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ABSTRACT

We present the Catalogue of High Resolution Spectra of Obscured Sources (CHRESOS) from the *XMM–Newton* Science Archive. It comprises the emission-line luminosities of H- and He-like transitions from C to Si, and the Fe 3C and Fe 3G L-shell ones. Here, we concentrate on the soft X-ray O VII (f) and O VIII Lyα emission lines to shed light on to the physical processes with which their formation can be related to active galactic nucleus (AGN) versus star-forming regions. We compare their luminosity with that of two other important oxygen key lines [O III] λ5007 Å, in the optical, and [O IV] 25.89 μm, in the infrared (IR). We also test O VII (f) and O VIII Lyα luminosities against that of continuum bands in the IR and hard X-rays, which point to different ionization processes. We probe into those processes by analysing photoionization and collisional ionization model predictions upon our lines. We show that both scenarios can explain the formation and observed intensities of O VII (f) and O VIII Lyα. By analysing the relationships between O VII (f) and O VIII Lyα, and all other observables: [O III] λ5007 Å, [O IV] 25.89 μm emission lines, and mid-infrared (MIR) 12 μm, far-infrared (FIR) 60 and 100 μm, 2–10 and 14–195 keV continuum bands, we conclude that the AGN radiation field is mainly responsible of the soft X-ray oxygen excitation.

Key words: galaxies: nuclei – galaxies: Seyfert – galaxies: starburst – galaxies: ISM – X-rays: galaxies.

1 INTRODUCTION

X-ray spectroscopy of celestial sources can probe hot (i.e. $\sim 10^6$ K) and cold (i.e. $10^{3–4}$ K) plasma ionized by an external radiation field. However, only with the advent of grating and transmission spectrometers on-board *Chandra* and *XMM–Newton*, X-ray spectroscopy has acquired a full maturity, allowing a complete diagnostic of the physical conditions and of the dynamics of plasma in a variety of astrophysical sources and contexts.

In this paper, we primarily deal with X-ray spectroscopy of gas in the narrow-line regions (NLRs) surrounding active galactic nuclei (AGNs). NLR gas is observationally characterized in the optical band by emission lines of moderately ionized species with a profile full width at half-maximum ≤500 km s^{-1}. The strongest observed spectral lines correspond to forbidden transitions such as [O III] λ5007 Å and [N II] λ6584 Å . These lines are believed to be excited by the intense radiation field emitted by the nuclear accreting black hole (Peterson 1997, and references therein). In nearby galaxies, NLRs are resolved to several hundreds or thousands of kpc (in the latter case called 'extended narrow-line region', ENLR).

The spectra of nearby obscured AGNs have systematically shown a strong soft X-ray excess above the extrapolation of the primary, absorbed nuclear continuum. High-resolution imaging and spectroscopy with *Chandra* and the *XMM–Newton*/Reflection Grating Spectrometer (RGS) have revealed that this component is dominated by strong recombination lines from He- and H-like transitions of light metals, as well as L transition of iron (Sako et al. 2000; Kinkhabwala et al. 2002; Guainazzi & Bianchi 2007). The presence of narrow radiative recombination continua, typical signatures of a low-temperature plasma (Liedahl & Paerels 1996), and plasma diagnostics based on the He-like triplets indicate that the X-ray emitting gas is photoionized, most likely by the AGN radiation field. Recently, radiation pressure compression (RPC) has been proposed as a universal scenario for the gas in the AGN nuclear environment, from the sub-kpc scale of the broad-line regions and the torus (Stern, Laor & Baskin 2014) to the ENLR (Bianchi et al. 2019). Deep high-resolution imaging with *Chandra* unveiled that a large fraction of the flux in the comparatively large RGS aperture is extended on scales of a few arcseconds. This extended soft X-ray emission exhibits a striking morphological coincidence with the NLR as observed in the optical (Young, Wilson & Shopbell 2001; Bianchi, Guainazzi & Chiaberge 2006; Levenson et al. 2006). While this evidence suggests a common origin between the optical and the X-ray emitting NLR gas, the ultimate proof of this connection is still to be found.

In this paper, we report for the first time on a systematic study of the correlation between spectroscopic measurements of He- and H-like oxygen transitions and multiwavelength spectroscopic and photometric indicators of AGN or star formation strength, aiming at understanding the ultimate origin of the X-ray ENLR. The results are based on the largest existing compilation of X-ray high-resolution spectra, the Catalogue of High Resolution Spectra of Obscured Sources (CHRESOS), which we present here. CHRESOS is an updated version of the sample first discussed in Guainazzi & Bianchi

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Table 1. List of emission lines within CHRESOS catalogue.

Emission line	Wavelength (Å)	Energy (keV)
C V Heβ	34.973	0.355
N VI (f)	29.534	0.420
N VII Lyα	24.780	0.5
O VII (f)	22.101	0.561
O VII (i)	21.806	0.569
O VII (r)	21.602	0.574
O VIII Lyα	18.967	0.654
Fe XVII 3G	17.054	0.727
Fe XVII 3C	15.015	0.826
Ne IX (f)	13.699	0.905
Ne X Lyα	12.132	1.02
Mg XI (f)	9.23	1.343
Mg XII Lyα	8.419	1.473
Si XIII (f)	6.69	1.853
Si XIV Lyα	6.181	2.006

(2007). This paper is structured as follows. Section 2 presents CHRESOS and summarizes the employed archival data. In Section 3, we compare the observed X-ray oxygen line ratios with prediction of state-of-the-art photoionized and optically thin collisionally ionized models. Section 4 presents the results of our correlations. We discuss and summarize our main results in Section 5.

2 DATA

CHRESOS comprises 100 sources of the local universe (redshift $z < 0.07$) that harbours a Seyfert-type AGN according to *XMM–Newton* observations in the soft X-ray band. It gathers spectra obtained by the RGS (den Herder et al. 2001) on-board *XMM–Newton*, sensitive in the 0.2–2.0 keV energy band, available in the public archive. In this paper, we present the catalogue with the emission-line luminosities in the soft X-ray band. The details of reduction procedure, spectral analysis, and emission-line measurements are fully described in Bianchi et al. (2019), where part of the CHRESOS sample has been used in the context of RPC analysis. Briefly, each line was fit with a Gaussian profile on top of a power-law continuum. A given line is considered to be detected if it yields an improvement in the quality of the fit at the 3σ confidence level for one interesting parameter (Lampton, Margon & Bowyer 1976). CHRESOS includes H- and He-like transitions from C to Si, and two L-shell emission lines from Fe XVII: 3G and 3C. The emission lines and their rest-frame wavelengths (Å) and energies (keV) are listed in Table 1. We present the observed emission-line luminosities (with their errors quoted at 1σ level) for each source in two separate tables. The H-like and Fe lines are listed in Table 2. The He-like transition forms a triplet composed of a resonant, an intercombination, and a forbidden line; we present the three emission lines for the He-like oxygen triplet, as well as the forbidden lines for the remaining species. These He-like emission lines are listed in Table 3.

As long as this paper is concerned, we are going to use oxygen emission lines: the forbidden component from the He-like O VII triplet [O VII (f)], and O VIII Lyα, the H-like transition. We will compare them with multiwavelength nuclear data, obtained from the literature: continuum luminosities in 14–195, 2–10 keV, mid-infrared (MIR) 12 µm, far-infrared (FIR) 60 and 100 µm, and luminosities of two other important oxygen lines: [O III] λ5007 Å in the optical, and [O IV] 25.89 µm in the IR. Since we aim to probe into the formation mechanism of O VII (f) and O VIII Lyα, those multiwavelength data were chosen because of their relationships

with the two scenarios from where these emission lines can emerge: the AGN and the (nuclear/near-nuclear) star-forming regions, or starbursts (SB; Guainazzi & Bianchi 2007).

The 2–10 and 14–195 keV [the *Swift*/Burst Alert Telescope (BAT) band] are the most reliable measurements of the nuclear (primary) continuum in non-Compton-thick sources (Weaver et al. 2010). Table 3 also includes the 2–10 keV absorption-corrected luminosities and references from the literature. When the data were not available, we obtained the intrinsic luminosities as part of this work through the European Photon Imaging Camera (EPIC)/MOS spectra available in the *XMM–Newton* Science Archive. The 14–195 keV data were obtained from the *Swift*/BAT 105-month Hard X-ray Survey (Oh et al. 2018).

The optical [O III] λ5007 Å emission line is an indicator of the AGN ionizing power. It forms in the NLR, the 100-pc scale nebular structure whose distribution, when mapped by [O III] λ5007 Å, usually coincides with the gas distribution in the soft X-ray band (Young et al. 2001; Bianchi et al. 2006, 2010; Levenson et al. 2006; Dadina et al. 2010; Fabbiano et al. 2018). Because of its extension, the NLR emission does not suffer significant dust obscuration from the toroidal structure that surrounds the innermost regions of the AGN (LaMassa et al. 2010). The use of [O III] λ5007 Å as a proxy of the AGN is supported by the much studied relationship between [O III] λ5007 Å and the 2–10 keV luminosities (Mulchaey et al. 1994; Bassani et al. 1999). The precise form of such a relation is strongly dependent on whether the data are selected from the optical or from X-rays (Heckman et al. 2005); and it has also been argued that, in some particular cases, the relationship is even absent (Berney et al. 2015; Rojas et al. 2017). However, in the vast majority of cases, for all kind of AGNs (from Seyferts to 3C sources), the luminosity of [O III] λ5007 Å emission line shows a strong and tight relationship with the hard X-ray 2–10 keV band, and is therefore widely accepted as an isotropic indicator of the primary continuum luminosity (e.g. Mulchaey et al. 1994; Bassani et al. 1999; Schmitt et al. 2003; Heckman et al. 2005; Meléndez et al. 2008; Hardcastle, Evans & Croston 2009; LaMassa et al. 2010; Zhang & Feng 2017).

