On the origin of soft X-rays in obscured AGN: answers from high-resolution spectroscopy with XMM-Newton

Matteo Guainazzi, Stefano Bianchi

European Space Astronomy Center of ESA, Apartado 50727, E-28080 Madrid, Spain

Mon. Not. R. Astron. Soc. 000, 000–000 (0000) Printed 10 November 2018

ABSTRACT

We present results of a high-resolution soft X-ray (0.2–2 keV) spectroscopic study of a sample of 69 nearby obscured Active Galactic Nuclei (AGN) observed with the Reflection Grating Spectrometer (RGS) on board XMM-Newton. This is the largest sample ever studied with this technique so far. The main conclusions of our study can be summarized as follows: a) narrow Radiative Recombination Continua are detected in about 36% of the objects in our sample (in 26% their intrinsic width is $\leq 10$ eV); b) higher order transitions are generally enhanced with respect to pure photoionization, indicating that resonant scattering plays an important role in the ionization/excitation balance. These results support the scenario, whereby the active nucleus is responsible for the X-ray “soft excess” almost ubiquitously observed in nearby obscured AGN via photoionization of circumnuclear gas. They confirm on a statistical basis the conclusions drawn from the detailed study of the brightest spectra in the sample. Furthermore, we propose a criterion to statistically discriminate between AGN-photoionized sources and starburst galaxies, based on intensity of the forbidden component of the O\text{vii} \text{He-} \alpha \text{triplet (once normalized to the O\text{viii} \text{Ly-} \alpha) coupled with the integrated luminosity in He-like and H-like oxygen lines.}

Key words: galaxies:active – galaxies:nuclei – galaxies: Seyfert – X-rays: galaxies

1 INTRODUCTION

Nearby X-ray obscured Active Galactic Nuclei (AGN) invariably exhibit excess emission above the extrapolation of the absorbed nuclear emission (Turner et al. 1997; Guainazzi et al. 2005). The origin of this component - which can represent a significant fraction of the active nucleus bolometric energy budget (Levenson et al. 2002) - is still largely unknown. Gas in the nuclear environment could be heated to million degrees by shocks induced by AGN outflows (King 2005) or episodes of intense star formation (Cid Fernandes et al. 1998; Gonzalez-Delgado et al. 2001). Alternatively, the AGN primary emission could photoionize and photoexcite circumnuclear gas.

The latter scenario has recently received direct observational support, thanks to high-resolution capabilities in the spatial and frequency domains that large X-ray observatories such as Chandra and XMM-Newton nowadays offer. High-resolution spectra unveiled signatures of photoionized plasma in a few bright objects: NGC 1068 (Kinkhabwala et al. 2002; Young et al. 2001), the Circinus Galaxy (Sambunara et al. 2001), Mkn 3 (Sako et al. 2000; Bianchi et al. 2005; Pounds et al. 2005); NGC 4151 (Schurch et al. 2004). In NGC 1068 the contribution of collisionally ionized plasma to the observed soft X-ray emission is constrained to be lower than 10% (Brinkman et al. 2002). These conclusions are based on three pieces of experimental evidence:

(i) the spectra are dominated by strong emission lines of highly-ionized species from Carbon to Silicon, as well as by L-shell transitions from Fe\text{xvii} to Fe\text{xxi}

(ii) narrow Radiative Recombination Continua (RRC) features from Carbon and Oxygen were detected. The width of these features indicates typical plasma temperatures of the order of a few eV (Kinkhabwala et al. 2002). These features are unequivocal signatures of photoionized spectra (Liedahl & Paerels 1996).

(iii) the intensity of higher-order series emission lines, once normalized to the K$_{\alpha}$, are larger than predicted by pure photoionization, and are consistent with an important contribution by photoexcitation (resonant scattering) (Band et al. 1990; Matt 1994; Krolik et al. 1995). This explains why standard plasma diagnostics (Porquet & Dubau 2000) fail to properly interpret the physical nature of the spectra.

A solution in terms of AGN-photoionized gas can also
explain the coincidence in extension and overall morphology between soft X-ray emission and the Narrow Line Regions (NLRs), the latter traced by O[{	extsc{iii}}] HST maps, on scales as large as a few hundred parsecs (Bianchi et al. 2006). Solutions satisfying the observed X-ray to optical flux ratio require an approximately constant ionization parameter (i.e., a density scaling as the inverse square of the distance from the ionizing source), similarly to what is often found using photoionization models of the NLRs.

So far, high-resolution X-ray spectra have been published only for a few X-ray bright obscured AGN. However, diagnostically important emission lines in these objects exhibit very large Equivalent Widths, EWs, as the continuum is often totally suppressed in the soft X-ray band. In this paper we present the first systematic high-resolution X-ray spectroscopic study on a sizable sample of obscured AGN. The Reflection Grating Spectrometer (RGS) on board XMM-Newton (der Herder et al. 2001) is the most suitable instrument currently flying for this purpose, due to its unprecedented effective area in the 0.2-2 keV band, as well as its good absolute aspect solution accuracy (∼8 mÅ).

## CIELO-AGN

### 2.1 The sample

Our sample comprises all the type $\geq 1.5$ AGN (according to the NED classification) observed by XMM-Newton, and whose data were public as of September 2006 (Tab. 1 shows the list of sources in the sample, together with their redshift and the combined exposure time for one RGS camera). After excluding H1320+551 and H1419+480 due to uncertainties in their classification, the sample includes 69 sources.

### 2.2 Data processing

For each observation, we have reprocessed RGS data starting with the Observation Data Files, using SASv6.5 (Gabriel et al. 2003), and the most advanced calibration files available as of May 2006. Background spectra were generated using blank field event lists, accumulated from different positions on the sky vault along the mission. Spectra of the same source from different observations were merged, together with their response matrices, after checking that no significant spectral variability occurred.

