------------------------|--------|------------|
|                       | Nucleus |            |
| [OII] λ3727/λ3725      | 25±6   | 300<n_e<6000 |
| [SII] λ6716/λ6716      | 1.00±0.07 | 400<n_e<800 |
| [NeV] 14.3μm/24.3μm   | 1.6±0.4 | 2000<n_e<12000 |
| [SIII] λ9531/λ6312     | ≥25    | T_e≤14000 |
|                       | Knot C |            |
| [OII] λ3727/λ3725      | 14±4   | 1400<n_e<11000 |
| [SII] λ6716/λ6716      | 0.89±0.06 | 200<n_e<500 |
| [ArIV] λ4711/λ4740     | 1.0±0.2 | 1500<n_e<10000 |
| [NII] λ6583/λ5755      | 50±13  | 9000<T_e<12500 |
| [OIII] λ5007/λ4363     | 46±9   | 14000<T_e<18000 |
| [SII] λ6716/λ4073      | ≤8     | T_e≤12000 |
| [SIII] λ9531/λ6312     | 26±7   | 11500<T_e<16000 |

a [NeV] FIR lines from M96

Fig. 4. Intensity contour plots in the position–λ plane. The long slit spectra are continuum subtracted and the levels are logarithmically spaced by 0.2 dex. The ordinate are arc-sec from the Hα peak along the two slit orientations (cf. Fig. 1). The dashed lines show the regions where the spectra displayed in Figs. 2, 3, 5 were extracted.

Fig. 5. Spectra of the various knots (cf. Figs. 1) at selected wavelength ranges including [OIII], Hβ, HeII (left panels) and [FeVII], [OI], [NII], Hα, [SII] (right hand panels). Fluxes are in units of 10^{-16} erg cm^{-2} s^{-1} Å^{-1} and λ's are in Å. The spectra are also scaled by a factor given in the plots to show faint features.

mostly directed to constraining the intrinsic shape of AGN photoionizing continuum. Quite different conclusions were drawn by M96, who found evidence for a prominent UV bump centered at ≃70 eV, and Binette et al. (1997, hereafter B97) who showed that equally good (or bad) results could be obtained using a combination of radiation and density bounded clouds photoionized by a pure power–law spectrum. In all cases the metal abundances were assumed to be solar and no attempt was made to constrain metallicities.

Here we mainly concentrate on knot C, an extranuclear cloud whose rich emission line spectrum and simple geometry (a plane parallel region) are better suited for deriving physical parameters from photoionization modelling. We first analyze the observational evidence against shock excitation and then describe in some detail the new modelling procedure which is primarily aimed at determining the gas metal abundances, (cf. Sects. 4.2 and 5.1). We also analyze the problems to reproduce the observed [FeVII]/[FeII] and [NII]/[NI] ratios (Sects. 4.3, 4.6), discuss the role of dust and reanalyze several crucial as-
The gas phase abundance could, in principle, be compatible with \[\text{FeII}\] IR lines (e.g. Oliva et al. 1989). Although the low Fe remnants whose near IR spectra are dominated by prominent Haro objects (e.g. Beck-Winchatz et al. 1994) and supernova 1993). This is confirmed by observations of nearby Herbig–Haro objects (e.g. Beck-Winchatz et al. 1994) and supernova remnants whose near IR spectra are dominated by prominent [FeII] IR lines (e.g. Oliva et al. 1989). Although the low Fe\textsuperscript{+} gas phase abundance could, in principle, be compatible with a very slow shock (∼50 km/s), this falls short by orders of magnitude in producing high excitation species.

Another argument comes from the HeII/H\textsc{β} and HeII/HeI ratios which are a factor >2 larger than those predicted by shocks models with velocities \(v\leq 500\) km/s (Dopita & Sutherland 1995). It should be noted that, although stronger HeII could probably be obtained by increasing the shock speed to ∼1000 km/s, these velocities are incompatible with the observed line profiles. More generally, the observed line widths (<150 km/s, D94) are difficult to reconcile with the fact that only shocks faster than 300 km/s can produce prominent high excitation lines such as [OIII] (Dopita & Sutherland 1996). This argument becomes even stronger when interpreting the nuclear spectra where the highest excitation lines, [FeX,XI], do not show any evidence of large scale motions at velocities >200 km/s. (cf. D94 and work in preparation).

Finally, it is worth mentioning that detailed shock + photoionization composite models recently developed by Contini et al. (1998) suggest that shock excited gas does not contribute significantly to any of the optical/IR lines from Circinus.

4.2. Details of the photoionization models

4.2.1. Single component, radiation bounded clouds

We constructed a grid of models covering a wide range of ionization parameters \((-3.5 < \log U < -1.5), \text{densities } (2.0 < \log n < 5.0), \text{metallicities } (0.08 < \text{He/H} < 0.16, -1.5 < \log Z/Z_{\odot} < 0)\) and shape of the ionizing continuum which we parameterized as a combination of a power law extending from 1 eV to 10 keV with index \(2 < \alpha < 0.4\) and a black–body with \(5 < \log T_{BB} < 6\), the relative fraction of the two components being another free parameter. All the parameters were varied randomly and about 27,000 models were produced using Cloudy (Ferland 1993) which we slightly modified to include the possibility of varying the N–H charge exchange rate. The line intensities were also computed using the temperature and ionization structure from Cloudy and an in–house data base of atomic parameters. The agreement with the Cloudy output was good for all the “standard” species while large discrepancies were only found for coronal species (e.g. [FeX]) whose collision strengths are still very uncertain and much debated.