The [O IV] 25.89 µm IR emission line forms in the NLR too (LaMassa et al. 2010). The emission of [O IV] 25.89 µm and [O III] λ5007 Å from nearby ($z < 0.08$) Seyfert sources was correlated against the two hard X-ray nuclear continuum bands: 2–10 and 14–195 keV by Meléndez et al. (2008). Although they noted that the relationship that arises from [O IV] 25.89 µm versus 2–10 keV is weaker than the well-known [O III] λ5007 Å versus 2–10 keV relationship, they also showed that the two oxygen emission lines are well correlated with the BAT band. They concluded that [O IV] 25.89 µm will be an isotropic proxy of the AGN power as long as the star formation can be neglected. In the same sense, Weaver et al. (2010) founded two important results for BAT-detected AGNs: (1) there exists a very tight relationship between [O IV] 25.89 µm and another important IR emission line, [Ne V] 14 µm, and (2) the [Ne V] 14 µm is formed by photoionization from the AGN, since very high energy photons are required in order to form the line (its ionization potential, IP, is 97.2 eV; see also Pereira-Santaella et al. 2010; Davies et al. 2017). Based on these two points they showed and concluded that the emission of [O IV] 25.89 µm (whose IP is almost half of that of [Ne V]) in BAT sources also responds to photoionization by the AGN.

So, according the AGN unification model (Urry & Padovani 1995), [O III] λ5007 Å and [O IV] 25.89 µm emission lines originate in the photoionized gas that forms the NLR. The same powerful radiation field provides the ionizing photons required to form both [O III] λ5007 Å and [O IV] 25.89 µm. While the optical [O III]

Table 2. CHRESOS catalogue: H-like emission lines and L-shell transitions of Fe.

Source (1)	C VI Lyα (2)	C V Heβ (3)	N VII Lyα (4)	O VIII Lyα (5)	Ne X Lyα (6)	Mg XII Lyα (7)	Si XIV Lyα (8)	Fe 3C (9)	Fe 3G (10)
Circinus	–	–	–	–	$37.95^{+0.08}_{-0.100}$	$38.05^{+0.08}_{-0.09}$	$38.45^{+0.12}_{-0.16}$	$38.12^{+0.41}$	–
ESO 138-G01	–	–	–	$39.49^{+0.08}_{-0.100}$	–	$39.45^{+0.12}_{-0.17}$	–	–	–
ESO 323-G077	–	–	–	$39.52^{+0.09}_{-0.14}$	–	–	–	–	–
ESO 362-G018	$39.99^{+0.05}_{-0.07}$	–	$39.46^{+0.09}_{-0.11}$	$39.85^{+0.05}_{-0.05}$	–	–	–	–	–
H0557−385	–	–	–	–	–	–	$41.32^{+0.06}_{-0.06}$	–	–
IRAS 05189−2524	–	–	$40.14^{+0.14}_{-0.18}$	$40.51^{+0.05}_{-0.12}$	–	–	–	–	–
MCG-03-34-064	–	–	–	$39.80^{+0.14}_{-0.20}$	–	–	–	$39.83^{+0.37}$	–
MCG 03-58-07	–	–	–	–	–	–	$41.08^{+0.14}_{-0.12}$	–	–
Mrk 231	–	–	$40.03^{+0.21}_{-0.19}$	–	$40.42^{+0.14}_{-0.17}$	–	–	–	–
Mrk 268	–	–	–	–	–	–	$41.92^{+0.04}_{-0.16}$	–	–
Mrk 273	–	–	–	$40.28^{+0.23}_{-0.21}$	–	–	–	–	–
Mrk 3	–	–	–	$40.16^{+0.04}_{-0.05}$	$39.85^{+0.101}_{-0.13}$	–	–	$39.4^{+0.43}$	–
Mrk 477	–	–	–	$40.31^{+0.19}_{-0.32}$	–	–	–	–	–
NGC 1052	–	–	$38.33^{+0.12}_{-0.16}$	$38.62^{+0.08}_{-0.09}$	–	–	–	–	$38.33^{+0.36}$
NGC 1068	$40.24^{+0.011}_{-0.008}$	$39.52^{+0.03}_{-0.04}$	$40.06^{+0.014}_{-0.006}$	$40.13^{+0.008}_{-0.008}$	$39.65^{+0.03}_{-0.012}$	$39.28^{+0.06}_{-0.07}$	–	$39.65^{+0.06}$	$39.74^{+0.06}$
NGC 1320	–	–	$39.36^{+0.16}_{-0.23}$	–	–	–	–	–	–
NGC 1365	$39.08^{+0.02}_{-0.098}$	–	$39.08^{+0.02}_{-0.03}$	$39.32^{+0.02}_{-0.02}$	$38.94^{+0.06}_{-0.06}$	–	–	–	–
NGC 2655	–	–	–	$39.06^{+0.11}_{-0.14}$	–	–	–	–	–
NGC 3393	–	–	–	$39.77^{+0.14}_{-0.19}$	–	–	–	–	–
NGC 4151	$39.50^{+0.009}_{-0.008}$	$38.81^{+0.04}_{-0.06}$	$39.13^{+0.02}_{-0.005}$	$39.54^{+0.005}_{-0.005}$	$38.73^{+0.03}_{-0.03}$	$38.52^{+0.07}_{-0.09}$	$39.03^{+0.11}_{-0.16}$	$38.44^{0.14}$	$38.58^{+0.14}$
NGC 424	–	–	–	$39.30^{+0.09}_{-0.12}$	$39.32^{+0.12}_{-0.16}$	–	–	–	–
NGC 4388	–	–	–	$39.46^{+0.12}_{-0.15}$	–	–	–	–	–
NGC 4507	$39.80^{+0.13}_{-0.17}$	–	–	$39.81^{+0.06}_{-0.07}$	–	–	–	–	$39.31^{+0.30}$
NGC 5252	–	–	–	$39.75^{+0.15}_{-0.21}$	–	–	–	–	–
NGC 5506	–	–	$38.44^{+0.11}_{-0.14}$	$39.15^{+0.04}_{-0.04}$	$38.79^{+0.10}_{-0.13}$	–	–	$38.81^{+0.17}$	$38.71^{+0.21}$
NGC 5548	$39.87^{+0.08}_{-0.10}$	–	–	$40.02^{+0.04}_{-0.04}$	–	–	–	–	–
NGC 5643	–	–	–	$38.38^{+0.12}_{-0.16}$	–	–	–	–	–
NGC 6240	–	–	–	$40.44^{+0.08}_{-0.1}$	$40.37^{+0.17}_{-0.16}$	–	–	–	–
NGC 7172	–	–	–	$38.92^{+0.07}_{-0.20}$	–	–	–	–	–
NGC 7582	–	–	$38.62^{+0.08}_{-0.1}$	$38.98^{+0.04}_{-0.04}$	$38.75^{+0.09}_{-0.11}$	–	–	$38.86^{+0.21}$	$38.63^{+0.31}$
NGC 777	–	–	–	$40.12^{+0.10}_{-0.10}$	$40.16^{+0.174}_{-0.15}$	–	–	–	–
PG 1411+442	–	–	–	–	$41.37^{+0.22}_{-0.14}$	–	–	–	–
PG 1535+547	–	–	–	$40.05^{+0.09}_{-0.13}$	–	–	–	–	–
UGC 1214	–	–	–	$40.11^{+0.14}_{-0.18}$	–	–	–	–	–

Note. Column (1): name of the source. Columns (2)–(10): line luminosities in units of log(erg s^{-1}); the errors on the line luminosity are quoted at the 1σ level (Bianchi et al. 2019). Places marked as '−' represent undetected lines.

λ5007 Å emission line is the widely accepted proxy of the AGN primary continuum (e.g. Bassani et al. 1999; Schmitt et al. 2003; Heckman et al. 2005; LaMassa et al. 2010; Zhang & Feng 2017), in the case of the IR [O IV] 25.89 μm emission line there has been a long standing debate trying to clarify if both its existence and intensity are related to the AGN or to the intense starburst continuum (e.g. Dale et al. 2006; Hao et al. 2009). However, it is now accepted that, albeit collisional ionization may play an important role in some cases, the AGN is the main responsible for the excitation of such a line, especially in the case of the bright AGN constituting the bulk of the extragalactic population in the BAT catalogue (LaMassa et al. 2010; Weaver et al. 2010). In this sense, we highlight that 24 out of 35 objects, where O VII (f) or O VIII Lyα was confidently measured, are BAT sources (69 per cent of the subsample). The [O III] data were collected from Schmitt et al. (2003), Heckman et al. (2005), Gu et al. (2006), Panessa et al. (2006), Bentz et al.

(2009), Schlesinger et al. (2009), and Greene et al. (2010), while [O IV] data were collected from Schweitzer et al. (2006), Deo et al. (2007), Diamond-Stanic, Rieke & Rigby (2009), Pereira-Santaella et al. (2010), Sales, Pastoriza & Riffel (2010), Tommasin et al. (2010), Weaver et al. (2010), Dasyra et al. (2011), and Wu, Zhao & Meng (2011).

Another well-known proxy of the AGN is the MIR 12 μm continuum emission; its strong relationship with the hard X-ray 2–10 keV band (Gandhi et al. 2009) makes it another indicator of the AGN power. According to the unified scenarios for AGNs, large amounts of gas and dust surround the central region. Therefore, their temperatures raise up by absorption of high-energy photons (UV, X-rays) of the primary continuum. The warm dust is mixed within the circumnuclear ionized gas and thus is mainly affected by the nuclear ionizing radiation and also by resonant-scattered Lyα photons created (and trapped) inside the nebula (Telesco 1988; Mouri & Taniguchi

Table 3. CHRESOS catalogue: He-like oxygen triplet; the forbidden emission line of He-like triplets is the only one shown for the remaining species.