Each spectrum was systematically searched for the presence of emission lines. We simultaneously fit together the spectra of the two RGS cameras, using XSPEC version 12.3.0. “Local” fits to the data were performed on the unbinned spectra on $\simeq 100$ channels wide intervals, using Gaussian profiles to account for any line features. In only a few cases (see Tab. 2) the width of the profiles accounting for bound-bound transitions is inconsistent with zero; hence in these cases only the intrinsic profile width has been left free in the fit. On the other hand, free-bound transitions were modeled with Gaussian profiles, where the intrinsic width was always considered an additional free fit parameter. We have always assumed the same intrinsic width for the components of a multiplet. Local continua were modeled with $\Gamma = 1$ power-laws, leaving free in each fit the continuum normalization ($\Gamma$ is the power-law photon index). No assumption was made a priori on the line centroid energies. However, fits of He-α triplets have been performed keeping the relative distance between the centroid energies of the components fixed to the value dictated by atomic physics. A line is considered to be detected when its flux is inconsistent with 0 at the 1-$\sigma$ level. In Appendix A we list energies, fluxes and intrinsic widths (for the RRC only) of the transitions individually presented in this paper, and discuss the consistency of our measurements with the expected laboratory energies [laboratory energies are extracted from the CHIANTI database (Dere et al. 2001)]. Line luminosities have been corrected for Galactic photoelectric absorption using column densities after Dickey & Lockman (1990).

We have as well checked whether the detected line energy centroids in each source were systematically shifted.

### Table 1. CIELO-AGN sources.

| Source         | $z$ | Exposure time (ks) |
|----------------|-----|--------------------|
| Circinus Galaxy | 0.001 | 102.2              |
| RX0909+366     | 0.045 | 13.6               |
| IC2560         | 0.010 | 81.4               |
| IC4305         | 0.036 | 22.1               |
| IC4905         | 0.016 | 11.5               |
| IRX0035        | 0.027 | 20.7               |
| IRA01475-0740  | 0.018 | 11.5               |
| IRA08572-3915  | 0.058 | 28.6               |
| IRA09104-4109  | 0.442 | 13.5               |
| IRA10214-4724  | 2.286 | 53.4               |
| IRA131197-1627 | 0.017 | 44.6               |
| IRA15480-0344  | 0.030 | 10.9               |
| MCG-6-30-16    | 0.000 | 61.8               |
| MRK3           | 0.014 | 180.8              |
| MRK6           | 0.019 | 96.4               |
| MRK311         | 0.019 | 17.9               |
| MRK348         | 0.015 | 46.3               |
| MRK612         | 0.020 | 11.8               |
| MRK744         | 0.009 | 22.7               |
| MRK993         | 0.015 | 22.6               |
| MRK1152        | 0.053 | 26.4               |
| NGC1068        | 0.004 | 86.8               |
| NGC1365        | 0.005 | 127.5              |
| NGC1386        | 0.003 | 18.9               |
| NGC1410        | 0.025 | 11.7               |
| NGC1614        | 0.016 | 23.5               |
| NGC2110        | 0.008 | 51.7               |
| NGC2273        | 0.006 | 12.5               |
| NGC2622        | 0.019 | 12.3               |
| NGC2992        | 0.008 | 28.5               |
| NGC34          | 0.020 | 21.8               |
| NGC3982        | 0.004 | 34.0               |
| NGC4138        | 0.003 | 14.3               |
| NGC4151        | 0.003 | 55.5               |
| NGC4168        | 0.007 | 23.0               |
| NGC424         | 0.012 | 7.9                |
| NGC4258        | 0.002 | 78.5               |
| NGC4393        | 0.005 | 42.8               |
| NGC4395        | 0.001 | 108.4              |
| NGC4472        | 0.003 | 1.5                |
| NGC4477        | 0.004 | 13.3               |
| NGC449         | 0.016 | 11.9               |
| NGC4507        | 0.012 | 44.5               |
| NGC4565        | 0.004 | 14.4               |
| NGC4639        | 0.003 | 14.6               |
| NGC4725        | 0.004 | 17.6               |
| NGC4945        | 0.002 | 63.8               |
| NGC4968        | 0.010 | 11.8               |
| NGC5033        | 0.003 | 19.7               |
| NGC5252        | 0.023 | 65.8               |
| NGC526A        | 0.019 | 46.9               |
| NGC5273        | 0.004 | 16.1               |
| NGC5506        | 0.006 | 32.9               |
| NGC5643        | 0.004 | 9.6                |
| NGC591         | 0.015 | 11.8               |
| NGC6572        | 0.026 | 6.8                |
| NGC7172        | 0.009 | 72.0               |
| NGC7212        | 0.027 | 13.7               |
| NGC7311        | 0.005 | 43.4               |
| NGC7479        | 0.008 | 12.6               |
| NGC7582        | 0.005 | 22.3               |
| NGC7674        | 0.020 | 10.3               |
| UGC1214        | 0.017 | 11.8               |
| UGC2456        | 0.012 | 17.1               |
| UGC2608        | 0.023 | 7.5                |
| UGC4203        | 0.014 | 7.8                |
| UGC6527        | 0.027 | 23.6               |
| UGC8621        | 0.020 | 11.8               |
| UM625          | 0.025 | 11.6               |
with respect to the laboratory energies. We define “systematic” energy shifts different from zero (in the same direction) at the 1σ level in at least two of the following transitions: Cvi Ly-α, Ovii He-α, Ovii He-β, and Oviii Ly-α. Our analysis found none of these systematic shifts. Nonetheless, we found some occurrences of discrepancies between the best-fit centroid and the laboratory energies in individual lines. We refrain from attributing any astrophysical meaning to these discrepancies, which may be due to contamination by nearby transitions, residual errors in the aspect solution of the RGS cameras, or spurious detections. The reader may find a more detailed discussion of this point in the Appendix.

In Fig. 1 we show the RGS spectra of the three still unpublished Seyfert 2 galaxies in our sample, which exhibit the largest number of line detections.

Hereafter, uncertainties on the fitting parameters are quoted at the 1σ level; likewise the upper limits represent a 1σ confidence level. Errors on the line centroid energies include a 8 mAsystematic error. Throughout this paper, energies/wavelengths of astrophysical lines are quoted in the source rest frame, unless otherwise specified.