Out of this large grid we selected about 400 models whose [OIII]/H\textsc{β}, [OIII]/[OII]/[OII], [ArV]/[ArIV]/[ArIII], [SIII]/[SII], [OIII]λ5007/λ4363, [OIII]λ3727/λλ7325, [SII]λ6716/λ6731, [ArV]λ4711/λ4740 line ratios were reasonably close to those observed in knot C. These were used as the starting point for computing the “good models”, with adjusted values of relative metal abundances, which minimized the differences between predicted and observed line ratios. Note that to reproduce both [FeVII] and [FeII] we were in all cases forced to vary the iron gas phase abundance between the fully and partially ionized regions (cf. also Sect. 4.3). The results of the best model are summarized in Table 4 and discussed in Sect. 4.3. Note the large discrepancy for [NI] which is overpredicted by a factor of ∼5, this problem is discussed in Sect. 4.3.

The most important results are the abundance histograms shown in Figs. 10–11 which were constructed by including all the “good” models with \(\chi^2_{red} < 5\). Although the choice of the cutoff is arbitrary, it should be noticed that variations of this parameter do not alter the mean values, but only influence the

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\(\chi^2_{red}\) The choice of a black–body does not have any direct physical implications. We used it just because it provides a simple way to parameterize the UV bump which seems to be a typical features of AGNs (e.g. Mathews & Ferland 1987, Laor 1990) and is predicted by accretion disk models (e.g. Laor & Netzer 1989).
shape of the distributions whose widths roughly double if the $x_{red}^2$ cutoff is increased to values as large as 30.

4.2.2. Multi-density components, radiation bounded clouds

The large grid described above was also organized to have at least 4 models with the same photon flux, continuum shape and abundances but different densities, and these were used as starting points to construct multi-density models. We simulated 2–density clouds by coupling all available models with different weights and selected about 300 of them, which were used as starting points to compute the “good models” following the same procedure adopted for the single-density case. We also simulated clouds with $\geq 3$ density components, but these results are not included here because this complication had virtually no effect on the quality of the fit.

The most important result is that single and multi-density models are equally good (or bad) in reproducing the observed line ratios. Obviously, this does not necessarily imply that knot C is a single-density cloud, but rather indicates that the stratifications which probably exist have little effect on the available density sensitive line ratios.

4.2.3. Mixed models with density and radiation bounded clouds

We constructed a grid of about 10,000 models photoionized by a power law AGN continuum with index $2 < \alpha < 0.3$, which turns into $\nu^{-0.7}$ beyond 500 eV, and covering the same range of physical parameters as the radiation bounded clouds described above. The column density of the radiation bounded component was always large enough to reach a temperature $< 3000$ K at its outer edge. For each model we also computed line intensities from a density bounded cloud which we defined as a layer with thickness $\Delta R$ equal to 5% of the nominal radius of the HII Strömgren sphere, numerically ($f =$ filling factor)

$$\Delta R \approx 2500 \frac{U}{n_H f} \text{ pc}$$

The relative contribution of density and radiation bounded regions was set by imposing HeII$\lambda 4686$/H$\beta = 0.6$.

This approach is somewhat similar to that adopted by B96 apart from the following details. The radiation bounded component here is formed by high density gas, a condition required to match the observed [ArIV]$\lambda 4711/\lambda 4740$, and is concentrated within the projected size of knot C, i.e. $< 80$ pc. In practice, the two components have the same densities and see un–filtered radiation from the AGN.

The “good models” were optimized, and the best abundances derived using the the same procedure depicted above. Worth mentioning is that most of the “good models” have spectral slopes in the range 1.3–1.5 which are in good agreement with those used by B96. The most important result is that these mixed models give similar, though slightly poorer (cf. Sect. 4.3) results than radiation bounded clouds.

4.2.4. The role of dust in extranuclear knots

Dust can modify the ionization and temperature structure because it competes with gas in absorbing the UV photons, and because it hides refractory elements such as iron. Given the low ionization parameters, however, the first effect is negligible, i.e. the ionization structure of the fully ionized region of knot C is not affected by dust although this plays an important role in modifying the heating–cooling balance of the partially ionized region heated by X–rays.

Cooling: the refractory species hidden in the grains cannot contribute to the line cooling and this effect is correctly computed by Cloudy. For example, depleting Fe on grains produces higher gas temperature and stronger [OI], [SII] etc. lines, because it suppresses the near IR lines of [FeII] which are among the major coolants for quasi–solar Fe/O gas phase abundances.