Source (1)	N VI (f) (2)	O VII (f) (3)	O VII (i) (4)	O VII (r) (5)	Ne IX (f) (6)	Mg XI (f) (7)	Si XIII (f) (8)	2–10 keV (9)	Ref. (10)
2MASX J12384342+09273	–	–	–	–	$41.58^{+0.11}_{-0.2}$	–	–	43.5	1
Circinus	–	–	–	–	$37.78^{+0.12}_{-0.15}$	$37.60^{+0.15}_{-0.22}$	$37.76^{+0.12}_{-1.19}$	42.63	2
ESO 103-G35	–	$39.85^{+0.26}_{-0.32}$	–	–	–	–	–	43.37	2
ESO 104-G11	–	–	–	–	$39.24^{+0.30}_{-1.16}$	–	–	40.7	1
ESO 137-G34	–	–	–	–	$38.73^{+0.64}_{-1.16}$	–	–	42.64	2
ESO 138-G01	–	$39.70^{+0.1}_{-0.12}$	$39.31^{+0.37}_{-0.32}$	$39.10^{+0.68}_{-0.43}$	$39.32^{+0.08}_{-0.10}$	–	–	44.09	2
ESO 323-G077	–	–	–	–	$39.08^{+0.19}_{-0.48}$	–	–	42.87	2
ESO 362-G018	$39.48^{+0.11}_{-0.14}$	$40.18^{+0.04}_{-0.04}$	$36.32^{+589.71}_{-0.43}$	$39.65^{+0.32}_{-0.40}$	$39.47^{+0.09}_{-0.12}$	–	–	42.96	2
ESO 383-G18	–	$39.90^{+0.16}_{-0.22}$	–	–	$39.17^{+0.26}_{-695.0}$	–	–	42.78	2
F00521−7054	–	–	–	–	–	$41.16^{+0.29}_{-0.90}$	–	43.43	3
FBQS J075800.0+392029	–	$41.66^{+0.13}_{-0.13}$	–	–	–	–	–	43.83	1
H0557−385	–	$40.59^{+0.10}_{-0.16}$	–	–	–	$40.05^{+0.50}_{-0.82}$	–	44.08	2
IC 1867	–	–	–	–	$40.13^{+0.24}_{-0.57}$	–	–	41.21	1
IGR J19473+4452	–	–	–	–	–	$40.92^{+0.13}_{-0.56}$	–	43.93	1
IRAS 01475−0740	–	–	–	–	$39.52^{+0.23}_{-0.77}$	–	–	42.04	4
IRAS 04507+0358	–	–	–	–	$40.03^{+0.25}_{-1.4}$	$40.43^{+0.18}_{-0.71}$	–	44.0	2
IRAS 05189−2524	–	$40.18^{+0.22}_{-0.39}$	–	–	$40.18^{+0.12}_{-0.21}$	–	$40.44^{+0.20}_{-0.49}$	43.40	2
IRAS 15480−0344	–	–	–	–	–	$39.93^{+0.25}_{-0.88}$	–	43.0	5
IRAS 18325−5926	–	$39.49^{+0.20}_{-0.36}$	–	–	–	–	–	43.3	6
MCG-01-05-047	–	–	–	–	$39.30^{+0.60}_{-0.33}$	–	–	42.74	2
MCG-03-34-064	–	$40.34^{+0.09}_{-0.11}$	$39.62^{+0.37}_{-0.33}$	$39.61^{+0.32}_{-0.29}$	–	–	–	43.4	2
MCG-03-58-07	–	–	–	–	$39.70^{+0.16}_{-0.46}$	–	–	42.78	5
Mrk 231	–	–	–	–	–	–	–	42.59	2
Mrk 268	–	–	–	–	–	–	–	43.55	2
Mrk 273	–	–	–	–	–	–	–	42.08	4
Mrk 417	–	–	–	–	–	$40.85^{+0.19}_{-0.30}$	–	43.72	2
Mrk 1298	–	$40.9^{+0.15}_{-0.17}$	$39.93^{+1.64}_{-0.43}$	$40.38^{+0.33}_{-0.43}$	–	–	–	43.3	7
Mrk 3	$39.35^{+0.28}_{-0.68}$	$40.18^{+0.06}_{-0.07}$	$39.46^{+0.25}_{-0.23}$	$39.95^{+0.11}_{-0.08}$	$39.75^{+0.08}_{-0.10}$	–	–	43.67	2
Mrk 463	$40.67^{+0.26}_{-0.50}$	–	–	–	$40.54^{+0.24}_{-0.27}$	–	–	43.09	2
Mrk 477	–	$40.85^{+0.15}_{-0.19}$	–	–	$40.14^{+0.24}_{-0.57}$	–	–	43.26	2
Mrk 6	–	$39.69^{+0.23}_{-0.50}$	–	–	–	–	–	43.08	2
Mrk 704	$40.66^{+0.10}_{-0.10}$	$40.96^{+0.09}_{-0.11}$	$40.45^{+0.19}_{-0.18}$	$39.45^{+1.68}_{-0.43}$	$40.33^{+0.10}_{-0.19}$	–	–	43.33	2
NGC 1052	–	$38.33^{+0.16}_{-0.22}$	–	–	$38.07^{+0.19}_{-0.32}$	–	–	41.62	2
NGC 1068	$40.16^{+0.02}_{-0.005}$	$40.37^{+0.01}_{-0.009}$	$39.70^{+0.03}_{-0.03}$	$40.18^{+0.02}_{-0.02}$	$39.65^{+0.03}_{-0.02}$	$39.07^{+0.07}_{-0.09}$	$39.10^{+0.10}_{-0.28}$	42.93	2
NGC 1320	–	$39.71^{+0.14}_{-0.17}$	–	–	$39.20^{+0.18}_{-0.28}$	–	–	42.85	2
NGC 1365	–	$39.16^{+0.05}_{-0.02}$	–	–	$38.90^{+0.04}_{-0.06}$	$38.32^{+0.22}_{-0.48}$	–	42.32	2
NGC 2110	–	–	–	–	$38.58^{+0.31}_{-1.55}$	–	–	42.68	2
NGC 2655	–	–	–	–	–	–	–	41.34	2
NGC 3227	$37.86^{+0.27}_{-0.83}$	$38.53^{+0.09}_{-0.12}$	$38.40^{+0.25}_{-0.23}$	$36.84^{+5.79}_{-0.43}$	–	–	–	42.07	2
NGC 3393	–	$40.08^{+0.12}_{-0.20}$	–	–	–	$39.75^{+0.19}_{-0.33}$	–	42.63	2
NGC 4151	$39.30^{+0.010}_{-0.009}$	$39.93^{+0.006}_{-0.004}$	$39.26^{+0.02}_{-0.02}$	$39.54^{+0.014}_{-0.014}$	$39.15^{+0.012}_{-0.012}$	$38.57^{+0.05}_{-0.06}$	–	42.31	2
NGC 424	$39.49^{+0.06}_{-0.17}$	$40.0^{+0.04}_{-0.05}$	–	–	$39.07^{+0.13}_{-0.18}$	–	–	43.77	2
NGC 4388	–	$39.70^{+0.11}_{-0.13}$	–	–	$38.88^{+0.32}_{-3.00}$	–	–	43.05	2
NGC 4395	–	$36.98^{+0.16}_{-0.24}$	–	–	–	–	–	40.45	2
NGC 4507	$39.23^{+0.24}_{-0.41}$	$40.34^{+0.04}_{-0.05}$	$39.29^{+0.27}_{-0.24}$	$39.87^{+0.09}_{-0.08}$	$39.59^{+0.08}_{-0.09}$	$39.05^{+0.28}_{-0.82}$	–	43.51	2
NGC 513	–	–	–	–	–	–	$40.62^{+0.14}_{-0.27}$	42.66	2
NGC 5252	–	$40.34^{+0.09}_{-0.15}$	$39.21^{+0.97}_{-0.43}$	$40.29^{+0.08}_{-0.14}$	$39.81^{+0.11}_{-0.26}$	–	–	43.01	2
NGC 5273	$38.07^{+0.28}_{-0.64}$	$38.65^{+0.14}_{-0.18}$	$38.52^{+0.26}_{-0.43}$	$38.46^{+0.26}_{-0.43}$	–	–	–	41.25	2
NGC 5506	–	$38.88^{+0.08}_{-0.102}$	$38.41^{+0.26}_{-0.23}$	$38.09^{+0.57}_{-0.43}$	$38.61^{+0.09}_{-0.11}$	–	–	42.99	2
NGC 5548	$39.74^{+0.08}_{-0.09}$	$40.59^{+0.02}_{-0.02}$	–	–	$39.69^{+0.07}_{-0.09}$	$39.32^{+0.28}_{-1.16}$	$39.93^{+0.18}_{-0.96}$	43.14	2
NGC 5643	$37.99^{+0.29}_{-0.92}$	$38.70^{+0.11}_{-0.13}$	$35.94^{+45.84}_{-0.43}$	$38.65^{+0.23}_{-0.20}$	–	$37.97^{+0.29}_{-0.83}$	–	42.43	2
NGC 6240	–	–	–	–	$39.81^{+0.24}_{-0.52}$	–	–	44.75	2
NGC 7172	–	–	–	–	–	–	–	42.74	2

Table 3 – *continued*

Source (1)	N VI (f) (2)	O VII (f) (3)	O VII (i) (4)	O VII (r) (5)	Ne IX (f) (6)	Mg XI (f) (7)	Si XIII (f) (8)	2–10 keV (9)	Ref. (10)
NGC 7582	–	$38.78^{+0.07}_{-0.11}$	$38.72^{+0.17}_{-0.16}$	$38.92^{+0.10}_{-0.10}$	$38.33^{+0.13}_{-0.17}$	$38.51^{+0.16}_{-0.25}$	–	43.48	2
NGC 777	–	–	–	–	$40.84^{+0.02}_{-0.03}$	–	–	40.97	1
NVSS 193013+341047	–	–	–	–	$40.74^{+0.32}_{-1.55}$	–	–	43.95	2
PG 1411+442	–	–	–	–	–	$41.24^{+0.17}_{-0.42}$	–	43.41	8
PG 1535+547	–	–	–	–	$39.74^{+0.22}_{-0.38}$	–	–	42.06	9
UGC 05101	–	–	–	–	–	$40.25^{+0.19}_{-1.05}$	–	44.2	2
UGC 1214	–	$40.45^{+0.12}_{-0.14}$	–	–	$39.51^{+0.30}_{-0.71}$	–	–	41.3	10
UGC 3142	–	–	–	–	–	–	$40.74^{+0.16}_{-0.72}$	43.05	11

Note. Column (1): name of the source. Columns (2)–(8): line luminosities in units of log(erg s^{-1}); the errors on the line luminosity are quoted at the 1σ level (Bianchi et al. 2019). Columns (9) and (10): unabsorbed intrinsic 2–10 keV luminosities (same units) and their references as follows: 1 – this work; 2 – Ricci et al. (2017); 3 – Tan et al. (2012); 4 – Huang et al. (2011); 5 – Brightman & Nandra (2011); 6 – Iwasawa et al. (2004); 7 – Giustini et al. (2011); 8 – Zhou & Zhang (2010); 9 – Inoue, Terashima & Ho (2007); 10 – Bianchi et al. (2010); 11 – Ricci et al. (2010). Places marked as '–' represent undetected lines (see text).