### 2.3 The catalog

The results of the procedure outlined above have been compiled into CIELO-AGN (Catalog of Ionized Emission Lines in Obscured AGN). Our study exhibit a high-detection efficiency, at least with respect to the most common lines observed in obscured AGN spectra, despite the overall low soft X-ray flux (sample median 6 × 10^{−13} erg cm^{-2} s^{-1}; see Tab. 3 for a complete list of the lines detected in CIELO-AGN).

### 3 RESULTS

In this Section we will use some results of our study to try and answer the following questions on the nature of soft X-ray emission in obscured AGN:

- is AGN photoionization the dominant physical process?
- does resonant scattering play an important role?
- do efficient X-ray line diagnostics exist, which could allow us to discriminate on a statistical basis between AGN- and starburst-powered spectra?

#### 3.1 RRC

The three most intense RRC transitions in the RGS energy bandpass are: Oviii at 14.228Å, Ovii at 16.771Å and Cvi at 31.622Å. At least one of these features is detected in 36% (25/69) of the objects of our sample. The few measurements of the RRC width, which represents a direct estimate of the temperature of the plasma (Liedahl & Paerels 1996), cluster in the range 1–10 eV. There is an obvious selection effect, favoring the detection of narrow features. Nonetheless, still in 29% (26%) of the objects in our sample the RRC width is constrained to be lower than 50 (10) eV (see Fig. 2). In 10 further objects we detect upper limits on the RRC luminosity in the range where measurements are found: in 7 (10)

### Table 2. 1-σ intrinsic widths for resolved Gaussian profiles in CIELO-AGN.

| Transition | Width (km s⁻¹) |
|------------|---------------|
| NGC1068    |               |
| FeXXV 3d-2p (^1P₁) | 670±110       |
| Nvii Ly-α | 820±90        |
| Ovii He-α | 550±20        |
| Ovii He-β | 3300±200      |
| Ovii He-γ | 650±150       |
| Oviii Ly-α| 460±50        |
| Oviii Ly-β| 1000±200      |
| NGC4151    |               |
| FeXXVIII 3s-2p | 1100±900    |
| Cvi Ly-α  | 490±90        |
| Cvi Ly-β  | 900±900       |
| NGC4507    |               |
| Ovii He-α | 520±110       |

### Table 3. Number of CIELO-AGN sources, N_{det}, for which a given Transition (laboratory wavelength λ_{lab}) has been detected, if N_{det} > 0

| Transition | λ_{lab} (Å) | N_{det} |
|------------|-------------|---------|
| SIIIv He-α | 6.740       | 5       |
| Mgxxi He-α (r) | 9.228 | 12      |
| Mgxxi He-α (f) | 9.314 | 13      |
| Nev Ly-α  | 12.134      | 20      |
| FeXXVIII 3d-2p | 12.282 | 21      |
| FeXX 3d-2p  | 12.845      | 19      |
| Neii He-α (r) | 13.447 | 13      |
| Neii He-α (r) | 13.553 | 6       |
| Oviii RRC  | 14.228      | 13      |
| FeXXVIII 3d-2p | 14.413 | 24      |
| Oviii Ly-β | 14.821      | 20      |
| FeXXVIII 3d-2p (^1P₁) | 15.015 | 25      |
| FeXXVIII 3d-2p (^3D₁) | 15.262 | 24      |
| Oviii Ly-β | 16.006      | 22      |
| FeXXVIII 3s-2p | 16.091 | 23      |
| Oviii RRC  | 16.771      | 17      |
| FeXXVIII 3s-2p (3G/M2) | 17.076 | 27      |
| Ovii He-γ  | 17.768      | 16      |
| Ovii He-β  | 18.027      | 20      |
| Ovii Ly-α  | 18.967      | 22      |
| Ovii He-α (r) | 21.602 | 22      |
| Ovii He-α (r) | 21.801 | 13      |
| Ovii He-α (f) | 22.101 | 23      |
| Nevii Ly-α | 24.785      | 24      |
| Cvi Ly-β  | 28.459      | 14      |
| Nviii He-α | 28.787      | 11      |
| Cv RRC    | 31.622      | 6       |
| Cvi Ly-α  | 33.737      | 23      |

^a doublet: λ₁ = 12.1321 Å, λ₂ = 12.1375 Å

^b triplet: λ₁ = 14.3760 Å, λ₂ = 14.4187 Å, λ₃ = 14.4210 Å

^c possible contamination by FeXX 3p²-2p² at λ = 14.8501 Å

^d doublet: λ₁ = 17.0500 Å, λ₂ = 17.0970 Å

^e possible contamination by FeXXVIII 3p²-2p² at λ = 17.8472 Å

^f doublet: λ₁ = 24.7790 Å, λ₂ = 24.7840 Å

^g doublet: λ₁ = 28.4612 Å, λ₂ = 28.4662 Å

^h doublet: λ₁ = 33.7342 Å, λ₂ = 33.7396 Å

...
Figure 1. RGS spectra for the three galaxies of our sample, which exhibit the largest number of detected emission lines (in brackets below) and whose RGS spectra have not been published yet: NGC 1365 (19), NGC 4507 (17), UGC 1214 (14) [for comparison the number of detected lines in the brightest Seyfert 2 of our samples are: 25 (NGC 1068), 19 (the Circinus Galaxy), 18 (NGC 4151), 17 (Mrk 3)]. Spectra of the two RGS cameras have been merged and smoothed with a 5-channels wide triangular kernel for illustration purposes only. The positions of the line transitions measured in CIELO-AGN are labeled.
of them the luminosity is constrained to be $\lesssim 10^{44.1}$ erg s$^{-1}$ ($\lesssim 10^{44.2}$ erg s$^{-1}$). Finally, in 34/69 (49\%) of the objects the quality of the data is too poor to allow a significant detection of any of the RRC features, and the upper limits on their luminosities are inconclusive.