Heating: the metals hidden in the dust still contribute to the heating of the gas because the X–rays have energies much larger than the binding energy of the grains, and cannot therefore recognize metals in dust from those in the gas phase.

The major problem is that Cloudy (and probably other photoionization models) does not include the X–ray heating from the grain metals and therefore underestimates the temperature of the partially ionized region and hence may predict weaker fluxes of [OI], [SII] and other low excitation lines. Therefore, the models for knot C, having most of iron depleted on grains, are not fully self–consistent and most probably require a too high flux of X–rays to reproduce e.g. [OI]/[OIII]. This may imply that the “true” models should have somewhat softer spectra than those of Fig. 5.

4.3. Best photoionization models of knot C: the shape of the AGN continuum and the role of density bounded clouds

Table 4 lists the results of the best photoionization models, selected from the several hundred which provided a reasonable fit to the spectrum of knot C. Note that the results of multi-density clouds (Sect. 4.2.3) are not included because they are virtually indistinguishable from those of single-density models.

Fig. 7 shows the AGN continuum adopted for the “best models” of Table 4. Radiation bounded models require a prominent UV bump centered (in $E_v$) at about 100 eV. This is slightly bluer than that found by M96 and somewhat harder than model spectra of more luminous accretion disks (cf. e.g. Laor 1990), but in qualitative agreement with the predicted dependence of spectral shape with AGN luminosity, i.e. that lower luminosity accretion disks should have harder spectra (Netzer et al. 1992).

The amplitude of the UV bump could be significantly decreased by relaxing the assumption on the gas density distribution and, with a properly tuned combination of density and radiation bounded clouds, one may probably get a similarly good fit with a power law. It is nevertheless instructive to analyze why our mixed models provide a worse fit to the data and, in particular, are unable to simultaneously reproduce the OII/OIII balance and the [ArV]/[ArIII] and
Table 4. Photoionization models for knot C

| Adopted parameters | Model 1 | Model 2 | Model 3 |
|--------------------|---------|---------|---------|
| Element            | Abundances<sup>(1)</sup> |         |         |
| Helium             | 11.1    | 11.1    | 11.1    |
| Nitrogen           | 8.05    | 8.20    | 8.05    |
| Oxygen             | 8.17    | 8.27    | 8.17    |
| Neon               | 7.27    | 7.37    | 7.27    |
| Sulphur            | 6.98    | 6.90    | 6.75    |
| Argon              | 6.38    | 6.45    | 6.20    |
| Silicon            | 6.85    | 6.95    | 6.85    |
| Fe low-ion<sup>a</sup> | 5.80    | 5.80    | 5.80    |
| Fe high-ion<sup>b</sup> | 6.90    | 7.00    | 7.00    |

| Gas density (n_H) | 2000 | 3000 | 2000 |
| Ionizing continuum<sup>c</sup> | UV-bump | ν−1.5 | ν−1.4 |
| Ionization parameter<sup>d</sup> (U) | 3.5 × 10<sup>−3</sup> | 4.7 × 10<sup>−3</sup> | 2.0 × 10<sup>−3</sup> |
| Fraction radiation bounded<sup>e</sup> | 100% | 4% | 3% |
| F(Hβ)/F(Hα)<sup>f</sup> | 100% | 6% | 6% |

| Line ratio<sup>(2)</sup> | Observed | Model 1 | Model 2 | Model 3 |
|--------------------------|----------|---------|---------|---------|
| [HeII]/Hβ                | 0.60 ± 0.08 | 0.60    | 0.60    | 0.60    |
| [HeII]/HeI               | 6.2 ± 0.9  | 6.8     | 5.8     | 6.3     |
| [NII]/Hα                 | 0.80 ± 0.08 | 0.83    | 0.79    | 0.77    |
| [NII]/[NI]               | 34 ± 7 | 8.0 (!!!) | 6.5 (!!!) | 4.7 (!!!) |
| λ6583/λ5755              | 50 ± 13 | 41      | 57      | 39      |
| [OIII]/Hβ               | 9.7 ± 1 | 10      | 9.8     | 9.3     |
| λ5007/λ4363             | 46 ± 9 | 31 (!) | 43      | 42      |
| [OII]/[OIII]             | 0.14 ± 0.02 | 0.12 | 0.057 (!!!) | 0.12 |
| [OI]/[OIII]             | 0.027 ± 0.003 | 0.027 | 0.024  | 0.028  |
| λ3727/λ7325             | 14 ± 4 | 14      | 12      | 13      |
| [NeIII]/Hβ              | 0.66 ± 0.1 | 0.68 | 0.70    | 0.73    |
| [SiVI]/Brγ              | <5       | 2.2     | 1.5     | 0.12    |
| [SII]/Hα                | 0.19 ± 0.02 | 0.20   | 0.20    | 0.19    |
| λ6731/λ6716             | 0.89 ± 0.06 | 0.95 | 0.88    | 0.91    |
| [SIII]/[SII]            | 2.8 ± 0.4 | 3.0  | 2.4     | 2.6     |
| λ9531/λ6312             | 26 ± 17 | 20     | 22      | 21      |
| [ArIII]/Hα              | 0.092 ± 0.011 | 0.089 | 0.098  | 0.092  |
| [ArIV]/[ArIII]          | 0.37 ± 0.1 | 0.56 | 0.57    | 0.25    |
| [ArV]/[ArIV]           | 0.24 ± 0.03 | 0.17 | 0.17   | 0.032 (!!!) |
| λ4711/λ4740            | 1.0 ± 0.2 | 0.88 | 0.96    | 0.88    |
| [FeII]/[FeIII]          | <0.7 | 0.70     | 1.2   | 4.1 (!!!) |
| [FeX][FeVII]          | <0.2 | 0.045     | 0.030 | 0.005 |
| [FeII]/Brγ<sup>f</sup> | ≈1.5 | 1.6  | 1.8     | 1.8     |