1992). Once the dust reaches the equilibrium temperature it reradiates in the MIR, reaching the maximum emission among 7–26 µm (Pier & Krolik 1992; Ramos Almeida et al. 2009; Asmus et al. 2014). MIR 12 µm continuum radiation is emitted by warm gas (200–600 K) after it absorbs the primary continuum. Lower temperature (∼10–100 K) gas also emits in the FIR ($\lambda \gtrsim 40$ µm) band, but the main contributors to this band are star-forming regions, as it will be discussed later. The 12 µm continuum has been pointed out as good tracer of warm–hot dust in the AGN scenario (Horst et al. 2006; Gürkan et al. 2015).

One of the most relevant advantages of using the MIR is the high angular resolution with which data are obtained. Nowadays, ground-based 8-m class telescopes allow us to reach arcsec and/or diffraction-limited resolution (Krabbe, Böker & Maiolino 2001). On-orbit telescopes, as the *Infrared Space Observatory* (*ISO*) and *Spitzer*, have been great instruments mainly due to their high sensitivity but they do not reach sub-arcsec resolution (Asmus et al. 2014). Horst et al. (2009) showed that 40 per cent of *Spitzer*'s data are contaminated by extended emission in comparison with the Very Large Telescope (VLT)/VLT Imager and Spectrometer for Mid-Infrared (VISIR)'s data. So, having sub-arcsec resolution is particularly important in the case of AGN in the local Universe because it is crucial to isolate the nuclear emission (dust mixed within circumnuclear ionized gas) as much as possible. Taking this into account, we are using the most recent collection of 12 µm data (Asmus et al. 2014), obtained with state-of-the-art ground-based IR instruments: VISIR from VLT, Cooled Mid-Infrared Camera and Spectrometer (COMICS) from Subaru, and Michelle and Thermal-Region Camera and Spectrograph (T-ReCS; yet retired instruments) from Gemini.

The FIR continuum emission, on the other hand, is produced by the very cold gas surrounding star-forming regions. The FIR 60 and 100 µm data (*IRAS* Point Source Catalog, version 2.0; Sanders et al. 1989, 2003; Moshir, Kopman & Conrow 1992; Surace, Sanders & Mazzarella 2004; Lisenfeld et al. 2007; Serjeant & Hatziminaoglou 2009) will be used as proxies of the SB activity (Rodriguez Espinosa, Rudy & Jones 1986, 1987; Mouri & Taniguchi 1992; Strickland et al. 2004; Hatziminaoglou et al. 2010).

Table 4 shows the facilities (telescopes and instruments) that were employed to obtain the data we are using along this paper.

2.1 An IR diagnostic diagram for obscured AGN

We are interested in using [O IV] as a proxy of the AGN, but we can be sure about that property only for 69 per cent of our sample, which

Table 4. List of telescopes and instruments used in this paper.

Telescope	Instrument
HST	WFPC2
	WF/PC1
	FOC
La Silla (1.52 m)	B&C
La Silla/MPI (2.2 m)	B&C
La Silla (3.6 m)	EFOSC
Palomar/Hale (5 m)	Double spec.
Lick/Shane (3 m)	Kast dual spec.
Las Campanas/du Pont (2.5 m)	B&C
Las Campanas/APO (3.5 m)	DIS
Subaru	COMICS
Gemini	Michelle
	T-ReCS
VLT	VISIR
Spitzer	IRS
IRAS	
Swift	BAT
XMM–Newton	EPIC
	RGS

constitutes the subsample of BAT sources within CHRESOS. This section is devoted to make a last test over [O IV] 25.89 µm in order to show that this line is a proxy of the AGN for the whole CHRESOS sources, regardless their BAT or non-BAT condition.

Fig. 1 shows IR-Baldwin–Phillips–Televich (BPT) diagnostic diagrams, which were developed by Hao et al. (2009) with the aim of distinguishing the [O IV] 25.89 µm emission from AGN and the [O IV] 25.89 µm emission from blue compact dwarf (BCD) galaxies. The diagnostic power of these diagrams relies on the high-energy photons (54.94 eV) required to form the [O IV] 25.89 µm: the radiation field of any main-sequence central star(s) H II region is not strong enough to account for the [O IV] observations. Instead, the harder ionizing field of Wolf–Rayet (WR) stars is able to account for [O IV] (and other high excitation/ionization) line emission, and this is what makes BCD galaxies so relevant: they are extreme SB, suspected to contain a significant number of WR stars (Lutz et al. 1998; Hao et al. 2009; Weaver et al. 2010; Burtscher et al. 2015). The panels of Fig. 1 are formed with MIR emission-line ratios: [O IV] 25.89 µm/[S III] 33.4 µm versus [Ne III] 15.5 µm/[Ne II] 12.8 µm (left-hand panel) and [O IV] 25.89 µm/[Ne II] 12.8 µm versus [Ne III] 15.5 µm/[Ne II] 12.8 µm (right-hand panel). Hao et al.
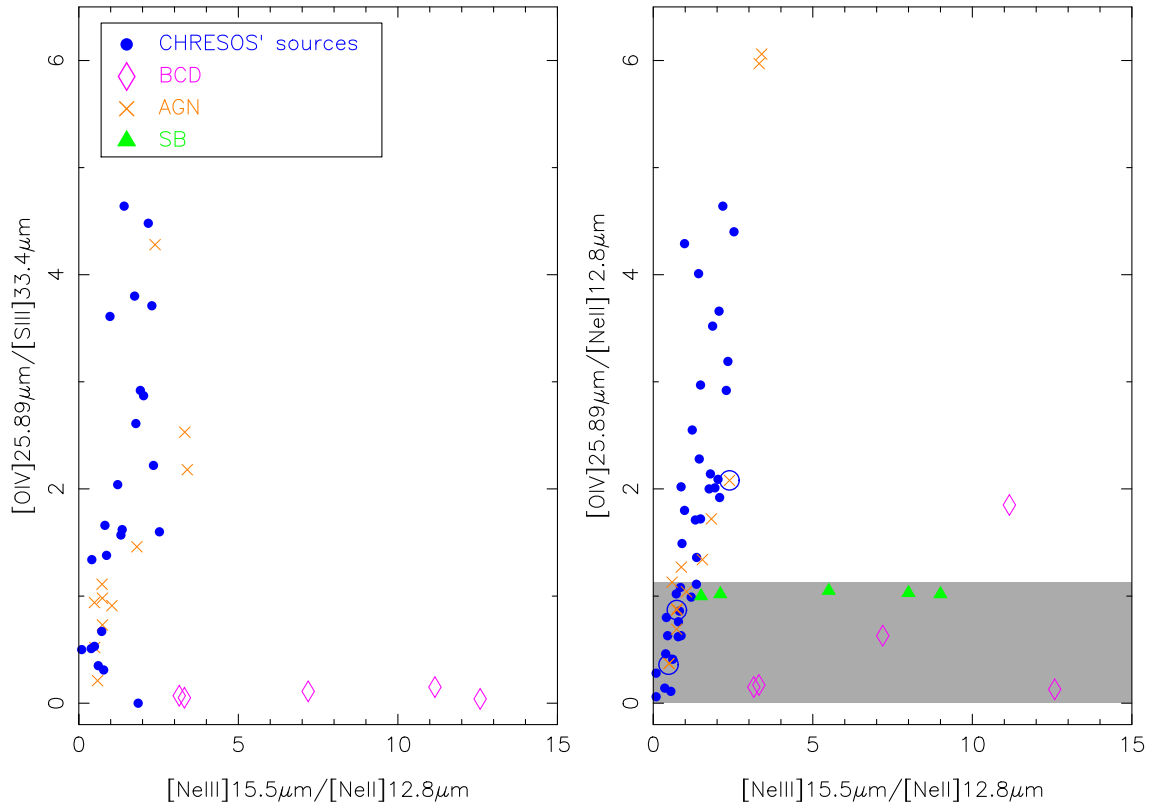
Figure 1. IR diagnostic diagrams aiming at separating AGNs from blue compact dwarf (BCD) galaxies (Hao et al. 2009). The AGN branch is the almost vertical one in the two panels. Most CHRESOS sources are distributed along the AGN branch. The sources located within the grey rectangle show an important contribution from star-forming regions.

(2009) have demonstrated that, in effect, BCDs and AGNs tend to be located in different zones because of [O IV] 25.89 μm being powered by different mechanisms. We have plotted the following.

(i) CHRESOS sources as (blue) filled circles (the IR data of CHRESOS sources were obtained from Gallimore et al. 2010; Weaver et al. 2010).

(ii) AGNs from Sales et al. (2010) as (orange) crosses; they are used as a control sample. The encircled sources also belong to CHRESOS.

(iii) SB galaxies from Lutz et al. (1996, 1998) as (green) filled triangles; in addition, SBs from Genzel et al. (1998) are not shown individually but globally as the grey rectangle (shaded area).

(iv) BCDs as examples of 'extreme starburst' (Hao et al. 2009); they are the (pink) empty diamonds. We assess their location within the diagrams in comparison to AGNs and 'normal' SB.

The diagrams actually separate AGNs from BCD galaxies in two branches (being the AGN branch the almost vertical one), but both of these branches also contain *normal* SB galaxies. They are equivalent to the optical BPT diagnostic diagram ([O III] λ5007 Å/Hβ versus [N II] λ6583 Å/Hα; Baldwin, Phillips & Terlevich 1981; Veilleux & Osterbrock 1987) in the sense that there exists a correspondence among the 'pure AGN' zone, intermediate zone, and SB-dominated BCD zone both in the IR and in the optical diagram according to Kewley et al. (2001), Kauffmann et al. (2003), and Hao et al. (2009). The sources for which [O IV] 25.89 μm/[S III] 33.4 μm ∼ 1–10 (left-hand panel) are clearly dominated by the AGN emission, and no SB is located in that zone (the 'pure AGNs'); however, the two branches

seem to have a common origin (vertex; see the fig. 1 of Hao et al. 2009), and many SB with and without WR contribution are located in that zone (each group tending to follow their respective branch). The distributions of sources in the two panels of Fig. 1 are very similar (Hao et al. 2009). As there are more [Ne II] 12.8 μm data than [S III] 33.4 μm data in the literature for both CHRESOS sample and comparison samples, this equivalence is particularly useful in our case.