In principle, measurements of the O\textsc{vii} RRC could be contaminated by the 3F component of the Fe\textsc{vii} triplet at 16.780\AA\ (Brown et al. 1998). However, the intensity ratio between the O\textsc{vii} RRC and the 3G/M2 components of the same triplet (which cannot be resolved by the RGS) exceeds 0.6, the largest expected value if the former feature were entirely due to the 3F component (Phillips et al. 1997; Mauche et al. 2001; Beiersdorfer et al. 2002), in 15 out of 16 cases (by more than a factor of 2 in 13 out of 16; cf Fig. 3). We are therefore confident that most of our measurements of the the emission line at 16.777\AA\ represent 	extit{bona fide} detections of the O\textsc{vii} RRC. The total number of sources for which at least one RRC feature is detected is reduced by 1 if the effect of this potential mis-identification is taken into account.

3.2 Higher order series

In addition to $n = 2p\rightarrow 1s$ transitions for H- and He-like atoms, \textit{CIELO-AGN} contains a fair number of detections of discrete higher order resonance transitions ($np\rightarrow 1s$, $n > 2$). These transitions are selectively enhanced by photoexcitation. Since the forbidden $f$ transition in He-like triplets is unaffected by photoexcitation, the intensity ratio between higher order series and $f$ transition intensities provides a potentially powerful diagnostic of the importance of resonant scattering in radiation ionized spectra (Kinkhabwala et al. 2002). An example of the application of this diagnostic test to \textit{CIELO-AGN} is shown in Fig. 4, where we display the intensity of the O\textsc{vii} He-$\beta$ against the $f$ component of the O\textsc{vii} He-$\alpha$ triplet. We compare the experimental results with the predictions of pure photoionization, and with models where radiative decay from photoexcitation and recombinations from photoionization are self-consistently calculated (model \textit{photoin}; Kinkhabwala et al. 2002). We have produced a grid of models for different values of O\textsc{vii} column densities ($N_{\text{O\textsc{vii}}} \in [10^{15}, 10^{20}$ cm$^{-2}$]), turbulence velocities ($v_{\text{turb}} \in [0, 500 \text{ km s}^{-1}]$), and temperatures ($kT \in [1, 20 \text{ keV}]$). The weighted mean of the He-$\beta$ versus $f$ intensity ratio is $0.25 \pm 0.03$, larger then expected for pure photoionization. It corresponds to O\textsc{vii} column densities $N_{\text{O\textsc{vii}}} \approx 10^{17}$--$18$ cm$^{-2}$ (the dependence on the other parameters is small). The measurements on the He-$\beta$ O\textsc{vii} transition at 18.6270\AA\ could be contaminated by the nearby N\textsc{v} RRC at 18.5872\AA. In order to minimize this contamination, we fit the X-ray spectra around the He-$\beta$ O\textsc{vii} feature in a range, which in principle does not include the contaminating feature. Moreover, we have verified that similar enhancements of higher-order lines to the Lyman-$\alpha$ of H-like Carbon and Oxygen are observed as well (cf. Tab. 4). The dependence on the temperature, column density and velocity distributions in H-like species is such that no meaningful constraints on column density can be drawn. However, in 8 of the individual brightest sources in our sample\textsuperscript{2} the ratio between the O\textsc{viii} Ly-$\beta$ and Ly-$\alpha$

\textsuperscript{2} For instance, the O\textsc{vii} He-$\beta$ width measured in in NGC 1068, $\sigma = 73 \pm 2$ eV (cf. Tab. 2), the largest measured in this spectrum, is most likely contaminated by the N\textsc{v} RRC

\textsuperscript{3} the Circinus Galaxy, IRAS 13197-1627, Mrk 3, NGC1068, NGC1365, NGC2110, NGC2992, NGC4945
The intensity of the O\textsc{vii} He-\textbeta line against the intensity of the \( f \) component of the He-\alpha triplet (only data points corresponding to a detection of the latter are shown; data points correspond to upper limits on the intensity of the former are shown as empty symbols). The dashed-dotted lines represent the predictions of the photoion code for O\textsc{vii} column densities increasing from \( N_{\text{OvII}} = 10^{15} \) to \( 10^{20} \) cm\(^{-2}\) in steps of one decade, assuming \( kT = 5 \) eV and \( v_{\text{turb}} = 200 \) km s\(^{-1}\). The long-dashed line represents the predictions for pure photoionization. The shaded areas represent the loci of the photoion predictions, when the turbulent velocity varies in the range 0–500 km s\(^{-1}\) at constant temperature and for the extreme values of the column density interval. The areas representing a variation of the temperature in the range 1–20 keV at constant velocity and column density are comparatively smaller, and therefore not shown.

### Table 4: Higher-order intensity ratios for selected transitions in CIELO-AGN

Each ratio is calculated as the weighted mean of the individual ratios on the \( N \) sources, where a measurement of both transitions is available, and using the statistical uncertainties on the ratio as weights. Expected values for pure photoionization (PIE) and collisional ionization (CIE) are extracted from Tab. 3 in Kinkhabwala et al. (2002)

| Ion | Ratio | \( N \) | PIE | CIE |
|-----|-------|-------|-----|-----|
| O\textsc{vii} Ly-\beta/Ly-\alpha | 0.51 ± 0.12 | 9 | 0.14 | 0.09 |
| O\textsc{vii} He-\beta/\beta | 0.25 ± 0.03 | 12 | 0.05 | ... |
| O\textsc{vii} He-\gamma/\gamma | 0.20 ± 0.09\( a \) | 9 | 0.017 | ... |
| O\textsc{viii} Ly-\beta/Ly-\alpha | 0.35 ± 0.05 | 13 | 0.14 | 0.10 |

\( a \)this measurement is likely to be affected by contamination of \( \text{Fe}^{\text{viii}} 3\text{p}^2-2\text{p}^2 \) at \( \lambda = 17.8472 \) Å

Intensities is large enough to be formally inconsistent with collisional ionization, and in 4 of them\(^4 \) with pure photoionization as well.