<sup>(1)</sup> 12+log(X/H) where X/H is the absolute abundance by number
<sup>(2)</sup> Abbreviation used: HeII=λ4686, HeI=λ5876, [NII]=λ6583, [NI]=λ5200, [OIII]=λ5007, [OII]=λ3727, [OII]=λ6300, [NeIII]=λ3869, [NeV]=λ3426, [SiV]=λ19629, [SiVII]=λ24827, [SiII]=λ6731, [SiIII]=λ9531, [ArIII]=λ7136, [ArIV]=λ4740, [ArV]=λ37006, [FeVII]=λ6087, [FeVII]=λ13514. [FeII]=λ16435

Fig. 7. The AGN ionizing continua used to compute the best models (Table 4) are plotted together with the observed X and IR continua. The solid line refers to a single density, radiation bounded component which provides a good fit for all lines but [NII]. The broken curves are for combinations of density and radiation bounded clouds, but these models cannot simultaneously reproduce the [OII]/[OIII] and [ArV]/[ArIII] ratios. The dashed curve provides the best fit for high excitations lines while the dotted curve best reproduces the OI/OII/OIII ionization balance (see Sect. 4.3 for details). Note that the curves show the spectra seen by knot C, and should be scaled by a coefficient which takes into account the “intrinsic beaming” of the AGN ionizing radiation (a factor of 2 for an optically thick disk) before being compared with the observed points. See Sect. 4.4 for a discussion of the AGN energy budget.

 Independently on the detailed results of the models, the following arguments indicate that density bounded clouds may indeed play an important role.

- Ionizing spectra with pronounced UV–bumps tend to produce too high [OIII] temperatures and model #1 is indeed quite hot, though still compatible (within 1.5σ) with the somewhat noisy measurement of [OIII]λ4363 (cf. Fig. 3 and Tab. 4). Curiously, though, the result of Model #1 is the opposite of that [FeVII]/[FeVI] ratios (cf. last two columns of Table 4). Model #2 has a high ionization parameter and correctly predicts high excitation lines but underestimates all [OII] lines while model #3, with a lower value of U, correctly reproduces the [OII]/[OIII] ratio but predicts very faint high excitation lines. The main reason for the above difference is that, for a given gas density, the [OII]/[OIII] ratio is a measure of the flux of soft ionizing photons (hν=13–54 eV), while [ArV]/[ArIII] and [FeVII]/[FeVI] depend on the flux of harder radiation (hν ≳ 60 eV). The spectrum of knot C is characterized by a quite large [OII]/[OIII] ratio, which points towards low fluxes of soft photons, and strong high excitation lines, which require large fluxes of hard photons. These somewhat contradictory requirements can be easily satisfied by a spectrum which steeply rises beyond the Lyman edge, and peaks at ≈100 eV, i.e. a spectrum similar to that of Model #1.
obtained by most previous models in the literature which failed to produce hot enough [OIII]. Therefore, the classical “[OIII] temperature problem” may just reflect the fact that past models were mostly biased toward high metallicities and rather flat temperature problem” may just reflect the fact that past models were mostly biased toward high metallicities and rather flat temperature problem” may just reflect the fact that past models were mostly biased toward high metallicities and rather flat

The Hβ flux from knot C is only ≃5% of that expected if the gas absorbed all the ionizing photon impinging on the 2'' x 2'' (40 x 40 pc²) geometrical cross-section of the cloud. Such a small “effective covering factor” could, in principle, be obtained by assuming a suitable distribution of radiation bounded, geometrically thin clouds or filaments. However, density bounded clouds seem to provide a more self-consistent interpretation because the measured value is remarkably close to the 6% predicted by models #2 and #3 (cf. note f of Tab. 3).

– The variation of line ratios between the different knots cannot be explained by radiation bounded clouds illuminated by the same ionizing continuum, but require e.g. intrinsic beaming of the AGN continuum and/or filtering by matter bounded clouds closer to the nucleus. Mixed models could give a more natural explanation to the spatial variation of line ratios (see also 396).