We observe the very same behaviour both in CHRESOS sources and in the control sample of Sales et al. (2010): all these sources are located along the (vertical) AGN branch. As expected, a significant fraction of our sample (37 per cent) is in the parameter space that is shared between AGN and SB. None the less, we emphasize that none of our sources show any kind of signature of WR stars accounting for the [O IV] line emission. The result of the current analysis is twofold. First, it reasserts the AGN nature of CHRESOS sources, which was expected since the hard X-ray luminosity for most of the sample is just too high ($L_{2-10\,\text{keV}} \gtrsim 10^{42}$ erg s^{-1}) not to harbour an AGN. On the other hand, it also confirms that [O IV] 25.89 μm is a bona fide indicator of the AGN power in CHRESOS sources, independently of their BAT/non-BAT condition.

3 MODEL PREDICTIONS

Ionizing power is very different in AGN and in SB. However, both the AGN and the SB scenarios are capable of producing soft X-ray line emission. Two distinct processes are involved in each case: photoionization (PIE) and collisional ionization/excitation (CIE). In this section, we show PIE and CIE predictions on to

O VIII Lyα/O VII (f) line ratio in order to compare them with our own observations.

PIE gathers two important processes: radiative decay after continuum photoexcitation and recombination plus radiative cascades after photoionization. Their relative weight is governed by the column density (N_H). The former dominates at low N_H, the latter dominates at high N_H (Kinkhabwala et al. 2002). Kallman et al. (2014) performed a very accurate spectral fitting analysis to the soft X-ray *Chandra*/Advanced CCD Imaging Spectrometer (ACIS) spectra of NGC 1068 by using a version of the XSTARcode, which incorporates the continuum excitation process. We have used this same separate version of XSTAR (Kallman & Bautista 2001) to compare the observed O VIII Lyα/O VII (f) line ratios in CHRESOS with its predictions. To do so, we have modelled a set of constant-density ($n_e = 10^4$ cm^{-3}) nebulae irradiated by an AGN-like radiation field. We have adopted the default solar abundances in XSTAR. The shape of the incident continuum between 0.1 eV and 200 keV was built according to the AGN spectral energy distribution (SED) after Korista et al. (1997), taking into account both the high-energy power law and the UV big blue bump as follows:

$$f_\nu = \nu^{\alpha(UV)} \exp(-h\nu/kT_{BB}) \exp(-kT_{IR}/h\nu) + a\,\nu^{\alpha_X},$$

with $\alpha(UV) = -0.5$; $kT_{BB} = 30$ eV; $kT_{IR} = 0.1$ eV, and $\alpha_X = -0.7$. A grid of models was obtained by varying the column density in the range $10^{21} < N_H < 10^{24}$ cm^{-2} and varying the ionization parameter ξ in the range $0 < \log(\xi) < 4$ (the ionization parameter is defined as $\xi = L_{ion}/n_H r^2$, where L_{ion} is the luminosity of the ionizing source, integrated from 13.6 eV, the H-ionizing energy; n_H is the hydrogen number density, and r is the distance from the gas cloud to the ionizing source). Changes in the ambient density (in the range $n_e \lesssim 10^{10}$ cm^{-3}, as stated by Kinkhabwala et al. 2002) do not change substantially the model predictions. Our model predictions on to the O VIII Lyα/O VII (f) ratio are shown in Fig. 2. The observed line ratios in CHRESOS are shown as grey, thin continuous lines.

PIE models fully reproduce the observed O VIII Lyα/O VII (f) ratio as long as the ionization parameter is in the range $2.7 < \log(\xi) < 4$ and the column density remains lower than 10^{22} cm^{-2}, in agreement with previous results of Kinkhabwala et al. (2002) and Kallman et al. (2014).

The nuclear SB, when present, can become important sources of X-rays too; they contribute to the X-ray spectra through different processes. The interstellar medium (ISM) can be heated up to very high temperatures ($T \sim 10^6$ K) due to winds of massive stars and supernovae (SNe) explosions. These processes account for thermal plasma emission, which mainly emerges in the soft X-ray band (Persic & Rephaeli 2002; Levenson et al. 2005; Mas-Hesse, Otí-Floranes & Cerviño 2008). But the bursts of star formation also give raise to accreting binary systems that are also sources of hard X-rays. While the latter processes are responsible for a power-law-type harder spectrum, the former produce a line-emission-dominated spectrum similar to (but still distinguishable in many aspects) that of PIE (Kinkhabwala et al. 2002).

We utilized XSPEC v12.9.1p and APEC v3.0.7 (Arnaud 1996) in order to obtain the line ratios. We used XSPEC FLUX command to calculate the fluxes of each line with respect to the underlying continuum model. For O VIII Lyα we considered the 0.647–0.661 band, and for O VII (f) the 0.556–0.566 keV band. We constructed a grid of APEC models considering 30 logarithmic steps in the plasma temperature: $0.04 < kT < 1.2$ keV. To obtain the underlying continuum level, we calculated the flux of the continuum model by setting the abundance parameter to zero. Then, we fixed the abundance to 30 logarithmic steps in the 0.01–4 range and we calculate the ratios by subtracting the
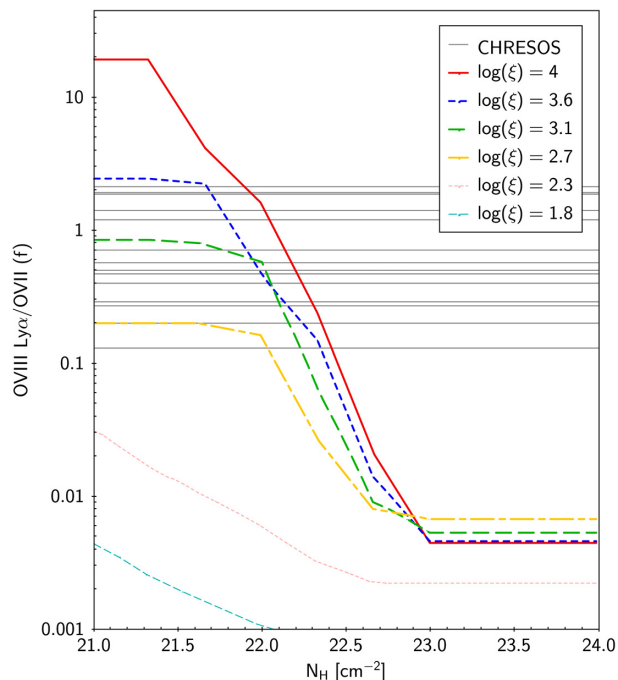

Figure 2. XSTAR model prediction on the O VIII Lyα/O VII (f) flux ratio as a function of column density (N_H) for different values of the ionization parameters. The thin (grey) horizontal lines represent our sources (see also Fig. 3).

flux obtained with the abundance fixed to zero as follows: $[F_2(kT, Z) - F_2(kT, Z = 0)]/[F_1(kT, Z) - F_1(kT, Z = 0)]$. By doing this, we observed that the line ratios were always independent of the abundance, as expected.

The results of CIE models are shown in the top panel of Fig. 3. The O VIII Lyα/O VII (f) flux ratio grows up while the gas temperature (kT) increases from 0.1 to ~0.8 keV. Most of the sources present O VIII Lyα/O VII (f) < 1, which means that collisional gas should have temperatures lower than 0.15 keV. Other few sources (5) show O VIII Lyα/O VII (f) up to 2.12, requiring a fitting temperature rising up to $kT \lesssim 0.25$ keV. This is illustrated in the bottom panel of Fig. 3, where we have shrunk the parameter space to the observed range of O VIII Lyα/O VII (f). Sources are shown individually over its own line ratio; the lowest (highest) ratios are shown in dotted (dashed) lines. According to the empirical criterion of Guainazzi & Bianchi (2007), SB contribution could be relevant for sources with O VIII Lyα/O VII (f) > 1, since this value represents (with an additional constraint on the total oxygen luminosity) the level at which SB could dominate the soft X-ray spectra. Hence, CIE models are able to reproduce all of our observations; there exists a set of parameters that can explain the observed data.

Our simple modelling of the PIE and CIE processes can predict the observed O VIII Lyα/O VII (f) line ratios. These results by themselves, however, are not enough to disentangle which is the main mechanism that powers the X-ray oxygen line emission.