#### 3.3 AGN and starburst soft X-ray spectra

We have analyzed the RGS spectra of a sample of 27 Starburst (SB) galaxies extracted from the Wu et al. (2002) sample (cf. Tab. 5) and observed by XMM-Newton, to identify diagnostic criteria, which may allow us to statistically discriminate between SB- and AGN-dominated soft X-ray spectra. This sample has been analyzed in the same way as the Seyfert 2 sample. Some of the criteria quoted in the literature provide inconclusive results. For instance, the distribution functions of the luminosity ratio between L shell iron and integrated oxygen He- and H-like lines are indistinguishable (Fig. 5). Kallman et al. (1996) had already pointed out that L-shell iron transitions can give an important contribution to the overall luminosity budget in photoionized nebulae. The standard \( G \) ratio (\( G \equiv (f + i)/r; \) Gabriel & Jordan 1969; Porquet et al. 2000), is also ambiguous. Previous studies have shown (c.f. Sect. 1) that the enhancement of resonant lines by resonant scattering mimics the behavior of a collisionally ionized plasma. In the collisionally ionized case, the fluxes of all the triplet lines are enhanced, with the greatest increase in the resonance line. Resonant scattering boosts all of the resonant lines with respect to the forbidden and intercombination lines in the triplet. The value of \( G \) is therefore decreased by both collisional excitation and resonant scattering. Finally, the fraction of SB spectra where narrow RRC features are detected is comparable to that observed in the Seyfert 2 sample, indicating that photoionization plays an important role in the ionization balance of starburst galaxies as well.

In Fig. 6 we compare the distribution of the O\textsc{vii} f transition intensity, normalized against the intensity of the O\textsc{vii} Ly-\alpha, as a function of the total luminosity in oxygen lines (integrated on all He- and H-like transitions). AGN are generally characterized by larger intensity ratios, \( \eta_{\text{AGN}} = 1.38 \pm 0.13 \); \( \eta_{\text{SB}} = 0.57 \pm 0.07 \) (5.8\% difference; the upper limits have been taken into account with a “bootstrap” method for censored data as in Schmitt 1985). The same figure also shows that the average line luminosity in AGN is larger than in starbursts. The median Oxygen lines

\(^4\) NGC1068, NGC1365, NGC2110, NGC2992
luminosity is $\sim 10^{41}$ erg s$^{-1}$ in the former and $\sim 10^{40}$ erg s$^{-1}$ in the latter (using strict detections only). Still, the overlap between the line diagnostic distributions is significant, and prevents strong statements on individual sources. This most likely reflects the intrinsic “composite” nature of several obscured AGN (Cid Fernandes et al. 2001).

4 CONCLUSIONS

In this paper we present results from a systematic study of high-resolution soft X-ray spectra for 69 obscured AGN observed with the XMM-Newton RGS. Our main conclusions can be summarized as follows:

- Radiative Recombination Continua: we detect RRC features in about 40% of the sample sources, and in 33% (27%) they allow us to constraint the temperature of the plasma $\leq 50$ eV ($\leq 10$) eV. This indicates that in a large fraction of objects in our sample photoionization dominates the ionization balance. Still, these percentages represent probably lower limits to the true fraction of photoionized sources in our sample: upper limits on narrow RRC features in almost 50% of the objects in our sample are still inconclusive due to the lack of statistics.

- Resonant scattering: higher order transitions are enhanced with respect to the expectation of pure photoionization, and inconsistent with the expectation of collisional ionization as well. This indicates that resonant scattering plays an important role in the ionization/excitation balance. The observed Ovii He-$\beta$ versus $f$ intensity ratios are consistent with Ovii column densities in the range $N_{O_{vii}} \sim 10^{17}$–$10^{18}$ cm$^{-2}$. Interestingly enough, these values are in good agreement with the column densities measured in “warm absorbers” observed along the lines of sight to unobscured AGN (Blustin et al. 2003; Steenbrugge et al. 2005; Blustin et al. 2005).

- Starburst contribution: the comparison between the spectra of obscured AGN in our sample and a control sample of nearby starburst galaxies suggests two empirical criteria to discriminate on a statistical basis between AGN- and starburst-powered spectra: a) total Oxygen line X-ray luminosity $> 10^{40}$ erg s$^{-1}$; b) ratio between the Ovii triplet $f$ component and the Oviii Ly-$\alpha \gtrsim 1$.

The currently available X-ray instrumentation allowed us to explore the nature of the soft X-ray emission in obscured AGN as weak as $\sim 0.03$ mCrab. From this study, we have gained confidence that conclusions on the properties of the gas in the circumnuclear region of AGN extracted from the detailed study of high-quality spectra of the brightest objects can be extended to the whole population of nearby obscured AGN. This is the main message we would like to convey with this paper, which opens interesting perspectives for future enlargements of this study once deeper exposures or more sensitive instrumentation are available.

APPENDIX

The tables in this Section list centroid energies and fluxes for the bound-bound transitions individually discussed in this paper: Cvi Ly-$\alpha$, Cvi Ly-$\beta$, Ovii He-$\alpha$, Ovii He-$\beta$, Oviii Ly-$\alpha$, and Oviii Ly-$\beta$ (Tab. 6 to 7). The same quantities are listed for the CV, Ovii, and Oviii RRCs, alongside their intrinsic width (Tab. 8 to 9).

The comparison between the best-fit centroid energy of detected lines in CIELO-AGN and the laboratory energies is an instructive exercise on the reliability of the catalog measurements. At the $2\sigma$ level, the number of He- and H-like Oxygen lines (out the total detected ones) which are inconsistent with the laboratory energies are: 0/25, 2/20, 2/30 and
### Table 6. Best-fit wavelengths for the transitions discussed in this paper. Dots indicates either lines not detected, or lines for which no constraints can be obtained (the luminosities in Tab. 7 are calculated in this case assuming the laboratory energies). In the table header, the laboratory wavelengths are in brackets.