4.4. Energy budget of the AGN

The ionizing photon flux seen by knot C is constrained by the U-sensitive and density sensitive line ratios which yield

\[
\Phi_{\text{ion}} = U \cdot n_H \cdot c \approx (1 - 4) \times 10^{33} \text{ cm}^{-2}
\]

This can be translated into \(Q(H)_{\text{AGN}}\), the total number rate of ionizing photons from the AGN, once the angular distribution of the UV ionizing radiation is known. Assuming that it arises from a geometrically thin, optically thick accretion disk, one finds \(Q(\theta) \approx \cos \theta\) (e.g. Laor & Netzer 1989) and

\[
Q(H)_{\text{AGN}} = 2\pi R_{\text{knC}}^2 \Phi_{\text{ion}} \approx \frac{(0.5 - 2.0) \times 10^{54}}{\cos^2 \theta} \text{ s}^{-1}
\]

where \(R_{\text{knC}}\) is the projected distance of knot C i.e. 15.5'' or \(d=300/cos \theta\) pc from the nucleus, \(\theta\) being the inclination angle of the cone relative to the plane of the sky. Detailed kinematical studies indicate \(|\theta| \leq 40^\circ\) (Elmouttie et al. 1998).

The AGN luminosity in the ionizing continuum is therefore

\[
L_{\text{ion}} = Q(H)_{\text{AGN}} < h\nu_{\text{ion}}> \approx \frac{1 - 4 \cdot 10^{33}}{\cos^2 \theta} L_{\odot}
\]

where \(< h\nu_{\text{ion}} >\) is the average photon energy which is here assumed to be ≃50 eV. The ionizing luminosity is therefore very large but compatible, within the errors, with the observed FIR luminosity \(L_{\text{FIR}} \approx 1.2 \times 10^{10} L_{\odot}\) (Siebenmorgen et al. 1997).

This implies that the AGN emits most of its energy in the ionizing continuum or, equivalently, that the AGN intrinsic spectrum has a prominent peak or bump in the ionizing UV, and much weaker emission at lower energies. This is in good agreement with computed models of accretion disks which also predict that low luminosity AGNs, such as Circinus, should be characterized by a quite hard ionizing continuum (cf. Laor 1994, Netzer et al. 1992).

The global properties of the AGN are summarized in Table 5 which also includes a comparison between \(Q(H)_{\text{AGN}}\) and the observed recombination rate, based on ISO observations of the Brα H-recombination line at 4.05 μm (cf. M96). The difference is remarkably large, with only ≃1% of the AGN ionizing photons being accounted for by emission from “normal” ionized gas. This indicates that the bulk of the Lyman continuum radiation either goes into ionizing regions which are obscured even at 4 μm (i.e. \(A_V > 50\) mag), or is directly absorbed by grains in dusty clouds lying very close to the AGN.

4.5. Iron depletion and the [FeVII]/[FeII] problem

The observed [FeVII]λ6087/[FeII]λ16435.1 ratio cannot be explained using the same iron gas phase abundance in the HeIII Strömgren sphere, where FeVII is formed, and in the partially ionized region, where iron is predominantly FeII due to the rapid charge exchange recombination reactions with neutral hydrogen. It should be noted that this is a fundamental problem unrelated to the details of the photoionization models and primarily reflects the fact that the [FeVII] line has a very small collision strength (\(T/\omega_i \approx 0.1\)) which is factor of about 10 lower than the [FeII] transition. A Fe⁺⁺/Fe⁺ ≳ 2 integrated relative abundance is thus required to reproduce the observed line ratio. This number is incompatible with the relative sizes of the HeIII and partially ionized regions which are constrained by e.g. the HeII and [OII] lines. It is also interesting to note that this problem is even exacerbated if the shock models of Dopita & Sutherland (1996) are adopted because these predict Fe⁺⁺/Fe⁺ ratios much smaller than the photoionization models described above.
(with errors) measured in knot C. The parameter model \#2 (cf. Table 4), and the dashed area show the value solid line refers to model \#1 while the dashed curve is for with a low (2% of solar) iron abundance (cf. Figs. 10, 11). How-

would reconcile the observed \([\text{Fe}^{\text{VII}}]\) and \([\text{Fe}^{\text{II}}]\) intensities collision strengths are underestimated by a factor of the standard rate coefficient used by Cloudy.

Therefore, Fe–bearing dust cannot be photo–evaporated the AGN and receives a relatively modest flux of hard UV pho-
tons. The alternative possibility is to assume that the iron deple-
tion is much larger in the partially than in the fully ionized region, NII is mostly neutralized via charge exchanges with H\(^+\) and adopting lower charge exchange efficiencies yield larger \([\text{NII}]/[\text{NI}]\) ratios. This is evident in Fig. 8 where this ratio is plotted as a function of the assumed value of \(\delta(N)\), the charge exchange rate coefficient. Assuming a N–H charge exchange a factor of \(\sim 30\) lower than presently adopted yields the correct \([\text{NII}]/[\text{NI}]\) ratio.

Noticeably, the problem we find here is exactly the opposite of what reported by Stasinska (1984) whose models systemat-
ically underpredicted the \([\text{NI}]/[\text{NII}]\) ratio in objects with low \([\text{O}^{\text{I}}]/[\text{OII}]\).