4 MULTIWAVELENGTH CORRELATIONS

In the following, we are going to test O VII (f) and O VIII Lyα against proxies of the AGN and the SB ionizing power throughout correlations between luminosities. We have studied both flux and luminosity diagrams, and have discarded flux correlation analysis
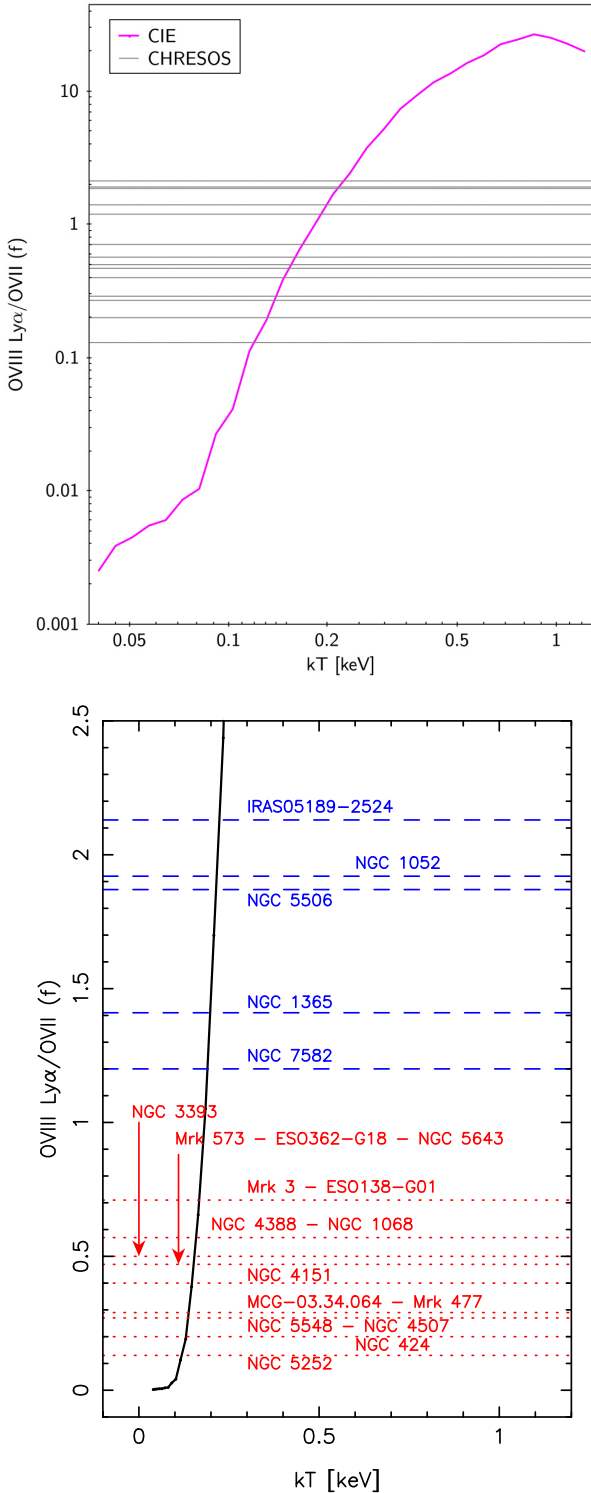
Figure 3. Top: CIE (APEC) model prediction on the O VIII Lyα/O VII (f) flux ratio. Bottom: CHRESOS sources shown individually according to their observed line ratios. The highest ratios (O VIII Lyα/O VII (f) > 1) are shown in (blue) dashed lines, while the lowest ratios are shown in (red) dotted lines. The continuous line represents the CIE model of the top panel.

because, in our very limited redshift range, all the corresponding relationships are heavily influenced by two sources that are significantly brighter than the others. They are the Seyfert 2 NGC 1068 and the Seyfert 1.5 NGC 4151. Their observed fluxes (both in O VII (f)

and O VIII Lyα) are almost two orders of magnitude higher than those for the remaining sample. In Appendix A, we will show that the luminosity correlations are not affected by the distance.

4.1 X-ray continuum photometry

In Fig. 4, we compare the luminosity of O VII (f) and O VIII Lyα with that of the primary continuum bands: 2–10 keV and the BAT band (14–195 keV). Hereafter, the sources are ordered in groups according to their Seyfert subtype: Seyfert 1–1.2 sources are plotted as empty (red) circles; Seyfert 1.5–1.9 are drawn as (blue) asterisks; and Seyfert 2 as filled (black) squares; not-yet-classified sources [as stated by NASA/IPAC Extragalactic Database (NED)] were drawn as empty (orange) diamonds.

We have chosen to work with two hard X-ray continuum bands with the aim of having direct, different, and complementary measurements of the primary continuum. Below 10 keV the central X-ray source in Seyfert 2 objects can be severely attenuated if the intervening column density is $N_H > 10^{22.5}$ cm^{-2}. Intermediate gas density ($N_H < 1.5 \times 10^{24}$ cm^{-2}) let the radiation above ∼10 keV penetrate the torus and reach the observer (Turner et al. 1997), but if the density is $N_H \gtrsim 3 \times 10^{24}$ cm^{-2} (the limit sets the Compton thick, CT, regime) the energy above 10 keV, i.e. the emission from the BAT band, will also be blocked (Meléndez et al. 2008; Weaver et al. 2010). We have a few CT sources in our sample, according to the last results of Baumgartner et al. (2013), Ricci et al. (2015), and Oh et al. (2018). In order to be conservative (2–10 keV luminosities from the literature are indeed absorption corrected), we have used the two bands. So even if the 2–10 keV luminosities were attenuated, the 14–195 keV luminosities would remain unaffected for most of the sample unless the column density is $\geq 10^{25}$ cm^{-2}. As long as our analysis is concerned, the CT sources do not occupy a specific locus in the 14–195 keV luminosity parameter space.

Linear fittings were performed in order to quantitatively analyse putative relationships among the luminosities. These and all other regression and correlation parameters are listed in Table 5: slopes and intercepts of every regression line; Spearman correlation coefficient, ρ_S; p-value, as a measurement of the statistical significance; and the sample size in each diagram. Data distribution and Spearman correlation coefficients suggest that the X-ray oxygen emission lines are more strongly correlated with the BAT band than with the 2–10 keV band. Note that the fitting slopes with the 2–10 and 14–195 keV bands are very different too, meaning that no single relationship applies to both of them.

According to the p-value, the relationship between O VII (f) and the hardest X-ray band (14–195 keV) is statistically significant (99 per cent confidence level). In fact, this is the strongest relationship we have found, out of five statistically significant relationships (boldfaced in Table 5). We have also ruled out that the correlation is governed by the distance by performing the so-called scrambling test (Appendix A). We obtain a probability lower than 1 per cent that the observed trend is driven by the distance.

4.2 IR/optical AGN spectroscopic indicators

In Fig. 5, we plot the luminosities of O VII (f) and O VIII Lyα against the luminosity of three multiwavelength proxies of the AGN ionizing power: [O III] in the top panels; [O IV] in the middle panels; and MIR 12 μm in the botttom panels. Linear fittings are superimposed on each diagram too; their parameters are listed in Table 5. Each one of the selected proxies holds one statistically significant relationship with the X-ray oxygen lines. These results are in agreement with
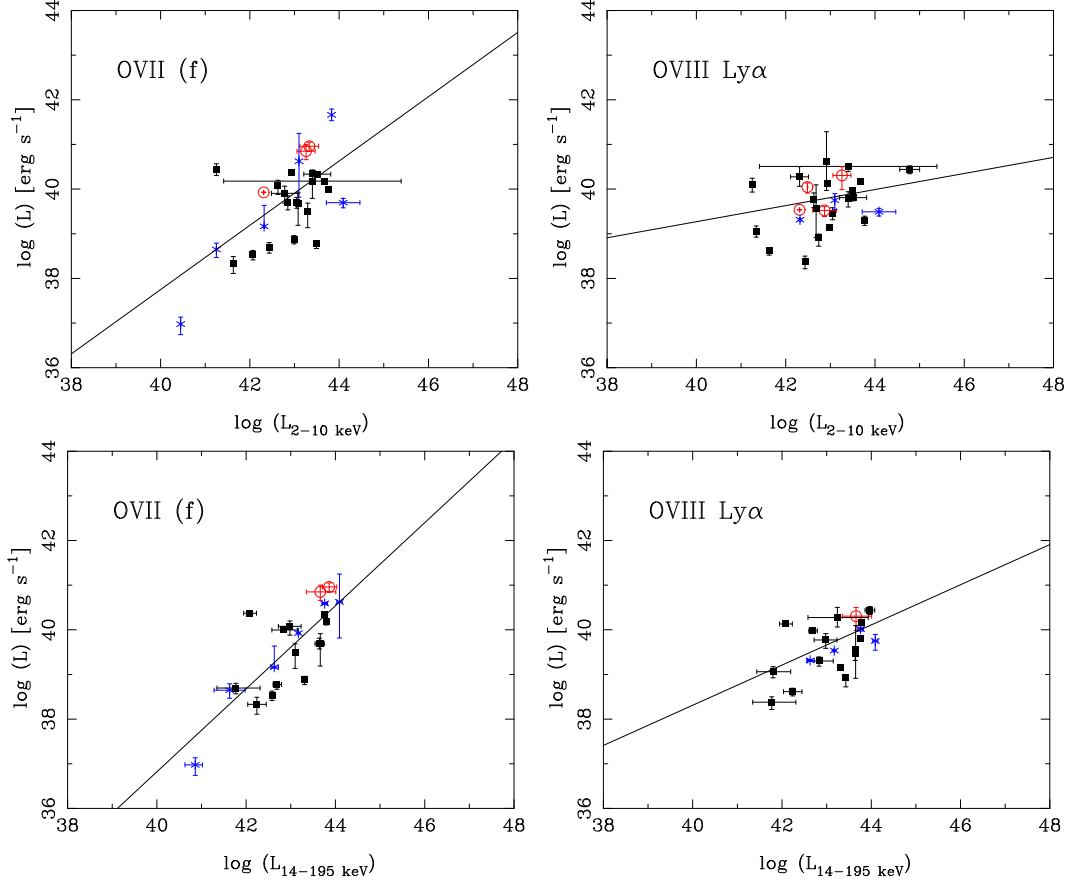
Figure 4. X-ray oxygen emission lines O VII (f) and O VIII Lyα versus the two primary, hard X-ray continuum bands: 2–10 keV (top panels) and 14–195 keV (bottom panels). Sources are described as follows: Seyfert 1–1.2 sources are plotted as empty (red) circles; Seyfert 1.5–1.9 as (blue) asterisks; and Seyfert 2 as filled (black) squares; unclassified sources were drawn as empty (orange) diamonds.. The continuous line represents the linear fitting.

Table 5. Linear fitting parameters, normalized to $L = 10^{40}$ erg s^{-1}.