![Table 6](image-url)

5/22 for OvII He-α, OvII He-β, OvIII Ly-α and OvIII Ly-β, respectively. The shifted measurements in the last case cluster around 783 eV (4 out of 5), where a strong Fe XVII 3s2p transition is located (λ = 15.83 Å), and are therefore probably due to a mis-identification. If we remove these suspicious cases, the ratio between the He-β and the f transition intensity in the remaining objects is still inconsistent with the expectation of pure photoionization: 0.26 ± 0.04 (cf. Tab. 4). The situation for the Cvi lines is more controversial. The centroid energies of 6 out of 23 Ly-α and 5 out of 14 Ly-β measurements are inconsistent at the 2σ level with the laboratory energies. There is no obvious explanation for these systematic discrepancies. No other potentially contaminating transition is present, which could confuse the identifi-
culation of the CVi lines. Moreover, the shifted measurements do not cluster in any well-defined spectral region. Uncertainties on the aspect solutions can be as high as 30Å in this wavelength range, still insufficient to explain the observed differences.

A similar analysis on the centroid energies of the RRC features shows that only 3 measurements (out of 16) of the OVII RRC are inconsistent with the laboratory energy (at the 2σ level; none for the CV or OVIII RRCs). In this case, as discussed in Sect. 3.1, the discrepancy is probably due to confusion with the nearby Fe xvii triplet.

**ACKNOWLEDGMENTS**

This paper is based on observations obtained with XMM-Newton, an ESA science mission with instruments and contributions directly funded by ESA Member States.
and the USA (NASA). This research has made use of data obtained through the High Energy Astrophysics Science Archive Research Center On-line Service, provided by the NASA/Goddard Space Flight Center and of the NASA/IPAC Extragalactic Database (NED) which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. Discussions with A.Pollock and J.Sanz allowed us to better understand the properties of high-resolution X-ray spectra of active stars. We are deeply grateful to Dr.A.Kinkhabwala, for providing us with an updated version of his phoion code, as well as for several enlightening and encouraging suggestions and comments. Comments and encouragement by an anonymous referee, which significantly improved the quality of this paper, are warmly acknowledged.

| Source | Cv RRC E<sub>0</sub> (Å, 31.622) | σ (eV) | Ovn RRC E<sub>0</sub> (Å, 16.771) | σ (eV) | Ovn RRC E<sub>0</sub> (Å, 14.228) | σ (eV) |
|--------|---------------------------------|--------|---------------------------------|--------|---------------------------------|--------|
| Circinus Galaxy | ... | ... | 16.775±0.169 | <33.2 | 14.182±0.058 | <4.1 |
| ES0509-G66 | ... | ... | 16.775±0.164 | <33.2 | 14.182±0.058 | <4.1 |
| IC2560 | ... | ... | 16.681±0.102 | <10.0 | ... | ... |
| IC4395 | ... | ... | 16.681±0.102 | <10.0 | ... | ... |
| IC4995 | ... | ... | 16.976±0.066 | <10.0 | ... | ... |
| HIZW035 | ... | ... | ... | ... | ... | ... |
| IRA01475-0740 | ... | ... | ... | ... | ... | ... |
| IRA02072-3305 | ... | ... | ... | ... | ... | ... |
| IRA08014-4159 | ... | ... | ... | ... | ... | ... |
| IRA10214-4724 | ... | ... | ... | ... | ... | ... |
| IRA13197-1647 | ... | ... | ... | ... | ... | ... |
| IRA15480-0344 | ... | ... | ... | ... | ... | ... |
| MCG-5-23-16 | ... | ... | ... | ... | ... | ... |
| MRRK3 | ... | ... | 16.747±0.042 | <2.2 | 16.166±0.069 | <4.8 |
| MRRK6 | ... | ... | 16.747±0.042 | <2.2 | 16.166±0.069 | <4.8 |
| MRRK31 | ... | ... | ... | ... | ... | ... |
| MRRK348 | ... | ... | ... | ... | ... | ... |
| MRRK612 | ... | ... | ... | ... | ... | ... |
| MRRK744 | ... | ... | ... | ... | ... | ... |
| MRRK903 | ... | ... | ... | ... | ... | ... |
| MRRK1152 | ... | ... | ... | ... | ... | ... |
| NGC1068 | 31.486±0.034 | 1.6±2.2 | 16.817±0.044 | 8.0±2.5 | 14.192±0.035 | 2.7±2.1 |
| NGC1365 | 31.511±0.085 | 1.6±2.6 | 16.775±0.044 | 3.2±1.0 | 14.197±0.044 | <1.9 |
| NGC1386 | ... | ... | 16.775±0.074 | ... | ... | ... |
| NGC1410 | ... | ... | ... | ... | ... | ... |
| NGC1614 | ... | ... | ... | ... | ... | ... |
| NGC2110 | ... | ... | 16.185±0.053 | ... | ... | ... |
| NGC2273 | ... | ... | ... | ... | ... | ... |
| NGC2633 | ... | ... | ... | ... | ... | ... |
| NGC2992 | ... | ... | ... | ... | ... | ... |
| NGC34 | ... | ... | ... | ... | ... | ... |
| NGC3982 | ... | ... | ... | ... | ... | ... |
| NGC4138 | ... | ... | 16.775±0.056 | ≤2.2 | 14.210±0.043 | 4.0±3.8 |
| NGC4151 | ... | ... | 16.730±0.041 | 2.2±0.7 | 14.200±0.052 | 4.0±3.8 |
| NGC4168 | ... | ... | ... | ... | ... | ... |
| NGC424 | ... | ... | ... | ... | ... | ... |
| NGC4258 | ... | ... | 16.929±0.051 | 5.5±1.4 | 14.197±0.061 | 7.2 |
| NGC4303 | ... | ... | 17.032±0.136 | <13.9 | 14.197±0.061 | ... |
| NGC4395 | ... | ... | ... | ... | ... | ... |
| NGC4472 | ... | ... | 16.740±0.049 | 2.3±1.1 | 14.533±0.072 | 9.6 ±3.0 |
| NGC4473 | ... | ... | 16.740±0.049 | 2.3±1.1 | 14.533±0.072 | 9.6 ±3.0 |
| NGC4477 | ... | ... | ... | ... | ... | ... |
| NGC4499 | ... | ... | ... | ... | ... | ... |
| NGC4507 | ... | ... | 16.740±0.049 | 2.3±1.1 | 14.533±0.072 | 9.6 ±3.0 |
| NGC4565 | ... | ... | ... | ... | ... | ... |
| NGC4639 | ... | ... | ... | ... | ... | ... |
| NGC4725 | ... | ... | ... | ... | ... | ... |
| NGC4945 | ... | ... | 16.538±0.061 | <5.0 | 14.292±0.251 | ... |
| NGC4968 | ... | ... | 16.538±0.061 | <5.0 | 14.292±0.251 | ... |
| NGC5033 | 31.626±0.100 | 1.12±2.1 | 16.775±0.080 | <5.6 | ... | ... |
| NGC5252 | ... | ... | ... | ... | ... | ... |
| NGC5256 | ... | ... | ... | ... | ... | ... |
| NGC5273 | ... | ... | ... | ... | ... | ... |
| NGC5506 | 31.630±0.091 | 1.1 | 16.775±0.080 | <5.6 | ... | ... |
| NGC5643 | ... | ... | ... | ... | ... | ... |
| NGC591 | ... | ... | <22.0 | ... | ... | ... |
| NGC6552 | ... | ... | ... | ... | ... | ... |
| NGC7172 | ... | ... | ... | ... | ... | ... |
| NGC7212 | ... | ... | ... | ... | ... | ... |
| NGC7314 | ... | ... | ... | ... | ... | ... |
| NGC7479 | ... | ... | ... | ... | ... | ... |
| NGC7582 | ... | ... | 16.709±0.123 | <6.3 | ... | ... |
| NGC7674 | ... | ... | ... | ... | ... | ... |
| UGC1214 | ... | ... | 16.897±0.271 | 3.5±3.3 | ... | ... |
| UGC2456 | ... | ... | 16.897±0.271 | 3.5±3.3 | ... | ... |
| UGC2608 | ... | ... | ... | ... | ... | ... |
| UGC4203 | ... | ... | ... | ... | ... | ... |
| UGC6527 | ... | ... | ... | ... | ... | ... |
| UGC6621 | ... | ... | ... | ... | ... | ... |
| UMG92 | ... | ... | ... | ... | ... | ... |