4.7. Modelling the nuclear spectrum: dusty, dust–free and diffuse components.

A puzzling aspect of the line emission from regions very close to the nucleus is the simultaneous presence of high (e.g. \([\text{Fe}^{\text{II}}]\) and low (e.g. \([\text{SII}]\), \([\text{OI}]\)) ionization species. More specifically, the images of \([\text{M94}]\) clearly show that \([\text{SII}]\) peaks at a distance of only \(\sim 0.5\)" or 10 pc from the nucleus (cf. Fig. 9 of \([\text{M94}]\)). This result is incompatible with the standard idea according to which low excitation lines are produced in clouds with low ionization parameters. Numerically, combining the ionizing continuum inferred from the spectrum of knot C with \(n=1.2 \times 10^4\ \text{cm}^{-3}\), the highest density compatible with the FIR \([\text{NeV}]\) doublet (Table 3.3), yields \(U \sim 0.5\) at \(r=10\) pc from the AGN, an ionization parameter far too large for the produc-
tion of low excitation species. Not surprisingly therefore, all
photons have already been absorbed by HeII. Therefore, OIV cannot be ionized above OIII because most of the OIII ionizing photons which keep oxygen in higher ionization stages on this parameter) and therefore have large fluxes of OIV ionization parameters” (cf. Sect. 3 of Oliva 1997 for a critical discussion follows. Compact models are characterized by large “ionization parameters (\(f=0.025\)) except for dust. The model without dust emits most of the coronal lines, while the dusty cloud accounts for the prominent low excitation lines observed close to the nucleus. However, both models fail to produce enough [OIV] and other intermediate ionization lines which therefore require a third, more diffuse component. See Sect. 4.7 for details.

Although the combined emission of dusty and dust–free clouds can account for the observed emission of low ionization and coronal species, it falls short by large factors in producing [OIV] and other relatively low ionization species which form within the HeIII sphere, and its relative abundance is therefore very low.

In practice, we found it impossible to construct a single model which simultaneously produces a compact coronal line region, such as that observed in [FeXI] (O94), and which comes anywhere close to the [OIV] \(\lambda 25.9\) [OIII]\(\lambda 5007\) \(\approx 0.3\) observed ratio. We did indeed construct many thousands of randomly generated dusty and dust–free models, and attempted an approach similar to that used for knot C (Sect. 4.2) but, in no case, could we find a model which satisfies these contradictory constraints. It should also be noted that B97 independently come to a similar conclusion.

The main conclusion therefore is that, regardless of the details of the models, the nuclear spectrum and line spatial distribution can only be modeled by adding a third “diffuse” component (e.g. with a lower filling factor) to the dusty and dust–free clouds discussed above and depicted in Fig. 8. Given the large number of free parameters, we abandoned the idea of using photoionization models to constrain abundances and other physical properties of the gas. We made some attempt to verify that a mixture of clouds exposed to the same continuum, and with the same abundances as Model #1 of knot C (Table 3 and Fig. 9) could reasonably well reproduce the observed properties of the nuclear spectrum. However, the results are not too encouraging and, apart from the much improved [SII] surface brightness and [OIV]/[OIII] ratio, the solutions are not significantly better than those already discussed by M96 and B97, and are not therefore discussed here.

4.8. Modelling other extra–nuclear knots

An analysis similar to that used for knot C was also applied to the other extra–nuclear knots using the more limited number of lines available in their spectra. The results can be summarized as follows.

The abundances derived in the Seyfert-type knots A, B, D, G, F (cf. Fig. 6) are similar those found in knot C but affected by much larger errors because of the more limited numbers of lines available for the analysis. In particular, the density sensitive [ArIV] doublet and the U–sensitive [ArV] line is not detected in any of these knots, and the reddening correction for [OII]\(\lambda 3727\) could be very uncertain in the high extinction regions (cf. note b of Table 2).

We also attempted to verify if the observed line ratios in these knots could be explained as photoionization by the same AGN continuum seen by knot C but could not find any satisfactory solution using radiation bounded clouds exposed to the same continuum. Adding matter bounded clouds alleviates the problem (as already stressed by B96) but requires an ad hoc choice of their photoelectric opacities, i.e. the radius at which the ionization structure is cut. In particular, explaining the drop of low excitation lines between the adjacent knots C and D (cf. Sect. 3.2) requires matter bounded clouds cut at about \(1.2\times\) the HI Strömgren radius, the exact position of the cut depending on the assumed shape of the AGN continuum. Another parameter affecting the ratio of low–to–high excitation lines (e.g.

Fig. 9. Ionization structure and spatial variation of the line emission from two nuclear clouds exposed to the AGN continuum of “Model #1” (cf. Fig. 3) and with identical physical parameters (\(n_{\text{HI}}=10^4\) cm\(^{-3}\) and filling factor \(f=0.025\)) except for dust. The model without dust emits most of the coronal lines, while the dusty cloud accounts for the prominent low excitation lines observed close to the nucleus. However, both models fail to produce enough [OIV] and other intermediate ionization lines which therefore require a third, more diffuse component. See Sect. 4.7 for details.
Fig. 10. Element abundances (in log of solar units) as derived from a comparison between the observed line strengths in knot C, and the predictions of a large grid of randomly generated photoionization models. The three columns refer to clouds with different gas density distributions, and the “good models” are those coming closer to reproducing the observed line ratios. See text, Sects. 5.1 and 4.2 for details.