Continuum band/proxy	Emission line	Slope	Intercept	ρ_S	*p*-value	Number of data points
2–10 keV	O VII (f)	0.72 ± 0.17	37.75 ± 0.49	0.45	1.2×10^{-2}	31
	O VIII Lyα	0.31 ± 0.13	39.22 ± 0.36	0.22	2.4×10^{-1}	29
14–195 keV	O VII (f)	0.93 ± 0.16	36.81 ± 0.49	0.77	$\mathbf{5 \times 10^{-5}}$	21
	O VIII Lyα	0.45 ± 0.16	38.2 ± 0.49	0.55	1.18×10^{-2}	20
[O III] λ5007 Å	O VII (f)	0.61 ± 0.11	39.28 ± 0.14	0.54	$\mathbf{3.29 \times 10^{-3}}$	28
	O VIII Lyα	0.3 ± 0.11	39.49 ± 0.13	0.48	1.46×10^{-2}	25
[O IV] 25.89 μm	O VII (f)	0.75 ± 0.15	38.94 ± 0.21	0.45	2.29×10^{-2}	25
	O VIII Lyα	0.53 ± 0.12	39.1 ± 0.16	0.68	$\mathbf{2.7 \times 10^{-4}}$	24
MIR 12 μm	O VII (f)	0.68 ± 0.12	37.59 ± 0.37	0.62	$\mathbf{1.26 \times 10^{-3}}$	24
	O VIII Lyα	0.57 ± 0.14	37.83 ± 0.45	0.61	2.14×10^{-2}	23
60 μm	O VII (f)	0.74 ± 0.19	37.04 ± 0.68	0.44	2.07×10^{-2}	28
	O VIII Lyα	0.42 ± 0.13	38.06 ± 0.49	0.51	$\mathbf{9.45 \times 10^{-3}}$	25
100 μm	O VII (f)	0.75 ± 0.22	36.87 ± 0.79	0.58	1.18×10^{-2}	18
	O VIII Lyα	0.46 ± 0.15	37.92 ± 0.57	0.55	1.75×10^{-2}	18

those of PIE models (Fig. 2): the same central ionizing field heats the gas in the 100-pc scale, and the gas cools down through emission of radiation. In that region ions with very different ionization states coexist. Under this hypothesis, the places where each emission line is formed within the NLR are strongly dependent on the gas density

profile as a function of distance to the radiation source, according to Bianchi et al. (2006) and Wang et al. (2011) and assuming that [O IV] can be formed there in the same way as [O III] does.

In this sense, Bianchi et al. (2019) recently showed that the RPC mechanism (Dopita et al. 2002; Draine 2011), which naturally drives
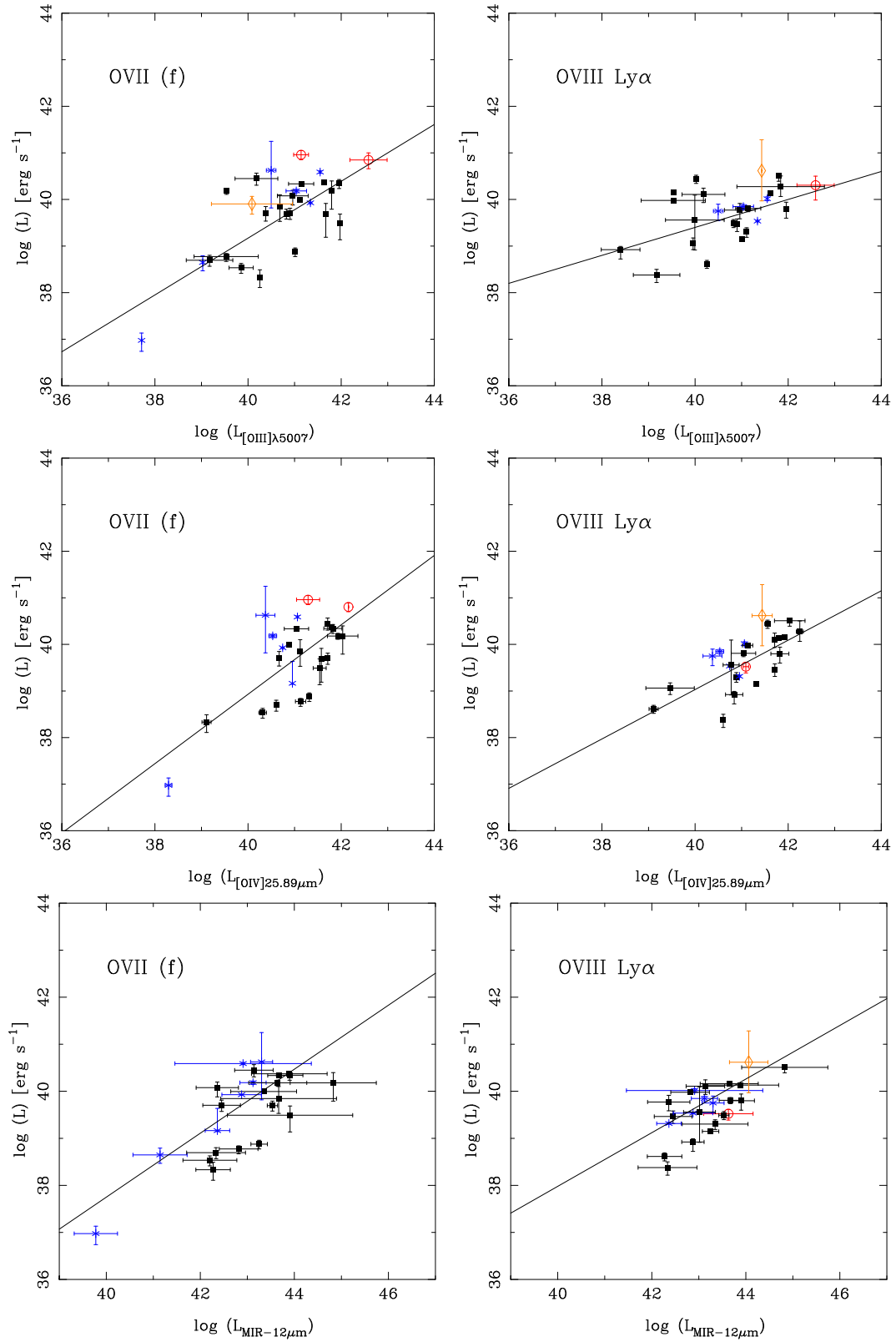
Figure 5. X-ray oxygen emission lines versus indicators of the AGN ionizing power: [O III] λ5007 Å from the optical (top panels); [O IV]25.89 μm from the IR (middle panels); and MIR 12 μm continuum (bottom panels). Sources are described in Fig. 4.

a density stratification in the gas clouds exposed to an ionizing field, can account for the soft X-ray spectra of CHRESOS sources. Bianchi et al. (2019) developed a theoretical differential emission measure (DEM)[1] for RPC context that nicely corresponds with the observed DEM in CHRESOS. Since the DEM gathers the contribution of every ionization zone in a nebulae to the total observed flux in a given emission line (and this applies to the entire soft X-ray spectrum), the relationships of Fig. 5 can also be understood in terms of RPC: the development of both the gas density profile and ionization profile within the NLR clouds may occur in response to the ionizing-field pressure exerted on them.

4.3 IR SB spectroscopic indicators

The very cold dust ($T \lesssim 40$ K) emission observed at FIR wavelengths both in AGNs and SB galaxies is widely accepted as a tracer of SB activity (Rodriguez Espinosa et al. 1986, 1987; Mouri & Taniguchi 1992; Hatziminaoglou et al. 2010). Cold dust is found in molecular clouds surrounding star-forming regions. Obviously, these regions can be located in the vicinity of the central engine (i.e. circumnuclear regions) and be affected by its radiation field, but even in those cases the heating of such cold gas and dust would be mainly produced by both UV photons and also non-ionizing photons from recently formed OB stars (Mouri & Taniguchi 1992; Magnelli et al. 2012), capable of penetrating higher density (lower temperature) gas, and reaching the dusty regions. In addition, the presence of high-mass X-ray binaries (HMXBs), low-mass X-ray binaries (LMXBs), young supernova remnants (SNRs), and cooling hot gas have made the star formation regions great laboratories to study how different emission processes take place. Such an analysis must be necessarily done in a multiwavelength approach, such as that of Tüllmann et al. (2006), who showed the relationships among radio (1.4 GHz), FIR (60 and 100 μm), Hα, B-band, UV, and soft X-rays.

While the radiation field of massive stars penetrates the cold phases of the ISM (gas and dust) and heats them triggering the FIR emission, the supernova explosions also accelerates free electrons producing the observed radio synchrotron emission: FIR and radio continuum (1.4 GHz) show a very well-known and very well-behaved relationship (van der Kruit 1973; Harwit & Pacini 1975; de Jong et al. 1985; Helou, Soifer & Rowan-Robinson 1985; Condon 1992; Tüllmann et al. 2006).

On the other side of the spectrum, the relationship between the soft X-ray band (0.5–3 and 0.3–2 keV) and FIR in SB is also largely known (Fabbiano 1989; Tüllmann et al. 2006; Rosa-González et al. 2007), and even the 2–10 keV has been proposed as an indicator of the star formation rate in some SB (Ranalli, Comastri & Setti 2003; Mas-Hesse et al. 2008, and references therein).

As we have already done with proxies of the AGN, we are also interested in probing connections between the X-ray oxygen emission lines and the SB activity throughout their FIR continuum fluxes at 60 and 100 μm. The diagrams are shown in Fig. 6. We found the same well-behaved relationship as in the other cases of study. The correlations with 100 μm luminosity are weaker than those with 60 μm luminosity, according to ρ_S. The O VIII Lyα versus 60 μm is the weakest relationship among the statistically significant ones (Table 5). Since our diagrams probe into relationships or connections driven by the SB radiation field, these correlations could be driven

by the correlation against the soft X-ray continuum described earlier.

However, the presence of HMXB, LMXB, hot plasma, SNR, and winds accounts for X-ray emission too. It is also known that the X-ray emission in SB can be generated by the injection of mechanical energy into the ISM through SN explosions, shocks, and/or stellar winds (Cerviño, Mas-Hesse & Kunth 2002; Persic & Rephaeli 2002; Mas-Hesse et al. 2008). The modelling of Castellanos-Ramírez et al. (2015) also showed that SN explosions are the main responsible for the injection of mass and energy that produce the observed soft and hard X-ray emission. Then, collisional processes should not be neglected in this analysis. As it was shown in Fig. 3, our model (albeit rather simple) tell us that there is a range of gas temperature where CIE can reproduce the observed O VIII Lyα/O VII (f) ratios. So, if a contribution from SB activity on to both the formation and observed intensities of O VII (f) and O VIII Lyα is indeed relevant, it is likely a product of CIE processes. A stratified nebula would be mandatory in this case, since the critical densities of these lines decrease while the oxygen ionization state increases ($n_{\rm crit}^{\rm [O III]} = 10^{5.845}$ cm^{-3}, Peterson 1997; $n_{\rm crit}^{\rm O VIII} = 10^{1.961}$ cm^{-3}, Goddard & Ferland 2003; $n_{\rm crit}^{\rm [O IV]} = 10^{4.06}$ cm^{-3}, Rigby, Diamond-Stanic & Aniano 2009).