**Table 8.** Best-fit wavelengths and widths for the RRCs discussed in this paper. Dots indicates either lines not detected, or lines for which no constraints can be obtained (the luminosities in Tab. 9 are calculated in this case assuming the laboratory energies.)

REFERENCES

Band D.L., Klein R.I., Castor I.J., Nash J.K., 1990, ApJ, 362, 90 Beiersdorfer P, Behar E., Boyce K.R., et al., 2002, ApJ, 576, L169 Bianchi S., Guainazzi M., Chiaberge M., 2006, A&A, 448, 499 Bianchi S., Miniutti G., Fabian A.C., Iwasawa K., 2005, MNRAS, 360, 380


### Table 9. Best-fit fluxes for the RRCs discussed in this paper. Dots indicate lines not detected.

| Source                  | Cn RRC $10^{-5}$ ph cm$^{-2}$ s$^{-1}$ | Ovi RRC $10^{-5}$ ph cm$^{-2}$ s$^{-1}$ | Ovi RRC $10^{-5}$ ph cm$^{-2}$ s$^{-1}$ |
|-------------------------|--------------------------------------|----------------------------------------|----------------------------------------|
| Circinus Galaxy         | ...                                  | 2.4±2.9                               | 2.6±1.7                                |
| IC2560                  | ...                                  | 0.3±0.2                               | ...                                    |
| IC4395                  | ...                                  | ...                                   | ...                                    |
| IC4895                  | ...                                  | ...                                   | ...                                    |
| IC5234                  | ...                                  | ...                                   | ...                                    |
| IMA01475-0740           | ...                                  | ...                                   | ...                                    |
| IMA05872-3915           | ...                                  | ...                                   | ...                                    |
| IRA26101+4109           | ...                                  | ...                                   | ...                                    |
| IRA30214+3724           | ...                                  | ...                                   | ...                                    |
| IRA31397-1627           | ...                                  | 0.6±0.5                               | 0.3                                    |
| IRS15489-0344           | ...                                  | ...                                   | ...                                    |
| MCG-5-23-16             | ...                                  | ...                                   | ...                                    |
| MK3                     | ...                                  | 1.6±0.7                               | 0.9±0.5                                |
| MK6                     | ...                                  | ...                                   | ...                                    |
| MK93                    | ...                                  | ...                                   | ...                                    |
| NGC3086                 | ...                                  | 67.2±10.1                             | 10.1±1.9                               |
| NGC3086                 | ...                                  | 65.9±2.1                               | 10.1±1.9                               |
| NGC3086                 | ...                                  | 65.9±2.1                               | 10.1±1.9                               |
| NGC1365                 | 0.8±0.5                              | 1.1±0.3                               | 0.5±0.2                                |
| NGC1366                 | ...                                  | 0.3±0.3                               | ...                                    |
| NGC1379                 | ...                                  | ...                                   | ...                                    |
| NGC1380                 | ...                                  | ...                                   | ...                                    |
| NGC1410                 | ...                                  | ...                                   | ...                                    |
| NGC1414                 | ...                                  | ...                                   | ...                                    |
| NGC2219                 | ...                                  | ...                                   | ...                                    |
| NGC2373                 | ...                                  | ...                                   | ...                                    |
| NGC2623                 | ...                                  | ...                                   | ...                                    |
| NGC2892                 | ...                                  | ...                                   | ...                                    |
| NGC34                    | ...                                  | ...                                   | ...                                    |
| NGC3982                 | 1.1±1.4                              | ...                                   | ...                                    |
| NGC4138                 | ...                                  | ...                                   | ...                                    |
| NGC4151                 | 13.9±8.5                             | 5.7±1.0                               | 4.3±1.6                                |
| NGC4168                 | ...                                  | ...                                   | ...                                    |
| NGC424                  | ...                                  | ...                                   | ...                                    |
| NGC4258                 | ...                                  | ...                                   | ...                                    |
| NGC4303                 | ...                                  | ...                                   | ...                                    |
| NGC4395                 | ...                                  | ...                                   | ...                                    |
| NGC4472                 | ...                                  | ...                                   | ...                                    |
| NGC4477                 | ...                                  | ...                                   | ...                                    |
| NGC449                  | ...                                  | ...                                   | ...                                    |
| NGC4507                 | ...                                  | ...                                   | ...                                    |
| NGC4565                 | ...                                  | ...                                   | ...                                    |
| NGC4639                 | ...                                  | ...                                   | ...                                    |
| NGC4725                 | ...                                  | ...                                   | ...                                    |
| NGC4945                 | ...                                  | ...                                   | ...                                    |
| NGC4968                 | ...                                  | ...                                   | ...                                    |
| NGC5033                 | 1.4±2.5                              | 1.4±2.5                               | ...                                    |
| NGC5252                 | ...                                  | ...                                   | ...                                    |
| NGC5264                 | ...                                  | ...                                   | ...                                    |
| NGC5273                 | ...                                  | ...                                   | ...                                    |
| NGC5506                 | 1.4±1.6                              | 0.9±0.4                               | ...                                    |
| NGC5643                 | ...                                  | ...                                   | ...                                    |
| NGC591                  | ...                                  | ...                                   | ...                                    |
| NGC6552                 | ...                                  | ...                                   | ...                                    |
| NGC6712                 | ...                                  | ...                                   | ...                                    |
| NGC7212                 | ...                                  | ...                                   | ...                                    |
| NGC7314                 | ...                                  | ...                                   | ...                                    |
| NGC7479                 | ...                                  | ...                                   | ...                                    |
| NGC7582                 | ...                                  | 0.5±0.3                               | 0.7±0.4                                |
| NGC7874                 | ...                                  | ...                                   | ...                                    |
| UGC1214                 | ...                                  | 1.5±0.5                               | 1.2±0.8                                |
| UGC2456                 | ...                                  | ...                                   | ...                                    |
| UGC2808                 | ...                                  | ...                                   | ...                                    |
| UGC4039                 | ...                                  | ...                                   | ...                                    |
| UGC5727                 | ...                                  | ...                                   | ...                                    |
| UGC6821                 | ...                                  | ...                                   | ...                                    |
| UGC6925                 | ...                                  | ...                                   | ...                                    |