\([\text{[OII]}]/[\text{OIII}]\) is the iron gas phase abundance which influences the cooling of the partially ionized region (cf. Sect. 5.2.4). If iron is more abundant in knot D, as indicated by its stronger [FeVII] line emission (cf. Table 2 and Sect. 3.2), than [OI], [SII], [NII] could be depressed by the increased [FeII] cooling.

The abundances derived for the LINER–like knots (H, I) are very uncertain (±1.3 dex at least). Their spectra are not compatible with illumination from the same continuum seen by knot C but require a harder (i.e. more X rays relative to 13–80 eV photons) spectrum which could be in principle obtained by filtering the AGN continuum through an absorber with a carefully tuned photoelectric opacity. Alternatively, the weak (in surface brightness) spectrum of these low excitation knots could be explained by shock excitation, in which case one expects [FeII])λ16435/Hβ≈1 and a factor >10 larger than in the case of pure photoionization.

Finally, the oxygen lines in the highly reddened HII–like knots (E, L) are too weak to allow any reliable abundance analysis.

5. Discussion

5.1. Element abundances

Deriving abundances of AGN clouds from photoionization models has generally been considered to be unreliable because the shape of the AGN ionizing continuum and the density distribution of the emitting regions (clouds) are both basically unknown. The more typical approach therefore has been to assume a metallicity and use photoionization models to constrain the AGN spectrum and/or the gas density distribution, or just to demonstrate that the gas is photoionized. Although explicit statements concerning the nitrogen abundance are often found in the literature (e.g. Storchi-Bergmann & Pastoriza 1989, Simpson & Ward 1996) these are based on a very limited choice of photoionization model parameters and in most cases find oxygen abundances close to solar, in disagreement with what is derived here. The only other piece of work which covers a model parameter range comparable to that presented here is that by Komossa & Schulz (1997) who analyzes a much more limited numbers of lines, e.g. do not include [ArIV,V], in a large sample of Seyferts. They find that, on average, oxygen is underabundant by a factor of ~2 and that the N/O ratio is only a factor of 1.5–2.0 above the solar value. We believe that the analysis presented here leads to more reliable metallicity estimates.

The results presented here indicate that, in spite of the above uncertainties, reliable metallicities can indeed be derived from spectra including a large enough number of lines, such as that of knot C. Our method has been described in Sect. 4.2 and, in short, is based on the computation of a large number of photoionization models with a minimal personal bias and preconceived ideas on the AGN ionizing spectrum and the gas den-
sity distribution. In particular, we also considered mixed models with combinations of density and radiation bounded clouds (B96) as well as models with multiple density components. We spanned a very wide range of model parameters which were varied randomly, and selected the relatively few (about 200) good models which came closest to reproducing the observed line ratios.

The main results are summarized in Figs. 4, 5 which show the distribution of element abundances required to reproduce the observed line ratios. The most remarkable feature is that the metal abundances are quite well constrained in spite of the very different assumptions made for the gas density distribution and shape of the AGN continua. In other words, models with very different abundances fail to match the observed lines ratios in knot C regardless of the AGN spectral shape and/or gas density distribution assumed.

Another encouraging result is that lines from different ionization stages yield similar abundances which simply reflects the fact that the models reproduce the observed line ratios reasonably well. There are however remarkable exceptions, such as the [NII]/[NI] and [FeII]/[FeVII] ratios which are both predicted too high. Possible explanations for these differences have been discussed above (Sects. 4.5, 4.6). We stress here, however, that the uncertainties on [NI] have little effects on the derived nitrogen abundance because N$^+$ is the most abundant ion within the partially ionized region. Therefore, the best–fit N abundance decreases by only a factor $\lesssim 1.3$ once the N$^+/N^0$ is increased to match the observed [NII]/[NI] ratio (cf. Fig. 4). Note also that the He/H abundance is only poorly constrained by the models, and although models with He/H>0.1 are somewhat favoured, no firm conclusion about He overabundance can be drawn from the data.

The derived abundances are summarized in Table 6 where the most striking result is the large overabundance of nitrogen relative to oxygen, $+0.7$ dex above the solar value, whose implications are discussed below.