5 SUMMARY AND CONCLUSIONS

The most complete soft X-ray oxygen emission-line observations up to now was combined with a variety of continua and emission-line data from the literature in different wavelengths aiming to identify the main process that give raise to such emission. Hard and very hard X-rays, FIR, and MIR continua, as well as optical and IR emission lines, were tested against the best-quality measurements of O VII (f) and O VIII Lyα so far obtained, through diagnostic diagrams to identify whether their formation is better associated with the AGN or to the SB ionizing power. We have seen that, in the latter case, the ionizing power is almost restricted to collisional ionizing processes since the energy required to photoionize the oxygen ions up to the highest levels cannot be reached by photons from *normal* SB radiation fields.

Our theoretical analysis shows that both photoionization and collisional ionization models are capable of predicting the observed O VIII Lyα to O VII (f) ratios, for a limited range of parameters, i.e. ionization parameter in combination with column density and gas temperature (and ambient density).

We have combined the X-ray oxygen emission-line luminosities with those of AGN and SB proxies, and with two hard X-ray continuum bands. Regression and correlation analyses were performed in order to find and assess for significant relationships. We have found five statistically significant relationships (at 99 per cent confidence level) according to their p-values. Three of them arise with optical/IR proxies of the AGN power in the NLR.

We conclude that the soft X-ray oxygen emission lines (being O VII (f) and O VIII Lyα our workhorses) are mainly powered by the AGN, whose radiation field can easily account for the high-energy photons required to let the oxygen six or seven times ionized. A density profile such as $\sim r^{-2}$ (Bianchi et al. 2006; Wang et al. 2011) and the interplay between the ionizing field and the column density $N_{\rm H}$ (Kallman et al. 2014) play a decisive role in this case. The recent results of Bianchi et al. (2019) on RPC scenario also point to the AGN as the main source of ionizing photons in the very same CHRESOS sample. Collisional processes principally linked to (but not restricted to) SB scenario, however, cannot be neglected at all and they might represent an important contribution in some cases. Only by enlarging the sample we will be able to both improve our knowledge on the

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[1]The differential emission measure distribution is defined as DEM = d(EM)/d(log ξ), where EM is the emission measure, EM = $\int_V n_e^2 \, dV$, and V is the emitting-gas volume.
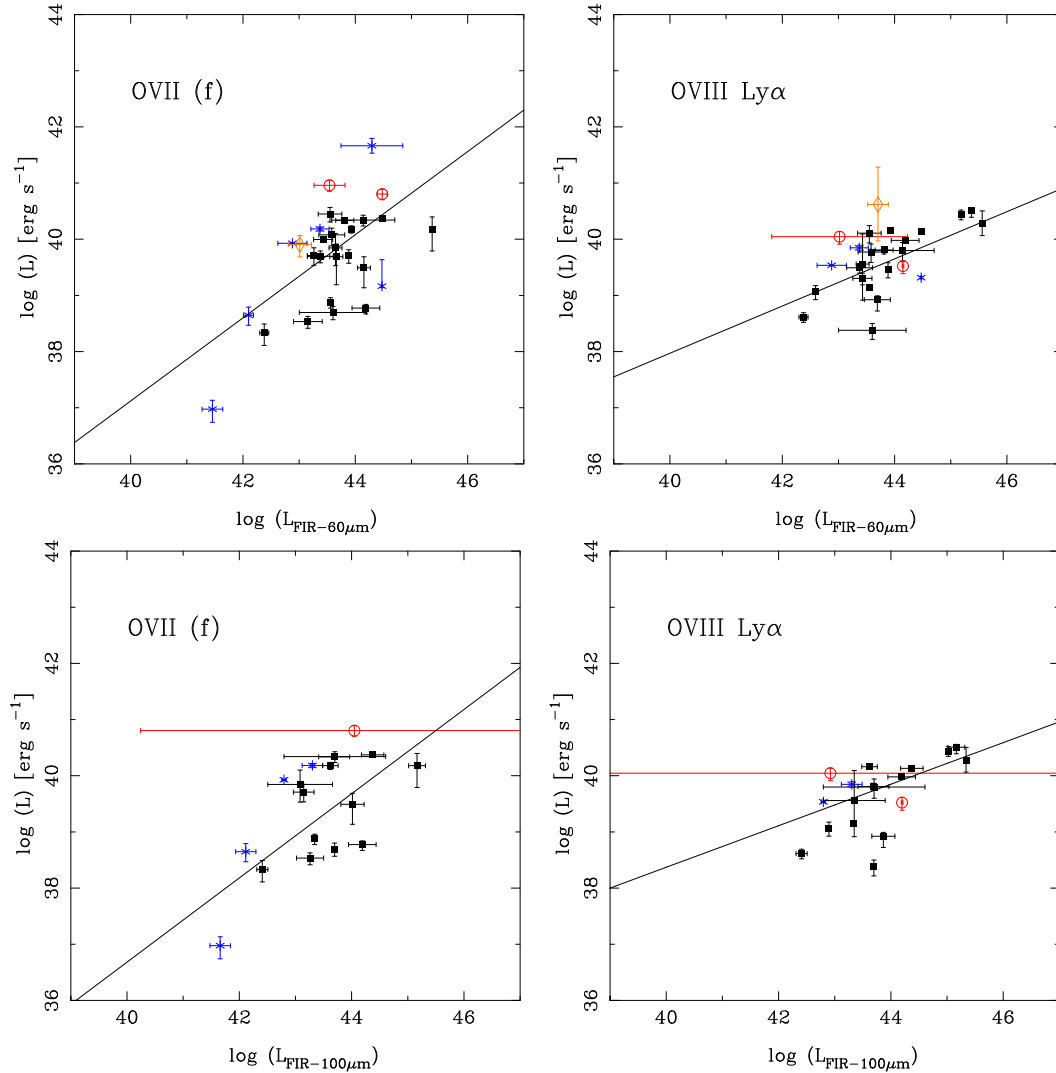
Figure 6. X-ray oxygen emission lines versus proxies of the SB activity: FIR fluxes at 60 μm (top panels) and 100 μm (bottom panels). Sources are (colour) symbol coded as in Fig. 4.

place where these lines are formed and quantify the role that SB activity plays.

DATA AVAILABILITY

The data underlying this paper are available in the paper and in its online supplementary material.

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APPENDIX A: CHECKING FOR SPURIOUS LINEAR FITTINGS: SCRAMBLING TEST

In order to verify that the luminosity–luminosity correlations in Section 4 is not dominated by a distance bias, we have performed the so-called scrambling test as proposed by Bianchi et al. (2009, and references therein). The aim of the analysis is as follows: we find a statistically significant relationship between two observed quantities; if we replace one of those quantities by a simulated data set, we expect not to recover the former real, physical, legitimate relationship between the two set of real data because there exists non-physical relation between one real data set and the other fake data set.

We have applied the test on to the best (most significant) relationship we have found, this is O VII (f) versus 14–195 keV. Two observed quantities are involved (the luminosities), which depend upon several parameters. For the simulated data sets we keep the parameter whose influence we are interested in testing for: the distance. To do so, we simulated 10^5 of these sets, by assigning a randomly generated value of O VII (f) *flux* (from a total of 2×10^6) $F^*_{\mathrm{O\,VII(f)}}$ to each fixed pair of observed BAT *luminosity* and redshift (L_{BAT}, z). $F^*_{\mathrm{O\,VII(f)}}$ values are then transformed to luminosities ($L^*_{\mathrm{O\,VII(f)}}$) (simulated O VII (f) *luminosity*) by using their z. The sample size of each new set is the same as that of the real one (21 data points), otherwise the statistical result would not be comparable.

On each of the 10^5 simulated data sets we performed the linear fittings and correlations analysis between L_{BAT} and $L^*_{\mathrm{O\,VII(f)}}$, i.e. the scrambling test. We need to know whether that large amount of correlations is acceptable or not according to the distribution (histogram) of emerging correlation coefficients (Spearman) in comparison with the real, observed one. The results are shown in Fig. A1. The histogram on the top panel represents the resulting Spearman correlation coefficients (ρ_S) of all simulated data sets; a vertical line superimposed on it shows the real one, ρ^r_S (see Table 5). The bottom panel shows the histogram of slopes, for completeness; it shows that the real slope (i.e. the slope in the observed data fitting) lies well within the distribution of random slopes. The main result of the test is that the mode of the distribution/histogram of correlation
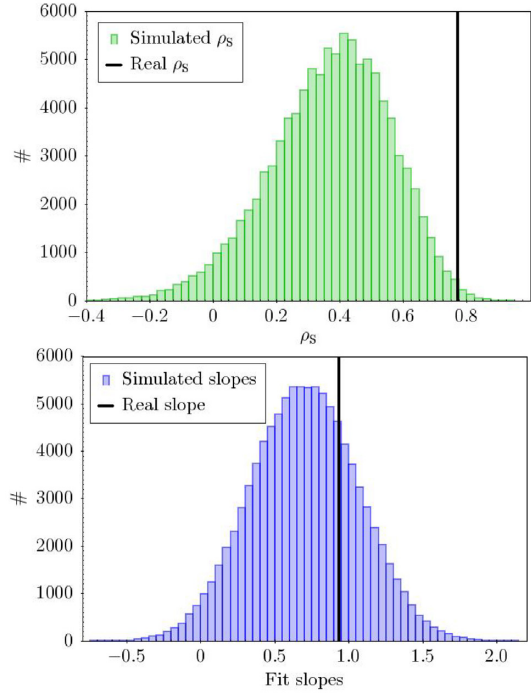

Figure A1. Scrambling test: histogram of ρ_S for the simulated data sets (top) and histogram of fit slopes (bottom). The vertical lines superimposed on each plot represent ρ_S and the slope for the real data set (see Table 5).

coefficient is $\rho^m_S \sim 0.42$. Since $\rho^m_S < \rho^r_S$ (i.e. ρ^m_S is less than the real, observed one, 0.77), this means that simulated data correlations are weak in comparison with the observed one. From the entire sample of 10^5 simulated data sets, only less than 1000 have a correlation coefficient higher than ρ^r_S. We then obtain a result in agreement with the test's hypothesis: there exists a genuine correlation on observed data that fades away when the simulated data are used. Hence, the probability that the observed $L_{\mathrm{O\,VII(f)}}$ versus L_{BAT} correlation (Fig. 4) would be distance driven is lower than 1 per cent.

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