Blustin A.J., et al., 2003, A&A, 403, 481  
Blustin A.J., Page M.J., Fürst S.V., et al., 2005, A&A, 431, 111  
Brinkman A.C., Kaasstra J.C., van der Meer R.J.L., Kinkhabwala A., Behar E., Kahn S., Paredes F.B.S.; Sako M., 2002, A&A, 396, 761  
Brown G.V., Beiersdorfer P., Liedhal D.A., Widmann K., 1998, ApJ, 502, 1015  
Cid Fernandes R., Storchi-Bergmann T., Schmitt H.R., 1998, ApJ, 501, 94  
Cid Fernandes R., Heckman T., Schmitt H., González-Delgado R.M., Storchi-Bergmann T., 2001, 558, 81  
Dere K.P., Landi E., Del Zanna G., Young P.R., 2001, ApJSS, 134, 331  
der Herder J., et al., 2001, A&A, 365, L7  
Dickey J.M., Lockman F.J., 1990, ARA&A 28, 215  
Gabriel A.H., Jordan C., 1969, MNRAS, 145, 241  
Gabriel C., Denby M., Fyfe D. J., Hoar J., Ibarra A., 2003, in ASP Conf. Ser., Vol. 314 ADASS XIII, eds. F. Ochsenbein, M. Allen, & D. Egret (San Francisco: ASP), 759  
Gonzalez Delgado R., Heckman T., Leitherer C., 2001, ApJ, 546, 845  
Guainazzi M., Matt G., Perola G.C., 2005, A&A, 444, 119  
Kallman T.R., Liedahl D., Osterheld A., Goldstein W., Kahn S., 1996, ApJ, 465, 994  
King A.R., 2005, ApJ, 635, L121  
Kinkhabwala A., et al., 2002, ApJ, 575, 732  
Krolik J.H, Kriss G.A., 1995, ApJ, 447, 512  
Levenson N.A., Krolik J.H., Życki P.T., Heckman T.M., Weaver
K.A., Awaki H., Terashima Y., 2002, ApJ, 573, L81
Liedahl D.A, Paerels F, 1996, ApJ, 469, L33
Matt G., 1994, MNRAS, 267, L17
Mauche C.W., Liedahl D.A., Fournier K.B., 2001, ApJ, 560, 992
Phillips K.J.H., Greer C.J., Bhatia A.K., Coffey I.H., Barnsley
R., Keenan F.P., 1997, A&A, 324, 381
Porquet D., Dubau J., 2000, A&AS, 143, 495
Pounds K.A., Page K.L., 2005, MNRAS, 360, 1123
Sambruna R., Netzer H., Kaspi S., Brandt W.N., Chartas G.,
Garmire G.P., Nousek J.A., Weaver K.A., 2001, ApJ, 546, L13
Sako M., Kahn S.M., Paerels F., Liedahl D.A., 2000, ApJL 543, L115
Schmitt J.H.M.M., 1985, A&A, 293, 178
Schuch N.J., Warwick R.S., Griffiths R.E, Kahn S.M., 2004, MNRAS, 350, 1
Steenbrugge K.C., et al., 2005, A&A, 434, 569
Turner T.J., George I.M., Nandra K., Mushotzky R.F., 1997, ApJS 113, 23
Young A.J., Wilson A.S., Shopbell P.L., 2001, ApJ, 556, 6
Wu W., Clayton G.C., Gordon K.D., Misselt K.A., Smith T.L.,
Calzetti D., 2002, ApJS, 143, 377