5.2. Comparison with other abundance estimates

An independent estimate of metallicity can be derived from the measured equivalent widths of CO stellar absorption features, using the new metallicity scale proposed and successfully applied to young LMC/SMC clusters by Oliva & Origlia (1998). In short, the method is based on the strength of the CO(6,3) band–head at 1.62 $\mu$m whose behaviour with metallicity is modelled using synthetic spectra of red supergiants. The equivalent width of the stellar CO lines from the central 100 x 100 pc$^2$ of Circinus are reported in Table 2 of Oliva et al. (1995) and yield an average metallicity of $-0.7 \pm 0.3$, a value remarkably close to the oxygen abundance derived above (cf. Table 4).

| Table 6. Metal abundances in knot C(a) |
|---------------------------------------|
| Element | 12+log(X/H)$^2$ [X/H]$^3$ | [X/O]$^4$ |
|----------|-----------------|-----------|
| Nitrogen$^a$ | 8.0 $^{+0.0}_{-0.7}$ | $^{+0.7}_{-0.3}$ |
| Oxygen | 8.2 $^{+0.0}_{-0.7}$ | $^{+0.7}_{-0.3}$ |
| Neon | 7.3 $^{+0.0}_{-0.7}$ | $^{+0.7}_{-0.3}$ |
| Sulphur | 6.9 $^{+0.0}_{-0.7}$ | $^{+0.7}_{-0.3}$ |
| Argon | 6.4 $^{+0.0}_{-0.7}$ | $^{+0.7}_{-0.3}$ |

Stellar metallicity$^c$ $-0.7$...

(b) All values are $\pm 0.2$ dex. Iron is not included because its relative abundance is very uncertain (cf. Sect. 4.5).
(c) Absolute abundance by number
(d) Log abundance by number relative to H=12.0, N=7.97, O=8.87, Ne=8.07, S=7.21, Ar=6.60, Fe=7.51, the adopted set of solar abundances
(e) $[X/O]=\log(X/O)-\log(O/H)$
(f) Derived for a $\approx 3 \times 10^7$ yr old starburst (Fig. 4 of Matteucci & Padovani 1993), see Sect. 5.3 for details
(g) From Fig. 4
(h) Derived from CO stellar absorption features (cf. Sect. 5.2)

5.3. Nitrogen overabundance and starburst activity

The nitrogen overabundance is of particular interest in view of its possible relationship with the (circum)nuclear starburst and N–enrichment from material processed through the CNO cycle. According to chemical evolutionary models of starburst events, the N/O relative abundance reaches a maximum value of [N/O] $\approx 0.6$ (i.e. 4 times the solar value) at about $3 \times 10^8$ yr and remains roughly constant for several $\times 10^8$ years (cf. Fig. 4 of Matteucci & Padovani 1993). The nitrogen overabundance mostly reflects the effect of the winds from He burning red supergiants whose surface composition is strongly N–enriched by gas dredged–up from the shell where hydrogen was burned through the CNO cycle. The amount and temporal evolution of the N/O abundance depends on model details, e.g. the shape of the IMF and the duration of the starburst, as well as on poorly known parameters such as the efficiency of the dredge–up and the contribution of primary N production by massive stars (e.g. Matteucci 1984). It is however encouraging to find that the observed N/O abundance (Table 6) is very close to that predicted at a time which is compatible with the age of the starburst in Circinus (cf. Fig. 9 of Maiolino et al. 1998). It should also be noticed that the observed absolute abundances are about an order of magnitude lower than the model predicted values, but this can be readily explained if the starburst transformed only $\approx 10\%$ of the available gas into stars, in which case the chemical enrichment was diluted by a similar factor. This hypothesis is in good agreement with the fact that Circinus is a very gas rich galaxy (e.g. Freeman et al. 1977).

In short, the observed N/O overabundance is fully compatible with what expected for a quite old (several $\times 10^8$ yr) starburst. The [NII]/H$\alpha$ and other line ratios measured in the
cone of Circinus are similar to those observed in many others Sy2’s and several observational results indicate that relatively old starburst events are common in type 2 Seyferts (e.g. Maiolino et al. 1995). This may therefore indicate that nitrogen is typically overabundant in Sy2’s due to enrichment by the starburst associated with the AGNs. This tantalizing conclusion should be however verified by detailed spectroscopic studies and analysis of a sufficiently large number of objects.

6. Conclusions

By modelling the rich spectrum of an extranuclear cloud in the ionization cone of the Circinus galaxy we have found that metal abundances are remarkably well constrained, regardless of the assumptions made on the shape of the ionizing continuum and gas distribution. This new result may open a new and interesting field of research using photoionization models to derive metallicities in AGNs which could in turn be related to the star formation activity in the recent past, i.e. old nuclear starbursts. In the case of Circinus, the large N/O overabundance found here is fully compatible with what expected from chemical evolution models of starbursts (Sect. 5).

Much less encouraging are the results on the AGN ionizing continuum whose shape cannot be constrained by the observed line ratios but depends on the assumed gas density distribution. Within the limits of the model parameters spanned here we somewhat favour an AGN spectrum with a “UV-bump” but cannot exclude that, with a different and better tuned combination of density and radiation bounded clouds, one could achieve similarly good fits with a power law AGN continuum (Sect. 5).

We also found that photoionization models cannot reproduce the observed [FeVII]/[FeII] and [NII]/[NI] ratios and argued that these may reflect errors in the collision strengths for [FeVII] and rate coefficient of N–H charge exchange reactions. It should be noted, however, that the problem [NII]/[NI] does not significantly influence the derived nitrogen abundance.

Finally, our data strongly indicate that shocks cannot play any important role in exciting the gas producing the observed line emission.

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